SHUTTLE CRYOGENIC SUPPLY SYSTEM
OPTIMIZATION STUDY
INTERIM PRESENTATION

30 September 1971

NAS 9-11330
PROGRAM SUMMARY

MAJOR CONCLUSIONS

RESULTS OF EVALUATIONS OF SUBSYSTEMS

RESULTS OF INTEGRATED SYSTEMS EVALUATIONS

COMPONENT EVALUATIONS RESULTS

TECHNOLOGY EVALUATIONS SUMMARY
LIFE SUPPORT SUPPLY SYSTEM
(INCLUDING ENVIRONMENTAL CONTROL ASPECTS)

POWER GENERATION
- FUEL CELL SUPPLY SYSTEM
- AUXILIARY POWER UNIT SUPPLY SYSTEM

PROPELLANT SUPPLY
- ORBIT INJECTION PROPULSION (ASCENT)
- ORBIT MANEUVER PROPULSION
- ATTITUDE CONTROL PROPULSION
- AIRBREATHING PROPULSION (INERTING ONLY)
- PURGING, INERTING, AND PNEUMATIC
OBJECTIVE:

TO PROVIDE SUFFICIENT INFORMATION AND RECOMMENDATIONS TO ALLOW NASA TO SELECT SPACE SHUTTLE CRYOGENIC SUPPLY SYSTEMS

MAJOR OUTPUTS:

- EVALUATIONS OF CONCEPTS
- SUFFICIENT INFORMATION TO ALLOW SELECTION OF REPRESENTATIVE DESIGNS
- DOCUMENTATION AND DATA BANKS OF CRYOGENIC SUPPLY SYSTEM RELATED DATA AND INFORMATION
- DEVELOPMENT OF AN INTEGRATED MATH MODEL FOR SUPPORT OF HARDWARE PROGRAMS (COMPUTER PROGRAMS WITH REFERENCE DESIGN PARAMETRIC DATA)
- PARAMETRIC DATA AND SENSITIVITY STUDIES
- EVALUATION OF RELATED TECHNOLOGY STATUS
TASK RELATIONSHIPS

TASK 1
CONCEPT EVALUATIONS
- REQUIREMENTS AND CRITERIA
- SUBSYSTEM EVALUATION
- INTEGRATED SYS EVALUATIONS

TASK 2
CRITICAL COMPONENT ANALYSIS
- COMPONENT CAPABILITY EXAMINATION
- REDUNDANT COMPONENT MODE ANALYSIS
- FAILURE MODE AND EFFECTS AND CRITICALITY ANALYSIS

TASK 3
ANALYTICAL CHARACTERIZATION
- SUBSYSTEM AND INTEGRATED SYSTEM CHARACTERIZATION
- INTEGRATED MATH MODEL
- DATA GENERATION

TASK 4
SYSTEM INTEGRATION AND MISSION APPLICATION ANALYSIS
- INTERFACE
- SAFETY AND MISSION COMPLETION

TASK 5 - DOCUMENTATION OF WBS TASK

TASK 6 - REPORTS AND REVIEWS
PROGRAM SCHEDULE

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Approximate Study Expenditure Breakdown

Integrated Math Model - 21%

Components 27.5% (53% of system and integrated system evaluation)

Subsystems and integrated systems evaluations - 52%

Cryogenic cooling 8.9% (components 20% of this task)

Reporting 18%
OVERALL APPROACH TO CONCEPT EVALUATIONS

CANDIDATE
SUBSYSTEMS

COMPONENT
EVALUATIONS

SUBSYSTEM
DETAILED
ANALYSES

CANDIDATE
INTEGRATED
SYSTEMS

SYSTEMS
EVALUATION

INTEGRATED
SYSTEM
EVALUATIONS

INTEGRATED
SYSTEM
TRADEOFF
STUDIES

INTEGRATED
SYSTEM
DATA
DISPLAYS

COMPONENT
PARAMETRIC
DATE

COMPONENT
DATA

RELIABILITY
AND
RELIABILITY
ANALYSIS

TECHNOLOGY
EVALUATION

CRITERIA
AND
REQUIREMENTS

SAFETY
EVALUATIONS

UPDATED
SUBSYSTEMS

SUBSYSTEM
SENSITIVITY
STUDIES

SUBSYSTEM
TRADEOFF
STUDIES

SUBSYSTEM
DATA
DISPLAYS

INSTRUMENTATION
AND
CONTROL
MAJOR STUDY CONCLUSIONS

OPTIMUM INTEGRATED SYSTEMS TEND TOWARDS MAXIMIZING LIQUID STORAGE

VACUUM JACKETING OF TANKS IS A MAJOR EFFECT ON INTEGRATED SYSTEMS

SUBCRITICAL STORAGE ADVANTAGES OVER SUPERCritical STORAGE DECREASES AS THE QUANTITY OF PROPELLANT OR REACTANT DECREASES.

SHUTTLE DUTY CYCLES ARE NOT SEVERE

OPERATIONAL MODE HAS A SIGNIFICANT EFFECT ON RELIABILITY

COMPONENTS ARE AVAILABLE FOR MOST SUBSYSTEM APPLICATIONS

SUBSYSTEMS AND COMPONENTS REQUIRE A MINIMUM AMOUNT OF TECHNOLOGY DEVELOPMENT
CRYOGENIC RELATED SUBSYSTEMS FOR CURRENT SHUTTLE CONCEPT:

- ORBIT INJECTION SUPPLY
- FUEL CELL SUPPLY
- LIFE SUPPORT SUPPLY
- PURGING, INERTING, AND PNEUMATIC SUPPLY
- CRYOGENIC COOLING (IF IMPLEMENTED)
- CRYOGENIC HELIUM PRESSURIZATION SUPPLY FOR STORABLES
ORBIT MANEUVERING

PROPELLANT SUPPLY
APPROACH TO ORBIT MANEUVERING PROPELLANT SUPPLY EVALUATIONS (NONINTEGRATED)
ORBIT MANEUVERING SUPPLY LO₂ FEED/FILL
MCDONNELL-DOUGLAS ORBITER

D02614
11m
ORBIT MANEUVERING SUPPLY LH₂ FEED/FILL
MCDONNELL-DOUGLAS ORBITER
ORBIT MANEUVERING SUPPLY LO₂ FEED/FILL
NORTH AMERICAN ROCKWELL ORBITER
ORBIT MANEUVERING SUPPLY LH₂ FEED/FILL

NORTH AMERICAN ROCKWELL ORBITER
OMPS FEED SYSTEM CONFIGURATION

LH₂

LO₂

ENGINE WITH PUMPS

PUMPS LOCATED AT TANK

START TANKS

SEPARATE TANKS

CASCADE TANKS
ORBIT MANEUVERING PROPULSION SUPPLY
GHe PRESSURIZATION - DUAL TANKS

PUMP AT ENGINE - (ONE PROPELLANT LOSS)

TO COMMON VENT SYSTEM (TYP)

\[ \dot{m} = 14.1 \text{ lb/sec} \]

DIA M - SEE TABLE 3-2

\[ \dot{m} = 26.2 \text{ lb/sec} \]

DIA M - SEE TABLE 2-2

\[ \dot{m} = 5.6 \text{ lb/sec} \]

DIA M - SEE TABLE 2-2

\[ \dot{m} = 2.8 \text{ lb/sec} \]

DIA M - SEE TABLE 3-2

\[ \dot{m} = 1.8 \text{ lb/sec} \]

DIA M - SEE TABLE 3-2

D03750
ORBIT MANEUVERING PROPULSION SUPPLY
GHe PRESSURIZATION - DUAL TANKS
PUMP AT ENGINE (5 AND 12 PROPELLANT LOSSES)
ORBIT MANEUVERING PROPULSION SUPPLY

GO2/GH2 PRESSURIZATION - SINGLE TANKS

PUMP AT ENGINE

T = 350°F, P = 700 PSIA, 0.75 IN. DIAM

\[ \Phi = 28.2 \text{ LB/SEC DIAM - SEE TABLE 3-2} \]

T = 350°F, P = 700 PSIA, 1.00 IN. DIAM

\[ \Phi = 5.6 \text{ LB/SEC DIAM - SEE TABLE 3-2} \]
FEEDLINE SCHEMATIC - PUMPS AT THE TANKS

NOTE: OPTIMUM LINE DIAMETER SAME FOR DUMP CASES 1 THROUGH 12
DETAILED ANALYSES
OMPS PRESSURIZATION ANALYSES SUMMARY

• VARIABLES:
  - HELIUM AND PROPELLANT GASES
  - INLET TEMPERATURES
  - EXPULSION PRESSURES
  - VENT PRESSURES
  - INSULATION THICKNESS
  - TANK GEOMETRY
  - DUTY CYCLES

• PREPRESSURIZATION:
  - MASS AND ENERGY BALANCES

• PRESSURIZATION:
  - MASS AND ENERGY BALANCE
  - HEAT TRANSFER BETWEEN ULLAGE AND TANK WALLS
  - HEAT ENTERING TANK EXAMINED FOR BOTH STORAGE AND BOILOFF
EFFECT OF INLET FLOW RESTRICTION ON SURGING

Peak Pressure Surge, psia

Inlet Orifice Diameter, Inches

- $\text{LO}_2 - D = 1.0''$
- $\text{LH}_2 \text{ Aft-D} = 1.0''$
- $\text{LO}_2 - D = 2.0''$
- $\text{LH}_2 \text{ Fwd-D} = 1.5''$
- $\text{LH}_2 \text{ Aft-D} = 3.0''$
# RESULTS OF FEEDLINE CHILLDOWN COMPUTATIONS

<table>
<thead>
<tr>
<th>Feed System Configuration</th>
<th>Mean Line Diameter (in.)</th>
<th>Inlet/Outlet Orifice Diameters (in.)</th>
<th>Childdown Time (sec)</th>
<th>Childdown Propellant (lb)</th>
<th>Estimated Max Surge Pressure (psia)</th>
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<tbody>
<tr>
<td>LH₂ Forward</td>
<td>1.50</td>
<td>None</td>
<td>5.1</td>
<td>15.1</td>
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<tr>
<td>LH₂ Forward</td>
<td>1.50</td>
<td>0.50/0.50</td>
<td>22.7</td>
<td>14.6</td>
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<td>LH₂ Aft</td>
<td>3.00</td>
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<td>26.2</td>
<td>75.0</td>
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<td>LH₂ Aft</td>
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<td>1.00/1.00</td>
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<td>LO₂</td>
<td>2.71&lt;sup&gt;(2)&lt;/sup&gt;</td>
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<td>LO₂</td>
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<td>6.1</td>
<td>8.2</td>
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<td>0.125/0.125</td>
<td>~300</td>
<td>7.9</td>
<td>30.0</td>
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</table>

**Notes:**

1. Inlet Pressure = 25 psia
2. Upstream Line Diameter = 2.00 in.
SENSITIVITY STUDIES
OMPS PROPELLANT STORAGE SYSTEM COMPARISON
(168-HOUR MISSION)

BASED ON LH₂ OPTIMUM INSULATION
OF 2 IN. SUPERFLOC IF SINGLE TANK
AND 2-1/4 IN. IF DUAL TANK
SENSITIVITIES OF LINE SIZE, START TRANSIENT, AND LINE RECOVERY
-LO₂ IN AFT TANKS (PUMP-AT-ENGINE)

PROPELLANT LOST AFTER EACH ENGINE OPERATION (5 OPERATIONS)

THrust = 15,000 LB
Iₜₚ = 444 SEC

WEIGHT PENALTY (LB)

PROPELLANT LOST ONLY ONCE

NEW TRANSIENT

RL-10 TRANSIENT

LINE DIAMETER (IN.)

WEIGHT PENALTY

- TANK
- LINE
- LOST PROPELLANT
- HELIUM PRESSURANT
- GH₃ RESIDUAL
- HELIUM STORAGE

DO2655 (1)

27
SENSITIVITIES OF LINE SIZE AND PROPELLANT RECOVERY
- LO₂ IN AFT TANKS (PUMP-AT-TANK)

THrust = 15,000 LB
Iₚ = 444 SEC

RL-10 OR NEW TRANSIENT

WEIGHT PENALTY (LB)

LINE DIAMETER (IN.)

12 DUMPS
5 DUMPS

1 DUMP

PROPELLANT LOST ONLY ONCE
SENSITIVITIES OF LINE SIZE, START TRANSIENT, AND LINE RECOVERY
-LH₂ IN AFT TANKS (PUMP-AT-ENGINE)

SINGLE LINE (CONSTANT DIAMETER)

THrust = 15,000 LB
\( I_{sp} = 444 \text{ SEC} \)

- RL-10 TRANSIENT
- NEW TRANSIENT
- PROPELLANT LOST ONLY ONCE
- PROPELLANT LOST AFTER EACH ENGINE OPERATION (5)
- 12 DUMPS
- 5 DUMPS
- 1 DUMP

WEIGHT PENALTY (LB)

LINE DIAMETER (IN.)

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Ilm
SENSITIVITIES COMPARISONS - H₂ IN AFT TANK
(PUMP-AT-TANK)

F = 15,000 LB, Iₚₑₙ = 444 SEC, O/F = 5.0
DUAL LINES (CONSTANT - DIAMETER)

WEIGHT - LB

LINE DIAMETER - IN.
START TANK CONFIGURATION

ASSUMED OPERATIONAL SEQUENCE - LH₂ TANK

TO RUN PRESSURE

OPEN INTERCONNECT VALVE

ASSUMPTIONS
3-IN. FEEDLINE
RL-10 ENGINE
He SPRING
VAPOUR PRESSURE = 16 PSIA

START TANK PRESSURE - He

MINIMUM START TRANSIENT PRESSURE AT START TANK

MINIMUM STEADY-STATE PRESSURE AT START TANK

H₂ PUMP

CHILDDOWN 100 SEC

START TRANSFER 2-3 SEC

MAIN TANK PROPELLANT SETTLING 5 SEC

START TANK REFILL TIME 4-5 SEC

STEADY-STATE BURN TIME ≥ 10 SEC

ENGINE H₂ BLEED

MAIN TANK PRESSURIZATION

MAIN TANK PRESSURE COLLAPSE

TIME (SEC) - NO SCALE
## OMPs System Characteristics

<table>
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<tr>
<th>CASE NO.</th>
<th>TANK CONFIGURATION</th>
<th>PUMP LOCATION</th>
<th>PRESSURANT</th>
<th>NUMBER OF DUMPS</th>
<th>O2 DUMP DIAMETER (IN.)</th>
<th>H2 DUMP DIAMETER (IN.)</th>
<th>ULLAGE PRESSURE (PSIA)</th>
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<td>3</td>
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<td>3 1/4</td>
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<td>12</td>
<td>2/3</td>
<td>3/3</td>
<td>34.4</td>
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**NOTE:** FOR THE DUAL TANK CASE, FEEDLINE DIAMETERS SIGNIFY: TANK OUTLET TO COMMON POINT/COMMON POINT TO ENGINE INLET.
## OMPS Weight Comparison

(All comparisons based on $I_{sp} = 444$, $O/F = 5.0$)

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<th>System Weight (lb)</th>
<th>Number of Propellant Feedline Dumps</th>
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### GO2/HH2 - Single Tank

- **Pump at Engine**
  - **Dry**: 3,249, 2,517, 3,423, 2,689, 3,676, 2,915
  - **Wet**: 32,357, 31,716, 32,825, 32,152, 33,542, 32,871

- **Pump at Engine Idle MODE START**
  - **Dry**: 2,655, 1,923, 2,679, 1,945, 2,856, 2,095
  - **Wet**: 31,763, 31,122, 31,936, 31,408, 32,722, 32,051

- **Pump at Tank**
  - **Dry**: 2,828, 2,144, 2,831, 2,138, 2,834, 2,145
  - **Wet**: 31,550, 30,940, 31,545, 30,894, 31,684, 31,035

### GH2 - Single Tank

- **Pump at Engine**
  - **Dry**: 2,657, 1,961, 2,715, 2,021, 2,812, 2,112
  - **Wet**: 31,500, 30,947, 31,707, 31,150, 32,079, 31,507

### GH2 - Single Tank

- **Pump at Tank**
  - **Dry**: 2,407, 1,665, 2,403, 1,663, 2,408, 1,665
  - **Wet**: 31,082, 30,410, 31,070, 30,401, 31,211, 31,538

### GH2 - Dual Tanks

- **Pump at Engine**
  - **Dry**: 3,097, 2,267, 3,280, 2,332, 3,367, 2,357
  - **Wet**: 31,989, 31,269, 32,355, 31,516, 32,955, 32,112

### Cascade Tank

- **Dry**: 3,273, 2,604
  - **Wet**: 32,532, 31,922

**D03714(1)**

Ilm
CONCLUSIONS REGARDING ORBIT MANEUVERING PROPELLANT SUPPLY (NONINTEGRATED)

- PUMP-AT-TANK LOWER WEIGHT SYSTEM
- HELIUM PRESSURIZATION RESULTS IN LOWER PRESSURIZATION WEIGHTS
- \( \text{GO}_2/\text{GH}_2 \) PRESSURIZATION:
  - SENSITIVITY TO DUTY CYCLE
  - USED ONLY WITH ORIENTED PROPELLANT
  - PROPELLANT ACQUISITION THERMAL PROBLEMS MORE SERIOUS
- VACUUM-JACKETED TANKS AND LINES HEAVIER, BUT PROTECT REUSABLE INSULATION SYSTEMS
- FEEDLINE SIZING AND PROPELLANT CONSERVATION IMPORTANT SENSITIVITIES
- USE OF CASCADE TANKS RESULTS IN WEIGHT PENALTY AS COMPARED TO DUAL TANKS
- START TANK NOT APPLICABLE TO NONINTEGRATED OMPS
ORBIT INJECTION PROPULSION SUPPLY
APPROACH TO ORBIT INJECTION PROPELLANT SUPPLY EVALUATIONS (NONINTEGRATED)
LO$_2$ TANKAGE AND FEEDLINE ARRANGEMENT
(NA-R HCR ORBITER)
LH₂ TANKAGE AND FEEDLINE ARRANGEMENT
(NA-R HCR ORBITER)
LO2 TANKAGE AND FEEDLINE ARRANGEMENT
(MACDONNELL-DOUGLAS HCR ORBITER)
LH$_2$ TANKAGE AND FEEDLINE ARRANGEMENT
(MACDONNELL-DOUglas HCR ORBITER)
COMMON VENT AND PRESSURIZATION LINES
COMMON PRESSURIZATION AND VENT LINES

GROUND VENT CONTROL
ASCENT (2160K FOR H₂) VENT CONTROL
WHEN ENGINE IS NOT RUNNING
AND WHEN ENGINE IS RUNNING

PREPRESSURE CONTROL
FROM ACPS

ENGINE INTERFACE
STEADY-STATE BOILOFF RATES

UNINSULATED O₂ TANK N₂ BLANKET AT 80°F

\[ \Delta h_{av} = 2.92 \text{ BTU/HR} \text{ FT}^2 \text{ OR} \]

\[ \Delta h_{v} = 90 \text{ BTU/LB} \]

MAX FAST FILL RATE
(3350 GPM)
VENT LINE PRESSURE LOSSES

VAPOR AT SAT. TEMP.
- - O₂
- - - H₂

MAX FAST FILL RATES
LO₂: 3350 GAL/MIN (1.9x10⁶ LB/HR)
LH₂: 11,970 GAL/MIN (415x10⁶ LB/HR)

MO₂ GAS = 1.958 LB/SEC
MH₂ GAS = 2.36 LB/SEC

PRESS. DROP ∝ (FILL RATE)²

VAPOR AT SAT. TEMP.

VENT LINE PRESSURE DROP PER VALVE (LB/IN²)

VENT LINE PRESSURE DROP PER VALVE (LB/IN²)

VENT LINE DIAMETER (IN)

3.0 4.0 5.0 6.0 7.0 8.0

Pi = 16 PSIA
Pi = 25 PSIA
Pi = 16 PSIA
Pi = 25 PSIA
GEOMETRIC EFFECTS ON LINE INLET PRESSURE - OXYGEN

![Graph showing geometric effects on line inlet pressure for oxygen with various line diameters and lengths.]

- L = 150 FT
- L = 90 FT
- L = 30 FT
- L = 0 FT

Po TANK = 32 PSIA
PRESSURIZATION APPROACHES
SENSITIVITY OF ORBIT INJECTION SUPPLY G0₂ RESIDUALS TO PRESSURANT INLET AND TEMPERATURE AND INSULATION CONDUCTIVITY

![Graph showing the sensitivity of orbit injection supply G0₂ residuals to pressurant inlet and temperature and insulation conductivity.](image)
SENSITIVITY OF ORBIT INJECTION SUPPLY $\text{GH}_2$
RESIDUALS TO PRESSURANT INLET AND
TEMPERATURE AND INSULATION CONDUCTIVITY

**Graph:**
- **Y-axis:** Residual Vapor Mass (LBm)
- **X-axis:** Pressurant Gas Inlet Temperature ($^\circ$R)
- **Legend:**
  - Insulation Thickness (IN.)
    - 0.50
    - 1.25
    - 2.00
- **Note:**
  - VENT PRESSURE 40 PSIA

**Figure Reference:**
DO2972

**Page Number:**
49
COMPARISON OF OIPS PRESSURIZATION METHODS
(OXYGEN TANK RESIDUALS PER TANK)

PRESSURANT TEMPERATURE = 700°F

- PRESSURIZED WITH
  CONSTANT FLOWRATE
  VENT - 25 PSIA

- PRESSURIZED WITH
  INTERMITTENT FLOW
  VENT - 25 PSIA

RESIDUAL GAS WEIGHT (LB)

INSULATION THICKNESS (IN.)

D03812 (1)
Hm
OIPS OXYGEN TANK VENTED WEIGHT PER TANK
WITH CONSTANT FLOWRATE PRESSURIZATION

![Graph showing the relationship between vented oxygen weight (lb) and insulation thickness (in.).](image-url)
COMPARISON OF OIPS PRESSURIZATION METHODS
(HYDROGEN TANK RESIDUALS PER TANK)

PRESSURIZED WITH INTERMITTENT FLOW
40 PSIA VENT

PRESSURIZED WITH CONSTANT FLOW RATE
40 PSIA VENT

RESIDUAL GAS WEIGHT (LB)

280
270
260
250
240
230

0.25 0.5 0.75 1.0 1.25 1.5 1.75 2.0 2.25

INSULATION THICKNESS (IN.)

D03788
Ilm
NO INSULATION

ENGINE START

LIFTOFF

ULLAGE PRESSURE (PSIA)

TIME FROM GROUND VENT CLOSURE (SEC)
LOX ASCENT TANK DRAINED LIQUID TEMPERATURE

(SELF-PRESSURIZED)

TEMPERATURE (°R)

TIME FROM GROUND VENT CLOSURE (SEC)

166.5
166.0
165.5
165.0
164.5
350 450 550 650
SELF-PRESSURIZED LIQUID-OXYGEN ORBIT INJECTION TANK

VAPOR RESIDUALS VS INSULATION THICKNESS

Graph showing the relationship between vapor residuals (in pounds) and insulation thickness (in inches). The curve indicates an increase in vapor residuals as the insulation thickness increases.
ONBOARD PREPRESSURIZATION

ORBIT INJECTION PROPULSION SYSTEM - LH\textsubscript{2} TANKS

![Graph showing storage pressure vs. total storage weight for hydrogen and helium in LH\textsubscript{2} tanks.](image)

- Ambient storage titanium tanks
- Stored gas weight (lb)
- Storage pressure (PSIA)
- Total storage weight (lb)

DO2981 (1)

IIm
FEEDLINE TEMPERATURE CONTROL
REQUIRED PUMP SHAFT HORSEPOWER FOR CIRCULATION LH₂ TANKS

CIRCULATION LINE SIZE: 2 IN. DIA
PUMP EFFICIENCY: 72%
ENGINE RECIRCULATION VALVE AREA: 1.5 IN.²

PUMP SHAFT POWER (HP)

CIRCULATION FLOW RATE PER ENGINE/LINE LOOP (LB/SEC)

NAR CONFIG (L - 62 FT)
MDAC CONFIG (L - 2 FT)

0 1 2 3 4 5 6 7 8 9 10

0 10 20 30 40 50
REQUIRED PUMP SHAFT HORSEPOWER FOR CIRCULATION LO₂ TANKS

CIRCULATION LINE SIZE: 2" DIA.
PUMP EFFICIENCY: 72%
ENGINE RECIRCULATION VALVE AREA: 0.75 IN²
LIQUID TEMPERATURE PROFILES LO₂ FEEDLINE - 0.5 IN. FOAM INSULATION

PUMP HEAT INPUT - 10 BTU/SEC

TIMES ARE DURATIONS FROM LIFTOFF

TANK OUTLET

0 SEC 144 SEC 216 SEC

TEMPERATURE (°R)
CONCLUSIONS REGARDING ORBIT INJECTION PROPELLANT SUPPLY

- Continuous bleed pressurization comparable to intermittent pressurization
- Common vent and pressurization lines satisfactory
- On-board prepressurization is low penalty (helium or hydrogen)
- Pressurization not sensitive to insulation thickness
- Feedline temperature control by circulation more effective than by insulation
ATTITUDE CONTROL

PROPELLANT SUPPLY
APPROACH TO ATTITUDE CONTROL PROPPELLANT SUPPLY EVALUATIONS (NONINTEGRATED)
LIQUID FEED ACPS SCHEMATIC

30 LB/IN.²
175° OR

STORAGE TANK

RELIEF VALVE 500 LB/IN.²

PUMP

CIRCULATION FAN

LIQUID LINES

HE TRANSFER TUBE

BELLOWS CONTRACTED

BELLOWS FULLY EXPANDED (P = 500 LB/IN.²)

ONE PROPELLANT SYSTEM SHOWN
OTHER PROPELLANT SYSTEM SIMILAR

D03431
EFFECT OF CHAMBER PRESSURE ON SUPERCRITICAL ACPS WEIGHT

The graph shows the effect of engine chamber pressure on supercritical ACPS weight. The weight includes the weight of thrusters, delivered propellants, conditioning propellants, storage tanks, accumulators, and residuals.

30 - 1850 LB THRUSTERS

Engine Chamber Pressure (PSIA)

Propellant System and Engine Weight (LBS)
ACPS LH₂ PROPELLANT – OPTIMIZATION OF SUPERCRITICAL STORAGE PRESSURE

![Graph showing weight index versus storage tank pressure for two temperatures: 350°R and 250°R.](image-url)
ACPS LO\textsubscript{2} PROPELLANTS - OPTIMIZATION OF SUPERCRITICAL STORAGE PRESSURE
### COMPARISON OF TURBOPUMPS AND PUMPS WITH ELECTRIC MOTORS

<table>
<thead>
<tr>
<th>TURBOPUMP CONCEPT(S)</th>
<th>THREE INSTALLED SETS*</th>
<th>FOUR INSTALLED SETS**</th>
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<tbody>
<tr>
<td><strong>COMPONENT</strong></td>
<td><strong>WT</strong></td>
<td><strong>COMPONENT</strong></td>
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<tr>
<td>H₂ TURBOPUMP (3) ((\bar{\omega} = 3.80)-LB/SEC AT 1043-PSIA ΔP EACH)</td>
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<td>H₂ PUMPS (3.80 LB/SEC AT 1043-PSI ΔP EACH)</td>
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<td>O₂ TURBOPUMP (3) ((\bar{\omega} = 14.81)-LB/SEC AT 940-PSIA ΔP EACH)</td>
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<td>O₂ PUMPS (14.81 LB/SEC AT 940-PSI ΔP EACH)</td>
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<tr>
<td>H₂ AND O₂ FOR 125/595 COOLING AND HEATING</td>
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<td>H₂ PUMP MOTORS</td>
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<td>O₂ PUMP MOTORS</td>
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<td>H₂ AND O₂ FOR 85 DRIVING TURBINES (500-SEC DURATION)</td>
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<td>GENERATOR WEIGHT (3 AT 360 kW) DELETE GENERATOR ON APU</td>
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<td></td>
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<td>-60.0</td>
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<td>SEPARATE TURBINES/ COMBUSTORS/CONTROLS</td>
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<td></td>
<td></td>
<td>H₂ AND O₂ TO DRIVE APU TURBINES (500 SEC)</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td><strong>409/880</strong></td>
<td></td>
</tr>
</tbody>
</table>

*1 OUT OF 3 MUST OPERATE (EACH SET Sized FOR FULL FLOW)
**2 OUT OF 4 MUST OPERATE (EACH SET Sized FOR HALF FLOW)
STARTING CURRENT REQUIREMENTS

STARTING CURRENT (% RATED)

STARTING TIME (SEC)

MOTOR - BRUSHLESS DC
PUMP - CENTRIFUGAL
SPEED - 25,000 RPM
CAPILLARY STABILITY MAP
(For Shuttle Cryogenic Subsystem Requirements)

Stabilized Head ($g_0$ - in.)

Pore Diameter (in. x 10^{-4})

Date includes a safety factor of 2
TYPICAL INLET PORT DETAIL

GASKETS, TEFLOM

PORT HOUSING, ALUMINUM

PORT COVER, ALUMINUM

ALUMINUM CAPILLARY
50 x 250 PLAIN DUTCH WEAVE

SPACER
26 x 26 SQUARE MESH
MAXIMUM GAS IN MULTIPLE SCREEN DEVICES

TYPICAL CONDITIONS

MESH
- 24 x 110
- 30 x 150
- 50 x 250
- 200 x 1400

VOLUME/INLET (IN.³)

PORE DIAMETER - (IN. x 10⁻⁴)

HELUM IN GH₂

GO₂

He IN GO₂

LH₂ ΔP = 0.04 PSIA
LO₂ ΔP = 0.24 PSIA
LH₂ ω = 25 LB/SEC
LO₂ ω = 12.5 LB/SEC
PROPELLANT ACQUISITION DEVICE CONFIGURATION

DIAMETER = 12 FT

DIAMETER = 10 FT
REQUIRED HEAD DIFFERENTIAL CAPABILITY VS. GALLERY LINE DIAMETER

RL-10 START TRANSIENT:

\[ \dot{m}_{O_2} = 190 \text{ LB/SEC}^2 \]
\[ \dot{m}_{H_2} = 32.4 \text{ LB/SEC}^2 \]

\[ L_{\text{MAX}} = \text{DISTANCE BETWEEN THE FURTHER MOST HEADS} \]

- \( O_2 \) (TANK DIA = 10 FT, \( L_{\text{MAX}} = 23.56 \text{ FT, 3/4 ARC} \))
- \( H_2 \) (TANK DIA = 12 FT, \( L_{\text{MAX}} = 27.25 \text{ FT, 3/4 ARC} \))

GALLERY LINE DIAMETER (IN.)

PHED (LB/IN\(^2\))

MAXIMUM

D04715

llm
LIQUID/LIQUID ACPS THERMODYNAMIC CYCLE
## COMPARISON OF LIQUID/LIQUID AND GAS/GAS ATTITUDE CONTROL
## PROPELLANT SUPPLY

<table>
<thead>
<tr>
<th>TYPE OF STORAGE</th>
<th>TYPE OF FEED</th>
<th>TYPE OF PUMP DRIVE</th>
<th>NO. OF GENs.</th>
<th>ACCUAT. BELLOWS CONTRACT. RATIO (%)</th>
<th>MAX H₂ TEMP (°R)</th>
<th>DRY WEIGHT (LB)</th>
<th>TOTAL SYSTEM WEIGHT (LB)</th>
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CONCLUSIONS REGARDING ATTITUDE CONTROL
PROPULSION SUPPLY

- SUBCRITICAL STORAGE RESULTS IN SUBSTANTIALLY LOWER DRY WEIGHTS THAN SUPERCRITICAL STORAGE

- LIQUID/LIQUID ACPS CAN HAVE COMPARABLE WEIGHTS TO GAS/GAS ACPS, DEPENDING UPON BELLOWS CONTRACTION RATIOS

- ELECTRICAL MOTOR-DRIVEN PUMPS ARE APPLICABLE TO THE ACPS SUBSYSTEM

- PROPELLANT ACQUISITION FOR THE ACPS IS A MAJOR TECHNOLOGICAL PROBLEM
AUXILIARY POWER UNIT SUPPLY SYSTEMS
APPROACH TO AUXILIARY POWER UNIT SUPPLY EVALUATIONS (NONINTEGRATED)
TYPICAL REENTRY ACCELERATION (g) (HIGH CROSS RANGE)

ACCELERATION LOADING (g)

TIME FROM 400,000 FEET (100 SEC)

NORMAL g LOADING

AXIAL g LOADING
## SUMMARY OF AUXILIARY POWER UNIT
### SUBCRITICAL SUPPLY SYSTEM

<table>
<thead>
<tr>
<th>Component</th>
<th>Mixture Ratio 0.5</th>
<th>Mixture Ratio 0.9</th>
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<tbody>
<tr>
<td></td>
<td>3-450 HP</td>
<td>2-850 HP</td>
</tr>
<tr>
<td><strong>TANKAGE:</strong></td>
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<td></td>
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<tr>
<td>$H_2$</td>
<td>110</td>
<td>123</td>
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<tr>
<td>$O_2$</td>
<td>12</td>
<td>12</td>
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<td><strong>$H_2$ TO APU</strong></td>
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<tr>
<td></td>
<td>332</td>
<td>342</td>
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<td><strong>$H_2$ TO CONDITIONING AND</strong></td>
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<td><strong>PUMPING</strong></td>
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<td><strong>$H_2$ RESIDUALS AND VENTED</strong></td>
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<td>171</td>
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<td><strong>He TANKS</strong></td>
<td>4</td>
<td>4</td>
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<tr>
<td><strong>TOTAL (LBS.)</strong></td>
<td>1,462</td>
<td>1,497</td>
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## SUMMARY OF AUXILIARY POWER UNIT SUPercritical supply system

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<tr>
<th></th>
<th>MIXTURE RATIO 0.5</th>
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<th>MIXTURE RATIO 0.9</th>
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<td>3-450 HP</td>
<td>2-850 HP</td>
<td>3-450 HP</td>
<td>2-850 HP</td>
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## COMPARISON OF AUXILIARY POWER UNIT SUPPLY SUBSYSTEMS

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<tr>
<th>SYSTEM DRY WEIGHT (LB)</th>
<th>SUBCRITICAL SUPPLY SYSTEM</th>
<th>SUPERCritical SUPPLY SYSTEM</th>
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<td>MIXTURE RATIO (0.5)</td>
<td>MIXTURE RATIO (0.9)</td>
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<td>3-450 HP      2-850 HP</td>
<td>3-450 HP      2-850 HP</td>
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<tr>
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<td><strong>831</strong></td>
<td><strong>818</strong></td>
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<td>1,462</td>
<td><strong>1,497</strong></td>
<td><strong>1,565</strong></td>
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<table>
<thead>
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<th>SYSTEM WET WEIGHT (LB)</th>
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<th>SUPERCritical SUPPLY SYSTEM</th>
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<td>MIXTURE RATIO (0.5)</td>
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<td>3-450 HP      2-850 HP</td>
<td>3-450 HP      2-850 HP</td>
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<tr>
<td>1,462</td>
<td><strong>1,497</strong></td>
<td><strong>1,565</strong></td>
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CONCLUSIONS REGARDING AUXILIARY POWER UNIT SUPPLY

- SUBCRITICAL STORAGE RESULTS IN THE LOWEST WEIGHT SUBSYSTEMS
- EFFECTS OF O/F RATIO ARE SMALL
- OPTIMUM TURBINE INLET PRESSURES:
  - SUBCRITICAL AT HIGHER PRESSURES (900 PSIA)
  - SUPERCRITICAL DEPENDENT UPON MIXTURE RATIO:
    O/F 0.5 NEAR 300 PSIA
    O/F 0.9 NEAR 600 PSIA
- APU REACTANT ACQUISITION IMPOSES MAJOR PROBLEM ON ACQUISITION DEVICES
- APU SUPPLY PUMP SHOULD OPERATE CONTINUOUSLY WHEN APU IS OPERATING
FUEL CELL SUPPLY SYSTEMS
<table>
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<th>ITEM</th>
<th>MIN. SUPPLY PRESSURE (psia)</th>
<th>SUPERCritical</th>
<th>SUBCRITICAL</th>
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<td>175</td>
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<td>RESIDUALS:</td>
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<tr>
<td>O₂</td>
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<td>4.4</td>
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<td>TOTAL</td>
<td>2202</td>
<td>2127</td>
<td>2153</td>
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</table>
CONCLUSIONS REGARDING FUEL CELL SUPPLY SUBSYSTEMS

- SUPERCritical AND SUBCRITICAL SUPPLY SYSTEMS ARE APPROXIMATELY THE SAME WEIGHT.

- THERE ARE NO ADVANTAGES TO A LOW-PRESSURE CELL SUPPLY.

- FUEL CELL SUPPLY SYSTEMS HAVE RELATIVELY HIGH COMPONENT REPLACEMENTS BECAUSE OF THE EXTENDED DUTY CYCLES.

- FUEL CELL PURGING TO REMOVE HELIUM (WHICH HAS ENTERED THROUGH BEING DISSOLVED IN LO₂ OR LH₂) IS NOT A SIGNIFICANT PENALTY.
LIFE SUPPORT SUPPLY
<table>
<thead>
<tr>
<th>ITEM</th>
<th>SUPERCRITICAL SUBSYSTEM (LB)</th>
<th>SUBCRITICAL SUBSYSTEM (LB)</th>
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<tr>
<td><strong>O₂ SUPPLY</strong></td>
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<td></td>
</tr>
<tr>
<td>· COMPONENTS</td>
<td>61.6</td>
<td>81.2</td>
</tr>
<tr>
<td>· LINES</td>
<td>7.3</td>
<td>7.3</td>
</tr>
<tr>
<td>· STORAGE TANK</td>
<td>8.4</td>
<td>3.4</td>
</tr>
<tr>
<td>· VACUUM SHELL PLUS INSULATION</td>
<td>3.6</td>
<td>3.6</td>
</tr>
<tr>
<td><strong>N₂ SUPPLY</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>· COMPONENTS</td>
<td>85.5</td>
<td>110.4</td>
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<td>· LINES</td>
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<td>7.3</td>
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<td>· STORAGE TANK</td>
<td>10.8</td>
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<td>· VACUUM SHELL PLUS INSULATION</td>
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<td>5.2</td>
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<td><strong>CONDITIONING</strong></td>
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<td></td>
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<tr>
<td>· TANK WEIGHT PENALTY (FUEL CELL SYSTEM)</td>
<td>1.8</td>
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<tr>
<td><strong>TOTAL DRY WEIGHT</strong></td>
<td>190.6 LB</td>
<td>225.0 LB</td>
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<td><strong>FLUIDS</strong></td>
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<tr>
<td>· USABLE O₂</td>
<td>50.0</td>
<td>50.0</td>
</tr>
<tr>
<td>· USABLE N₂</td>
<td>65.0</td>
<td>65.0</td>
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<tr>
<td>· CONDITIONING CRYOGENS</td>
<td>6.0</td>
<td>6.0</td>
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<tr>
<td>· RESIDUALS</td>
<td>1.2</td>
<td>1.2</td>
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<tr>
<td><strong>TOTAL FLUIDS</strong></td>
<td>122.2 LB</td>
<td>122.2 LB</td>
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<tr>
<td><strong>TOTAL SUBSYSTEM WEIGHT</strong></td>
<td>312.8 LB</td>
<td>347.2 LB</td>
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PURGING, INERTING, AND PNEUMATIC SUPPLY
HELIUM-STORED AT LH₂ TEMPERATURE

FROM ACPS

H₂

O₂

TO H₂ TANK
INSULATION PURGE

20 PSIA

PRO3

SV05

TO PILOT VALVES

TO RL-10 H 1

TO RL-10 H 2

TO RL-10 H 3

1500 PSIA

1500 PSIA

500 PSIA

TO MAIN ENGINE

SV02

SV03

PRO2

D04923

RVOI

BD01

FV01

SV01

PRO1

HX01

GG01

Ne

T = 37°F
P = 4500 PSIA
HELIUM STORED AT AMBIENT TEMPERATURE

FROM ACPS

O₂
H₂

TO MAIN ENGINE

O₂
H₂

TO PILOT VALVES

TO RL-10

TO H₂ TANK INSULATION PURGE

20 PSIA

PR03

SV05

500 PSIA

D04681

11m
SUBCRITICAL STORAGE OF NITROGEN

- LN₂ at 170°R, 35 PSIA
- O₂, H₂
- RV02, BD02
- TS05
- HX03
- SV06
- SV09
- SV07
- SV10
- SV08
- SV11
- GG02
- C001
- C002
- C003
- PR05
- PR06
- PR07

- TO O₂ TANK
- INSULATION PURGE
  - P = 20 PSIA
  - T = 520°R
- TO TANK INERTING
  - P = 15 PSIA
  - T = 520°R
- TO PROPELLANT COMPARTMENT PURGE
  - P = 0.1 TO 15 PSIA

GSE PURGE ONLY
FLOW RATES ARE VEHICLE-DESIGNED DEPENDENT

PHASE B CONTRACTORS SELECTIONS RANGED FROM 25,000 TO 65,000 LB/HR (7 TO 18 LB/SEC).

POSSIBLE APPROACHES INCLUDE:

- INTRODUCTION THROUGH LOW-PRESSURE DUCTS
- INTRODUCTION THROUGH MODERATE TO HIGH-PRESSURE LINES WITH DIFFUSERS

EVALUATION RESULTS

- LINE SIZES
  - 10 LB/SEC - 3.5 IN.
  - 20 LB/SEC - 4.5 IN.
- PRESSURE - 100 PSIA
ASSUMPTIONS FOR STRUCTURE TEMPERATURE VS TIME FOR REENTRY

$T_s$ - STRUCTURE TEMPERATURE ($^\circ$F)

$T_0$ - 70°F

HELIUM PURGE OF INSULATION

ATMOSPHERIC ENTRY

200°F

START STRUCTURE COOLING

START AIR ENGINES 40,000 FT

LAND

$t$ - TIME FROM HELOIUM PURGE OF INSULATION (MIN)
ATMOSPHERIC AND DEW OR FREEZING TEMPERATURES FOR AIR

(MID-LATITUDES)

\[ T_{\text{AIR}} \] - ATMOSPHERE TEMP

\[ T_{\text{F}} \] - DEW OR FREEZING TEMP

\[ T_{\text{F}} = 70^\circ \text{F} \]

\[ T_{\text{F}} = 37^\circ \text{F} \]

AT SEA LEVEL

\[ h - \text{ALTITUDE (10^3 \text{ FT})} \]

\[ T - \text{TEMPERATURE (}^\circ \text{R}) \]
TEMPERATURES ASSOCIATED WITH REENTRY OF LH$_2$
OMS TANK EMPTIED AFTER RETRO

- HELIUM PURGE OF INSULATION
- $T_S$ - STRUCTURE TEMPERATURE
- $T_F$ = 70°F AT SEA LEVEL
- $T_F$ = 37°F AT SEA LEVEL
- LAND
- START STRUCTURE COOLING
- $T_F$ - DEW OR FREEZING TEMP
- START AIR ENGINES 40,000 FT

$T$ - PURGE BAG TEMP

$T$ - TEMPERATURE (°R)

$T$ - TIME FROM HELIUM PURGE OF INSULATION (MIN)

DO4709
11m
VARIOUS TEMPERATURES VS TIME FROM HELIUM PURGE OF INSULATION

- $T_1$ - Helium inlet temp
- $T_S$ - Structure temp
- $T_{\text{MIN}}$ - Minimum purge bag temp
- $T_2$ - Helium outlet temp
- $T_F$ - Dew or freeze temp

- Atmospheric entry
- Start structure cooling
- Start air engines 40,000 ft
- Start air engines 100,000 ft

$t$ - Time from helium purge of insulation (min)

Temperature (°F)

- 200
- 300
- 400
- 500
- 600
- 700

Time (min)

- 12
- 24
- 36
- 48
- 60
- 72
- 84
HEAT LEAK PER UNIT AREA VS REENTRY TIME FOR LH₂ TANKS WITH 1.0-IN. INSULATION

- $T_1 = 600^\circ R$, $\frac{w}{A} = 0.246 \text{ LB/HR FT}^2$
- $T_1 = 500^\circ R$, $\frac{w}{A} = 0.285 \text{ LB/HR FT}^2$
- $T_1 = 400^\circ R$, $\frac{w}{A} = 0.361 \text{ LB/HR FT}^2$
- $T_1 = 300^\circ R$, $\frac{w}{A} = 0.570 \text{ LB/HR FT}^2$

- T_MIN = 200°R TO 340°R
- CLOSED PURGE BAG
- LAND
- START STRUCTURE COOLING
- MINIMUM PURGE BAG TEMP T_MIN = 200°R
- CIRCULATING GAS PURGE BAG
- HELIUM PURGE OF INSULATION

- ATMOSPHERIC ENTRY
- $h = 70,000 \text{ FT}$
- Time $t = 57 \text{ MIN}$
- START AIR ENGINES, 40,000 FT

$q - \text{ HEAT LEAK PER UNIT TANK WALL AREA (BTU/HR FT}^2\text{)}$

$t - \text{ TIME FROM HELIUM PURGE OF INSULATION (MIN)}$
<table>
<thead>
<tr>
<th>SUBSYSTEM</th>
<th>FUNCTION</th>
<th>REENTRY WITHOUT LH₂ IN TANKS (LB)</th>
<th>REENTRY WITH LH₂ IN TANKS (LB)</th>
<th>PRESSURE (PSIA)</th>
<th>TEMPERATURE (°R)</th>
<th>FLOWRATE (LB/SEC.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OIPS</td>
<td>ENGINE PNEUMATIC AND PURGE</td>
<td>60</td>
<td>60</td>
<td>1,500</td>
<td>490-600</td>
<td>6 (MAX)</td>
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<tr>
<td></td>
<td>PNEUMATIC VALVES</td>
<td>5</td>
<td>5</td>
<td>1,500</td>
<td>490-600</td>
<td>0.6 (MAX)</td>
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<tr>
<td>OMPS/ACPS</td>
<td>RL-10 PURGE &amp; PNEUMATIC</td>
<td>1.7</td>
<td>1.7</td>
<td>470 ± 30</td>
<td>140-620</td>
<td>&lt; 0.01</td>
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<tr>
<td></td>
<td>WITHOUT CONTINUOUS BLEED</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td>WITH CONTINUOUS BLEED</td>
<td>27</td>
<td>27</td>
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<tr>
<td></td>
<td>H₂ TANK INSULATION PURGE</td>
<td>1.5-3</td>
<td>15</td>
<td>520 (INLET)</td>
<td>&lt; 0.01</td>
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<td></td>
<td>10 (INVENTORY)</td>
<td>15</td>
<td>520 (INLET)</td>
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<td>PNEUMATIC VALVES</td>
<td>0.95</td>
<td>0.95</td>
<td>700</td>
<td>460-600</td>
<td>&lt; 0.01</td>
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<tr>
<td>APU</td>
<td>PNEUMATIC VALVES</td>
<td>0.04</td>
<td>0.04</td>
<td>700</td>
<td>460-600</td>
<td>&lt; 0.01</td>
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<tr>
<td>FUEL CELL/EC/LSS</td>
<td>PNEUMATIC VALVES</td>
<td>0.35</td>
<td>0.35</td>
<td>700</td>
<td>460-600</td>
<td>&lt; 0.01</td>
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NITROGEN PURGING REQUIREMENTS FOR COMPONENT HYDROGEN LEAKAGE

(MAINTAIN BELOW FLAMMABILITY LIMITS)

EXPECTED HYDROGEN LEAKAGE (SCCM)

NITROGEN PURGE GAS REQUIRED (LB)

ASCENT - 200 SEC
REENTRY - 3,000 SEC

ESTIMATED RANGE
## PURGING, INERTING, AND PNEUMATIC SUPPLY NITROGEN REQUIREMENTS

<table>
<thead>
<tr>
<th>SUBSYSTEM</th>
<th>FUNCTION</th>
<th>WITHOUT TANK INERTING (LB)</th>
<th>WITH TANK INERTING (LB)</th>
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<tbody>
<tr>
<td>ORBIT INJECTION PROPULSION SUPPLY</td>
<td>TANK INERTING</td>
<td>1,230</td>
<td>1,820</td>
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<td>LEAKAGE PURGING</td>
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<td>340 (ASCENT)</td>
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<td>OMPS/ACPS</td>
<td>TANK INERTING</td>
<td></td>
<td>150</td>
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<td></td>
<td>LEAKAGE PURGING</td>
<td>66</td>
<td>35</td>
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<td>OXYGEN INSULATION PURGING</td>
<td>4</td>
<td>4</td>
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<tr>
<td>APU</td>
<td>LEAKAGE PURGING</td>
<td>13</td>
<td>–</td>
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<tr>
<td>FUEL CELL/ECLSS</td>
<td>LEAKAGE PURGING</td>
<td>10</td>
<td>–</td>
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<tr>
<td>AIRBREATHING ENGINE</td>
<td>O₂ REMOVAL</td>
<td>–</td>
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<td>TANK INERTING</td>
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<td>10</td>
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</table>
## PURGING, INERTING, AND PNEUMATIC SUPPLY

<table>
<thead>
<tr>
<th>ITEM</th>
<th>(1) WITH LH₂ IN OMPS TANK DURING REENTRY</th>
<th>(1) WITH LH₂ IN OMPS TANK DURING REENTRY</th>
<th>(2) NO RECIRCULATION OF PURGE BAG He VACUUM-JACKATED</th>
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<tbody>
<tr>
<td>HELIUM REQUIREMENTS</td>
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<td>Conditioning Reactants:</td>
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<tr>
<td>O₂</td>
<td>80</td>
<td>72</td>
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<td>H₂</td>
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<td>12</td>
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<tr>
<td>TANKAGE</td>
<td>310 (433)</td>
<td>280 (390)</td>
<td>270 (379)</td>
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<td>RESIDUAL HELIUM</td>
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<td>122</td>
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<td>TOTAL DRY</td>
<td>712 (835)</td>
<td>607 (717)</td>
<td>596 (706)</td>
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<td>TOTAL FLUID</td>
<td>467</td>
<td>221</td>
<td>216</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1,179 (1,302)</td>
<td>828 (938)</td>
<td>812 (922)</td>
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</tbody>
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D04504 (1)

11m
## PURGING, INERTING, AND PNEUMATIC SUPPLY NITROGEN SUBSYSTEM ALTERNATIVES

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<tbody>
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<tr>
<td>Inerting</td>
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<tr>
<td>Total N₂</td>
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<td><strong>CONDITIONING REACTANTS:</strong></td>
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<tr>
<td>O₂</td>
<td>0.8</td>
<td>0.77</td>
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<tr>
<td>H₂</td>
<td>0.8</td>
<td>0.77</td>
<td>6.77</td>
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<td>65</td>
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<td>Tankage</td>
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<td>25</td>
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<td>444</td>
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<tr>
<td>Other Components</td>
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<td>113</td>
<td>170</td>
<td>183</td>
<td>158</td>
<td>213</td>
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<td>Trapped N₂</td>
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<td>26</td>
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<td>8</td>
<td>1.5</td>
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<tr>
<td>Total Dry Weight</td>
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<td>141</td>
<td>133</td>
<td>172.25</td>
<td>187.25</td>
<td>185</td>
<td>238</td>
<td>453</td>
<td>2,479</td>
<td>314</td>
<td>682</td>
<td>4,334</td>
<td>218</td>
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<td>319</td>
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</tr>
<tr>
<td>Total Fluid Weight</td>
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<td>11</td>
<td>11</td>
<td>16.6</td>
<td>16.5</td>
<td>16.5</td>
<td>1,488</td>
<td>1,581</td>
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<td>2,646</td>
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<td>Total</td>
<td>103</td>
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<td>144</td>
<td>189</td>
<td>204</td>
<td>202</td>
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<td>2,033</td>
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<td>2,977</td>
<td>3,507</td>
<td>6,978</td>
<td>323</td>
<td>332</td>
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**Notes:**
- D04505
- 11m
INTEGRATED SYSTEMS
SYSTEMS INTEGRATION APPROACH

DEVELOPED GENERAL CONCEPTS

- SUBSYSTEM STORAGE COMBINATIONS (30 CASES)
- LINES
- TANK PRESSURE CONTROL
- THERMAL CONTROL
- FLUID CONTROL
- FLUID CONDITIONING

DEVELOPED CONCEPT BLOCK FLOW CHARTS

COMMON STORAGE MAINTAINED AS PRIMARY INTEGRATION MODE
INTEGRATION MODES

COMMON CRYOGENS STORAGE IS PRIMARY MODE OF INTEGRATION - 8 SYSTEMS

- SUBCRITICAL TANKS
- SUPERCRITICAL TANKS

SECONDARY INTEGRATION MODES - 16 SYSTEMS

- PUMPS - COMMON OR SEPARATE
  - AT TANK
  - AT ENGINE
- PRESSURIZATION - HELIUM - CRYOGENS GAS
- VACUUM JACKET
- ACQUISITION SYSTEMS
# Subsystem Cryogenic Fluid Requirements

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<tr>
<th>Subsystem</th>
<th>O2 Quantity (LB)</th>
<th>O2 Flow Rate (LB/Sec)</th>
<th>H2 Quantity (LB)</th>
<th>H2 Flow Rate (LB/Sec)</th>
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<td>OIPS</td>
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<td>2,374</td>
<td>86,000</td>
<td>396</td>
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<tr>
<td></td>
<td>Min 360,000</td>
<td>593</td>
<td>60,000</td>
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<tr>
<td>OMPS</td>
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<td>38</td>
<td>5,400</td>
<td>8</td>
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<td></td>
<td>Min 18,300</td>
<td>13</td>
<td>3,700</td>
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<td>ACPS</td>
<td>Max 6,900</td>
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<tr>
<td>ABE</td>
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<td>FUEL CELL</td>
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<td>.0053</td>
<td>175</td>
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<tr>
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<td>.02</td>
<td>100</td>
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<td>LIFE SUPPORT</td>
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<td>.0001</td>
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### Cryogen Weights Used for Comparison

<table>
<thead>
<tr>
<th></th>
<th>( O_2 )</th>
<th>( H_2 )</th>
<th>( I_{sp} )</th>
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<tbody>
<tr>
<td>OIPS</td>
<td>450,000</td>
<td>75,000</td>
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<td>OMPS</td>
<td>23,128</td>
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<td>ACPS(2)(3)</td>
<td>5,793(4)</td>
<td>1,645</td>
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<td>APU</td>
<td>408</td>
<td>454</td>
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<td>FC(5)</td>
<td>1,475</td>
<td>175</td>
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<tr>
<td>EC/LSS</td>
<td>50</td>
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</table>

(1) BASED ON RL-10 \( I_{sp} \) FOR COMPARISON - HIGHER VALUES CAN BE READILY ACHIEVED
(2) BASED ON A \( \Delta V \) SPLIT WHICH DEVOTES 185 FT/SEC TO THE ACPS
(3) TOTAL IMPULSE = 1,687,000 LB/SEC S.S., 1,018,000 LB/SEC PULSING
(4) THESE VALUES RESOLVE TO \( O_2 = 5,230 \) AND \( H_2 = 1,310 \) DELIVERED AT THE THRUSTER FOR \( I_{sp} = 430 \) S.S. AND 388 PULSING
(5) OTHER VALUES USED DEPENDING ON INTEGRATION MODES AT MR = 0.9
(6) NEAR THE MAXIMUM WAS USED. CURRENT NOMINAL VALUES ARE APPROXIMATELY 750 LB TOTAL
# INTEGRATED SYSTEMS

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
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<td>OMPS</td>
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<tr>
<td></td>
<td>ACPS</td>
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<td>ACP</td>
<td>FC</td>
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<td>EC/LSS</td>
<td>EC/LSS</td>
<td>EC/LSS</td>
<td>EC/LSS</td>
</tr>
</tbody>
</table>

| **SYSTEM WEIGHT** | | | | | | | | | |
| **DRY (INERT) WT** | 8,678 | 9,155 | 8,895 | 9,373 | 8,854 | 12,705 | 9,410 | 12,424 | 9,936 |
| **CRYOGENS** | 40,020 | 39,803 | 39,415 | 39,780 | 40,549 | 41,035 | 39,391 | 40,363 | 39,754 |
| **TOTAL** | 48,698 | 48,958 | 48,110 | 49,153 | 49,403 | 53,740 | 49,101 | 52,789 | 49,690 |
| **NO. OF COMPONENTS** | 375 | 451 | 679 | 608 | 433 | 431 | 519 | 488 | 774 |

All cases include OIPS feed and fill component weights but not included in component D03617(1)

---

IIIm
### Reference System

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<thead>
<tr>
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<th>Pump</th>
<th>Pressurization</th>
<th>Vacuum Jacket</th>
<th>Acquisition</th>
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<td>Helium</td>
<td>NO</td>
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</tr>
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<td></td>
<td></td>
<td>ACPS</td>
<td>Channels &amp; Heads</td>
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<td>ACPS</td>
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<td>APU</td>
<td>APU</td>
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<td></td>
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<tr>
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<td>Separate with APU</td>
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### Integrated System I

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<table>
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<table>
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D04438 (1)
INTEGRATED SYSTEM II

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<td>b) SUBCRITICAL</td>
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START TANK WITH HEADS

OMPS ACPS APU
### Integrated System III

#### a) Store
- **Subcritical**
  - OMPs
  - ACPS
- **Subcritical**
  - APU
- **Supercritical**
  - FC
  - EC/LSS

#### b) Pump
- **Common at Tank**
  - OMPs
  - ACPS
- **Separate at APU**
  - APU
- **None**
  - FC
  - EC/LSS

#### Pressurization
- **Helium**
  - OMPs
  - ACPS
- **O₂, H₂**
  - FC
  - EC/LSS

#### Vacuum Jacket
- **No**
  - OMPs
  - ACPS
- **Yes**
  - APU
  - FC
  - EC/LSS

#### Acquisition Compartment with Heads
- **None**
  - FC
  - EC/LSS
## INTEGRATED SYSTEMS IV

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### Table c)

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D04441

11m
INTEGRATED SYSTEM VI

a) STORE
   - SUBCRITICAL
     - OMPS
   - SUPERCRITICAL
     - ACPS
     - APU
     - FC
     - EC/LSS

   PUMP
   - SEPARATE AT ENGINE
     - OMPS

   PRESSURIZATION
   - GO₂ GH₂
     - OMPS

   VACUUM JACKET
   - NO
   - OMPS

   ACQUISITION
   - START CONTAINER
     - OMPS

b) SUBCRITICAL
   - OMPS
   - REFILL
     - ACPS
     - APU
     - FC
     - EC/LSS
   - SUPERCritical
     - ACPS
     - APU
     - FC
     - EC/LSS

   SAME
   - PLUS
   - REFILL PUMP
     - PUMP AT OMPS TANK
   - GO₂ GH₂
     - ACPS
     - APU
     - FC
     - EC/LSS
   - YES
   - ACPS
   - APU
   - FC
   - EC/LSS

   COMPARTMENTED WITH HEADS
   - NONE
   - ACPS
   - APU
   - FC
   - EC/LSS

D04443
11m
### Integrated System VII

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<td>Helium</td>
<td>No</td>
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<tr>
<td>Subcritical</td>
<td>Common at tank</td>
<td>Helium</td>
<td>Yes</td>
<td>Channels &amp; Heads</td>
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<tr>
<td>ACPS APU</td>
<td>ACPS APU</td>
<td>ACP APU</td>
<td>ACP APU</td>
<td>ACP APU</td>
</tr>
<tr>
<td>SuperCritical</td>
<td>None</td>
<td>O₂ &amp; H₂</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>FC EC/LSS</td>
<td>FC EC/LSS</td>
<td>FC EC/LSS</td>
<td>FC EC/LSS</td>
<td>FC EC/LSS</td>
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<tr>
<td>STORE</td>
<td>PRESSURIZATION</td>
<td>VACUUM JACKET</td>
<td>ACQUISITION</td>
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<td>----------------</td>
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<tr>
<td>SUBCRITICAL</td>
<td>Go₂, H₂</td>
<td>NO</td>
<td>NONE</td>
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<tr>
<td>OMPS</td>
<td></td>
<td>OMPS</td>
<td>ACPS, APU</td>
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<tr>
<td>SUPERCritical</td>
<td>NONE</td>
<td>YES</td>
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<td>O₂, H₂</td>
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<td>FC, EC/LSS</td>
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<tr>
<td>APU</td>
<td>ACPS</td>
<td></td>
<td></td>
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<tr>
<td>FC</td>
<td></td>
<td></td>
<td>FC, EC/LSS</td>
<td></td>
</tr>
<tr>
<td>EC/LSS</td>
<td>APU</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
# SUMMARY OF WEIGHTS AND COMPONENTS

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<thead>
<tr>
<th>Integrated Systems</th>
<th>Ia</th>
<th>Ib</th>
<th>Ic</th>
<th>Iia</th>
<th>Iib</th>
<th>IIVa</th>
<th>IVb</th>
<th>IVc</th>
<th>Va</th>
<th>Vb</th>
<th>Via</th>
<th>Vb</th>
<th>VII</th>
<th>VIII</th>
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<tbody>
<tr>
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<td>Inert/</td>
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<td>Inert/</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APU</td>
<td>5,398/</td>
<td>5,983/</td>
<td>6,123/</td>
<td>5,289/</td>
<td>5,497/</td>
<td>477/</td>
<td>1,601/</td>
<td>2,129/</td>
<td>3,472/</td>
<td>3,450/</td>
<td>7,323/</td>
<td>6,930/</td>
<td>9,297/</td>
<td>6,468/</td>
<td>8,191</td>
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<tr>
<td>FC</td>
<td>681</td>
<td>574/</td>
<td>574/</td>
<td>1,675</td>
<td>1,675</td>
<td>1,675</td>
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<td>1,675</td>
<td>1,675</td>
<td>1,675</td>
<td>1,675</td>
<td>1,675</td>
<td>63</td>
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<tr>
<td>EC/LSS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Total</td>
<td>11,578</td>
<td>11,319</td>
<td>11,421</td>
<td>11,421</td>
<td>11,421</td>
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<td>11,421</td>
<td>11,421</td>
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<tr>
<td>Number of Components (1)</td>
<td>375</td>
<td>396</td>
<td>422</td>
<td>481</td>
<td>477</td>
<td>679</td>
<td>622</td>
<td>608</td>
<td>634</td>
<td>608</td>
<td>433</td>
<td>443</td>
<td>431</td>
<td>484</td>
<td>519</td>
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</table>

(1) Does not include OIPS components

D04456
### OIPS PREPRESSURANT CHANGES

#### REMOVED FROM OOMPS (433 LB TOTAL)

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>NO.</th>
<th>WEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>O2</td>
<td>5</td>
<td>5.7</td>
</tr>
<tr>
<td>GH2</td>
<td>15</td>
<td>13.5</td>
</tr>
<tr>
<td>TANKS (4,000 PSIA)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O2</td>
<td>17</td>
<td>3.0</td>
</tr>
<tr>
<td>H2</td>
<td>350</td>
<td>5.2</td>
</tr>
</tbody>
</table>

#### ADDED TO ACPS (109 LB TOTAL)

<table>
<thead>
<tr>
<th>PREPRESSURANT</th>
<th>CONDITIONING</th>
<th>STORAGE TANK ΔWEIGHT</th>
<th>LINE WEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>O2 (350°F)</td>
<td>6.0</td>
<td>2.0</td>
<td>15.0</td>
</tr>
<tr>
<td>GH2 (250°F)</td>
<td>8.0</td>
<td>40.0</td>
<td>15.0</td>
</tr>
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</table>
# Heat Generation and Rejection - First Two Orbits

<table>
<thead>
<tr>
<th>Phase</th>
<th>Duration (HR)</th>
<th>Cabin and Crew Min. (BTU/HR)</th>
<th>Cabin and Crew Max. (BTU/HR)</th>
<th>Electronic Min. (BTU/HR)</th>
<th>Electronic Max. (BTU/HR)</th>
<th>Total Min. (BTU)</th>
<th>Total Max. (BTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prelaunch</td>
<td>0.083</td>
<td>860</td>
<td>2,600</td>
<td>24,200</td>
<td>34,130</td>
<td>2,100</td>
<td>3,010</td>
</tr>
<tr>
<td>Ascent</td>
<td>0.11</td>
<td>1,860</td>
<td>4,600</td>
<td>24,270</td>
<td>36,860</td>
<td>2,970</td>
<td>4,670</td>
</tr>
<tr>
<td>Phasing</td>
<td>3.0</td>
<td>0</td>
<td>3,600</td>
<td>19,440</td>
<td>43,680</td>
<td>58,100</td>
<td>142,000</td>
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</tbody>
</table>

7,680 BTU through ascent - no venting $\Delta P = 0.15$

## Component Table

<table>
<thead>
<tr>
<th>Component</th>
<th>No.</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP53</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>SV57</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>SV58</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>SV59</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>SV60</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>HX58</td>
<td>2</td>
<td>2</td>
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</tbody>
</table>

Radiator By-Pass

Diagram showing connections between components CP53, SV57, SV58, SV59, SV60, HX58, and OIPS H2 Tank.
OMPS PREPRESSURANT SYSTEM CHANGES

**REMOVED FROM OMPS (965 LB TOTAL)**

<table>
<thead>
<tr>
<th>COMPONENTS</th>
<th>NO.</th>
<th>WEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>PREPRESSURANT (520°R ISOTHERM)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{GO}_2$</td>
<td>359 LB</td>
<td></td>
</tr>
<tr>
<td>$\text{GH}_2$</td>
<td>3 LB</td>
<td></td>
</tr>
<tr>
<td>TANKS (4,000 TO 200 PSI)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{O}_2$</td>
<td>435 LB</td>
<td></td>
</tr>
<tr>
<td>$\text{H}_2$</td>
<td>155 LB</td>
<td></td>
</tr>
</tbody>
</table>

**ADDED TO ACPS (541 LB TOTAL)**

<table>
<thead>
<tr>
<th>COMPONENTS</th>
<th>NO.</th>
<th>WEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{GO}_2$ (350°R)</td>
<td>420</td>
<td></td>
</tr>
<tr>
<td>$\text{GH}_2$ (250°R)</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>CONDITIONING</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>STORAGE TANK ΔWEIGHT</td>
<td>~61</td>
<td></td>
</tr>
</tbody>
</table>

**ADDED TO ACPS (541 LB TOTAL)**

<table>
<thead>
<tr>
<th>COMPONENTS</th>
<th>NO.</th>
<th>WEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{GO}_2$ (350°R)</td>
<td>420</td>
<td></td>
</tr>
<tr>
<td>$\text{GH}_2$ (250°R)</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>CONDITIONING</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>STORAGE TANK ΔWEIGHT</td>
<td>~61</td>
<td></td>
</tr>
</tbody>
</table>
FUEL CELL TO CRYOGENS HEAT TRANSFER SYSTEM

Alternate System Required
### HEAT TRANSFER SYSTEM WEIGHTS

<table>
<thead>
<tr>
<th>Components</th>
<th>Number</th>
<th>Weight</th>
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</thead>
<tbody>
<tr>
<td>HX 61</td>
<td>2</td>
<td>0.8</td>
</tr>
<tr>
<td>HX 62</td>
<td>2</td>
<td>0.4</td>
</tr>
<tr>
<td>HX 55</td>
<td>2</td>
<td>1.0</td>
</tr>
<tr>
<td>HX 56</td>
<td>2</td>
<td>0.4</td>
</tr>
<tr>
<td>CP 56</td>
<td>2</td>
<td>4.0</td>
</tr>
<tr>
<td>CP 55</td>
<td>2</td>
<td>8.0</td>
</tr>
<tr>
<td>YV 53</td>
<td>4</td>
<td>12.0</td>
</tr>
<tr>
<td>YV 54</td>
<td>4</td>
<td>12.0</td>
</tr>
<tr>
<td>SV 63</td>
<td>6</td>
<td>18.0</td>
</tr>
<tr>
<td>CV 51</td>
<td>3</td>
<td>4.5</td>
</tr>
</tbody>
</table>

**Total**

61.0

**Lines (Estimate)**

10.0

71.1

Conditioning required if fuel cell heat is not used to condition fuel cell reactant.

- **Condition**: 175 lb $\text{H}_2$ = 64 lb
- **Condition**: 1,450 lb $\text{O}_2$ = 80 lb
- **Condition**: 144 lb
## Refill Comparison for ACPS + FC + APU + EC/LSS

<table>
<thead>
<tr>
<th>Component</th>
<th>No Refill</th>
<th>Refill</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>O(_2) Tank</td>
<td>1,020</td>
<td>280</td>
<td>-740</td>
</tr>
<tr>
<td>Insulation</td>
<td>8</td>
<td>3</td>
<td>-5</td>
</tr>
<tr>
<td>Vacuum Jacket</td>
<td>59</td>
<td>16</td>
<td>-43</td>
</tr>
<tr>
<td>H(_2) Tank</td>
<td>3,600</td>
<td>2,240</td>
<td>-1,360</td>
</tr>
<tr>
<td>Insulation</td>
<td>61</td>
<td>39</td>
<td>-22</td>
</tr>
<tr>
<td>Vacuum Jacket</td>
<td>217</td>
<td>138</td>
<td>-79</td>
</tr>
<tr>
<td>O(_2) Residual</td>
<td>515</td>
<td>113</td>
<td>-402</td>
</tr>
<tr>
<td>H(_2) Residual</td>
<td>203</td>
<td>72</td>
<td>-131</td>
</tr>
<tr>
<td>Added Components</td>
<td>-</td>
<td>370</td>
<td>+370</td>
</tr>
<tr>
<td>Added Conditioning</td>
<td>-</td>
<td>53</td>
<td>+53</td>
</tr>
<tr>
<td>Added Storage, OMPS Tanks</td>
<td>-</td>
<td>123</td>
<td>+123</td>
</tr>
<tr>
<td>Acquisition</td>
<td>-</td>
<td>200</td>
<td>+200</td>
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</tbody>
</table>

**Total Weight Savings** = 2,036
START TANK CONCEPT

ADVANTAGES:

- LIMITS HELIUM USE
- PROVIDES FINITE ACQUISITION METHOD
- PERMITS ELIMINATION OF VACUUM JACKETING

DISADVANTAGES:

- HEAVY
- DUTY CYCLE RESTRICTED
- HEATED HELIUM PURGE REQUIRED
CASE 1a INTEGRATED PURGING, INERTING, PNEUMATIC, AND PRESSURIZATION SUPPLY HELIUM REQUIREMENTS

<table>
<thead>
<tr>
<th>SUBSYSTEM</th>
<th>FUNCTION</th>
<th>HELIUM WEIGHT (LB)</th>
<th>PRESSURE (PSIA)</th>
<th>TEMPERATURE (°R)</th>
<th>FLOW RATE (LB/SEC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OIPS</td>
<td>ENGINE PNEUMATIC AND PURGE</td>
<td>60</td>
<td>1500</td>
<td>490-600</td>
<td>6 (MAX)</td>
</tr>
<tr>
<td></td>
<td>PNEUMATIC VALVES</td>
<td>5</td>
<td>500-700</td>
<td>490-600</td>
<td>0.6 (MAX)</td>
</tr>
<tr>
<td>OMPS/ACPS/APU/FC/EC/LSS</td>
<td>H₂ TANK INSULATION PURGE</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>VACUUM-JACKET TANKS</td>
<td>ACPS VALVES</td>
<td>0.95</td>
<td>500-700</td>
<td>460-600</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>APU VALVE</td>
<td>0.04</td>
<td>500-700</td>
<td>460-600</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>FC/EC/LSS VALVES</td>
<td>0.35</td>
<td>500-700</td>
<td>460-600</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>H₂ TANK PRESSURIZATION</td>
<td>45</td>
<td>18 (MIN)</td>
<td>37</td>
<td>0.4 (MAX)(1)</td>
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<tr>
<td></td>
<td>O₂ TANK PRESSURIZATION</td>
<td>6</td>
<td>20 (MIN)</td>
<td>165</td>
<td>0.046 (MAX)(1)</td>
</tr>
</tbody>
</table>

(1) BASED ON THREE TURBOPUMPS OPERATING AT 2.9 LB/SEC FOR H₂ AND 14.5 LB/SEC EACH FOR O₂.
<table>
<thead>
<tr>
<th>SUBSYSTEM</th>
<th>FUNCTION</th>
<th>HELIUM WEIGHT (LB)</th>
<th>PRESSURE (PSIA)</th>
<th>TEMPERATURE (°R)</th>
<th>FLOW RATE (LB/SEC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OIPS</td>
<td>ENGINE PNEUMATIC AND PURGE</td>
<td>60</td>
<td>1500</td>
<td>490-600</td>
<td>6 (MAX)</td>
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<tr>
<td></td>
<td>PNEUMATIC VALVES</td>
<td>5</td>
<td>500-700</td>
<td>490-600</td>
<td>0.6 (MAX)</td>
</tr>
<tr>
<td>OMPS/ACPS (PUMPS-AT-TANKS)</td>
<td>H₂ TANK INSULATION PURGE WITH LH₂ IN TANK</td>
<td>10</td>
<td>15</td>
<td>520 (INLET)</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>PNEUMATIC VALVES</td>
<td>0.95</td>
<td>500-700</td>
<td>460-600</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>H₂ TANK PRESSURE</td>
<td>43</td>
<td>22 (MIN)</td>
<td>37</td>
<td>0.4 (MAX)</td>
</tr>
<tr>
<td></td>
<td>O₂ TANK PRESSURE</td>
<td>5</td>
<td>2 (MIN)</td>
<td>165</td>
<td>0.046 (MAX)</td>
</tr>
<tr>
<td>APU</td>
<td>PNEUMATIC</td>
<td>0.04</td>
<td>500-700</td>
<td>460-600</td>
<td>&lt; 0.01</td>
</tr>
<tr>
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<td>H₂ TANK PRESSURE</td>
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<td>31</td>
<td>37</td>
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<td>O₂ TANK PRESSURE</td>
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<td>165</td>
<td>&lt; 0.01</td>
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<tr>
<td>FC/EC/LSS</td>
<td>PNEUMATIC</td>
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<td>500-700</td>
<td>460-600</td>
<td>&lt; 0.01</td>
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</table>
## CASE IIla (1) INTEGRATED PURGING, PNEUMATIC, AND
PRESSURIZATION SUPPLY HELIUM REQUIREMENTS

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Function</th>
<th>Helium Weight (LB)</th>
<th>Pressure (PSIA)</th>
<th>Temperature (°R)</th>
<th>Flow Rate (LB/SEC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OIPS</td>
<td>Engine Pneumatic and Purge</td>
<td>60</td>
<td>1500</td>
<td>490-600</td>
<td>6 (MAX)</td>
</tr>
<tr>
<td></td>
<td>Pneumatic Valves</td>
<td>5</td>
<td>500-700</td>
<td>490-600</td>
<td>0.6 (MAX)</td>
</tr>
<tr>
<td>OMPs/ACPS</td>
<td>RL-10 Purge</td>
<td>1.7</td>
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<td>Pumps-At-Engine</td>
<td>Pneumatic</td>
<td>10</td>
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<td>Hydrogen Tank Insulation</td>
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<td>Purge with LH₂ in Tank</td>
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<td>Hydrogen Tank Pressure</td>
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<td>37</td>
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<td>500-700</td>
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<td>&lt; 0.01</td>
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</table>

(1) MODIFIED FOR USE OF RL-10 ENGINES FOR THE OMPs.
(2) BASED ON H₂ AT 8.5 LB/SEC AND O₂ AT 45.5 LB/SEC

D04932
HELIUM SUPPLY TANK AND USABLE HELIUM WEIGHT

**Graph:**
- **Y-axis:** Total Helium + Tank Weight (lb)
- **X-axis:** Maximum Tank Pressure (PSIA)
- **Legend:**
  - Minimum Blowdown Pressure (PSIA) markers:
    - 50 lb
    - 100 lb
    - 500 lb
    - 600 lb
    - 700 lb
## INTEGRATED PIP AND PRESSURIZATION HELIUM SUPPLY

<table>
<thead>
<tr>
<th>ITEM</th>
<th>PIPS WT (LB)</th>
<th>PRESSURIZATION SYSTEM WEIGHT (LB)</th>
<th>INTEGRATED SYSTEM WEIGHT (LB)</th>
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<tr>
<td></td>
<td>la</td>
<td>IIIa</td>
<td>la</td>
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<td>HELIUM REQUIREMENTS</td>
<td>72</td>
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<td>45</td>
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<td></td>
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<tr>
<td>O₂</td>
<td>12</td>
<td>127</td>
<td>-</td>
</tr>
<tr>
<td>H₂</td>
<td>12</td>
<td>127</td>
<td>-</td>
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<td>TANKAGE</td>
<td>280</td>
<td>310</td>
<td>50</td>
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<tr>
<td>COMPONENTS</td>
<td>327</td>
<td>402</td>
<td>64</td>
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<tr>
<td>RESIDUAL He</td>
<td>125</td>
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<td>3</td>
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<tr>
<td>TOTAL DRY</td>
<td>607</td>
<td>712</td>
<td>114</td>
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<tr>
<td>TOTAL FLUID</td>
<td>221</td>
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<tr>
<td>TOTAL</td>
<td>828</td>
<td>1,197</td>
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<td>WEIGHT SAVINGS</td>
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**TOTAL WEIGHT SAVINGS:**

- la: 130
- IIIa: 295
- IIIa MOD: 286
COMPARABILITY BETWEEN PROPELLANT USAGE
UNCERTAINTY AND PROPELLANT USAGE CONTROL

MR 4.8:
MR 5.5:
WITHOUT MR
CONTROL:
ADD 170 LB LH₂
ADD 238 LB LO₂
ADD 82 LB LO₂
107 LB LH₂

MR OF RL-10 DURING RETROBURN

O₂ CONTROL CAPABILITY
H₂ CONTROL CAPABILITY
O₂ USAGE UNCERTAINTY
H₂ USAGE UNCERTAINTY

D04938
COMPATIBILITY BETWEEN PROPELLANT USAGE UNCERTAINTY AND PROPELLANT USAGE CONTROL

MR 4.8: ADD 170 LB LH₂
MR 5.5: ADD 238 LB LO₂
WITHOUT MR CONTROL: ADD 82 LB LO₂
107 LB LH₂

O₂ CONTROL CAPABILITY
H₂ CONTROL CAPABILITY
O₂ USAGE UNCERTAINTY
H₂ USAGE UNCERTAINTY

ΔWEIGHT

MR OF RL-10 DURING RETROBURN

D04938
INTEGRATED OMPS/ACPS WITH PUMP-AT-ENGINE
SUMMARY OF EFFECTS
OF
DEGREE OF INTEGRATION
AND
OPERATIONAL MODE
INTEGRATED SYSTEMS RESULTS

- WEIGHT PENALTY OF 600 LB FOR USING TWO RL-10 ENGINES INSTEAD OF LIQUID-FED OMPS THRUSTERS
- WEIGHT PENALTY OF 180 LB FOR A START TANK SYSTEM
- FULLY INTEGRATED SYSTEM IS LIGHTEST AND HAS FEWER COMPONENTS (Ia)
- SYSTEM WITH SEPARATE SUBCRITICAL APU IS NEXT LIGHTEST – LARGE COMPONENT COUNT (IIa)
- VACUUM JACKET ON OMPS TANKS RESULTS IN WEIGHT PENALTY OF 550-TO-750 LB
- INTEGRATED SYSTEMS CAUSE DIFFICULT ACQUISITION PROBLEMS
- HELIUM REQUIRED IN ALMOST ALL ATTRACTIVE SYSTEMS
REFILL OF SUPERCRITICAL TANKS SAVES 2000 LB, BUT
INTRODUCES DISADVANTAGES ORIGINALLY ELIMINATED BY
USE OF SUPERCRITICAL STORAGE

ASCENT TANKS USABLE FOR HEAT SINK PRIOR TO DEPLOYMENT
OF RADIATORS

ASCENT TANKS CAPABLE OF PREPRESSURIZATION FROM ACPS
ACCUMULATORS

EC/LSS HEAT USABLE FOR FUEL CELL REACTANT CONDITIONING

COMMON PUMPS CAPABLE OF SUPPLYING LIQUID TO OMPS
AND TO ACPS CONDITIONERS

APU REACTANTS USABLE AS HEAT SINK FOR EC/LSS DURING
REENTRY
REUSABILITY/RELIABILITY EVALUATIONS
TYPICAL FAILURE RATES AS FUNCTION OF TIME

DEBUGGING REGION

USEFUL-LIFE REGION

WEAROUT REGION

FAILURE RATES

TIME
OMPS/ACPS SYSTEMS (PUMP-AT-TANK) - SYSTEM III

Component Replacement:
- Flight 64: PRO1, PRO2
- Flight 71: SV04A, SV04B, PS03
- Flight 93: SV06"
COMPARISON OF PUMP-AT-TANK AND PUMP-AT-ENGINE -
PRESELECTED PUMP-RUN SCHEDULE - SYSTEM III

COMPONENTS REPLACED:

PUMP-AT-ENGINE

FLIGHT 22; PRO1
FLIGHT 43; PRO1
FLIGHT 64; PRO1, PRO2
FLIGHT 73; SV03A, SV03B, PS04
FLIGHT 85; PRO1
FLIGHT 96; SV10A, SV12A

PUMP-AT-TANK

FLIGHT 64; PRO1, PRO2
FLIGHT 71; SV04A, SV04B, PS03, SV09
FLIGHT 93; SV06A

PROJECTED NUMBER OF FLIGHT MISSIONS

PROBABILITY OF SYSTEM FAILURE
COMPARISON OF PUMP-AT-TANK AND PUMP-AT-ENGINE - SEQUENTIAL PUMP-RUN SCHEDULE - SYSTEM III

COMPONENTS REPLACED:
- FLIGHT 21; PR01
- FLIGHT 43; PR01
- FLIGHT 64; PR01, PR02
- FLIGHT 73; SV03A, SV03B, PS04
- FLIGHT 85; PR01

COMPONENTS REPLACED: (SINGLE REPLACEMENTS)
- FLIGHT 64; PR01, PR02
- FLIGHT 71; SV04A, SV04B, PS03

PROJECTED NUMBER OF FLIGHT MISSIONS
INTEGRATED AUXILIARY POWER UNIT SYSTEM

COMPONENTS REPLACED:
FLIGHT 85; PT02

PROJECTED NUMBER OF FLIGHT MISSIONS

D04467
11m
INTEGRATED FUEL CELL AND ENVIRONMENTAL CONTROL -
LIFE SUPPORT SYSTEMS

**Component Replacements:** (At ground servicing for flight indicated)

<table>
<thead>
<tr>
<th>Flight</th>
<th>Components</th>
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<tr>
<td>26</td>
<td>CU02, CU03, CU01</td>
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<tr>
<td>43</td>
<td>CU04</td>
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<tr>
<td>46</td>
<td>PP01A, PP01B, PP01C</td>
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<tr>
<td>51</td>
<td>CU02, CU03, CU01</td>
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<td>64</td>
<td>RO05, RO06, RO02A, RO02B, RO02C, RO03, RO04, RO01A, RO01B, RO01C</td>
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<tr>
<td>76</td>
<td>CU02, CU03, CU01</td>
</tr>
<tr>
<td>85</td>
<td>PT02, CU04</td>
</tr>
<tr>
<td>91</td>
<td>PP01A, PP01B, PP01C</td>
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</tbody>
</table>

**Graph:**

**Projected Number of Flight Missions**

**Probability of System Failure**

---

**D04482**

11m
COMPARISON FOR PRESELECTED AND SEQUENTIAL PUMP ARRANGEMENT FOR PUMP-AT-ENGINE - SYSTEM 1

COMPONENT REPLACEMENTS: (AT GROUND SERVICING FOR FLIGHT INDICATED)

- FLIGHT 22 - PROI
- FLIGHT 26 - CU01, CU02, CU03
- FLIGHT 43 - PROI, CU05
- FLIGHT 46 - PP01A, PP01B, PP01C
- FLIGHT 51 - CU01, CU02, CU03
- FLIGHT 64 - PRO1, PRO2, PRO5, PRO6, PRO7, PRO8, PRO9A, PRO9B, PRO9C, PR01A, PR01B, PR01C
- FLIGHT 71 - SV04A, SV04B, PS03
- FLIGHT 76 - CU01, CU02, CU03
- FLIGHT 85 - PRO1, CU05
- FLIGHT 86 - PT01
- FLIGHT 91 - PP01A, 01B, PP01C
- FLIGHT 100 - CU01, CU02, CU03
COMPARISON OF RELATIVE RELIABILITY
OF SYSTEM 1, SYSTEM III, AND
NONINTEGRATED SYSTEMS (PUMP-AT-ENGINE)
EFFECT OF OPERATIONAL MODE
AS COMPARED TO INTEGRATION METHOD

- Nonintegrated System (SPA) (0.028169)
- Integrated Vehicle System (SPA) (0.026193)
- System Three (SPA) (0.023469)
- Sequential Operation
- Preselected Operation

Probability of System Failure

0.000 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000

0 10 20 30 40 50 60 70 80 90 100

Projected Number of Flight Missions

D04911
CONCLUSIONS REGARDING EFFECTS OF INTEGRATION ON REUSABILITY AND RELIABILITY

- Component replacement requirements as a result of wearout are relatively low.

- Integration has a significant effect on per-flight reliability, but little on reliability/reusability.

- Operational mode (use of redundancy) has a significant effect on relative reliability, and moderate effect on replacement.
INSTRUMENTATION AND CONTROL
INSTRUMENTATION AND CONTROL APPROACH

EACH SUBSYSTEM AND INTEGRATED SYSTEM EXAMINED FOR INSTRUMENTATION AND CONTROL AND MODIFIED ACCORDINGLY.

- DETAILED INFORMATION PROVIDED FOR
  - INTEGRATED OMPS/ACPS SUPPLY
  - SUBCRITICAL AUXILIARY POWER
  - INTEGRATED FUEL CELL/LIFE SUPPORT SUPPLY

- INFORMATION CONSISTS OF:
  - FUNCTIONAL FLOW
  - EVENT FLOW CHART
  - CONTROL SCHEMATICS FOR EACH MAJOR SUBSYSTEM FUNCTION (CONDITIONING, PRESSURIZATION, ETC.)
COMPONENT EVALUATIONS
TYPICAL REENTRY STRUCTURAL TEMPERATURES (HIGH CROSS RANGE)

- Maximum 300°F
- Maximum 200°F
- Ground-cooling on
- Touchdown

TIME FROM 400,000 FEET (100 SEC)

STRUCUTRAL TEMPERATURE (°F)

0 50 100 150 200 250 300

0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300
EFFECT OF HELIUM LEAKAGE INTO TANKS WITH INTEGRATED OMPS/ACPS PROPELLANTS

(TYPICAL DUTY CYCLE - 17TH ORBIT RENDEZVOUS)

LIQUID OXYGEN TANK

VAPOR PRESSURE = 16 PSIA
INITIAL PRESSURE = 26 PSIA

MAXIMUM PRESSURE OCCURS DURING PERIOD WHEN DOCKED (OR PARKED)

LIQUID HYDROGEN TANK

COMPONENT HELIUM LEAKAGE INTO TANKS (SCCM)
EFFECTS OF PRESSURE CONTROL APPROACH ON OMPS LH₂ TANK

EXPULSION PRESSURE - 28 PSIA
VENT PRESSURE - 23 PSIA (OR EQUIVALENT VAPOR PRESSURE)
MAINTAINING NPSH - 5 PSIA

RESULTS USING TEMPERATURE CONTROL

- BOILOFF
- RESIDUAL HYDROGEN
- BOILOFF HYDROGEN
- RESIDUAL HYDROGEN
- RESIDUAL HELIUM (PRESSURANT)
- RESIDUAL HELIUM (PRESSURANT)

PRESSURANT TEMPERATURE (°R)
WEIGHT (LB)
COMPARISON OF EFFECTS ON OMPS FROM PRESSURIZATION AND INSULATION VARIABLES

$\text{GH}_2$ PRESSURIZATION ($350^\circ R - 36 \text{ PSIA}$)

- BOIL-OFF (LB)
- VENT PRESSURE (PSIA)
- INSULATION THICKNESS (IN.)

INSULATION 0.75 IN.

D02948

Um

165
CONCLUSIONS RELATED TO COMPONENTS MECHANICAL AND ELECTRICAL

- COMPONENTS ARE AVAILABLE AND PRESENT TECHNOLOGY SATISFACTORY FOR MOST APPLICATIONS.
- COMPONENT REPLACEMENT AS A RESULT OF WEAROUT WILL NOT BE SEVERE.
- LIFETIME FACTORS ASSOCIATED WITH ORGANIC MATERIALS IS MAJOR CAUSE FOR REPLACEMENT.
- COMPONENT FAILURES BY WEAROUT MOST LIKELY IN:
  - SEATS
  - BELLOWS AND DIAPHRAGMS.
- COMPONENT LEAKAGES CAN BE "MODERATE" TO "HIGH".
- DISCONNECTS SHOULD BE IMPROVED.
CONCLUSIONS RELATED TO COMPONENTS INSTRUMENTATION AND CONTROL

- PRESSURE SWITCHES REQUIRE IMPROVEMENT.
- LIQUID-HYDROGEN PRESSURE TRANSDUCERS ARE NEEDED.
- CONTROL OF LH\textsubscript{2} TANK VENTING BY TEMPERATURE IS DESIRABLE.
- ZERO-g SENSING DEVICES ARE NOT NECESSARY.
- LEAKAGE DETECTION IMPROVEMENT IS NEEDED.
TANKAGE REUSABILITY APPROACHES ARE SATISFACTORY, BUT FRACTURE MECHANICS DATA ARE SHORT.

ACCUMULATOR WEIGHT REDUCTION IS DESIRABLE (COMPOSITE TANKS).

FEEDLINE COMPONENTS ARE CAPABLE OF DESIRED CYCLE LIFE.

FEEDLINE WEIGHTS CAN BE REDUCED BY ALUMINUM FEEDLINES WITH STAINLESS STEEL EXPANSION JOINTS.

VACUUM SEALOFF VALVE LIFETIME IMPROVEMENT IS NEEDED.

FIBERGLASS SUPPORTS FAIL IN TENSION LOADING AT WARM END.

PROPELLANT ACQUISITION IS A MAJOR PROBLEM.
CONCLUSIONS RELATED TO COMPONENTS INSULATION

- SUBSYSTEMS ARE NOT SENSITIVE TO:
  - MULTILAYER INSULATION TYPE
  - THERMAL CONDUCTIVITY OF FOAM (WEIGHT TO PREVENT AIR LIQUIFICATION AND EXCESSIVE ICING IMPORTANT).

- MULTILAYER INSULATION REQUIRES LITTLE DEVELOPMENT. PROTECTION FROM ENVIRONMENT IS PRINCIPAL PROBLEM.

- REUSABLE GROUNDHOLD AND ASCENT (AND REENTRY) INSULATION NEEDED.

- FEEDLINE INSULATION DESIGNS NEED IMPROVEMENT.
TECHNOLOGY EVALUATION
TECHNOLOGY EVALUATION SUMMARY
PROPELLANT ACQUISITION

MAJOR CRYOGENIC TECHNOLOGY REQUIRING ADVANCEMENT

CONSIDERATIONS

- Adverse acceleration requirements are high, probably requiring multiple screens

- Severe start transients

- Gas ingestion may not be excludable

- Thermal problems in subcooled systems may not be as severe as gas ingestion
TECHNOLOGY EVALUATION SUMMARY
MECHANICAL AND ELECTRICAL COMPONENTS

- VALVES AND REGULATORS REQUIRE LITTLE TECHNOLOGY ADVANCEMENTS OTHER THAN DESIGN IMPROVEMENTS. DISCONNECTS NEED ADVANCEMENT.

- CRYOGENIC-COOLED ELECTRICAL MOTORS TECHNOLOGY ADVANCEMENT (AND RELATED ALTERNATORS)

- ATTITUDE CONTROL PROPELLANT SUPPLY PUMP:
  - LINEAR START TRANSIENT
  - LOW HEAT SOAK BACK

- AUXILIARY POWER UNIT SUPPLY PUMP SHOULD OPERATE CONTINUOUSLY
TECHNOLOGY EVALUATION SUMMARY
INSTRUMENTATION AND CONTROL

- PRESSURE SWITCH LIFETIME IMPROVEMENT
- LIQUID-HYDROGEN PRESSURE TRANSDUCER DEVELOPMENT
- LEAKAGE-DETECTION DEVICES
- TEMPERATURE CONTROL OF HYDROGEN VENTING
TECHNOLOGY EVALUATION SUMMARY
TANKAGE AND FEEDLINES

- REUSABLE COMPOSITE TANKAGE FOR ACCUMULATOR WEIGHT REDUCTION
- IMPROVEMENTS IN VACUUM SHELLS FOR LARGE TANKS
- ALUMINUM FEEDLINE TECHNOLOGY
- VACUUM SEALOFF VALVE IMPROVEMENT
TECHNOLOGY EVALUATION SUMMARY
INSULATION

- MULTILAYER INSULATION DOES NOT REQUIRE SIGNIFICANT TECHNOLOGY ADVANCEMENT. SOME DESIRABLE PROGRAMS ARE:
  
  "BREATHEING" TYPE DEVICE TO REMOVE WATER AND MOISTURE IN AREAS WHERE REENTRY PURGING IS NOT REQUIRED.

  PURGING STUDIES TO IMPROVE ANALYTICAL TECHNIQUES.

- GROUNDHOLD, ASCENT, AND REENTRY INSULATION IMPROVEMENT (FOAMS, SURFACE TENSION, ETC.)

- REMOVABLE FEEDLINE INSULATION SYSTEM
TECHNOLOGY EVALUATION SUMMARY
ANALYTICAL TECHNIQUES

- PRESSURIZATION ANALYTICAL TECHNIQUES

- CRYOGENIC LIQUID-STRATIFICATION ANALYTICAL TECHNIQUES, COUPLED WITH PRESSURIZATION

- IMPROVEMENTS IN ANALYSIS OF INSULATION PURGING AND VENTING OF PURGE GAS
TECHNOLOGY EVALUATION SUMMARY
BASIC DATA

- HELIUM SOLUBILITY IN CRYOGENICS
- HYDROGEN FLAME DATA (LOW LEAKAGE)
- FRACTURE MECHANIC DATA FOR TANKAGE REUSABILITY
- GENERAL BELLOWS DATA
- ORGANIC MATERIALS LIFETIME DATA FOR SHUTTLE DUTY CYCLE
- CRYOGENIC FLUID CAPILLARY-RETENTION PROPERTIES
TECHNOLOGY EVALUATION SUMMARY

SUBSYSTEM TECHNOLOGY

- LIQUID/LIQUID ATTITUDE CONTROL EVALUATION
- ELECTRICAL INTEGRATION OF CRYOGENIC SUBSYSTEMS (AIRCRAFT APPROACH - MAXIMIZATION OF ELECTRICAL MOTORS)
- CRYOGENIC COOLING SUBSYSTEM FOR ENVIRONMENTAL CONTROL, HYDRAULICS, ETC.
- INSTRUMENTATION AND CONTROL INTEGRATION