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Task 4 Supporting Technology
Densification Requirements Definition
and Test Objectives
Payment Milestone No. PD1
WBS 1850
Cooperative Agreement NCC8-79

May 30, 1995

Tibor Lak

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Principal Investigator

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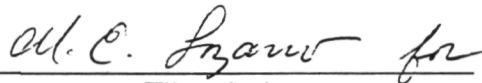
D. P. Weeks
Technology Team Leader

(NASA-CR-198629) TASK 4 SUPPORTING TECHNOLOGY. DENSIFICATION REQUIREMENTS DEFINITION AND TEST OBJECTIVES. PROPELLANT DENSIFICATION REQUIREMENTS DEFINITION (Rockwell International Corp.) 22 p

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PROPELLANT DENSIFICATION REQUIREMENTS DEFINITION

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INTRODUCTION

The primary challenge of the X-33 CAN is to build and test a prototype LO2 and LH2 densification GSE unit, and perform tank thermodynamic testing within the 15 month Phase 1 period. The LO2 and LH2 propellant densification system will be scaled for the IPTD LO2 and LH2 tank configurations. The IPTD tanks were selected for the propellant technology demonstration because of the potential benefits to the Phase 1 plan:

- Tanks will be built in time to support tank thermodynamic testing
- Minimum cost
- Minimum schedule risk
- Future testing at MSFC will build on Phase 1 data base
- Densification system will be available to support X-33 and RLV engine test at IPTD

The LO2 GSE unit will be built and tested at the Rockwell Downey cryogenic test facility, while the LH2 GSE unit will be built and tested at the NASA LeRC K-Site test facility. Due to the simpler design of the LO2 GSE (LN2 bath heat exchanger), the LO2 densification unit will be completed first. After completion of LO2 GSE testing tank thermodynamic testing will be performed. The LO2 IPTD tank, which will be at Downey during this time for modification, test and check-out (cryo shock, proof pressure test, SOFI installation, test structure assembly) will be retrofitted with the recirculation system and used in tank thermodynamic testing at Downey. At the completion of the tank thermodynamic testing the LO2 IPTD tank will be shipped to MSFC for installation into the IPTD test stand.

The schedule to accomplish the Phase 1 implementation plan is presented in **Figure 1**.

REQUIREMENTS DEFINITION (Task 1.0)

The objective of the Task 1 effort is to define the preliminary requirements of the propellant densification GSE and tank recirculation system. The key densification system design parameters to be established in Task 1, prior to detailed system analysis and design are:

- Recirculation flow rate
- Heat exchanger inlet temperature
- Heat exchanger outlet temperature
- Maximum heat rejection rate
- Vent flow rate (GN2 and GH2)
- Densification time
- Tank pressure level

The RLV design has been used as the basis to scale the propellant densification GSE and recirculation system for subscale testing with the IPTD tanks. The propellant densification system design requirements for the IPTD tanks are summarized in Table 1. The GSE heat exchanger outlet temperature, densification time, and tank operating pressure are based on the RLV design. The recirculation flow rate level however was modified based on tank capacity and densification time. The recirculation flow rate is equal to the tank mass divided by the time to densify. Because the RLV and IPTD tank volume to diameter ratios are different, the tank fluid velocity and Reynolds number are slightly lower in the IPTD tank than in the RLV tanks. The difference however will result in lower velocity and turbulent flow will therefore result in slightly more conservative test demonstration. Because the analytical model of the tank recirculation flow and thermal gradient will be verified with test results the effect of the higher tank velocity can be predicted.

The maximum heat rejection rate of the GSE unit will be designed to accept the maximum liquid flow rate from the tank recirculation system. This maximum fluid inlet temperature is based on the saturated liquid corresponding to the maximum tank relief valve cracking pressure of 20 psig. The liquid evaporation rate during the maximum heat rejection phase of operation is based on the heat exchanger boiling point pressure of 15 psia for LN2 and 1.4 psia for LH2.

The preliminary GSE redundancy requirements were jointly established during the Preliminary Requirements Review (PRR) telecon held on 15 May 1995. Those participating in the telecon included NASA KSC (James Fesmire, Frank Howard, Robert Johnson), MSFC (Jim Martin, who represented Dr George Schmidt), and LeRc (Nancy McNelis, Tom Tomsik). The agreed upon requirements of the Task 1 effort are documented in Appendix A of this report.

TEST OBJECTIVES DEFINITION

In addition to the design parameters discussed above, the densification test objectives and the preliminary GSE redundancy requirements were also jointly established during the PRR telecon. Page 10 of the appendix provides a summary of the test objectives for both the LO2 GSE unit and the Tank Thermodynamics Validation test series. The agreed upon test objectives were based primarily on the issues raised by a joint NASA/contractor "Tiger Team". The densification system redundancy requirements, which are provided on page 11 of the appendix, were defined to maximize safe operations during testing.

Because of the early completion of Task 1, the preliminary design effort for the GSE units (LO2 and LH2) and the LO2 tank recirculation system is ahead of schedule. The next phase of the design activity will conclude in a PDR as indicated in Figure 1.

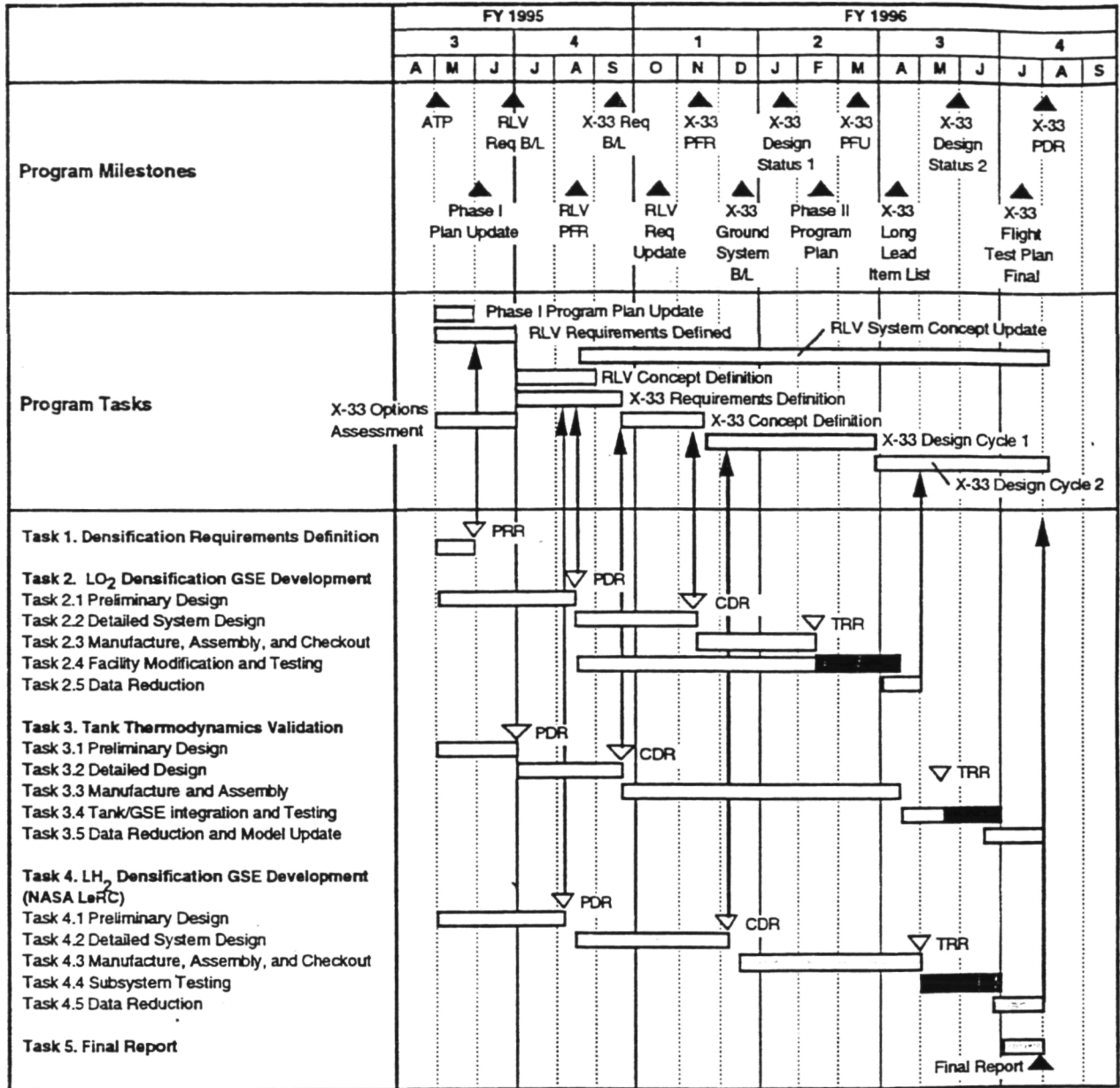


Figure 1 Propellant Densification Technology Demonstration Schedule

Table 1. LO2 and LH2 Densification System Design Requirements

| TANK DESIGN | IPTD LO2 TANK | IPTD LH2 TANK |
|--|----------------------|----------------------|
| Volume (cu ft) | 1601 | 2706 |
| Ullage Volume (%) | 4 | 4 |
| Liquid Mass (lbm) | 115964 | 12235 |
| Max. Pressure (psia) | 35 | 35 |
| Densification Time (hr) | 1.5 | 2.0 |
| Recirculation Flow Rate (lbm/sec) | 21.5 | 1.7 |
| Recirculation Flow Rate (GPM) | 128 | 162 |
| Velocity (in/sec) | 0.04 | 0.06 |
| Reynolds Number | 12922 | 14463 |
| HEAT EXCHANGER DESIGN | | |
| <u>Hot Side (Liquid Recirculation)</u> | | |
| Liquid Flow Rate (lbm/sec) | 21.5 | 1.7 |
| Max. inlet Temp (Sat @ 35 psia) (R) | 178.9 | 42.5 |
| Outlet Temp (R) | 140.5 | 27 |
| Max. Heat Rejection Rate (Btu/sec) | 335 | 58 |
| <u>Cold Side (Vent Side)</u> | | |
| Heat Exch. Bath Pressure (psia) | 15 | 1.4 |
| Liquid Boiling Temperature (R) | 139.5 | 26 |
| Max. Evaporation Rate (lbm/sec) | 3.9 | 0.3 |

APPENDIX A

PRELIMINARY REQUIREMENTS REVIEW (Final Briefing)

Preliminary Requirements Review (Task 1.0)

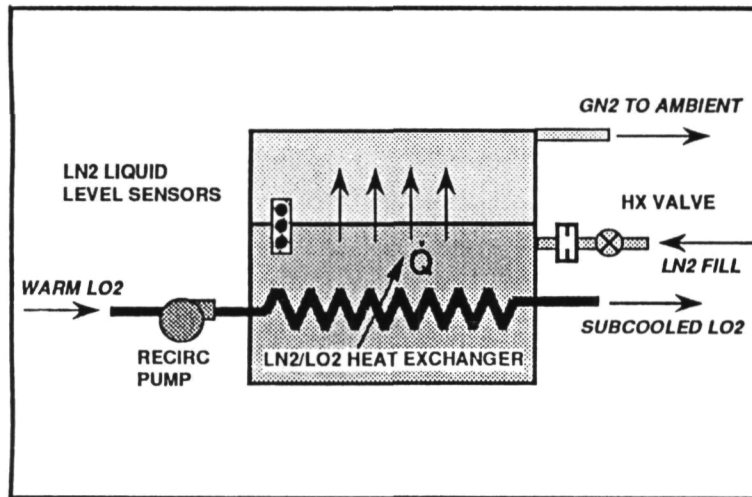
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PROPELLANT DENSIFICATION PHASE I OBJECTIVES

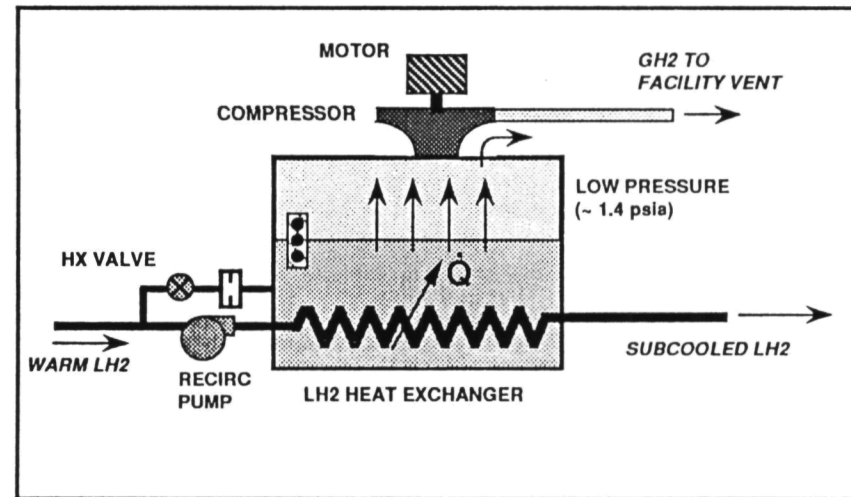
- **DEMONSTRATE THE PROPELLANT DENSIFICATION CONCEPT THROUGH SUBSCALE TESTING**
- **LO2 & LH2 GSE DESIGN & TEST**
 - DESIGN AND BUILD PROTOTYPE GSE DENSIFICATION UNITS
 - DEMONSTRATE THROUGH TESTS THE ABILITY TO GENERATE SUBCOOLED LO2 AND LH2
- **TANK THERMODYNAMIC TESTING**
 - DESIGN AND BUILD TANK RECIRCULATION SYSTEM (USING IPTD LO2 TANK)
 - DEMONSTRATE TANK THERMODYNAMICS ASSOCIATED WITH DENSIFICATION
 - » THE ABILITY TO PRODUCE & MAINTAIN SUBCOOLED PROPELLANT IN PROPELLANT TANK
 - » DENSIFICATION TIME
 - » TEMPERATURE GRADIENT & PROPELLANT BULK MASS
 - » PRESSURIZATION PERFORMANCE
 - ADDRESS ISSUES RAISED BY JOINT NASA/CONTRACTOR “TIGER TEAM”
 - » LIQUID LEVEL CONTROL WITH PRESSURIZED TANK (NON-BOILING SURFACE)
 - » OFF NOMINAL PERFORMANCE (STOP FLOW, RAPID TANK VENT-DOWN, EMERGENCY DRAIN, etc.)
- **DEVELOP & VERIFY ANALYTICAL MODEL BASED ON TEST RESULTS**

LO2 & LH2 GSE DESIGNS

- Propellant Densification GSE Units are Based on Simple Thermodynamic Principles and Conventional Heat Exchanger Designs



LO2 GSE IS BASED ON LN2 HEAT EXCHANGER BATH CONCEPT



LH2 GSE IS BASED ON THERMODYNAMIC VENT PRINCIPLE & COMPACT HEAT EXCHANGER DESIGN

Tank Recirculation Design

- Recirculation System Required to Maintain Subcooled Liquid in Tank

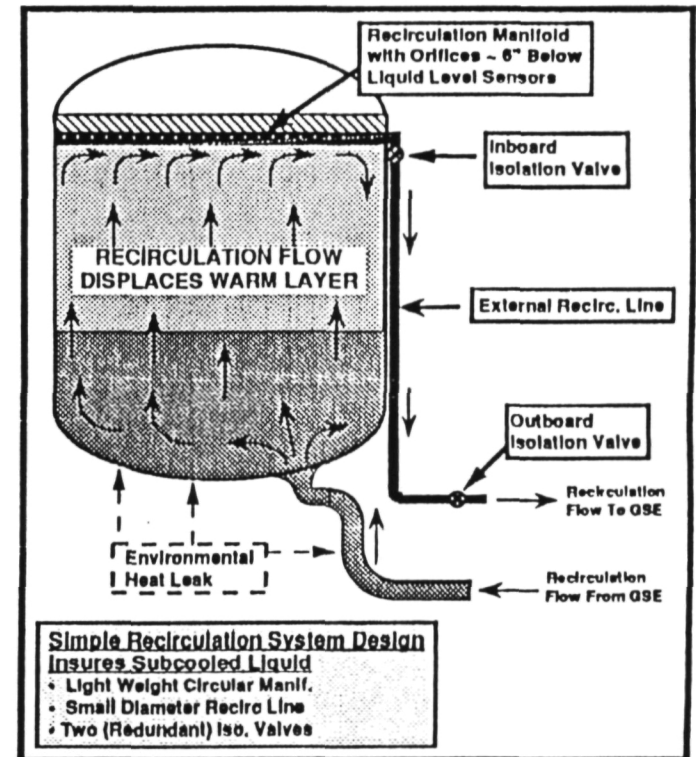
RECIRCULATION SYSTEM CONSISTS OF:

- MULTI ORIFICE RING MANIFOLD
- TWO EXTERNAL SHUT-OFF VALVES
- EXTERNAL RECIRCULATION LINE

RECIRCULATION MANIFOLD LOCATED BELOW LIQUID SURFACE

- PREVENTS ULLAGE GAS INGESTION
- ESTABLISHES WARM THERMALLY STRATIFIED LAYER TO CONTROL TANK VENT DOWN (EMERGENCY VENT)

"COLD" RECIRCULATION FLOW ENTERING TANK BOTTOM DISPLACES "WARMER" LIQUID THROUGH RECIRC. MANIFOLD TO GSE



PRELIMINARY REQUIREMENTS DEFINITION

OBJECTIVES

- DEFINE LO2 & LH2 GSE DENSIFICATION UNIT DESIGN REQUIREMENTS
 - RECIRCULATION FLOWRATE
 - HEAT EXCHANGER INLET TEMPERATURE
 - HEAT EXCHANGER OUTLET TEMPERATURE
 - MAXIMUM HEAT REJECTION RATE
 - VENT FLOWRATE
- DEFINE LO2 TANK RECIRCULATION SYSTEM DESIGN REQUIREMENTS
- GSE DESIGN REDUNDANCY REQUIREMENTS
- DEFINE PHASE I TEST OBJECTIVES
 - GSE UNIT
 - TANK THERMODYNAMICS

APPROACH

- SCALE DENSIFICATION SYSTEM TO IPTD LO2 & LH2 TANKS BASED ON RLV TANK SIZE AND DENSIFICATION TIME

LO2 & LH2 DENSIFICATION SYSTEM DESIGN REQUIREMENTS

IPTD TANK DESIGN

| TANK DESIGN | LO2 TANK | LH2 TANK |
|--|----------|----------|
| Volume (cu ft) | 1601 | 2706 |
| Ullage Volume (%) | 4 | 4 |
| Liquid Mass (lb) | 115964 | 12235 |
| Max Pressure (psia) | 35 | 35 |
| Densification Time (hr) | 1.5 | 2.0 |
| Recirculation Flowrate (lb/sec) | 21.5 | 1.7 |
| Recirculation Flowrate (GPM) | 128 | 162 |
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| <u>Hot Side (Liquid Recirculation)</u> | | |
| Liquid Flowrate (lb/sec) | 21.5 | 1.7 |
| Max. Inlet Temp (Sat @ 35 psia) (R) | 178.9 | 42.5 |
| Outlet Temp (R) | 140.5 | 27 |
| Max. Heat Rejection Rate (Btu/sec) | 335 | 58 |
| <u>Cold Side (Vent Side)</u> | | |
| Heat Exch. Bath Pressure (psia) | 15 | 1.4 |
| Liquid Boiling Temperature (R) | 139.5 | 26 |
| Max. Evaporation Rate (lb/sec) | 3.9 | 0.3 |

LO2 & LH2 DENSIFICATION SYSTEM DESIGN REQUIREMENTS

RECIRCULATION FLOWRATE

- RECIRC FLOW DEFINED BASED ON LIQUID MASS AND DENSIFICATION TIME (MASS/TIME)
- RECIRCULATION FLOWRATE SCALED TO IPTD TANK SIZE
 - DENSIFICATION TIME BASED ON RLV LOADING TIMELINE (1.5 hrs for LO2, & 2.0 hrs for LH2)
- INTERNAL TANK RECIRCULATION FLOW CHARACTERISTICS WITH RECIRC FLOW:
 - GOOD MATCH IN LO2 TANK VELOCITY, 0.04 in/sec (IPTD) vs. 0.05 in/sec (RLV)
 - TURBULENT FLOW (Reynolds Number > 13,000)

HEAT EXCHANGER INLET TEMPERATURE

- MAX INLET TEMPERATURE IS BASED ON SYSTEM HEAT LEAK AND DENSIFICATION TIME
 - HEAT LEAK TO TANK RESULTS IN LIQUID TEMPERATURE INCREASE WITH LOCKED-UP TANK
 - WARM LIQUID RISES TO SURFACE FORMING THERMAL STRATIFIED LAYER DURING INITIAL TANK MASS EXCHANGE
 - MAXIMUM LIQUID TEMPERATURE POSSIBLE AT MANIFOLD INLET IS DICTATED BY TANK PRESSURE
- MAXIMUM GSE INLET TEMPERATURE IS THEREFORE BASED ON SATURATED LIQUID AT MAX TANK OPERATING PRESSURE
 - MAXIMUM TANK PRESSURE IS 35 psia (RELIEF VALVE CRACKING PRESSURE)
 - SATURATED LIQUID TEMPERATURE AT 35 psia IS 42.5 R (LH2) & 178.9 R (LO2)

LO2 & LH2 DENSIFICATION SYSTEM DESIGN REQUIREMENTS (Cont.)

HEAT EXCHANGER OUTLET TEMPERATURE

- SIMILAR TO RLV DESIGN (27 R for LH2 & 140.5 R for LO2)
 - BASED ON BOILING LIQUID TEMPERATURE PLUS 1 DEGREE
 - SUPPORTED BY HEAT EXCHANGER ANALYSIS WITH BOILING LIQUID

MAXIMUM HEAT REJECTION RATE HEAT REJECTION RATE IS BASED ON RECIRC. FLOWRATE, MAX. INLET TEMPERATURE & HEAT EXCHANGER OUTLET TEMPERATURE

- THE HEAT REJECTION REQUIREMENT FOR THE GSE UNITS (NOT INCLUDING GSE HEAT LEAKAGE RATE) ARE:
 - LH2 GSE - 58 Btu/sec
 - LO2 GSE - 335 Btu/sec

MAX VENT FLOWRATE

- MAX VENT FLOWRATE IS DEFINED BASED ON THE MAX HEAT REJECTION RATE AND THE HEAT OF VAPORIZATION OF BOILING FLUID
 - 194 Btu/lb for LH2 BOILING AT 1.4 psia
 - 85.3 Btu/lb for LN2 BOILING AT 15 psia
- MAX VENT FLOWRATE (NOT INCLUDING GSE HEAT LEAK) IS:
 - 0.3 lb/sec GH2 (COMPRESSOR CAPACITY)
 - 3.9 lb/sec GN2

LO2 TANK RECIRCULATION SYSTEM PRELIMINARY DESIGN REQUIREMENTS

- RECIRCULATION SYSTEM PROVIDES FLOW PATH BETWEEN TANK AND GSE
- MINIMIZING DENSIFICATION SYSTEM PRESSURE LOSS RESULTS IN:
 - INCREASED SUPPLIED NPSP AT PUMP INLET
 - SMALLER PUMP SIZE & COST
 - REDUCED PUMP POWER
 - REDUCED LIQUID HEATING
- PRELIMINARY SYSTEM PRESSURE LOSS REQUIREMENTS ARE (LO2 flow at 130 GPM, LH2 flow at 170 GPM)
 - FROM MANIFOLD TO RECIRC PUMP INLET < 5 PSID
 - HEAT EXCHANGER PRESSURE DROP
 - » < 5 PSID (LO2)
 - » < 3 PSID (LH2)
 - FROM HEAT EXCHANGER OUTLET TO TANK INLET < 5 PSID
 - PRESSURE LOSS VALUES ARE DERIVED FROM SHUTTLE SYSTEM SIZING ANALYSIS

PHASE I TEST OBJECTIVES

GSE UNIT

- DEMONSTRATE GSE START, STEADY STATE, SHUTDOWN, & RESTART OPERATIONS
- DEMONSTRATE ABILITY TO GENERATE SUBCOOLED LIQUID WITH MAXIMUM INLET TEMPERATURE
- DEFINE GSE PERFORMANCE
 - » POWER CONSUMPTION
 - » RECIRCULATION FLOWRATE & PRESSURE LOSS
 - » FLUID CONSUMPTION (LH2, LO2, LN2, He, etc...)
 - » SYSTEM HEAT LEAK

TANK THERMODYNAMICS (LO2 GSE WITH LO2 IPTD TANK)

- DEMONSTRATE ABILITY TO TRANSFER & MAINTAIN SUBCOOLED PROPELLANT IN IPTD TANK
- DEMONSTRATE ABILITY TO MAINTAIN CONSTANT PRESSURE
- DEMONSTRATE LIQUID LEVEL CONTROL
- DEMONSTRATE STOP FLOW & RESTART DURING DENSIFICATION
- DEMONSTRATE SAFE RAPID TANK VENT DOWN (VENT VALVE OR RELIEF VALVE FAILURE)
- DEMONSTRATE EMERGENCY DRAIN IN EVENT OF MISSION ABORT
- DEFINE SYSTEM PERFORMANCE
 - » DENSIFICATION TIME
 - » TEMPERATURE GRADIENT & BULK TEMPERATURE
 - » LIQUID MASS
 - » SYSTEM HEAT LEAK RATE
 - » PRESSURIZATION REQUIREMENT (He MASS, FLOWRATE)
- DEMONSTRATE TANK CHILL & FILL OPERATIONS USING GSE MOUNTED VENT VALVE (OPTIONAL)

DENSIFICATION SYSTEM REDUNDANCY REQUIREMENTS (Preliminary)

- **THE DENSIFICATION GSE UNIT AND TANK RECIRCULATION SYSTEM SHALL BE FAIL SAFE**
 - ONE COMPONENT OR INSTRUMENTATION FAILURE SHALL NOT RESULT IN
 - » UN-SAFE OR HAZARDOUS CONDITION
 - » DAMAGE/LOSS OF HARDWARE
 - TERMINATION OF TEST OR LOSS OF DATA IS CONSIDERED TO BE ACCEPTABLE IN THE EVENT OF ONE OR MORE FAILURES

- **ELEMENTS WHICH REQUIRE REDUNDANCY (FACILITY NOT INCLUDED)**
 - LIQUID LEVEL SENSORS (PREVENT OVERFILL/SPILL OF LH2 OR LN2)
 - » HEAT EXCHANGER BATH
 - » TANK 100% FILL LEVEL
 - TANK PRESSURE TRANSDUCER (TANK OVER PRESSURE PROTECTION)
 - TANK RECIRCULATION LINE ISO. VALVES (2)
 - COMPRESSOR & RECIRC PUMP OVERSPEED PROTECTION

BACKUP CHARTS

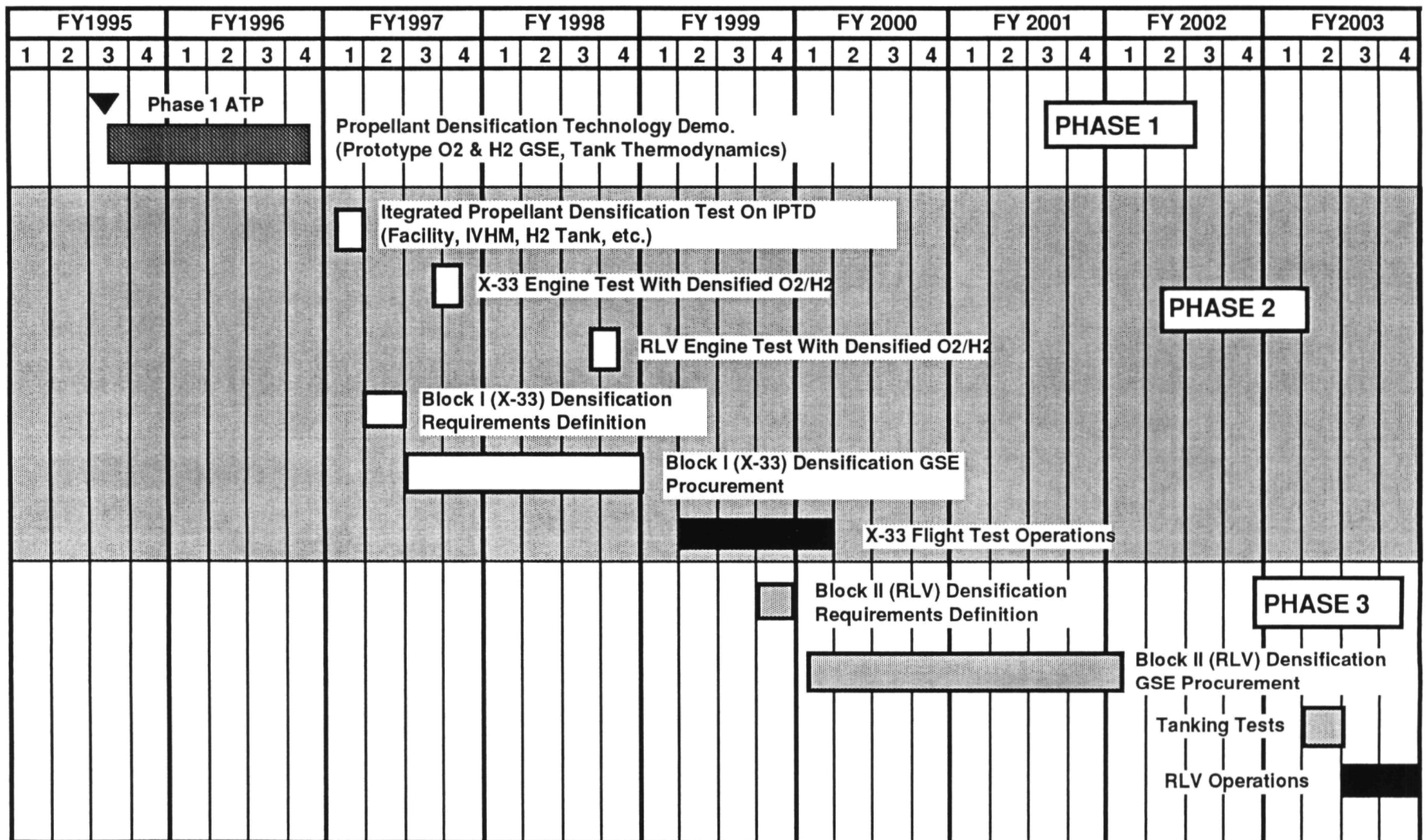
ADDITIONAL TESTING REQUIRED IN PHASE II

DELIVER LH2 & LO2 DENSIFICATION UNITS TO MSFC IPTD (AUG. 1996)

INTEGRATED TESTS CURRENTLY PLANNED ON IPTD (PHASE II)

- **LH2 TANK THERMODYNAMICS TEST VALIDATION**
 - DESIGN & BUILD LH2 RECIRCULATION SYSTEM BASED ON LO2 TESTS RESULTS
- **DEFINE LOADING TIMELINES & PROCEDURES INCLUDING PROPULSION CHECKOUT AND CONTROL SYSTEM (PCCS)**
- **CONTINUE TO GATHER OPERABILITY AND RELIABILITY DATA ON DENSIFICATION**
- **VERIFY OPERABILITY WITH IVHM**
- **ENGINE TESTS WITH DENSIFIED PROPELLANT ON THE IPTD (~ OCT. 1996)**
 - DEMONSTRATE START WITH SUBCOOLED PROPELLANTS
 - DEFINE SPECIFIC IMPULSE WITH DENSIFIED PROPELLANT
 - SUPPORT X-33 AND RLV ENGINE TESTS

PROPELLANT DENSIFICATION IMPLEMENTATION PLAN



PROPELLANT DENSIFICATION TECHNOLOGY DEMONSTRATION SCHEDULE

