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CRYOGENIC ON-ORBIT LIQUID DEPOT STORAGE, ACQUISITION AND TRANSFER SATELLITE (COLD-SAT) FEASIBILITY STUDIES

Final Report
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FOREWORD

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The data in this report are presented in the International System of Units as the primary units and English Units as the secondary units. All calculations and data plots were made in English Units and converted, where possible, to International Units.

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ACRONYM LIST FOR THIS STUDY

AC	ALTERNATING CURRENT
ACC	ACCURACY
ACE	ATTITUDE CONTROL ELECTRONICS
ACCEL	ACCELERATION
ACS	ATTITUDE CONTROL SUBSYSTEM
ADC	ALTERNATING TO DIRECT CONVERTER
AFETR	AIR FORCE EASTERN TEST RANGE
AH	AMPERE-HOUR
AL	ALUMINUM
ALT	ALTERNATE
AMP	AMPLIFIER
ANT	ANTENNA
ARTIC	ARTICULATION
ASME	AMERICAN SOCIETY OF MECHANICAL ENGINEERS
ASSY	ASSEMBLY
ATR	ACTUATOR SUBMODULE
ATT	ATTITUDE
A/V	RATIO OF AREA TO VOLUME
AVAIL	AVAILABLE
AVG	AVERAGE
AZ	AZIMUTH
BCU	BUS COUPLER UNIT
BD	BURST DISK
BLDG	BUILDING
BO	BOND NUMBER
BO_{cr}	CRITICAL BOND NUMBER
BOL	BEGINNING OF LIFE
BP	BACK PRESSURE
BTU	BRITISH THERMAL UNITS
C	CONTROL NETWORK
C	IMPERICAL CONSTANT FOR NUSSLET NUMBER
°C	DEGREES CENTIGRADE
C&DH	COMMAND AND DATA HANDLING
CAP	CAPACITY
CAT	CATEGORY
CC	THE VELOCITY OF SOUND IN GAS
CCAFS	CAPE CANAVERAL AIR FORCE STATION
CFM	CRYOGENIC FLUID MANAGEMENT
CG	CENTER OF GRAVITY
CHX	COMPACT HEAT EXCHANGER
CL	CLASS
CM	CENTIMETER
CMDS	COMMANDS
CNTR	CENTER
C/O	CHECKOUT
COMM	COMMUNICATION
CONN	CONNECTOR
CONV	CONVERTER
COTS	COMMERCIAL OPERATING TELEMETRY SYSTEM
CP	HEAT CAPACITY
Cp	SPECIFIC HEAT AT CONSTANT PRESSURE

ACRONYM LIST FOR THIS STUDY

CPIA	CHEMICAL PROPULSION INFORMATION AGENCY
CRES	CORROSION RESISTANT STEEL
C_pW	WALL SPECIFIC HEAT
CR	REQUIRED BATTERY CAPACITY
CR	CONCEPT REVIEW
CRYOCHIL	CHILLDOWN PROGRAM DEVELOPED BY LERC
CTRL	CONTROL
CU	CENTRAL UNIT
CV	SPECIFIC HEAT AT CONSTANT VOLUME
D, DIA	DIAMETER
DB	DECIBEL
DC/AC	DIRECT CURRENT/ALTERNATING CURRENT
DCE	DATA CARRIER EQUIPMENT
DEG	DEGREE
DEV	DEVELOPMENT
DOD	DEPTH OF DISCHARGE
DID	DATA ITEM DESCRIPTION
DIV	DIVISION
DM_I	INCOMING FLOW STREAMS DIFFERENTIAL MASS
DO	NOZZLE DIAMETER
DOD	DEPTH OF DISCHARGE
DOT	DEPT OF TRANSPORTATION
DR/DT	CHANGE IN RESISTANCE PER DEGREE OF TEMPERATURE
DSCS	DEFENSE SATELLITE COMMUNICATION SYSTEM
D_T	TANK DIAMETER
DTE	DATA TRANSMISSION EQUIPMENT
DV/DT	CHANGE IN VOLTAGE PER DEGREE OF TEMPERATURE
E	EXPONENT, ENERGY
EDAC	ERROR DETECTION & CORRECTION
EFF	EFFECTIVE
EGSE	ELECTRICAL GSE
EG	FOR EXAMPLE
ELEC	ELECTRICAL
EL, ELEV	ELEVATION
ELV	EXPENDABLE LAUNCH VEHICLE
EMC	ELECTROMAGNETIC COMPATIBILITY
EMSIM	ELECTROMAGNETIC INTERFERENCE SAFETY MARGIN
ENVIRON	ENVIRONMENT
EOL	END OF LIFE
EOM	END OF MISSION
ERD	EXPERIMENT REQUIREMENTS DOCUMENT
ES	EARTH SENSOR
ESD	ELECTROSTATIC DISCHARGE
EST	ESTIMATED
EU	EXTENDER UNIT
EVE	EXPERIMENT VALVE EQUIPMENT
EX, EXP	EXPERIMENT
EXCH	EXCHANGER
F	ABSORPTION FRACTION, DIMENSIONLESS GEYSER HEIGHT
F/D	FILL/DRAIN
FAB	FABRICATION

FEC	FORWARD ERROR CORRECTION
FIFO	FIRST IN FIRST OUT
FLOW-3D	FLOW SCIENCES COMPUTATIONAL FLUID DYNAMICS CODE
FLT	FLIGHT
FM	FLOW METER
FOV	FIELD OF VIEW
FR	FROUDE NUMBER
FS	FACTOR OF SAFETY
FT	FEET
FT-LBS	FOOT POUNDS
FTS	FLIGHT TELEROBOTIC SERVICER
FUT	FIXED UMBILICAL TOWER
FWD	FORWARD
G	ACCELERATION
G'S	GRAVITY'S
GEN	GENERATOR
GEOMOD	COMPUTER AIDED ENGINEERING PROGRAM
GEOSYNC	GEOSYNCRONOUS
GG	GRAVITY GRADIENT
GH2	GASEOUS HYDROGEN
GHe	GASEOUS HELIUM
GN2	GASEOUS NITROGEN
GND	GROUND
GOVT	GOVERNMENT
GPS	GLOBAL POSITIONING SATELLITE
GRND	GROUND
GRO	GAMMA RAY OBSERVATORY
GRT	GERMANIUM RESITANCE THERMOMETER
GSFC	GODDARD SPACEFLIGHT CENTER
GSE	GROUND SUPPORT EQUIPMENT
GSTDN	GROUND STATION NETWORK
H	GAS INGESTION HEIGHT
H	SOLAR INTENSITY FACTOR, SPECIFIC ENTHALPY
H_l	SPECIFIC ENTHALPY OF INCOMING NEW STREAMS
H_l SAT	INCOMING SATURATED LIQUID ENTHALPY
H_g SAT	SATURATED VAPOR ENTHALPY
H2	HYDROGEN
HDBK	HANDBOOK
HPF	HAZARDOUS PROTECTION FACILITY
HR	HOUR
H_S	LIQUID HEIGHT ABOVE NOZZLE OUTLET
HT	HEAT
HX	HEAT EXCHANGER
HTRS	HEATERS
HW	HARDWARE
HZ	HERTZ
I	INERTIA, CURRENT
I/V	CURRENT/VOLTAGE
I_C	COLD LENGTH OF THE TUBE
ID	IDENTIFY, INSIDE DIAMETER
I/F	INTERFACE

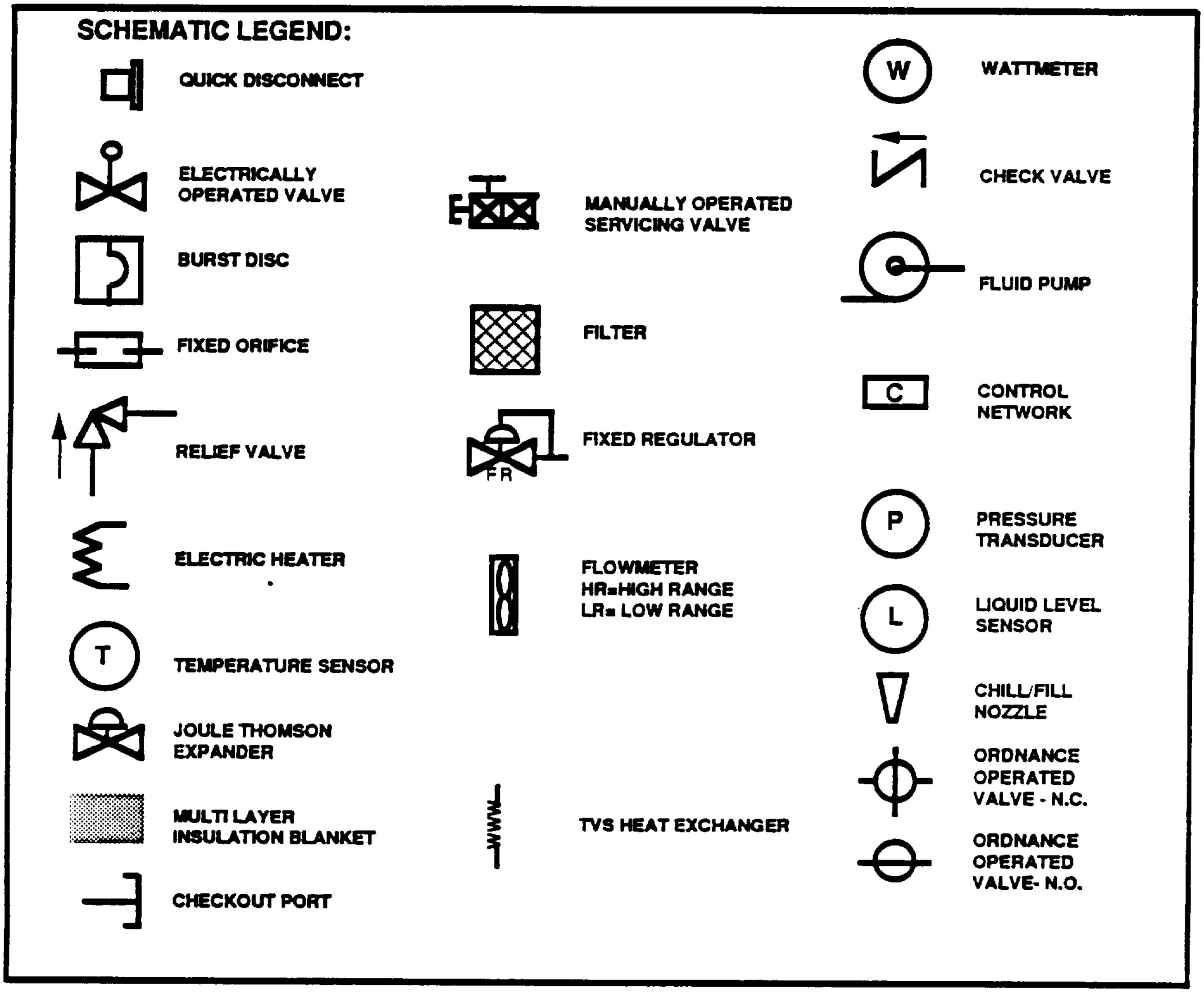
IN	INCHES
INST	INSTRUMENTS
IPD	INFORMATION PROCESSING DIV
IQ	INFORMATION QUESTIONS
IRAD	INTERNAL RESEARCH & DEVELOPMENT
IRU	INERTIAL REFERENCE UNIT
IU	INTERFACE UNIT
J	JOULE
°K, K	DEGREES KELVIN
K	ISOTHERMAL COMPRESSIBILITY, $1/v(\partial v/\partial P)_T$
KBPS	KILOBITS PER SECOND
KG	KILOGRAM
kPa	KILOPASCALS
KSC	KENNEDY SPACE CENTER
K-T	KEPNER-TREGOE
L	LIQUID, LENGTH
L/D	LENGTH/DIAMETER
LAD	LIQUID ACQUISITION DEVICE
LAN	LONGITUDE OF ASCENDING NODE
LBF	POUNDS FORCE
LBM	POUNDS MASS
LBS	POUNDS
LC	LAUNCH COMPLEX
LERC	LEWIS RESEARCH CENTER
LH2	LIQUID HYDROGEN
LO	NOZZLE CHARACTERISTIC LENGTH
LOC	LINES OF CODE
LV	LAUNCH VEHICLE
LVPD	LIQUID VAPOR POSITION DETECTOR
M	MASS, METER
M_G	VISCOSITY OF GAS
M/V	MASS/VOLUME
MA	MULTIPLE ACCESS
MACS	MULTIMISSION ACS MODULE
MAX	MAXIMUM
MB	MEGABYTE
MDAC	MCDONNELL DOUGLAS
MDB	MULTIPLEX DATA BUS
MECO	MAIN ENGINE CUTOFF
MEOP	MAXIMUM EXPECTED OPERATING PRESSURE
MGA	MEDIUM GAIN ANTENNA
MGMT	MANAGEMENT
MGR	MANAGER
MGSE	MECHANICAL GSE
MIL-STD	MILITARY STANDARD
MINI-MITAS	IBM PERSONAL COMPUTER VERSION OF MITAS
MISC	MISCELLANEOUS
MITAS	MARTIN INTERACTIVE THERMAL ANALYSIS SYSTEM
MLI	MULTILAYER INSULATION
MLII	INNER MULTILAYER INSULATION
MLIO	OUTER MULTILAYER INSULATION

MMAG	MARTIN MARIETTA AEROSPACE GROUP
MMCAP	MARTIN MARIETTA CRYOGENIC ANALYSIS PROGRAM
MMMS	MARTIN MMS
MMS	MULTIMISSION MODULAR SPACECRAFT
MMU	MANNED MANEUVERING UNIT
MODS	MODIFICATIONS
MP	MISSION PLANNING
MPS	MODULAR POWER SUBSYSTEM
MRS	MODULE RETENTION SYSTEM
MSPRAY	CHARGE MASS FOR CHILLDOWN CYCLE
MST	MOBILE SERVICE TOWER
MW	MASS OF WALL
N	NEWTON, TRANSMISSION EFFICIENCY FRACTION
N/A	NOT APPLICABLE
N2H4	HYDRAZINE
NASA	NATIONAL AERONAUTICAL AND SPACE ADMINISTRATION
NASCOM	NASA COMMUNICATION NETWORK
NAV	NAVIGATION
NBAT	BATTERY EFFICIENCY
NBDC	PEAK POWER TRACKER EFFICIENCY
NC	NORMALLY CLOSED
NCC	NETWORK CONTROL CENTER
NEC	NATIONAL ELECTRICAL CODE
NDEG	DEGRADATION FACTOR
NDS	DIODE EFFICIENCY
NF	FUSE EFFICIENCY
NGT	NASA GROUND TERMINAL
NICD	NICKEL CADMIUM
NMI	NAUTICAL MILES
NO	NORMALLY OPEN
NPSH	NET POSITIVE SUCTION HEAD
NSAY	SOLAR ARRAY UTILIZATION FACTOR
NSI	NASA STANDARD INITIATOR
NTB	NATIONAL TEST BED
Nu	NUSSELT NUMBER
NWB	BATTERY CABLING EFFICIENCY
NWL	LINE EFFICIENCY [CABLING LOSS]
NWS	SOLAR ARRAY CABLING EFFICIENCY
OBC	ON-BOARD COMPUTER
OD	OUTSIDE DIAMETER
OFHC	OXYGEN FREE, HIGH CONDUCTIVITY
OP	OPEN
OPS	OPERATIONS
OPT	OPTION
OR	ORIFICE
ORS	ORBITAL RESUPPLY SYSTEM
OSCRS	ORBITAL SPACECRAFT CONSUMMABLE RESUPPLY SYSTEM
OSCF	OPERATIONS SUPPORT COMPUTING FACILITY
OTV	ORBITAL TRANSFER VEHICLE
OV	ORDNANCE VALVE
P	PRESSURE, PRESSURE TRANSDUCER, POWER

Pa	PASCAL
P-V-T	PRESSURE-VOLUME-TEMPERATURE
P/N	PART NUMBER
PCDM	POWER CONTROL & DISTRIBUTION MODULE
PETS	PAYLOAD ENVIRONMENTAL TRANSPORTATION SYSTEM
PI	PRINCIPAL INVESTIGATOR
PIC	PYRO INITIATOR CONTROLLER
PB	PLAYBACK
PLAT	PLATFORM
PLCS	PLACES
PME	PROPULSION MODULE EQUIPMENT
POS	POSITION
PPF	PAYLOAD PROCESSING FACILITY
PR	PRANDTL NUMBER
PROP	PROPULSION
PRSD	POWER REACTANT STORAGE AND DISTRIBUTION
PRT	PLATINUM RESITANCE THERMOMETER
PSI	POUNDS PER SQUARE INCH
PSIA	POUNDS PER SQUARE INCH ABSOLUTE
PSID	POUNDS PER SQUARE INCH DIFFERENTIAL
PSIG	POUNDS PER SQUARE INCH GAUGE
PSL	POWER - SPACECRAFT LOAD
PV	PRESSURE VESSEL
Q	HEAT FLUX, HEAT RATE, NET THERMAL DIFFERENTIAL ENERGY
QD	QUICK DISCONNECT
QEXT	HEAT ADDED FROM EXTERNAL SOURCES
QFLUID	HEAT ABSORBED BY CHILLDOWN FLUID FROM TANK WALL AND HEAT LEAK
QHX	HEAT FROM TANK WALL HEAT EXCHANGER
QO	VOLUMETRIC FLOW RATE AT THE NOZZLE OUTLET
QS	VOLUMETRIC FLOW RATE AT THE SURFACE
QUAL	QUALIFICATION
QWALL	SENSIBLE HEAT STORED IN TANK WALL
°R, R	DEGREES RANKINE
R	RECEIVER TANK, INSIDE RADIUS OF TUBE/TANK, RESISTANCE
R2P2	RAPID RECOVERY/PRECISION POINTING
R_a	RAYLEIGH NUMBER
RAM	RANDOM ACCESS MEMORY
RC	DENSITY OF GAS
RC, RCVR	RCVR TANK
REC	RECORDER
REG	REGULATOR
RE_L	REYNOLDS NUMBER
REM	ROCKET ENGINE MODULE
REQT	REQUIREMENT
RESLT	RESOLUTION
RF	RADIO FREQUENCY
RID	REVIEW ITEM DEFICIENCY
RIU	REMOTE INTERFACE UNIT
RO	JET RADIUS AT NOZZLE OUTLET
ROM	READ ONLY MEMORY

RS	JET RADIUS AT SURFACE
RTN	RETURN
RV	RELIEF VALVES
S/A	SOLAR ARRAY
S/C	SPACECRAFT
S/S	SUBSYSTEM
S/W	SOFTWARE
SAT	SATURATED, SATELLITE
SCATHA	SPACECRAFT CHARGING AT HIGH ALTITUDE
SE	SUPPORT EQUIPMENT
SEN	SENSOR
SEP	SEPARATE, SEPARATION
SGLS	S/C TO GND LINK SYSTEM
SOCC	SATELLITE OPERATIONS CONTROL CENTER
SHM	SAFE HOLD MODE
SM	SUBMODULE
SOW	STATEMENT OF WORK
SPEC	SPECIFICATIONS
SPS	SAMPLES PER SECOND
STA	STATION
STD	STANDARD
STDN	GODDARD GROUND STATION NETWORK
STRAT	STRATIFICATION ANALYSIS PROGRAM
STS	SPACE TRANSPORTATION SYSTEM
SUBSYS	SUBSYSTEM
SUP	SUPPLY TANK
T	DIMENSIONLESS MIXING TIME
T, TEMP	TEMPERATURE
TAM	THREE AXIS MAGNETOMETER
TAO	THERMOACOUSTIC OSCILLATION
TARGET	CHILLDOWN TEMPERATURE PROGRAM
TBD	TO BE DETERMINED
TC	TEMPERATURE COEFFICIENT
TCS	THERMAL CONTROL SUBSYSTEM
TCS	THERMALLY CONTROLLED SHIELD
TD	TECHNICAL DIRECTION
TDRSS	TRACKING & DATA RELAY SATELLITE SYSTEM
TE	TIMELINE ECLIPSE
TL	TRANSFER LINE
TLM	TELEMETRY
TLP	TRANSFER LINE PUMP
TOS	TRANSFER ORBIT STAGE
TRASYS	THERMAL RADIATION ANALYSIS SYSTEM
TSL	THRUSTER SELECT LOGIC
TT&CS	TELEMETRY,TRACKING AND COMMAND SUBSYSTEM
TV	TRANSFER VALVE
TVS	THERMODYNAMIC VENT SYSTEM
Tw	WALL AVERAGE TEMPERATURE
TWOPHS	TWO PHASE FLUID PRESSURE DROP PROGRAM
U	BUBBLE RISE VELOCITY
UARS	UPPER ATMOSPHERE RESEARCH SATELLITE

U_g	INTERNAL ENERGY OF VAPOR BEFORE VENTING
$U_{g\ sat}$	INTERNAL ENERGY OF VAPOR AT SATURATION
UTC	UNIVERSAL TIME CONSTANT
V	VOLUME, VAPOR, SPECIFIC VOLUME, VELOCITY
VAC	VACUUM, VOLTS, ALTERNATING CURRENT
VDC	VOLTS, DIRECT CURRENT
V_B	LIQUID VOLUME
VCS	VAPOR COOLED SHIELD
VJ	VACUUM JACKET
VLV	VALVE
VV	VENT VALVE
W	WEIGHT, WATTS, RATE
W/	WITH
WE	WEBER NUMBER
WK	WORK
WSGT	WHITESANDS GROUND TERMINAL
XFR	TRANSFER
Y_C	TAO DIMENSIONLESS PARAMETER
Z	RATIO OF HOT TO COLD LENGTH OF COLD OF TUBE [THERMOACOUSTIC OSCILLATION DIMENSIONLESS PARAMETER]
α	RATIO OF HOT TO COLD END TUBE TEMPERATURES
α/ε	ALPHA/EPSILON - SOLAR ABSORPTIVITY/EMISSIVITY
η	EFFICIENCY
σ	STEFAN-BOLTZMANN CONSTANT, SURFACE TENSION
μ	VISCOSITY, MICRO
ε	EMISSIVITY
ρ	DENSITY
ϕ	PHASE
β	COEFFICIENT OF THERMAL EXPANSION, $1/v\ (\partial v/\partial T)_P$
Δ	CHANGE
#	NUMBER
Ω	RESISTANCE


SCHEMATIC LEGEND:
QUICK DISCONNECT
ELECTRICALLY OPERATED VALVE
BURST DISC
FIXED ORIFICE
RELIEF VALVE
ELECTRIC HEATER
TEMPERATURE SENSOR
JOULE THOMSON EXPANDER
MULTI LAYER INSULATION BLANKET
CHECKOUT PORT
MANUALLY OPERATED SERVICING VALVE
FILTER
FIXED REGULATOR
FR
FLOWMETER
HR=HIGH RANGE
LR= LOW RANGE
TVS HEAT EXCHANGER
W
WATTMETER
CHECK VALVE
FLUID PUMP
C
CONTROL NETWORK
P
PRESSURE TRANSDUCER
L
LIQUID LEVEL SENSOR
CHILL/FILL NOZZLE
ORDNANCE OPERATED VALVE - N.C.
ORDNANCE OPERATED VALVE- N.O.
T

1.0 EXECUTIVE SUMMARY

The Cryogenic On-Orbit Liquid Depot Storage, Acquisition and Transfer Satellite (COLD-SAT) is an experimental spacecraft launched on an expendable launch vehicle which is designed to investigate the systems and technologies required for efficient, effective and reliable management of cryogenic fluid in the reduced gravity space environment. Fundamental data required for the understanding and design of systems to meet this need are lacking; the COLD-SAT program will provide this necessary database and provide low-g verification of fluid and thermal models of cryogenic storage, transfer, and resupply concepts and processes. Future applications such as Space Station, Space Transfer Vehicle (STV), Lunar Transfer Vehicle (LTV), External Tank (ET), Aft Cargo Carrier (ACC), propellant scavenging, storage depots, and lunar and interplanetary missions, among others have provided the impetus to pursue this technology in a timely manner to support the design efforts.

A baseline conceptual approach has been developed and an overview of the results of the 24-month COLD-SAT Phase A Feasibility Study Program is described which includes the following: 1) a definition of the technology needs and the accompanying experimental three month baseline mission, 2) a description of the experiment subsystem, major features and rationale for satisfaction of primary and secondary experiment requirements using liquid hydrogen (LH2) as the test fluid, and 3) a presentation of the conceptual design of the COLD-SAT spacecraft subsystems which support the on-orbit experiment with emphasis on those areas which posed the greatest technical challenge.

1.1 Introduction

The COLD-SAT satellite (shown in Figure 1.1-1) is an integrated experimental spacecraft designed to investigate the fluid thermo-physics of subcritical cryogens in a low-gravity space environment and to provide data and criteria to correlate in-space performance with analytical and numerical modeling of cryogenic fluid management systems. It has evolved from the Cryogenic Fluid Management Facility (CFMF) program which was to demonstrate this technology by a series of Shuttle Orbiter bay experiments (Ref 1.1-1). After the Challenger accident, LH2 payloads (such as Centaur and CFMF) were excluded from the bay. The COLD-SAT approach, which this study produced, resulted in a design concept which would be checked out, serviced, and launched from the Cape Canaveral Air Force Station (CCAFS) on the Delta II expendable launch vehicle. On orbit, the three month mission consists of a series of liquid hydrogen tests covering the full range of technology categories.

Technical objectives of the COLD-SAT mission are divided into Class I experiments which form the highest priority of the mission and Class II experiments which generally support the Class I experiments although they are considered a secondary set of cryogenic technologies. Collectively they form the COLD-SAT Experiment Set which are primarily scientific in nature and are considered supporting technologies for future space missions, providing fluid management technology in the following areas of emphasis: 1) liquid storage, 2) liquid supply, 3) fluid transfer, 4) fluid handling, and 5) advanced instrumentation.

The experimental spacecraft will provide an opportunity to demonstrate the feasibility of combining various methods of integrating pressure control, liquid acquisition, and fluid transfer approaches into subscale experimental tankage concepts that will provide on-demand vapor-free liquid cryogens in space. Supplying single-phase liquid to accomplish transfer and resupply/top-off of tankage is essential to having a space-based operational capability. Performance in the reduced gravity space environment remains unproven and unverified.

As the design of the COLD-SAT evolved, the approach went through several iterations which are documented in this report. See Reference 1.1-2 for an earlier conceptual approach to the COLD-SAT which shows the concept as it existed at the end of Task III at the Preliminary Requirements Review.

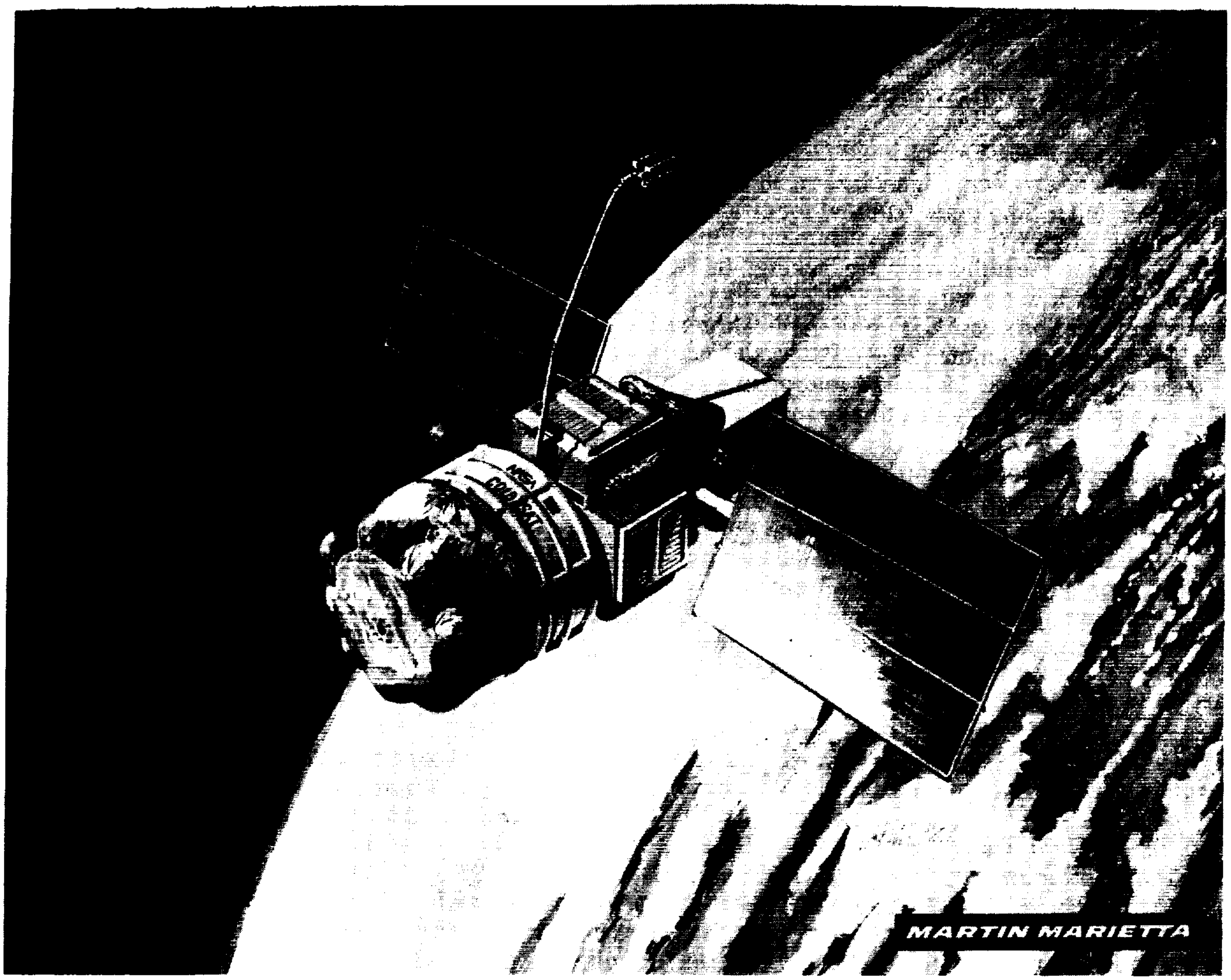


Figure 1.1-1 COLD-SAT Satellite On-Orbit Configuration

1.2 Low-Gravity Cryogenic Fluid Management Technologies

Subcritical cryogenic fluid management technology contains many elements which are required to successfully support future space system development and mission goals associated with the cost of system operation and reuse. In-space systems are currently end-of-life limited by depletion of on-board consumables. Extending the useful life of these systems can be realized by periodic resupply of cryogenic fluids. Various mission scenarios are totally dependent on transfer and resupply for mission success.

Figure 1.2-1 reflects a three step approach to providing these technologies starting with (I) individual component and hardware development, progressing to (II) subsystem element ground based testing, and finally to (III) in-space experimentation. All result in the establishment of a cryogenic data base and the development of refined analytical models which make use of the available data for validation and correlation purposes. Achieving the right blend of demonstration versus purely scientific investigations of processes and phenomenon relating to low-g characterizations is cost effective.

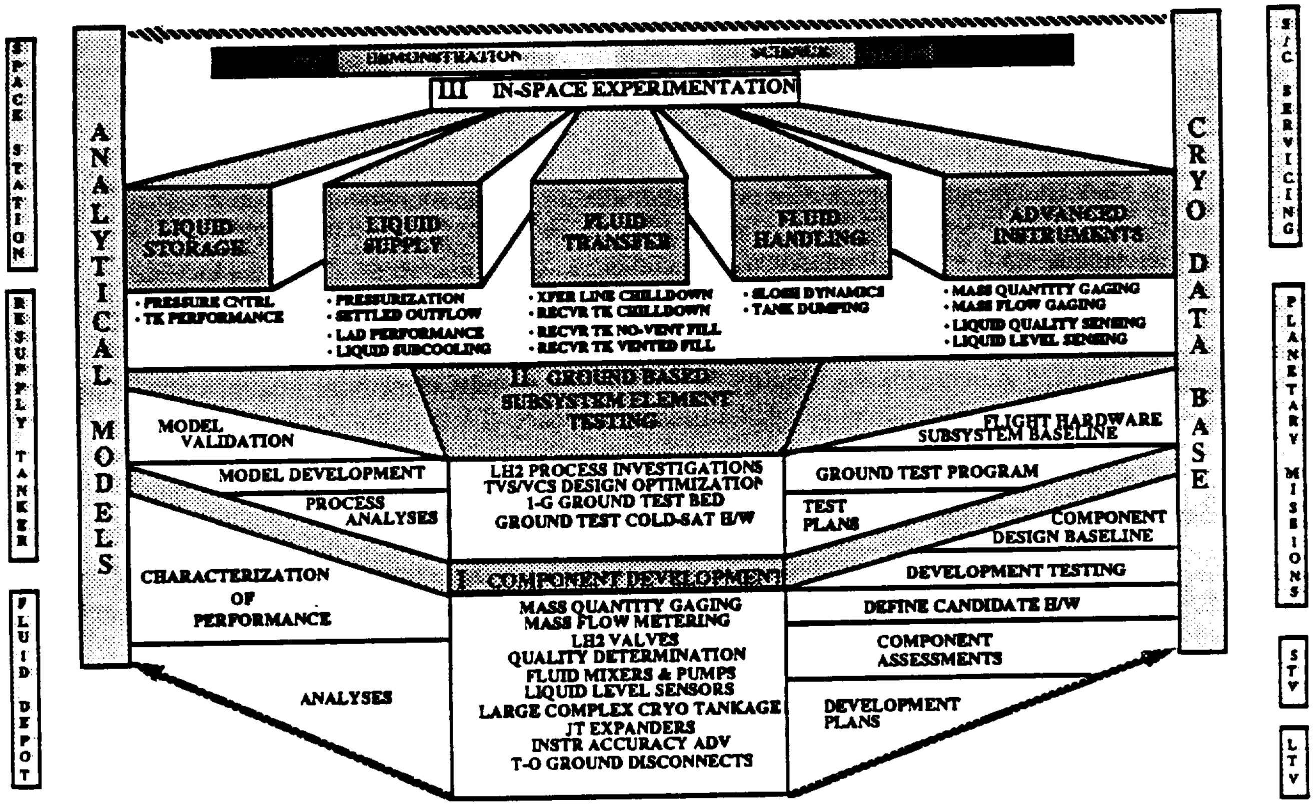


Figure 1.2-1 Cryogenic Fluid Management Technology Needs

1.3 COLD-SAT Experiment Set Overview

The Class I and Class II experiment set categories comprise the primary and secondary experiment mission objectives. Tests in each category include low-g fluid and thermal process investigations, demonstrations of performance capabilities, as well as technology evaluations to achieve an overall test mix that provides for a maximized technological return over the duration of the mission. A brief listing of individual experiment objectives is as follows:

CLASS I

Tank Pressure Control - Investigate phenomena associated with controlling heat flux and tank pressure rise of cryogenic tankage including 1) thermal stratification, 2) fluid mixing, 3) passive thermodynamic vent system heat exchanger performance, and 4) active mixer heat exchanger performance.

Tank Chilldown - Investigate the tank chilldown process associated with removing heat from the tank system by heat transfer between the chilldown fluid (both liquid and vapor) and the tank bulk mass. The process (mainly using a charge-hold-vent multiple cycle technique) will be characterized for fluid utilization and efficiency.

Tank No-Vent Fill/Refill - Investigate the tank resupply process using mainly the no-vent fill technique for two different sizes and geometries associated with evaluating the final fill level that can be achieved for various flow introduction techniques and mixing modes.

LAD Fill/Refill Characterization - Demonstrate the filling and refilling characteristics of liquid acquisition devices in low-g to verify capabilities for vapor-free outflow.

Liquid Mass Gaging - Assess performance of a mass gage to accurately determine tank liquid quantity for varying tank conditions (this objective has been deleted from the current set of experimental objectives).

Liquid Dynamics and Slosh Control - Determine the liquid motion resulting from specifically produced acceleration environments (this objective has been deleted from the current set of experimental objectives).

CLASS II

Tank Pressurization - Evaluate the pressurization process whereby pressurant is introduced into cryogenic tankage to provide the force (and subcooling effect) for tank outflow.

Direct Liquid Outflow - Investigate tank expulsion using a low-g acceleration to settle and orient the liquid as it is drained.

Vented Fill - Investigate the vented fill/top-off process which uses settling to orient the liquid to the tank outlet so that vapor can be vented at the opposite end while minimizing liquid lost out the vent.

Vapor Venting - Assess the capability to reduce tank pressure by venting vapor using liquid settling while minimizing liquid lost out the vent.

Lad Performance - Investigate the capability of supply and receiver tank LAD's to provide vapor-free liquid under varied operating conditions including determining expulsion efficiencies.

Transfer Line Chilldown - Evaluate the transfer line chilldown process associated with removing heat from the transfer line system by heat transfer between the chilldown fluid (both liquid and vapor) and the transfer line bulk mass.

Control of Liquid Thermodynamic State - Using a supply tank outlet subcooler (heat exchanger), characterize the capability to provide single phase fluid during liquid transfer tests. Compare results with subcooling provided by tank pressurization.

Liquid Dumping - Investigate the process of rapid tank dumping.

Advanced Instrumentation - Demonstrate the case of state-of-the-art cryogenic two-phase flow meters, temperature sensors, and liquid/vapor detectors.

The relationship of each Class I and Class II experiment is shown in Figure 1.3-1. For each experiment category the number of tests associated with it are shown. Convenient departure points are highlighted (tank pressure control) for ease in relating experiment interdependency. Collectively the experiment set drives out requirements which have to be met by specific elements of the experiment subsystem. This overview of experiment relationship defines the order of experiment test sequencing and aided in the development of the experiment data base for sequential ordering of tests and the assembly of a mission timeline.

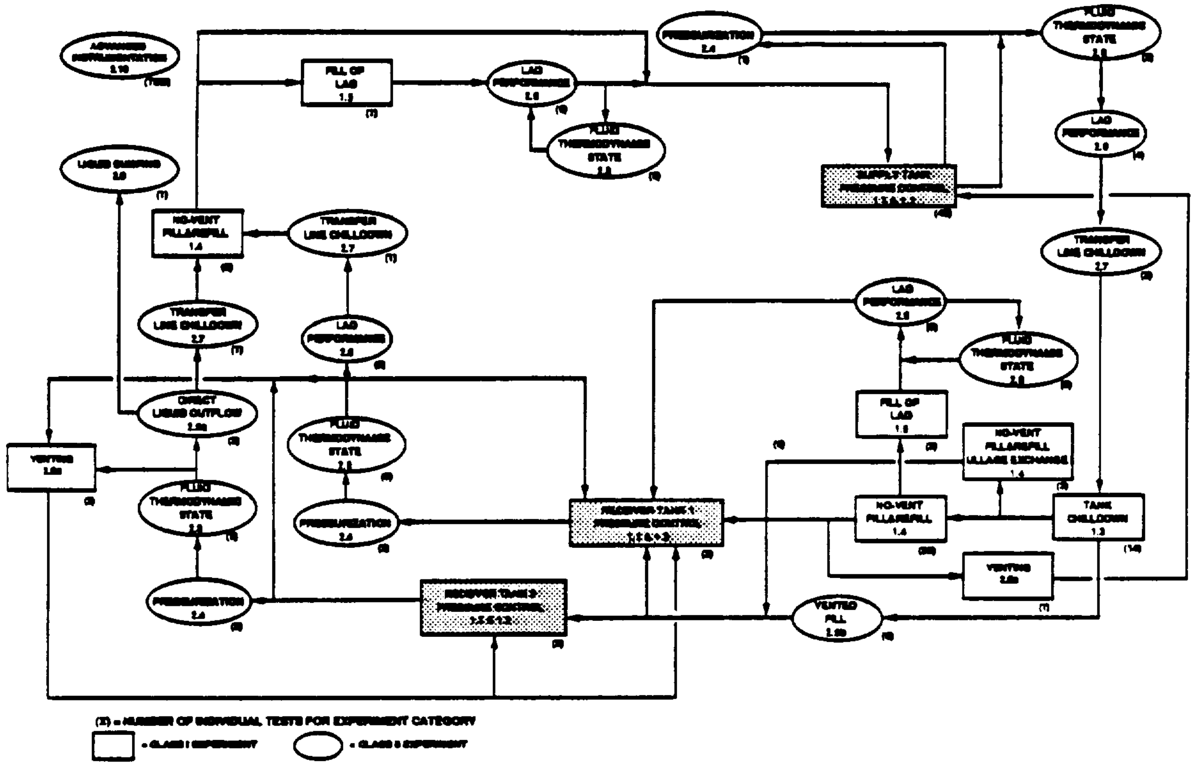


Figure 1.3-1 Interdependency of Class I and Class II Experiments

1.4 <u>Experiment Subsystem Description</u>

The COLD-SAT Experiment Subsystem is composed of the following major elements: liquid hydrogen storage and supply tank, receiver tank 1, receiver tank 2, gaseous pressurant storage and pressurization control subsystem, fluid distribution subsystem, experiment control and monitoring subsystem, and experiment instrumentation subsystem. Figure 1.4-1 is a schematic of the inter-relationships of the experiment subsystem elements. A summary definition of the major experiment subsystem elements is as follows:

<u>Supply Tank</u> - This tank is vacuum jacketed (VJ), 4.25 m^3 (150 ft^3) capable of holding 286 kg (630 lbs) of LH2 at 95% full. The tank has a diameter of 234 cm (92 in) and a length of 211 cm (83 in) to completely utilize the available space in the payload fairing. The pressure vessel (PV) contains a total communication LAD with an outlet at the bottom of the tank. A vent/pressurization penetration which feeds directly into the tank via a diffuser is located at the opposite end. Two spray systems are provided through which liquid can be introduced from one or two mixer pumps to provide mixing of the bulk fluid. Return fluid from either receiver tank can be introduced into the radial or axial spray for increased top-off potential and minimizing residuals during receiver to supply tank transfers.

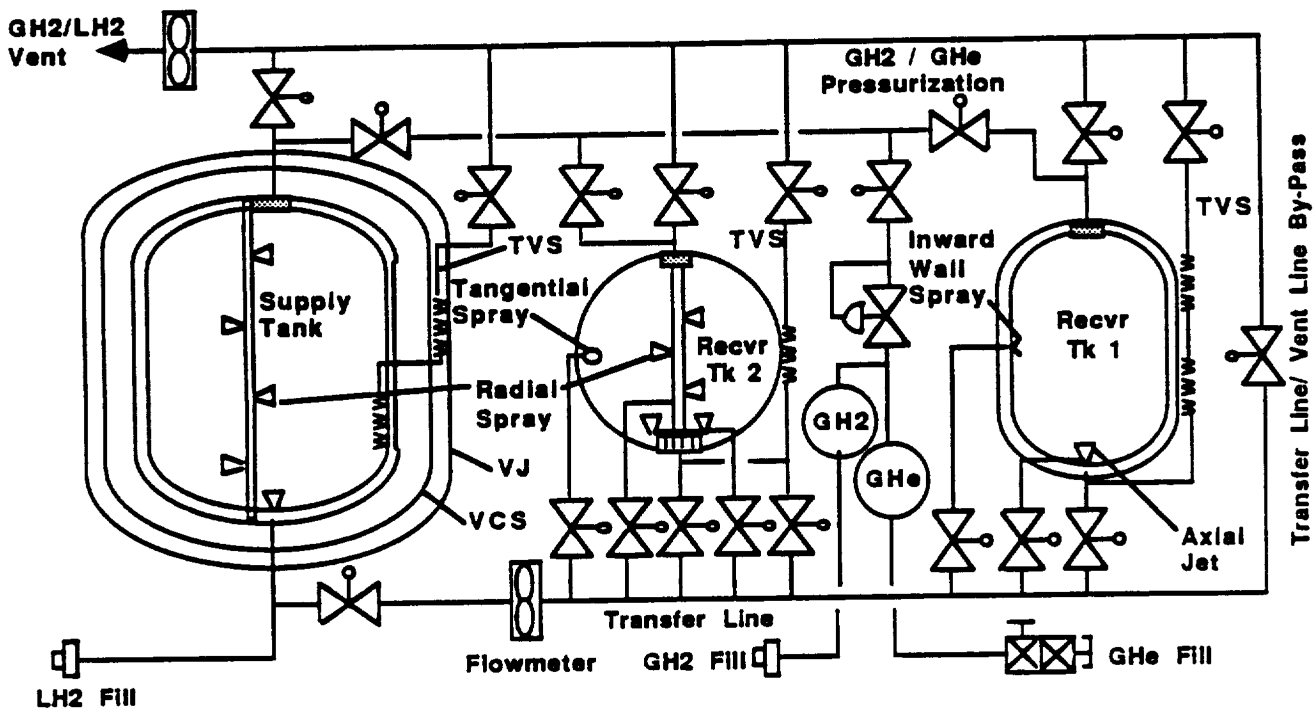


Figure 1.4-1 Experiment Subsystem Simplified Schematic

An internal thermodynamic vent system (TVS) heat exchanger (HX) routed on the LAD and on other critical surfaces is provided to cool the bulk fluid, control tank pressure and provide subcooling to the LAD and outlet fluid. The TVS HX is then routed to a vapor cooled shield (VCS) located between the PV and the VJ. Thermal control heaters uniformly cover the pressure vessel with assorted heating elements which are used to vary the tank heat flux for pressure control experiments. Multi-layer insulation (MLI) is located between the PV and the VCS, as well as between the VCS and the VJ. All plumbing penetrations from the PV are routed internal to the VJ and exit at the girth ring area. Outlet components are sandwiched between the PV and the VJ with component access provided for contingency maintenance (see Figure 1.4-2). The PV connects to the VJ with a composite strap suspension system. LH2 is loaded on the ground before launch and provides the total LH2 mission budget.

Receiver Tank 1 - Receiver tank 1 is an insulated, non-vacuum jacketed, 1.13 m^3 (40 ft^3) tank capable of holding 74 kg (163 lbs) of LH2 at 95% full. The length is 188 cm (74 in) with a diameter of 97 cm (38 in). The M/V is approximately 2 and the L/D is 1.95. The PV contains a LAD to provide liquid at the inlet/outlet penetration. A vent/pressurization penetration exits at the tank top. Axial and wall mounted inward pointing spray systems are provided for chilldown and no-vent fill testing. An external wall mounted tank TVS HX routed on the PV and on other critical surfaces is provided to cool the tank and bulk liquid. A MLI blanket covers the entire tank. The tank is supported to the S/C structure with 8 composite struts.

Receiver Tank 2 - This tank is an insulated, non-vacuum jacketed 0.56 m^3 (19.9 ft^3) tank capable of holding 37 kg (81 lbs) of LH2 at 95% full. The tank is almost spherical 97 cm (38 in) in diameter with a minimal girth ring section. The M/V is approximately 2 and the L/D is 1. The PV does not contain a LAD but has a simple screen/plate baffle at the outlet to minimize residuals during settled expulsions and prevent vapor intrusion. A combined vent/pressurization penetration exits at the opposite end. The PV contains an exterior wall mounted TVS HX (no VCS) for pressure control.

Axial, radial, and tangential spray systems are provided for chilldown and no-vent fill testing. An optimized MLI blanket surrounds the PV. Tankchilldown can also be accomplished by introducing chilldown fluid into the TVS HX. Support is provided to S/C structure by two trunnion mounts and a torsion support.

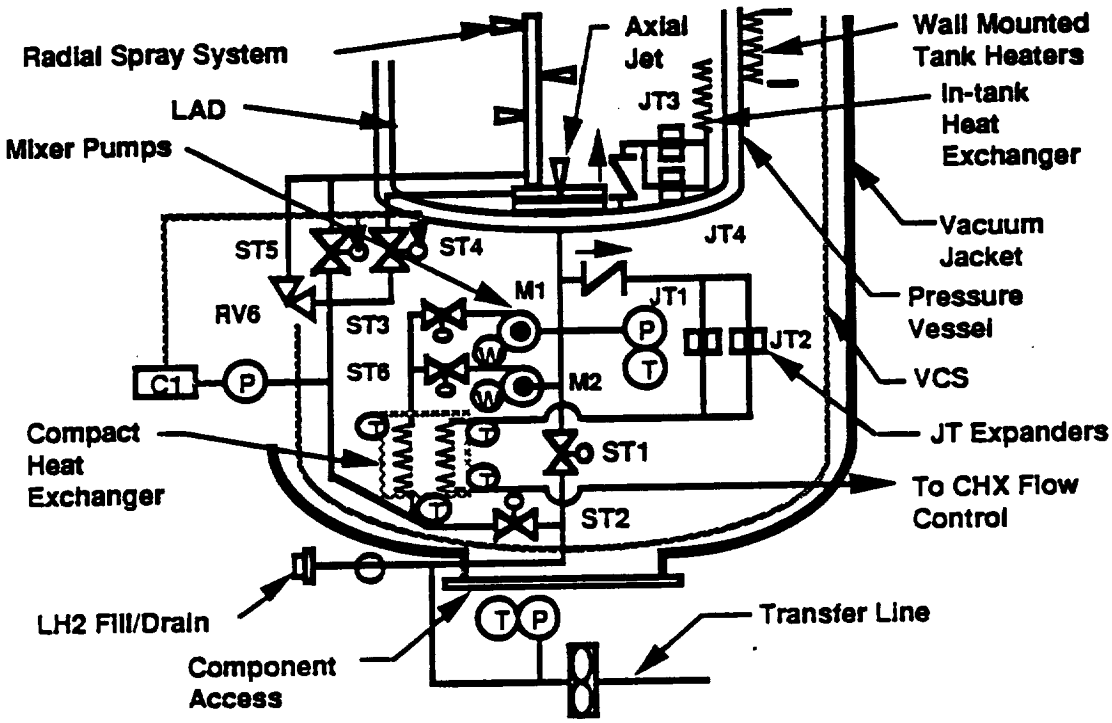


Figure 1.4-2 Supply Tank Outlet Details

Pressurization - Pressurant storage is provided by nine bottles, each 29.8 cm (11.75 in) diameter by 122 cm (48 in) length with a volume of 0.076 m^3 (2.7 ft^3) tanks pressurized to 20670 kN/m^2 (3000 psia) on the ground prior to flight. Seven tanks store 8 kg (17.5 lbs) of GH2 while the remaining two contain 4.5 kg (10 lbs) of GHe. Either pressurant can be used for receiver tank pressurization while only GH2 will be used for the supply tank. Fixed regulators control delivered pressurant to 276 kN/m^2 (40 psia). Pressures less than this maximum are controlled by tank isolation valves.

Fluid Distribution - Experiment tankage is interconnected with a common transfer line containing a transfer pump and vent line plumbing and associated components and instrumentation. Ground fill/drain and vent needs of the supply tank are also provided.

Experiment Control and Monitoring - Control and data handling of the experiment and its subelements is managed via Remote Interface Units (RIUs) which receive commands from the spacecraft Telemetry, Tracking, and Command (TT&C) subsystem and operate needed functions. Instrumentation and sensor data is also collected via the RIUs which provides the data to the TT&C for processing or downlinking.

Instrumentation - Instrumentation required to monitor the Class I and Class II experiments consists of temperature, pressure, flowrate, valve position, liquid/vapor and liquid level detection, and fluid quality discrimination measurements required to monitor specific experiment needs. Table 1.4-1 provides a summary of these devices.

Table 1.4-1 Experiment Instrumentation Summary

Type	Supply Tank	RT 1	RT 2	Press.
Temperature	87	50	51	27
Pressure	6	6	7	17
Flowrate	2	1	1	8
Liquid level	2	2	2	-
Events	50	50	50	18
Acceleration	3	-	-	-
Other Types	4	-	1	1

1.5 Spacecraft Subsystem Description

The spacecraft (S/C) subsystems support the experiment subsystem in the accomplishment of the mission science and operational objectives. Together they comprise the satellite flight segment of the COLD-SAT System. The following provides a brief description of the spacecraft subsystems. Figure 1.5-1 views the COLD-SAT inside the 3.05 m (10 ft) Delta II payload fairing with vehicle station locations and payload envelope constraints shown. The approach for the spacecraft bus which supports the experiment subsystem is to utilize the existing flight qualified and proven Multi Mission Spacecraft (MMS) Modules. Over the years Martin Marietta, in consonance with Fairchild, has refined and expanded on the original MMS design to produce an upgraded version of the modules. They are ideally suited for the COLD-SAT and provide a design which requires only minor modification for COLD-SAT use.

A summary description of the major elements of the spacecraft subsystem is as follows:

Structures Subsystem - This subsystem provides the structural mounting for all S/C and experiment subsystems and for the satellite to Delta II launch vehicle attachment interface which utilizes a V-band clamp. Four Multimission Modular Spacecraft (MMS) modules provide most of the support and attachment for electrical and avionic equipment. These modules mount to a rectangular tube support structure which also supports both receiver tanks. Eight support longerons attach to the supply tank vacuum jacket girth rings. Two sets of eight upper and sixteen lower support struts connect to the longerons for transition to the upper MMS module support frame and to the lower separation system ring frame. Mechanisms are provided to deploy, stow and lock deployable items such as the solar arrays and the TDRSS antenna.

Attitude Control System (ACS) - The ACS, in conjunction with the on-board computer (OBC), performs the attitude determination function and controls the attitude of the satellite and of the independent appendages, as well as controlling the thrust vector during orbital adjust maneuvers and experiment accelerations. Attitude error is corrected using thruster pulsing or reaction wheels and magnetic torquers, depending on the S/C mode of operation. The commands to the wheels, torquers, or thrusters are issued by the flight software to the hardware via interface electronics. Coarse sun sensors initially lock on to the sun, then fine sun sensors provide the pointing reference. Horizon sensors in the control system, in conjunction with an inertial reference unit, will determine the present orientation and then the desired orientation commands will be issued from the flight computer's control software, as required. The ACS is contained in the existing MMS Attitude Control System module.

Electrical Power Subsystem (EPS) - The EPS utilizes two flight proven MMS modules. The Modular Power Subsystem (MPS) module provides power generation , regulation and battery charging, and electrical storage capabilities. A Power Control & Distribution Module (PCDM) provides protection, control and distribution of electrical power to electrical elements external to the subsystem modules(ACS, MPS, and C&DH). The PCDM also provides control of solar array and TDRSS antenna articulation, power to the experiment mixer pumps, and firing control of ordnance devices. Command and data handling functions are provided by the TTCS via remote interface units (RIUs). Two solar arrays and two rechargeable 50 amp hour batteries are the power sources during orbit operations.

Telemetry, Tracking and Command Subsystem (TTCS) - The TTCS provides for storage, formatting and transmission of telemetry and experiment data and the capability for the decoding and distribution of commands. The TTCS also provides for the transmission of data downlink and the acceptance of ground command uplink via the Tracking Data Relay Satellite System (TDRSS) or the Ground Space Tracking & Data Network (GSTDN). The TTCS utilizes MMS hardware and contains a Command & Data Handling subsystem element, as well as a Communication Subsystem element. Multiple remote interface units (RIUs) and extender units (EUs) allow control and monitoring of the extensive sensors, valves, and other components of the experiment subsystem. Control of the experiment sequencing functions and the attitude control function are both handled by the on-board computer (OBC). Communications between the TTCS and the other subsystems is via a multiplex data bus (MDB) that consists of a supervisory bus and a reply bus both of which are redundant. A central unit (CU) within the TTCS controls the distribution of commands and the acquisition of data. The RIUs in each of the subsystems interface to the MDB, process commands and acquire data requested by the CU. The CU also controls the processing of ground uplinked commands and software loads. Two solid state recorders can accommodate up to 24 hours of data storage. The Communication Subsystem provides the capability to communicate with ground stations or TDRSS. TDRSS is the primary communication link while two omni antennas provide a backup link to the ground. A major portion of the TTCS is contained within the MMS Command and Data Handling (C&DH) module.

Thermal Control Subsystem (TCS) - The TCS consists of thermal coatings, insulation, louver assemblies, sensors, heaters and associated thermostats, and radiative surface plates required to control and monitor the thermal environment to within proper operating ranges for all satellite hardware. This design approach provides passive thermal balance of the entire spacecraft using the above specified techniques, as appropriate combined with S/C aft pointing towards the sun for the major portion of the mission.

Propulsion and Ordnance Subsystem - This subsystem provides the delta velocity to perform orbital maneuvers and attitude adjustments, and maintain controlled acceleration levels for the experiments. Reaction control thrusters act as a supplement to attitude control provided by reaction wheels and magnetic torquers and also are used to desaturate the reaction wheels. Ordnance pyrotechnic devices are used for separation, deployment, actuation, and release of satellite devices, and system activation. The propulsion subsystem uses hydrazine stored in eight 48.3 cm (19 in) diaphragm tanks. Pressurant regulation at fixed levels maintains selected constant thrust levels for given experiments which require specified accelerations in the range of 10 to 100 micro G for durations up to 14 hours in length. Twenty 0.89 N (0.2 lbf) thrusters are used to meet experiment acceleration and attitude control requirements. Forward and aft propulsion modules provide for vehicle X-axis thrusting, as well as pitch and yaw control. Roll thrusters are located on the aft side of the S/C.

Vehicle Flight Software - Vehicle flight software, resident in the OBC, will perform command executions and computations in support of spacecraft and experiment functions, provide control for the ACS and the experiment, manage data collection and recorder use, control the telemetry, and provide redundancy management and fault protection.

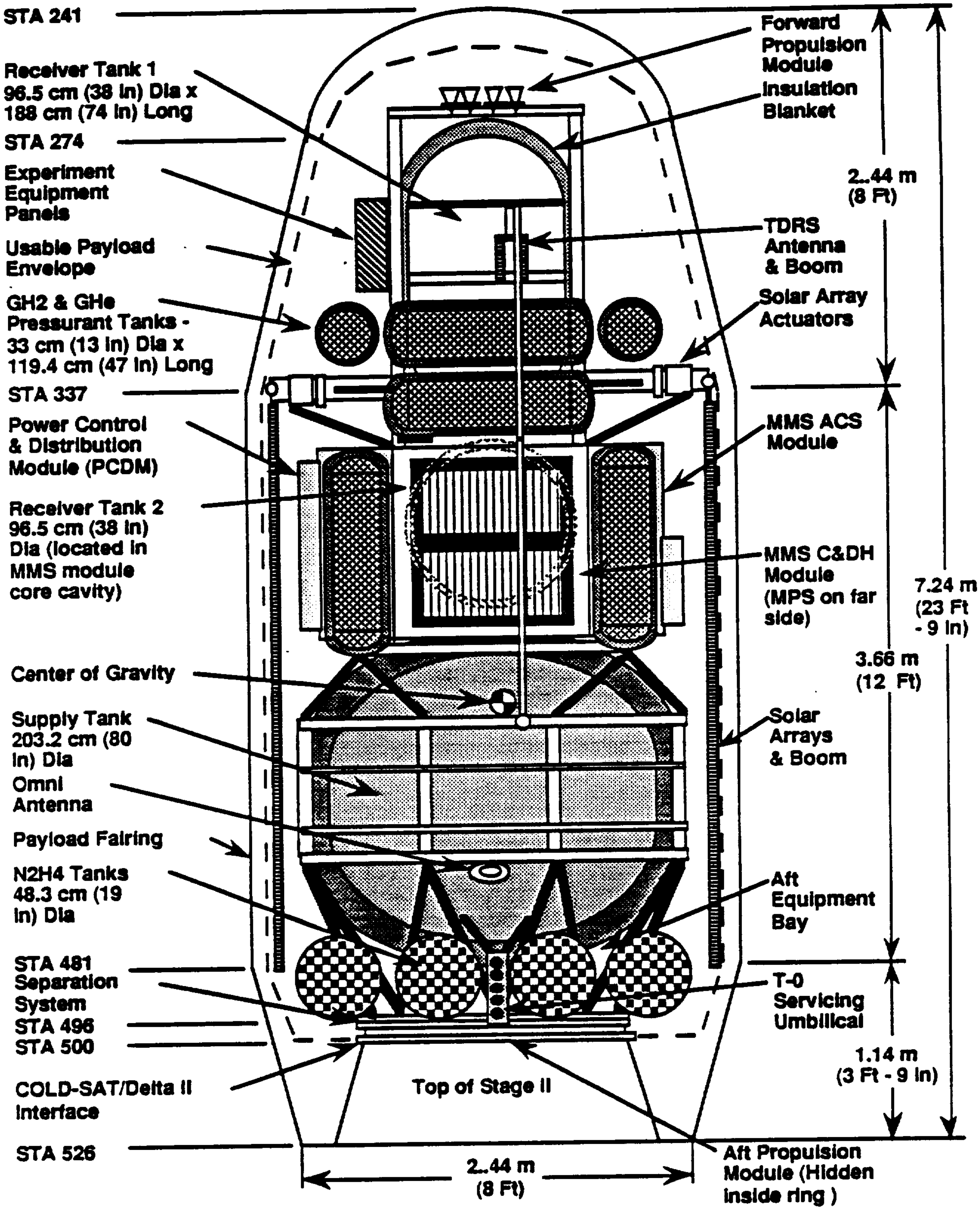


Figure 1.5-1 COLD-SAT Configuration in the Delta II Payload Fairing

Table 1.5-1 lists the general top-level characteristics of the COLD-SAT satellite.

Table 1.5-1 COLD-SAT Characteristics

Size : 2.54 M Dia X 5.89 M Height (8 Ft 4 In X 19 Ft 4 In)
Dry Weight: 2420 Kg (5336Lbs)
Consumables: LH2 285 Kg (628 Lbs)
Propellant 434 Kg (956 Lbs)
GH2 Pressurant 8 Kg (17.5 Lbs)
GHe Pressurant 6.8 Kg (15.1 Lbs)
Launch Weight: 3221 Kg (7103 Lbs) (without margin)
Launch Condition: Powered up and recording experiment data
Mission Duration: Three months active
Orbit: Circular at 926 Km (500 Nmi) - 103 minutes at 28.8 deg orbit becomes slightly elliptical after thrusting
Attitude: Inertial with S/C -X-axis (aft end) pointing at projection of the sun in the orbit plane
Average Power Requirement: 1167 watts
Operations Approach: TDRSS 10 Min contact per orbit record and downlink all data realtime data is also available
S/C Subsystems: Existing, qualified designs
Experiment Subsystem: New tank development required

1.6 Ground Segment and Interfaces Description

Figure 1.6-1 provides a definition of the COLD-SAT System and the functional interfaces required to operate the system . Internal satellite and ground support equipment and facility interfaces (both mechanical and electrical), as well as man machine interfaces are also shown.

The COLD-SAT Ground Segment provides for associated pre-flight, in-flight, and post-flight support functions as follows:

Mechanical Ground Support Equipment (MGSE) - The MGSE provides ground servicing, handling support, transportation support, and maintenance functions for the satellite. The major MGSE structural hardware items include a transporter with protective cover, handling and rotation dolly, handling/lifting slings & strongback, holding fixtures and installation tools. In addition, a separation interface test set and alignment test equipment are provided. Support equipment for the experiment and propulsion subsystem includes a propellant servicing/deservicing cart, propellant high pressure GHe pressurant servicing panel, LH2 servicing/deservicing system, high pressure GH2 experiment pressurant servicing system, high pressure GHe experiment pressurant servicing panel, experiment and propellant system leak check kits, fluid support equipment and miscellaneous calibration equipment.

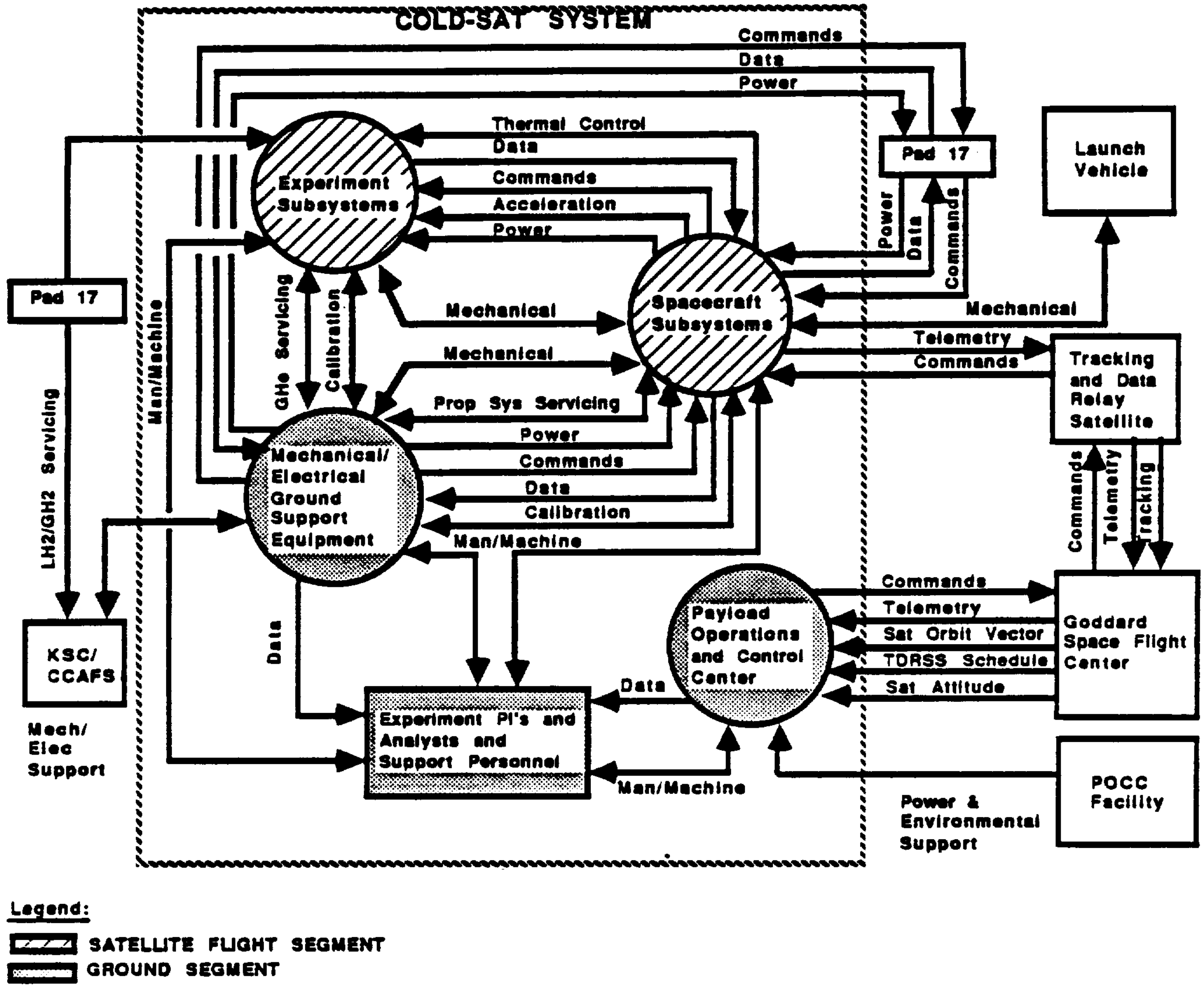


Figure 1.6-1 COLD-SAT Internal and External Functional Interfaces

Electrical Ground Support Equipment (EGSE) - The EGSE provides command, control, calibration, simulation, ground 28 Vdc power to the satellite, and data management of the spacecraft and experiment subsystems during ground test and checkout operations. A major portion of the EGSE hardware is comprised of the spacecraft TTCS support equipment comprised of a RF test set, sun sensor simulator, articulation simulator, EPS simulator, ACS simulator, mission sequence and command generation system, monitoring system, display equipment and printer. In addition, a power distribution system, spacecraft electrical power subsystem support equipment, an electronics integration test set, and solar panel test equipment are provided.

Satellite Operations Control Center (SOCC) - The SOCC provides in-flight command, control and management of flight data (both realtime and recorded) for COLD-SAT. Operations software is included in the SOCC. The SOCC includes a router, telemetry preprocessor, data management work stations, mission planning and scheduling work stations, and personal computers for experiment monitoring and data processing.

Ground Servicing Considerations - The terminal countdown servicing of LH2 and GH2 after the COLD-SAT is integrated to the Delta II launch vehicle is a critical driver on LC-17 launch site modifications required to provide the capability to safely perform these operations. It also impacts meeting COLD-SAT requirements for tank thermal stabilization and how the chilldown of the supply tank is going to be accomplished on the ground. Pad safety considerations and restrictions require that this servicing be accomplished in the final 8 hours prior to launch after the pad is cleared of personnel. This imposes remotely controlled LH2 and GH2 loading operations using an umbilical connected to the spacecraft via the launch vehicle fixed umbilical tower. The umbilical disconnects at launch.

1.7 Mission Description

COLD-SAT mission design requirements were derived primarily from the need to reduce the background acceleration during certain experiment performance to less than 1 micro G in order to minimize fluid perturbations and slosh interactions. The capability to transmit experiment data and uplink command information was also considered. Launch on a Delta II expendable launch vehicle (ELV) was selected as the most cost effective option. A final orbital altitude greater than 926 km (500 nmi) was selected to provide a 500 year lifetime, in order to circumvent a detailed reentry breakup study. Launch to a circular orbit was baselined, with experiment thrust maneuvers performed to minimize the growth of eccentricity. Although circularity is not a strict requirement, it is beneficial in order to maintain a more consistent experiment environment due to atmospheric drag variations with altitude. An initial altitude of 926 km (500 nmi) was selected to provide a margin on the minimum altitude requirement. The background acceleration at 926 km (500 nmi) is less than 0.001 micro G. Figure 1.7-1 shows some of the COLD-SAT orbital mission requirements.

The attitude of the COLD-SAT satellite was selected so that the long -X axis of the S/C is in the orbit plane pointed at the projection of the sun vector in the orbit plane. This arrangement allows adequate solar array contact with the sun, minimizes the perturbation of the experiment environment and minimizes the need to desaturate reaction wheels during experiment steady state micro G quiet periods. This orientation also keeps the propellant tanks pointed towards the sun for the majority of the mission and eliminates the need for tank heaters. A slow roll, pitch and yaw of the satellite is required, as the orbit regresses and the earth moves around the sun, which amounts to less than 2 degrees per day.

The TDRSS is baselined as the primary communication mode for downlinking experiment data and uplinking command information and software loads. The GSTDN is included as a backup ground link to provide health and status data only. TDRSS contact has been baselined for at least a 10 minute per orbit downlink/uplink communication period.

A three month mission is planned, based on the projected consumption of the liquid hydrogen budget. At the end of the mission, propellants, pressurants, and remaining hydrogen will be depleted/purged from S/C tankage as a shut down procedure in order to safe the satellite prior to S/C powerdown.

1.8 Program Status

The COLD-SAT Phase A Feasibility Studies program was concluded in early 1990. It will be followed with a phase B program which will take the design approach through a Preliminary Design Review (PDR) subject to continued NASA supporting budget activities. Phase B will begin in mid 1991 followed by a competitive phase C/D procurement leading to a flight in the 1997 timeframe. Current activities include concepts for supporting technology experiments for focused small scale flight experiments to augment the overall technology needs of low-g cryogenic fluid management throughout the 1990's.

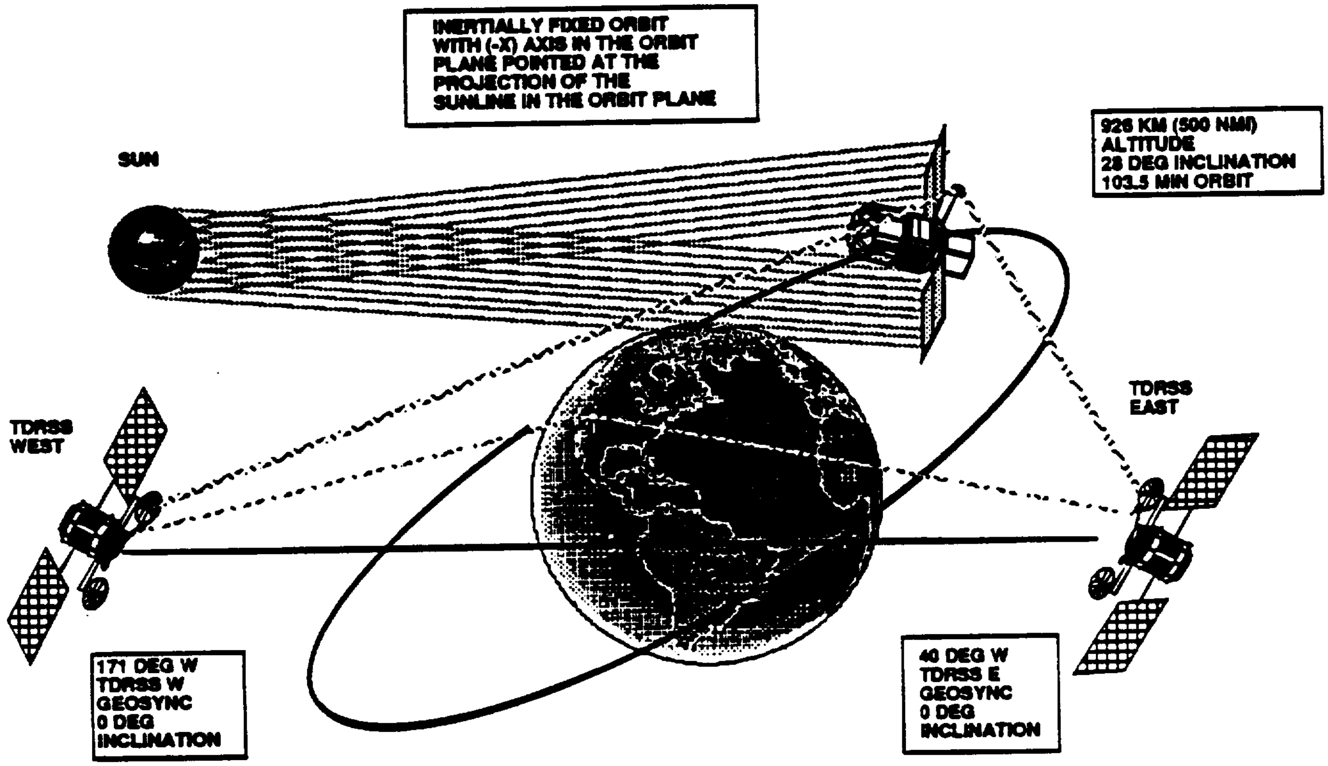


Figure 1.7-1 COLD-SAT On-Orbit Mission Requirements

1.9 Technology Issues

Technology issues have been identified for the COLD-SAT in the area of component and hardware development and then progressing to subsystem element and individual process investigation testing on the ground. These items were previously identified on Figure 1.2-1. They fall into the category of open technology issues that must be addressed prior to Phase C/D program commitment. This category is of a much higher order when compared to those which provide technology enhancement by improving performance and reducing risk, but which are not prerequisites to proceeding with the Phase C/D program. The only item which falls into this later category is tank mass gaging which can be deleted as a requirement without effecting the other experimental objectives. Open technology with respect to hardware includes the development of new hardware and demonstrating the required new performance and capability of existing hardware. Open process technology involves techniques associated with the low-g environment that are not certifiable by ground testing alone, but rather provide design and performance data which aids in the understanding of the process involved.

1.10 Conclusions and Recommendations

The following major conclusions and recommendations were compiled during the course of the COLD-SAT feasibility study effort:

- We have selected the Delta II as the most cost effective ELV for launching a payload in the defined weight class of 4082 kg (9000 lbs) with margin included. This choice also took into account the cost of launch pad modifications required to accommodate LH2/GH2 servicing and attendant operational impact.

• Our selected spacecraft bus approach utilizes an existing qualified and flight proven Multi Mission Spacecraft (MMS) derivative which is an expansion and improvement on the original MMS hardware.

• Electrical hazard proofing of the spacecraft subsystems to operate in a potential hydrogen environment is accomplished by operation in a vacuum environment during ground testing or by GN2 purging for the ground loading scenario.

• Selection of a suitable supply tank size, which established the mission LH2 budget, resulted in a final size of 4.25 m^3 (150 ft^3). While this size fluctuated over the study and was driven to a smaller (minimum recommended) size due to cost and payload fairing packaging constraints, an upper limit of around 5.67 m^3 (200 ft^3) is the maximum size capability. A vacuum jacket was baselined for safe LH2 servicing and containment on the ground.

• Two receiver tanks of approximately 0.57 m^3 (20 ft^3) and 1.13 m^3 (40 ft^3) form the basis for the rest of the experiment subsystem tankage configuration. The smaller receiver tank is close to spherical in size, while the larger is cylindrical with a total communication liquid acquisition device.

• The mission duration is 3 months and should not exceed 6 months.

Several recommendations for changes to our baseline configuration call for additional study effort beyond the work performed from our study activities. These include:

• A non-vacuum jacketed supply tank design. [Reduce complexity and weight (cost)]

• Reduction in the number of GH2 pressurant tanks and using LH2 for ground loading and on-orbit recharge of the pressurant system [Increase reliability].

• Delete the forward propulsion module and eliminate regulated pressurant to the propulsion tanks. Blowdown propulsion would be used. Both changes affect experiment science and are a compromise between cost and technology return for these features.

• Change to fixed solar arrays. [Reduce complexity (cost)]

• Reconfigure the satellite and move spacecraft MMS modules to an aft location. [Center of Gravity and ease of installation]

2.0 INTRODUCTION AND SCOPE

The replenishment of spacecraft cryogenic consumables provides an effective and efficient method for extending the useful life of spacecraft on-orbit. A wide variety of orbital cryogenic liquid storage and supply systems are defined in current NASA and DOD planning. These systems vary in size from small cooling applications to large chemical propellant and electrical orbital, lunar, and interplanetary transfer vehicles, on-orbit depots and resupply tankers. Other applications include power reactants, life support, and experiment or process consumables. Many of these applications will make use of in space cryogenic storage or will require orbital transfer of cryogens for replenishment of spent or depleted systems. Initial loading of these systems in space may also be required, creating various initial thermal conditions from completely cold to warm, which require chilldown operations. All of these needs have the common requirement of low-g fluid management to accomplish gas-free liquid expulsion, transfer, and resupply and efficient thermal control to manage heat leak and tank pressure. The focus of the COLD-SAT Program is to develop technology required to meet these needs for the purpose of establishing an adequate technology base to enable the design and operation of those systems utilizing subcritical cryogenic fluid in the reduced low-g space environment . The COLD-SAT satellite will be utilized to develop the technology required to effectively manage cryogens in space by performing a series of cryogenic fluid management flight experiments. These experiments will provide essential low-g data to enrich the understanding of the thermophysics of subcritical cryogens and to validate analytical and numerical models. The technology developed will permit the establishment of a cryogenic data base containing methodologies and criteria for in space subcritical cryogenic system design.

2.1 Objective and Scope

The major thrust of the twenty-four month COLD-SAT Feasibility Studies contract was to produce an in-depth assessment and conceptual design approach, supported by appropriate trade studies and analyses, for a cryogenic fluid management flight experimental satellite to be carried into a suitable low earth orbit using an expendable launch vehicle (ELV). This satellite consists of spacecraft subsystems supporting an experiment subsystem capable of performing various cryofluid management experiments falling into high priority (Class I) and secondary (Class II) categories. Included in this definition is a development of the system concept, analyses of the system and spacecraft and experiment elements, and conceptual and preliminary design descriptions. Other needed efforts consist of mission design, operations planning (both ground and flight), experiment definition, requirements documentation, specification development, interface definition, project planning and cost estimation. The study is divided into the following three stages which began in February 1988 and concluded in February 1990:

1) The Initial Concept Development stage lasted approximately six months and consisted of the development of concepts for the satellite and associated support systems including a recommendation for the ELV. A Concept Review (CR) concluded this phase.

2) The Concept Refinement and Requirements Definition stage had a duration of approximately six months and ended with a Preliminary Requirements Review (PRR). Refinements were made to the preferred approach selected after the CR.

3) The Preliminary Experiment Design stage comprised the last twelve months of the program and consisted of refinements and updates to the baselined approach presented at the PRR with emphases on experiment subsystem level definition. This phase was concluded with an Experiment Review (ER) which also included presenting a complete and comprehensive COLD-SAT concept.

This report addresses all aspects of the COLD-SAT System concept development which included the following:

a) Definition of the COLD-SAT satellite approach concept and configuration which includes:
    1. Design evolution during the study.
    2. Experiment Subsystem definition and design.
    3. Spacecraft Subsystem definition and design.

b) Mission design and analysis considerations, requirements, and launch vehicle needs.

c) Experiment set goals and objectives for primary and secondary test requirements including the development of an experiment test data base for the on-orbit mission.

d) Mass properties data, weights, center of gravity information, and consumables capabilities.

e) Power, command and data requirements and capabilities.

f) Subsystem performance predictions.

g) Component and instrumentation assessments.

h) Ground segment design and requirements for mechanical and electrical equipment and facilities and ground control of the satellite.

i) COLD-SAT system internal and external interface definition.

j) Generation of functional block diagrams and schematics.

k) Preliminary operational scenario development which included ground processing, launch pad, on-orbit, and post mission operational assessments, as well as contingency considerations and satellite operations control center support.

l) Preliminary safety analysis.

m) Discussion of technology issues.

n) Associated trade studies, analyses, and rationale.

o) Reliability predictions.

p) Project planning and cost estimating activities.

2.2 Design Guidelines, Groundrules and Priorities

A set of design guidelines was established for the purpose of providing top level guidance for the development of the COLD-SAT approach concept. They represent a set of groundrules and goals addressing the nature of the COLD-SAT System, how it has to operate and interface, and how related issues, requirements, and priorities were established and handled early in the program to create a reference set of baseline intent.

The following top level design decisions represent given, implied and derived basic features which were used in the development of the COLD-SAT concept:

a) A maximized total technological return for a minimum total system cost.

b) Reliability for the proper execution of Class I experiments of 0.92 or greater.

c) Minimum technological risk through the use of existing hardware and proven designs and approaches.

d) Minimum modification to the ELV launch facilities.

e) Maximum use of existing test facilities.

f) Primary uplink/downlink communications with the COLD-SAT with a 10 minute TDRSS contact per orbit with backup communications directly to the ground using GSTDN.

g) Launch weight less than 3401 kg (7500 lbs) with a 20 % contingency (established after the PRR).

h) The final end-of-mission orbit for the COLD-SAT satellite with a larger than 500 year reentry life by having a minimum end-of-mission altitude of 926 km (500 nmi).

i) A supply tank and two receiver tanks with pressurization and associated support elements for the experiment subsystem.

j) The system must be "fail operational" - no single point failure preventing the accomplishment of all Class I and the majority of Class II experiment objectives.

k) The system must meet safety requirements of ESMCR 127-1, as a minimum.

2.3 Design Approach and Methodology

Our approach for the conceptual Phase "A" design study for the COLD-SAT is to produce a cost effective and technically suitable satellite design which accomplishes the defined experimental and mission objectives while incorporating the established design guidelines, groundrules and priorities. In particular, our efforts concentrated upon the effects of the low-g space environment on the cryogenic storage, acquisition, and transfer technologies which are critical to the COLD-SAT program. Key towards this end has been the application of systems engineering techniques to optimize the total system design in terms of performance and cost, as well as insuring that contract/SOW requirements are met. A broad spectrum of engineering disciplines are necessary for a system as complex as COLD-SAT and the systems engineering approach serves to tie the process together, permits the rapid identification of problems, inhibits a drifting from system objectives, and allows recognition of process completion through required program reviews, technical interchange and customer agreements.

The extensive nature of the experimental requirements created a systems requirements definition dominated by the need to accomplish these objectives. As a result, the experiment subsystem drove the spacecraft subsystems design in the following major areas:

- attitude control
- propulsion
- data acquisition and control
- structures

When applicable, an identification was made of experimental requirements which imposed excessive and costly requirements on the spacecraft subsystems along with options to simplify the spacecraft design. Implementation of such simplification, however, often resulted in unacceptable experiment science changes that were considered to be important to the mission and, therefore not candidates for deletion or restriction.

Table 2-1 shows some of the key requirements that were used to design the COLD-SAT and the rationale for why these requirements are drivers of the design. Many impact more than one discipline; collectively they demonstrate the complexities associated with the systems engineering activity. Even though there are many design drivers identified, both given and derived, which cover a broad range of experimental and mission needs, it is important that the design resulting from the trade studies, analyses, and experiment desires not result in a spacecraft that is overly sophisticated and costly. Rather, the design should present a realistic compromise between spacecraft and experiment subsystem complexity, weight, development requirements, life cycle costs, and how much of the desired potential mission and on-orbit testing can be accommodated.

Table 2-1 Requirements That Drive the COLD-SAT Design and Rationale

Requirement	Rationale
1. Supply tank volume	1. Delta II payload fairing envelope and component accessability
2. Propellant tank(s) volume	2. Experiment acceleration requirements and spacecraft attitude control needs
3. Satellite total weight	3. Delta II capability @ 926 km (500 nmi)
4. MMS electronics	4. Interface compatibility and existing off the shelf hardware and software
5. Solid state recorders	5. Eliminates external torque considerations on the experiment from a tape recorder drive motor
6. Articulated solar array	6. Maintain sun pointing with minimum array size
7. Articulated antenna	7. TDRSS pointing
8. Reaction wheels & mag torquers for attitude control	8. Eliminates external torque produced by thrusters used for attitude control
9. Thruster size/quantities/location	9. Experiment acceleration regimes with minimized transverse components
10. Number of RIU's and EU's	10. Number of experiment analog channels
11. Earth horizon sensors	11. Less H/W & S/W complexity than star scanners
12. Fine and coarse sun sensors	12. Accuracy (± 2 deg) for sun pointing
13. Aft end pointing towards the sun	13. Minimizes propellant thermal conditioning with heaters
14. Mission duration (approx 90 days)	14. Experiment consumption of 286 kg (630 lb) LH2 budget
15. Final mission altitude of 926 km (500 nmi)	15. Exceeds 500 year lifetime requirement
16. Initial mission altitude	16. Minimizes background gravity environment
17. Redundant S/C systems and experiment subsystem components	17. Needed to meet 92% reliability
18. Receiver tank size and shape	18. Remaining volume left after supply tank, MMS module, and propellant tank integration
19. Satellite configuration	19. Delta II cg constraint above the separation plane

3.0 EXPERIMENT REQUIREMENTS AND DEFINITION

The need for advanced cryogenic fluid management technology is driven by future space missions which will transport, store, and consume cryogenic fluids as part of their everyday mission operation. Various past activities have examined these needs and have categorized cryogenic technology requirements requiring in-space testing under one or more of the following five major headings:

- Liquid Storage (thermal and pressure control)
- Liquid Supply (pressurization, acquisition and subcooling)
- Liquid Transfer (chilldown and fill)
- Fluid Handling (slosh and dumping)
- Advanced Instrumentation (mass gaging and flow metering)

The following logic was employed to further categorize technology requirements and experimentation objectives:

Class I Experiment Objectives - Objectives for this class are primarily scientific in nature and are considered enabling technologies for future space missions. Class I experiments comprise the highest experiment priority and must be executed properly. On-orbit testing is essential since they involve processes which are significantly affected by the low gravitational environment.

Class II Experiment Objectives - This class of experiments forms a lower level of testing priority and has a correspondingly lower science value and are considered supporting in nature. Objectives may include component and system demonstration which provide future space missions with reduced operational complexity and/or performance enhancement. For the most part , Class II technologies are required for the successful accomplishment of Class I objectives.

Figure 1-2 previously presented in Section 1 shows these levels of in-space experimentation, as well as prerequisite levels of ground based subsystem element testing and individual component development.

Two levels of Cryogenic Fluid Management (CFM) technology have been identified which have to be initiated and completed (or well under way with appropriate confidence levels established) before the COLD-SAT Phase C/D Critical Design Review (CDR). The two levels support the on-orbit testing objectives of the COLD-SAT program, and they both contribute to the accumulation of a Cryogenic Fluid Management Data Base and the development/validation of required analytical and design tools.

The first level of technology need begins with component development needed to support the COLD-SAT experiment subsystem hardware design development and subsequent fabrication and assembly of the flight hardware. Some of this activity has already been initiated by NASA and has to be continued in a timely and effective programmed approach to support the Phase C/D effort. The second level of technology need is associated with storage, transfer, and resupply processes either at a particular element level (such as spray nozzle characterization) or at a subsystem level (spray system characterization for chilldown and associated filling of a particular tank configuration). The number of activities in these areas are extensive and requires an immediate development approach and planning for the carrying out of these tasks.

The basic CFM technology that is desired to be investigated by COLD-SAT on-orbit low-g experimentation is also depicted in Figure 1-2 and falls under one of the five major headings as shown. Some of these items have been deleted from the current mission objectives due to experiment complexity and costing considerations. This does not detract from the technology need for these areas such as mass gaging and slosh dynamics. The development of a ground test bed dedicated to this effort would tremendously support these investigations, as would ground simulations of the on-orbit mission (as best as can be conducted in a one-g thermal vacuum environment) using COLD-SAT flight hardware tested with LH2.

All of the above will produce data that will contribute to the building of a Cryogenic Fluid Data Base. This data base will feed into the development and eventual verification, validation and correlation of analytical models which will be needed to support planned and future programs that will require that this technology be developed. They are shown at the far left and right on Figure 1-2.

Finally, the need to have an appropriate mix of both scientific experimentation and system or component level demonstration is required for the COLD-SAT system (with the heavier weight biased towards the collection of scientific data).

3.1 Technology Goals - A brief summary of cryogenic fluid management technology goals for the five general categories is presented below.

Liquid Storage - Future applications require that cryogens be stored in space for periods of time ranging from several hours, to several days, to several years and involves minimizing liquid boil-off and controlling tank pressure. Various continuous storage scenarios for depots and Space Station Freedom needs have also been suggested. Cryogenic storage systems are dependant on effective thermal control system performance and tank pressure control to provide reasonable boil-off losses with passive thermodynamic vent system (TVS) control for long-term storage and active mixing for thermal stratification management for shorter duration needs. Some applications may require active refrigeration.

Heat reaches cryogenic tanks through the tank insulation, the support system, the plumbing penetrations, and through instrumentation lead wires. Heating rates are also strongly influenced by the external thermal environment and by any attempt to limit such heating by using thermal coatings and protections. While much of these influences can be well characterized, the performance of thick MLI blanket systems on large tankage with respect to heat transfer, attachment at the tank surface and reducing compression/maintaining adequate blanket density, as well as seam and closeout discontinuities, is difficult. All of these are issues which have to be addressed. They have implications associated with ground processing, ground servicing, launch environment, ascent effects and on-orbit influences. Other ground servicing factors for LH2 tanks that are loaded on the ground and then transported to orbit and which play an important part in this area include insulation options other than conventional vacuum-jacketed systems. These options might include application of closed-cell foam directly on the tank with MLI over the foam and having the entire system purged with dry nitrogen gas to preclude condensation of nitrogen or oxygen (if air were allowed to contact the tank). Requirements for a purge bag around the tank system is another complication that has to be considered.

Tank pressure control is accomplished through proper tank thermal management resulting from direct tank venting while the liquid is settled, or by using a thermodynamic vent system to both intercept and remove heat from the tank system, or by inhibiting/regulating thermal stratification by mixing the tank contents. A TVS is termed a passive control system where sacrificial tank fluid is flashed through a throttling Joule-Thomson expander and then routed through internal tank heat exchangers and then into a heat exchanger on the vapor-cooled shield (VCS) that surrounds the tank. Active control is accomplished with circulation devices that mix the tank contents to provide quick, short term pressure control without regard for the heat energy management of the system. It is highly desirable to maintain the stored liquid at as low a pressure as possible to maximize the potential use of the fluid, and to minimize the weight of the tankage system. Optimization of these approaches and their efficient integration into tankage designs remains to be characterized. Other considerations include LH2 cooling enhancement provided by para-to-ortho conversion in which a fluid thermal performance advantage can be gained from endothermic conversion of the vented hydrogen in its conversion from its initial para form to near its equilibrium para-ortho composition. Fluid utilization improvements are made possible by using more than one VCS and coupling VCS's when LH2 and other cryogens are stored in close proximity.

Finally, for very long-term storage applications, mechanical refrigerators could reduce venting losses by absorbing the majority of the heat input to the fluid storage tank.

Liquid Supply - This technology area will investigate the unproven process of feeding single-phase, vapor-free subcritical cryogenic liquid at a required and controlled thermodynamic state from a storage tank outlet to a user interface in the low-gravity space environment. The process involves the acquisition of tank fluid at the tank outlet using settling techniques or management of fluid using surface tension and capillary forces that make use of the characteristics of total communication fine mesh screen devices. Fluid expulsion is accomplished by autogenous gas pressurization or by pressurizing with a non-condensible pressurant such as helium. Helium imposes very different gas requirements and influences on system performance. Expulsion using this technique also accounts for necessary subcooling effects that the liquid experiences as part of the process of going to a higher pressure condition. Heat exchangers can also be used to achieve desired levels of temperature reduction. Mechanically-pumped outflow can also be used where the pump ΔP provides both the driving force, as well as the required subcooling effect on the fluid. Proper inlet conditions have to be maintained at the pump inlet so as not to induce fluid vaporization. This can be accomplished by a slight pressurization of the tank or by heat exchanger fluid conditioning.

Liquid Transfer - This portion of the technology needs involves the requirement to transfer liquid from a supply tank to a receiver tank in the low-gravity space environment while minimizing liquid losses associated with the transfer process and controlling both the supply and specifically the receiver tank pressure during the chilldown and filling process. Low-g effects and the inability to readily vent the receiver tank during the filling process presents new problems that have to be overcome. These issues are all related to low-g influences on heat transfer rates and fluid motion/positioning.

The first step in the procedure is to chilldown the transfer line interconnecting the supply and receiver tank and then to chilldown the receiver tank while optimizing the amount of fluid consumed. The time required to accomplish these operations is also very dependant on low-g phenomenon and the amount of extra fluid available to be used to reduce the chilldown time. Tank chilldown can be performed using a direct contact wall-mounted heat exchanger through which chilldown fluid is routed on the tank wall, or by a charge-hold-vent technique whereby a fixed liquid charge is introduced into the tank via the spray systems. For the latter, the charge is held in the tank, allowing the transfer of heat from the tank wall to the fluid to take place until all of the fluid is vaporized. The fluid in the charge-hold-vent chilldown technique is ideally allowed enough time to come into thermal equilibrium with the tank wall. In reality, the fluid is allowed to nearly achieve the tank wall temperature since the heating time becomes substantial. The warm vapor is then vented to space and the process is repeated until the desired initial temperature for tank filling is reached. This entire process is dependant upon several heat transfer processes which are all operating under the unknown low-g influence. These heat transfer properties are expected to be also highly influenced by the fluid properties, liquid injection technique, tank wall temperature and tank size/shape.

The process of filling the receiver tank after chilldown from an initially empty configuration can be accomplished using the following approaches:

- no-vent fill
- vented fill
- ullage exchange

Variations in the above techniques can also be used to top-off a partially full tank.

It is highly desirable to accomplish resupply of user tanks without venting as the transfer proceeds, since establishing an acceleration environment to settle liquid and clear a vent port may significantly impact the user system. Many systems are very sensitive to proximity venting and in certain cases may not be allowed or are severely restricted. The no-vent fill process accomplishes the tank filling without venting and can be divided into the following three phases. The first phase starts at the beginning of the transfer and proceeds until liquid starts to accumulate. It is characterized by vaporization and flashing of incoming liquid. Phase-two covers most of the remaining fill process, where incoming liquid causes compression of the vapor. The final phase occurs throughout the fill process but is most important near the end of the process and involves condensation of vapor to make room for more liquid before vapor compression stops the process. It becomes very important to "find" the ullage with fine liquid sprays to maximize the fill level. The no-vent fill process involves the various heat transfer processes operating in the unknown effects of the low-g environment. These processes have to be investigated.

The vented-fill technique can be used if both venting and a settling acceleration environment can be created. Liquid is introduced into the tank via the outlet to try to allow the liquid to accumulate in this area as determined by fluid momentum and tank acceleration levels. When the tank pressure equals the saturated condition of the incoming fluid the tank vent can be opened to vent vapor and maintain the tank slightly above this condition. The settling acceleration will hopefully maintain a stable interface and allow only vapor to be vented as the tank fills. If fluid momentum is greater than a critical level, the incoming fluid will likely penetrate the fluid interface, resulting in geysering and probable liquid flow out the vent. When this occurs, the vent will be closed and the process terminated if a stable interface cannot be re-established. Venting prematurely can adversely effect the process by causing flashing and liquid carryover out the vent. Again, various unknown fluid and gravity effects are working and an understanding of the effects cannot be confidently predicted.

The last transfer technique, ullage exchange, is a form of a no-vent fill. The ullage exchange technique is a method of transferring liquids in a low-g environment which eliminates problems associated with vented or no-vent fill processes. Fluid transfer with the ullage exchange technique is accomplished by connecting the supply and receiver tank fill and vent lines to each other so that there is a closed fluid loop connecting the two tanks. The supply tank has a liquid acquisition device (LAD) to deliver liquid to the tank outlet. The liquid is transferred to the receiver tank with a liquid pump. Pressure is relieved in the receiver tank as the tank is being filled by venting through the vent line. The position of the ullage is uncertain in such a process, so liquid or gas may be vented. All fluid vented from the receiver tank is collected in the supply tank. The ullage exchange approach offers several design and operational advantages over other techniques such as the no-vent fill approach, including a less complex receiver tank configuration, the capability to handle a non-condensible pressurant, and greater flexibility in performing receiver tank top-offs. The unknown technology issue is the capability of the process to sweep out ullage from the receiver tank so that significant ullage does not become trapped and thereby limit the fill level that can be obtained by the process.

Inherent in all of the above liquid transfer processes is the added complication of insuring that if the receiver tank contains a liquid acquisition device (LAD) that it is properly and completely filled during the tank filling process, and particularly for the initially empty case. For a tank top-off, it is also critical that the top-off process does not violate or compromise the integrity of the fluid in the LAD.

Fluid Handling - In the technology area of fluid handling, various issues associated with fluid motion resulting from spacecraft maneuvering and its dynamic interaction with the spacecraft have to be better understood. The ambient, low-gravity, on-orbit environment will influence the static orientation of the liquid and accelerations produced by satellite operations, specifically those produced from maneuvers will cause liquid motion. The effect of the applied environments on the liquid motion, including such variables as tank size and shape, tank fill fraction, and presence of slosh baffling, are areas requiring on-orbit investigations so that safe and predictable spacecraft operations can be predicted. The forces on the tank wall resulting from the liquid motion influence the maneuvering of the spacecraft. Space missions which are aborted may require that the tank contents be rapidly dumped overboard. This process is not well understood.

Advanced Instrumentation - There is a recognized need in the area of advanced cryogenic instrumentation to develop devices that can perform the following:

- determine the quantity or mass of liquid in a tank under low-g conditions
- measure liquid and cold gas mass flow rates
- detect two phase flow (indicate when vapor is present)
- perform liquid level detection under settled low-g conditions where surface tension forces can still be dominant
- high accuracy thermometry (±0.1 K) and associated signal conditioning circuit design necessary to maintain this accuracy

An in-space cryogenic experiment will provide an ideal test bed for the evaluation of these devices.

3.2 Experiment Set Requirements - An integrated on-orbit cryogenic experiment which incorporates all of the the above technology requirements as experimental objectives would result in an overly complex (for both experimental and associated spacecraft support systems) and very costly system that is at risk in various areas due to required component immaturity, as well as the value of the data that could be expected for the money spent. Pertinence to specific applications must also be considered in prioritizing the items and assessing whether they are candidates for inclusion into the COLD-SAT experimentation. Table 3.2-1 provides information on how these technologies are being addressed by COLD-SAT. This table shows that various technology areas are not being addressed by the current COLD-SAT experiment set. Rationale for the exclusion of these areas is provided as follows:

- All tank thermal performance experiments were deleted by customer technical direction.

- Launch effects on thick MLI cannot be assessed since no experiment tank contains a thick enough insulation blanket [thick blankets range on the order of 5-7.6 cm (2-3 in)]. Thermal performance of receiver tanks were fixed by customer technical direction to a heat flux of 1.58 W/m^2 (0.5 Btu/hr-ft^2) which limit MLI blanket size to less than 2.54 cm (1 in). Also the tank being assessed should contain a cryogen so that any deleterious effects of reduced thermal performance may be observed during launch, ascent, and on-orbit.

- The COLD-SAT mission currently has a 3-month life. Long-term space effects on MLI cannot be evaluated during this short time. One year or more is required.

- The supply tank currently contains a vacuum jacket for LH2 ground servicing safety. Combined foam/MLI systems can only be evaluated on non-vacuum jacketed tanks.

- Para-to-ortho thermal performance gains can be assessed on the ground and is an added complexity that is not cost effective.

- Multiple/coupled VCS were also judged to be an added complexity and not cost effective by the customer. Also, the performance of multiple VCS can be evaluated on the ground.

- Refrigerator and liquifier designs have not matured sufficiently to be cost effective. They require extra power, large radiators, and a great complexity to the experiment subsystem design.

- Tank quantity mass gaging design has not sufficiently matured at this time to be included as part of the COLD-SAT baseline. The requirement was deleted per customer direction.

- The high orbit of the COLD-SAT as directed by the customer creates such a low gravity field that settled outflows using background acceleration levels will not work. Surface tension forces predominate in this gravity regime.

- The amount of heat required to affect LAD performance is many orders of magnitude greater than the supply tank heaters are currently sized. This was not considered to be an important test requirement and is supported by ground testing results.

- All liquid dynamics and slosh control experiments were deleted per customer technical direction. They imposed excessive propulsion and instrumentation requirements upon the system.

- Slush hydrogen technology is being developed as part of NASP and was never considered to be a part of COLD-SAT. It is too complicated and not cost effective.

Table 3.2-1 Cryogenic Fluid Management Technology Criticality Needs Met by COLD-SAT

Area	Subarea	CFM Technologies	Criticality	COLD-SAT Experiments (Current COLD-SAT In-Space Experimentation)	Class I	Class II	Tank
LIQUID STORAGE	THERMAL CONTROL	LAUNCH EFFECTS ON THICK MLI	2	NONE			
		LONG TERM SPACE ENVIRON EFFECTS ON MLI	2	NONE			
		COMBINED FOAM/MULTILAYER INSULATION	2	NONE			
		PARA-TO-ORTHO CONVERSION	2	NONE			
		MULTIPLE/COUPLED VAPOR COOLED SHIELDS	2	NONE			
	PRESSURE CONTROL	THERMODYNAMIC VENT SYSTEM PERFORMANCE	1	1.1 TANK PRESSURE CONTROL (ACTIVE)	●		A,D
		FLUID MIXING FOR STRATIFICATION CONTROL	1	1.2 TANK PRESSURE CONTROL (PASSIVE)	●		A
		REFRIGERATION/LIQUEFACTION	3	NONE			
		DIRECT ULLAGE VENTING *	2	2.5c SETTLED TANK ULLAGE VENTING		●	A,D
LIQUID SUPPLY	PRESSURIZATION	AUTOGENOUS (GH2)	2	2.4 TANK PRESSURIZATION		●	A,D
		NON-CONDENSIBLE - HELIUM	2	2.4 TANK PRESSURIZATION		●	D
		MECHANICAL PUMPS	2	1.4 TANK FILL/REFILL	●		E
	LIQ ACQUISITION & SUBCOOLING	LAD PERFORMANCE	2	2.6 LAD PERFORMANCE		●	A,B
		FLUID SETTLING & OUTFLOW WITH ACCEL	2	2.5a SETTLED OUTFLOW		●	C
		FLUID SETTLING & OUTFLOW (LOW-G)	2	NONE			
		THERMAL EFFECTS ON LAD PERFORMANCE	2	NONE			
LIQUID TRANSFER		THERMAL SUBCOOLING	2	2.8 LIQUID THERMODYNAMIC STATE		●	A
		TRANSFER LINE CHILLDOWN	2	2.7 TRANSFER LINE CHILLDOWN		●	E
		TANK CHILLDOWN WITH SPRAY	1	1.3 TANK CHILLDOWN	●		D
		TANK CHILLDOWN VIA HEAT EXCHANGER *	2	1.3 TANK CHILLDOWN	●		C
		TANK NO-VENT FILL	1	1.4 TANK NO-VENT FILL	●		D
		LOW-G VENTED FILL	2	2.5b TANK VENTED FILL		●	D
		ULLAGE EXCHANGE *	2	1.4 TANK FILL	●		D
		LAD FILL	1	1.5 LAD FILL CHARACTERIZATION	●		A,B
FLUID HANDLING		LIQUID DYNAMICS/SLOSH CONTROL	1	NONE			
		FLUID VENTING/DUMPING	2	2.9 TANK DUMPING		●	C
		SUBCOOLED LIQUID/SLUSH TRANSPORT	4	NONE			
INSTRUMENTATION		TANK QUANTITY MASS GAGING	3	NONE			
		FLOW METERING	2	VARIOUS	●	●	
		TWO PHASE FLOW DETECTION *	2	VARIOUS	●	●	
		SETTLED LIQUID FILL LEVEL MEASURING	2	VARIOUS	●	●	
		HIGH ACCURACY THERMOMETRY & SIGNAL COND	2	VARIOUS	●	●	

CRITICALITY:
1 - ENABLING FOR FUTURE SPACE MISSIONS
2 - ENHANCING FOR FURURE SPACE MISSIONS
3 - LIMITED BY MATURITY OF COMPONENTS REQUIRED TO OBTAIN THIS TECHNOLOGY
4 - LIMITED IN FOCUS TO A VERY SPECIFIC APPLICATION

TANKS:
A - SUPPLY TANK
B - RECEIVER TANK 1
C - RECEIVER TANK 2
D - BOTH RECEIVER TANKS
E - TRANSFER LINE

* Technologies recommended by MMAG and accepted by LeRC

Table 3.2-2 list the COLD-SAT Class I and Class II experiment set categories which form the experimental technical objectives of the mission. Several requirements (as shown) have been deleted over the course of the program by customer technical direction.

Table 3.2-2 The COLD-SAT Experiment Set

Class I Experiment Categories	
1.1 } 1.2	Tank Pressure Control (Active and Passive)
1.3	Tank Chilldown in Low-Gravity
1.4	Low-G No-Vent Fill and Refill of Cryo Tanks
1.5	Capillary Liquid Acquisition Device (LAD) Fill/Refill Characterization
1.6	Liquid Mass Gaging in Low-Gravity (Requirement Deleted)
1.7	Liquid Dynamics and Slosh Control (Requirement Deleted)
Class II Experimental Categories	
2.1 } 2.2 2.3	Tank Thermal Performance (Requirements Deleted)
2.4	Tank Pressurization with GH and GHe
2.5	Liquid Settling in Low-Gravity a. Tank Direct Liquid Outflow b. Tank Vented Fill c. Tank Ullage Venting
2.6	Liquid Acquisition Device Performance in Low-G
2.7	Transfer Line Chilldown
2.8	Control of Liquid Thermodynamic State During Outflow
2.9	Tank Liquid Dumping in Low-G
2.10	Advanced Instrumentation for Cryo in Low-G

3.2.1 Class I Experiments - A discussion of the Class I experiment requirements as they apply to each of the individual ERD (Ref. 3.2-1) experiments is presented in the following paragraphs:

Tank Pressure Control (Experiment Series 1.1 and 1.2) - Table 3.2-3 provides the top level requirements for the tank pressure control experiments. Four major areas make up the experiment objective for both the active and passive pressure control portions of the experiment. Efficient tank pressure control of on-orbit cryogenic tankage is dependent on the capability of the thermodynamic vent system (TVS) heat exchanger, the vapor-cooled shield (VCS), and the compact heat exchanger (CHX) to control the heat flux into the tank and/or remove heat from the system. This heat removal capability will be augmented in the supply tank with a compact heat exchanger that can remove heat from the tank at many times the rate of the TVS heat exchanger. Pressure control accomplished by thermal destratification will be investigated. The mixer system will aid in destratifying the fluid while also removing heat from the bulk fluid with the compact heat exchanger.

So that the influences that contribute to mixer and TVS performance can be investigated, the listed parameters in Table 3.2-3 will be varied for the supply tank (majority of tests performed in this series) and receiver tank pressure control tests.

Key measurements required to provide data necessary to the understanding of the processes being investigated, as well as verification of analytical predictions are also defined in Table 3.2-3. These include tank wall temperatures, bulk fluid temperatures, tank pressure, accelerations, liquid and vapor detectors, and TVS and liquid outflow rates.

Table 3.2-3 Tank Pressure Control Experiment Principal Requirements

- OBJECTIVE - INVESTIGATE PHENOMENA ASSOCIATED WITH CONTROLLING TANK PRESSURE (CONCENTRATING ON SUPPLY TANK)
  - THERMAL STRATIFICATION
  - FLUID MIXING (JET INDUCED AND SPRAY)
  - PASSIVE THERMODYNAMIC VENT SYSTEM HEAT EXCHANGER PERFORMANCE
  - ACTIVE MIXER HEAT EXCHANGER PERFORMANCE
- PARAMETERS BEING VARIED
  - HEAT FLUX INTO THE TANK 0.315 TO 1.89 W/M^2 (0.1 TO 0.6 BTU/HR-FT2)
  - ACCELERATION ENVIRONMENT (1E-06 TO 1.4E-04 G'S)
  - LIQUID FILL LEVEL (90%, 75% AND 50%)
  - MIXER FLOWRATE 20.4 TO 24.9 KG/HR (45 TO 55 LB/HR) AND 40.8 TO 49.9 KG/HR (90 TO 110 LB/HR)
  - HEAT FLUX OUT OF THE TANK BY TVS HX 0.022 TO 0.045 KG/HR (0.05 TO 0.1 LB/HR)
  - HEAT FLUX OUT OF THE TANK BY MIXER HX 0.73 TO 1.45 KG/HR (1.6 TO 3.2 LB/HR)
- KEY MEASUREMENTS REQUIRED
  - TANK TEMPERATURE PROFILE BOTH WALL AND BULK FLUID
  - TANK PRESSURE CHANGE BOTH INCREASE AND DECREASE
  - ACCELERATION ENVIRONMENT
  - LIQUID/VAPOR INTERFACE POSITION
  - OUTFLOW RATES FOR TVS AND MIXER HEAT EXCHANGERS

The tank pressure control experiment is comprised of the following individual tests:

<u>1.1&1.2 Low Gravity Tank Pressure Control - Active and Passive - Near Full</u>

Test #1: Prelaunch and Ascent
Test #2: Supply Tank Thermal Stratification - Low Heat 0.315 W/m^2 (0.1Btu/hr-ft^2)
Test #3: Supply Tank Axial Jet Low Flow Mixing - Low Heat 0.315 W/m^2 (0.1Btu/hr-ft^2)
Test #4: Supply Tank TVS Operation - Low Heat 0.315 W/m^2 (0.1Btu/hr-ft^2)
Test #5: Supply Tank Axial Jet Low Flow Mixing & CHX Operation - Low Heat 0.315 W/m^2 (0.1Btu/hr-ft^2)
Test #6: Supply Tank Axial Jet High Flow Mixing & CHX Operation - Low Heat 0.315.W/m^2 (0.1Btu/hr-ft^2)
Test #7: Supply Tank Radial Spray High Flow Mixing & CHX Operation - Low Heat 0.315 W/m^2 (0.1Btu/hr-ft^2)
Test #8: Supply Tank Thermal Stratification - Medium Heat 0.95 W/m^2 (0.3 Btu/hr-ft^2)
Test #9: Supply Tank Axial Jet Low Flow Mixing - Medium Heat 0.95 W/m^2 (0.3 Btu/hr-ft^2)
Test #10: Supply Tank Axial Jet Low Flow Mixing & CHX Operation - Medium Heat 0.95 W/m^2 (0.3 Btu/hr-ft^2)
Test #11: Supply Tank Axial Jet High Flow Mixing & CHX Operation - Medium Heat 0.95 W/m^2 (0.3 Btu/hr-ft^2)

Test #12: Supply Tank Radial Spray High Flow Mixing & CHX Operation - Medium Heat 0.95 W/m^2(0.3 Btu/hr-ft^2)
Test #13: Supply Tank Thermal Stratification - High Heat 1.9 W/m^2 (0.6 Btu/hr-ft^2)

Test #14: Supply Tank Axial Jet High Flow Mixing - High Heat 1.9 W/m^2 (0.6 $Btu/hr\text{-}ft^2$)
Test #15: Supply Tank Axial Jet Low Flow Mixing & CHX Operation - High Heat 1.9 W/m^2 (0.6 $Btu/hr\text{-}ft^2$)
Test #16: Supply Tank Axial Jet High Flow Mixing & CHX Operation - High Heat 1.9 W/m^2 (0.6 $Btu/hr\text{-}ft^2$)
Test #17: Supply Tank Radial Spray High Flow Mixing & CHX Operation - High Heat 1.9 W/m^2 (0.6 $Btu/hr\text{-}ft^2$)

1.1&1.2 Low Gravity Tank Pressure Control - Active and Passive - 75% Full

Test #18: Supply Tank Thermal Stratification - High Heat 1.9 W/m^2 (0.6 $Btu/hr\text{-}ft^2$)
Test #19: Supply Tank Axial Jet Low Flow Mixing - High Heat 1.9 W/m^2 (0.6 $Btu/hr\text{-}ft^2$)
Test #20: Supply Tank Radial Spray High Flow Mixing - High Heat 1.9 W/m^2 (0.6 $Btu/hr\text{-}ft^2$)
Test #21: Supply Tank TVS Operation - Low Heat 0.315 W/m^2 (0.1$Btu/hr\text{-}ft^2$)
Test #22: Supply Tank Axial Jet Low Flow Mixing & CHX Operation - Low Heat 0.315 W/m^2 (0.1$Btu/hr\text{-}ft^2$)
Test #23: Supply Tank Axial Jet High Flow Mixing & CHX Operation - Low Heat 0.315 W/m^2 (0.1$Btu/hr\text{-}ft^2$)
Test #24: Supply Tank Radial Spray High Flow Mixing & CHX Operation -Low Heat 0.315 W/m^2 (0.1$Btu/hr\text{-}ft^2$)

1.1&1.2 Low Gravity Tank Pressure Control - Active and Passive - 50% Full

Test #25: Supply Tank Thermal Stratification - High Heat 1.9 W/m^2(0.6 $Btu/hr\text{-}ft^2$)
Test #26: Supply Tank Axial Jet Low Flow Mixing - High Heat 1.9 W/m^2 (0.6 $Btu/hr\text{-}ft^2$)
Test #27: Supply Tank Radial Spray High Flow Mixing - High Heat 1.9 W/m^2 (0.6 $Btu/hr\text{-}ft^2$)
Test #28: Supply Tank Thermal Stratification - High Heat 1.9 W/m^2 (0.6 $Btu/hr\text{-}ft^2$) & Medium Thrust (1.0E-05)
Test #29: Supply Tank Axial Jet Low Flow Mixing - High Heat 1.9 W/m^2 (0.6 $Btu/hr\text{-}ft^2$) & Medium Thrust (1.0E-05)
Test #30: Supply Tank Thermal Stratification - High Heat 1.9 W/m^2 (0.6 $Btu/hr\text{-}ft^2$)& High Thrust (4.7E-05)
Test #31: Supply Tank Axial Jet Low Flow Mixing - High Heat 1.9 W/m^2 (0.6 $Btu/hr\text{-}ft^2$) & High Thrust (4.7E-05)
Test #32: Supply Tank TVS Operation - Low Heat 0.315 W/m^2 (0.1$Btu/hr\text{-}ft^2$)
Test #33: Supply Tank Axial Jet High Flow Mixing & CHX Operation - Low Heat 0.315 W/m^2 (0.1$Btu/hr\text{-}ft^2$)
Test #34: Supply Tank TVS Operation - Low Heat 0.315 W/m^2 (0.1$Btu/hr\text{-}ft^2$) & Medium Thrust (1.0E-05)
Test #35: Supply Tank Axial Jet High Flow Mixing & CHX Operation - Low Heat 0.315 W/m^2 (0.1$Btu/hr\text{-}ft^2$) & Medium Thrust (1.0E-05)
Test #36: Supply Tank TVS Operation - Low Heat 0.315 W/m^2 (0.1$Btu/hr\text{-}ft^2$) & High Thrust (4.7E-05)

Test #37: Supply Tank Axial Jet High Flow Mixing & CHX Operation - Low Heat 0.315 W/m^2 (0.1$Btu/hr\text{-}ft^2$) & High Thrust (4.7E-05)

1.1&1.2 Low Gravity Tank Pressure Control - Active and Passive - Other Supply and Receiver Tank Operating Conditions

Test #38: Supply Tank Nominal TVS Operation Without Mixing
Test #39: Supply Tank Nominal TVS Operation With Mixing
Test #40: Supply Tank Nominal TVS Operation for Pressure Decrease With Mixing
Test #41: Supply Tank Maximum TVS Operation for Pressure Decrease With Mixing
Test #42: Supply Tank Compact Heat Exchanger (CHX) Operation With One Mixer
Test #43: Supply Tank Compact Heat Exchanger (CHX) Operation With Two Mixers
Test #44: Receiver Tank 1 Nominal TVS Operation
Test #45: Receiver Tank 1 Maximum TVS Operation
Test #46: Receiver Tank 2 Nominal TVS Operation
Test #47: Receiver Tank 2 Maximum TVS Operation
Test #48: Supply Tank Thermal Stratification (Near Empty) - Medium Heat 0.95 W/m^2 (0.3 $Btu/hr\text{-}ft^2$)
Test #49: Supply Tank Empty Tank TVS Operation (LAD Residuals Only)
Test #50: Receiver Tank 1 Empty Tank TVS Operation (LAD Residuals Only)
Test #51: Receiver Tank 1 Warm-up Evaluation
Test #52: Receiver Tank 2 Warm-up Evaluation
Test #53: Supply Tank Warm-up Evaluation

Tank Chilldown (Experiment Series 1.3) - Table 3.2-4 provides the top level requirements for the tank chilldown experiments. Tank chilldown is a precursor to the filling of a depleted subcritical cryogenic system in the space environment. Proper tank chilldown is essential to the efficient filling of tankage to high fill levels. The process of removing energy from the system involves optimizing the heat transfer between the chilldown fluid (both liquid and vapor) and the tank wall and other associated internal/external plumbing, hardware and structure. Optimization of the process (limiting the fluid used while maximizing the heat transfer) is an important test requirement. In some instances, it may be desirable to limit the time for the chilldown process, which will presumably use more fluid for chilldown since efficiency will be less. The amount of chilldown LH2 will be determined for various chilldown scenarios, as well as the time required to achieve the desired predetermined target temperature.

So that the effects of influences which contribute to receiver tank chilldown can be investigated, the parameters listed in Table 3.2-4 will be varied, primarily for receiver tank 2 where the majority of the chilldown testing will be concentrated. Four tests are currently baselined for receiver tank 1, whereas ten tests have been allocated for receiver tank 2. The initial tank wall temperatures will be varied due to the varying warm-up period durations between tests and with the use of tank wall-mounted heaters.

Key measurements required to provide data necessary to the understanding of the processes being investigated, as well as verification of analytical tank chilldown predictions are also defined in Table 3.2-4. Pressures are crucial for accurate determination of venting stages that offer additional wall cooling and separate the charge-hold-vent cycle until the target temperature is attained.

The tank chilldown experiment is comprised of the following individual tests:

1.3 Tank Chilldown in Low-G

Test #1: Receiver Tank 2 Chilldown Using the Tangential Spray Only with Nominal Flow
Test #2: Receiver Tank 1 Chilldown Using the Circumferential Spray Only with Nominal Flow
Test #3: Receiver Tank 2 Chilldown Using the Radial Spray Only with Nominal Flow
Test #4: Receiver Tank 2 Chilldown Using the Radial Spray Only with Maximum Flow
Test #5: Receiver Tank 2 Chilldown Using Nominal Tangential Spray Flow and Nominal Radial Spray Flow (Simultaneous Spray Operation)
Test #6: Receiver Tank 2 Chilldown Using Flow Into the Inlet/Outlet Baffle Spray Flow (Radial/Tangential Sequencing of the Sprays)
Test #7: Receiver Tank 2 Chilldown Using Nominal Tangential Flow and Nominal Axial Spray Flow (Simultaneous Spray Operation)
Test #8: Receiver Tank 1 Chilldown Using Nominal Circumferential Spray Flow and Nominal Axial Spray Flow (Simultaneous Spray Operation)
Test #9: Receiver Tank 2 Chilldown Using Tank Wall Heat Exchanger
Test #10: Receiv fiank 2 Chilldown Using the Radial Spray Only with Nominal Flow and High Acceleration (4.7E -05)
Test #11: Receiver Tank 1 Chilldown Using the LAD
Test #12: Receiver Tank 2 Chilldown Using the Axial Spray Only with Nominal Flow
Test #13: Receiver Tank 1 Chilldown Using the Axial Spray Only with Nominal Flow
Test #14: Receiver Tank 2 Warm-up Using Tank Heaters

Table 3.2-4 Tank Chilldown Experiment Principal Requirements

- OBJECTIVE - INVESTIGATE THE TANK CHILLDOWN PROCESS ASSOCIATED WITH REMOVING HEAT FROM THE TANK SYSTEM BY HEAT TRANSFER BETWEEN THE CHILLDOWN FLUID (BOTH LIQUID AND VAPOR) AND THE TANK BULK MASS. THE PROCESS WILL BE CHARACTERIZED FOR FLUID UTILIZATION/EFFICIENCY.

- PARAMETERS BEING VARIED
  - TANK MASS TO VOLUME RATIOS (BECAUSE 2 TANKS ARE BEING TESTED)
  - SELECTION OF SPRAY SYSTEM BEING USED
  - CHARGE MASS QUANTITY AND FLOW RATE
  - VAPOR HOLD TIME AND VENTING TECHNIQUE (VENT CYCLES & TVS VENTING)
  - INITIAL STARTING TEMPERATURE OF THE TANK SYSTEM
  - ACCELERATION ENVIRONMENT
  - INLET FLUID THERMODYNAMIC CONDITIONS

- KEY MEASUREMENTS REQUIRED
  - TANK TEMPERATURE PROFILE BOTH WALL AND FLUID
  - TANK PRESSURE CHANGE FOR CHARGE, HOLD , AND VENT CYCLES
  - MASS QUANTITY USED FOR EACH CHARGE CYCLE
  - FLOW RATE USED FOR EACH CHARGE CYCLE
  - TIME TAKEN FOR CHARGE, HOLD, AND VENT CYCLES
  - FLOWRATE FOR VENT CYCLES
  - ACCELERATION ENVIRONMENT

Tank No-Vent Fill (Experiment Series 1.4) - Table 3.2-5 provides the top level requirements for tank no-vent fill and refill experiments. Filling of a cold empty or partially full cryogen tank in low-g poses many challenges. The ability to fill or refill tankage to desired fill levels without early termination due to excessive vapor generation will be addressed in these tests. During the filling process vapor is generated by a combination of flashing to low pressure and cooling of the tank wall (from target temperature to LH_2). Ullage vapor pressure is controlled during the fill process by promoting condensation due to fluid mixing. A variety of spray nozzles will be used to investigate the filling

Table 3.2-5 Tank No-Vent Fill and Refill Experiment Principal Requirements

- OBJECTIVE - INVESTIGATE THE TANK NO-VENT FILL AND REFILL PROCESS FOR TANKS OF TWO DIFFERENT SIZES AND GEOMETRIES ASSOCIATED WITH EVALUATING THE FINAL FILL LEVEL THAT CAN BE REACHED FOR VARIOUS FLUID INJECTION AND MIXING CONDITIONS
- PARAMETERS BEING VARIED
  - TANK L/D RATIOS (BECAUSE 2 TANKS ARE BEING TESTED)
  - SELECTION OF SPRAY SYSTEMS BEING USED
  - FLOW RATE OF INCOMING FLUID TO RADIAL & AXIAL SPRAY SYSTEMS
  - INLET FLUID THERMODYNAMIC CONDITIONS
  - ACCELERATION ENVIRONMENT
  - INITIAL FILL CONDITIONS OF THE TANK
- KEY MEASUREMENTS REQUIRED
  - TANK TEMPERATURE PROFILE BOTH WALL AND FLUID
  - TANK PRESSURE CHANGE WITH TIME
  - INCOMING FLUID FLOW RATE
  - TOTAL MASS TRANSFERRED
  - LIQUID/VAPOR INTERFACE POSITION
  - ACCELERATION ENVIRONMENT

process which includes optimization of the condensation of vapor at the end of the process in order to maximize the fill level.

So that the effects of influences that contribute to the filling process can be investigated, the parameters listed in Table 3.2-5 will be varied for the two receiver tanks being tested. In addition to varying the listed parameters in the individual tests, a staged-fill process will be investigated by performing intermediate fluid mixing steps during staged-filling operations in an independent test.

Key measurements required to provide data necessary to the understanding of the process being investigated are also listed in Table 3.2-5. These data will be required to aid in the understanding of the fluid, thermodynamic and thermal processes occurring, as well as being used for verification of analytical model tank no-vent fill predictions.

The tank no-vent fill/refill experiment is comprised of the following individual tests:

<u>1.4 Low Gravity No-Vent Fill and Refill of Tanks</u>

Test #1: Receiver Tank 2 Fill Using Tangential and Then Nominal Flow Radial Spray
Test #2: Receiver Tank 1 Fill Using Simultaneous Circumferential and Nominal Flow Axial Spray
Test #3: Receiver Tank 2 Fill Using Tangential and Then Nominal Flow Axial Spray
Test #4: Receiver Tank 1 Nominal Flow Fill Using Axial Spray - Medium Acceleration to Settle Towards Vent
Test #5: Receiver Tank 1 High Flow Fill Using Axial Spray
Test #6: Receiver Tank 2 Nominal Flow Fill Via Tank Baffled Inlet/Outlet
Test #7: Receiver Tank 2 Fill Using Tangential and Then High Flow Radial Spray
Test #8: Receiver Tank 1 Fill Via Tank Inlet/Outlet LAD
Test #9: Receiver Tank 2 Fill Using Tangential and Then High Flow Axial Spray
Test #10: Receiver Tank 1 Fill Using Simultaneous High Flow Circumferential and Axial Spray
Test #11: Receiver Tank 2 Fill Using Simultaneous Tangential and Nominal Radial Spray
Test #12: Receiver Tank 1 70% Topoff Using High Flow Axial Spray
Test #13: Receiver Tank 2 30% Topoff Using Nominal Flow Radial Spray
Test #14: Supply Tank Topoff Via Radial Spray System
Test #15: Supply Tank Topoff Via Radial Spray System - High Acceleration

(4.7E-05 or 1.4E-04)
Test #16: Supply Tank Topoff Via LAD/Outlet with Mixer On
Test #17: Supply Tank Topoff Via LAD/Outlet with Mixer Off
Test #18: Supply Tank Topoff Via LAD/Outlet with Mixer On - High Acceleration (4.7E-05 or 1.4E-04)
Test #19: Supply Tank Topoff Via LAD/Outlet with Mixer Off - High Acceleration (4.7E-05 or 1.4E-04)
Test #20: Supply Tank Topoff Via Axial Spray System
Test #21: Supply Tank Topoff Via Axial Spray System - High Acceleration (4.7E-05 or 1.4E-04)
Test #22: Receiver Tank 2 Ullage Exchange - One Mixer Pump Circulation
Test #23: Receiver Tank 2 Ullage Exchange - Two Mixer Pump Circulation
Test #24: Receiver Tank 1 Ullage Exchange - Two Mixer Pump Circulation with Medium Acceleration (4.7E-05) Settling to the Outlet End
Test #25: Receiver Tank 1 Fill Using Nominal Flow Axial Spray
Test #26: Receiver Tank 2 Interrupted Fill Via Tank Baffled Inlet/Outlet

LAD Fill/Refill (Experiment Series 1.5) - Table 3.2-6 provides the top level requirements for the total communication LAD fill/refill experiments. As part of the receiver tank 1 filling process, the ability to completely fill a LAD that is chilled down to the target temperature will be evaluated. As the LAD filling process proceeds, the device will generate vapor until the LH2 temperature is reached. Some of this vapor may become entrained in the device after liquid starts to accumulate and remain after filling is complete. During refill tests of receiver tank 1 the capability of the LAD to remain full will be assessed. Similar assessments will be made when receiver tank liquid is back-transferred to the supply tank.

By performing a short outflow of the LAD after the transfer is complete, the expulsion of vapor-free liquid will be verified. If vapor is detected (using transfer line flow meter output), methods of bubble collapse will be used by either cooling the LAD fluid with TVS fluid (so that vapor condensation is promoted) or by increasing the tank pressure with GH2 (which is a secondary method only to be used if TVS cooling fails). Table 3.2-1 identifies a need for a fluid quality (or two-phase) flow meter. This flow meter will be used to detect vapor that may have been ingested into the LAD during the brief outflow period. The LAD thermodynamic conditions such as the pressure in the tank and the temperature of the fluid in the LAD will be measured to determine fluid thermodynamic states at which vapor-free outflow can be obtained.

Table 3.2-6 Total Communication LAD Fill/Refill Experiment Principal Requirements

• OBJECTIVE - DEMONSTRATE THE FILLING AND REFILLING CHARACTERISTICS OF LIQUID ACQUISITION DEVICES IN LOW-G TO VERIFY CAPABILITIES FOR VAPOR FREE OUTFLOW
• PARAMETERS BEING VARIED
- INITIALLY EMPTY VS FULL LAD CHANNELS
- FILLING INTERNAL VS EXTERNAL
- ACCELERATION ENVIRONMENT
• KEY MEASUREMENTS REQUIRED
- TRANSFER LINE FLOWMETER QUALITY DISTINCTION
- TRANSFER LINE TEMPERATURES
- ACCELERATION ENVIRONMENT
- LAD TEMPERATURES
- TANK PRESSURE LEVEL

The LAD fill/refill experiment is comprised of the following individual tests:

1.5 Total Communication Capillary Liquid Acquisition Device Fill/Refill Characterization

Test #1: Receiver Tank 1 LAD Empty Fill
Test #2: Receiver Tank 1 LAD Refill
Test #3: Supply Tank 1 LAD Refill

The following Class I experiment requirements (ERD 1.6 and 1.7) have been deleted from the current COLD-SAT Experiment Set by customer direction. They are provided for information on the type of experiments that were originally contemplated.

Liquid Mass Gaging (Experiment Series 1.6) - The mass gaging experiment was comprised of the following individual tests prior to the deletion of this experiment requirement:

1.6 Liquid Mass Gaging in Low-G

Test #1: Supply tank mass gaging during steady-state nominal storage operations
Test #2: Performance when fluid stratification is present
Test #3: Performance when fluid is well mixed
Test #4: With settling accelerations tending to position fluid to known locations
Test #5: During and after tank inflow/outflow

Table 3.2-7 provides the top level requirements for the liquid mass gaging experiment. Parameters which influence mass gaging would be varied parametrically to attempt to quantify their effects on the process. Performance and accuracy of the mass gage output would be assessed against a known condition (where fluid is not being removed or added to the tank) for various orientations of the fluid contents. Predicted mass in the supply tank would be measured using the mass gage and compared with integrated flow meter readings and settled liquid level measurements.

Table 3.2-7 Mass Gaging Experiment Principal Requirements

- OBJECTIVE - ASSESS THE PERFORMANCE OF A MASS GAGE TO ACCURATELY DETERMINE SUPPLY TANK LIQUID QUANTITY FOR DIFFERENT TANK CONDITIONS

- PARAMETERS BEING VARIED
  - TANK FLUID THERMAL CONDITIONS (STRATIFIED OR MIXED)
  - TANK PRESSURE CONDITIONS
  - ACCELERATION ENVIRONMENT CAUSING SETTLED LIQUID POSITION
  - TANK FILL LEVEL CAUSED BY OUTFLOW/INFLOW

- KEY MEASUREMENTS REQUIRED
  - MASS GAGE READING
  - INTEGRATED OVERBOARD FLOW DETERMINATION
  - MASS IN OTHER TANKS DETERMINATION
  - LIQUID/VAPOR INTERFACE POSITION
  - TANK PRESSURE
  - TANK FLUID TEMPERATURES

Liquid Dynamics and Slosh Control (Experiment Series 1.7) - The liquid dynamics and slosh control experiment was comprised of the following individual tests prior to the deletion of this experiment requirement:

1.7 Liquid Dynamics and Slosh Control

Test #1: Supply Tank Slosh Investigation
- a. 75-80% Full - Receiver Tank 2 90% Full
- b. 62% Full - No Liquid in Receiver Tanks
- c. 50% Full - Receiver Tank 1 90% Full
- d. 25% Full - Receiver Tank 1 90% Full
- e. 25% Full - No Liquid in Receiver Tanks

Test #2: Receiver Tank 1 Slosh Investigation
- a. Nearly Full - Supply Tank 50% Full
- b. Nearly Full - Supply Tank 25% Full
- c. 80% Full - No Liquid in Other Tanks
- d. 50% Full - No Liquid in Other Tanks

Test #3: Receiver Tank 2 Slosh Investigation
- a. Nearly Full Tank - Supply Tank 80% Full
- b. 75% Full - No Liquid in Other Tanks
- c. 50% Full - No Liquid in Other Tanks

Table 3.2-8 provides the top level requirements for the liquid dynamics and slosh control experiments. The ambient, low-gravity, on-orbit environment will influence the static orientation of the liquid, and accelerations produced by satellite operations and specifically produced maneuvers would cause liquid motion. The effect of the applied environments on the liquid motion, including such variables as tank size and shape, tank fill fraction, and presence of slosh baffling would be investigated. The forces on the tank wall resulting from the liquid motion, although small [less than 4.45 N (1 lbf) for the maximum acceleration condition possible] have an influence that must be accounted for in maneuvering of the spacecraft.

Table 3.2-8 Liquid Dynamics and Slosh Control Experiment Principal Requirements

• OBJECTIVE - DETERMINE THE LIQUID MOTION RESULTING FROM SPECIFICALLY PRODUCED ACCELERATION ENVIRONMENTS
• PARAMETERS BEING VARIED - ACCELERATION LEVELS AND DIRECTION - TIME ACCELERATION IS APPLIED - LIQUID LEVEL IN THE TANK - FILL CONDITIONS IN OTHER TANKS - TANK GEOMETRY (THREE TANKS WILL BE TESTED WITH LH2)
• KEY MEASUREMENTS REQUIRED - TANK LIQUID QUANTITY - LIQUID/VAPOR INTERFACE POSITION - ACCELERATION ENVIRONMENT

The approach for slosh testing (which is our independent recommendation) is to produce a wide range of slosh conditions using the hydrogen stored in each of the experiment tanks at various phases of the mission. The near zero-g environment on-orbit provides the conditions for performing these tests. The satellite propulsion system would be used to provide the needed disturbances, such as translations, rotations, and impulses, to cause fluid motion. Following the disturbance, the satellite would return to near zero-g and the response of the liquid and satellite would be monitored.

3.2.2 Class II Experiments - A discussion of the Class II experiment requirements as they apply to each of the individual ERD experiments is presented in the following paragraphs:

Tank Thermal Performance (Experiment Series 2.1, 2.2 and 2.3). - Thermal performance is measured during the operation of the remaining tests.

Tank Pressurization (Experiment Series 2.4) - Efficient tank pressurization of on-orbit cryogenic tankage is dependent on the capability of the pressurant gas injection to supply gas to the ullage to maintain pressure while maximizing stratification and minimizing heat addition to the bulk fluid. Control of tank pressure in low-g will be evaluated using the GH2 pressurization system for each of the cryogenic tanks which comprise the experiment subsystem configuration. GHe will be used to pressurize the receiver tanks only. Tests will be performed to evaluate the pressurization process for the purpose of pressurizing tankage for liquid outflow and transfer. The performance of hydrogen and helium pressurization will be assessed.

The supply tank will be pressurized to 68.9 kPa (10 psid) overpressure for pressurized transfers (25%) and 13.8 kPa (2 psid) for pumped transfers (75%). In turn, the receiver tanks will be pressurized to a 68.9 kPa (10 psid) overpressure condition for back-transfers to the supply tank. Of these back-transfers, 50% will each be performed with GH2 and GHe pressurant. GHe pressurant will not be used in the supply tank in order to avoid contamination with the condensible. Most of the GHe receiver tank back-transfers will be conducted towards the end of the mission for similar reasons. The parameters being varied in the pressurization experiment are listed in Table 3.2-9.

Table 3.2-9 Tank Pressurization Experiment Principal Requirements

• OBJECTIVE - EVALUATE THE PRESSURIZATION PROCESS WHEREBY PRESSURANT IS INTRODUCED INTO CRYOGENIC TANKAGE TO PROVIDE THE FORCE (AND SUBCOOLING EFFECT) FOR TANK OUTFLOW
• PARAMETERS BEING VARIED
- USE OF EITHER GH2 OR GHE
- AMOUNT OF OVER PRESSURE CONDITION FROM TANK LH2 SATURATED CONDITION
- TANK PRESSURE BLOWDOWN VERSUS MAINTAINING TANK PRESSURE DURING TANK OUTFLOW
• KEY MEASUREMENTS REQUIRED
- TANK PRESSURE CHANGE WITH TIME
- FLOWRATE OF REGULATED PRESSURANT
- TEMPERATURE OF THE ENTERING PRESSURANT
- TEMPERATURE OF THE TANK ULLAGE
- POSITION OF THE TANK ULLAGE
- RATE OF CHANGE OF TANK LIQUID VOLUME
- TRANSFER LINE FLOW RATE

The GH2 and GHe pressurization subsystem is conservatively sized so that there will be adequate gaseous pressurant available on-orbit to provide pressurant for the entire COLD-SAT mission. Many of the key measurements required will be used for on-orbit system monitoring, control, and pressurant quantity use calculations. The others will be used for correlating with analytical models for purposes of predicting pressurant performance and use.

The tank pressurization experiment is comprised of the following individual tests:

2.4 Tank Pressurization with Gaseous Hydrogen and Gaseous Helium

Test #1: Pressurize Supply Tank with GH2
Test #2: Pressurize Receiver Tank 1 with GH2
Test #3: Pressurize Receiver Tank 2 with GH2

Test #4: Pressurize Receiver Tank 1 with GHe
Test #5: Pressurize Receiver Tank 2 with GHe

Liquid Settling Direct Liquid Outflow (Experiment Series 2.5a) - Table 3.2-10 shows the top level requirements for this experiment. Receiver tank 2 (which does not have a LAD) expulsion using low-g acceleration to settle and orient the liquid while it is drained will be assessed. Settling characteristics, quality of required vapor-free liquid expelled and liquid residuals resulting when vapor carryover predominates will form a part of the test objectives. Receiver tank 2 is configured with a simple plate baffle at the outlet to prevent suction dip and intrusion of vapor into the outflow stream until the tank is depleted. Tank residuals may be on the order of 5%.

Table 3.2-10 Liquid Settling Direct Liquid Outflow Experiment Principal Requirements

• OBJECTIVE - INVESTIGATE TANK EXPULSION USING A LOW-G ACCELERATION TO SETTLE AND ORIENT THE LIQUID AS IT IS DRAINED
• PARAMETERS BEING VARIED
- MAGNITUDE OF INITIAL SETTLING ACCELERATION - MAGNITUDE OF ACCELERATION MAINTAINED DURING OUTFLOW - OUTFLOW RATE BEING MAINTAINED DURING EXPULSION
• KEY MEASUREMENTS REQUIRED
- ACCELERATION ENVIRONMENT - LIQUID/VAPOR INTERFACE POSITION - TRANSFER LINE FLOWRATE

The parameters being varied include the settling acceleration, acceleration being maintained during outflow, and the outflow rate during which vapor-free liquid is obtained during the expulsion. It is intended to make liquid/vapor position measurements so that the liquid/vapor interface may be determined and characterized with respect to the quality of the expelled liquid. In addition, expulsion flow rates will be noted at which times vapor is identified in the outflowing liquid.

The liquid settling direct liquid outflow experiment is comprised of the following individual tests:

2.5a Low-G Direct Liquid Outflow with Liquid Settling

Test #1: Receiver Tank 2 Outflow with Settling Via Baffled Outlet Using High Acceleration (1.4E-04) Initial Settling Maintained During Outflow
Test #2: Receiver Tank 2 Outflow with Settling Via Baffled Outlet High Acceleration (1.4E-04) Initial Settling Reduced to Medium Acceleration (4.7E-05) During Outflow
Test #3: Receiver Tank 2 Outflow with Settling Via Baffled Outlet Intermediate Acceleration (4.7E-05) Initial Settling Maintained During Outflow

Liquid Settling Vented Fill (Experiment Series 2.5b) - Table 3.2.11 provides the top level requirements for tank vented fill experiments under settled conditions. Filling of a cold-empty or refill of a partially-full cryogenic tank in low-g poses many challenges. Techniques which use liquid settling combined with vapor venting will be assessed. The fill is accomplished under a settling acceleration to accumulate liquid at the inlet end and vapor at the vent end. This separation attempts to preferentially orient vapor so that it can be vented to control the tank pressure during the filling process while minimizing liquid carryover exiting through the vent.

Table 3.2-11 Liquid Settling Vented Fill Experiment Principal Requirements

• OBJECTIVE - INVESTIGATE THE VENTED FILL PROCESS WHICH USES LIQUID SETTLING FOR FILLING AN EMPTY TANK AS WELL AS FOR TANK TOP-OFF
• PARAMETERS BEING VARIED
- MAGNITUDE OF SETTLING ACCELERATION - RATE AT WHICH VAPOR IS VENTED - RATE AT WHICH LIQUID IS INTRODUCED INTO THE TANK
• KEY MEASUREMENTS REQUIRED
- ACCELERATION ENVIRONMENT - LIQUID/VAPOR INTERFACE POSITION - TRANSFER LINE FLOWRATE - TANK VENT LINE TEMPERATURE - TANK VENT LINE LIQUID SENSOR - VENT LINE FLOW RATE

A couple of different options have been identified with which to perform the vented fill process. The first would be to vent during the fill with the intent of venting vapor only. Since flight weight tanks are designed for low pressure operation, it would be important to balance the inflow rate and the vent rate in order to optimize the process and control the thermodynamics involved in vapor generation as the process is being accomplished. A problem inherent with this method is the likelihood of venting liquid at the same time due to the fill dynamics when liquid is flowing into the tank. The second approach considers intermittent fill and venting steps accompanied by settling maneuvers to insure vapor venting only. This could be accomplished by venting when the tank pressure level reaches a critical value.

The parameters being varied in the experiment and the key measurements required are also listed in Table 3.2-11. Using the various techniques described and the tank and fluid conditions specified, the ability to fill the receiver tanks to acceptable levels without loosing excessive liquid overboard through the open vent will be addressed in this series of tests.

The liquid settling vented fill experiment is comprised of the following individual tests:

<u>2.5b Low-G Vented Fill with Liquid Settling</u>

Test #1: Receiver Tank 1 Vented Fill Using High Settling Acceleration (1.4E-04)
Test #2: Receiver Tank 1 Vented Fill Using Medium Settling Acceleration (4.7E-05)
Test #3: Receiver Tank 2 Vented Fill Using High Settling Acceleration (1.4E-04)
Test #4: Receiver Tank 2 Vented Fill Using Medium Settling Acceleration (4.7E-05)
Test #5: Receiver Tank 2 Vented Fill Using CHX Subcooling
Test #6: Receiver Tank 1 50% Full Topoff Using High Settling Acceleration (1.4E-04)

<u>Liquid Settling Vapor Venting (Experiment Series 2.5c)</u> - Table 3.2-12 shows the top level requirements for the tank vapor venting experiment under settled liquid conditions. Controlling cryogenic tank pressure on-orbit using vapor venting is a process that will be assessed by this series of tests. Settling accelerations are required to attempt to orient the liquid to the outlet end while collecting the vapor at the vent end. Opening the tank vent will allow some of the contents to be vented with a

goal to minimize the amount of liquid lost overboard. The process of reducing the tank pressure is complicated by the thermodynamics of the tank fluid at or close to the saturated condition of the liquid.

Table 3.2-12 Liquid Settling Vapor Venting Experiment Principal Requirements

• OBJECTIVE - INVESTIGATE THE CAPABILITY TO REDUCE TANK PRESSURE BY VENTING VAPOR USING LIQUID SETTLING
• PARAMETERS BEING VARIED
- THERMODYNAMIC CONDITION OF THE ULLAGE - VENTING GH2 OR GHe - TANK GEOMETRY - RATE OF ULLAGE VENTING
• KEY MEASUREMENTS REQUIRED
- ACCELERATION ENVIRONMENT - TANK PRESSURE - ULLAGE TEMPERATURE - LIQUID/VAPOR INTERFACE POSITION - TANK VENT LINE TEMPERATURE - TANK VENT LINE LIQUID SENSOR - VENT LINE FLOW RATE

A possible implication is the reduced pressure when venting that could possibly cause bulk boiling in the tank with the possibility of subsequent loss of liquid out the vent. The reduced pressure which promotes boiling of the liquid will cause turbulence at the liquid/vapor interface and generation of additional vapor to be vented. These are all undesirable conditions for optimal vapor venting process performance, and an attempt will be made to understand and reduce their effects on the process.

The thermodynamic conditions of the tank bulk fluid and ullage (pressure and temperatures) will be measured to characterize the venting process in terms of the quality of vented fluid for the conditions being varied. Vent line flow rates and fluid quality sensors will be used to make measurements for controlling the vent flow during the experiments. The parameters being varied and the key measurements for monitoring and process characterization are listed in Table 3.2-12.

The liquid settling venting experiment is comprised of the following individual tests:

<u>2.5c Low-G Venting with Liquid Settling</u>

Test #1: Receiver Tank 1 Superheated GH2 Ullage Venting
Test #2: Receiver Tank 2 Superheated GH2 Ullage Venting
Test #3: Supply Tank Superheated GH2 Ullage Venting

<u>LAD Performance (Experiment Series 2.6)</u> - Table 3.2-13 provides the top level requirements for the LAD performance experiments. The supply tank and receiver tank 1 both contain total communication liquid acquisition devices which will be used to provide for vapor-free outflow from the tanks to support various experiment set objectives. This series of tests will characterize the performance of these devices over a wide range of nominal and off-nominal operational conditions in order to verify vapor-free operation, as well as acceptable expulsion efficiency where screen breakdown occurs (less than 1% of the tank volume preferably).

Table 3.2-13 LAD Performance Experiment Principal Requirements

- OBJECTIVE - INVESTIGATE THE CAPABILITY OF SUPPLY AND RECEIVER TANK 1 LAD'S TO PROVIDE VAPOR FREE LIQUID UNDER VARIED OPERATING CONDITIONS INCLUDING DETERMINING EXPULSION EFFICIENCIES
- PARAMETERS BEING VARIED
  - LAD DESIGN (TWO DEVICES WILL BE TESTED)
  - ACCELERATION ENVIRONMENT
  - LIQUID POSITION (BEST VS WORST CASE)
  - LAD OUTFLOW RATES
- KEY MEASUREMENTS REQUIRED-OUTFLOW
  - ACCELERATION ENVIRONMENT
  - LIQUID/VAPOR INTERFACE POSITION
  - TRANSFER LINE FLOW RATES
  - TRANSFER LINE FLOW METER QUALITY INDICATION
- KEY MEASUREMENTS REQUIRED- EXPULSION EFFICIENCY
  - TRANSFER LINE FLOW METER QUALITY INDICATION
  - TVS FLOW RATE
  - TANK FLUID TEMPERATURE
  - TANK PRESSURE

The parameters being varied include examination of two different LAD designs, one in the COLD-SAT supply tank and the other in receiver tank 1 (receiver tank 2 does not have a LAD, only a baffle device). The acceleration level and direction will be varied to impose best and worst case liquid orientations on the device channels while providing for vapor-free liquid acquisition and high expulsion efficiencies. Measurements to characterize the process and to provide for a higher level of understanding include acceleration, fluid pressure and temperature states, LAD temperatures, and transfer line fluid flow and quality measurements. These measurements will allow for determining conditions at which vapor-free liquid can be expelled for given LAD design configurations.

The LAD performance experiment is comprised of the following individual tests:

<u>2.6 Liquid Acquisition Device Performance in Low-G</u>

Test #1: Supply Tank LAD Outflow Under Nominal Low-g Conditions
Test #2: Supply Tank LAD Outflow With Liquid Settling to the Vent End (-4.7E-05)
Test #3: Supply Tank LAD Outflow With Liquid Settling to the Outlet End (4.7E-05)
Test #4: Receiver Tank 1 LAD Outflow Under Nominal Low-g Conditions
Test #5: Receiver Tank 1 LAD Outflow With Liquid Settling to the Vent End (-4.7E-05)
Test #6: Receiver Tank 1 LAD Outflow With Liquid Settling to the Outlet End (4.7E-05)
Test #7: Receiver Tank 1 LAD Expulsion
Test #8: Supply Tank LAD Expulsion Efficiency
Test #9: Receiver Tank 1 LAD Expulsion Under Settled Acceleration (1.4E-04)

<u>Transfer Line Childown (Experiment Series 2.7)</u> - Table 3.2-14 provides the top level requirements for the transfer line chilldown experiments. Transfer line chilldown is a precursor to the filling/refilling of tankage on-orbit. Proper line chilldown is essential to the efficient filling of tankage to high fill levels because thermally subcooled liquid is desired with which to fill a tank. The process of removing energy from the line involves optimizing the heat transfer between the chilldown fluid (both liquid and vapor) and the line wall and other associated internal/external plumbing, hardware, components and structure so that the efficiency of the chilldown fluid is utilized to the maximum.

Table 3.2-14 Transfer Line Chilldown Experiment Principal Requirements

• OBJECTIVE - INVESTIGATE THE TRANSFER LINE CHILLDOWN PROCESS ASSOCIATED WITH REMOVING HEAT FROM THE TRANSFER LINE SYSTEM BY HEAT TRANSFER BETWEEN THE CHILLDOWN FLUID (BOTH LIQUID AND VAPOR) AND THE TRANSFER LINE BULK MASS. THE PROCESS WILL BE CHARACTERIZED FOR FLUID UTILIZATION/EFFICIENCY.
• PARAMETERS BEING VARIED - INITIAL STARTING TEMPERATURE OF THE TRANSFER LINE SYSTEM - CHILLDOWN FLUID THERMODYNAMIC CONDITIONS
• KEY MEASUREMENTS REQUIRED - TRANSFER LINE TEMPERATURE PROFILE - PRESSURE AND FLUID TEMPERATURE OF TANK PROVIDING THE CHILLDOWN FLUID - TRANSFER LINE PRESSURES

Transfer line chilldown will be investigated and demonstrated during this experiment. Optimization of the process (limiting the fluid used while maximizing the heat transfer) is an issue which will be addressed. But, also important as a Class II objective, is to provide the initial conditions for the filling experiments. Chilldown from initially warm conditions to various degrees of initially cold conditions will be accomplished.

The thermodynamic conditions of the chilldown fluid introduced into the lines will be varied as conditions permit and the initial thermal states of the transfer line hardware including valves, lines, etc. will be measured to the extent possible with the instrumentation employed. Temperature profiles in the transfer line systems will be measured as will the pressure responses. The parameters being varied and the key measurements are also listed in Table 3.2-14.

The transfer line chilldown experiment is comprised of the following individual tests:

2.7 Transfer Line Chilldown in Low - G

Test #1: Transfer Line Chilldown
Test #2: Combined Transfer Line and Tank Chilldown

Control of Liquid Thermodynamic State (Experiment Series 2.8) - Table 3.2-15 shows the top level requirements for the control of liquid thermodynamic state experiments. This series of experiments addresses the control of liquid subcooling during outflow using techniques other than tank pressurization. The outlet of the supply tank is provided with a configuration that allows the fluid to pass through a compact heat exchanger (CHX) which provides 1.4 K (2.5 R) of liquid subcooling for a maximum recirculation flow of 50 kg/hr (110 lb/hr). A high boiloff rate [up to 1.45 kg/hr (3.2 lb/hr)] is utilized to perform this function, however tank pressurization (and associated energy input to the tank) is not required.

Some of the data taken from this experiment will be used to characterize the compact heat exchanger (CHX) performance since numerous warm and cold side heat exchanger temperature and pressure measurements will be taken and compared to the thermal performance achieved in the tank in terms of the fluid thermodynamic conditions. The use of the CHX is the quickest method for removing heat from the tank other than possibly venting down the pressure which imposes demanding propulsive requirements for liquid settling. The results of using the CHX for thermal subcooling of the liquid before liquid transfer will be compared to those obtained for thermodynamically-subcooled liquid (pressurization).

Table 3.2-15 Control of Liquid Thermodynamic State Experiment Principal Requirements

• OBJECTIVE - USING A SUPPLY TANK OUTLET SUBCOOLER (COMPACT HEAT EXCHANGER), CHARACTERIZE THE CAPABILITY TO PROVIDE SINGLE PHASE FLUID DURING LIQUID TRANSFER TESTS. COMPARE RESULTS WITH SUBCOOLING PROVIDED BY TANK PRESSURIZATION.
• PARAMETERS BEING VARIED
- SUBCOOLER COLD SIDE FLUID FLOW RATE - SUBCOOLER WARM SIDE FLUID FLOW RATE
• KEY MEASUREMENTS REQUIRED
- SUBCOOLER WARM SIDE TEMPERATURES AND PRESSURES - SUBCOOLER WARM SIDE DELTA-PRESSURE - SUBCOOLER COLD SIDE TEMPERATURES AND PRESSURES - SUBCOOLER WARM SIDE FLUID FLOW RATE - SUBCOOLER COLD SIDE FLOW RATE - SUPPLY TANK OUTFLOW FLUID TEMPERATURE

The control of liquid thermodynamic state experiment is comprised of the following individual tests:

<u>2.8 Control of Liquid Thermodynamic State During Outflow</u>

Test #1: Supply Tank Subcooled Outflow Compact Heat Exchanger (CHX) Low Flow
Test #2: Supply Tank Subcooled Outflow Compact Heat Exchanger (CHX) High Flow

<u>Liquid Dumping (Experiment Series 2.9)</u> - In certain situations the contents of a cryogenic tank must be rapidly dumped overboard in order to safe the system. A final dumping of the remaining contents of receiver tank 2 at the end of the mission will be accomplished to determine the effectiveness of the dumping technique. Approximately 50% of the tank volume in liquid will be allocated for the dumping experiment in receiver tank 2. This tank does not contain a LAD and no settling accelerations will be provided to aid the process, thus a worst case condition will be examined using tank pressurization for the expulsion driver. Table 3.2-16 provides the top level requirements for the liquid dumping experiment.

Liquid and vapor will be outflowed, with no regard to the quality of the expelled fluid. When the outflow rate and tank pressure have dropped to near zero, expulsion will be considered to be complete. Subsequent tank lock-up and monitoring of pressure and temperature and the TVS flowrate for venting will determine the amount of fluid remaining in the tank following the dump process.

Table 3.2-16 Liquid Dumping Experiment Principal Requirements

• OBJECTIVE - INVESTIGATE THE PROCESS OF RAPID TANK DUMPING
• PARAMETERS BEING VARIED
- NONE (ONE TEST)
• KEY MEASUREMENTS REQUIRED
- TANK TEMPERATURE AND PRESSURE PROFILE - PRESSURANT QUANTITY USED - TIME TO ACCOMPLISH THE DUMP - RESIDUALS LEFT IN THE TANK

<u>Advanced Instrumentation for Cryo in Low-G (Experiment Series 2.10)</u> - Advanced instrumentation for cryogenic usage has not been sufficiently developed as of this report. Sufficient capacity is reserved to incorporate sensors as they are developed.

3.3 Experiment Definition - The following paragraphs contain descriptions and a definition of the COLD-SAT experiments and the processes associated with each experiment by ERD.

Tank Pressure Control (ERD 1.1 and 1.2) - The experiment processes to be studied in ERD 1.1 and 1.2 include thermal stratification and pressure rise, mixing, passive pressure control, and active pressure control. A definition and description of the experimental configuration (hardware) related to the processes being examined is presented as well, with schematic representations.

Stratification and Pressure Rise - The pressure in a cryogenic tank will rise if thermal energy is added to the tank. The rate of pressurization is influenced by the rate of heat addition, the fill level of the tank, and the degree of thermal stratification in the tank. Thermal stratification is important because a warm liquid layer adjacent to the ullage will impose its vapor pressure on the ullage, thereby raising the tank pressure above the value it would have if the tank contents were mixed. In the presence of an acceleration field, warm liquid will move to the surface while colder liquid will move to the bottom of the tank, resulting in thermal stratification along the acceleration axis. Acceleration level is a significant factor in the development of the thermal stratification because the buoyant movement of liquid is dependent on acceleration. In the absence of an acceleration field, however, thermal stratification can still develop due to thermal transients, non-uniform heating, or fluid transfer operations such as filling or venting.

The expansion of the warming liquid (same mass, lower density) also affects stratification by performing work on the ullage, resulting in a pressure rise. Work on the ullage raises the ullage temperature due to compression which in turn increases the heat transfer rate at the liquid/vapor interface, thereby raising the temperature of the liquid near the surface. Localized heating of the ullage has the same effect on heat and mass transfer at the interface and on the pressure rise characteristics in response to this phenomenon.

Acceleration level can influence direct ullage heating and the thermodynamics at the liquid/vapor interface by affecting the shape of the liquid/vapor interface. In a low-g environment, the meniscus of a wetting liquid may completely surround the ullage, thereby preventing direct heating of the ullage from the tank wall and heating only the liquid. The magnitude of the wall heating rate influences heating of the liquid and the pressure rise in the tank. Low-g values will cause small buoyancy effects in the liquid that will be gravity and tank geometry dependent. In this case, heat transfer in the liquid could occur by liquid conduction if no gravity environment exists for buoyant thermal stratification. Buoyancy will be diminished in the extreme low-g case. The formation of the warm liquid layer adjacent to and possibly surrounding the ullage as a consequence of these low-g effects are some of the physical processes to be studied in the stratification and pressure rise experiments.

Mixing - Mixing reduces the pressure in the tank by destratifying the fluid contents to a saturated two-phase condition. Mixing is accomplished by pumping liquid from the tank and injecting the liquid back into the tank with a jet nozzle. The effect of injecting the liquid into the tank is to impart motion to the bulk liquid which disperses the warm liquid layer. The liquid adjacent to the ullage is cooled as the liquid is mixed, causing condensation from the warmer ullage to the L/V interface and to the liquid. This process results in tank pressure decay. The process is complete when the tank contents reach a homogeneous saturated state. The tank pressure reaches a minimum value when the two-phase conditions are achieved. Further mixing does not cause any further reduction in pressure and may raise the tank pressure because energy, in the form of work, is added to the tank during mixing. The physical processes to be studied include the elimination of thermal stratification in the tank mixing experiments.

Passive Pressure Control - The pressure in a cryogenic tank will rise if thermal energy is added to the tank and the tank is not vented. It is desirable to vent gas from a tank to minimize the mass of vented fluid. In an environment with a relatively large acceleration field, such as on the Earth's surface or on a thrusting rocket, the position of the ullage is known and gas can be easily vented. In a low-g environment, however, the position of the ullage may not be known and it may be impossible to vent gas directly from the tank. This difficulty can be overcome with a Thermodynamic Vent System (TVS). A TVS takes advantage of the fact that it is possible to position or locate liquid in a low-g environment by using a LAD so that liquid can usually be withdrawn from the tank when it may be difficult to withdraw gas. A TVS functions by using liquid withdrawn from the tank LAD and passing the liquid through a Joule-Thomson (J-T) expander. The J-T expander causes flashing of the liquid, which reduces the liquid's pressure and temperature. The two-phase fluid downstream of the J-T expander is routed through a heat exchanger in contact with the bulk liquid. Since the bulk liquid is warmer than the two-phase fluid in the TVS HX, heat is transferred from the bulk liquid to the two-phase fluid. Heat transfer causes boiling in the two-phase HX side, and boiling continues until all liquid has evaporated. The gas may then be vented overboard. The J-T expander, heat exchanger, and control components comprise the TVS. It should be noted that a LAD is not required to operate a TVS. Without a LAD, liquid or vapor could enter the TVS. Since the intent of a TVS is to vent vapor from the tank, the ingestion of vapor would not degrade TVS operation. Operating a TVS without a LAD would, however, require some form of J-T expander control to accommodate the different flow conditions. A LAD assures relatively constant inlet conditions to the TVS and permits a simpler J-T expander design.

TVS venting is similar to direct venting of the ullage, with the exception that the pressure of the vented TVS HX gas is lower. The TVS gas can be used to reduce heat leak to the bulk liquid if it is routed prior to venting through a heat exchanger surrounding the pressure vessel. The vented gas is sensibly heated in the Vapor-Cooled Shield (VCS), and the thermal energy is transported out of the system by the vent flowstream. A properly positioned and designed VCS can reduce the heat leak to an LH_2 tank by 50% if conduction or convection are the dominant modes of heat transfer to the tank. The heat leak can be reduced further if radiation heat transfer dominates. Passive pressure control refers to the use of a wall or LAD-mounted TVS to control tank pressure. The thermal performance of a passive TVS is controlled by free convection heat transfer in the bulk fluid and two-phase heat transfer in the TVS, neither of which is well understood in a low-g environment. The thermal performance of a passive TVS and VCS is the physical process to be studied in the passive pressure control experiments.

<u>Active Pressure Control</u> - Active pressure control is similar to passive pressure control except that the heat exchanger is not attached to the tank wall or LAD. The heat exchanger is a separate component through which the bulk liquid and two phase fluid flow. In the case of the COLD-SAT experiment, a Compact Heat Exchanger (CHX) will be used for active pressure control experimentation. There is forced convection heat transfer on both sides of the heat exchanger, and it should be capable of transferring more heat per unit area than the wall mounted heat exchangers. A pump must be included in the bulk liquid flow leg to force the liquid through the CHX. The thermal performance of the CHX is the physical process to be studied in the active pressure control experiments.

<u>Experimental Configuration</u> - A schematic of the supply tank is shown in Figure 3.3-1, which illustrates the principal components used in the stratification, mixing, and pressure control experiments. Not included in the schematic are flow control valves, unused flow legs, the LAD, radial jets, or instrumentation. The supply tank has an LAD which delivers liquid to the tank outlet. Flow legs branch off the outlet line to a J-T expander or a pump. Flow through the J-T expander branches to either the TVS heat exchanger attached to the LAD or the CHX. The TVS flow passes through the VCS and is vented after it exits the VCS heat exchanger. The CHX flow is vented after leaving the heat exchanger. Flow through the pump passes through the CHX and is injected into the tank through

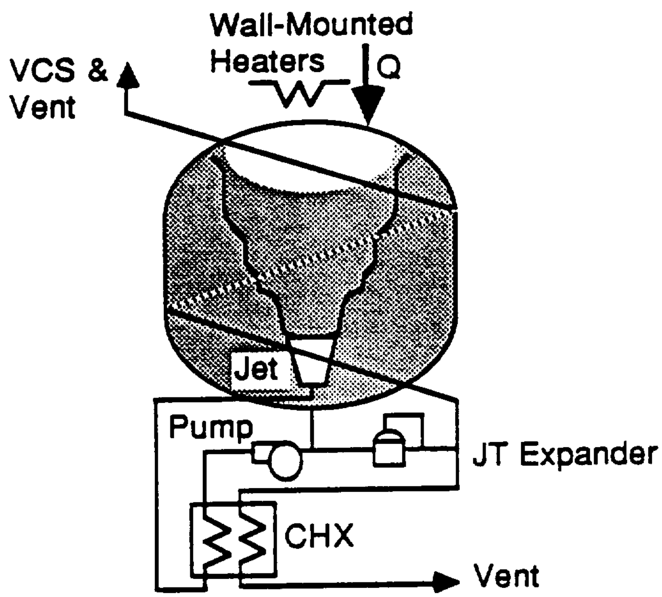


Figure 3.3-1 Pressure Control Principal Components (Supply Tank)

an axial jet or several radial jets. Thermal energy is supplied to the tank by wall heaters externally mounted to the pressure vessel.

Thermal stratification will be induced by turning off the TVS and CHX, controlling the acceleration to some predetermined value and direction, and activating tank wall heaters. The only components involved in establishing the thermal stratification are the wall heaters. Figure 3.3-2 illustrates the acceleration direction and magnitude for the stratification tests. The liquid orientation with background acceleration is shown as arbitrary because the direction of the very small acceleration will vary and may rotate around the tank several times during a test.

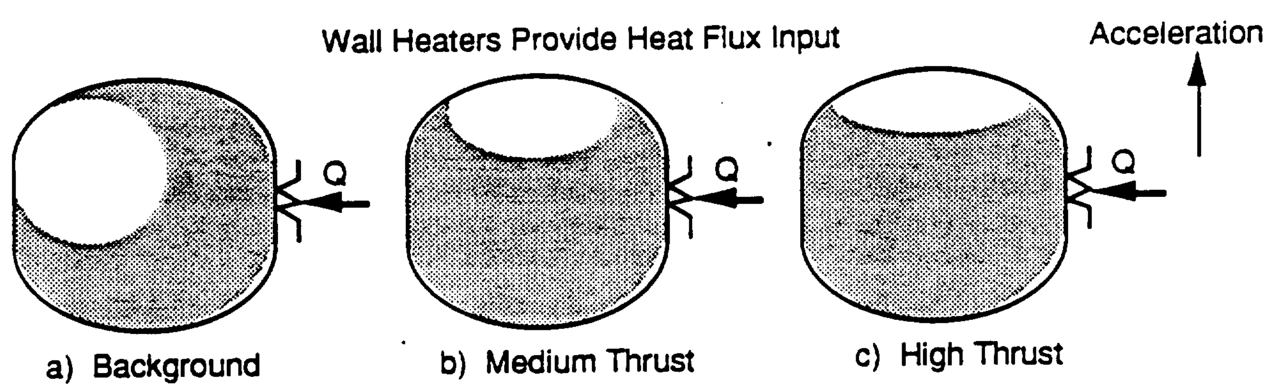


Figure 3.3-2 Accelerations for Stratification Testing

The mixing tests are performed after the liquid in the tank has been thermally stratified. The liquid in the tank is mixed by withdrawing liquid from the tank, pumping it through the inactive CHX, and injecting the liquid into the tank with the axial or radial jets. The CHX is inactive when there is no flow through the two-phase side and there is no cooling of the liquid. Flowrate through the system is controlled by the variable speed pump. Routing of the flow through axial or radial jets is controlled by latching valves. Heat flux is controlled to the tank during these tests with the tank wall heaters. Figure 3.3-3 illustrates the flow path for the axial mixing tests.

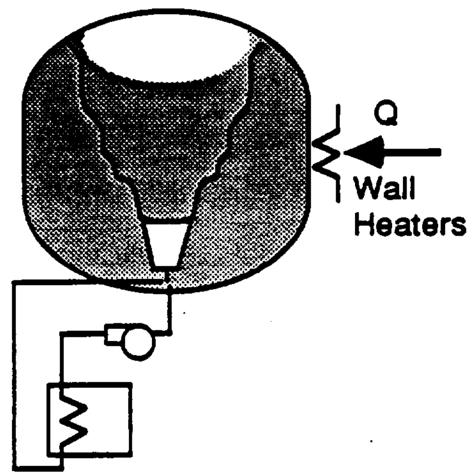
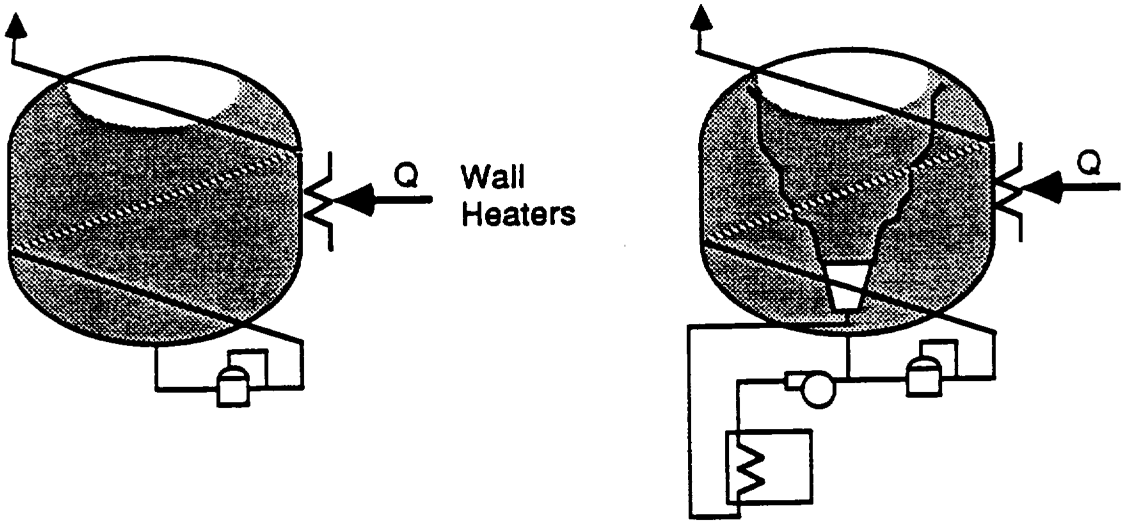


Figure 3.3-3 Axial Mixing Flow Path Used for Mixing Tests

The passive pressure control experiments use the LAD mounted heat exchanger to remove heat from the tank. Liquid is withdrawn from the LAD, throttled through the J-T expander, routed through the heat exchanger and VCS, and vented overboard. TVS flow is controlled by several flow control orifices which are selected by latching valves. Valve operation is controlled by tank pressure. These tests are usually performed without the mixer, but some tests do use the mixer. Figure 3.3-4 shows the flow paths for the passive pressure control experiments with and without the mixer, including the tank heating with the tank wall heaters. The pressure control experiments in the receiver tanks are similar to the experiments in the supply tank without the mixer and without inducing stratification.

The active pressure control experiments use the CHX and the pump to withdraw liquid from the tank, cool the liquid in the CHX, and inject the liquid into the tank with the axial jet. Figure 3.3-5 shows the flow path for the active pressure control experiments with and without the mixer, including the tank heating with the tank wall heaters. CHX flow is controlled by several flow control orifices which are selected by latching valves. Liquid side flow control is accomplished by varying the speed of the pump.

Tank Chilldown (ERD 1.3) - The ultimate purpose of the tank chilldown experiment is to investigate the tank chilldown process associated with removing heat from the tank system by heat transfer from the tank wall to the chilldown fluid. The process will be characterized by performing a multitude of tests designed to evaluate various methods of chilldown with different spray systems and a tank wall heat exchanger in order to assess time utilization and fluid efficiency. These processes will be evaluated as functions of spray system selection, spray system sequencing, flow rates, acceleration, subcooling, tank mass-to-volume (M/V) ratio, tank area-to-volume (A/V) ratio, and venting methodologies. Optimal methods for efficiently and quickly chilling down a warm cryogenic tank will be identified. The results of the tests will be correlated with analytical models and existing data.



a) Without Mixer b) With Mixer

Figure 3.3-4 Passive Pressure Control Flow Paths for the TVS HX and Mixer

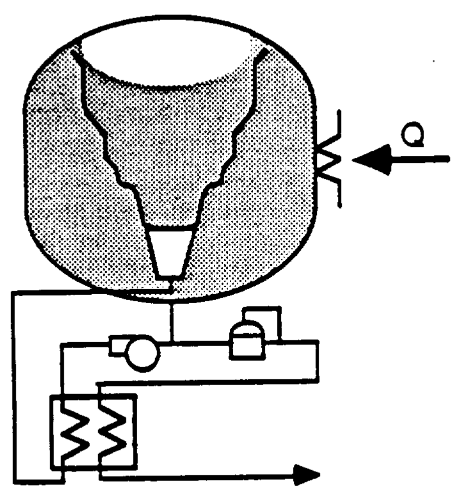


Figure 3.3-5 Active Pressure Control Flow Paths

Tank chilldown is a precursor to the filling of an initially warm depleted subcritical cryogenic system in the space environment (on-orbit). Proper tank chilldown is essential to the efficient filling of tankage to high fill levels (generally 90-95%). The process of removing energy from the system involves optimizing the heat transfer between the chilldown fluid (both liquid and vapor) and the tank wall and other associated internal/external plumbing, hardware and structure. The processes pertinent to tank chilldown will be investigated and demonstrated in the two COLD-SAT receiver tanks. Optimization of the process (limiting the fluid used and time for chilldown while maximizing the heat transfer) is an important issue which will be addressed and evaluated. The amount of chilldown LH2 as well as the time required to achieve the desired predetermined "target" temperature will be determined for various chilldown scenarios involving the use of the spray systems and tank wall heat exchangers.

The "target" temperature is a threshold condition (may be a range of temperatures for different fills) which allows for proper tank filling to proceed without overcooling the tank during chilldown. If the tank temperature is chilled down to a temperature which is too warm, an unoptimized fill may result, with the chance that the maximum tank pressure may be attained before the tank is fully cooled and filled to the final fill level. For this condition, pressure control may be difficult and result in intermediate venting steps with unwanted fluid loss. Chilldown to a temperature which is lower than necessary results in an excessive and inefficient use of LH2 for cooling, but may enhance the subsequent filling process.

The experiment processes to be studied in ERD 1.3 include spray system chilldown and tank chilldown via the tank wall-mounted heat exchanger. A definition and description of the experimental configuration (hardware) related to the processes being examined is presented as well, along with schematic hardware representations of the systems being used.

Spray System Chilldown - The spray chilldown process involves the introduction of chilldown fluid into the tank via one or more of the spray nozzle systems. The spray systems function to initiate fluid injection and motion for the purpose of putting the cold fluid in contact with the warm tank wall and the associated tank internal hardware, and for inducing thermodynamic mixing between liquid and vapor. Liquid spray droplet patterns are introduced at saturated fluid enthalpies with kinetic energy which is ultimately converted to a higher internal energy state during the process of heat transfer from the tank wall to the fluid. The available spray nozzle systems impart a variety of fluid motions in different regions of the tank that persist for finite periods of time. The internal hardware may interfere with fluid motions, patterns, and the time that fluid motion persists.

With the goal in mind to reduce the fluid consumption and time for the chilldown process to occur, a unique "charge-hold-vent" procedure has been adopted for this purpose. Each of a number of charge-hold-vent cycles is characterized so that only an appropriate amount of charge mass is admitted to a receiver tank, allowing maximum utilization of its available cooling (within time constraints) before venting overboard. The entire chilldown process is assumed to start from an initial tank temperature and finish when the tank temperature reaches the target temperature. The vent stage pressure drop is another parameter that controls the process since the number of vent stages for a given cycle varies. A smaller vent stage pressure drop will better utilize isentropic cooling of the gas and require less chilldown fluid, but an increase in the number of vent stages and the chilldown time will be realized. Larger vent stage pressure drops will substantially reduce the chilldown process time and only slightly increase the fluid demand for an equivalent chilldown process. This latter approach will be adopted for COLD-SAT since the time limitation imposed with multiple vent stages poses more of an impact than the fluid usage.

Initially, a charge mass of liquid and/or liquid droplets will be admitted into one of the evacuated receiver tanks. The tanks will be evacuated by means of the back-pressure and free vent systems to drop the tank pressure down to a space vacuum. At this time, processes such as fluid dynamic splattering, liquid flashing, film boiling, vapor and liquid heating, etc. will occur simultaneously or independently. The initial flashing process to a saturated vapor occurs relatively rapidly as long as the saturation pressure of the fluid is higher than the tank pressure. If the charge mass is small, then considerable film boiling will contribute to the increase in tank pressure in addition to the flashing. This process involves transient convective heat transfer between the resulting saturated vapor fluid state (liquid vaporized) and the tank wall. For free convection, the process is relatively slow, however, if a persisting fluid motion is induced, forced convection between the vapor and the tank wall will result and chilldown will occur more rapidly. The chilldown time may be reduced many times that for free convection.

The performance of the spray chilldown process can be altered by injecting fluid at different rates and through different nozzle systems. The thrust of the spray system chilldown experiments will be to examine different methods to accomplish receiver tank chilldown of scaled model tanks that in turn may be scaled to larger and full-scale flight tanks. Optimal methods will be identified through careful characterization of the COLD-SAT receiver tank chilldown tests.

Tank Wall Heat Exchanger (HX) Chilldown - An alternate method to chilldown of cryogenic pressure vessels involves the routing of cold chilldown liquid through the tank's TVS tank wall heat exchanger. The process is performed by admitting higher pressure liquid into the tank wall heat exchanger downstream of and bypassing the J-T expansion valve and allowing this fluid to absorb heat from the tank wall. The chilldown fluid will continually flash as it flows through the heat exchanger while dropping to a lower pressure. The flashing of the chilldown fluid effectively restricts heat exchanger flow causing a self-regulating critical flow situation to exist. Flashing will continue all of the way down to the target temperature with the HX flow rate increasing as the tank wall temperature is reduced. Since the range of tank wall temperatures during chilldown are much higher than the saturation temperature of the chilldown fluid and because the flow will be restricted due to flashing, the fluid should fully vaporize and be efficiently utilized in this process. High heat transfer rates from the tank wall to the HX and the chilldown fluid are anticipated to effectively increase the forced heat transfer coefficient and the rate of tank wall cooling. When expelled from the heat exchanger, the fluid will warm to a superheated vapor condition at or near the tank temperature. Since the process is self-regulating, the time for chilldown is unknown until a test demonstrates the performance. The employment of this chilldown method may pose difficulty in chilling the internal hardware down to the target temperature.

Experiment Configuration - The two receiver tanks will be configured with various spray systems which will be used individually and in combination to optimize and assess the chilldown process from the standpoint of liquid mass consumption and operational time requirements. Numerous parameters will be controlled so that their effects on the process may be examined. A chilldown test will also be performed using the tank wall heat exchanger and introducing chilldown fluid directly into the tank through the inlet/outlet port. This test will be performed as a process demonstration so that comparisons can be made with the various spray techniques. Descriptions of the receiver tank test configurations are presented below. Figures 3.3-6 and 3.3-7 illustrate the experiment system schematics and their associated hardware for receiver tank 1 and receiver tank 2, respectively.

A description of the receiver tank spray systems and the alternate method of introducing chilldown fluid into a tank wall heat exchanger is discussed below. The series of individual tests in this experiment are designed to collectively characterize the chilldown processes for use of the spray systems and wall-mounted heat exchanger. Parameters that affect the chilldown process will be varied parametrically in an attempt to quantify their effects. Appropriate measurements will be made that allow the quantitative assessment of the processes to be performed.

Receiver Tank 1 - This tank originally had a tangential spray system which was deleted by customer technical direction since it was felt that the motion of the spray tangential to the tank wall would be interrupted by the LAD. In its place, a circumferential spray system with six nozzles has been provided to promote forced fluid contact with the tank wall. Since this tank is only chilled down from ambient temperature once, with subsequent chilldowns starting at an initially cold condition, creating persistent fluid motion with this system is not that great an experimental driver. A single axial nozzle has been designed into this tank to provide for internal mixing in the center of the tank. A radial spray system has not been incorporated into this tank because it would interfere with the objectives of the single axial spray which represents a radial nozzle in a full-scale tank. Flow control of the axial nozzle consists of low and nominal flow rate orifices in parallel with each (legs) other so that a total of three rates are possible. The third "high" flow rate is obtained by operating both legs in tandem. The

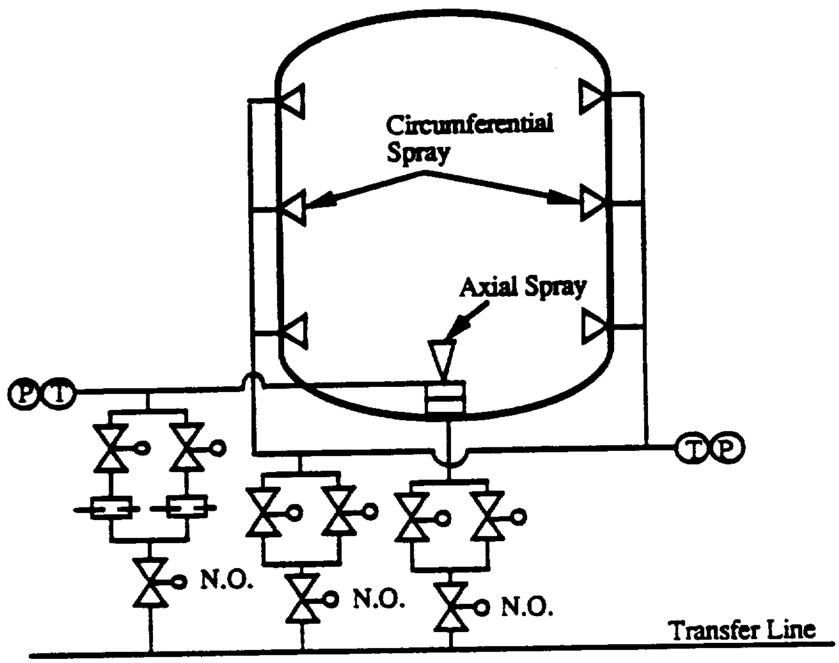


Figure 3.3-6 Hardware Schematic of Receiver Tank 1 for Chilldown

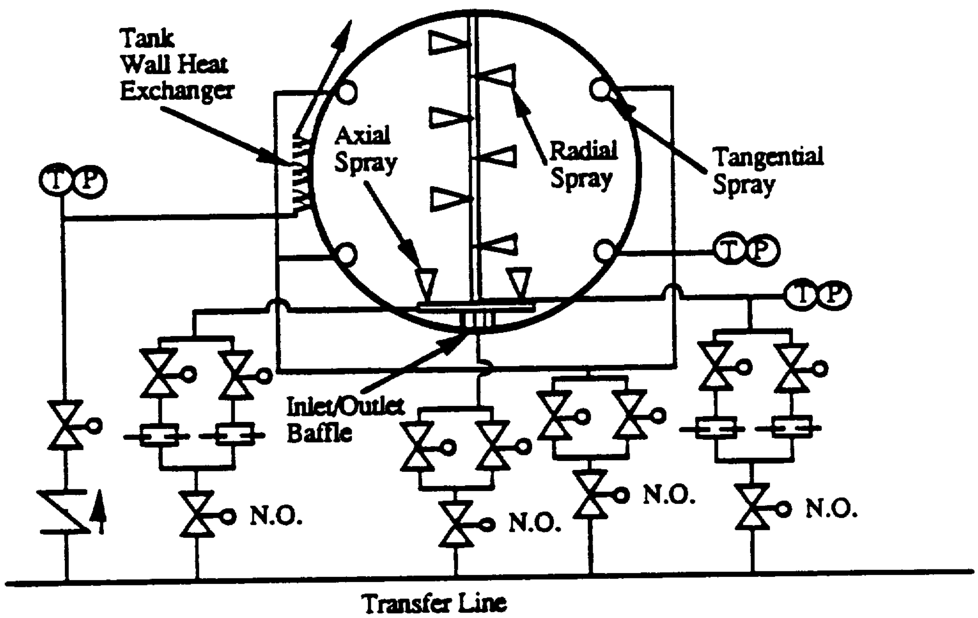


Figure 3.3-7 Schematic of Receiver Tank 2 for Chilldown

circumferential nozzle system provides a full maximum flow rate capability dictated by the supply tank pressure and transfer line characteristics. It is operated by opening either electrically-actuated valve for a full flow condition. Nozzles selected for this configuration are selected to dictate the small droplet size characteristics required of this system.

Unlike receiver tank 2, receiver tank 1 does not have a tank wall-mounted heater for thermal conditioning at the start of chilldown. The initial temperature conditions at the start of chilldown for receiver tank 1 will be the natural temperature the tank realizes from its environment at the time testing commences. The number of tests in receiver tank 1 is only four with the last three probably having only a single chilldown cycle to reach the target temperature. Chilldown testing will be concentrated in receiver tank 2. Currently, this tank has a metal mass-to-volume (M/V) ratio that is about 2:1. Final M/V needs of the receiver tanks have to be determined and incorporated into the design. The M/V of this tank needs to be increased (mass added).

Receiver Tank 2 - Most of the chilldown testing will be performed in receiver tank 2. Since this tank is a smaller scale version of a spherical OTV tank more commonly requiring chilldown, and since the M/V ratio is expected to be smaller than receiver tank 1 for a more rapid chilldown process, the focus for chilldown testing is concentrated here. More tests can be accomplished in this tank as opposed to the larger receiver tank.

Three different spray systems (tangential, radial, and axial) are provided so that various charge mass characteristics and fluid motions can be induced in the tank. There are four tangential nozzles in this tank that are controlled with a solenoid valve system for maximum flow capability. No flow control is provided with this spray system. Both low and nominal flow capabilities are provided for each the radial and axial spray systems to provide three different flow rates each. The radial spray system has six nozzles and the axial system has three for uniform spray distribution.

Chilldown with the tank wall heat exchanger will be examined in this tank. The wall-mounted TVS heat exchanger will serve as a chilldown direct contact chilldown device in a single test. Flow control will be inherently regulated by critical two-phase flow in the tank wall heat exchanger which is externally mounted. This approach will chilldown the tank in the least amount of time by permitting the maximum flowrate through the heat exchanger.

A tank warm-up heater is provided to return the tank to its predetermined initial temperature starting conditions. Multiple chilldowns with the same starting conditions will be accomplished using this heater from ambient down to colder conditions.

Also, the inlet/outlet baffle at the bottom of the tank will be used in the spray class of tests to introduce chilldown fluid into the tank for the same charge-hold-vent cycle procedures.

The mass-to-volume (M/V) ratio of this tank is currently 2:1. Work is needed to reduce the M/V of this tank and increase the M/V of receiver tank 1 so that it will be about one-half of the M/V of receiver tank 1 for chilldown performance comparison.

Other Tank Chilldown Considerations - No chilldown tests will be conducted on the supply tank since it will always contain some liquid.

Initially, the transferred chilldown fluid will be subcooled either by the compact heat exchanger (CHX) to reduce the saturation pressure 34.5 kN/m^2 (5 psia) or by supply tank pressurization. The final conditions of the chilled tank will be in the vicinity of the target temperature. Venting will be accomplished through the tank vent down to a final value of 13.8 kN/m^2 (2 psia) or less at the end of each cycle. The 345 kN/m^2 (50 psia) maximum pressure is the maximum allowable tank condition employed for vent staging during any cycle.

The supply tank pressure for chilldown fluid transfer will not be maintained during the chilldown process unless the pressure condition becomes substantially reduced. A single pressurant charge should suffice and provide adequate subcooling for chilldown fluid transfer. In addition, the transfer line will be chilled down prior to tank chilldown so that pure subcooled liquid may be admitted into the tank.

The initial temperature at the start of some chilldowns will be as warm as possible, hopefully near ambient conditions of 294 K (530 R). This should be easily controlled in receiver tank 2 with the tank heater. By starting the process with a warm tank, more data can be acquired for a larger number of chilldown cycles, and over a wider temperature range. This will aid in providing data for the variety of thermodynamic process phenomena that might occur over the chilldown temperature range. The wall temperature of receiver tank 1 will be at or near the ambient S/C condition for the first test. For subsequent tests in receiver tank 1, the start temperature will probably be lower than the ambient S/C temperature because there will probably not be enough time for the tank warm up.

The tank temperature at the end of the multiple cycle chilldown process should at least attain the value of the target temperature, if not extending below the ideal calculated values to insure a successful no-vent fill. Final chilldown temperatures should be in the range of 78 K (141 R) or less for the COLD-SAT experiment receiver tanks if a 90-95% fill is going to be realized.

At the start of each chilldown cycle, the tank will be at an evacuated pressure condition provided by the space vacuum through the free vent system. The free vent system will also be opened to space vacuum during vent staging and following each vent cycle. A fully evacuated condition will be established in the tank after the chilldown is complete to provide initial conditions for tank filling.

<u>No-Vent Fill and Refill of Tanks (ERD 1.4)</u> - The first set of objectives of this experimentation series is to investigate the process of filling tanks using a subcritical cryogen without venting and to gather data that will allow the accurate modeling and design of future no-vent fill systems. This data primarily consists of the following parameters:

1. Initial tank temperature (empty tank) and inlet flow conditions
2. Fluid condition (state) in the tank
3. Fluid mixing system performance
4. Condensation rate at interface and liquid position (not a direct measurement)
5. Final fill conditions of tank

The second objective consists of the studying of the ullage exchange process. This process will couple the vent systems of the supply and receiver tanks during a fluid transfer, thereby allowing the transfer to become a no-vent fill even though the receiver tank will be venting.

This experimentation series can be broken into three separate groups of experiments. These consist of (1) a no-vent fill, (2) a topoff (a no-vent fill that begins with some liquid initially in the tank), and (3) an ullage exchange. A definition and description of the experimental configuration related to the processes being examined is presented as well, along with schematic hardware representations of the systems being used.

<u>(1) No-Vent Fill</u> - The first test, a no-vent fill, is a method of filling a cryogenic tank without venting. This test inherently requires three separate processes to be successfully completed. The processes are the following:

1. Initial pressure rise (due to flashing and liquid evaporation)
2. Ullage condensation (via mixing of tank fluid)
3. Ullage compression (final pressure rise)

Initial Pressure Rise - This step of a no-vent fill occurs during the first few seconds of the experiment. In this process the tank is pressurizing from an initial pressure of ~6.89 kN/m^2 (1 psia) to the saturation pressure of the inlet fluid flow. Upon entering the tank, part of the liquid inflow to the tank will flash due to the drop in pressure and most of the remaining liquid will boil after contacting the tank wall. This boiling also reduces the tank wall temperature and will cease once the wall temperature has been reduced to the saturation temperature of the fluid. Analysis has shown that the time required for this pressure rise is highly dependent on the heat transfer between the liquid and the wall. The general consensus is that all of the fluid will boil due to the expected high heat transfer coefficient that will develop.

The pressure rise time and final wall temperature are controlled by many factors. The initial tank temperature has a great effect on the time required to reach the saturation pressure of the inlet liquid. If the initial temperature is too low then the tank wall will cool down quickly, the boiling will stop, and the pressure rise rate becomes very low. The heat transfer between the liquid and the wall is the primary driver of the wall cooling rate, and the tank pressure rise rate. Other factors include the liquid flow rate, the tank geometry, plus the inlet liquid conditions.

Ullage Condensation - Once the tank pressure has exceeded the saturation pressure of the inlet flow, the flashing will cease. If after this point the proper mixing conditions can be achieved the liquid can be used to condense the ullage, thereby maintaining the tank pressure at a fairly constant level. To achieve the necessary condensation of the ullage, convective forces of a great enough magnitude must be achieved. The flow configuration (flow rate, nozzle choices, etc.) used and the acceleration level will have a major impact on and control this process. The choice of acceleration level will inherently control the location of the ullage, whereas the flow configuration will affect the resultant heat transfer between the liquid and the ullage by providing various fluid motions. In addition, the ullage condensation process will be the starting point for a topoff test since the fluid tank will already have liquid accumulated in the tank.

As stated before, the interfacial heat and mass transfer is the driving parameter for the effectiveness of the no-vent fill process. This parameter is mainly controlled by the spacecraft acceleration, liquid flow rate, and nozzle configuration. In addition, the tank geometry and initial tank conditions (i.e. is this a fill or a topoff) will have some effect on the process.

Ullage Compression - This process occurs at the end of the no-vent fill and results in a final pressure rise that continues until the receiver tank pressure rises to the level of the supply tank. Once this occurs, the fill will cease ending the experiment. The exact point where compression exerts a greater effect than condensation on the ullage is determined by the heat transfer.

(2) Topoff - Topoff is simply a no-vent fill which is initiated with liquid present in the receiver tank. This process must be studied since one cannot be assured that all resupplies on-orbit will be to a tank that has been emptied. The processes involved are the same as ullage condensation and ullage compression of the no-vent fill process.

(3) Ullage Exchange - The last test, ullage exchange, is a form of a no-vent fill. In this case, the vents of the receiver tank and the supply tank are interconnected. This action allows the venting of liquid from the receiver tank since it will be captured by the supply tank instead of being lost overboard. This transfer method is very desirable since it will allow a resupply of cryogens to be performed without the requirement for the tank spray systems that no-vent fill has. The processes involved with this task are:

1. Initial pressure rise (due to flashing and liquid evaporation)
2. Liquid transfer and vent fluid recirculation to supply tank (ullage exchange)

Initial Pressure Rise - This process is basically the same as the initial pressure rise process of a no-vent fill in that the tanks being chilled down from an initial target temperature to a point at which liquid will begin to accumulate in the receiver tank. During this process the tank pressure is also increasing to a level greater than that in the supply dewar. This is to allow the transfer of the receiver tank ullage to the supply tank.

Liquid Transfer and Vent Fluid Recirculation to Supply Tank - This process is the heart of an ullage exchange. Once the receiver and supply tank pressures equalize, the vents of the two tanks will be connected by opening a valve in the pressurization system. The use of the pressurization system allows this test to be implemented with little hardware impact. The liquid is transferred into the receiver tank through the inlet/outlet, and allowed to move due to its own momentum (i.e. no nozzles are used to position or control the fluid motion). Whatever fluid is in the vicinity of the vent will be transferred back to the supply tank. Thus liquid or gas can be returned to the supply tank. The fluid transferred from the receiver tank back to the supply tank will chilldown the pressurization line, so no prechilling of the pressurization line is necessary. The vent line will be monitored for liquid flow, and once the flow is predominantly liquid, the process will be terminated.

For the ullage exchange process, the major driver of the final fill rate is whether liquid or gas is venting to the supply tank. This parameter clearly affects the fill rate since if the vent fluid is mainly liquid, this transfer process will be very inefficient and cannot produce good results. The fill level of the receiver tank will be determined by performing a supply tank topoff after each exchange and recording the flowmeter reading. Acceleration will affect the probability of venting liquid so it must be considered when performing the process. Keeping the liquid settled at the tank outlet end will aid in minimizing liquid carryover through the vent which is a desired feature that enhances the process.

Experiment Description - No-vent fill will be demonstrated for the two receiver tanks using various spray systems to characterize the ability to control maximum fill level and maximum pressure during fill. Variables which influence tank fill and tank pressure will be varied parametrically in an attempt to quantify these effects. Spray flow, acceleration environments, and the "target" temperature are the key parameters which will be varied in an attempt to understand the thermodynamic and fluid conditions of this process.

These tests will be accomplished using the two receiver tanks which respectively possess a LAD and outlet end baffles with a variety of spray systems. The following summarizes those tests that will be accomplished in each tank.

A. Receiver tank 1
   1. Single axial spray at bottom of tank
   2. Combination of axial spray and inward spray (circumferential spray system) mounted at the tank circumference
   3. Inflow through the LAD

B. Receiver tank 2
   1. Tangential/radial/axial spray operated in various combinations
   2. Inflow through the inlet/outlet baffle
   3. Ullage exchange with inflow through the inlet/outlet baffle

Experiment Configuration - The following provides a brief description of the conceptual experiment configuration required to investigate low-g no-vent fill, topoff, and ullage exchange.

Spray Characterization - Spray jet orientation location and flow characteristics are uniquely configured for each receiver tank. Receiver tank 1 possesses a circumferential spray system that is located on the tank wall to provide a spray flow directed towards the center of the tank and is designed to promote ullage condensation. This tank also has a single axial jet which is located in the bottom of the tank to represent a full scale region of an OTV/depot tank's spray nozzle. On the other hand, receiver tank 2 has three spray systems that are located in the spherical tank geometry to provide: (1) wall-mounted circumferential spray flow producing across-the-tank spray liquid flow, (2) radial flow from the center axis out to the wall to mix with a centrally located ullage, and (3) axial jets aimed along the axis from either end to reach the centrally located ullage.

Fill/Injection Techniques - Flow can be directed through the spray nozzles to promote mixing, or by direct injection through the outlet (receiver tank 2) or LAD (receiver tank 1) to use as a basic reference test for a bare tank fill. Outlet baffles (receiver tank 2) will affect the spray patterns in either a beneficial or detrimental way.

The interrupted fill technique will be conducted by performing a series of staged fills interceded with the use of the passive TVS HX for conditioning the fluid prior to each fill stage. This technique will demonstrate the feasibility of performing a no-vent fill to high fill levels in terms of the efficiency and time required to attain a desired fill level. The fill level obtained from a single stage no-vent fill is relatively unknown and can only be demonstrated, and therefore, this method provides an absolute means to achieve a desired end fill condition.

Thermodynamics/Heat Transfer - The "target" temperature which is related to the mass/volume ratio of the tank and was evaluated in the chilldown tests will be explored as a function of mixing method and flow rate. The fluid injection flow and state will also affect the maximum fill level and pressure. This will be evaluated in this experiment by controlling the supply tank pressure and liquid temperature.

Fluid Mass Gauging - Knowledge of the receiver tank fill level requires an accurate measurement of fluid mass by using the integrated flow into the tank. Fill level will also be determined by settling the liquid and measuring fill level with liquid/vapor probe. The liquid/vapor probe provides a means of measuring the settled fluid level in the tank.

Conceptual schematics of both receiver tanks 1 and 2 are presented in Figures 3.3-8 and 3.3-9, respectively. These figures show the spray systems utilized for each tank and the associated fluid components required to provide flow control for the spray systems (same configurations for chilldown). The inlet/outlet baffle (for receiver tank 2) and the LAD (for receiver tank 1) are also shown since these devices will be used in tests to provide a baseline fill level against which to compare the no-vent fill data.

LAD Fill/Refill Characterization (ERD 1.5) - The acquisition of liquid in a low-g environment can be difficult because its position may be unknown due to the dominance of surface or inertial forces over body forces (Bond and Weber Numbers). A total communication capillary liquid acquisition device (LAD) can overcome this difficulty. A LAD consists of one or several channels in a tank having one side covered with a fine mesh screen. The screen serves as a vapor barrier because, when fully wetted, it resists penetration of gas into the liquid-filled channel. If a tank with a LAD is filled, it is essential to remove all vapor from the channel to ensure that the screen is completely wetted. Otherwise vapor can flow through the screen and out of the tank. Bubbles in the LAD can be removed by pressurizing the tank or cooling the LAD with a heat exchanger. Techniques to fill a LAD and remove any vapor bubbles in the channel are the physical processes to be studied in the LAD fill/refill experiments.

Experimental Configuration - A schematic of the COLD-SAT components used in the LAD fill/refill experiments is presented in Figure 3.3-10. These consist of the supply tank, receiver tanks, GHe and GH2 pressurization systems, LAD's, TVS's, fill nozzles, and flowmeters. The supply tank and receiver tank 1 contain LAD's. The LAD in the supply tank and receiver tank 1 consists of four channels positioned circumferentially in the tank along the tank axis at right angles to each other. A TVS heat exchanger is attached to the LAD in the supply tank to provide localized cooling of the LAD.

The LAD in receiver tank 1 does not contain a TVS heat exchanger in an attempt to simplify the tank design. Localized cooling, or an increase in the tank pressure above the bulk fluid saturation pressure, can collapse bubbles in the channels or prevent their formation. GHe and GH2 pressurization is available to all tanks, although only GH2 pressurization will be used in the supply tank. Flowmeters are included in the transfer line to measure flowrates and detect entrained vapor in the flowstream.

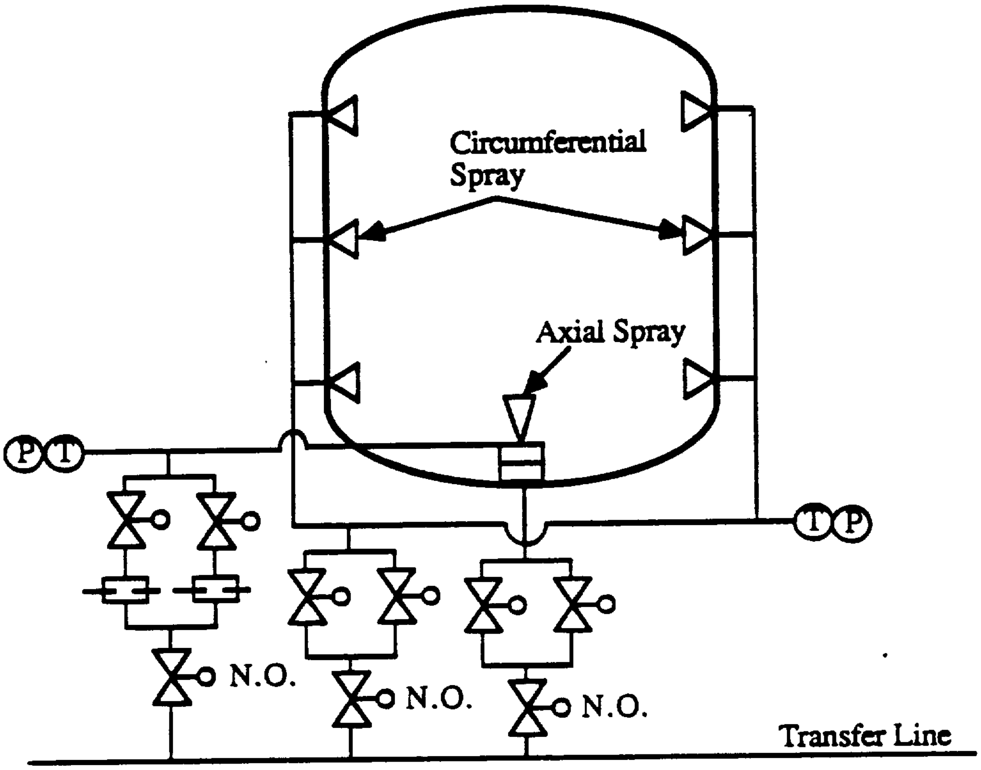


Figure 3.3-8 Receiver Tank 1 Fill Schematic

Tank Pressurization with Gaseous Hydrogen and Gaseous Helium (ERD 2.4) - The primary objective of this experiment is to investigate pressurization of the supply and receiver tanks for purposes of providing the force necessary to drive liquid outflow and transfer, and to use a higher pressure level to promote subcooling of the tank liquid. The performance of gaseous pressurization required of the COLD-SAT supply and receiver tanks for transfer, fill, and back-transfer operations will be investigated. Pressurization will be performed while maintaining fixed pressure setpoints for initial pressurization followed by tank pressurized transfer. The process will be characterized by providing tests with which to evaluate the pressurization process with both gaseous hydrogen and gaseous helium pressurant. The effects of varying parameters such as acceleration environment and orientation, liquid fill levels, liquid outflow rates, and pressure setpoints on pressurization performance and pressurant use will be examined. This experiment is designed to support the primary enabling cryogenic fluid management, transfer, and storage process technologies conducted in the Class I experiment set.

Efficient tank pressurization of on-orbit cryogenic tankage is essential to the outflow and transfer processes associated with receiver tank fills and supply tank back-transfers. Pressurization efficiency is dependent on the capability of the pressurant gas supplied to be diffused properly into the tank ullage region in order to maximize stratification and minimize liquid/vapor interface heat transfer. Lack of fluid stratification (destratification) results in subsequent pressure loss and an increased demand for gaseous pressurant to sustain desired tank pressure levels. Pressurant consumption under certain conditions could become exorbitant, demanding more pressurant over the mission than could be feasibly stored in pressure bottles if these processes are not optimized.

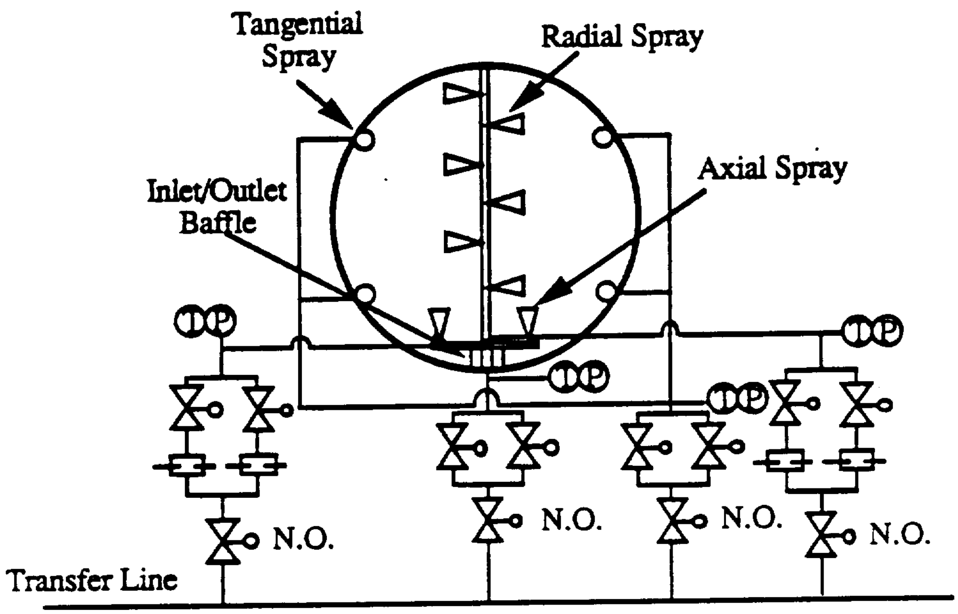


Figure 3.3-9 Receiver Tank 2 Fill Schematic

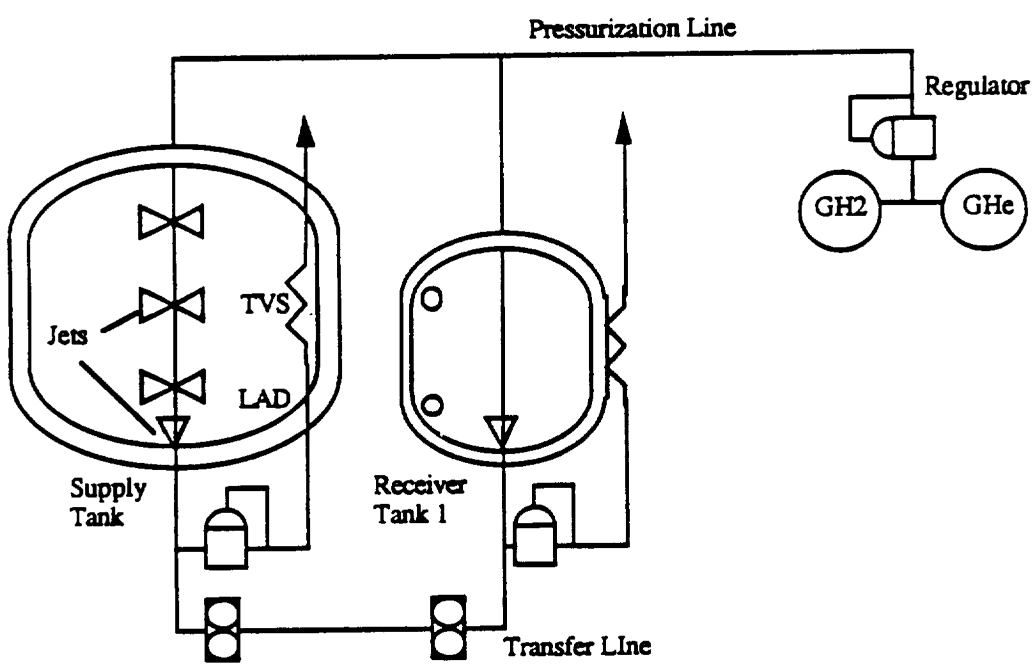


Figure 3.3-10 LAD Fill/Refill Principal Components

Control of tank pressure in low-gravity will be evaluated using the GH2 pressurization process for all of the cryogenic tanks which comprise the experiment subsystem configuration and with the GHe pressurization system for each of the receiver tanks. No GHe pressurization will be conducted in the supply tank so that the thermodynamics examined in this tank are governed by a single fluid constituent only consistent with the condensible hydrogen fluid.

Pressurization with Gaseous Hydrogen - Pressurization with warm gaseous hydrogen will be performed for all supply tank pressurizations and approximately one-half of the receiver tank back-transfers to the supply tank. The pressurant will be added to the tank through the pressurant diffuser at a flow rate that is adequate enough to maintain pressure for the maximum anticipated liquid outflow and transfer rate. The pressurization system flow rate will be designed with the larger of the required hydrogen or helium flow rates as the limiting case. The required flow rate of hydrogen will be determined from pressurant consumption calculations determined from analytical models developed for hydrogen pressurant.

Pressurization with Gaseous Helium - Pressurization with warm gaseous helium will be performed for about one-half of the receiver tank back-transfers to the supply tank. The pressurant will be added to the tank through the same diffuser system that hydrogen is admitted to the tanks. The helium pressurant flow rate will be determined from pressurant consumption calculations determined from analytical models that use helium pressurant.

Other Pressurization Considerations - The foregoing discussion pertains to both pressurization processes, pressurization with hydrogen and pressurization with helium. Each of the pressurization methods will be compared to one another so that their performance can be assessed from the standpoint of pressurant quantity consumed, thermal energy added from the pressurant, thermal conditioning following pressurization, and pressurization subsystem control.

The initial tank pressure will vary at the start of any given pressurization test because it may not always be advantageous or possible to reduce the tank pressure down to nominal conditions of 103.4 kN/m^2 (15 psia) between pressurizations. These varying initial tank pressure conditions will just provide additional data points with which to conduct a performance assessment of the initial pressurization process. Initial pressurization quantities and the time required to achieve setpoint pressure values from various initial tank pressure conditions will be dependent also on the thermodynamic state of the fluid in the tank. The tank pressure and fluid thermodynamic state will inherently govern the heat and mass transfer characteristics of the pressurant with the fluid once injected.

The ability to maintain tank pressure is a function of the degree of fluid stratification which, in turn, is a function of acceleration level, acceleration orientation, and tank fluid stability. A fluid dynamically unstable tank system (sloshing tank fluid) will cause the liquid and vapor constituents to mix with each other, thus enhancing the liquid vapor (L/V) heat and mass transfer and effectively reducing tank pressure. With the presence of fluid sloshing, the potential exists for the tank liquid come in contact with the pressurant and pressurant diffuser. Injected pressurant in contact with the tank bulk liquid can induce higher than desired forced heat transfer coefficients resulting in rapid cooling and condensation of the pressurant with no added benefit towards the goal of tank pressurization. Therefore, increased L/V interface heat and mass transfer will defeat the purpose of stratifying the fluid for efficient pressurization and so the fluid constituents should be separated and the liquid settled so that the pressurant may diffuse properly to stratify the vapor ullage. The rate of pressure buildup or reduction and the pressurant control and consumption variables will be affected by the mechanics of these fluid dynamic processes. Different acceleration levels and induced disturbances during flight can have a definite impact.

The temperature at which pressurant is introduced into the tank will affect the pressurant consumption to varying degrees. A colder gaseous pressurant will consume many times more pressurant because less thermal energy is stored in the gas and more has to be added to get the desired ullage compressibility effects. Less of a warmer pressurant may be required if appropriately stratified in a low-g situation with liquid settling. However, in cases where the acceleration environment is relatively high and warm pressurant is introduced, buoyancy effects may drive up the heat transfer rate at the L/V interface and actually increase the demand for warm gaseous pressurant. An optimal situation for pressurant use exists when warm pressurant is used and the liquid is settled at a minimum Bond number that effectively settles the liquid and allows stratification to occur.

For optimal pressurization performance, the pressurant should be diffused into the ullage near the top of the tank and away from the liquid to avoid heat transfer and condensation which would demand larger quantities of pressurant. The idea is to inject the thermal energy (pressurant) into the uppermost region of the vapor ullage on the opposite end of the tank to the direction of the acceleration vector. Although COLD-SAT tests requiring pressurization for outflow, transfer, or subcooling of liquid hydrogen will not necessarily induce these ideal conditions, these factors should be considered for application to realistic space systems where objectives may outline the need to conserve as much pressurant as possible.

<u>Experiment Configuration</u> - The experiment pressurization system is required of the COLD-SAT for cryogenic hydrogen fluid outflow and transfer operations such as no-vent fill, chilldown, etc. This system is comprised of high-pressure gaseous hydrogen and helium pressure bottles and the associated fluid system hardware for the plumbing and flow control. The high pressure gas bottles are initially charged on the ground during ground support functions. The system is sized and designed without recharging the system on-orbit and is able to provide pressurant margin for the entire COLD-SAT mission. A warm gas pressurization system is simple, easy to facilitate, and eliminates hardware complexities involved with autogenously pressurizing cryogenic tanks. The pressurant bottles will be insulated with MLI to minimize on-orbit cooling.

The pressurant storage bottles will be charged on the ground at approximately 20.7 MPa (3,000 psia), a pressure only to be maintained initially before the tanks are blown down during their on-orbit use.

The design currently baselined for the COLD-SAT experiment subsystem is a composite graphite-epoxy overwrapped pressure bottle with a fluid compatible aluminum liner. A total of nine pressurant bottles are required to deliver the necessary hydrogen and helium pressurant for COLD-SAT experimentation. Seven of these are required for GH2 and two for GHe requirements. Figure 3.3-11 illustrates the pressurization system from a schematic point of view, showing the necessary hardware requirements.

The entire system is represented in the schematic, including all of the relevant hardware with redundancy for pressurant flow and control. Valves, filters, and flow regulation with a fixed pressure regulator and redundant flow control orifices have been established to control the pressurant flow rate to a fixed value as required. The pressure bottles will deliver pressurant down to about 689-1379 kN/m^2 (100-200 psia) at which point pressure regulation may become difficult. Pressures and temperatures will be continually monitored not only within the individual pressurant tanks themselves, but at the pressurant inlet and within the tank fluid, especially in the ullage region.

<u>Low-G Expulsion, Fill, and Venting of Tanks Using Settling Acceleration (ERD's 2.5a, b, and c)</u> - This experiment series is required to study various processes under low-g settling acceleration environments. The series will be broken up into three distinct areas of study. These consist of (2.5a) tank expulsion, (2.5b) a vented tank filling operation, and (2.5c) a settled tank venting, all to be

performed in low-g. These tests will allow one to determine if, by judicious use of acceleration to position the liquid, fluid control can be maintained while on-orbit.

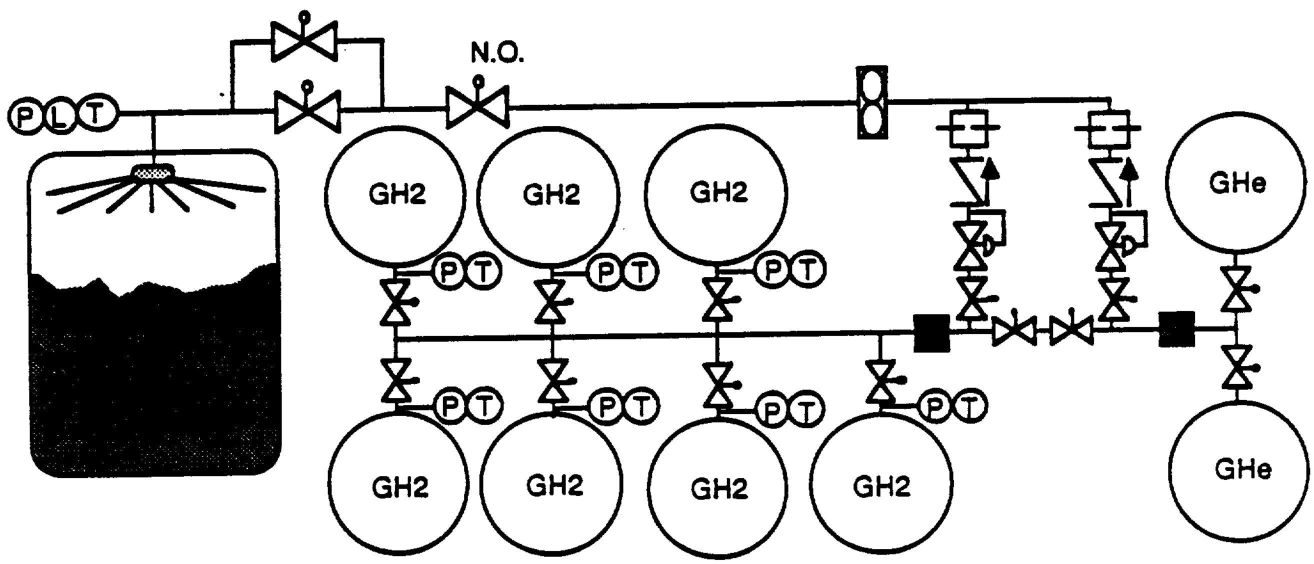


Figure 3.3-11 Hardware Schematic of the COLD-SAT Pressurization System

Low-G Expulsion (ERD 2.5a) - The first test will study the expulsion of liquid out of a tank without the use of a LAD. In this test, receiver tank 2 will be used since it contains no liquid acquisition device. The processes involved with this test are settling and outflow. This test consists of applying a known acceleration field to the spacecraft to settle the liquid over the outlet, and expelling liquid out of the inlet/outlet baffle. The test will terminate when liquid no longer flows out the baffle. Once the test is over the liquid residual in the tank will be measured.

Settling - Accelerations above the background level of 10^{-9} g's will be used to orient the liquid over the inlet/outlet baffle of the tank. This settling maneuver has been used as the principle method of ensuring liquid acquisition for decades. The settling time and resultant interface shape is a function of the applied thrust level and duration, and the tank geometry. The use of two different thrust levels will allow the study of the affect this variable has on the outflow.

Outflow - Once the liquid has settled in a desired location, the liquid outflow will begin. This process is a simple flow analysis, as long as the liquid interface remains stable. The interface of the fluid will not be flat and will even vary with time. Near the end of the outflow, the interface will break down allowing vapor into the transfer line. At this point the outflow will terminate and the amount of liquid remaining in the tank will be referred to as the residual.

Vented Fill (ERD 2.5b) - Vented fill is a task in which a tank is filled with a cryogen while venting to relieve pressure. This method is commonly used on the ground to fill a dewar. In low-g though, there are no gravitational forces to ensure a stable interface between the liquid and the ullage. Therefore if this method were to be tried in a bare tank in zero-g, the fluid would geyser and probably exit the tank directly through the vent. By providing a settling acceleration and limiting the fluid inflow rate to a level that will ensure a stable interface, this method of tank filling could be made to work. This experiment can be broken into two processes, tank chilldown and tank fill.

Tank Chilldown - This process is basically the same as the normal tank chilldown in that the tank is being chilled down from an initial temperature to a point at which liquid will begin to accumulate in the receiver tank. During this process the inlet fluid will be flashing and vaporizing due to the drop in pressure and the heat exchange to the warm wall.

Tank Fill - This process will naturally begin once the tank wall has cooled down to the saturation temperature of the incoming liquid. During this process liquid will be entering the tank and accumulating in locations determined by the fluid momentum and tank acceleration levels. If the fluid momentum is greater than a critical level, the incoming fluid stream will likely penetrate the fluid interface, resulting in liquid geysering and probable flow of liquid out of the vent. When this event occurs (or when the tank fills to a level at which liquid will vent), the transfer will be terminated.

Low-g Tank Venting (ERD 2.5c) - This test will study the venting of a cryogen without the use of a TVS system. This practice is risky since it is difficult to control the liquid position, therefore LH2 could vent overboard instead of gas. The processes involved with this test are settling and low-g venting. This test consists of applying a known acceleration field to the spacecraft to settle the liquid over the outlet, and venting gas out of the pressurant diffuser at the top of the tank. The test will terminate when the tank pressure has dropped to a set level. When liquid has been detected in the vent fluid, the test will be momentarily stopped and the liquid will be reoriented over the inlet. At this point venting will begin again.

Settling - Accelerations on the order of 10^{-5} to 10^{-4} g's will be used to orient the liquid away from the tank vent. This settling maneuver has been used before as a method of ensuring gas venting, with limited success. The settling time and resultant interface shape is a function of the tank geometry and the applied thrust level and duration.

Venting - Once the fluid has been oriented over the inlet/outlet baffle, the vent will begin. This process is very simple to analyze except for the question of whether liquid or gas is venting. Another factor that will be varied is the tank fluid initial condition. The question is whether or not the fluid in the tank will be at saturation or superheated ullage conditions. In the superheated case it is assumed that the tank will vent without much bulk fluid boiling. In the saturated case, the tank fluid will likely bulk boil and froth, leading to excessive liquid entrainment into the vent gas. This second case is expected to produce worse results than the first one and therefore venting will only be accomplished for superheated vapor conditions. One last factor that will be studied will be the effect of having a non-condensable gas in the ullage (i.e. GHe instead of GH2).

Experiment Description - These low-g fluid transfer experiments will be performed with two receiver tanks to study the effect of tank scaling along with the previously mentioned parameters. These parameters are primarily the acceleration environment of the spacecraft, the fluid flow rate, and the tank initial conditions. These tests will be accomplished using the two COLD-SAT receiver tanks which respectively possess a LAD and outlet end baffles. The following summarizes those tests that will be accomplished in each tank.

A. Receiver Tank 1
   1. Vented fill through the LAD
   2. Low-g vent of superheated ullage

B. Receiver Tank 2
   1. Low-g outflow through the inlet/outlet baffle
   2. Vented fill through the inlet/outlet baffle
   3. Low-g vent of superheated ullage

C. Supply Tank
   1. Low-g vent of superheated ullage

Experiment Configuration - The following provides a brief description of the conceptual experiment configuration required to investigate low-g no-vent fill and ullage exchange:

Fill/Injection Techniques - Flow will be directed into the tank via the outlet (receiver tank 2) or LAD (receiver tank 1). Inlet flow baffles (receiver tank 2) will affect the flow patterns in either a beneficial or detrimental way.

Venting Techniques - The vent fluid will be directed out of the tank via the pressurant diffusers located in both receiver tanks and the supply tank. The back pressure vent systems will be used to ensure that no fluid will freeze in the line.

Liquid Detection - To ensure that no liquid will be vented overboard during a fill or a vent, liquid sensors will be placed in the vent line. Detection of vapor in the transfer line, required for the low-g expulsion, will be provided by the flow meters.

Fluid Mass Gauging - Knowledge of the receiver tank fill level requires an accurate measurement of fluid mass by using the integrated flow into the tank. If the fluid is settled, then the fill level probe will also provide a means of measuring the fluid level.

Conceptual schematics of both receiver tanks 1 and 2 are presented in figures 3.3-12 and 3.3-13 respectively. These figures show the inlet/outlet baffle (for receiver tank 2), the LAD (for receiver tank 1), and the pressurant diffusers.

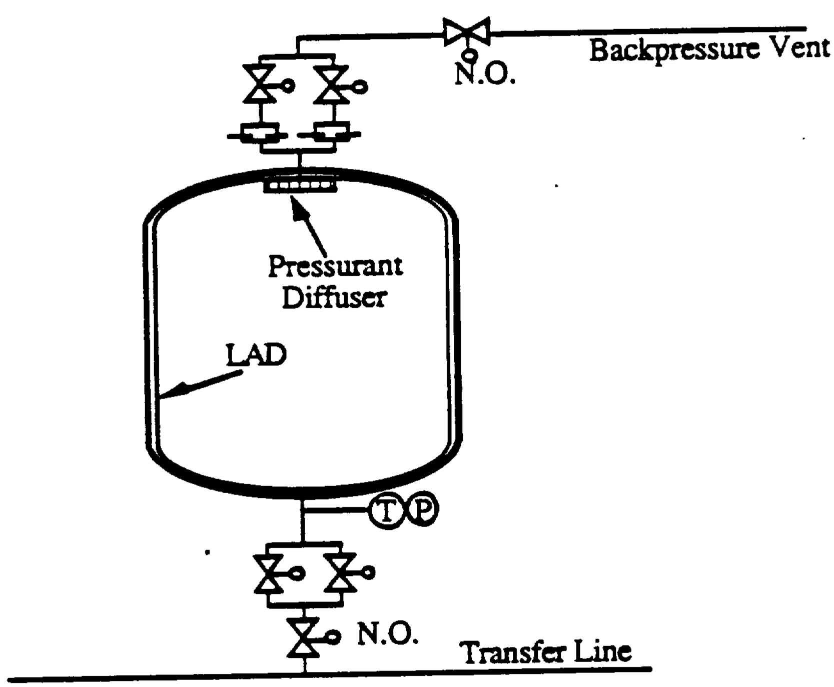


Figure 3.3-12 Receiver Tank 1 Liquid Settling Schematic

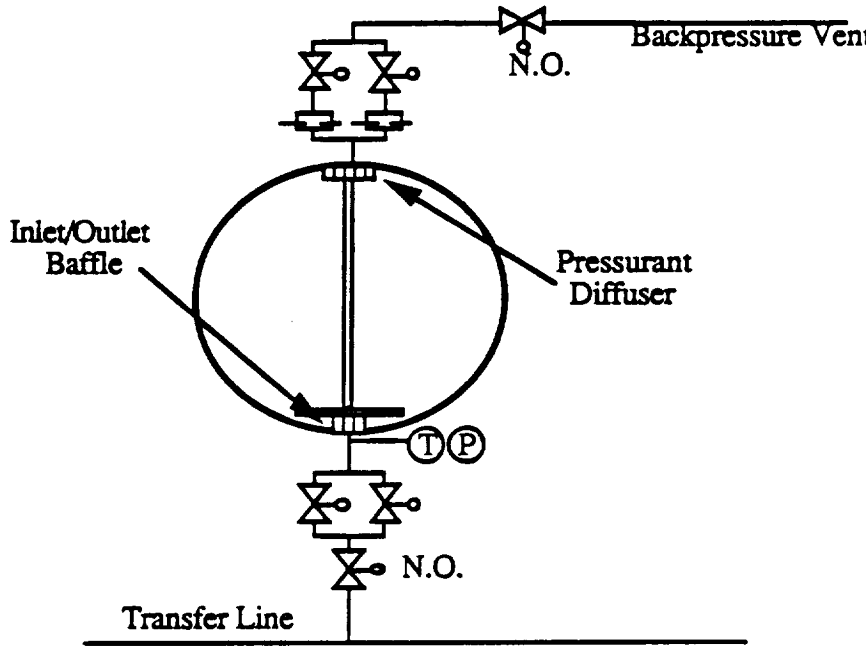


Figure 3.3-13 Receiver Tank 2 Liquid Settling Schematic

LAD Performance (ERD 2.6) - The use of a liquid acquisition device (LAD) to deliver vapor-free liquid in a low-g environment has been discussed in earlier sections. The ability to do this depends on the extent that vapor can penetrate the LAD screen. Vapor penetration is resisted by liquid wetting the screen, and the maximum differential pressure which can be resisted is the bubble point. The pressure difference across the screen is caused by flow losses through the screen and channels, hydrostatic head, hydraulic transients, and external vibrations. The sum of these pressure losses must not exceed the screen bubble point or the screen will break down and vapor will penetrate the channel. Also, the total pressure difference must not exceed the extent of liquid subcooling or flashing may occur, introducing vapor in the channel. This is particularly important in cryogenic systems where the liquid is stored near its boiling point. The determination of the conditions under which the LAD's in the supply and receiver tank 1 break down are the physical processes to be studied in the LAD performance experiments.

Experimental Configuration - A schematic of the COLD-SAT components used in the LAD performance experiments is presented in Figure 3.3-14. These consist of the supply tank and receiver tank 1 with LAD's and TVS's, GHe and GH2 pressurization systems, and flowmeters. The LAD's consist of four channels positioned circumferentially in the tank along the tank axis at right angles to each other. A TVS heat exchanger is attached to the LAD in the supply tank to provide localized cooling of the LAD. Localized cooling can collapse bubbles in the channels or prevent their formation. GHe and GH2 pressurization is available in both tanks to provide the differential pressure for expulsion, but only GH2 pressurization will be used in the supply tank. Flowmeters are included in the transfer line to measure flowrates and detect entrained vapor in the flowstream.

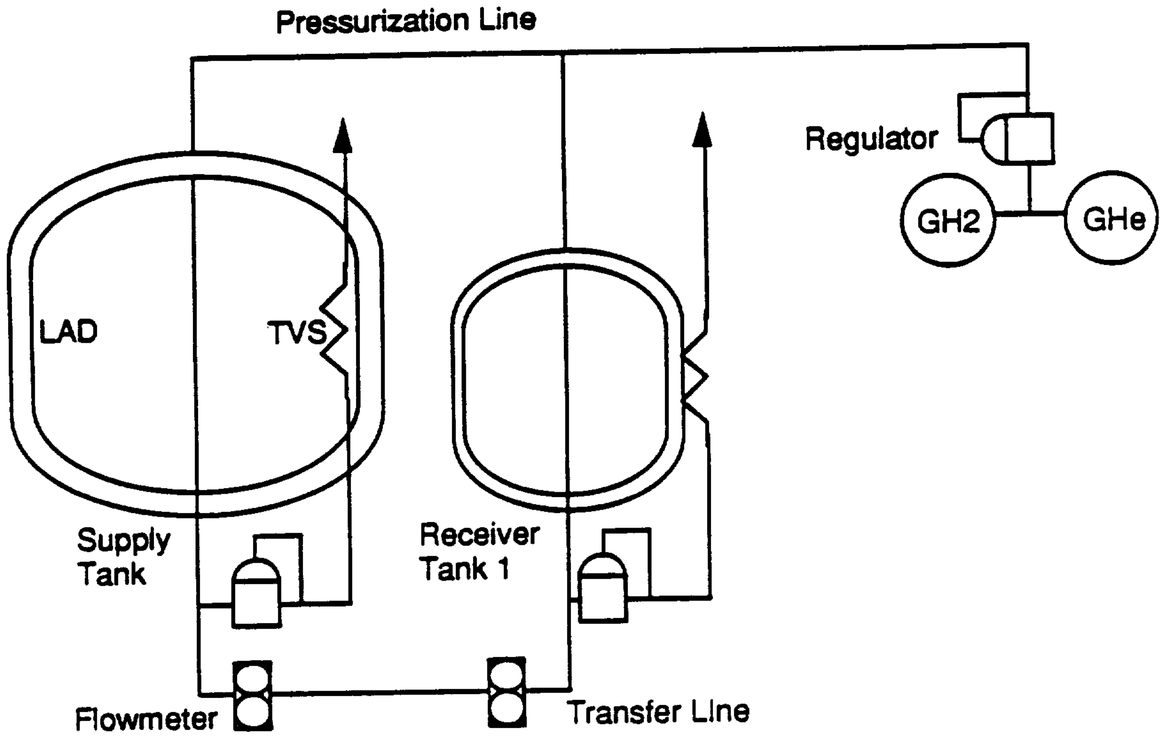


Figure 3.3-14 LAD Performance Principal Components

Transfer Line Chilldown (ERD 2.7) - On-orbit transfer of cryogenic fluids requires chilldown of the transfer line before the process can proceed. The transfer line must be chilled down so that excessive heat transfer does not cause flashing in the line. Chilldown has been studied in a 1-g environment, but no studies have been performed in low-g. The process may be sensitive to acceleration level, so 1-g data may not be applicable to low-g chilldowns. Monitoring of the transfer line chilldown is the physical process to be studied in the transfer line chilldown experiments.

Experimental Configuration - A schematic of the COLD-SAT components used in the transfer line chilldown experiments is presented in Figure 3.3-15. These consist of the supply tank and receiver tanks, the LAD in the supply tank and receiver tank 1, GHe and GH2 pressurization system, transfer lines, vents, and flowmeters. GH2 and GHe pressurization is available in all tanks but only GH2 pressurization will be used in the supply tank. Flowmeters are included in the transfer line to measure flowrates and detect entrained vapor in the flowstream. Transfer line chilldown is accomplished by flowing a small amount of liquid into the transfer line from the supply tank and venting the fluid from the line.

Control of Liquid Subcooling During Outflow (ERD 2.8) - Most fluid transfer operations require subcooled liquid conditions in the line to prevent flashing. This is particularly important in cryogenic systems where the liquid is stored near the boiling point. It is also necessary to provide subcooled liquid during a no-vent fill process so that the incoming liquid can absorb the heat of vaporization of condensing vapor. Otherwise, pressure would build up in the tank, halting the fill process. Subcooled conditions can be achieved by either raising the pressure of the liquid in the supply tank or reducing the liquid temperature. The former method is used in pressurization experiments. The latter method of achieving subcooling is used in this experiment. Temperature reduction is accomplished during fluid transfer from the supply tank to one of the receiver tanks by outflowing through the CHX.

The thermal performance of the CHX is the physical process to be studied in liquid subcooling experiments.

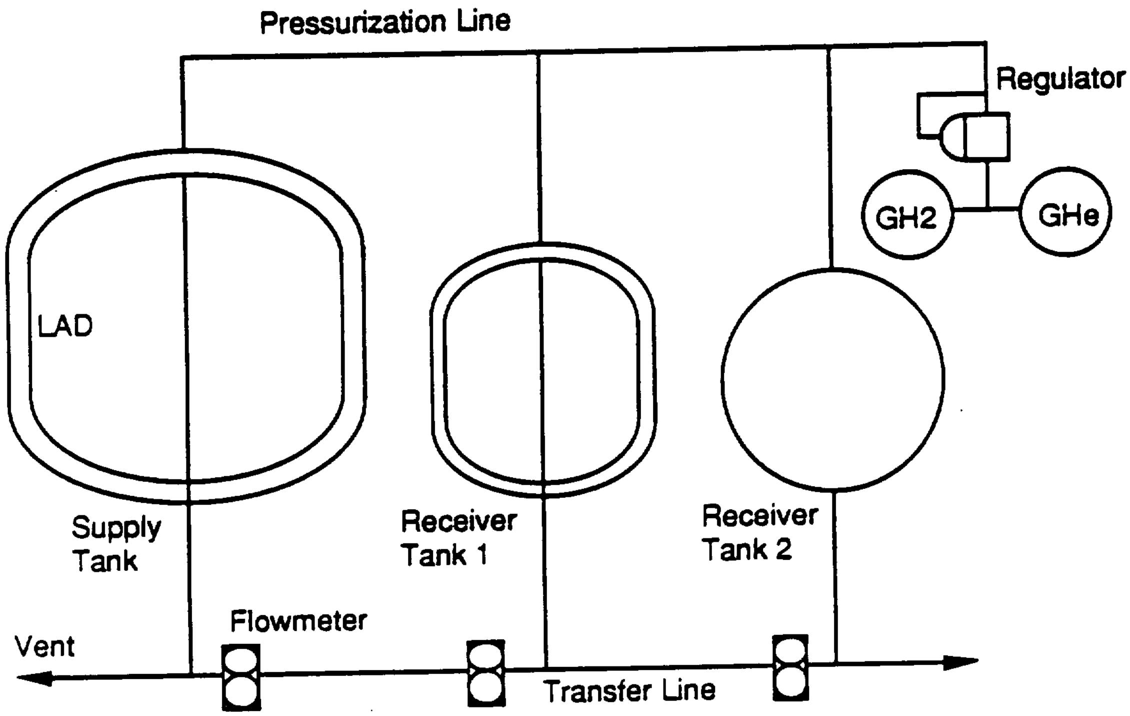


Figure 3.3- 15 Transfer Line Chilldown Principal Components

Experimental Configuration - A schematic of the COLD-SAT components used in the CHX performance experiments is presented in Figure 3.3-16. These consist of the supply tank and receiver tanks, the CHX and LAD in the supply tank, the mixer/transfer pump, the GH2 pressurization system, and flowmeters. The LAD consists of four channels positioned circumferentially in the supply tank along the tank axis at right angles to each other. GH2 and GHe pressurization is available in all tanks but only GH2 pressurization will be used in the supply tank. Liquid can be withdrawn from the tank either by pressurization or with the pump. Flowmeters are included in the transfer line to measure flowrates. Cooling of the outflow fluid is accomplished by diverting some of the outflow fluid through the J-T expander which reduces the CHX fluid pressure to 34.5 kN/m^2 (5 psia). The fluid downstream of the expander is colder than the bulk liquid, and heat is transferred from the bulk liquid to the two-phase fluid in the CHX.

Liquid Dumping in Low-G (ERD 2.9) - The primary objective of the liquid dumping experiment is to investigate the process of rapid tank dumping. Contingency operations may require dumping of hazardous cryogens without liquid positioning in order to safe the system. The effectiveness of the low-g dumping technique will be investigated without a LAD or settling accelerations as a worst case condition. The remaining experiment hydrogen from receiver tank 2 will be dumped overboard to space from the tank outlet through the free vent system while pressurizing the tank with helium to aid in the expulsion.

The low-g liquid dumping process involves the rapid dumping of a tank's remaining fluid. This process is required if a cryogenic fluid system would have to be safed in the event of a mission abort resulting from some occurrence that might pose a hazard to keeping the cryogen in the tank.

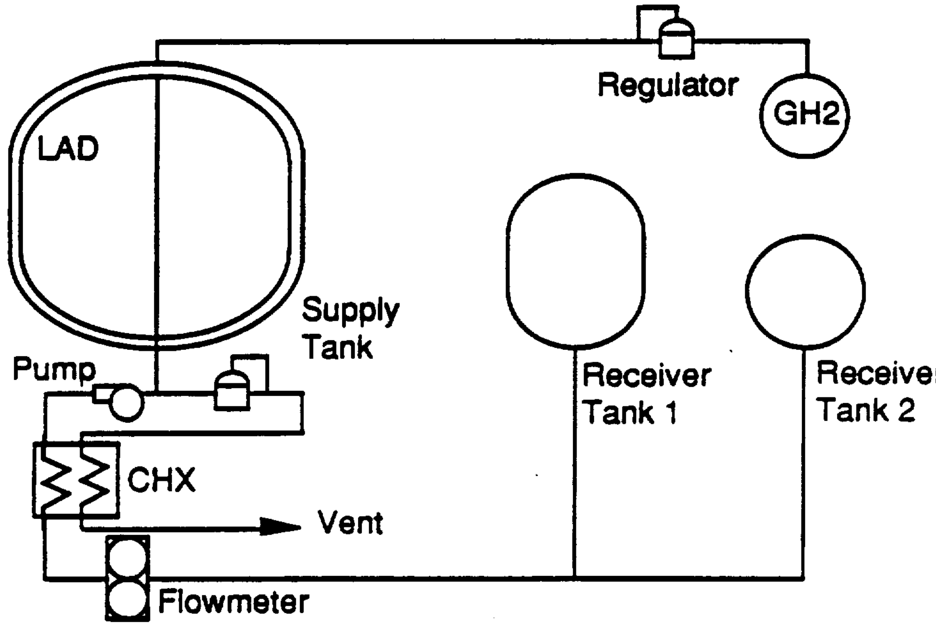


Figure 3.3-16 CHX Performance Principal Components

Ideally, it would be desirable to position the liquid towards the outflow line or vent by inducing a settling acceleration. In addition, if the tank possessed a liquid acquisition device to aid in the liquid expulsion, dumping of the remaining tank fluid would be well supported. To obtain near complete dumping of liquid, expulsion of liquid in preference to vapor is desired.

Under more realistic circumstances, however, the opportunity to dump fluid under these conditions will not be available. The tank containing the liquid to be dumped may not even have a LAD to aid in expulsion. Such is the case with the COLD-SAT receiver tank 2. Tank liquid dumping will have to be performed under more severe, less desirable conditions. Liquid dumping from receiver tank 2 will be accomplished without a LAD and without any settling accelerations. The fluid will be dumped out of the tank outlet at the bottom of the tank. This will provide a worse case condition with which to demonstrate the process when combined with the effects of using the free vent to investigate sub-triple point effects.

The outlet baffle provided in this receiver tank will be used for expulsion out of the tank outlet by aiding somewhat in the liquid expulsion. The outlet baffle will be used to help delay the ingestion of vapor during low-g draining, ensuring more effective removal of liquid. A baffle over the outlet would provide a more uniform velocity field to direct the outflowing liquid, and delay the drawing of vapor into the outlet. Capillary forces act to uniformly distribute the liquid over the tank wall, which aids in promoting continual draining.

The fluid will be dumped overboard as liquid and vapor with no regard to the quality of the expelled fluid. When the outflow rate and tank pressure drop down to near zero where flow essentially ceases, the dump will be considered complete. This final expulsion of the tank will depend upon the continuing orientation of the liquid under the effect of capillary and flow forces at the outlet/baffle.

Subsequently, the tank will be locked-up and the fluid pressure and temperature allowed to increase so that the residuals can be vented through the TVS vent system. Subsequent monitoring of the tank pressure while the tank and fluid temperatures increase will establish the quantity of residual liquid in the tank.

The potential for freezing of the dumped liquid and vapor exists in instances where the fluid may be vented too rapidly to a vacuum condition. If the pressure in the tank, the tank outlet, or the vent line falls below the triple point of hydrogen, the liquid could freeze. Freezing of the liquid will result in blockage of the vent line and halted dump flow and is a part of the process that will be evaluated.

Experiment Configuration - Receiver tank 2 has no configuration hardware specific to liquid dumping in low-g. This experiment will use receiver tank 2 and its hardware as configured for the other COLD-SAT experiments. The fluid will be forced out of the tank outlet with helium pressurization and dumped through the free vent. The tank will be pressurized to 344 kN/m^2 (50 psia) initially and allowed to vent down to 13.8 kN/m^2 (2 psia) as a final pressure at which time the dump process will cease.

3.4 Recommended Experiment Set Modifications

Suggested design changes that could be implemented for a more cost effective design are included in the following recommendations. The following are still unresolved issues that would result in experiment set modifications that would provide enhancement to the current baseline:

- The experiment set was developed with a defined set of Class I and Class II objectives but without a methodical approach to insure that the best experiment mix is being performed for each experiment class. An evaluation of the experiment set is needed using a statistically-designed approach for each experiment class to establish the correct mix of parametric conditions to ensure adequate experiment data quality for the minimum number of experiments and so that experiment results can be properly understood.

- Further assessment of receiver tank 1 LAD design requirements and associated breakdown/stress testing desires is needed. Analysis on the type of LAD for receiver tank 1 showed that a very coarse screen device would be needed to induce breakdown under stressed conditions and that the nominal performance of the device could be compromised as a result. Such coarse screen may not even wick properly under nominal use. Sensitivity to acceleration was found to be low, where as flow rate and associated frictional loses predominated. Additional requirements definition and assessment in this area is needed.

- Long-duration pressure control tests are required to understand the full transient nature of pressure control with a passive TVS heat exchanger system. The supply tank never is allowed to reach a steady state condition for a nominal heat flux test. Such a test is required for many in-space storage applications. Current tests occur in highly transient thermal situations.

- Nominal and overflow TVS flow rate conditions need to be further defined for the transient thermal situation that exists with tank pressure control and for LAD subcooling. Recent supply tank TVS analysis demonstrated a tremendous system inertia and a need for additional analysis and understanding in this area so that proper testing can be suggested, as well as for proper flow rate control and determination.

- All stratification tests are currently performed under as close to quiescent conditions as are possible to obtain (within the limits of ACS and propulsion system design). A stratification test under nominal S/C ACS operation would be useful in demonstrating a truer to life situation.

- The process of tank pressure control/ pressure reduction/ LAD conditioning, using the TVS, induces stratification and can be influenced by other stratification occurring in the tank. Such effects will be difficult to ascertain and affect to such a degree the understanding and analytical determination of the process that it may be impossible to analytically correlate the tank pressure control using the TVS, with analytical models.

- All mixing for destratification is currently performed with mixer pumps. Mixing using normal ACS or some defined thruster firing should be investigated.

- Increasing the nominal heat flux value for the receiver tanks to 1.56 w (0.5 Btu/hr-ft^2) resulted in excessive use of LH2 for chilldown and pressure control that could be used better elsewhere. Assessments of TVS/MLI capabilities showed that a value closer to 0.63 w (0.2 Btu/hr-ft^2) is attainable and cost effective.

4.0 EXPERIMENT SUBSYSTEM DEFINITION

The COLD-SAT Experiment Subsystem is composed of the following major elements:

- liquid hydrogen storage and supply tank
- receiver tank 1
- receiver tank 2
- gaseous pressurant storage and pressurant control
- fluid distribution and control
- experiment control and monitoring
- instrumentation

The functional requirement of the experiment subsystem is to provide the capability to perform the required experiments, tests and demonstrations of the experiment set which was defined in Section 2. This will be accomplished with the configuration defined in the following sections

4.1 Experiment Subsystem Evolution Overview

The experiment concept definition became the design driver for the entire spacecraft approach due to the size constraints imposed by the payload fairing and the need to integrate the spacecraft systems around the experiment subsystem tankage. Due to this limitation it quickly became apparent that it was impractical to attach an experiment subsystem package directly to an existing spacecraft bus. In evolving the experiment concept, an experiment set defining experiment requirements was assembled and included an allocation of technology requirements to one or more of the tankage elements of the approach. This exercise determined the adequacy of a three tank (supply and two receiver tanks) design and led to the development of the design concept for each tank. A point of departure was thus created to satisfy the experiment set. When the tankage design was integrated with gas pressurization, plumbing and valving, sensor instrumentation and experiment control, an initial experiment concept was developed which was iterated and refined over the duration of the program to meet changing experiment set needs. The parallel development and refinement of the experiment set for both Class I and Class II experiments and the detailed testing required for each experiment class resulted in the evolution of requirements, experiment, and supporting spacecraft subsystems into the COLD-SAT satellite and COLD-SAT system. Certain experiment subsystem features and design considerations have been recommended for incorporation into the COLD-SAT concept above and beyond those requirements provided in the SOW or at the Kick-off conference. Many of these recommendations became a part of the baseline.

Figure 4.1-1 provides an integrated experiment schematic showing the major elements of the design in a simplified form, along with the interrelationships of these elements which are required to satisfy the detailed initial experiment set. Table 4.1-1 provides a listing of the major features of the initial experiment subsystem as it was configured for the Concept Review (CR). The following provides a summary definition of major subsystem elements as configured for the Concept Review:

CR Supply Tank - This tank is vacuum jacketed (VJ), 6.15 m^3 (217 ft^3) capable of holding 413 kg (911 lbs) of LH2 at 95% full. The tank has a diameter of 239 cm (90 in) and a length of 227 cm (90 in) to completely utilize the available space in the payload fairing.A 82.6 cm (32.5 in) barrel section for the PV having a 208.3 cm (82 in) diameter connects to elliptical, square root of 2, domes. The pressure vessel (PV) contains a total communication LAD with an outlet at the bottom of the tank. A vent/pressurization penetration which feeds directly into the tank via a diffuser is located at the opposite end. Two spray systems are provided through which liquid can be introduced from a mixer pump to provide mixing of the bulk fluid. The tank contains slosh baffles at yet to be determined fill heights for fluid dynamic investigations. Return fluid from either receiver tank can be introduced into the radial or axial spray for increased top-off potential and minimizing residuals during receiver to supply tank transfers. An internal thermodynamic vent system (TVS) heat exchanger (HX) routed on the LAD and on other critical surfaces is provided to cool the bulk fluid, control tank pressure and provide subcooling to the LAD and outlet fluid. The TVS HX1 is then routed to a vapor cooled shield (VCS) located between the PV and the VJ. A second TVS HX2 is routed directly to the VCS. Para-to-Ortho conversion is provided in the TVS HX. A GHe vacuum degradation system is used to vary the tank heat flux for pressure control experiments is provided on the VJ. A hot spot heater at the vent is included to investigate high localized heating phenomena. Multi-layer insulation (MLI) is located between the VCS and the PV, as well as between the VCS and the VJ. All plumbing penetrations from the PV are routed internal to the VJ and exit at the girth ring area. Outlet components are sandwiched between the PV and the VJ with component access provided for contingency maintenance. The PV connects to the VJ with a strut suspension system. LH2 is loaded on the ground before launch and provides the total LH2 mission budget. The tank has a mass gage to determine liquid quantity. The design of this tank was intended to represent a scaled down version of an earth-to-orbit tanker to evaluate the integrated thermal performance characterization of the configuration.

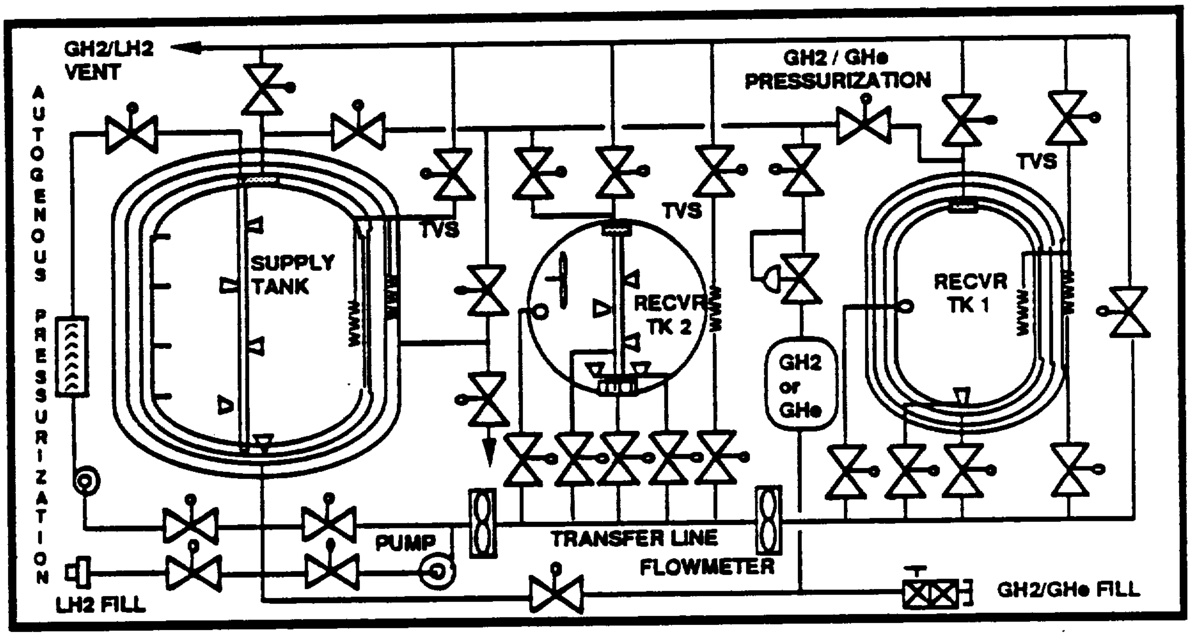


Figure 4.1-1 Concept Review Experiment Subsystem Schematic

Table 4.1-1 Concept Review Experiment Subsystem Features

Supply Tank	Receiver Tank 1	Receiver Tank 2	Pressurization	Other
Pressure Vessel	Pressure Vessel	Pressure Vessel	GHe Storage	Transfer Line
- LAD	- LAD	- Outlet Baffle	GH2 Storage	- Flowmeters
- Radial Spray & Jet	- Axial Spray	- Axial Spray	Regulation	- Pump
- Axial Jet	- Tangential Spray	- Radial Spray	Distribution	LH2 Fill/Drain
- Internal TVS HX1	- Internal TVS HX1	- Tangential Spray	Isolation	GH2 Bottle Recharge
- Hot Spot Heater	Instrumentation	- Fluid Mixer	GH2 Bottle Vent	Back Pressure Vents
Instrumentation	Dual VCS	Instrumentation	Relief Protection	- Flowmeters
Vacuum Jacket	- TVS HX1	Wall TVS HX1	GH2 and GHe Ground Fill	- Check Valve
- Para-to-Ortho	- TVS HX2	MLI Blanket	Instrumentation	Free Vent
- VCS	- Para-to-Ortho	Warm Up Heater		- Cross Over
- TVS HX1	Warm Up Heater	Pressure Relief		- Flow meter
- TVS HX2	MLI Blankets			
- MLI Blankets	Mass Gage			
- GHe Degradation	Pressure Relief			
Autogeneous Pressurization				
Mass Gage				
Pressure Relief				

CR Receiver Tank 1 - Receiver tank 1 is an insulated, non-vacuum jacketed, 1.2 m^3 (42.6 ft^3) tank capable of holding 77 kg (170 lbs) of LH2 at 95% full. To maximize the science of characterizing a single nozzle in a tank with a L/D close to 2, the length was selected to be 183 cm (72 in) with a diameter of 102 cm (40 in). The barrel section of the PV is 81.3 cm (32 in) long. The dome ends are spherical and use the same forgings and tooling as receiver tank 2. The M/V is 4.9 and the L/D is 1.8. The PV contains a LAD feeding an inlet/outlet penetration. A vent/pressurization penetration is routed from the vent end to the girth area for exiting the PV. This design arrangement provides for minimal clearance at the tank ends and allows for a tighter packaging arrangement. Axial and tangential spray systems are provided for chilldown and no-vent fill testing. An internal tank TVS HX routed on the LAD and on other critical surfaces is provided to cool the bulk liquid. This HX is then routed to dual VCS's. MLI is located between the PV and the VCS1, between VCS1 and VCS2, and outside the VCS. A second TVS HX2 is routed directly to the dual VCS (first to VCS1 and then to VCS2). Para-to-Ortho conversion is provided in the TVS HX. Tank chilldown can also be accomplished by introducing chilldown fluid into the TVS HX mounted to internal tank components. A wall mounted tank warm-up heater is used for establishing initial conditions for multiple chilldown tests. The tank has a mass gage to determine liquid quantity. The tank is supported to the S/C structure with 8 alumina-epoxy struts. The design of this tank was intended to represent a scaled down version of an on-orbit depot to evaluate the integrated thermal performance characterization of the configuration.

CR Receiver Tank 2 - This tank is an insulated, non-vacuum jacketed 0.55 m^3 (19.4 ft^3) tank capable of holding 35 kg (77 lbs) of LH2 at 95% full. The tank is almost spherical 102 cm (40 in) in diameter with a minimal girth ring section. The M/V is approximately 4.4 and the L/D is 1. The PV does not contain a LAD but has a simple screen/plate baffle at the outlet to minimize residuals during settled expulsions and prevent vapor intrusion. A combined vent/pressurization penetration is routed to the girth ring (in a similar manner to receiver tank 1) to provide for minimal clearance at the vent end. The PV contains an exterior wall mounted TVS HX (no VCS) for pressure control and an internal type fluid mixer (type TBD). Axial, radial, and tangential spray systems are provided for chilldown and no-vent fill testing. An optimized MLI blanket surrounds the PV. Tank chilldown can also be accomplished by introducing chilldown fluid into the TVS HX. A wall mounted tank warm-up heater is used for establishing initial conditions for multiple chilldown tests. Support is provided to S/C structure by two trunnion mounts. The design of this tank was intended to represent a scaled down version of an OTV tank to evaluate the integrated thermal performance characterization of the configuration.

CR Pressurization - Pressurant storage is provided by six 63.5 cm (25 in) diameter 0.12 m^3 (4.18 ft^3) tanks pressurized to 20670 kN/m^2 (3000 psia) on the ground prior to flight. Four tanks store 7.3 kg (16 lbs) of GH2 while the remaining two contain 11.4 kg (25 lbs) of GHe. Either pressurant can be used for receiver tank pressurization while only GH2 will be used for the supply tank. The GH2 tanks can be recharged on-orbit using residual receiver tank LH2 and allowed to warm-up to meet the GH2 pressurant needs. Fixed regulators control delivered pressurant to 345 kN/m^2 (50 psia). Pressures less than this maximum are controlled by tank isolation valves. Manual GH2 and GHe servicing is provided. An additional supply tank GH2 pressurization option is to autogenously pressurize through a pumped vaporizer using transfer line LH2.

CR Fluid Distribution - Experiment tankage is interconnected with a common transfer line and back pressure and free vent line plumbing and associated components and instrumentation. A transfer line/vent by-pass is provided at both the supply tank and receiver tank end of the system so that transfer line chilldown can be accomplished using fluid from any tank.. Ground fill/drain and vent needs of the supply tank are also provided.

CR Experiment Control and Monitoring - Control and data handling of the experiment and its subelements is managed via Remote Interface Units (RIUs) which receive commands from the spacecraft Tracking, Telemetry, and Command (TT&C) subsystem and operate needed functions.

Instrumentation and sensor data is also collected via the RIUs and provides the data to the TT&C for processing or downlinking.

CR Instrumentation - Instrumentation required to monitor the Class I and Class II experiments consists of temperature, pressure, flowrate, valve position, liquid/vapor detection, mass gaging, and fluid quality discrimination measurements required to monitor specific experiment needs. Table 4.1-2 provides a summary of these devices and compares sensor evolution to the PRR configuration .

Table 4.1-2 Experiment Subsystem Instrumentation Evolution

Type	Supply Tank		RCVR TK 1		RCVR TK 2		Press./Pwr	
	CR	PRR	CR	PRR	CR	PRR	CR	PRR
Temperature	110	112	92	81	65	65	36	34
Pressure	5	4	4	3	3	3	23	25
Flowrate	2	1	2	1	2	1	7	9
Liquid level	24	24	8	8	4	4	-	-
Valve Position	40	20	20	21	20	22	24	9
Acceleration	9	3	-	-	3	3	-	-
Power/Current	6	10	3	-	6	2	-	3

Following the Concept Review, refinements, modifications and changes to the experiment subsystem were made that resulted in several iterations to the experiment subsystem approach and configuration. Figure 4.1-2 provides an integrated experiment schematic showing the major elements of the design in a simplified form, along with the interrelationships of these elements which are required to satisfy the modified PRR experiment set. Table 4.1-3 provides a listing of the major features of the refined experiment subsystem as it was configured for the Preliminary Requirements Review. An updated configuration was presented at the Preliminary Requirements Review and included the following definition of major subsystem elements:

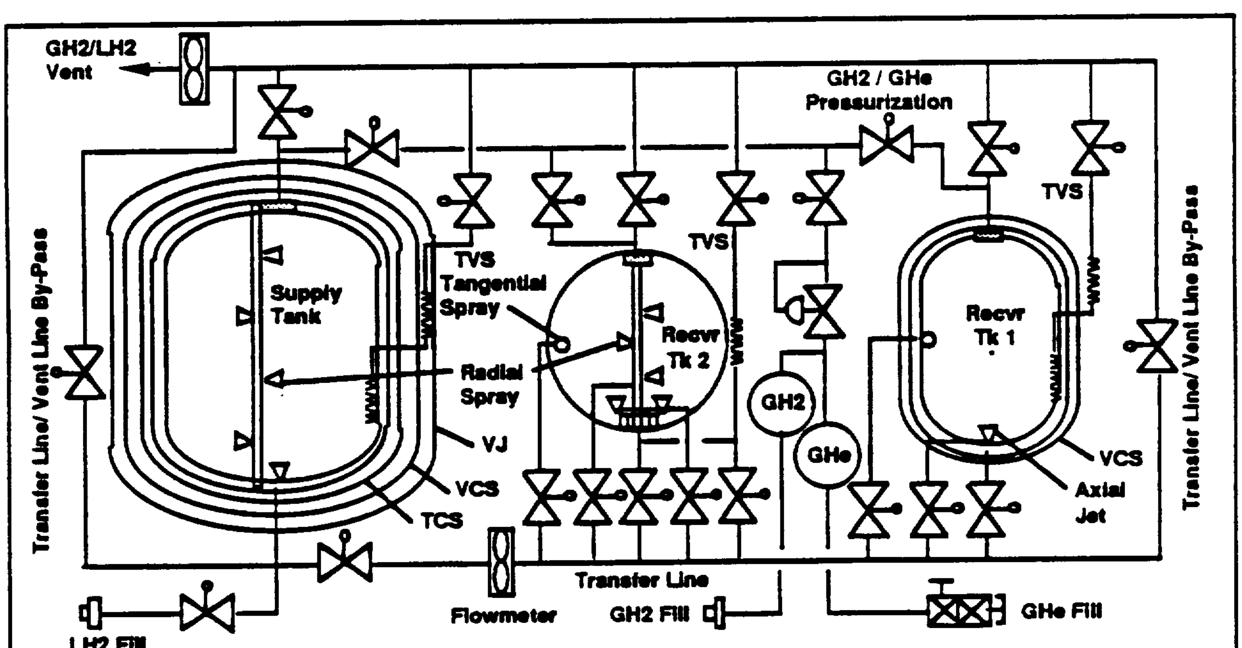


Figure 4.1-2 Preliminary Requirements Review Experiment Subsystem Simplified Schematic

Table 4.1-3 Preliminary Requirements Review Experiment Subsystem Features

Supply Tank	Receiver Tank 1	Receiver Tank 2	Pressurization	Other
Pressure Vessel	Pressure Vessel	Pressure Vessel	GHe Storage	Transfer Line
- LAD	- LAD	- Outlet Baffle	GH2 Storage	LH2 Fill/Drain
- Radial Spray & Jet	- Axial Spray	- Axial Spray	Regulation	GH2 Bottle Recharge
- Axial Jet	- Tangential Spray	- Radial Spray	Distribution	Back Pressure Vent
- Internal TVS HX1	- Internal TVS HX1	- Tangential Spray	Isolation	- Flowmeters
- Hot Spot Heater	Instrumentation	- Fluid Mixer	Relief Protection	- Check Valve
Instrumentation	Single VCS	Instrumentation	GH2 and GHe Ground Fill	Free Vent
Vacuum Jacket	- TVS HX1	Wall TVS HX1	Instrumentation	- Cross Over
- VCS	MLI Blankets	MLI Blanket		- Flow meter
- TVS HX1	Mass Gage	Warm Up Heater		Instrumentation
- Expose VJ to space	Pressure Relief	Pressure Relief		
- MLI Blankets				
- Thermal Control Shield				
- Mixer pumps				
- Compact Heat Exchanger				
Mass Gage				
Pressure Relief				

<u>PRR Supply Tank</u> - This tank is vacuum jacketed (VJ), 6.15 m^3 (217 ft^3) capable of holding 413 kg (911 lbs) of LH2 at 95% full. The tank has a diameter of 239 cm (94 in) and a length of 227 cm (90 in) to completely utilize the available space in the payload fairing. A 63.5 cm (25 in) barrel section for the internal PV having a 218 . cm (86 in) diameter connects to elliptical root 3 dome ends. The pressure vessel (PV) contains a total communication LAD with an outlet at the bottom of the tank. A vent/pressurization penetration which feeds directly into the tank via a diffuser is located at the opposite end. Two spray systems are provided through which liquid can be introduced from a mixer pump to provide mixing of the bulk fluid. Return fluid from either receiver tank can be introduced into the radial or axial spray for increased top-off potential and minimizing residuals during receiver to supply tank transfers. The tank contains slosh baffles at yet to be determined fill heights for fluid dynamic investigations. An internal thermodynamic vent system (TVS) heat exchanger (HX) routed on the LAD and on other critical surfaces is provided to cool the bulk fluid, control tank pressure and provide subcooling to the LAD and outlet fluid. The TVS HX is then routed to a vapor cooled shield (VCS) located between the PV and the VJ. A thermal control shield (TCS) covered with assorted heating elements which are used to vary the tank heat flux for pressure control experiments is provided just outside the PV. Multi-layer insulation (MLI) is located between the TCS and the VCS, as well as between the VCS and the VJ. All plumbing penetrations from the PV are routed internal to the VJ and exit at the girth ring area. On-orbit the annular vacuum region can be exposed to the space vacuum by operating an ordnance valve. Outlet components are sandwiched between the PV and the VJ with component access provided for contingency maintenance. The PV connects to the VJ with a strut suspension system. LH2 is loaded on the ground before launch and provides the total LH2 mission budget. The tank has a mass gage to determine liquid quantity.

<u>PRR Receiver Tank 1</u> - Receiver tank 1 is an insulated, non-vacuum jacketed, 1.2 m^3 (42.6 ft^3) tank capable of holding 77 kg (170 lbs) of LH2 at 95% full. The length is 183 cm (72 in) with a diameter of 102 cm (40 in). The M/V is approximately 5 and the L/D is 1.8. The PV contains a LAD feeding an inlet/outlet penetration. A vent/pressurization penetration exits the vent at the tank top. Axial and tangential spray systems are provided for chilldown and no-vent fill testing. An internal tank TVS HX routed on the LAD and on other critical surfaces is provided to cool the bulk liquid. This HX is then routed to a VCS. MLI is located between the PV and the VCS and outside the VCS. The tank is supported to the S/C structure with 8 composite struts.

<u>PRR Receiver Tank 2</u> - This tank is an insulated, non-vacuum jacketed 0.55 m^3 (19.4 ft^3) tank capable of holding 35 kg (77 lbs) of LH2 at 95% full. The tank is almost spherical 102 cm (40 in) in diameter with a minimal girth ring section. The M/V is approximately 4 and the L/D is 1. The PV does

not contain a LAD but has a simple screen/plate baffle at the outlet to minimize residuals during settled expulsions and prevent vapor intrusion. A combined vent/pressurization penetration exits at the opposite end. The PV contains an exterior wall mounted TVS HX (no VCS) for pressure control. Axial, radial, and tangential spray systems are provided for chilldown and no-vent fill testing. An optimized MLI blanket surrounds the PV. Tank chilldown can also be accomplished by introducing chilldown fluid into the TVS HX. Support is provided to S/C structure by two trunnion mounts.

PRR Pressurization - Pressurant storage is provided by seven 63.5 cm (25 in) diameter 0.12 m3 (4.18 ft 3) tanks pressurized to 20670 kN/m^2 (3000 psia) on the ground prior to flight. Five tanks store 9.1 kg (20 lbs) of GH2 while the remaining two contain 11.4 kg (25 lbs) of GHe. Either pressurant can be used for receiver tank pressurization while only GH2 will be used for the supply tank. Fixed regulators control delivered pressurant to 345 kN/m^2 (50 psia). Pressures less than this maximum are controlled by tank isolation valves.

PRR Fluid Distribution - Experiment tankage is interconnected with a common transfer line and back pressure and free vent line plumbing and associated components and instrumentation. A transfer line/vent by-pass is provided at the receiver tank end of the system. Ground fill/drain and vent needs of the supply tank are also provided.

PRR Experiment Control and Monitoring - Control and data handling of the experiment and its subelements is managed via Remote Interface Units (RIUs) which receive commands from the spacecraft Telemetry, Tracking, and Command (TT&C) subsystem and operate needed functions. Instrumentation and sensor data is also collected via the RIUs and provides the data to the TT&C for processing or downlinking.

PRR Instrumentation - Instrumentation required to monitor the Class I and Class II experiments consists of temperature, pressure, flowrate, valve position, liquid/vapor detection, mass gaging, and fluid quality discrimination measurements required to monitor specific experiment needs. Table 4.1-3 provides a summary of these devices and compares sensor evolution from the CR configuration .

By comparing Tables 4.1-1 and 4.1-3 the major changes to the experiment subsystem configuration become evident. Justification for most of these modifications were driven by the desire to reduce complexity and simplify the approach, reduce the need for the development of new components or processes and, thereby, reduce the overall cost of the approach.

After the PRR additional changes and refinements to the experiment system were made . The rest of section 4 describes the finalized experiment subsystem configuration which resulted from the study and the supportive analyses that were conducted to define the experiment processes being accomplished. Section 1 already provided a summary description of the finalized experiment subsystem major elements and features. Figure 4.1-3 shows the finalized baseline experiment subsystem integrated schematic and provides the interrelationship of the major elements to one another, as well as the important design features of each. Additional details of each of the elements is provided in the following sections.

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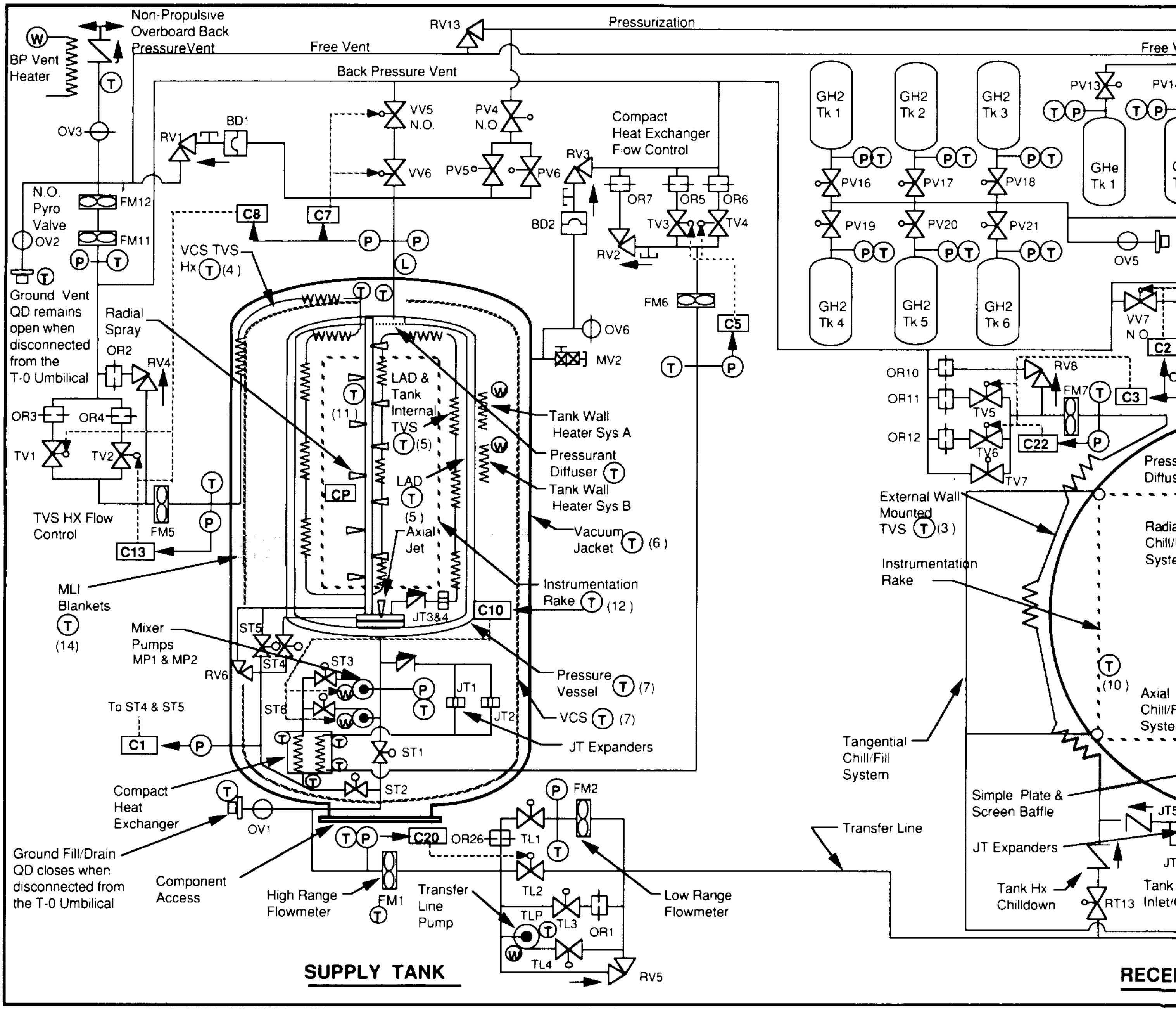

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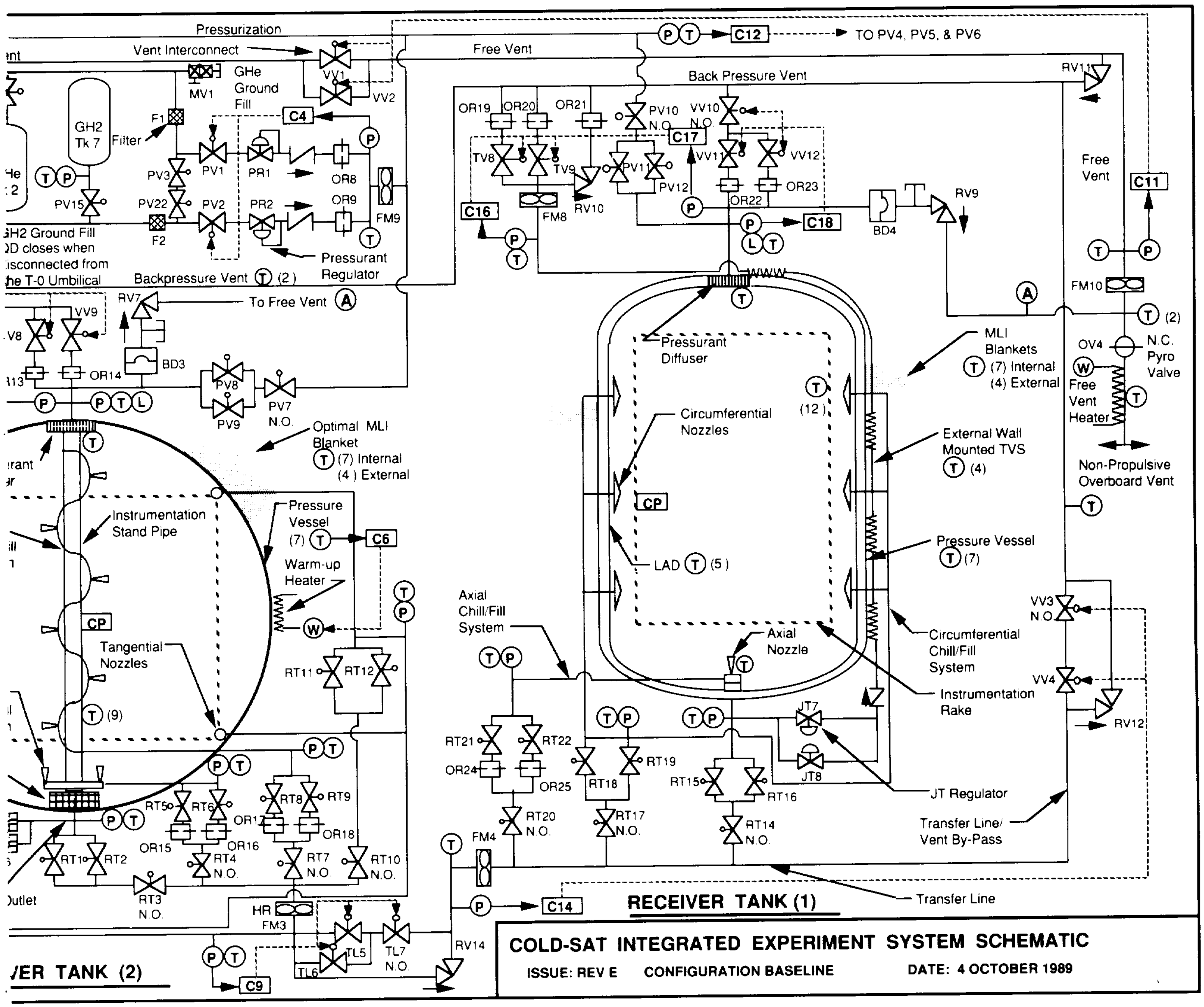


COLD-SAT INTEGRATED EXPERIMENT SYSTEM SCHEMATIC

ISSUE: REV E CONFIGURATION BASELINE DATE: 4 OCTOBER 1989

Figure 4.1-3 Integrated Schematic

4.2 Supply Tank

The LH2 supply tank provides the liquid hydrogen storage capability for the COLD-SAT mission and consists of the following subelements:

- Supply tank pressure vessel
  - Total communication Liquid Acquisition Device (LAD) for the tank outlet
  - Radial spray system
  - Axial jet (spray)
  - Internal tank TVS heat exchanger on the LAD
  - Vent line pressurant diffuser
  - Tank wall mounted heaters
  - Instrumentation rake
  - Instrumentation
- Vacuum jacket
  - Vapor Cooled Shield (VCS)
  - VSC TVS heat exchanger (routed from internal tank)
  - Multi Layer Insulation (MLI) blankets
  - Expose VJ annulus to space environment ordnance valve
  - Compact Heat Exchanger (CHX)
  - Mixer Pumps
  - Support Straps
  - Instrumentation
- Fluid distribution and control
  - TVS & CHX flow control
  - Outflow line isolation valving in the VJ
  - Vent line connection and isolation valving to the back pressure vent
  - Ground fill/drain & vent system connection and QD interface to the T-0 umbilical
  - Instrumentation

The supply tank is a vacuum jacketed, 4.25 m^3 (150.4 ft^3) tank capable of holding 286 kg (630 lbs) of LH2 at 95% full. To completely utilize the available space in the payload fairing and maintain as low a center of gravity as is possible for the entire satellite, the tank was designed to be as wide as possible in diameter and as short as possible in length for the required volume. The tank has a diameter of 234 cm (92 in) and a length of 211 cm (83 in). A 35.6 cm (14 in) barrel section for the internal PV, having a 203.2 cm (80 in) diameter, connects to elliptical, square root of 2, dome ends. The PV contains a total communication LAD with an outlet at the bottom of the tank. A vent/pressurization penetration which feeds directly into the tank via a diffuser is located at the opposite end. Two spray systems are provided through which liquid can be introduced from mixer pumps to provide mixing of the bulk fluid. Return fluid from either of the receiver tanks can be introduced into the radial or axial spray for increased top-off potential and minimizing residuals during receiver to supply tank transfers. An internal tank TVS routed on the LAD is provided to cool the bulk fluid, control tank pressure, and particularly to provide subcooling to the LAD. This TVS heat exchanger is then routed to a VCS located between the PV and the VJ. MLI insulation is located between the PV and the VCS, as well as between the VCS and the VJ where the majority of the insulation will be located. Thermal control heaters uniformly cover the pressure vessel with assorted heating elements which are used to vary the tank heat flux for pressure control and stratification experiments. All plumbing penetrations from the PV are routed internal to the VJ and exit at the girth ring area. Outlet components are sandwiched between the PV and the VJ with component access provided for contingency maintenance. The PV connects to the VJ with a strap suspension system. The tank is completely instrumented to provide necessary experimental data. The supply tank is loaded on the ground before launch and provides the total LH2 budget for the mission.

Figure 4.2-1 shows a cutaway view of the supply tank with major subelements identified.

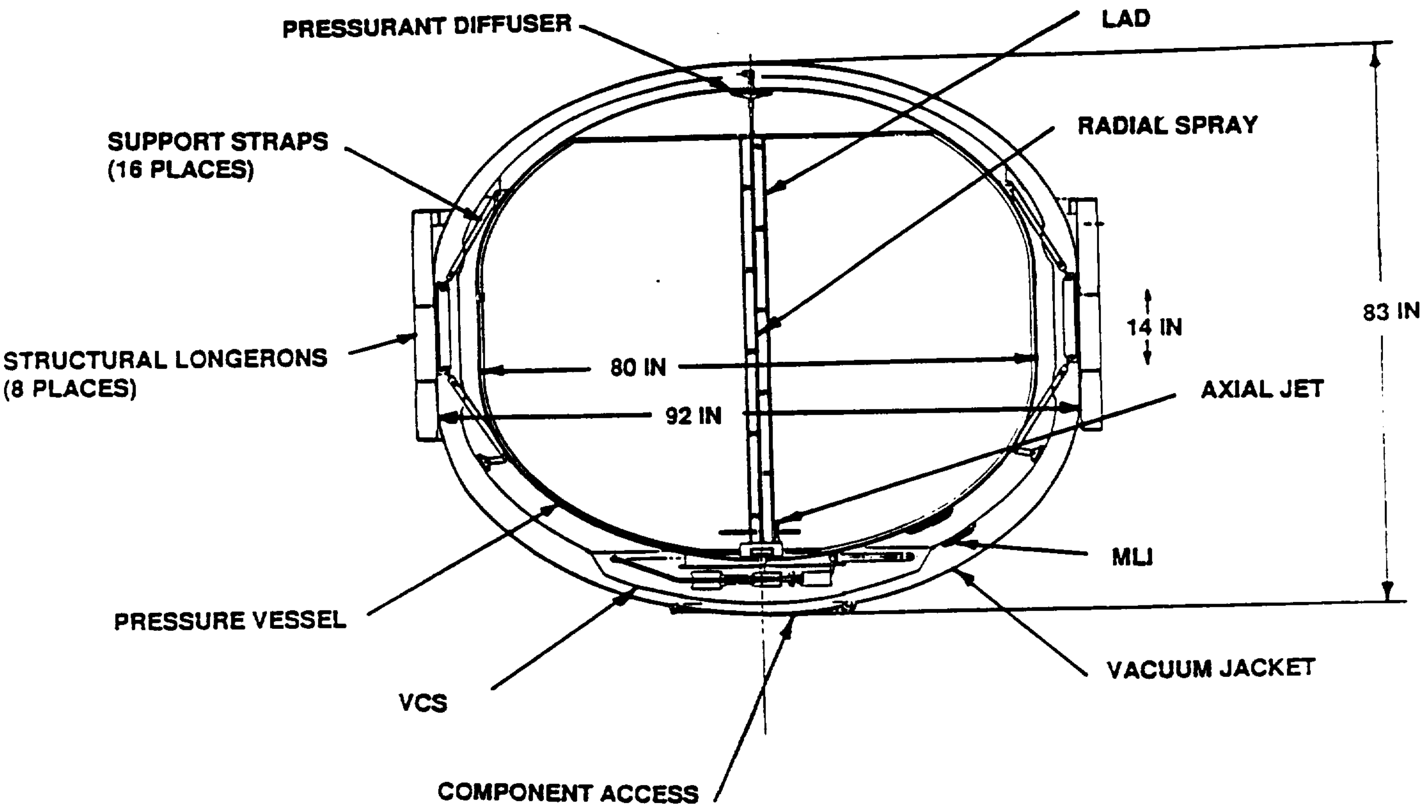


Figure 4.2-1 Supply Tank Design

Figure 4.2-2 is the supply tank portion of the integrated experiment subsystem schematic. It is extracted to show the details associated with instrumentation locations, and/or groupings, control network functions, plumbing/flow routings, component configurations, internal arrangements, along with interfaces to vents, to the fill/drain line, and to the pressurization system.

4.2.1 Pressure Vessel (PV) - This tank is an integrated cylindrical assembly consisting of a 4.25 m^3 (150 ft^3) 2219-T62 aluminum PV holding a quantity of 4019 liters (1060 gals) of LH2 at a maximum operating pressure of 482 kN/m^2 (70 psia) when loaded to 95% full. The assembly consists of two square root of 2, ellipsoidal shaped, domes welded to a short equatorial barrel section 35.6 cm (14 in) long by 203 cm (80 in) diameter. The dome wall thicknesses are a minimum of 0.25 cm (0.10 in) with increasing thickness at the poles and at the attachment girth ring interface of 0.36 cm (0.14 in). An increased thickness of 0.36 cm (0.14 in) is also provided at the 8 strap attachment locations on each dome. The barrel section has a constant wall thickness of 0.36 cm (0.14 in). These wall thicknesses resulted from a 2.0 safety factor (derived requirement) imposed on the design yield point using a maximum analyzed pressure of 965 kN/m^2 (140 psia). This configuration results in a leak before burst design. A requirement for design collapse pressure has also been incorporated into the design. The PV contains the following internal parts:

Liquid Acquisition Device (LAD) - The PV contains a total communication LAD that interfaces at the poles of the tank (± X axis). It makes use of the surface tension forces produced at the interface between the gas and liquid within the pores of a fine-mesh screen and is the key element for subcritical gas-free expulsion of LH2 in the low-g space environment. The outlet

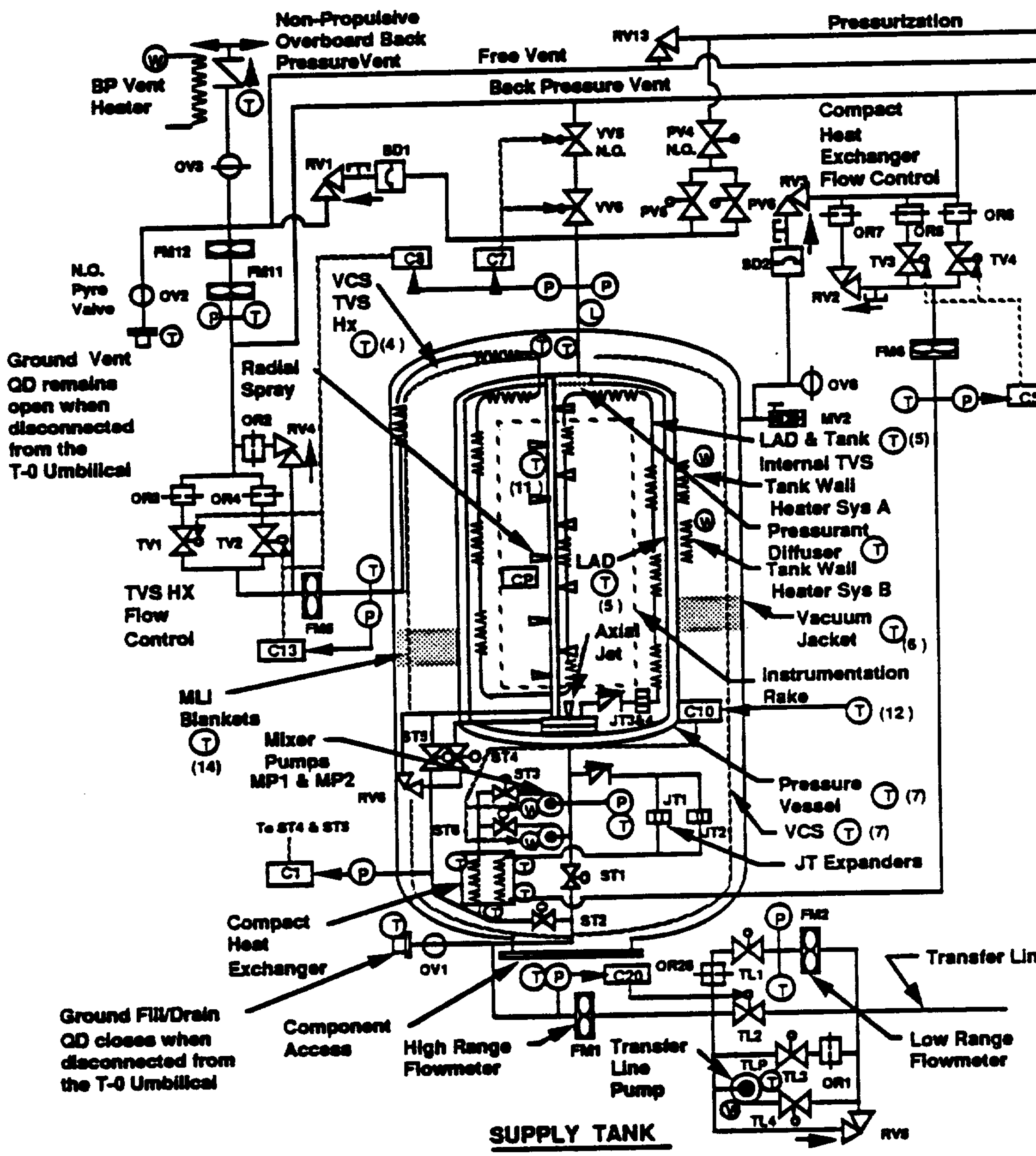
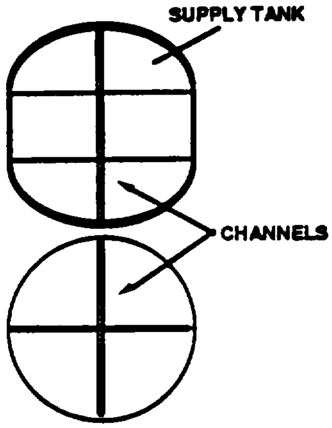


Figure 4.2-2 Supply Tank Schematic

end is fixed by a welded stainless steel to aluminum bi-metallic transition tube between the acquisition device and the PV. Four 7.6 cm x 1.27 cm (3 in x 0.5 in) continuous stainless steel channels manifolded at the outlet make up the configuration which is shown in Figure 4.2-3. The channels are truncated at the top of the tank, terminating the flow passage such that the four channels join at the top of the tank to provide rigidity and support. The channels are terminated at the top to prevent exposure of the screen to the tank ullage during the ground loading and launch phase of the mission. The 128 x 905.5 wires/cm (325 x 2300 wires/inch) stainless steel double Dutch twill screen is welded to the channel side facing the tank wall and is backed up by perforated plate for structural support. This configuration provides for continuous screen continuity within each channel to maintain the necessary wetting and wicking characteristics near the PV wall that result in high expulsion efficiencies estimated to be 99.5% for the supply tank and high resistance to breakdown. Attachment to the PV is provided at the top and bottom of the barrel section using slip fit clips to allow for needed LAD movement across the required thermal range.



- FOUR CHANNELS USING 325 X 2300 FINE MESH SCREEN BACKED WITH 50% OPEN PERFORATED PLATE
- CHANNEL DIMENSIONS: 3" X .5" X 97"
- EXPULSION EFFICIENCY: ~99.5%

Figure 4.2-3 Supply Tank LAD Configuration

Radial Spray System - This system of ten 0.159 cm (0.0625 in) diameter orifice sized spray nozzles are located on a radial standpipe which is off-set from the tank center line so as to minimize interference with the spray action from the axial jet. They are evenly located along the standpipe and symmetrically spaced at 36° to provide uniform coverage to optimize ullage cooling during back transfers from the receiver tanks to enhance supply tank top-off. Fluid from the mixer pump(s) can also be routed to these nozzles for tank fluid mixing and destratification tests.

Axial Jet Spray - The prime mixing mode for the supply tank for purposes of reducing thermal stratification will utilize a single 2.54 cm (1 in) diameter jet which is located at the outlet end of the tank along the tank centerline with the spray directed towards the vent end. Mixer pump flow between 18.1 to 49.9 kg/hr (40 to 110 lb/hr) can be routed to the jet so that mixing can be evaluated for both geysering and non-geysering conditions. Flow rate is controlled by varying the speed of the pump.

LAD Mounted TVS HX - The LAD does not control the location of the ullage within the tank in a low-g environment, so venting of the tank (controlling tank pressure) in the conventional manner of opening the tank vent is not possible. The TVS HX internal to the tank mounted on the four LAD channels provides a means for relieving the tank pressure increase due to heat input. The TVS HX will be utilized to remove heat from the cryogen in the COLD-SAT supply tank. This HX can be used in two modes. The first is labeled nominal and is a situation where the heat removal rate (i.e. line flow rate) is equal to the heating rate of the fluid. This case will be utilized to maintain a constant tank pressure. The other operational mode will be where the flow rate exceeds the nominal case to reduce tank pressure. As of now, the TVS HX will only be utilized in the nominal mode, but the capability for the excess flow must be accommodated for in the design.

In the TVS, LH2 is withdrawn from the LAD and passed through Joule-Thomson expanders. This chilled fluid at a reduced pressure is then routed into a manifold that diverts the flow into a 0.64 cm (0.25 in) diameter heat exchanger tube mounted to the back side of each of the four

LAD channels. The vented fluid is used as a refrigerant to reduce or maintain the net heat input to the tank based on TVS flow adjustment. At the vent end of the tank the fluid enters another manifold where the flow comes back together where it exits the PV for routing to the VCS.

The other function for the HX will be to ensure vapor free operation of the tank Liquid Acquisition Device (LAD). By routing the HX tubing properly over the surface of the LAD, the cooling capability of the fluid can be used to condense any vapor bubbles that might form in the LAD. These two requirements provide a complication in the design, since to provide cooling to the entire LAD might present a different flow rate than the heat removal/pressure control requirement would call for.

Vent Line Pressurant Diffuser - The pressurant diffuser at the end of the vent line is designed to disperse incoming GH2 pressurant and to prevent direct pressurant impingement on the liquid. It is important, for optimized use of the fixed quantity of stored GH2 pressurant, not only to introduce pressurant at a warm condition, but also to prevent pressurant mixing into the liquid. The diffuser will also tend to retard migration of liquid out of the vent during settled vent tests.

External Wall Mounted Heaters - Tank stratification is induced by external wall mounted surface heaters that provide both uniform and very low heating to establish heat fluxes of 0.315, 0.95, and 1.9 w/m^2 (0.1, 0.3 and 0.6 Btu/hr-ft^2). Heater blankets that provide heating densities of 0.315 to 1.9 w/m^2 (0.03 to 0.18 w/ft^2) are required. Total heater power for these cases varies from 4.14 to 24.8 watts.

Instrumentation Rake - A composite tube instrumentation rake is attached to the back side of the LAD channels at the 95% and 5% full levels, respectively. It provides mounting for tank fluid temperature sensors at various locations with respect to both fill level and position within the fluid.

4.2.2 Vacuum Jacket (VJ) - An annular vacuum region of 15.2 cm (6 in) surrounds the pressure vessel and is provided by a cylindrical vacuum jacket made of 2219-T62 aluminum. The assembly consists of two square root of 2, ellipsoidal shaped, domes welded to a short equatorial barrel section 45.7 cm (18 in) long by 234 cm (92 in) in diameter. The dome wall thicknesses are 0.51 cm (0.22 in) with similar thickness at the poles and at the attachment girth ring interface. The barrel section also has a constant wall thickness of 0.51 cm (0.22 in) and has added strength provided by 8 spacecraft structural longerons and girth ring supports. These wall thicknesses resulted from a 1.5 safety factor (derived requirement) imposed on the design yield point using a maximum analyzed collapse pressure of 101.3 kN/m^2 (14.7 psia). The lower dome contains a penetration for contingency component access. The VJ contains the following internal/external parts:

Vapor Cooled Shield (VCS) & TVS HX - The heat flux requirement has set the nominal TVS flow rate to 0.157 kg/hr (0.071 lb/hr). This flow after it exits the internal tank HX is routed onto the VCS using the same sized tubing. At this point the fluid in the HX is all cold gas which is used to intercept heat on the VSC before it reaches the tank. The VCS is 6061-T62 aluminum and is placed so that 38% of the insulation thickness is below it.

Multi Layer Insulation (MLI) - The thermal design of the COLD-SAT supply tank MLI system was based on achieving a nominal heat leak into the tank with the TVS off. Via the use of a Thermodynamic Vent System (TVS), a Vapor Cooled Shield (VCS), and Multi-Layer Insulation (MLI) the heat flux into the tank can be controlled to whatever is required. The heat flux value for the COLD-SAT supply tank was set at 0.315 w/m^2 (0.1 Btu/hr-ft^2) per direction from NASA LeRC. This value resulted in a required tank heat leak of 43.2 w (13.7 Btu/hr). Another imposed requirement was that the heat transfer into the cryogen via conduction paths should be less than 10% of the total. The two customer directions plus the functional requirement to control tank pressure were the primary design drivers for the MLI system.

The above were used to determine the derived design requirements of the tank insulation system. Analysis of the tank lockup case showed that the desired heat flux can be obtained with 1.9 cm (0.75 in) of MLI on the inner tank and 3.18 cm (1.25 in) on the VCS. The conduction can be limited to ~7% of the total heat leak via the use of thermal intercepts between the VCS and the tank supports and plumbing.

The MLI configuration consists of 3.8 x 10^{-3} mm (0.15 mil) double aluminized Mylar radiation shields separated by two Dacron B4A net spacers, assembled to a layer density of 24 reflectors/ cm (60/in).

Expose VJ Annulus to Space Environment - Once the COLD-SAT is on-orbit an ordnance valve will be actuated open to expose the vacuum jacket annular region to the hard space vacuum. This will aid in thermal performance of the system should small leaks develop from all of the components and fittings located in the annulus.

Compact Heat Exchanger (CHX) - The functional requirement of the compact heat exchanger (CHX) system is to provide active pressure control for the supply tank and thermal subcooling to outflow fluid. The CHX must provide sufficient heat removal capacity for a heat flux of 1.9 w/m^2 (0.6 BTU/ft^2-hr), which is 6 times the nominal tank heating rate and is equivalent to 265 w (84 BTU/hr). It was assumed that the CHX should provide 34.5 kN/m^2 (5 psi) of subcooling to the outflow at 45.4 kg (100 lbm/hr), which is equivalent to 1701 w (540 BTU/hr) of heat removal. The CHX system analysis produced the design requirement of a 3 m (10 ft) concentric tube heat exchanger.with a 2.54 cm (1.0 in) outer tuber and 1.6 cm (0.625 in) inner tube. The two phase fluid flows thru the inner tube at a rate of 0.73 to 1.45 kg/hr (1.6 to 3.2 lb/hr). The CHX is mounted to the bottom of the PV so that it is thermally shorted to the tank as shown in Figure 4.2-4.

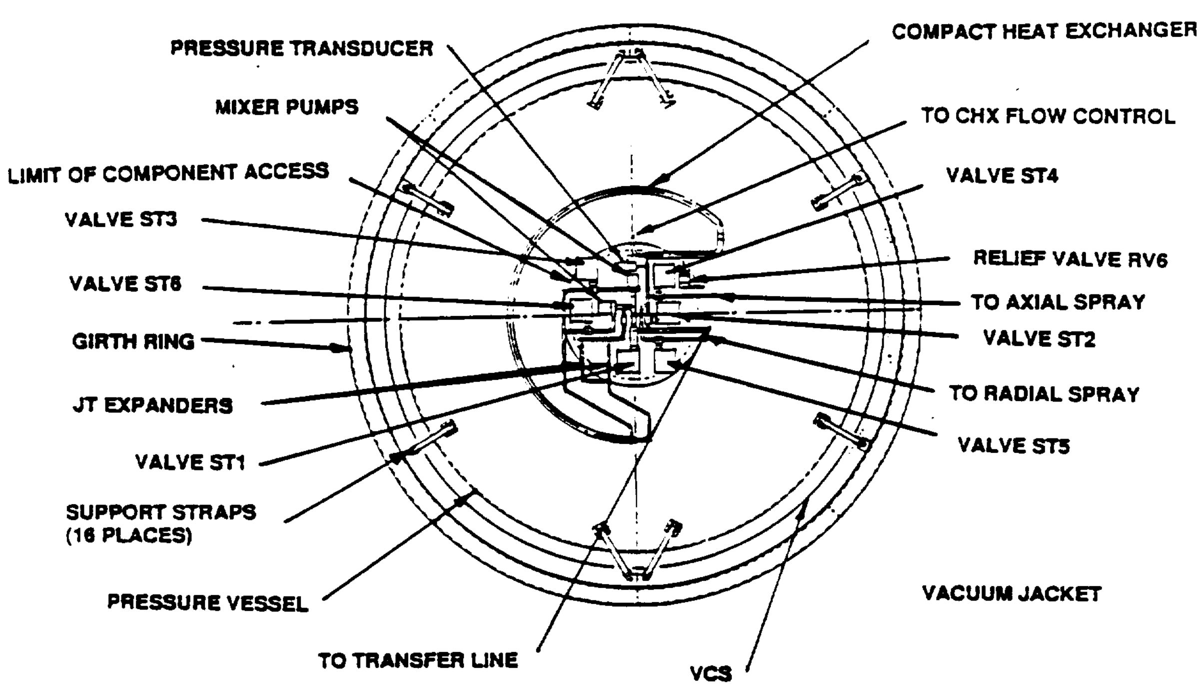


Figure 4.2-4 Supply Tank Vacuum Annular Region Design Details

Mixer Pumps - Figure 4.2-5 illustrates the single pump concept for mixing and transfer functions. The pump consists of a 3-phase variable speed ac motor connected to a partial emission impeller by low thermal conductivity shaft. The pump can operate at different speeds. This is accomplished by varying the ac power to the motor. The ac power is provided by a controller external to the pump. The controller contains inverters to generate ac power from the dc power available on COLD-SAT. The pump and motor housing is completely welded to provide a hermetically sealed package which could be placed inside the supply tank vacuum annulus. The motor housing is aluminum whereas the electrical feed-through and impeller housing are stainless steel, so bi-metallic unions are included in the design. The motor housing is aluminum to promote heat dissipation via conduction to the supply tank. Heat dissipation is important to prevent vapor formation in the motor which could migrate across the seal and cavitate the pump. The pump is designed so that the impeller, shaft, and motor cavities are flooded with LH2. There are labyrinth seals separating the motor and impeller, but they are included only to prevent large flows along the shaft. LH2 can slowly migrate across the seal. The impeller has a partial emission design which permits adequate efficiency at relatively low pump speeds. The impeller also features a screw type inducer at the inlet to provide low NPSH operating capability.

The characteristics for the pump are shown in Table 4.2-1 for the three operating modes. The physical characteristics of the pump are shown in the first three lines and remain constant for all modes of operation. The operating characteristics are listed below the physical characteristics. These include for each mode the head rise, flow rate, head coefficient (y), flow coefficient (j), actual speed, specific speed, and pump efficiencies. It can be seen that the pump efficiency is over 40% for all modes, so the impeller design is adequate for all modes of operation. The overall efficiency, which includes pump and motor efficiencies, is lower than the pump efficiencies because of the motor contribution. The lowest overall efficiency occurs in the low mixing mode, but this does cause excessive heating because of the low power level required for mixing. The table also presents the motor characteristics. The input power varies from 6.0 watts for the low flow mixing to 80.9 watts for transfer. These power levels are broken out into pump and motor power dissipation at the bottom of the table. The worst case heat input is for mixing where 36.32 watts are dissipated in the motor and 44.59 are dissipated in the pump. Motor heat dissipation is shown for an ambient temperature condition. Motor operation at LH2 conditions is expected to result in an order of magnitude less heat dissipation.

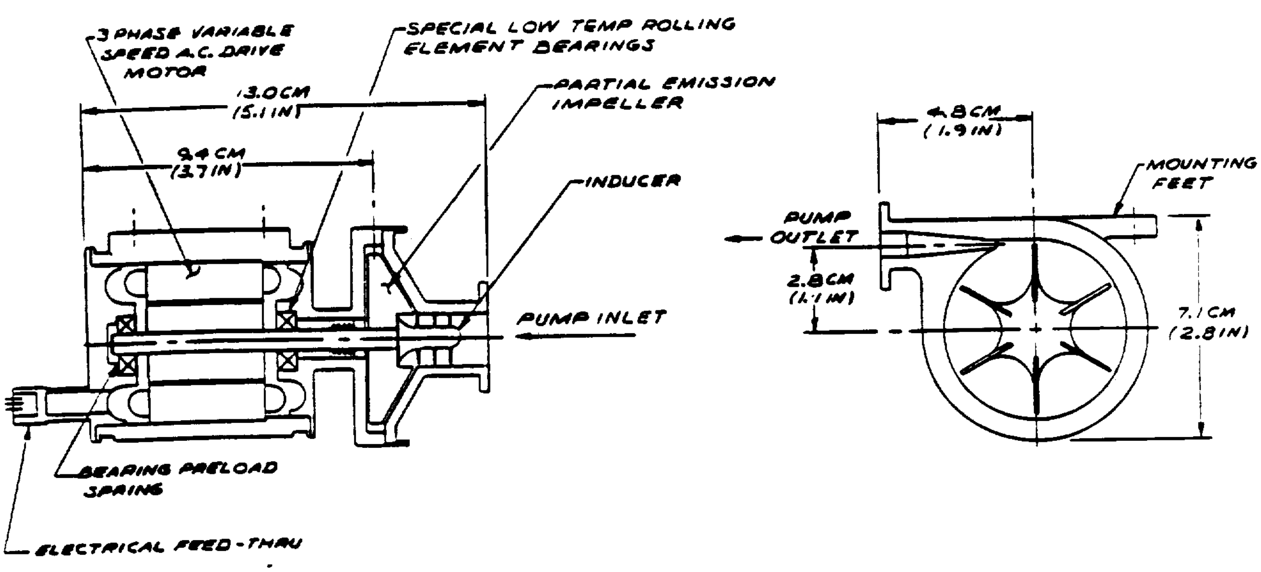


Figure 4.2-5 LH2 Mixer/Transfer Pump Design Details

Table 4.2-1 LH2 Mixer/Transfer Pump Characteristics

	LOW MIXING	HIGH MIXING	TRANSFER
PUMP:			
IMPELLER DIAMETER (IN)	2.2	2.2	2.2
THROAT DIAMETER (IN)	0.169	0.169	0.169
BLADE HEIGHT (IN)	0.204	0.204	0.204
HEAD (FEET)	16.3	65.0	260.1
FLOW RATE (LBM/HR)	55	110	200
HEAD COEFFICIENT	0.682	0.682	0.687
FLOW COEFFICIENT	0.800	0.800	0.729
SPEED (RPM)	2890	5770	11,500
SPECIFIC SPEED	20.9	20.9	19.9
PUMP EFFICIENCY (%)	41.4	43.5	43.9
OVERALL EFFICIENCY (%)	2.5	16.8	24.1
MOTOR:			
VOLTAGE (VAC 3-PHASE 400 HZ)	51.0	102.0	200.0
INPUT POWER (WATTS)	6.0	16.6	80.9
MOTOR EFFICIENCY (%)	13.5	37.3	55.1
HEAT INPUT TO SYSTEM:			
MOTOR (WATTS)	5.19	10.41	36.32
PUMP (WATTS)	0.82	6.19	44.59
TOTAL(WATTS)	6.01	16.60	80.91

Support Straps - The PV is supported to the VJ by 16 composite tension support straps. The straps are mounted to thickened areas on the PV domes and to the VJ barrel section. This allows for the installation of the completed PV, VCS and MLI including all plumbing penetrations that interface with the VJ barrel to be assembled and installed prior to the closure of VJ dome to barrel section welds.

4.2.3 Fluid Distribution and Control - Four plumbing penetrations exit the supply tank at the VJ barrel section. They all require isolation and control valving and instrumentation to contain and control the outflow and inflow of LH2 and GH2. Functions provided are as follows:

TVS & CHX Flow Control - Flow in both the TVS and CHX is controlled by electrically operated on-off latching valves actuated by commands routed to RIU's 11 to 14. Two flow control legs containing orificed restrictions provide the capability to regulate flow to three levels. TVS tubing is 0.64 cm (0.25 in) OD with a 0.17 cm (0.065 in) wall thickness. Associated components are all 0.64 cm (0.25 in) in size. The tubing after exiting the CHX is 1.3 cm (0.50 in) OD with similar sized components.

Outlet/Inlet Line - This 1.9 cm (0.75 in) OD line carries the LH2 from the tank LAD to the transfer line for routing to either receiver tank or to the vent system via the transfer/vent by-pass. Internal to the vacuum jacket LH2 from this line can be routed to the mixer pumps or to the two phase side of the CHX via a JT expander.

Vent Line - The tank vent line is 2.5 cm (1.0 in) OD exiting the tank through similar sized relief devices to the ground vent interface. Vent isolation is provided by 1.3 cm (0.5 in) electrically operated valves that interface with the 1.9 cm (0.75 in) OD BP/Free vent. Pressurant is introduced into this line via 1.3 cm (0.5 in) sized pressurant valves.

Ground LH2 Fill/Drain & Vent - The 1.9 cm (0.75 in) ground fill/drain QD at the T-0 umbilical interfaces with the LH2 ground servicing system and provides both fill and contingency drain capability for the tank.

Instrumentation - The tank and associated lines are fully instrumented. See section 4.7 for details.

4.3 Receiver Tank 1

Receiver tank 1 is one of two tanks that provide an initially empty container for on-orbit LH2 childown, transfer and resupply evaluation and is composed of the following major subelements:

- Pressure Vessel
  - Total communication LAD for the tank outlet
  - Axial spray system and associated flow control
  - Inward facing wall mounted circumferential spray system
  - External tank wall mounted TVS heat exchanger
  - Vent line pressurant diffuser
  - MLI blankets
  - Tank supports

- Fluid distribution and control
  - Tank inlet/outlet
  - Back pressure and free vent system
  - Vent line
  - TVS flow control
  - Spray system flow control
  - Instrumentation

Receiver tank 1 is an insulated, non-vacuum jacketed, 1.13 m^3 (40.2 ft^3) tank capable of holding 74 kg (163 lbs) of LH2 at 95% full. To maximize the science of characterizing a single nozzle in a tank with a L/D of close to 2 when compared to the other receiver tank, the tank was configured to be empty of internal devices along the central axis. The length of the receiver tank 1 was selected to be 188 cm (74 in) with a diameter of 97 cm (38 in). The barrel section of the PV is 91 cm (36 in) long. The dome ends are spherical and can use the same forgings and tooling as receiver tank 2 [which is also 97 cm (38 in) in diameter]. The M/V is approximately 2.1 and the L/D is 1.95. The PV contains a total communication LAD with an outlet/inlet penetration which exits at a polar boss in the lower hemisphere. A vent/pressurization penetration exits at the dome pole. Axial and wall mounted inward pointing (circumferential) spray systems are provided for childown and fill/refill testing. An external tank TVS routed on the tank wall and on other critical surfaces is provided to cool the tank contents. An optimized MLI blanket [2.5 cm (1.0 in) or less] covers the entire tank. The tank is supported to the spacecraft structure with 8 composite struts. Figure 4.3-1 shows a cutaway view of the tank with major subelements identified.

An integrated experiment subsystem schematic has been previously shown in Figure 4.1-3. The receiver tank 1 portion of this schematic has been extracted in Figure 4.3-2 to show the details associated with it. These include design details, instrumentation locations and/or groupings, control network functions and plumbing/flow routings and component relationships. Interfaces with vents, fill/drain lines,transfer lines, pressurization system and other system features are shown.

4.3.1 Pressure Vessel - This tank is an integrated cylindrical assembly consisting of a 1.13 m^3 (40.2 ft^3) 2219-T62 aluminum PV holding a quantity of 1040 liters (274 gals) of LH2 at a maximum operating pressure of 482 kN/m^2 (70 psia) when loaded to 95% full. The assembly consists of two spherical shaped domes welded to a 91 cm (36 in) long by 97 cm (38 in) diameter equatorial barrel section. The dome wall thicknesses are a minimum of 0.11 cm (0.045 in) with increasing thickness at the poles and at the attachment barrel section interface of 0.25 cm (0.10 in). The barrel section has a constant wall thickness of 0.25 cm (0.10 in). These wall thicknesses resulted from a 2.0 safety factor (derived requirement) imposed on the design yield point using a maximum analyzed pressure of 965 kN/m^2 (140 psia). This configuration results in a leak before burst design. A requirement for design collapse pressure has also been incorporated into the design. The PV contains the following internal/external parts:

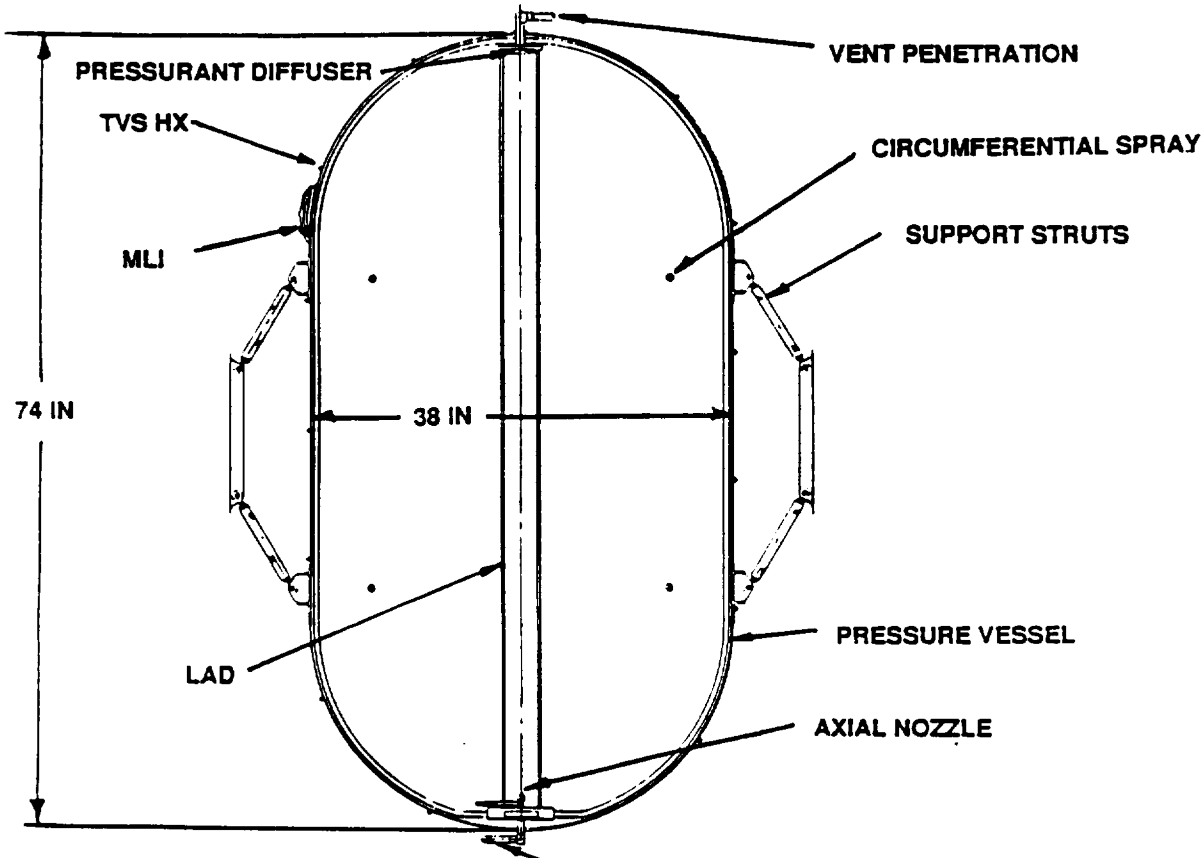


Figure 4.3-1 Receiver Tank 1 Design

Liquid Acquisition Device (LAD) - The PV contains a total communication LAD that interfaces at the poles of the tank (± X axis). It makes use of the surface tension forces produced at the interface between the gas and liquid within the pores of a fine-mesh screen and is the key element for subcritical gas-free expulsion of LH2 in the low-g space environment. The outlet end is fixed by a welded stainless steel to aluminum bi-metalic transition tube between the acquisition device and the PV. Four 7.6 cm x 1.27 cm (3 in x 0.5 in) continuous stainless steel channels manifolded at the outlet make up the configuration which is similar to the supply tank LAD design shown in figure 4.2-3. The channel flow passages terminate at the top of the tank such that the four channels structurally connect to provide rigidity and support. The 128 x 905.5 wires/cm (325 x 2300 wires/inch) stainless steel double Dutch twill screen is welded to the channel side facing the tank wall and is backed up by perforated plate for structural support. This configuration provides for continuous screen continuity within each channel to maintain the necessary wetting and wicking characteristics near the PV wall that result in high expulsion efficiencies estimated to be greater than 99% for this tank and high resistance to breakdown. Attachment to the PV is provided at the top and bottom of the barrel section using slip fit clips to allow for needed LAD movement across the required thermal range. This device is not configured to be able to be stressed or compromised by flowrate or acceleration. See section 4.9 for analysis regarding this requirement.

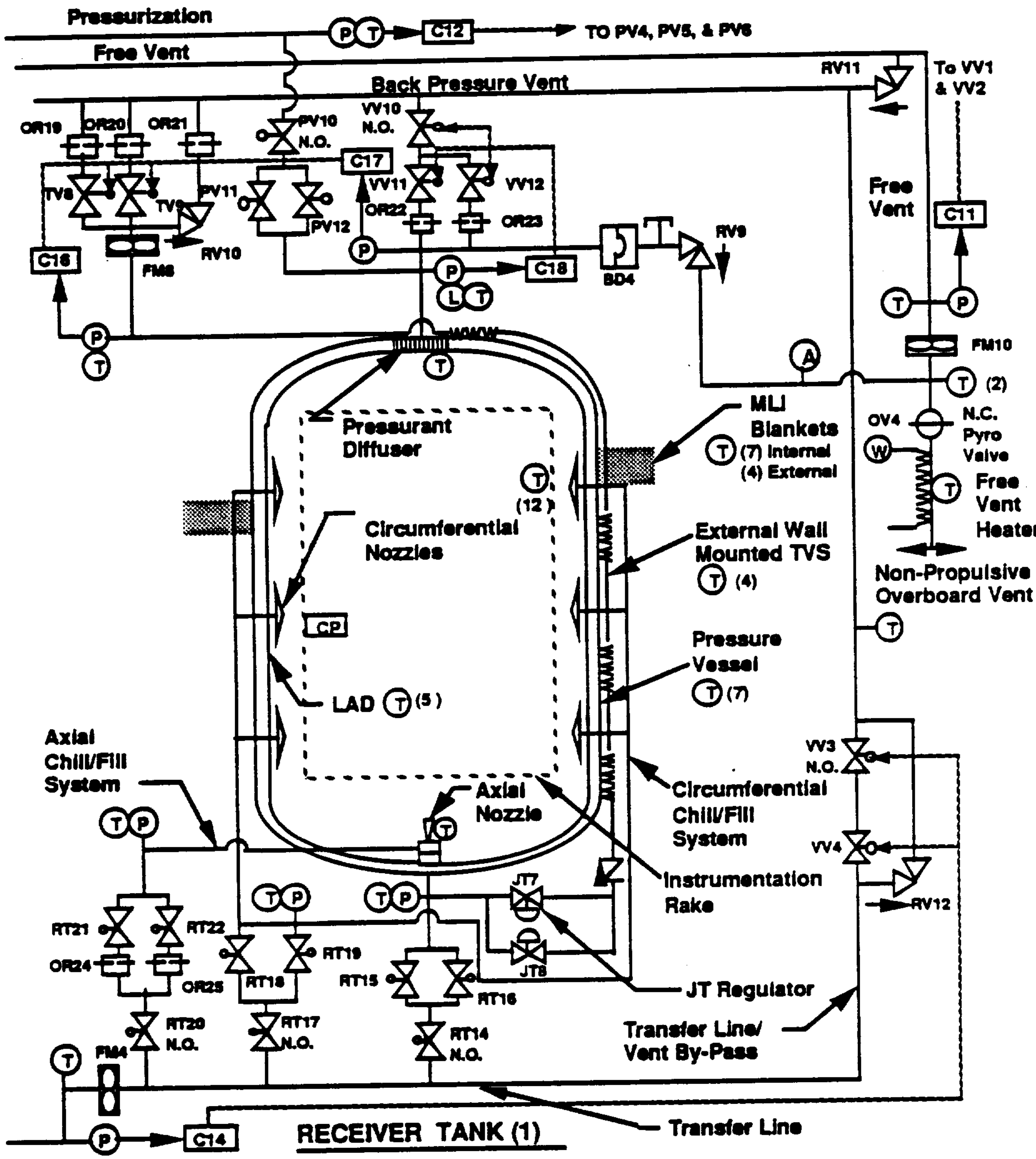


Figure 4.3-2 Receiver Tank 1 Schematic

Axial Spray System - A large part of the investigations to be performed with this single nozzle is to simulate the effect of nozzles mounted on a central radial spray stand pipe in a 3.66 m (12 ft) diameter tank. A nozzle with an orifice diameter of 0.4 cm (0.156 in) was selected to promote a hollow spray pattern with a minimal risk to clogging while producing small droplet sizes that result in droplet heating up to 90% of the saturation temperature for the contact time provided by the tank length and droplet velocity. Tests were desired for cases where liquid was settled away from the nozzle to collect at the vent end, as well as, where liquid was settled over the nozzle so that jet effects could be studied. Only the former could be incorporated into the experiment set due to LH2 budget constraints. Use of the axial spray without settling acceleration will also be performed. The tank is centrally empty to accommodate these tests.

Circumferential Spray System - This spray system consists of 6 inward facing spray nozzles mounted on the circumference of the tank wall. They will be used for both chilldown and fill assessments. An extra wide angle type of nozzle spray pattern is desired to simultaneously direct the flow pattern both inward and along the wall. A nozzle with an orifice diameter of 0.16 cm (0.0625 in) was selected to promote a 165° spray pattern while producing small droplet sizes that result in droplet heating up to 90% of the saturation temperature for the contact time provided by the tank diameter and droplet velocity.

TVS Heat Exchanger - The LAD does not control the location of the ullage within the tank in a low-g environment, so venting of the tank (controlling tank pressure) in the conventional manner of opening the tank vent is not possible. The TVS HX is mounted external to the tank on the wall and provides a means for relieving the tank pressure increase due to heat input. The TVS HX will be utilized to remove heat from the cryogen in the receiver tank. This HX can be used in two modes. The first is labeled nominal and is a situation where the heat removal rate (i.e. line flow rate) is equal to the heating rate of the fluid. This case will be utilized to maintain a constant tank pressure where the TVS flowrate just balances the incoming heat leak. The other operational mode will be where the flow rate exceeds the nominal case to reduce tank pressure. In this mode the TVS flow rate will be increased by a factor of 2-3 to drop tank pressure by subcooling the tank contents.

In the TVS, LH2 is withdrawn from the LAD and passed through Joule-Thomson expanders. This chilled fluid at a reduced pressure is then routed into a manifold that diverts the flow into a 0.64 cm (0.25 in) diameter heat exchanger tube mounted to the tank wall exterior. The vented fluid is used as a refrigerant to reduce or maintain the net heat input to the tank based on TVS flow adjustment.

Vent Line Pressurant Diffuser - The pressurant diffuser at the end of the vent line is designed to disperse incoming GH2 or GHe pressurant and to prevent direct pressurant impingement on the liquid. It is important not only to introduce pressurant at a warm condition, but also to prevent pressurant mixing into the liquid for optimized use of the fixed quantity of stored GH2 and GHe pressurant. The diffuser will also tend to retard migration of liquid out of the vent during settled vent tests and for ullage exchange transfers.

MLI Blankets - The thermal design of COLD-SAT receiver tank 1 MLI system was based on achieving a nominal heat leak into the tank with the TVS off. Via the use of a Thermodynamic Vent System (TVS) heat exchanger and Multi-Layer Insulation (MLI) the heat flux into the tank can be controlled to whatever is required. The heat flux value for the COLD-SAT supply tank was set at 1.58 w/m^2 (0.5 $Btu/hr\text{-}ft^2$) per direction from NASA LeRC. This value resulted in a required tank heat leak of 97.7 w (31 Btu/hr). This requirement plus the functional requirement to control tank pressure were the primary design drivers for the MLI system.

The above were used to determine the derived design requirements of the tank insulation system. It was estimated that the desired heat flux can be obtained with no more than 2.5 cm (1.0 in) of MLI on the tank.

The MLI configuration consists of 3.8×10^{-3} mm (0.15 mil) double aluminized Mylar radiation shields separated by two Dacron B4A net spacers, assembled to a layer density of 24 reflectors/ cm (60/in).

Tank Supports - Eight composite tube support struts with aluminum end fittings connect the PV to the spacecraft rectangular tube support structure. The struts mount to clevis attachment fittings on the barrel section. Figure 4.3-3 shows a top view of the tank mounted to the structure.

4.3.2 Fluid Distribution and Control - Nine plumbing penetrations exit receiver tank 1 along with a TVS flow control line. They all require isolation and control valving and instrumentation to contain and control the outflow and inflow of LH2 and GH2. Functions provided are as follows:

TVS Flow Control - Flow in the TVS is controlled by electrically operated on-off latching valves actuated by commands routed to RIU's 11 to 14. Two flow control legs containing orificed restrictions provide the capability to regulate flow to three levels. TVS tubing is 0.64 cm (0.25 in) OD with a 0.17 cm (0.065 in) wall thickness. Associated components are all 0.95 cm (0.375 in) in size.

Outlet/Inlet Line - This 1.9 cm (0.75 in) OD line carries the LH2 from the tank LAD to the transfer line for routing to either the supply tank or to the vent system via the transfer/vent by-pass.

Vent Line - The tank vent line is 1.3 cm (0.5 in) OD that connects to vent isolation provided by 1.3 cm (0.5 in) electrically operated valves that interface with the 1.9 cm (0.75 in) OD BP/Free vent. Two orificed vent paths are provided to accomplish various rates of gas venting to accommodate vented fill tests that require restricted venting capability. Pressurant is introduced into this line via 1.3 cm (0.5 in) sized pressurant valves.

Spray System Flow Control - Flow in the axial nozzle is controlled by electrically operated on-off latching valves actuated by commands routed to RIU's 11 to 14. Two flow control legs containing orificed restrictions provide the capability to regulate flow to three levels.

Instrumentation - The tank and associated lines are fully instrumented. See section 4.7 for details.

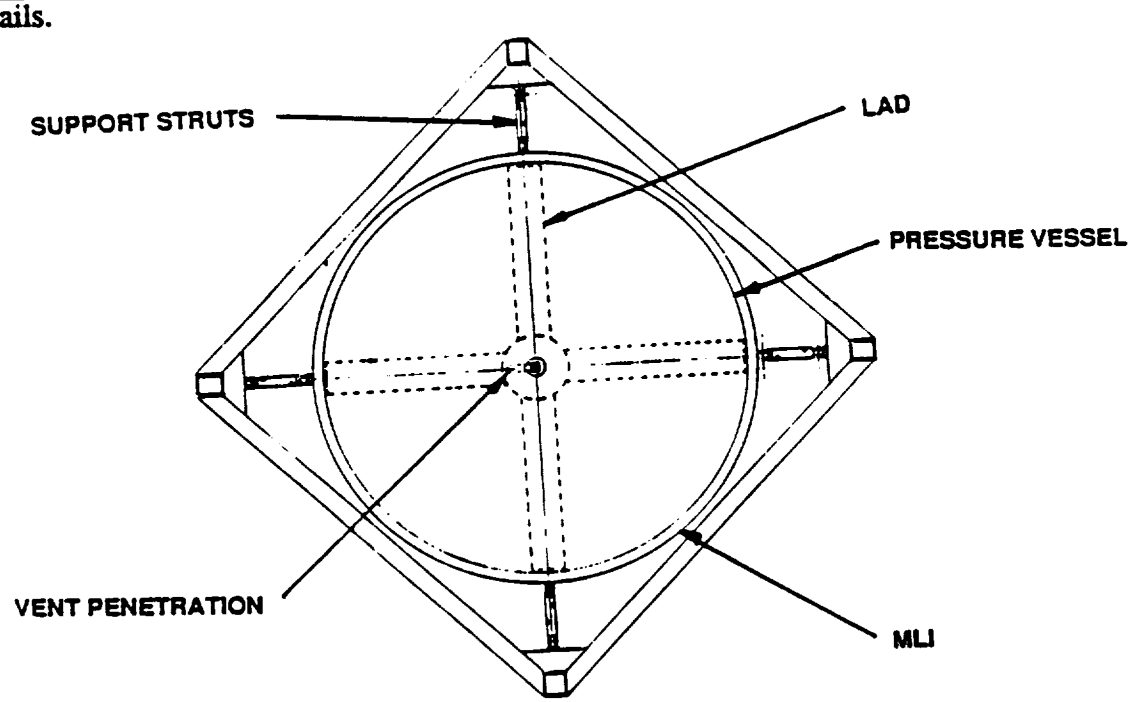


Figure 4.3-3 Receiver Tank 1 Mounting Configuration

4.4 Receiver Tank 2

Receiver tank 2 is one of two tanks that provide an initially empty container for on-orbit LH2 chilldown, transfer and resupply evaluation and is composed of the following major subelements:

- Pressure Vessel
  - Simple plate/screen baffle at the outlet
  - Axial spray system
  - Radial spray system
  - Tangential spray system
  - External wall mounted TVS heat exchanger
  - TVS heat exchanger chilldown
  - Vent line pressurant diffuser
  - MLI blanket
  - Warm-up heater
  - Trunnion support mounts
- Fluid distribution and control
  - Inlet/outlet
  - Back pressure & free vent system
  - Vent line
  - TVS flow control
  - Spray system flow control
  - Instrumentation

Receiver tank 2 is an insulated, non-vacuum jacket, 0.56 m^3 (19.9 ft^3) tank capable of holding 37 kg (81 lbs) of LH2 at 95% full. The tank is almost spherical 97 cm (38 in) diameter with a minimal 12.7 cm (5 in) girth ring section. The M/V is approximately 2.1 and the L/D is 1.1. The PV does not contain a LAD but has a simple screen/plate baffle at the outlet to minimize residuals during settled expulsions and prevents suction dip and vapor intrusion. During inflow through the inlet, the baffle also serves to direct the flow towards the tank wall and not towards the vent at the opposite end. The vent penetration exits the tank at the dome pole. The PV contains an exterior wall mounted TVS heat exchanger (no VCS) for pressure control. Axial, radial, and tangential spray systems are provided for tank chilldown and fill/refill testing. An optimized MLI blanket of 2.5 cm (1.0 in or less) thickness surrounds the PV. The tank is supported to the spacecraft structure with 2 trunnion supports. The current relationship of M/V of the two receiver tanks is 1 and should be as close to 2 as possible. Adding weight to receiver tank 1 is also an option. More detailed analysis is required to trim weight from receiver tank 2. In addition, a better definition of the mass of components and tank internals is required. Since chilldown testing is now concentrated in receiver tank 2, the desire is to achieve as low a M/V ratio as possible for it. The tank is mounted within the MMS rectangular tube support structure of the spacecraft using tank support trunnions mounted to the structure. Figure 4.4-1 shows a cutaway view of the tank with major subelements identified.

An integrated experiment subsystem schematic has been previously shown in Figure 4.1-3. The receiver tank 2 portion of this schematic has been extracted in Figure 4.4-2 to show the details associated with it. These include design details, instrumentation locations and/or groupings, control network functions and plumbing/flow routings and component relationships. Interfaces with vents, fill/drain lines, transfer lines, pressurization system and other system features are shown.

4.4.1 Pressure Vessel - This tank is an integrated, almost spherical, assembly consisting of a 0.56 m^3 (19.9 ft^3) 2219-T62 aluminum PV holding a quantity of 517 liters (136 gals) of LH2 at a maximum operating pressure of 482 kN/m^2 (70 psia) when loaded to 95% full. The assembly consists of two spherical shaped domes welded to a 12.7 cm (5 in) long by 97 cm (38 in) diameter equatorial barrel section. The dome wall thicknesses are a minimum of 0.11 cm (0.045 in) with increasing thickness at the poles and at the attachment barrel section interface of 0.25 cm (0.10 in). The barrel section has a constant wall thickness of 0.25 cm (0.10 in). These wall thicknesses resulted from a 2.0 safety factor (derived requirement) imposed on the design yield point using a maximum analyzed pressure of 965 kN/m^2 (140 psia). This configuration results in a leak before burst design. A requirement for design collapse pressure has also been incorporated into the design. The PV contains the following internal/external parts:

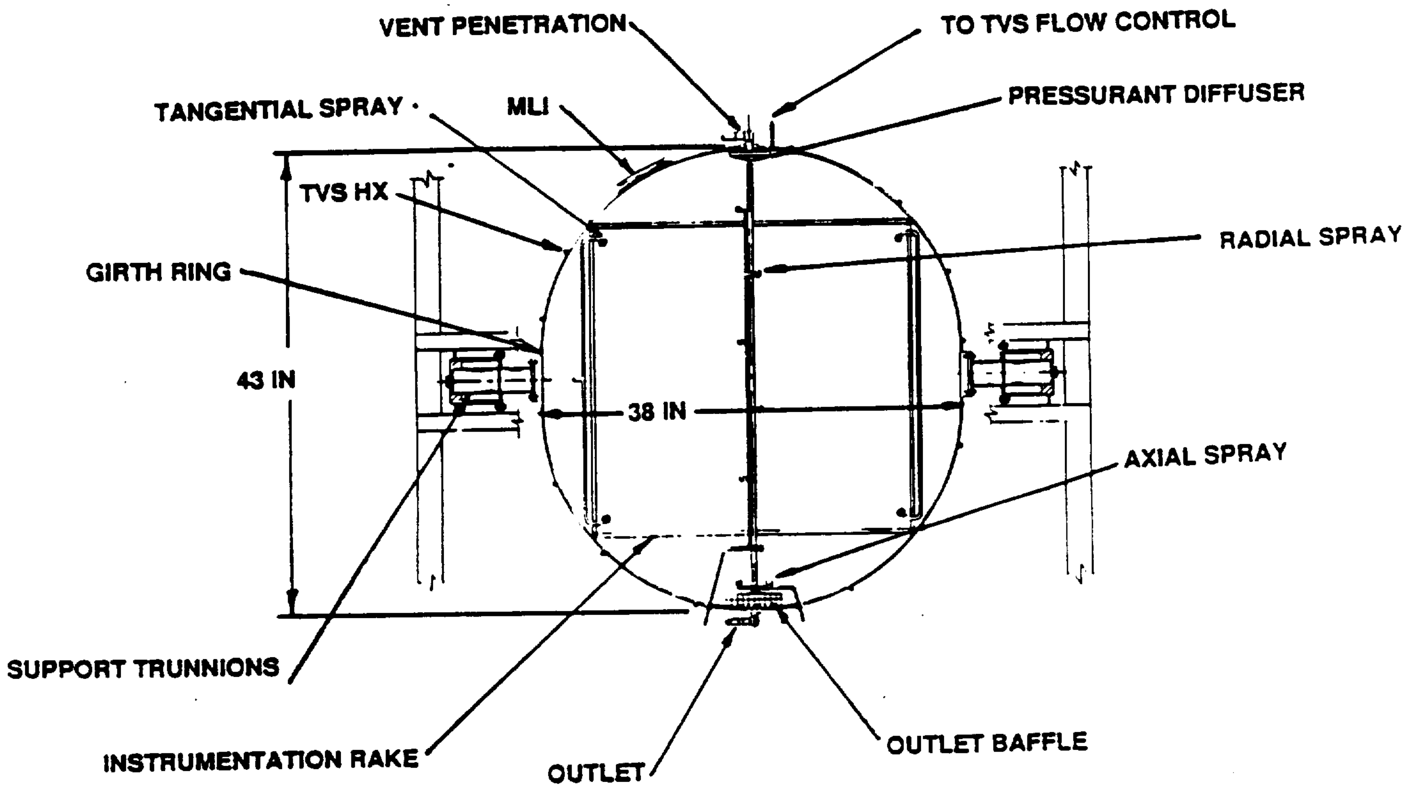


Figure 4.4-1 Receiver Tank 2 Details

Simple Plate/Screen Baffle - In order to keep the interior walls of this receiver tank "clean" so that persistent fluid motion/flow patterns may develop, a total communication type LAD was not desired. Use of settling accelerations during both tank inflow and outflows dictated the type of device that was needed to both accommodate inflow diffusion and minimize tank residuals during expulsions. These needs are accomplished by the use of a simple plate/screen baffle at the tank outlet. During settled tank outflows it prevents suction dip and resulting vapor intrusion. For settled vented fills and ullage exchange resupply, incoming fluid is directed towards the tank walls as to not directly impinge on the open vent line. Since TVS fluid is withdrawn from the tank outlet for tank pressure control, this device cannot guarantee the quality of fluid to the JT expander.

Axial Spray System - Two manifolded axial nozzles surrounding the radial spray stand pipe provide the capability to spray axially along the tank centerline for the purpose of contacting vapor for condensation during tank filling. They will also be used for tank chilldown. A nozzle with an orifice diameter of 0.32 cm (0.125 in) was selected to promote a hollow spray pattern with a minimal risk to clogging while producing small droplet sizes that result in droplet heating up to 90% of the saturation temperature for the contact time provided by the tank length and droplet velocity.

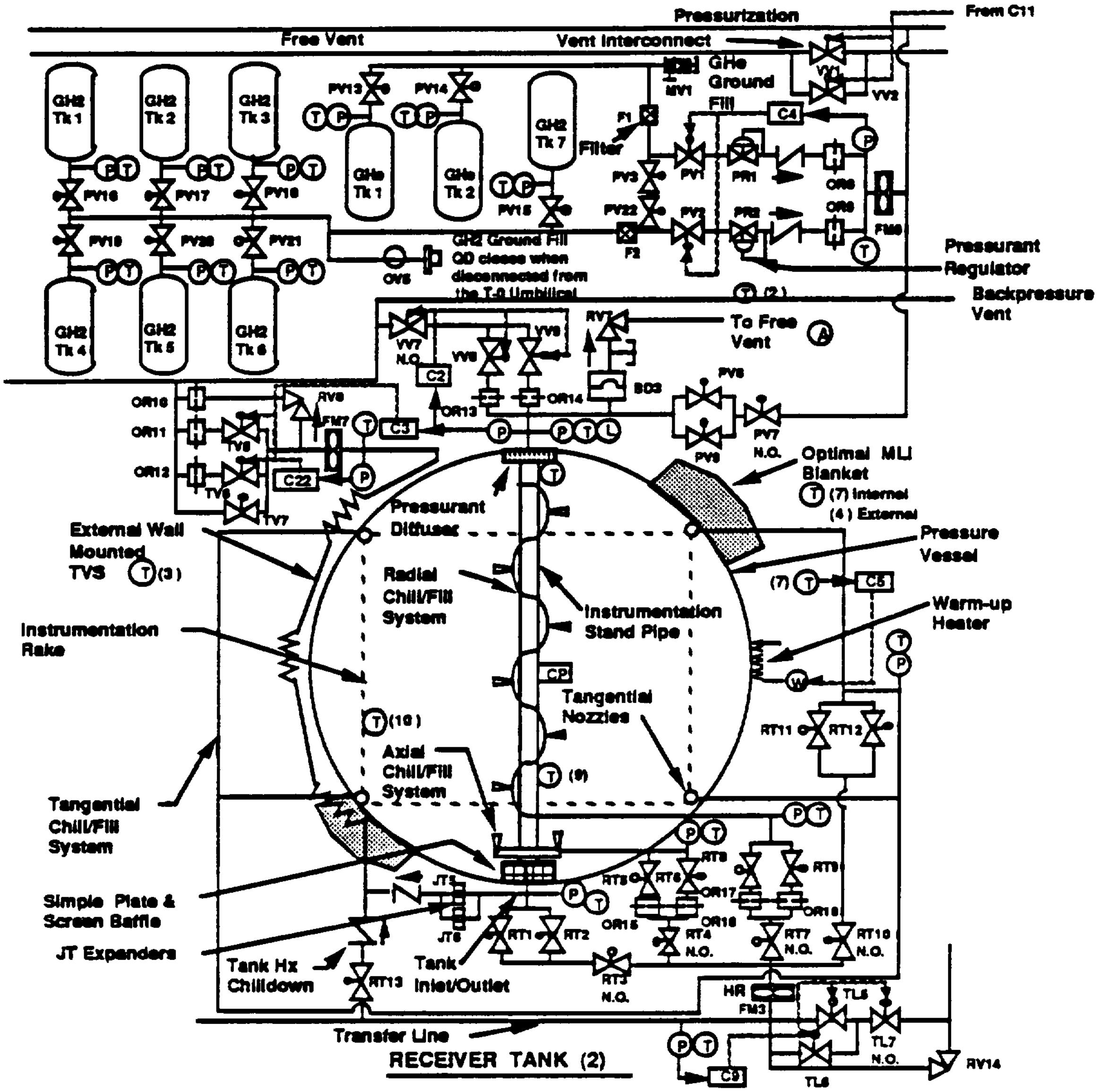


Figure 4.4-2 Receiver Tank 2 Schematic

Radial Spray System - Six manifolded radial nozzles evenly spaced around (at 60° intervals) and along the length of the radial spray stand pipe provide the capability to spray radially perpendicular to the tank centerline for the purpose of contacting vapor for condensation during tank filling. They will also be used for tank chilldown. A nozzle with an orifice diameter of 0.16 cm (0.0625 in) was selected to promote a hollow spray pattern with a minimal risk to clogging while producing small droplet sizes that result in droplet heating up to 90% of the saturation temperature for the contact time provided by the tank diameter and droplet velocity.

Tangential Spray System - This system consists of 4 spray nozzles which penetrate the tank wall and direct incoming liquid into a spray pattern tangential to the inner wall surface. Since full flow is desired from these nozzles a diameter of 1.1 cm (0.44 in) was selected to provide a maximum flow area while still providing for a velocity increase at the nozzle exit to promote the desired tangential fluid motion.

TVS Heat Exchanger - The LAD does not control the location of the ullage within the tank in a low-g environment, so venting of the tank (controlling tank pressure) in the conventional manner of opening the tank vent is not possible. The TVS HX is mounted external to the tank on the wall and provides a means for relieving the tank pressure increase due to heat input. The TVS HX will be utilized to remove heat from the cryogen in the receiver tank. This HX can be used in two modes. The first is labeled nominal and is a situation where the heat removal rate (i.e. line flow rate) is equal to the heating rate of the fluid. This case will be utilized to maintain a constant tank pressure where the TVS flowrate just balances the incoming heat leak. The other operational mode will be where the flow rate exceeds the nominal case to reduce tank pressure. In this mode the TVS flow rate will be increased by a factor of 2-3 to drop tank pressure by subcooling the tank contents.

In the TVS, LH2 is withdrawn from the LAD and passed through Joule-Thomson expanders. This chilled fluid at a reduced pressure is then routed into a manifold that diverts the flow into a 0.64 cm (0.25 in) diameter heat exchanger tube mounted to the tank wall exterior. The vented fluid is used as a refrigerant to reduce or maintain the net heat input to the tank based on TVS flow adjustment.

TVS Heat Exchanger Chilldown - Since the TVS heat exchanger tubing is in direct contact with the tank wall, chilldown fluid can be introduced into it to access tank chilldown using this technique.

Vent Line Pressurant Diffuser - The pressurant diffuser at the end of the vent line is designed to disperse incoming GH2 or GHe pressurant and to prevent direct pressurant impingement on the liquid. It is important not only to introduce pressurant at a warm condition, but also to prevent pressurant mixing into the liquid for optimized use of the fixed quantity of stored GH2 and GHe pressurant. The diffuser will also tend to retard migration of liquid out of the vent during settled vent tests and for ullage exchange transfers.

MLI Blanket - The thermal design of COLD-SAT receiver tank 2 MLI system was based on achieving a nominal heat leak into the tank with the TVS off. Via the use of a Thermodynamic Vent System (TVS) heat exchanger and Multi-Layer Insulation (MLI) the heat flux into the tank can be controlled to whatever is required. The heat flux value for the COLD-SAT supply tank was set at 1.58 w/m^2 (0.5 Btu/hr-ft^2) per direction from NASA LeRC. This value resulted in a required tank heat leak of 56.7 w (18 Btu/hr). This requirement plus the functional requirement to control tank pressure were the primary design drivers for the MLI system.

The above were used to determine the derived design requirements of the tank insulation system. It was estimated that the desired heat flux can be obtained with no more than 2.5 cm (1.0 in) of MLI on the tank.

The MLI configuration consists of 3.8 x 10^{-3} mm (0.15 mil) double aluminized Mylar radiation shields separated by two Dacron B4A net spacers, assembled to a layer density of 24 reflectors/ cm (60/in).

Warm-up Heater - Two banks of wall heaters provide 30 w of power each to receiver tank 2 for thermal conditioning to desired levels during experiment operations. Each bank provides uniform wall heating from dual element blanket type heaters which are bonded to the outer tank wall surface. Required heating density for the blanket is 0.08 w/m^2 (0.83 w/ft^2) for each redundant element.The wall heaters are controlled from separate RIU's and EVE's providing totally redundant and isolated control capability.

Trunnion Support Mounts - The girth ring provides the tank mounting location for two S-glass/ epoxy trunnions. One trunnion is fixed, and is adjusted to provide for proper positioning of the tank by a threaded fitting that is welded in place. The other trunnion has on open end that is free to move to allow for contraction and expansion of the pressure vessel/trunnion assembly. The trunnions have been successfully designed, fabricated and qualification tested for fatigue, loading, failure and design margin, under contract NAS3-23245 and were delivered to LeRC at the end of the program (Ref 4.4-1). Figure 4.4-3 shows a top view of the tank installed into the MMS rectangular tube support structure core cavity by the trunnion mounts.

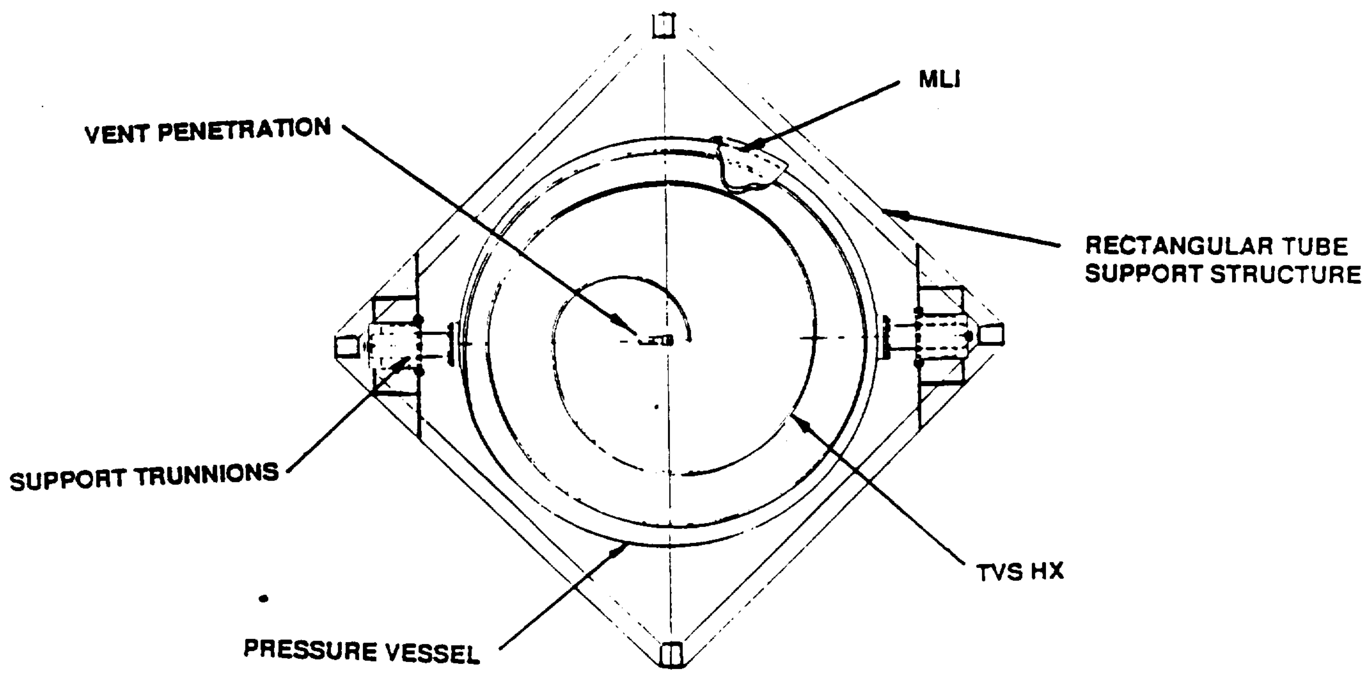


Figure 4.4-3 Receiver Tank 2 Mounting Configuration

4.4.2 Fluid Distribution and Control - Seven plumbing penetrations exit receiver tank 2 along with a TVS flow control line. They all require isolation and control valving and instrumentation to contain and control the outflow and inflow of LH2 and GH2. Functions provided are as follows:

TVS Flow Control - Flow in the TVS is controlled by electrically operated on-off latching valves actuated by commands routed to RIU's 11 to 14. Two flow control legs, containing orificed restrictions, provide the capability to regulate flow to three levels. TVS tubing is 0.64 cm (0.25 in) OD with a 0.17 cm (0.065 in) wall thickness. Associated components are all 0.95 cm (0.375 in) in size.

Outlet/Inlet Line - This 1.9 cm (0.75 in) OD line carries the LH2 from the tank baffle to the transfer line for routing to either the supply tank or to the vent system via the transfer/vent by-pass.

Vent Line - The tank vent line is 1.3 cm (0.5 in) OD that connects to vent isolation provided by 1.3 cm (0.5 in) electrically operated valves that interface with the 1.9 cm (0.75 in) OD BP/Free vent. Two orificed vent paths are provided to accomplish various rates of gas venting to accommodate vented fill tests that require restricted venting capability. Pressurant is introduced into this line via 1.3 cm (0.5 in) sized pressurant valves.

Spray System Flow Control - Flow in the axial and radial spray systems is controlled by electrically operated on-off latching valves actuated by commands routed to RIU's 11 to 14. Two flow control legs containing orificed restrictions provide the capability to regulate flow to three levels.

Instrumentation - The tank and associated lines are fully instrumented. See section 4.7 for details.

4.5 Pressurization

The pressurization system consists of the following functions that are provided to support tank pressurizations to accomplish the experiment set:

- GH2 & GHe pressurant storage at 20670 kN/m^2 (3000 psia)
- GH2 & GHe pressurant regulation to 276 kN/m^2 (40 psia)
- GH2 & GHe regulated pressurant distribution to experiment tankage
- GH2 & GHe ground fill

Pressurant storage is provided by nine tanks 29.8 cm (11.75 in) diameter by 122 cm (48 in) length with a volume of 0.076 m^3 (2.7 ft^3) pressurized to 20670 kN/m^2 (3000 psia) on the ground prior to flight. Seven tanks store 8 kg (17.5 lbs) of GH2 while the remaining two contain 4.5 kg (10 lbs) of GHe. Either pressurant can be used for receiver tank pressurization while only GH2 will be used for the supply tank. Fixed regulators control delivered pressurant to 276 kN/m^2 (40 psia). Pressures less than this maximum are controlled by tank isolation valves. The pressurization part of the schematic has been previously shown on Figure 4.4-2 and comprise the following major subelements:

Gaseous Hydrogen Storage - This pressurant storage capability provides warm hydrogen gas for autogenous pressurization for liquid expulsion from either the supply or receiver tanks. Seven 0.076 m^3 (2.7 ft^3) composite overwrapped, 6061-T6 aluminum cylindrical bottles pressurized to 20670 kN/m^2 (3000 psia) provide the storage capability for this function. Each bottle holds 1.14 kg (2.5 lbs) of gaseous hydrogen. The bottles are manifolded together and provided with an isolation valve at each bottle so that bottles can be depleted individually. Isolation from high pressure GHe is provided by series crossover valves. Under normal operation either the GHe or GH2 pressurant systems would be available for use at any one time. Servicing the GH2 bottles is accomplished as a total pad clear terminal count hazardous servicing operation via the common manifold and QD at the T-0 umbilical.

Gaseous Helium Storage - This pressurant storage capability provides warm helium gas for pressurization for liquid expulsion from either of the receiver tanks using a non-condensable pressurant. Two 0.076 m^3 (2.7 ft^3) composite overwrapped, 6061-T6 aluminum cylindrical bottles (the same as those used for GH2 storage) pressurized to 20670 kN/m^2 (3000 psia) provide the storage capability for this function. Each bottle holds 2.27 kg (5.0 lbs) of gaseous hydrogen. The bottles are manifolded together and provided with an isolation valve at each bottle so that bottles can be depleted individually. Isolation from high pressure GH2 is provided by series crossover valves. Under normal operation either the GHe or GH2 pressurant systems would be available for use at any one time.

Servicing the GHe bottles is accomplished as a locally hazardous servicing operation via the common manifold, servicing port and manual servicing valve.

Pressurant Regulation and Control - Pressurant regulation is controlled by manual fixed regulator legs set to deliver 276±27.6 kN/m^2 (40±4 psia). One leg is normally dedicated for GH2 regulation while the other is used for GHe regulation. The two legs are redundant to one another, if required, via the series crossover valves. Isolation valves, filtering and orifice control to establish maximum flowrates are included in each leg. Flow metering, temperature and pressure instrumentation is accommodated at the branch connect of the two legs.

Pressurant Distribution - The regulated GH2 and GHe is distributed to all of the experiment tanks simultaneously. Control valves at the vent lines to each tank control the individual pressurization of a given tank at a time. These valves also serve as control devices regulating tank pressurizations below the regulator setpoint and maintain tank pressure to within 6.89 kN/m^2 (1 psia) of the desired value. Line and component size is 1.27 cm (0.5 in).

4.6 Fluid Distribution and Control

Control of the experiment subsystem process consumables and the distribution of these commodities (LH2, GH2 and GHe) is accomplished between tankage, other subsystem elements and/or overboard using the following fluid distribution subelements:

- Transfer line
- Back pressure, free and ground vents
- Pressurant distribution lines
- Spray system control
- TVS & CHX control
- Over pressure protection
- Plumbing/ component insulation

A brief overview of these subelements is provided as follows:

Transfer Line - This line carries LH2 from the supply tank LAD and routes it to either receiver tank or to the vent system via a transfer/vent line by-pass. The line and all full flow components are a 1.9 cm (0.75 in) OD size. Other lower flow legs are a 1.3 cm (0.5 in) OD size. The line is configured as shown in Figure 4.1-3. Isolation valving is provided for receiver tank 2 tests so that only that portion of the line being used is exposed to the transfer fluid.

Back Pressure and Free Vents - The back pressure and free vents provide paths to route fluid overboard when on-orbit. While on the ground these vents are isolated with normally closed ordnance valves which are operated for mission use on-orbit. All ground venting for test and launch operations is via the ground vent interface at the T-0 umbilical. The QD is poppetless and is open at all times until orbital operations begin at which time a normally open ordnance valve is operated closed. The back pressure vent features a check valve that maintains 13.8 kN/m^2 (2 psia) to preclude hydrogen freezing. The free vent provides an unobstructed path to the space vacuum. The vents are interconnected by crossover valves for redundancy and for tests which require no vent back pressure. Normal venting operations are out of the back pressure vent. Both vent interfaces with the space environment contain redundant 100 w heaters that cycle on before the LH2 triple-point temperature is reached as a back-up to preclude freezing. The back pressure vent exits at the aft centerline of the spacecraft and contains a non-propulsive diffuser so as to not perturb attitude control. The free vent exits with a similar configuration at the forward end centerline location. All vent line tubing and associated components are 1.9 cm (0.75 in) OD. Instrumentation is provided as shown in the experiment subsystem integrated schematic (Figure 4.1-3)

Pressurant Distribution - The regulated GH2 and GHe is distributed to all of the experiment tanks simultaneously. Control valves at the vent lines to each tank control the individual pressurization of a given tank at a time. These valves also serve as control devices regulating tank pressurizations below the regulator setpoint and maintain tank pressure to within 6.89 kN/m^2 (1 psia) of the desired value. Line and component size is 1.3 cm (0.5 in).

Spray System Flow Control - Flow in the axial and radial spray systems is controlled by electrically operated on-off latching valves actuated by commands routed to RIU's 11 to 14. Two flow control legs containing orificed restrictions provide the capability to regulate flow to three levels.

TVS & CHX Flow Control - Flow in both the TVS and CHX is controlled by electrically operated on-off latching valves actuated by commands routed to RIU's 11 to 14. Two flow control legs containing orificed restrictions provide the capability to regulate flow to three levels. TVS tubing is 0.64 cm (0.25 in) OD with a 0.17 cm (0.065 in) wall thickness. Associated components are all 0.64 cm (0.25 in) in size. The tubing after leaving the CHX is 1.3 cm (0.50 in) OD with similar sized components.

Over Pressure Protection - Each experiment subsystem tank contains a burst disk and a relief valve plumbed in series to the tank vent line and route fluid to the free vent line to provide over pressure protection. They are set to relieve at 413±27.6 kN/m^2 (60±4 psia). While on the ground the supply tank relief is routed to the ground vent interface. See section 4.10 for a description of electrical over pressure protection.

Plumbing/Component Insulation - A foam/MLI system is a requirement for much of the experiment subsystem fluid distribution system in order to :

- Minimize heat transfer to the LH2 during loading (and contingency detanking) to assure that required fluid conditions and servicing timelines are achieved.
- Prevent LN2 or liquid air formation (the payload fairing AC system is providing GN2 during LH2 servicing operations) on lines and components reaching cryogenic temperature during the servicing or contingency detanking operations.
- Prevent atmospheric or payload fairing purge moisture condensation and frost build-up on all components reaching water condensing or freezing temperatures.
- Provide for on-orbit thermal protection during experiment process investigations involving fluid transfers.

The insulation system consists of 1.3 cm (0.5 in) of polyurethane foam over all plumbing and components that are exposed to LH2 on the ground. The insulation is sealed against cryopumping by an outer covering of kevlar cloth impregnated with a polyurethane resin sealer. In order to provide for required thermal performance on-orbit, certain parts of the plumbing system will contain an overwrap of 10 layers of MLI.

Figure 4.6-1 shows the experiment subsystem schematic with the experiment tankage removed. The remaining components and interconnecting plumbing comprise the Fluid Distribution and Control subsystem. Components located in the same area performing similar or related functions associated with specific tankage have been grouped into seven individual valve panels with interconnection plumbing lines. Components in each panel are identified with the valve panel designation in Figure 4.6-1. Table 4.6-1 list the valve panels by number, function, size and weight. Each panel is a subassembly that is built and tested at the panel level.

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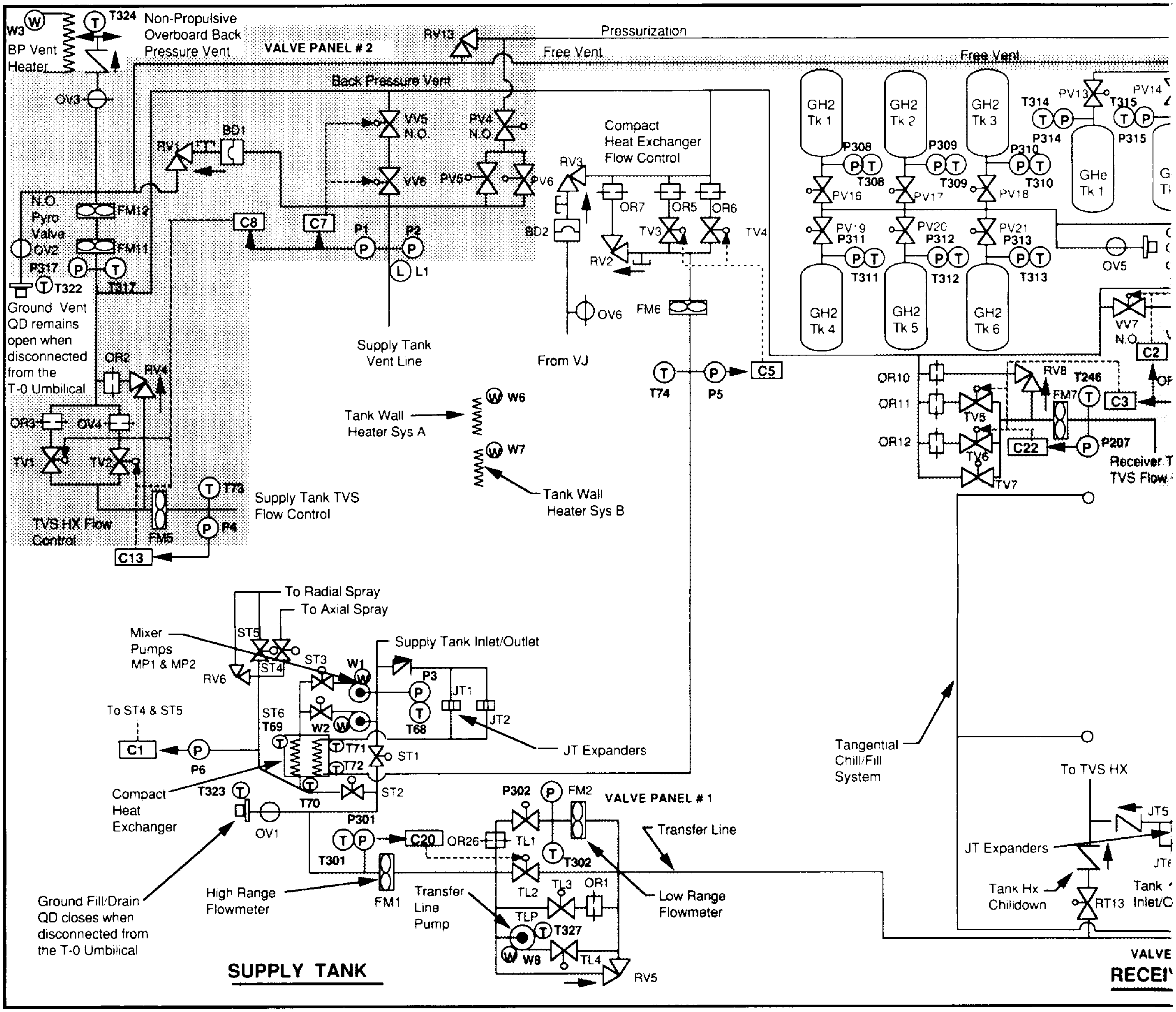

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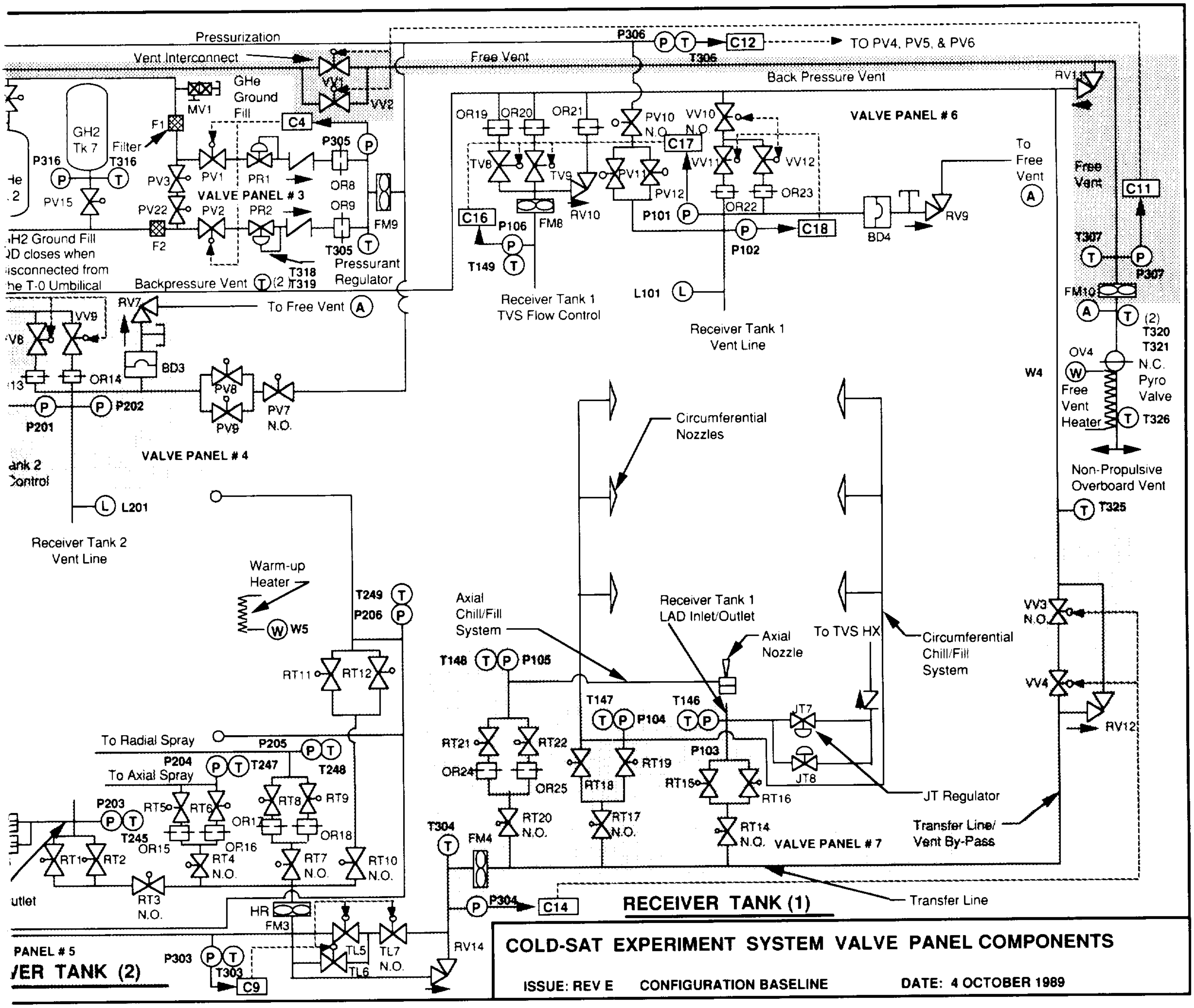


Figure 4.6-1 Experiment Subsystem Fluid Distribution and Control

Table 4.6-1 Experiment Subsystem Valve Panel Approach

PANEL NO.	PANEL FUNCTION	DIMENSIONS H W D	WEIGHT
1	SUPPLY TANK OUTLET, TRANSFER LINE & CHX CONTROL	26.7 X 50.8 X 20.2 CM (10.5 X 20 X 8 IN)	15.87 KG (35 LBS)
2	SUPPLY TANK VENT, TVS CONTROL, BP VENT, FREE VENT & GROUND VENT	30.5 X 50.8 X 20.2 CM (12 X 20 X 8 IN)	19.73 KG (43.5 LBS)
3	GH2 & GHe PRESSURIZATION CONTROL, REGULATION & DISTRIBUTION	27.9 X 50.8 X 12.7 CM (11 X 20 X 5 IN)	11.02 KG (24.3 LBS)
4	RECEIVER TANK 2 VENT, TVS CONTROL & PRESSURIZATION CONTROL	34.3 X 50.8 X 20.2 CM (13.5 X 20 X 8 IN)	13.83 KG (30.5 LBS)
5	RECEIVER TANK 2 INLET, SPRAY SYSTEM CONTROL & TRANSFER LINE	75.3 X 67.3 X 20.2 CM (29.25 X 26.5 X 8 IN)	37.46 KG (82.6 LBS)
6	RECEIVER TANK 1 VENT, TVS CONTROL & PRESSURIZATION CONTROL	34.3 X 50.8 X 20.2 CM (13.5 X 20 X 8 IN)	12.11 KG (26.7 LBS)
7	RECEIVER TANK 1 INLET, SPRAY SYSTEM CONTROL & TRANSFER LINE	58.4 X 67.9 X 17.8 CM (23 X 26.75 X 7 IN)	29.21 KG (64.4 LBS)

Valve panel 3 which is associated strictly with the pressurization system is shown in Figure 4.6-2. Figure 4.6-3 shows the arrangement of the six experiment subsystem valve panels associated with tankage, transfer and vent lines. Panel relationship to tankage and to one another are also depicted along with major functions into and out of each panel. Proximity relationships are also shown. Major interfacing of the panels occurs with the tankage. Panel to panel interfacing consists of transfer, pressurization and vent line routing which can easily be accommodated in the various empty space between components and structure.

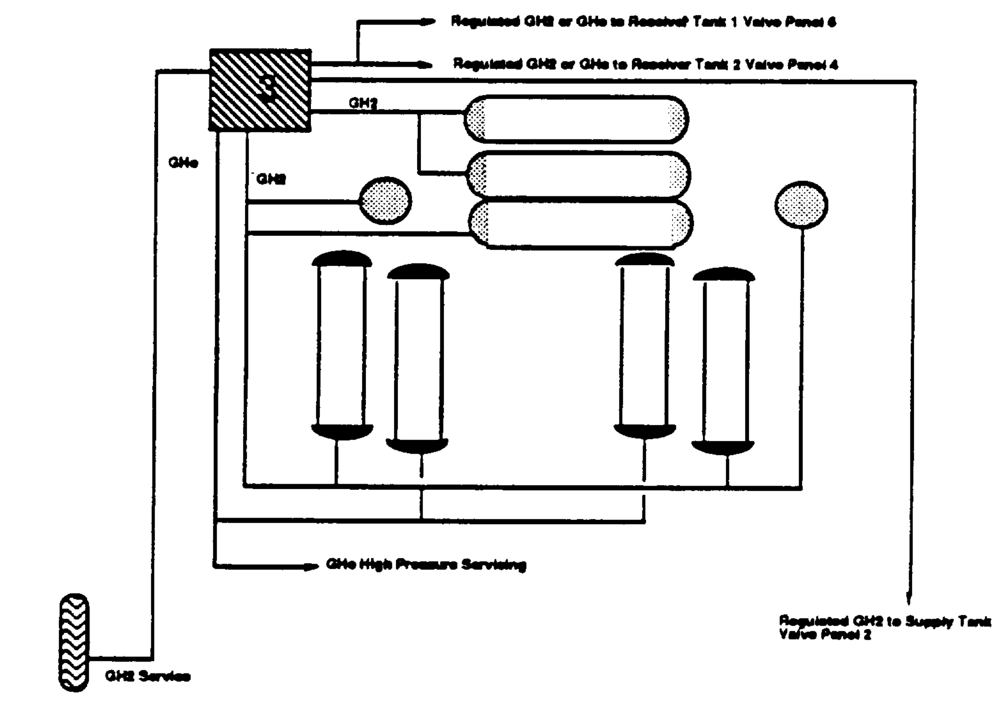


Figure 4.6-2 Experiment Subsystem Pressurization Valve Panel 3 and Plumbing Concept

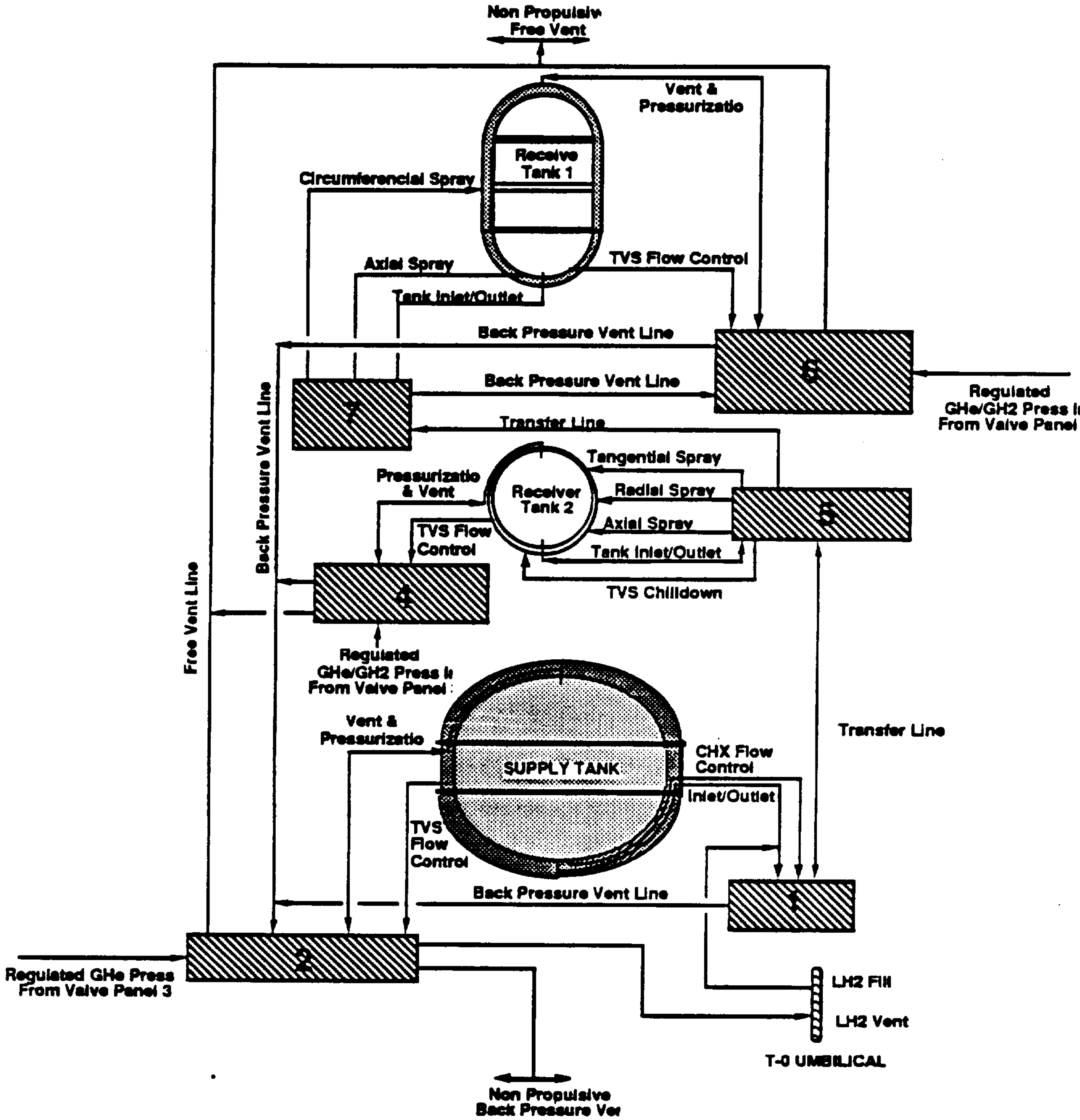


Figure 4.6-3 Experiment Subsystem Fluid Distribution Valve Panel and Plumbing Approach

A brief definition of each of the valve panels is provided as follows:

Valve Panel 1- This valve panel has a size and weight as shown in Table 4.6-1. It contains the components as shown in Figure 4.6-4 and is located below the supply tank in the aft equipment bay at Station 490. It serves to interface with the supply tank inlet/outlet line and contains the transfer line flow control elements, including the transfer pump for distribution of fluid to either receiver tank via valve panel 5 or 7. It also contains the CHX flow control components which interface with the back pressure vent line.

Certain components (pressure transducer P301) still require incorporation into the panel. Other components originally assigned to the panel and the rational of why they are not located in the panel are defined below which include being installed in other off panel locations:

- OV1 LH2 ground fill/drain QD isolation pyro valve and OV6 vacuum jacket space vacuum exposure valve will be installed in an accessible location for ordnance initiator installation.
- P301 requires incorporation into the panel design.
- Vacuum jacket over pressure protection burst disk BD2 and relief valve RV3 will be installed on the vacuum jacket near the pump out port.

The panel will be insulated from the external environment and will be thermally isolated from mounting structure. The plate to which the components are mounted is a composite structure to isolate components from one another as much as possible. Additional analysis is required to determine the need to further isolate transfer line components or provide cooling with heat exchangers (not an attractive design option) to prevent component warm up during tank chilldown cycles.

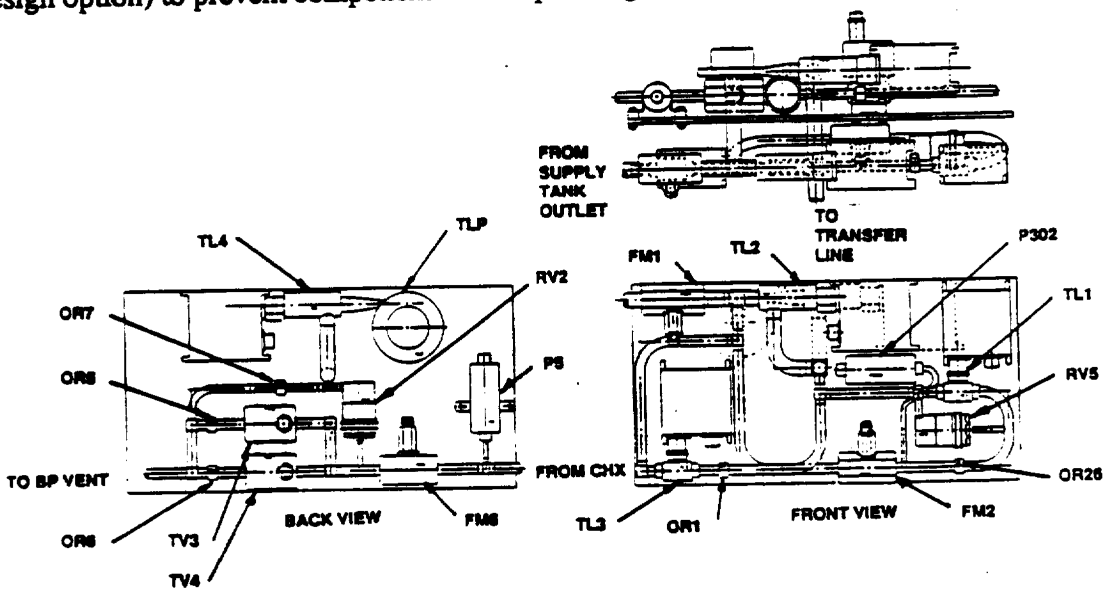


Figure 4.6-4 Valve Panel 1 Equipment Design Configuration

Valve Panel 2 - This valve panel has a size and weight as shown in Table 4.6-1. It contains the components as shown in Figure 4.6-5 and is located below the supply tank in the aft equipment bay at Station 490.

It serves to interface with the supply tank vent line and contains the vent line flow measuring and BP/free vent interconnect elements, including the interface for distribution of fluid to the ground vent during ground operations. It also contains the TVS flow control components which interface with the back pressure vent line.

Certain components (pressure transducer P307, Burst disk BD1, and Relief Valves RV1, RV11, and RV13) still require incorporation into the panel design or installation at some other location. Other components (OV2, and OV3) originally assigned to the panel and the rational of why they are not located in the panel are defined below which include being installed in other off panel locations:

- OV2 LH2 ground vent QD isolation pyro valve and OV3 back pressure vent isolation pyro valve will be installed in an accessible location for ordnance initiator installation.
- BD1, RV1, RV11, RV13, and P307 require incorporation into panel design.

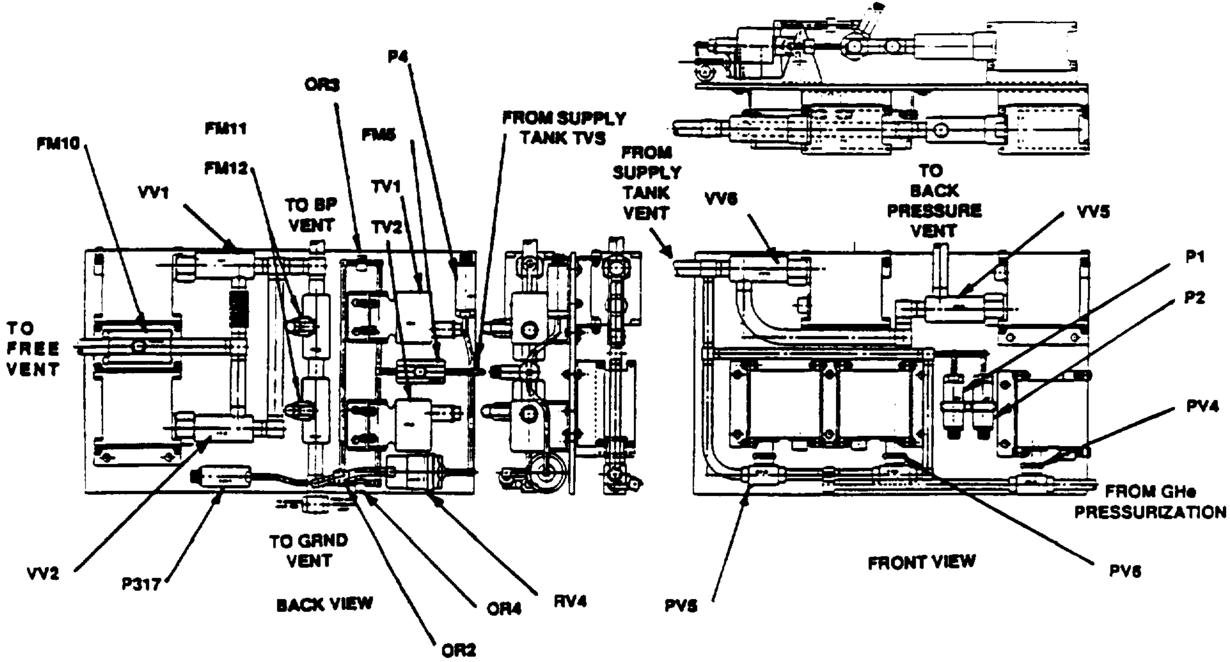


Figure 4.6-5 Valve Panel 2 Equipment Design Configuration

The panel will be insulated from the external environment and will be thermally isolated from mounting structure. The plate to which the components are mounted is a composite structure to isolate components from one another as much as possible. Cooling of components within this panel is not a consideration.

Valve Panel 3 - This valve panel has a size and weight as shown in Table 4.6-1. It contains the components as shown in Figure 4.6-6 and is mounted to the rectangular tube support structure by receiver tank 1 at Station 313. It serves to interface with the GH2 and GHe high pressure pressurant storage tanks and the experiment tankage providing regulated pressurant to each via valve panels 2, 4, and 6. The panel contains dual regulation legs, including particulate filtering and leg crossover provisions.

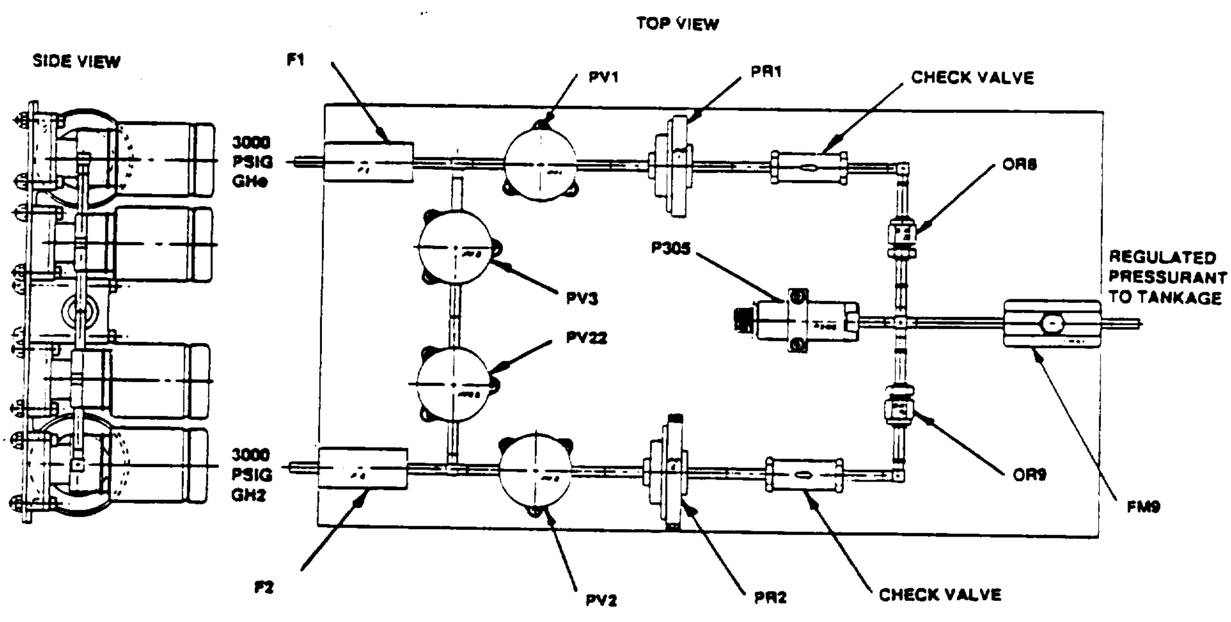


Figure 4.6-6 Valve Panel 3 Equipment Design Configuration

Two components (MV1 and OV5) originally assigned to the panel and the rational of why they are not located in the panel are defined below as being installed in other off panel locations:

- MV1 high pressure manual ground servicing valve will be installed in an accessible location for GHe servicing operations and connection to facility GHe pressure panel.
- OV5 GH2 ground QD isolation pyro valve will be installed in an accessible location for ordnance initiator installation.

The panel will be insulated from the external environment and does not have to be thermally isolated from mounting structure. The plate to which the components are mounted can be a composite structure or a metal plate. Components need not be thermally isolated from one another. The panel should be kept as warm as possible to provide the tankage with warm pressurant.

Valve Panel 4 - This valve panel has a size and weight as shown in Table 4.6-1. It contains the components as shown in Figure 4.6-7 and is located behind the MMS MPS module near receiver tank 2 at Station 360. It serves to interface with receiver tank 2 vent and pressurization penetration. It also contains the TVS flow control components which interface with the back pressure vent line and the tank relief system that interfaces with the free vent.

The panel will be insulated from the external environment and will be thermally isolated from mounting structure. The plate to which the components are mounted is a composite structure to isolate components from one another as much as possible. Cooling of components within this panel is not a consideration.

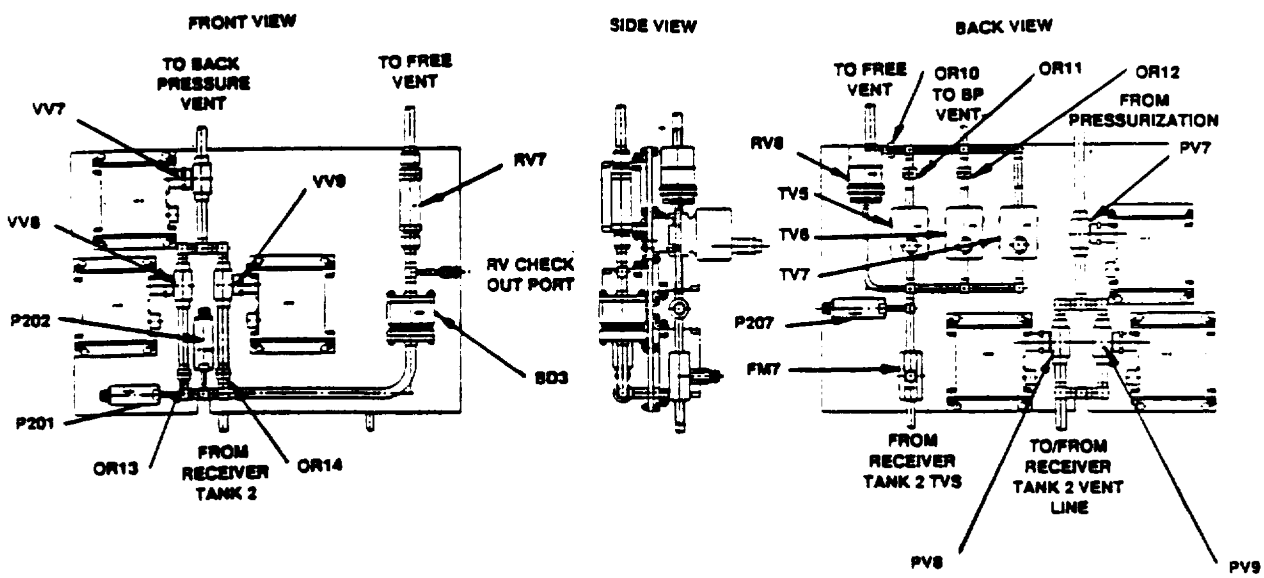


Figure 4.6-7 Valve Panel 4 Equipment Design Configuration

Valve Panel 5 - This valve panel has a size and weight as shown in Table 4.6-1. It contains the components as shown in Figure 4.6-8 and is located behind the MMS C&DH module at Station 377. It serves to interface with receiver tank 2 inlet/outlet line and contains the transfer line isolation elements. It also contains the TVS heat exchanger chilldown leg. All of the chill/fill spray isolation and flow control components are also located on this panel

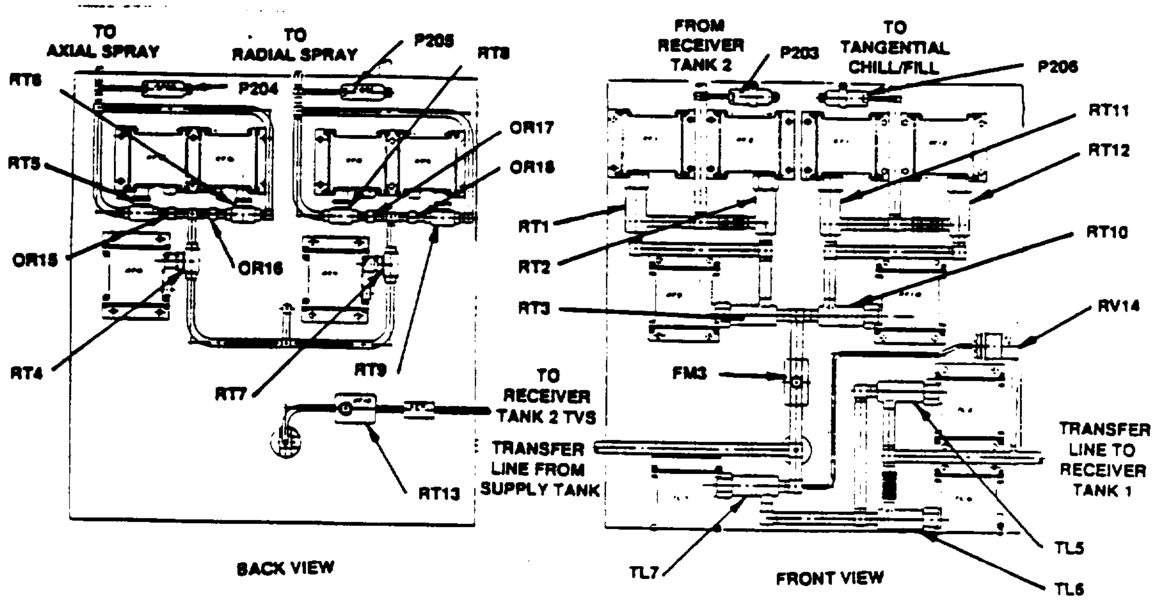


Figure 4.6-8 Valve Panel 5 Equipment Design Configuration

The panel will be insulated from the external environment and will be thermally isolated from mounting structure. The plate to which the components are mounted is a composite structure to isolate components from one another as much as possible. Additional analysis is required to determine the need to further isolate transfer line components or provide cooling with heat exchangers (not an attractive design option) to prevent component warm up during tank chilldown cycles.

Valve Panel 6 - This valve panel has a size and weight as shown in Table 4.6-1. It contains the components as shown in Figure 4.6-9 and is located behind the MMS MPS module near receiver tank 1 at Station 312. It serves to interface with receiver tank 1 vent and pressurization penetration. It also contains the TVS flow control components which interface with the back pressure vent line and the tank relief system that interfaces with the free vent.

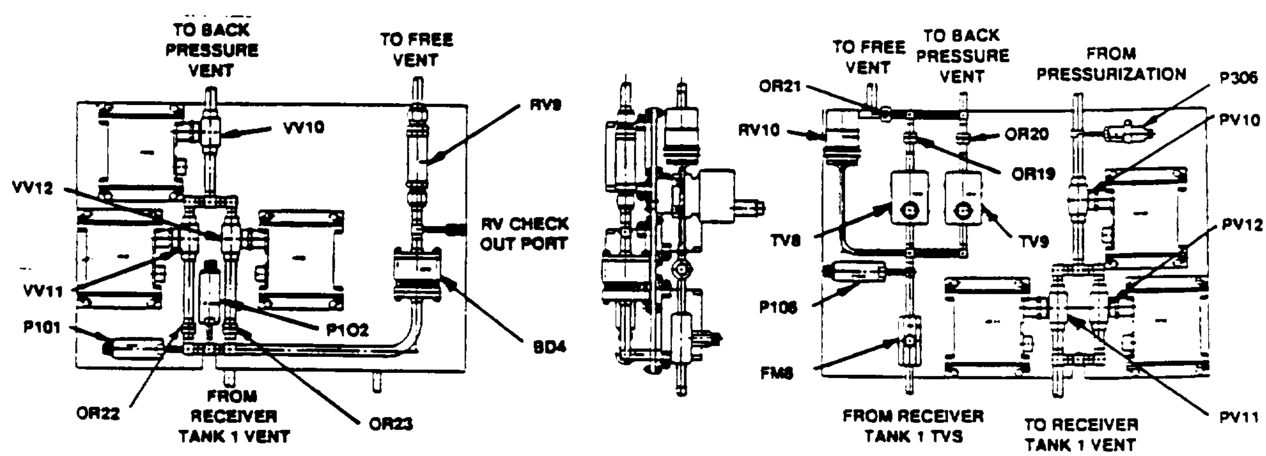


Figure 4.6-9 Valve Panel 6 Equipment Design Configuration

The panel will be insulated from the external environment and will be thermally isolated from mounting structure. The plate to which the components are mounted is a composite structure to isolate components from one another as much as possible. Cooling of components within this panel is not a consideration.

Valve Panel 7 - This valve panel has a size and weight as shown in Table 4.6-1. It contains the components as shown in Figure 4.6-10 and is mounted to the rectangular tube support structure by receiver tank 1 at Station 380. It serves to interface with receiver tank 1 inlet/outlet line and contains the transfer line/vent by-pass interface elements. All of the chill/fill spray isolation and flow control components are also located on this panel.

The panel will be insulated from the external environment and will be thermally isolated from mounting structure. The plate to which the components are mounted is a composite structure to isolate components from one another as much as possible. Additional analysis is required to determine the need to further isolate transfer line components or provide cooling with heat exchangers (not an attractive design option) to prevent component warm up during tank chilldown cycles.

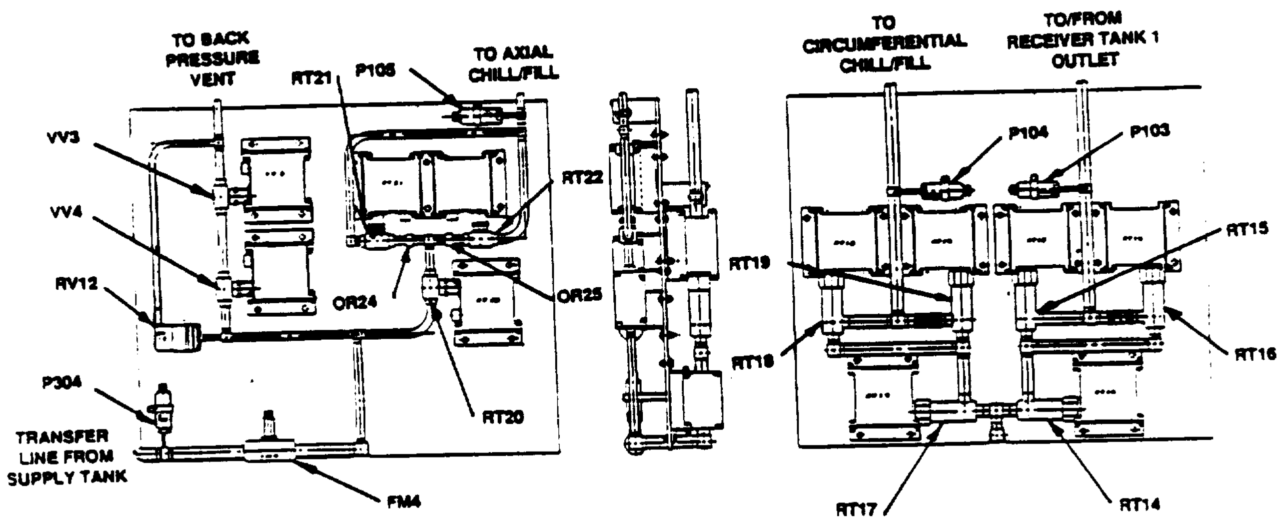


Figure 4.6-10 Valve Panel 7 Equipment Design Configuration

4.7 Instrumentation

This section discusses those measurements required to successfully conduct the COLD-SAT Class I and Class II categories of experiments which were defined in Section 3 and instrumentation necessary to obtain the required experimental data for an understanding of the associated processes, as well as for the verification and correlation of analytical predictions.

The instrumentation for the COLD-SAT experiment subsystem consists of those sensors, status and position indication devices required to perform the following:

- insure the safety of the operation of the experiment subsystem;
- provide data and control capability necessary to conduct the experimental tests;
- provide data for experiment analyses; and

- provide additional and redundant data both to enhance experimental analyses and obtain an understanding of the involved processes.

These devices will interface with existing 8-bit MMS data handling and processing equipment to the maximum extent possible without equipment modification. One area, however, that will require modification to the equipment is high accuracy in thermometry. Needed equipment impacts are discussed in Section 4.10.

A listing of the Experiment Subsystem data requirements was prepared and is included in its entirety in Ref 4.7-1. It gives a summary of the data requirements which describes the use for each measurement (or groups of measurements) with regard to applicable experiment and associated model or analysis that will utilize the data. Recommendations for sampling rate needs are also provided.

Table 4.7-1 is a summary listing of the Experimental Subsystem Instrumentation. The Instrumentation Report (Ref 4.7-1) contains a more complete listing where for each measurement an identification number is provided along with the function and location of the instrument. Range, accuracy, sample rate requirements, and resolution information (based on an 8-bit data word) are also provided. A recommended source for each type of device, as well as part number/model number information is included.

Redundancy Concept - For the most part, no attempt has been made to duplicate transducers at a single location for redundancy purposes. Similar sensors are installed in close proximity to each other and are of sufficient numbers that a form of redundancy is provided. Loss of data from any single device will not result in the inability to complete experimental analyses or prediction verification or to accomplish required control functions.

Sensor Locations - Figure 4.1-3 provides an integrated schematic of the experiment subsystem defining locations for instrumentation. Ref 4.7-1, Appendix A contains a more detailed definition of tankage temperature and other sensor locations.

4.7.1 Instrumentation Definition

The following sensors and instrumentation devices have been identified as having the proper characteristics to meet the data needs of the COLD-SAT. Figures 4.7-1 and 4.7-2 contains additional information on each instrument.

Acceleration - The Bell Aerospace Model XI accelerometer is the recommended device to provide acceleration data in the micro-g range for experimental use. It consists of an analog accelerometer assembly composed of an orthogonal, triaxial set of accelerometer sensors, associated analog servo and temperature control electronics, power conditioning electronics and housekeeping data signal electronics to provide accurate measurement of low level accelerations (micro-g to hundreds of milli-g range). The unit uses 28 $\pm$ 4 vdc input power and has outputs of 0 - 5 vdc for each of the three axis sensors. Device characteristics will be customized to meet specific COLD-SAT needs.

Liquid Hydrogen Density and Flow Rate - Transfer line LH2 flow rate of supply and receiver tank outflow will be bidirectionally measured using turbine Model FT designed and manufactured by Flow Technology. These units require 28 vdc power only to condition the output 0-5 vdc signal which is proportional to the fluid velocity over the flow range of the instrument. Two phase flow can be detected by a sudden change in the indicated velocity. Device accuracy is 0.3%.

Gaseous Hydrogen TVS/CHX Flow Rate - The GH2 flow rate from the supply and receiver tank thermodynamic vent systems will be measured using turbine units Model FTO designed and manufactured by Flow Technology. These units require 28 vdc power only to condition the output 0-5 vdc signal which is proportional to the flow range of the given instrument. Device accuracy is 0.05%.

Table 4.7-1 Experiment Subsystem Instrumentation List

INSTRUMENT ID	RANGE (°R)	SAMPLE RATE	NUMBER SENSORS	LOCATION	ACCURACY (±°R)
TEMPERATURE					
VACUUM JACKET	400-600	C	7	SUPPLY	1.34
INSULATION	30-250/540	C	14	SUPPLY	1.07/1.25
INSULATION	30-250,400-600	C	11	RECEIVER1	1.07/1.34
INSULATION	30-540,400-600	C	11	RECEIVER2	1.25/1.34
VAPOR COOLED SHIELD	30-250/540	C	7	SUPPLY	1.07/1.25
TANK WALL	28-55,30-540	C	7	SUPPLY	0.29/1.25
TANK WALL/CHILL-FILL	28-55,30-90/540	A,B,C	9	RECEIVER1	0.29/0.29/1.25
TANK WALL/CHILL-FILL	28-55,30-90/540	A,B,C	10	RECEIVER2	0.29/0.29/1.25
TANK FLUID	28-55,30-90/540	A,C	22	SUPPLY	0.29/0.29/1.25
TANK FLUID	28-55,30-90/540	A,B,C	12	RECEIVER1	0.29/0.29/1.25
TANK FLUID/MID	28-55,30-90/540	A,B,C	19	RECEIVER2	0.29/0.29/1.25
LAD FLUID	28-55	B,C	5	SUPPLY	0.29
LAD FLUID	28-55	A,C	5	RECEIVER1	0.29
SUPRT/PENTR/OUTLET	28-55,30-90/540	A,C	7	SUPPLY	0.29/0.29/1.25
SUPRT/PENTR/OUTLET	28-55,30-540,400-600	A,C	7	RECEIVER1	0.29/1.25/1.34
SUPRT/PENTR/OUTLET	28-55,30-90/540	A,C	6	RECEIVER2	0.29/0.29/1.25
TVS FLUID/HX/DIFSR/FM	28-55,30-90/250/540	A,B,C	11	SUPPLY	0.29/0.29/1.07/1.25
TVS FLUID/DIFSR/FM	28-55,30-250/540	A,B,C	6	RECEIVER1	0.29/1.07/1.25
TVS FLUID/DIFSR/FM	28-55,30-540	A,B,C	5	RECEIVER2	0.29/1.25
VENT FLUID	30-90/540	B	9	OTHER	0.29/1.25
STORED PRESSURANT	400-600	A,B,C	11	OTHER	1.34
TRANSFER LINE FLUID	30-250/540	A,B,C	7	OTHER	1.07/1.25
COMPACT HEAT EXCHANGER	28-55,30-540	A,C	5	SUPPLY	0.29/1.25
MIXER PUMP	30-90	B,C	2	SUPPLY	0.29

Table 4.7-1 Experiment Subsystem Instrumentation List (Continued)

INSTRUMENT ID	RANGE	SAMPLE RATE	NUMBER SENSORS	LOCATION	ACCURACY (±)
PRESSURE (PSIA)					
TANK	15-30,0-75	A,B	3	SUPPLY	0.1/0.5 PSIA
TANK	0-50/75	A,B	5	RECEIVER1	0.25/0.5 PSIA
TANK	0-50/75	A,B	6	RECEIVER2	0.25/0.5 PSIA
TVS	0-75	A,B	1	SUPPLY	0.5 PSIA
TVS	0-75	A,B	1	RECEIVER1	0.5 PSIA
TVS	0-75	A,B	1	RECEIVER2	0.5 PSIA
VENT FLUID	0-50	A,B	2	OTHER	0.25 PSIA
STORED PRESSURANT	0-50/75/4000	A,B	11	OTHER	0.25/0.5/25 PSIA
TRANSFER LINE FLUID	0-50/75	A,B	4	OTHER	0.25/0.5 PSIA
COMPACT HEAT EXCHANGER	15-30,0-75	A,B	2	SUPPLY	0.1/0.5 PSIA
FLOWRATE (LB/HR)					
TRANSFER LINE FLUID	0-100/200/300	A,C	4	OTHER	1/2/3 LB/HR
TVS	0-0.3	A,B	1	SUPPLY	0.003 LB/HR
TVS	0-0.3	A,B	1	RECEIVER1	0.003 LB/HR
TVS	0-0.3	A,B	1	RECEIVER2	0.003 LB/HR
VENT FLUID	0-100/200	A,C	3	OTHER	1/2 LB/HR
PRESSURANT	0-100	A,C	1	OTHER	1 LB/HR
HEAT EXCHANGER	0-5	A,B	1	SUPPLY	0.05 LB/HR
QUANTITY GAUGING					
TANK FILL VOLUME	0-100%	N/A	1	SUPPLY	0.5 IN
TANK FILL VOLUME	0-100%	N/A	1	RECEIVER1	0.5 IN
TANK FILL VOLUME	0-100%	N/A	1	RECEIVER2	0.5 IN
LIQ/VAPOR POS DETECTOR	WET/DRY	A,C	1	SUPPLY	N/A
LIQ/VAPOR POS DETECTOR	WET/DRY	A,C	1	RECEIVER1	N/A
LIQ/VAPOR POS DETECTOR	WET/DRY	A,C	1	RECEIVER2	N/A

Table 4.7-1 Experiment Subsystem Instrumentation List (Concluded)

INSTRUMENT ID	RANGE	SAMPLE RATE	NUMBER SENSORS	LOCATION	ACCURACY (±)
SPACECRAFT					
3-AXIS ACCELERATION	1-500 MG	A	3	RECEIVER 2 SUPT	5.0 MG
PUMPS					
MIXER	0-5 W	B	1	PUMP PWR SOURCE	0.05 W
MIXER	0-5 W	B	1	PUMP PWR SOURCE	0.05 W
TRANSFER PUMP PWR	0-30 W	B	1	PUMP PWR SOURCE	0.3 W
HEATERS					
SUPPLY TANK HEATERS A&B	0-30W	B	2 (8 ELMTS)	HTR PWR SOURCE	0.3 W
VENT LINE	0-100W	B	2 (4 ELMTS)	HTR PWR SOURCE	5.0 W
RECEIVER TANK 2 HEATER	0-100W	B	1 (2 ELMTS)	HTR PWR SOURCE	5.0 W
EVENTS					
VALVE POS	OP/CLOSE	A	50	SUPPLY	N/A
VALVE POS	OP/CLOSE	A	50	RECEIVER1	N/A
VALVE POS	OP/CLOSE	A	50	RECEIVER2	N/A
VALVE POS	OP/CLOSE	A	18	OTHER	N/A

NOTE: SAMPLE RATES ARE CLASSIFIED AS FOLLOWS:
1 SAMPLE PER SEC = A
1 SAMPLE PER MINUTE = B
1 SAMPLE PER 10 MINUTES = C

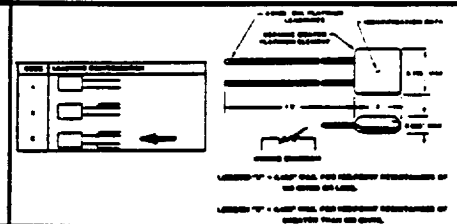
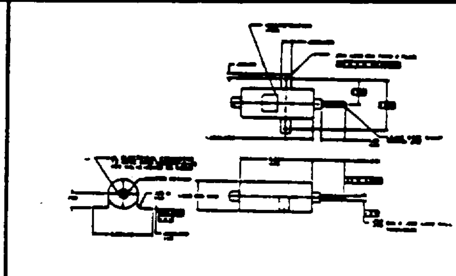
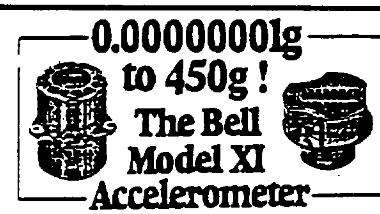
SENSOR TYPE	CHARACTERISTICS	SOURCE	CONFIGURATION
TEMPERATURE	Platinum Resistance Thermometers (PRT) 28-55 R 30-90 R 30-250 R 30-540 R 400-600 R	Rosemount Model 118MF2000C	
PRESSURE	Variable Reluctance Pressure Transducer 28 Vdc Input 0 - 5 Vdc Output 0 - 50 Psia 0 - 75 Psia 15 - 30 Psia 0 - 4000 Psia	Tavis Corporation Model 10417 Model P-106	
ACCELERATION	3 Axis Accelerometer 28 Vdc Input 0 - 5 Vdc Output 1 - 500 micro g	Bell Aerospace Model XI Triaxial	

Figure 4.7-1 Experiment Subsystem Temperature, Pressure, and Acceleration Sensor Information

<u>Gaseous Hydrogen Free Vent Flow Rate</u> - The GH2 flow rate from the Free Vent System will be measured using turbine unit Model FT designed and manufactured by Flow Technology. This unit requires 28 vdc power only to condition the output 0-5 vdc signal which is proportional to the flow range of the 0-100 lb/hr instrument. Device accuracy is 0.3%.

<u>Temperature</u> - All temperature sensors will be Rosemount Model 118MF2000C four-wire Platinum Resistance Thermometers (PRT). PRT's will be excited from 10 ma constant current sources. Five full scale temperature ranges 16-31° K(28-55° R), 17-50° K (30-90° R), 17-139° K (30-250° R), 17-300° K (30-540° R), and 222-333° K (400-600° R) cover all desired experimental data needs. The (30-540° R) range will be split into two equal parts to maintain desired accuracy. In order to maintain desired accuracy and linearity of output to be compatible with existing 0-5 vdc analog-to-digital converter (ADC) all ranges [except 222-333° K (400-600° R)] require special signal conditioning circuits between the sensor output and the ADC.

<u>Pressure</u> - The pressure transducers selected for the experiment subsystem is the basic variable reluctance unit designed and built by the Tavis Corporation. The unit operates with a 28 vdc input and provides an output of 0 - 5 vdc which is linear within the pressure range of the unit. In some locations temperature limitations on sensor electronics requires a modification which removes the electronics away from cryogenic temperature extremes.

<u>Liquid Level & Liquid Detection</u> - The settled LH2 liquid level will be determined for each tank by a capacitance probe or super conductor type of probe that is compatible with surface tension and wicking characteristics of LH2. These sensor systems are designed and produced by Simmonds Precision and are similar to units currently in use on the STS. They require 28 vdc for operation and provide a conditioned 0 - 5 vdc output signal to provide a linear indication of the liquid level in the tank. The actual tank fluid quantity will then be determined by tank geometry.

Liquid detection in tankage vent lines will be determined with a liquid/vapor point sensor. These warm wire sensors are also made by Simmonds Precision and are currently in use on the STS External Tank. The sensor is essentially a platinum wire to which a controlled 175 milliampere current is applied. If the sensor is dry, self-heating generates enough temperature that resistance increases significantly (20 ohms wet to 100 ohms dry). A discrete 28 vdc signal represents the dry state, while 0 vdc indicates wet.

The accuracy for either type is ±0.25 cm (±0.1 in).

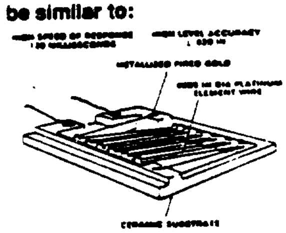
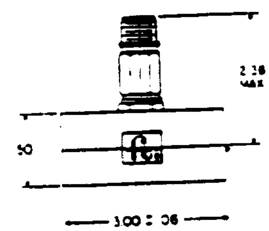
SENSOR TYPE	CHARACTERISTICS	SOURCE	CONFIGURATION
LIQUID/VAPOR	Hot Wire Point Sensor 28 Vdc Input 0 - 5 Vdc Output	Simmonds Precision	May be similar to: 
FLOWRATE	Turbine Flow Meter for gas 0 - 0.3 lb/hr Turbine Flow Meter for liquid 0 - 100 lb/hr 0 - 200 lb/hr 0 - 300 lb/hr Bidirectional capability	Flow Technology Model FT & FTO	
FLUID QUANTITY	Device indicates tank liquid level when settled	Simmonds Precision Capicitance Probe or Super Conducting Probe	Configuration TBD

Figure 4.7-2 Experiment Subsystem Liquid/Vapor, Flowrate and Fluid Quantity Sensor Information

4.7.2 <u>Thermometry Options Assessment</u>

The relative advantages and disadvantages of six types of commercially available cryogenic temperature sensors were compared. The objective was to determine how to best meet the ± 0.055°K (0.1°R) accuracy requirement for COLD-SAT in the 16 to 31 °K (28 to 55°R) temperature range; this ΔT translates into a requirement of about ± 0.5 % at the high end. However, sensor output and sensitivity (mV/°K), together with accuracy and low noise, comprise only one factor in the thermometry tradeoff. Consideration must also be given to the effects of : 1) sensor self-heating; 2) thermal-emfs generated in sensor lead wiring, 3) lead wire arrangements, 4) time constant of the sensor/leads, 5) requirement for additional amplification or signal conditioning, 6) packaging/mounting of sensor, and 7) cost. These considerations are discussed below.

It is clear that the concept of using "interchangeable" sensors is probably not useful because no resistance thermometers behave exactly alike and the so-called interchangeable DT-470-SD-11 diode, e.g., exhibits a sensor-to-sensor ΔT of ± 0.25°K at best, over the range of interest. It is more likely that carefully selected PRTs could be interchangeable, with the advantage that signal conditioning circuits could be standardized. However, individually calibrated sensors of whatever type, with the signal-conditioning gain/offset adjustments customized for each sensor, will always provide the highest accuracy.

Temperature Sensor Discussion - Thermometer self-heating occurs if the heat dissipated in the sensor due to the excitation current cannot be conducted easily to the medium under measurement, assuming that the medium can serve as a thermal reservoir. A ΔT is generated causing the measured value to be too high. Given other sources of error as well, we need $\Delta T << 0.1°K$ (0.18°R). (The error sources are related to sensor repeatability, current source regulation, the 8 bit resolution limit, mathematical modeling of the sensor output linearization process, and total output errors inherent in each stage of the signal conditioner.) Assuming an adequate thermal reservoir, the best technique for avoiding this problem is good heat sinking of the sensor case and leads. Heat sinking the leads is also required to intercept parasitic heat from warmer temperature regions which would also cause an unwanted ΔT. At very low temperature, in vacuum, the dissipation should be $<10^{-12}$ Watts. The requirement at 20°K (36°R) in a liquid hydrogen environment is not nearly so stringent. For example, a PRT will be in error by ~0.4°K/mW (0.72°R/mW) in a N_2 gas environment at room temperature. One way to determine a safe level of self-heating is to begin with a relatively larger current than is required and reduce it incrementally until there is no further change in the voltage readout.

Thermal emfs are voltages generated in the lead wiring due to mechanical stresses (Ref. 4.7-2) when the leads carry a temperature gradient. Other sources are potentials generated by thermocouple effects at solder joints, etc., when dissimilar lead materials are joined, e.g., phosphor-bronze to manganin or copper. The problem here is that in a single polarity dc measurement the thermal emf adds to the sensor voltage drop, causing an error. For a given sensor the thermal emf can be determined by reversing the polarity of a low level current (~1μA) and using an accurate DVM: Thermal emf = $(V_+ - V_-)/2$. Typical values are ≤ 0.1 mV, but the measured value might not remain constant after thermal cycling. Therefore, it is possible to correct for this offset voltage in the signal conditioning or software only if it is known to be a repeatable effect. To reduce the error, a larger excitation current could be used, so that the sensor voltage would always be much greater than the thermal emf. A problem arises when the required current is large enough to cause self-heating, so that a tradeoff is usually required between self-heating and thermal emfs.

A four wire lead arrangement is always preferred for the most accurate temperature measurements, regardless of the sensor type. The leads should be twisted pairs (± I, ± V) to reduce EMI in adjacent sensors and to reduce voltage pickup from external sources. If the sensor resistance is very large compared to the lead resistance, then 2 or 3 wire arrangements can be used with negligible error. But sensor resistances at 20°K are typically less than 100 Ω, and the lead resistance is comparable if manganin wire, e.g., is used to reduce parasitic heat leaks from the warm (≥250°K [480°R]) electronics environment.

If several sensors must be scanned, then the excitation current must be applied long enough to ensure a steady state sensor voltage. The sensor wiring and connections contribute to the time constant, but the sensor itself is also important. Diodes typically respond faster than resistance thermometers to dynamic thermal conditions (0.1 sec vs 0.5 sec), but under static or slowly changing thermal conditions resistance sensors and diodes alike can be scanned at a rate of ~50 per second.

If the sensor output voltage is too low it must be amplified. If an offset is also required (to provide the optimum zero reference for the 0-5 volt analog signal), then the electronics can cause additional errors if there is amplifier instability.

Sensor packaging should promote easy attachment of the sensor and good heat sinking to the medium under measurement. If the case is nonmetal then the heat-sinking must be totally accomplished using the sensor lead wires. Except for certain diode packages, most sensors must be held in place by miniature brackets (or inserted into blind holes) and epoxied with a low temperature bonding agent. Used as a probe, a sensor can be heat-sunk into a hollow OFHC (oxygen-free, high conductivity) copper insert, which has been previously brazed into position; this eliminates the need for lead wire feed throughs as normally required in probe-type installations. If the flow channel or pipe dimension is of the order of the sensor size (I.D. < 1.3 cm (0.5 in)], then the sensor must be thermally bonded to the external wall, ensuring that the lead wires are also heat sunk near the sensor, as described above, and that there is radiation shielding and/or insulation around the sensor depending on the surrounding thermal environment.

Many of the foregoing sensor selection factors are summarized in Table 4.7-2 The unit cost of each candidate temperature sensor is also given.

Temperature Sensor Recommendation - There is no "perfect" sensor for the 16 to 31°K (29 to 56°R) temperature range, because all sensors exhibit some nonlinear behavior and none are perfectly matched for a 1 mA source. Signal conditioning is required for any sensor type. The Germanium Resistance Thermometer (GRT) has the best accuracy, but the diode has the largest output voltage and good sensitivity. However, all diode curves exhibit a severe anomaly at ~25°K (45°R), and they require a 10 μA current source. The GRT is typically noisy, and offers little advantage over the GRT in a low magnetic field except for its slightly greater output voltage. The rhodium-iron sensor characteristic is nearly linear, but not quite linear enough to preclude signal conditioning to meet the ± 0.055 °K(±0.099°R) requirement. At I = 1 mA its output voltage is very low, and it is the most expensive sensor. Use of a chromel / gold (0.07%) thermocouple was also considered because of its high degree of linearity, especially in the 16 to 55°K (29 to 99°R) range. However, its sensitivity (dV/dT = 16.8 μV/°K [9.3μV/°R]) and output voltage are very small; spurious thermal emfs induced by lead wire stresses would compromise its accuracy; and a very well-regulated warm temperature reference junction would have to be incorporated. (A cold reference junction would improve the accuracy, eliminating most of the thermal emf problem and reducing the required precision of the voltage measurement.) The applicability of a very linear manganin/nickel film thermometer described by D. R. Snelson (Temperature 4, 871, 1972) has also been investigated. Its output at 1 mA varies linearly from 220 mV at 4.2°K (7.6°R) to 290 mV at 295°K (531°R), its sensitivity is 0.239 mV/°K (0.163 μV/°R), and its resolution is 0.01°K (0.02°R). Unfortunately, this sensor is not commercially available and would have to be flight-qualified (see Ref 4.7-3). At this time the 2000 Ω (icepoint) PRT appears to be the best compromise when signal conditioning and current source requirements are considered, but the film thermometer would be the more ideal choice if commercially available and if proven reliable for space applications.

4.8 Component Assessments

This section addresses all of the component equipment required for the Experiment Subsystem. The components defined below is the initial selection based upon current COLD-SAT requirements. They are based upon the existing design maturity of the various components and their capability to perform required functions with minimum modification and the greatest potential for use with LH2.

JT Expanders - Joule-Thompson expanders designed and produced by General Pneumatics were selected due to the ability of this device to a) be adjusted and b) self-cleaning ability. That is to say; when the flow is reduced the device "warms" and the flow passage area increases. This device will require further development and qualification testing but has been demonstrated in ground tests. General Pneumatics has considerable experience with the proper materials selection to achieve the proper "motion" with the device.

Pressure Regulator - Sterer Engineering now a division of Vickers has been designing, manufacturing and qualifying aerospace valves and related components for over 30 years. Their design for the regulating valve for COLD-SAT is based on this experience and the specific design utilized on the Manned Maneuvering Unit (MMU) regulator, which they developed. The MMU regulator was required to reduce 24800 kN/m^2 (3600 psig) to 1460 kN/m^2 (212 psig) with an output tolerance of ±103 kN/m^2 (±15 psi) while flowing GN2 at 1.2- 3.7 m^3 (42-132 standard cubic feet per minute). The regulation tolerance applies to the GN2 outlet pressure throughout the inlet pressure range and the

Table 4.7-2 Typical Characteristics of Commercially Available Temperature Sensors

Sensor Type	Temp (°K)	Resistance or Voltage	dR/dT (Ω/°K)	(1mA) Sensitivity (dV/dT) (mV/°K)	(1mA) Output Voltage (mV)	Self-Heating Power (1mA) $P = I^2R$ (μW)	Heat-Sinking Attachment	Worst Case Thermal Emf (0.1 mV) % error %	Theoretical 4 wire Accuracy	Comment
1. GRT (GR-200B-2500)	16	37.52 Ω	-6.212	-6.212	37.5	38	OK, Metal	0.27	± .01 °K	• Moderate sensitivity and output • Most stable, accurate • Nonlinear • Thermal emf typically negligible • Current reversal or 10mA possibly required
SN 20753	20	21.50	-2.460	-2.46	21.5	22	Case,	0.47		
Lakeshore	24	14.42	-1.240	-1.24	14.4	14	epoxy	0.70		
Cost, Calibrated = $360	28	10.60	-0.722	-0.722	10.6	11		0.94		
(4 - 40°K)	32	08.28	-0459	-0.459	08.3	8		1.20		
2. CGRT-1-500	16	71.4 Ω	-4.52	-4.52	71.4	71	OK, Metal	0.14	-± .05°K	• Moderate sensitivity and output • Noisy • Nonlinear • Current reversal or 10mA possibly required
SN C6076	20	56.9	-2.88	-2.88	56.9	57	Case,	0.18		
Lakeshore	24	47.4	-2.00	-2.00	47.4	47	epoxy	0.21		
Cost, Calibrated = $375-395	28	40.5	-1.46	-1.46	40.5	41		0.25		
(4 - 40°K)	32	35.4	-1.12	-1.12	35.4	35		0.28		
3. PRT (118 MF)	15	06.3 Ω	0.72	0.72	06.3	24	Poor,	0.83	± .02°K	• Moderate sensitivity and output • Can match sensors ±0.1°K or better in the range of interest • Requires extra voltage leads • Best output at high temp
(2000 Ω Ice Point)	20	11.8	1.55	1.55	11.8	28	Ceramic	0.67		
Rosemount	25	22.0	2.0	2.0	22.0	41	Case, must	0.49		
Cost, Calibrated = $500	30	38.0	3.5	3.5	38.0	59	use leads	0.34		
(15 - 40°K)	35	60.0	5.0	5.0	60.0	81	and epoxy	0.25		
4. RhFe (RF-800-4)	10	2.38 Ω	.061	.061	2.38	2	Poor,	4.2	± .02°K	• Low sensitivity and output • Good linearity • Thermal emf effects moderate • Most expensive
Lakeshore	16	2.72	.049	.049	2.72	3	ceramic case,	3.7		
Typical Data	25	3.07	.041	.041	3.07	3	must use	3.3		
Cost, Calibrated = $795	30	3.24	.037	.037	3.24	3	leads and	3.1		
(4-40°K)	40	3.64	.032	.032	3.64	4	epoxy	2.7		
5. Gold-Chromel	16	0.228 mV		17.0 μV/°K	0.228	negligible	OK,	43	± 0.1°K	• Poor sensitivity and output • Best linearity • Thermal emf effect is largest • Reference junction required • Least expensive
Thermocouple	20	0.295		17.0	0.295		epoxy	34	w/o	
(0.07 % Iron)	24	0.363		16.8	0.363		preferred;	28	thermal	
Cost = Cost of wire	28	0.430		16.6	0.430		could weld	23	emfs	
	32	0.496		16.5	0.496		wires	20		
6. Diode (DT-470-SD-13)	16	1.2853 V		-18.6	1285	13	OK,	negligible	± .02°K	• Best sensitivity below 24°K • Anomaly in sensitivity and output at ~25°K • Requires extra voltage leads • Requires 10μA source • Has fastest thermal response (0.1 sec)
Calibrated ± .02°K	20	1.2144		-17.6	1214	12	various case			
Lakeshore	24	1.1360		-15.9	1136	11	configur.,			
I = 10 μA	28	1.1121		-02.82	1112	11	screw &			
Typical Data, Curve #10	32	1.1026		-02.08	1103	11	epoxy			
Cost, Calibrated = $350 (4 - 40°K)										

GN2 temperature range of 205-338° K (370-610° R). Figure 4.8-1 provides additional information on the JT expander and GH2/GHe pressure regulator.

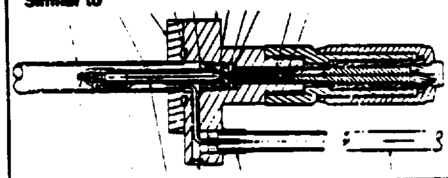
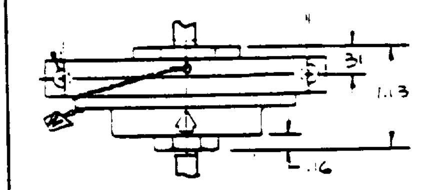
COMPONENT	CHARACTERISTICS	SOURCE/ SOURCES	DEVEL STATUS	QUANTITY	CONFIGURATION
Joule-Tompson LH2 Expanders (JT1~JT8)	- Thermally operating flow control throttling device - AdjustableLH2 flow from 0.08 to 3.5 lb/hr - Self cleaning due to thermal increase in flow area	General Pneumatics	Full Qual Required	8	Similar to 
GH2/GHe Pressure Regulators (PR1&PR2)	- Single stage 3000 psia to 40±4 psia - MMU derivative - Thermal variability is ± TBD for regulation band - 1/4 " tube	Sterer	Similar to MMU Δ Qual Required	2	

Figure 4.8-1 JT Expander and GH2/GHe Pressure Regulator Component Status

Mixer and Transfer Pump - The operating conditions and requirements for the liquid H2 mixer pump are best met with a partial emission type pump driven by an induction motor fed from a variable frequency power source. This configuration provides for efficient matching of the pump capabilities to any desired flow operation level of the system. By varying the pump and motor speed through a variable frequency drive, the pump and motor can be operated at their best efficiency at all times and power is not wasted in throttling devices to achieve a desired system flowrate. A single pump design can perform both the mixing and transfer functions. The range of flow rates and associated head rise covers the range required to both mix the supply tank contents at various fill levels, as well as transfer fluid to the receiver tanks. This approach together with appropriate component design also provides the greatest reliability achievable.

A pump and motor design approach that provides the features and reliability required for this cryogenic application is shown in Figure 4.8-2. A 3-phase induction drive motor is short coupled to the pump and sealed to eliminate the need for shaft seals. The motor shaft is mounted on preloaded ball bearings with the pump impeller cantilevered from one end of the shaft. The partial emission pump is equipped with a screw type inducer to further enhance its capability to operate at very low net positive suction head (NPSH). Prior cryogenic experience has verified this performance and has also demonstrated the capability of the pump to move vapor. The partial emission pump configuration was selected over a full emission design because it allows for a lower NPSH requirement with only a 10% loss in pump efficiency. This pump utilizes existing technologies and is based on Barber-Nichols designs currently in operation. It has not yet been built or tested. Further information is contained in this section on pump characteristics.

Flow Control Orifice - Flow control orifices will be designed in accordance with ASME standards and practices and verified by test with the media and the adjacent tube runs.

Figure 4.8-2 provides additional information on the LH2 mixer and transfer pumps and flow control orifices.

Check Valve - The check valve selected for the COLD-SAT experiment is an all CRES design except for the KEL-F seals. The unit is all welded to minimize leakage and is available from sources such as Ametek/Straza and Circle Seal as flight qualified units in various sizes and pressure ratings.

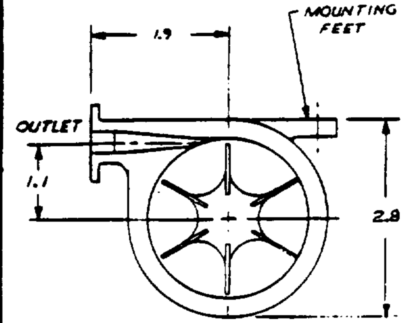
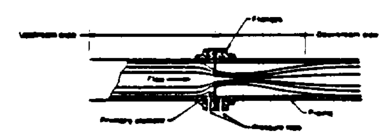
COMPONENT	CHARACTERISTICS	SOURCE/ SOURCES	DEVEL STATUS	QUANTITY	CONFIGURATION
LH2 Mixer Pump (MP1&MP2)	See Other Information In This Section	Barber Nichols Engineering	New	2	
LH2 Transfer Pump (TLP)	See Other Information In This Section	Barber Nichols Engineering	New	1	
LH2 & GH2 Flow Control Orifices (OR1-OR25)	- Simple - Designed, fab & test to ASTM standards	MMAG	N/R	25	Similar to without pressure taps 

Figure 4.8-2 LH2 Mixer Pump, Transfer Pump and Flow Control Orifice Component Status

Motor Driven Cryogenic Valve - This valve utilizes a 28 VDC stepper motor through a ball screw gear train to move the poppet. The valve body is a basic CRES Nupro unit with the Torlon (high density) poppet sealing on the CRES seat. The two elements are hand lapped to achieve the necessary Fit/Finish. The poppet/seat interface of this valve has a common angle (not limited to line contact). The seat load is maintained constant (somewhat) by the use of Belleville washers in series with the drive linkage. The drive from the stepper motor to the poppet utilizes a CRES ball screw which is lubricated with a dry film molydisulfide. The helium leakage through this valve is less than 1×10^{-8} scc/sec. This is achieved due to; a) good poppet/seat fit, b) good poppet/seat finish, c) very high seat load. External leakage is less than 1×10^{-10} scc/sec (6.1×10^{-12}). The 1.3 cm (0.5 in) and 1.9 cm (0.75 in) valves have very high seat loads. These high seat loads do not enhance cycle life. This valve, manufactured by Space Systems Engineering, is basically designed for super fluid helium use at temperatures in the 2°K (3.6°R) region.

Another Cryogenic Valve Option - Flodyne is a supplier and has designed and qualified various ball valves for ground and flight cryogenic applications. However for the COLD-SAT application of this valve to be sealed within the vacuum jacket of the supply tank, work needs to be done to qualify their valve for this installation. A magnetic drive coupling would be very advantageous to avoid problems with the motor and GH2/Vacuum.

The following identifies some of the valve requirements, valve applications, and candidate valve types that are needed for COLD-SAT :

- Desirable Requirements (These requirements are not necessarily combined for each use.)

- Small pressure drop
- Reliable

- Self relieving internally for trapped volume control
- "0" external leakage
- Position indication for both open and closed states
- Low temperature operation (16° K)
- Construction compatible with LH2/GH2
- Sizes for various applications 0.95-1.9 cm (0.375 -0.75 in)
- All welded construction and installation
- Bi-directional flow capability for certain applications

• Applications

- Control of LH2/GH2
- Transfer (Fill & Drain)
- Thermodynamic vent
- Over-pressure protection
- Isolation

• Candidates

- Ball
- Torque Motor
- Solenoid
- Modified Motor Driven

Figure 4.8-3 provides additional information on LH2 valves.

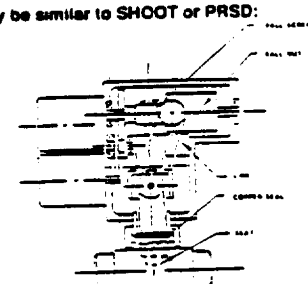
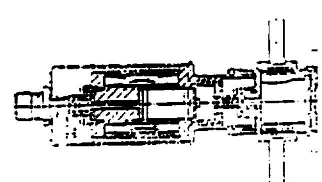
COMPONENT	CHARACTERISTICS	SOURCE/ SOURCES	DEVEL STATUS	QUANTITY	CONFIGURATION
LH2 Valves (VV1-VV12, ST1-ST8, PV4-PV12, TL1-TL7, RT1-RT22)	- 1/2" & 3/4" sizes - All welded construction - ΔP < 0.5 psia at 300 lb/hr LH2 - Motor or solenoid operated - Open/close position indication - Max 5 amp power - Latching - Fast operating less than 2 sec - 70 psia operating	Space Systems Engineering or Consolidated Controls	New	56	May be similar to SHOOT or PRSD:  Stepper Motor Driven Cryogenic Valve  Consolidated Controls

Figure 4.8-3 LH2 Valve Component Status

LH2 Disconnect - The LH2 disconnects provide an interface at a T-O umbilical with facility servicing and vent equipment. They facilitate the transfer of LH2 to the supply tank from the LH2 loading systems, as well as venting of boiloff gases from the tank. The disconnects are composed of a flight half coupling and a ground half coupling that has a pull away quick release feature. Both halves are self sealing when unmated (for the fill side) and provide for effective interface sealing when mated. The flight half vent side remains unsealed (open) by having the poppet removed. The flight half will be similar to the Orbiter PRSD QD. The ground half will be a much simpler version of the Orbiter T-4 PRSD QD and does not have to be pressure operated. Both halves are made by Fairchild.

GH2 Disconnect - The GH2 disconnects provide an interface at a T-O umbilical with facility high pressure GH2 servicing equipment. It facilitates the transfer of high pressure GH2 to the pressurant storage tanks from the GH2 loading system. The disconnect is composed of a flight half coupling and a ground half coupling that has a pull away quick release feature. Both halves are self sealing when unmated and provide for effective interface sealing when mated. The QD is currently in use for recharging the MMU pressurant bottles, both on the ground and in-flight. A T-O release feature will have to be incorporated into the design which is made by Symetrics.

Figure 4.8-4 provides additional information on T-0 Quick Disconnects (QD) needed for COLD-SAT.

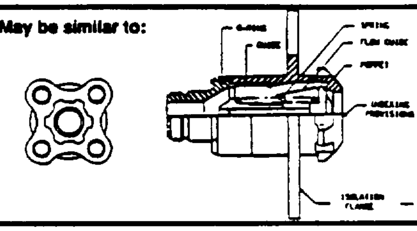
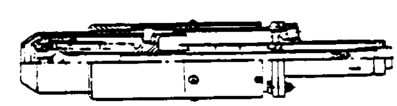
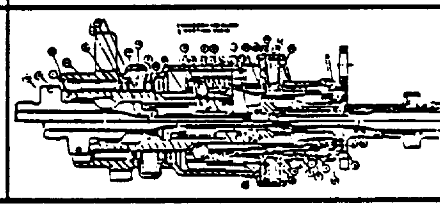
COMPONENT	CHARACTERISTICS	SOURCE/ SOURCES	DEVEL STATUS	QUANTITY	CONFIGURATION
LH2 Quick Disconnect (QD1 &2) Flight Half	- QD1 closes when disconnected from grnd - QD2 remains open when disconnected from grnd - Enclosed with a purged GHe environment - 70 psia operation - T-0 operation - Bellows seals - Mechanical coupling	Fairchild	New Qual reqd for size	2	May be similar to: 
LH2 Quick Disconnect (QD1 &2) Ground Half	- QD1 closes when disconnected from grnd - QD2 remains open when disconnected from grnd - Enclosed with a purged GHe environment - 70 psia operation - T-0 operation - Bellows seals - Mechanical coupling	Fairchild	New Qual reqd for size	2	May be similar to: 
GH2 Quick Disconnect (QD3)	- Closes when disconnected from grnd - 3000 psia operation - T-0 operation	Symetrics	Similar to MMU Δ Qual reqd	1	

Figure 4.8-4 LH2/GH2 T-0 Quick Disconnect Component Status

Cold GH2 Valve - Torque motor valve (Consolidated Controls/HRT) HRT(Space Products Group) recently acquired by Consolidated-Eaton. This supplier has designed and qualified various torque motor valves for space applications. However, they have very limited experience with this valve in a cryogenic application. The reason this design is attractive is due to:

a) Remote location of the motor relative to the cryogenic flow stream.
b) Inherent self-relieving feature which is available for this type valve.
c) Available as a latch or normal open/close valve.
d) Proper design of motor can provide adequate force for motor operation at cryogenic temperatures with margin.

Figure 4.8-5 provides additional information on cold GH2 valves.

Filter - The gas and liquid filters selected for the COLD-SAT application are designed and produced by either WINTEC or VACCO. The filters are totally welded and shall be of all stainless steel construction. The filter element is either pleated wire mesh or an etched disc, with a 25μ absolute rating. The design of the filter could permit removal of the filter element for cleaning, repair, or replacement with the filter body installed if necessary. However, since all media is filtered prior to entering the system this is not considered necessary and the filters are just added insurance to prevent any contamination from causing a problem.

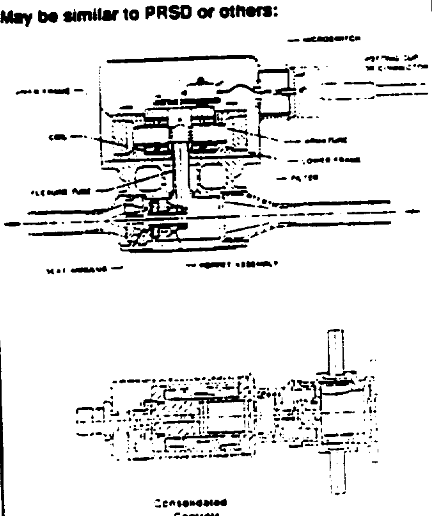
COMPONENT	CHARACTERISTICS	SOURCE/ SOURCES	DEVEL STATUS	QUANTITY	CONFIGURATION
Cold GH2 Valves (TV1-TV9)	- 1/4" tube - All welded construction - Motor or solenoid operated - Open/close position indication - Max 5 amp power - Latching - Need not be fast operating - 70 psia operating	Consolidated Controls	New	9	May be similar to PRSD or others: 

Figure 4.8-5 Cold GH2 Valve Component Status

Service Valves - The GHe pressurant storage tanks will be loaded through high pressure service valves provided by Pyronetics, a subsidiary of OEA. This valve utilizes a metal-to-metal poppet/seat design wherein the internal pressure within the system tends to assist seating the poppet. This valve also incorporates dual seals and the potential for three independent seals, if necessary. This design is utilized on many high pressure gas systems as well as storables. The valve materials are basically CRES with the seat being 15-5 PH. All seals are teflon or KEL-F. The service valves for evacuation of the vacuum system will utilize a standard 5.1 cm (2 in) tube port. These are available from sources such as CVI and commercial hardware.

Figure 4.8-6 provides additional information on filters and service valves.

Burst Disk - The burst disks selected for the COLD-SAT application are designed and produced by Ametek/Straza Division of Ketema. The burst disc incorporates a Belleville spring with the diaphragm. The principle of operation results in a change from increasing to decreasing force during the stroke as opposed to a coil spring which requires a uniformly increasing force to compress it. The snap over action of the Belleville results in a clean shear of the diaphragm as it is driven into a hollow punch. The burst disk shall be of stainless steel construction and shall incorporate a downstream screen to trap the cut out section, thus preventing contamination of the relief valve, which is downstream of the burst disk. The COLD-SAT unit will be similar to the design used for the "SHOOT" program. The "SHOOT" design is repeatable to within 3% of the design point at 77°K. Helium leakage is reported to be less than 1 x 10-6 scc/s at 4°K.

Relief Valves - The relief valves selected for the COLD-SAT application are designed and produced by Ametek/Straza Division of Ketema. The valves shall be of stainless steel construction and utilize teflon or KEL-F for seats and "O"-rings. Valve construction uses a secondary pressure pickup area which increases valve sensitivity. At valve cracking pressure the flow past the poppet flows into the secondary chamber. The secondary pressure buildup then acts over a larger diameter of the poppet thereby reducing the band from cracking to full flow.

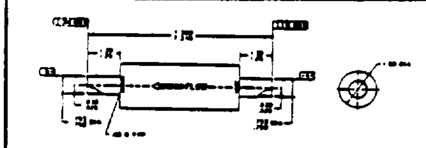
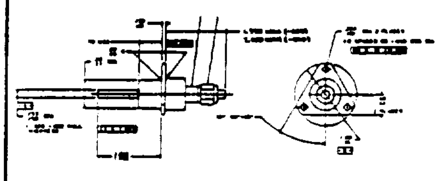
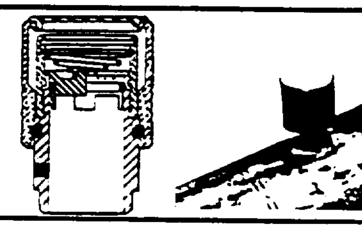
COMPONENT	CHARACTERISTICS	SOURCE/ SOURCES	DEVEL STATUS	QUANTITY	CONFIGURATION
Pressurant GH2/GHe Filters (F1&F2)	- 3000psia operating - SS construction - 25 μ absolute rating - All welded - 1/4 " tube	Wintec or Vacco	Flown MMU (Wintec)	2	
GHe High Pressure Manual Service Valve (MV1)	- 3000 psia operating -1/4 " AN servicing port 1/4" tube stub other end - Tethered 1/4 " AN cap - Manual wrench operated dual seal valve	Pyronetics	Flown MMU	1	
VJ Manual Valve & Pumpout Port (MV2)	- Welded installation - Aluminium construction - Simple operation for pumpout & valve install - Dust cover for flight - Two seals to leakage with cap installed	CVI or Cryolab	Flown CVI P/N V-1046-2	1	

Figure 4.8-6 Filter, Service Valve, and Pump out Port Component Status

Figure 4.8-7 provides additional information on LH2/GH2 burst disks and relief valves.

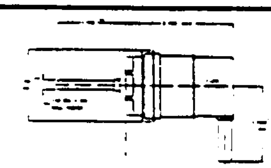
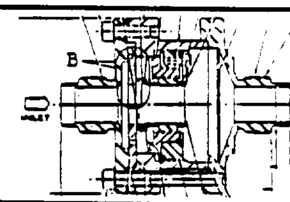
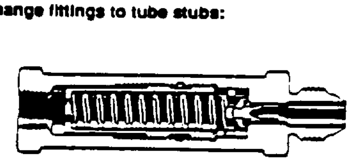
COMPONENT	CHARACTERISTICS	SOURCE/ SOURCES	DEVEL STATUS	QUANTITY	CONFIGURATION
GH2 Relief Valves (RV3,RV4,RV8, RV10,RV11 & RV13)	- R/V set at 60±4 psia - Reseat at 52 psia min - Flow rate TBD - Leakage 10 scc/hr	Ketema	Flown Apollo Δ Qual Required	6	
LH2 Burst Disk (BD1-BD4)	- Leakage 1x10 - 6 SCC/SEC - All CRES - Contains Fragments - Resists reverse back pressure	Ketema	Flown P/N 8-050159 Δ Qual Required	4	
LH2 Relief Valve (RV1,RV2,RV5, RV6,RV7,RV9, RV12, & RV14)	- Tube stubs reqd - 1' &3/4" size - indicator switch - 60±4 psia operation - Allwelded CRES	Circle Seal	Similar to STS application Δ Qual	8	Change fittings to tube stubs: 

Figure 4.8-7 LH2/GH2 Burst Disk and Relief Valve Component Status

Ordnance Valve - The ordnance valves for the COLD-SAT experiment would be supplied by Pyronetics. Their model 1420 & 1421 valves were developed during and in support of the Viking Program. These valves use redundant ordnance - any one would operate the valve. N.C. valves each contain dual seats of parent CRES material which is sheared upon operation to open the valve. For the normally open configuration the closing operating is accomplished by the RAM which seals (metal-to-metal) both the inlet and outlet tubes of the valve.

The 1420 valve is the 1.9 cm (0.75 in) valve which requires a pressure cartridge in addition to the NASA Standard Initiator (NSI) for activation whereas the Model 1421 valve is a 0.65 cm (0.25 in) size which only requires the NSI for operation. Pyronetics has developed and qualified many valves of various sizes which are very similar. The final flow requirements will determine the actual valve size. Figure 4.8-8 provides additional information on ordnance valves.

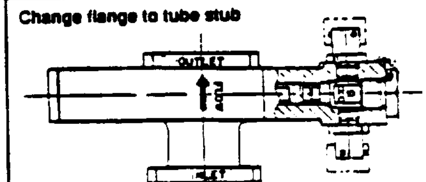
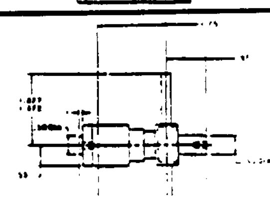
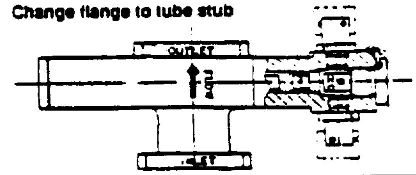
COMPONENT	CHARACTERISTICS	SOURCE/ SOURCES	DEVEL STATUS	QUANTITY	CONFIGURATION
LH2 Ordnance Isolation Valve (OV1-OV4)	- OV1&2 normally open - OV3&4 normally closed - Dual NASA std Initiators for actuation - 70 psia operation - All steel construction - 3/4 or 1 " tube all welded	Pyronetics	Flown Similar to Peace Keeper Δ Qual for cryo	4	Change flange to tube stub 
GH2 Ordnance Isolation Valve (OV5)	- Normally open - Dual NASA std Initiators for actuation - 3000 psia operation - All steel construction - 1/4 " tube all welded	Pyronetics	Flown Viking Δ Qual	1	
VJ Ordnance Isolation Valve (OV6)	- Normally closed - Dual NASA std Initiators for actuation - 20 psia operation - All steel construction - 1' tube all welded	Pyronetics	Flown Peace keeper	1	Change flange to tube stub 

Figure 4.8-8 Ordnance Valve Component Status

GH2/GHe High Pressure Storage Bottle - The experiment gaseous pressurant bottle design is illustrated in Figure 4.8-9. The design was established through a discussion with Structural Composite Industries (SCI) based on our design space and weight requirements and their existing technology and fabrication capabilities. The geometrical constraints of the pressurant tank design comply with the COLD-SAT spacecraft design. Where spherical pressurant bottles had been the pr· ious design baseline for the S/C, the current design reflects a long cylindrical tank with root-two domes to fit within the existing design space. From a packaging point of view, this design is more efficient since bottles can be located in small slender spaces whereas a spherical bottle design uses space less efficiently.

The pressurant bottle was designed using the highest performing state-of-the-art materials for high pressure bottle performance. The bottle is fabricated with a high-strength 6061-T6 aluminum liner and is wrapped with a carbon fiber composite overwrap for strength. SCI typically produces more of the cylindrical and near-sphere shaped tanks since they perform better for the same weight. The spherical tanks require more fiber strength reinforcing in all directions and thus add to the composite weight. The carbon-fiber overwrapped aluminum-lined high pressure gas bottle has a performance factor (PF = BP x VOL / WT) on the order of 800,000 to 1,000,000 which is the highest performing light weight composite design commonly manufactured and flown in space type applications.

Our experiment gaseous pressure bottle conceptual design has been proposed with the use of existing technology, tooling and materials in mind. It is similar in design, size and shape to other space-qualified pressure vessels currently in use on many orbiting space satellite applications. The operating pressure is 20670 kN/m^2 (3000 psia) and the burst pressure is 41340 kN/m^2 (6000 psia) with a safety factor of 2.0 (greater than 1.5 required by NASA). The volume is approximately 75400 cm^3 (4600 in^3) and the entire tank weight including mounting bosses, etc. is estimated at around 11.3 kg (25 lbs). The aluminum liner is very thin and combined with the carbon fiber composite overwrap amounts to 0.41 cm (0.162 in) in thickness. The tank is 122 cm (48 in) long and 29.8 cm (11.75 in) in diameter to fit within S/C space constraints between and alongside the electronics modules. A total of nine pressurant tanks are required for the experiment subsystem pressurant.

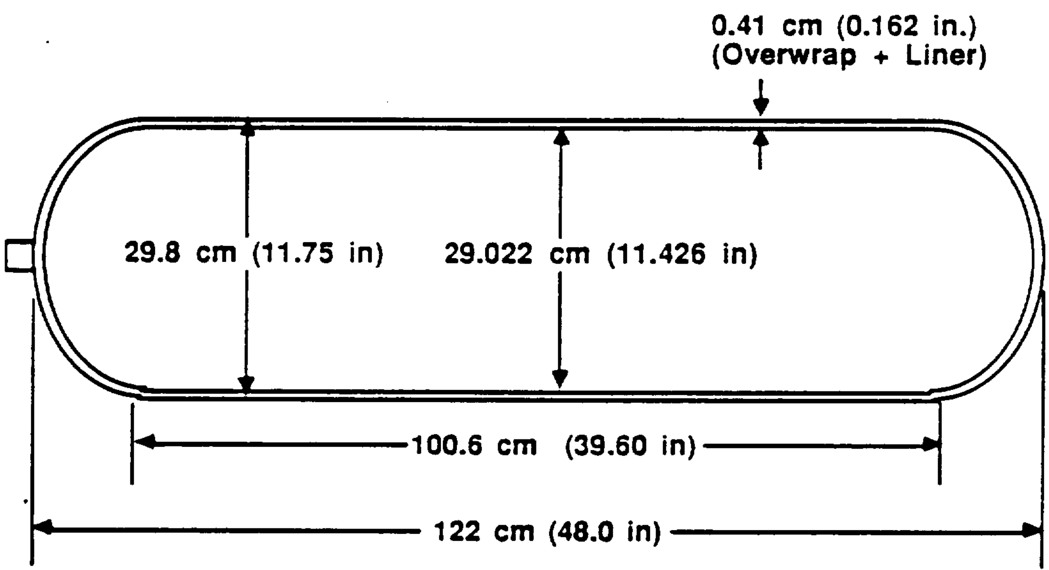


Figure 4.8-9 GH2/GHe Pressurant Bottle Configuration

GH2/GHe High Pressure Valves - The high pressure gas valve for GH2 and GHe service is shown in Figure 4.8-10. It is a latching, single stage, solenoid operated, helium shut-off valve. Electrically, the coils are designed to operate with a 28 VDC power supply and poppet motion is achieved with 0.9 amperes of current. It is designed for high pressure 34,500 kPa (0-5000 psig) with low pressure drop less than 172.5 kPa (25 psid) at rated flow 0.136 kg/min (0.3 lbs/min) with an inlet pressure of 1725 kPa (250 psig). This valve displays low internal leakage, less than 0.82 standard cubic inches per hour (20 standard cubic centimeters per hour), at a pressure up to and including 34,500 kPa (5000 psid). The unit includes a positive position indicator switch and a "spike" suppression network. It is hermetically sealed and is compatible with N2O4 and hydrazine fumes. This unit weighs less than 0.95 kg (2.1 pounds) and features a long life, hard seat to enhance its durability. It will responds to command signals that are less than 0.025 seconds duration. Random vibration levels in excess of 30 g's were experienced during qualification and evaluation testing in both the open and closed valve positions. The valve is qualified for man-rated spacecraft and is presently in production.

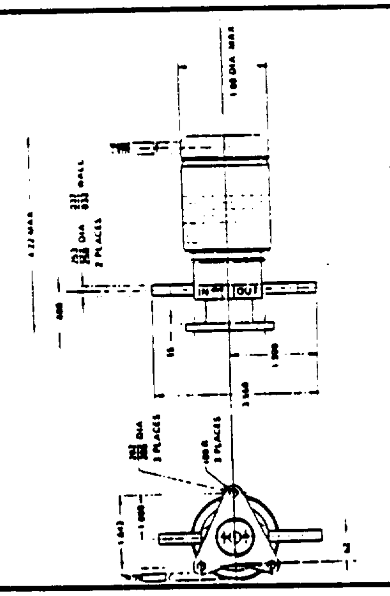
COMPONENT	CHARACTERISTICS	SOURCE/ SOURCES	DEVEL STATUS	QUANTITY	CONFIGURATION
GH2/GHe High Pressure Valves (PV1,PV2,PV3 &PV22)	- Low helium leakage 20 scc/hr - 28 Vdc 2.1 amp max Position indication - Latching - All welded - Hard seat - 3000 psia operating	Consolidated Controls	Flown Apollo & STS Model 6699	4	
GH2/GHe High Pressure Valves (PV13-PV21)	- Low helium leakage 20 scc/hr - 28 Vdc 2.1 amp max Position indication - Latching - All welded - Hard seat - 3000 psia operating	Consolidated Controls	Flown Apollo & STS Model 6699	9	

Figure 4.8-10 High Pressure GH2/GHe Valve Component Status

4.9 Experiment Analyses

During the course of the COLD-SAT study certain detailed analyses were performed to allow for the generation of the experiment list. These analyses are detailed in the following sections.

4.9.1 Pressure Control

The functional requirement of the mixer system is to destratify the contents of the supply tank after the tank has been intentionally thermally stratified with wall mounted heaters. The customer directed that the mixing jet should not induce excessive geysering for most tests although some geysering would be acceptable for a few tests. Excessive geysering is prevented if the dimensionless geyser height is less than 0.4. The dimensionless geyser height, denoted as F, is the height of the geyser divided by the tank radius. The geysering consideration determines the nozzle size and flow rate, so the time required to mix the tank is permitted to "float". The mixer system analysis produced the design requirement of a variable speed mixer pump with a flow rate of 20.4 - 24.9 kg/hr (45 - 55 lbm/hr). The pressure rise across the pump at 24.9 kg/hr (55 lbm/hr) is 3.45 kPa (0.5 psid).

Supply Tank Mixer System Sizing/Analysis - The mixer system was designed to maintain the dimensionless geyser height, F, below 0.4. The following correlation by Aydelott (Ref. 4.9-1) was used to correlate acceleration, surface tension, and jet momentum to geyser height:

$$F = (1.6\ We - 0.5) / (1.0 + 0.6\ Bo)$$

where: F is the dimensionless geyser height
We is the Weber number at the surface
Bo is the Bond number at the surface

Evaluation of the dimensionless groups required the jet radius and flow rate at the surface. The following relation by Symons and Staskus (Ref. 4.9-2) was used to determine the jet radius at the surface:

$$R_S = 0.11\ R_O + 0.19\ H_S$$

where: R_S is the jet radius at the surface
R_O is the jet radius at the nozzle outlet
H_S is the liquid height above the nozzle outlet

The following relation was used to determine jet flow rate at the surface (Ref. 4.9-3).

$$Q_S / Q_O = 0.25\ H_S / L_O$$

where: Q_S is the volumetric flow rate at the surface
Q_O is the volumetric flow rate at the nozzle outlet
L_O is the nozzle characteristic length, nozzle area$^{0.5}$

The dimensionless geyser height was evaluated for different flow rates at tank fill levels to determine the flow rate and fill conditions satisfying the geysering requirement. The results are presented in Figure 4.9-1 which shows the jet characterization parameter, F, as a function of flow rate for three fill levels. The geysering requirement is satisfied in the region described as "Flow Pattern I", where geysering through the liquid surface does not occur. A variable flow rate between 20.4 - 24.9 kg/hr (45-55 lbm/hr) permits operating in the Flow Pattern I region for all fill levels.

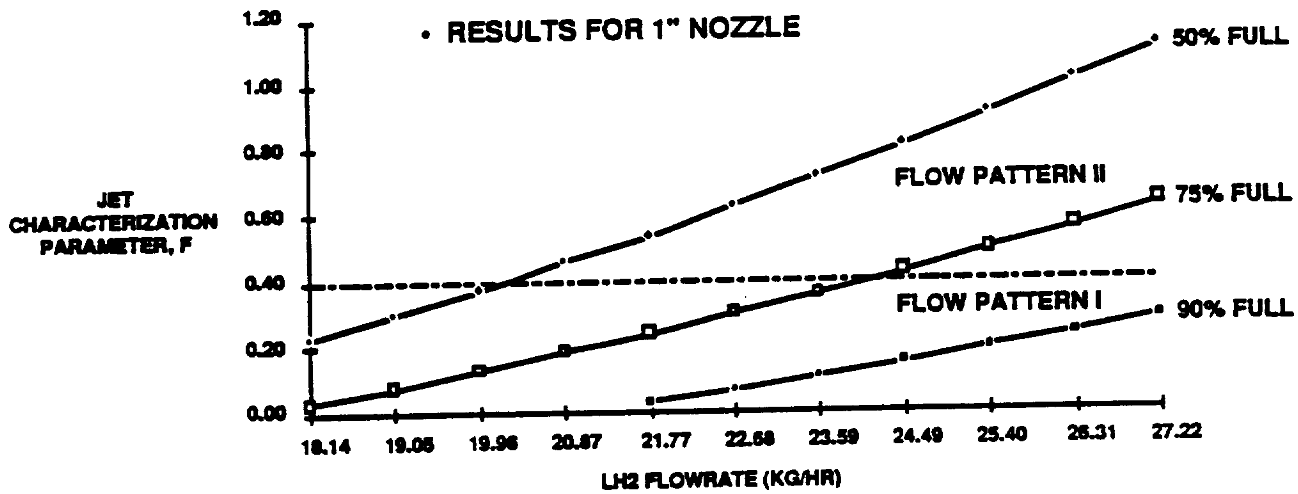


Figure 4.9-1 F-Factor as a Function of LH2 Flowrate and Tank Fill Level

The mixing time was calculated with two correlations. The first correlation is the following equation by Aydelott (Ref. 4.9-4):

$$T = Q_o t V_b$$

where: T is the dimensionless mixing time
Q_o is the jet flow rate at the nozzle
t is the actual mixing time
V_b is the liquid volume

The following equation correlates dimensionless mixing time with the dimensionless geyser height, F:

$$T = 0.09 + 0.01 \ln(F)$$

The second correlation for mixing time is the following equation by Poth and Van Hook (Ref 4.9-5):

$$T = V_o D_o t / D_t^2$$

where: V_o is the jet velocity at the nozzle
D_o is the nozzle diameter
D_t is the tank diameter

The value for the dimensionless mixing time, T, was assumed to be 5. The mixing time for the supply tank was evaluated using both correlations and a flow rate of 24.9 kg/hr. The results of the two correlations are reasonably close and indicate a mixing time of 1.0 - 1.5 hours, as shown in Figure 4.9-2 below.

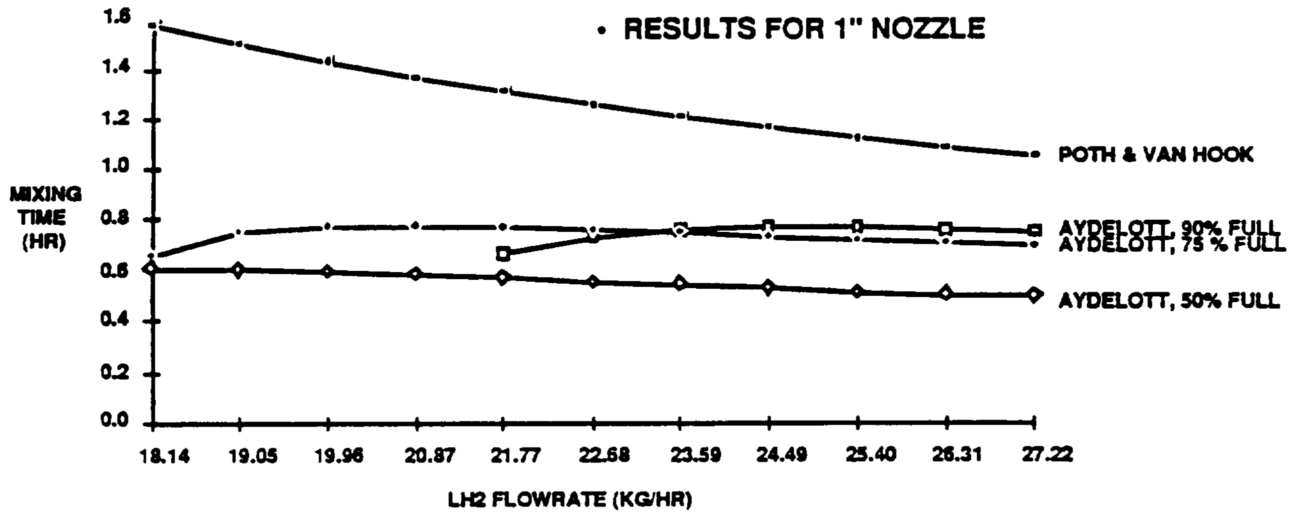


Figure 4.9-2 Mixing Time Predictions as a Function of LH2 Flowrate

Supply Tank Internal TVS Heat Exchanger Sizing/Analysis - The internal Thermodynamic Vent System (TVS) Heat Exchanger (HX) will be utilized to remove heat from the cryogen in the COLD-SAT supply tank. This HX can be used in two modes. The first is labeled nominal and is a situation where the heat removal rate (i.e. line flow rate) is equal to the heating rate of the fluid. This case will be utilized to maintain a constant tank pressure. The other operational mode will be where the flow rate exceeds the nominal case to reduce tank pressure. As of now, the TVS HX will only be utilized in the nominal mode, but the capability for the excess flow must be accommodated for in the design. The other function for the HX will be to ensure vapor-free operation of the tank Liquid Acquisition Device (LAD). By routing the HX properly over the surface of the LAD, the cooling capability of the fluid can be used to condense any vapor bubbles that might form in the LAD. These two requirements provide a complication in the design, since to provide cooling to the entire LAD might present a different flow rate than the first requirement would call for.

This analysis was performed to determine a required HX line diameter. The primary design driver for the HX sizing was the amount of heat transfer that would occur between the HX and the tank fluid. This parameter is not controllable, so limiting cases had to be evaluated, and a design chosen that best covers the entire range of conditions. The line length was bound by geometry of the tank to between 10.67 and 15.24 m (35 and 50 feet). This also became a requirement on the system. The analysis has shown that a 0.635 cm (1/4 inch) O.D. tube with a 1.651 cm (0.650 inch) wall thickness is the best choice to satisfy the requirements. To ensure that the two functional requirements can be met, separate flow control legs will be needed (i.e. if the nominal flow will not cool the entire LAD, extra flow will be required for a short time to meet that objective). This aspect of the design will also provide for the modulation of the heat removal capability, to allow for variances in the nominal heat flux into the cryogen.

The analysis was performed using two computer programs. The first was a specially written analysis routine that predicts the length of pipe required to completely vaporize a two-phase flow. This model was used to perform the parametric analysis required to size the line. The code uses Chen's two-phase heat transfer correlation for the boiling heat transfer value. The second model used was TWOPHS. This code was used to verify the predictions of the first model (once a particular size had been chosen) and to predict the pressure drop through the line. In all cases run, the environmental variables were kept fixed. The assumed environment was an inlet pressure of 34.5 kPa (5 psia) throttled from a tank pressure of 103.4 kPa (15 psia) and an acceleration level of 1 micro-g. These values certainly will alter the results if changed but they were chosen since they represent the nominal values for COLD-SAT.

The models were run with two different limiting values for the external heat transfer, natural convection and conduction. Since low-g heat transfer is a great unknown, these values were used as an upper and lower bound on the amount of heat transfer to the heat exchanger. In reality, the true value will fall in between the two limits. Other limits on the analysis were that the flow must be fully vaporized before exiting the tank (so that no fluid cooling capacity is wasted) and that the pressure drop in the line will be limited to 6.89 kPa (1 psid). This limit was placed so that the flow control orifices would be the point of greatest pressure drop, therefore providing true flow control.

Three different line diameters were investigated. These were a 0.3175 cm (1/8 inch) line with a 0.089 cm (.035 inch) wall, a 0.476 cm (3/16 inch) line with a 1.245 cm (0.49 inch) wall and a 0.635 cm (1/4 inch) tube with a 1.651 cm (0.65 inch) wall. The large wall thicknesses were chosen to reduce the net heat transfer through the tube, and to allow for ease of fabrication. The required line lengths for the necessary vaporization to occur are plotted for different cases in Figure 4.9-3. Here it can be seen that if the heat transfer is dominantly via convection, the flow will vaporize before exiting the tank, whereas if conduction dominates, then the chosen length is approximately correct. This plot leads one to feel that the HX should be the 0.3175 cm (1/8 inch) line, since this configuration is closest to the desired design. However, the pressure drop analysis shows another result. The 0.3175 cm (1/8 inch) line is such a restriction to flow, that the nominal flow rate cannot be achieved in the line even if the pressure drop is the full 34.5 kPa (5 psid). Only the 0.635 cm (1/4 inch) line can achieve the desired flow rate with a 6.89 kPa (1 psid) pressure drop.

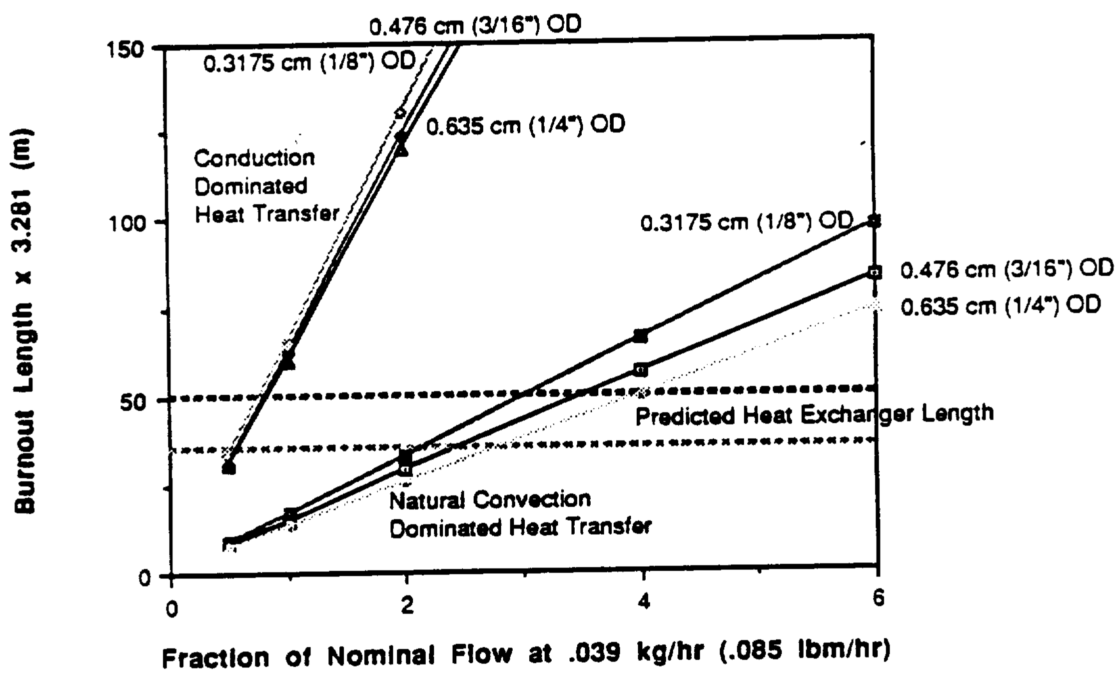


Figure 4.9-3 Heat Exchanger Performance for Different Line Sizes

The analysis has lead to certain design requirements for the TVS HX. The first is that the line will be a 0.635 cm (1/4 inch) stainless steel tube with a 1.651 cm (0.65 inch) wall thickness. This requirement has been shown to be driven more by the pressure loss in the line than the heat transfer characteristics.

Since the flow in the 0.635 cm (1/4 inch) line will probably completely vaporize at around the 6.10 m (20 foot) point of the line, the requirement to cool the entire LAD will not be met. To achieve this, the capability to have 3 to 4 times the nominal flow will be needed. This extra flow will result in excessive pressure loss in the line, so flow control may not be possible for this amount of flow. One option is to have three flow control legs. Two of these legs (for < nominal and > nominal) will be used for heat removal and the third will provide flow control for the LAD if the need arises. Another option that is not as desirable is to dump the flow directly overboard in the high flow case. This would alleviate the possibility of overcooling the VCS during this mode of TVS operation. The drawback to this is the requirement for another thermal short to the VCS. Finally, the use of a 0.476 cm (3/16 inch) line could be studied in more depth. This would be a better choice from a heat transfer point of view, but not from others.

Supply Tank Compact Heat Exchanger (CHX) Sizing/Analysis - Although the CHX will be used in the Pressure Control Experiment, the analysis for sizing and performance has been performed for the Liquid Subcooling During Outflow Experiment. The design requirements of the CHX are based on the outflow requirements of this experiment and the CHX capability is employed for pressure control. Therefore, the results of this analysis and design study are presented in Section 4.9.8 later in this report.

Supply Tank Pressure Control Thermal Analysis - The thermal design of the COLD-SAT supply tank was undertaken to ensure that thermal control of the cryogen could be obtained. With the use of a Thermodynamic Vent System (TVS), a Vapor-Cooled Shield (VCS), and Multi-Layer Insulation (MLI), the heat flux into the tank can be controlled to whatever level is required by the thermal design. The heat flux value for the COLD-SAT supply tank was set at 0.315 W/m^2 (0.1 Btu/hr-ft^2) per direction from NASA LeRC. This value resulted in a required tank heat leak of 4.01 W (13.7 Btu/hr). Another imposed requirement was that the heat transfer into the cryogen via conduction paths should be less than 10% of the total tank heat leak value. The two customer directions plus the functional requirement to control tank pressure were the primary design drivers for the system.

The two customer directions were used to determine the derived design requirements of the tank insulation system. Analysis of the tank lockup case has shown that the desired heat flux can be obtained with 1.905 cm (3/4 inches) of MLI on the inner tank and 3.175 cm (1-1/4 inches) on the VCS. The conduction can be limited to ~7% of the total heat leak via the use of thermal intercepts between the VCS and the tank supports and plumbing. The heat flux requirement has set the nominal TVS flow rate to 0.032 kg/hr (0.071 lbm/hr). The TVS analysis assumed an internal heat exchanger length of 6.10 m (20 feet) and VCS HX length of 9.14 m (30 feet). The TVS tank thermal analysis has shown that this flow rate will indeed provide control of the tank pressure for the HX designs derived.

The thermal analysis of the COLD-SAT supply tank was initiated by constructing a tank thermal schematic. This schematic accounts for all fluid and thermal nodes to be used in the model. As can be seen in Figure 4.9-4, the tank wall and fluid have been broken into 5 separate nodes, with the sectioning propagated out through the MLI layers and the VCS. From this schematic, a thermal R-C network of the system was generated which fed into the MMCAP model input deck. The MLI was broken up into two sets of nodes to represent the middle and the surface of the insulation. The tank model also includes the TVS Heat Exchangers (HX) in the tank and on the VCS.

To finish the development of the MMCAP model, the conduction paths had to be accurately accounted for. First an estimate of the wiring cross sectional area required to service the instrumentation, pumps, and valves was made. This estimate looked at the size of wire needed to prevent self-heating of the wire itself. A better estimate could be made if the component data were more developed. In that case, the wire could be sized so as to not produce too much voltage drop upstream of the component. To account for this factor, a sizeable margin of safety has been applied to the wire area.

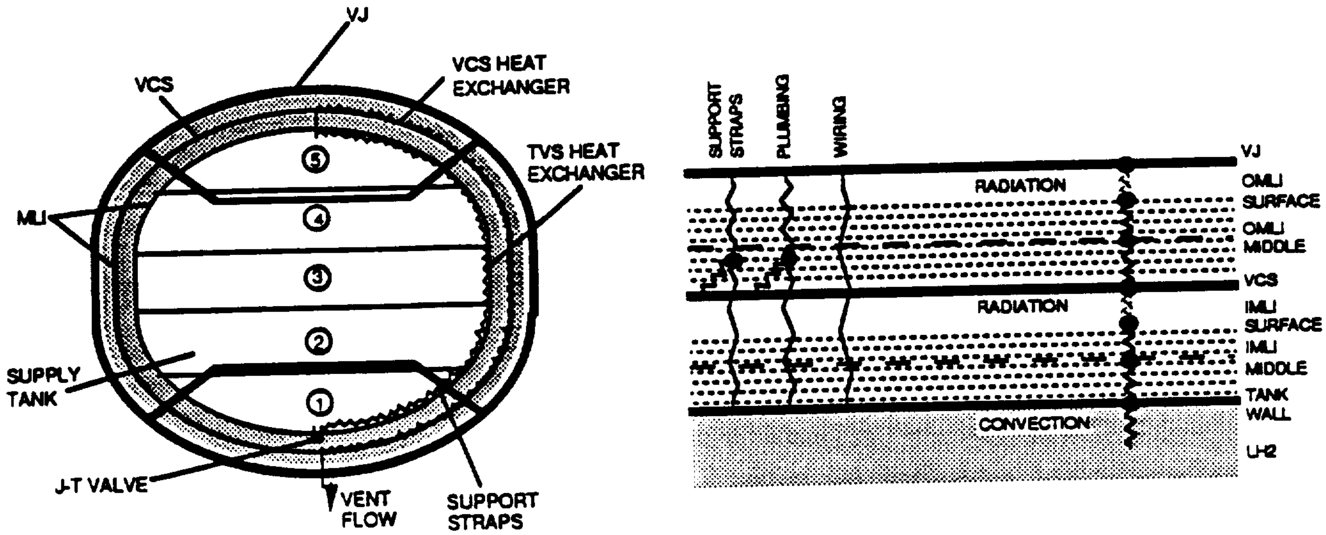


Figure 4.9-4 Thermal Model Representation of MMCAP Thermal Model (R-C Network)

Next, a summary of all the conduction parameters was made. The support sizes were scaled from those proposed for the Superfluid Helium Tanker. The pipe sizes were calculated from the fluid system schematic, and the wiring size was generated as explained above.

The first analysis performed was a modeling of the pressure rise that will occur when the tank is locked up (i.e. ERD 1.1 & 1.2). This analysis was performed to predict a tank heat flux in an attempt to determine the required amount and distribution of MLI. The tank pressure can be predicted, but this value cannot be modeled with high fidelity since the fluid has only been broken into 5 nodes. After numerous runs it was found that the required heat flux can be obtained with 1.905 cm (3/4 inches) of MLI on the inner tank wall and 3.175 cm (1-1/4 inches) on the VCS. The chosen boundary (vacuum jacket) temperature for this analysis was 278 K (500 R) which is an average environmental value. This temperature was relatively high to ensure that the heat flux goal could be met and if the value decreases as expected, the amount of MLI will be allowed to decrease also. The lockup analysis has also shown that to limit the conduction heat leak to less than 10% of the total, a 0.305 m (1-foot) piece of 12-gauge wire will be needed to thermally tie the supports and plumbing to the VCS, otherwise this value would have been 40% of the total heat leak without thermal intercepts to the VCS.

The lockup model was also used to predict the warm-up time of the dewar once the cryogen has been depleted, since there was interest in including this experiment in the ERD (Ref. 4.9-6). The analysis was run for 500 hours and the tank wall had only risen to ~111 K (200 R). From this model an estimate of 3 to 4 months to warm the tank to ambient was made.

Figure 4.9-5 presents the pressure rise of the fluid during the tank lockup case. The STRAT code has typically been used to predict the true pressure during the test, but the results of this model compare very well with the results of the STRAT predictions (the STRAT model lock-up stratification predictions will be presented in the following section). The lockup case modeled here is at the 95% fill level, with a nominal heat flux of 0.315 W/m^2 (0.1 Btu/hr-ft^2) in a 1x10^{-6} g environment. The initial hump in the pressure curve is controlled by the choice of initial conditions. The lockup was assumed to have begun immediately after tank mixing, therefore the fluid was in a homogeneous two-phase condition. A review of recent ground testing of a similar condition has shown that this initial hump does show up in the data. The hump is caused by the ullage needing a superheat to transfer heat and mass to the liquid. Thus when the lockup begin, the gas will have an initial temperature rise resulting in the pressure hump before condensation starts to occur that reduces the pressure rise rate.

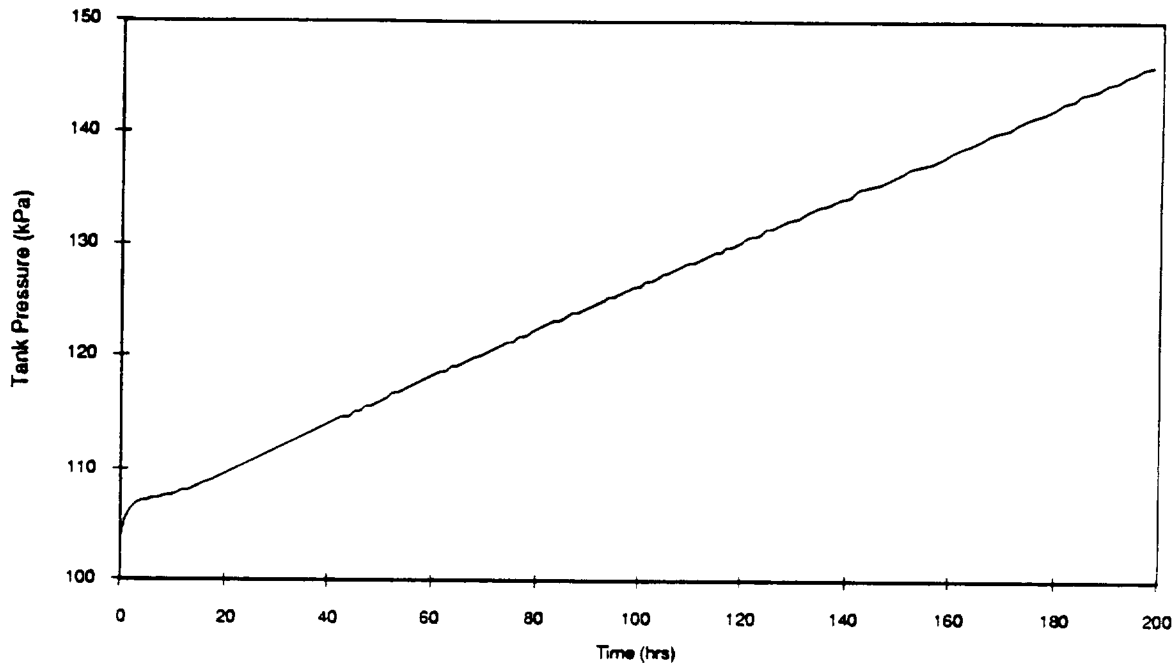


Figure 4.9-5 MMCAP Model Tank Pressure Rise During Lock-Up (95% Fill)

After the lockup case was finished, the task of modeling the TVS operations was begun. The supply tank TVS analysis runs have shown that the nominal flow rate will indeed reduce the tank pressure, allowing this variable to be controlled without free venting to space. The amount of time for this pressure reduction to take place has been found to be very dependent on the choice of initial conditions for the model. As can be seen from the pressure profile plot in Figure 4.9-6, the first cycle can take much longer than subsequent ones. In fact, the first cycle proceeds for 50 hours before the pressure stops rising. A more detailed model that has a set of boundary layer fluid nodes in contact with the TVS only might provide a better modeling of the pressure response.

The thermal part of the model has proven to be more stable and predictable. The TVS HX flow has shown to become fully vaporized at the 6.10 m (20 foot) point in the line, just as other modeling had predicted. The VCS does develop a 28 K (50 R) temperature differential during TVS operations, but this could be alleviated by the use of non-uniform spacing of the tubing on the VCS. Finally, the use of the VCS HX has reduced the tank heat leak to a value ~30% of the lockup value. This reduction in heat leak will provide the capability to store the LH2 over a longer period of time than originally allocated for, or conversely less fluid will have to be budgeted for boiloff.

Figure 4.9-6 presents the pressure profile during one particular TVS run. The case modeled is for a 95% fill level in a 1×10^{-6} g environment with a boundary temperature of 278 K (500 R). The pressure profile is very dependent on initial conditions. In the case modeled here, the tank is assumed to be in a two-phase condition (as it would be after a mixing test) when the TVS is turned on. If the tank had been initially stratified then the pressure response would have been much different. Another parameter that could be varied is position of the ullage. In this run the ullage is assumed to be at the top of the tank (meaning positioned at the far end from the inlet of the TVS HX). Due to this configuration the flow has completely boiled by the time it reaches the ullage resulting in little direct cooling of the gas. If the reverse had been assumed the gas would have cooled off much quicker, and the pressure response would have been more dramatic. One idea to better model this system would be to include fluid nodes that act as a thermal barrier between the bulk fluid and the HX. These nodes would be along the wall and could be set up to act as a thermal boundary layer that would pump heat into or out of the ullage depending on the configuration.

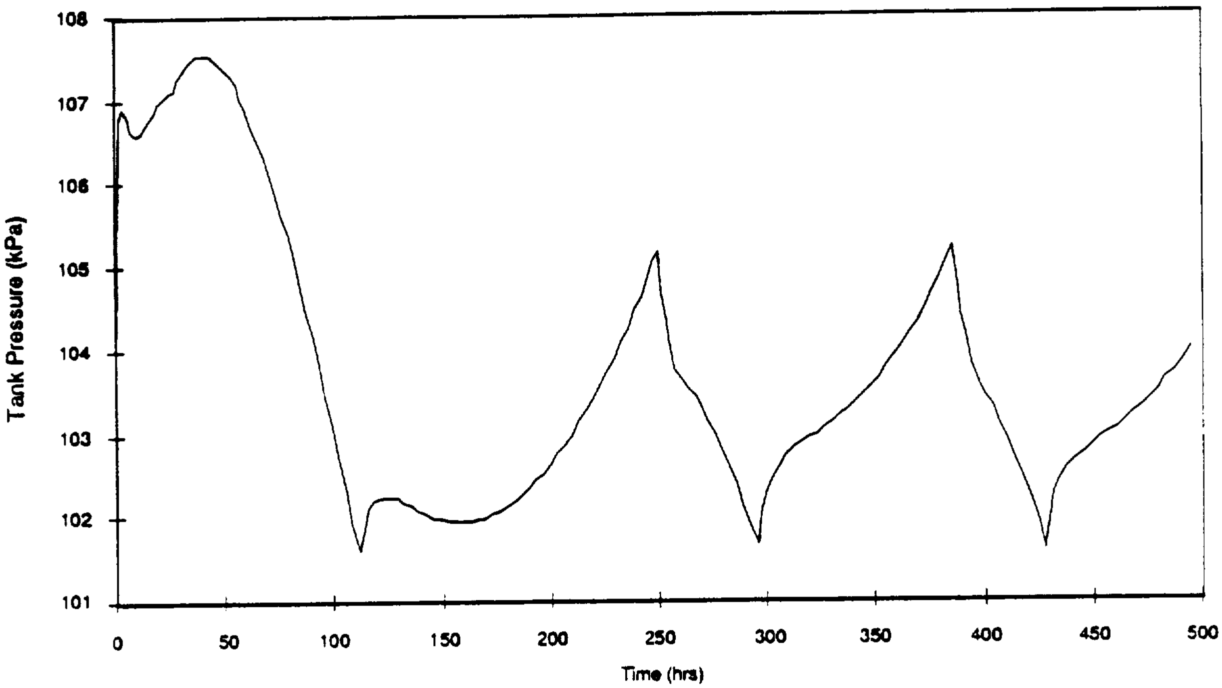


Figure 4.9-6 Supply Tank Pressure Response During TVS Operations

The conclusions that can be drawn from this analysis are quite interesting. If the pressure actually takes 250 hours to respond to the TVS flow, then the time allocated for TVS testing is not adequate. If the test had only been run 50 hours, no reduction in the pressure rise rate would have been seen at all. Further modeling is required to determine if these large thermal time constants are required, but it does seem that it would be very desirable to modify the ERD to include some long term (20 days or more) steady state TVS tests where all other systems are left idle.

The temperatures of the fluid nodes and the interface illustrate the degree of stratification that results during TVS pressure control. The gas temperatures tend to exhibit a similar response pattern as seen in the pressure plot. The stratification in the remaining fluid nodes (liquid) contributes to the node-to-node heat transfer. The choice of ullage position will dictate the level of stratification in the liquid and in the gas. If the ullage were in direct contact with the TVS HX, the gas would become less stratified relative to the liquid, resulting in a lower overall tank pressure.

Figure 4.9-7 below presents a slice through the insulation system showing the temperatures of all the nodes progressing radially outward from the tank wall, and at the bottom of the tank. Temperature results at the top of the tank are similar but are not presented here. The plot shows the reduction in the VCS and MLI node temperatures due to the vent gas flow in the VCS HX. It can be seen that the vent flow cools the VCS substantially, and that it also cools the MLI layers as well via radiation from the VCS. The inner MLI (IMLI) layer actually becomes warmer than the VCS while the TVS is operating. This is expected since conduction through aluminum is a much better driver of a heat flow than radiation to the MLI. If the vent flow rate were to be reduced to a value lower than the one needed for the nominal lockup case (i.e. to a point where its heat removal capability would be equal to the heat flux) the TVS would not have to cycle on and off and a new steady-state temperature profile would develop. In reality, hitting this point would be very hard to do, so the best idea would be to have one flow leg with a rate less than required, along with a second higher flow leg that would be periodically turned on and off to maintain relatively constant tank pressure.

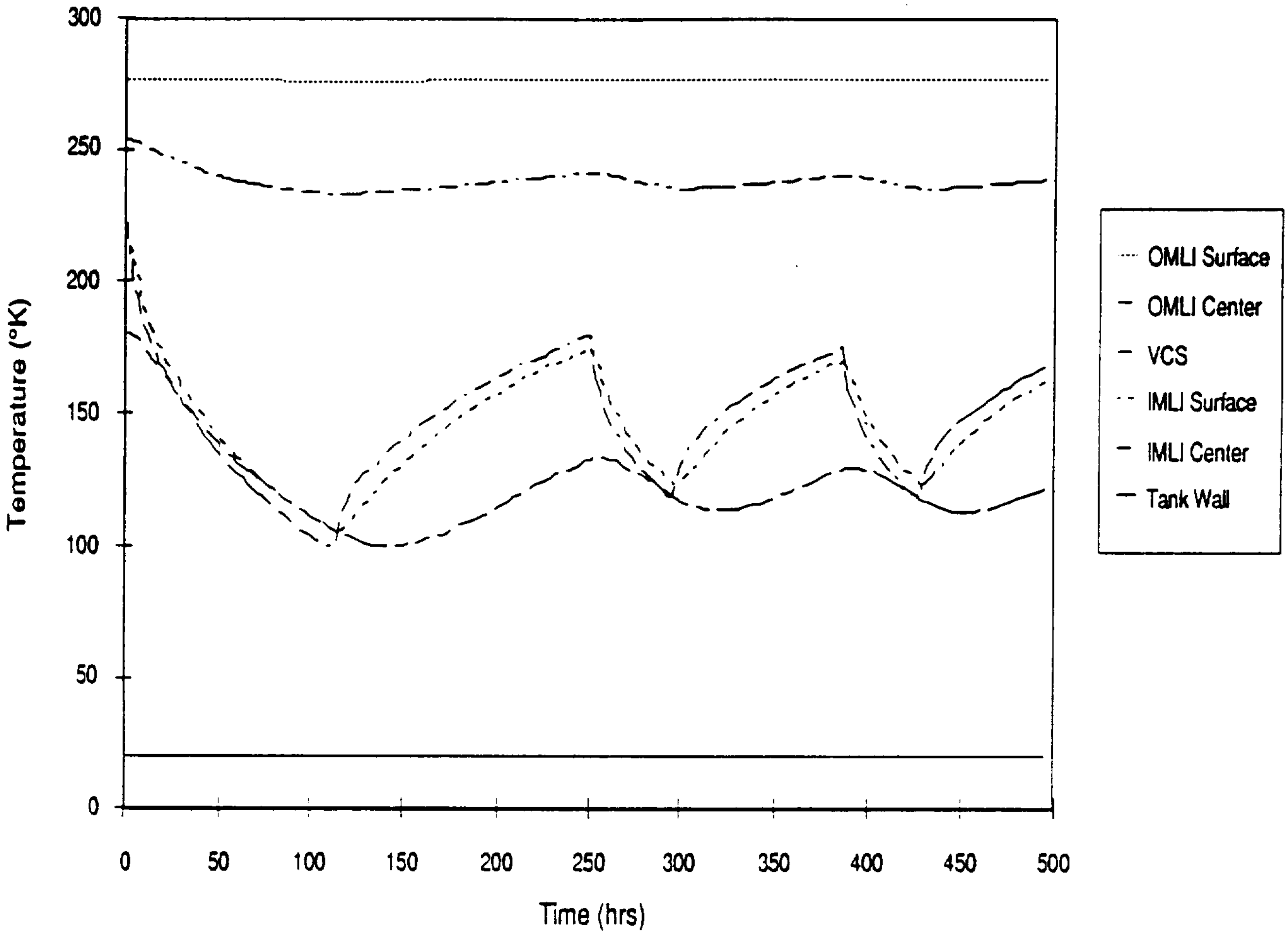


Figure 4.9-7 Tank Temperature Profiles During TVS Operation (Bottom of Tank)

The maximum temperature difference that develops on the VCS heat exchanger operations is approximately 28 K (50 R). The temperature difference develops as a result of colder TVS fluid entering at the bottom of the shield that exits at a warm gas condition at the exit of the HX at the top of the shield. This temperature difference could be reduced to maintain uniform thermal conditions on the shield if the VCS heat exchanger tubing is routed in a non-uniform manner alternating from the bottom to the top of the shield continuously. The reduction in TVS flow resulted in a net drop in the tank heat leak from a value of 4w (13.7 Btu/Hr) when the TVS was not operating to 1.5w (5 Btu/Hr).

Supply Tank Thermally-Induced Stratification Modeling Analyses (STRAT) - The STRAT code was developed for the specific purpose of analyzing thermal stratification in cryogenic hydrogen and nitrogen tankage systems via a buoyant flow boundary layer simulation in low-g that accounts for boundary layer convection heat and mass transfer. The STRAT code has the capability to model multiple fluid layers (up to 200) subject to boundary layer flow conditions, allows modeling of arbitrary tank geometries with insulation, allows the user the capability to prescribe slowly-varying uni-directional g-fields, and to prescribe time-dependent tank wall heat fluxes. The model is applicable to acceleration levels of 10-7 g's or more and for heat fluxes less than the nucleate boiling threshold, which is consistent with the COLD-SAT experiment tank environments. The finite-difference equations for boundary layer and bulk fluid heat and mass transfer are solved in conjunction with a liquid/vapor interface heat and mass transfer balance. The latest thermal stratification analyses for COLD-SAT have been performed with the use of this code.

A container of cryogenic fluid in a gravity field subjected to heating or cooling at the container walls will develop free-convection boundary layers at the wall-fluid interface. These boundary layers will develop flow such that the heated fluid is carried towards the top of the container, or in a direction opposite of that to the direction of the gravity vector due to buoyancy forces. It is the result of buoyancy forces that causes a boundary layer to develop along the inside of the tank wall. The boundary layer flow starts from the bottom of the tank and grows within each fluid constituent (liquid and gas), thus developing to its utmost at the top of each fluid constituent. The boundary layer mass flow is dumped into the top liquid and gas nodes. The net effect of boundary layer flow into the topmost liquid and gas layers causes a net downward flow in the core of the bulk fluid. As a result of these processes, thermal stratification of the fluid (temperature and density variations in the fluid layers) in the tank results, the degree to which depends on the heating rate, g-level, fluid properties, and the tank geometry.

In STRAT, the stratification process is handled by a series of fluid mass and heat transfer processes in the tank wall, the boundary layer flow, and the bulk fluid elements in the tank. A physical representation of a tank fluid stratification model and these processes is depicted by Figure 4.9-8 below.

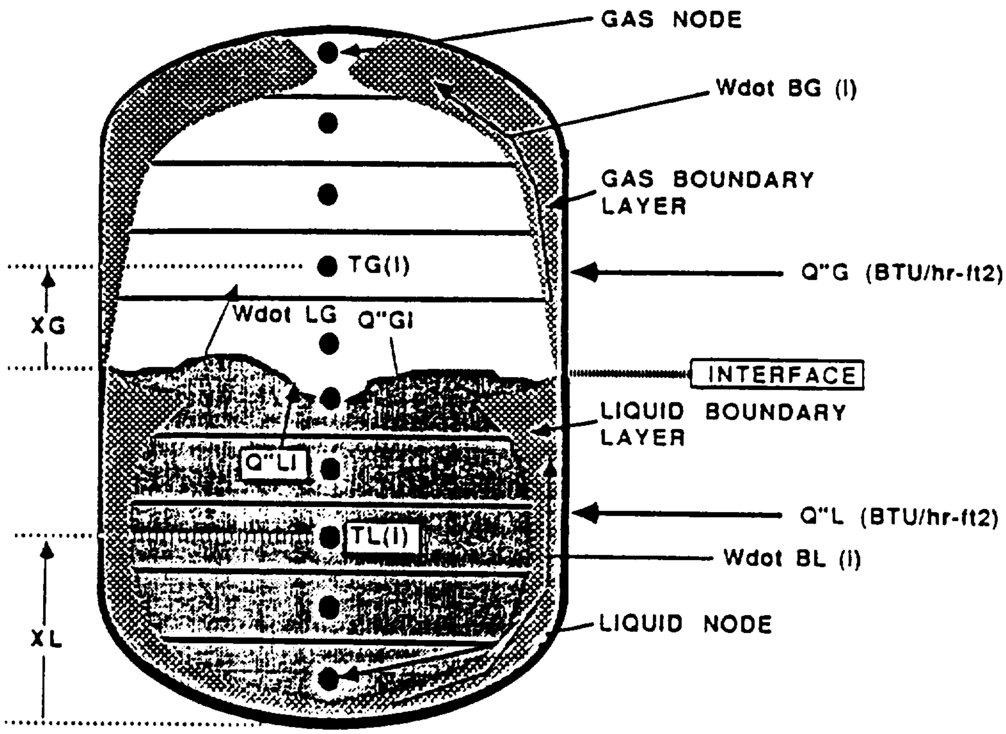


Figure 4.9-8 Physical Representation of Fluid Stratification Model

The tank wall and fluid are modeled by a series of interconnected tank wall and bulk fluid elements as shown. The wall and fluid elements are mated to one another in a one-to-one correspondence since the STRAT computer program builds an internal conductor network on this basis. Each of the wall and fluid elements (nodes) are horizontal flat layers perpendicular to the direction of the gravity vector, with the liquid nodes at the bottom and building upward in the opposite direction of the gravity vector into the vapor ullage nodes.

An insulation thickness can be built uniformly around the tank wall through which an external tank heat flux is calculated. If a heat flux is known as a system design requirement, the option exists to the user to specify a fixed tank wall heat flux or a heat flux that varies with time. Both of these heat flux options will be superimposed to yield a net tank wall heat flux. This heat flux is a necessary condition to cause stratification in the fluid.

A comparison of two independent computer models for predicting stratification in the COLD-SAT liquid hydrogen supply tank has been accomplished. The STRAT boundary layer flow model simulation was cross-validated with Flow Sciences computational fluid dynamics code, FLOW-3D. This was a preliminary comparison for purposes of cross-validation of the predictive ability of the new STRAT code for predicting cryogenic fluid thermal stratification in low-g with reasonable heat fluxes imposed on the fluid. The validation was preliminary since little or no valid test data is available at low enough heat fluxes and controlled fluid conditions with which to validate its capability.

The COLD-SAT supply tank was modeled using both models for a 95% full tank condition. With a high fill level, the fluid stratification process will be primarily restricted to the liquid constituent and not the gas since the FLOW-3D model is not able to handle a two-phase fluid system. Only the liquid portion of the system could be modeled by FLOW-3D, so this provided similar conditions in both analyses for purposes of valid results comparison. The analysis was conducted to assess the validity of STRAT's buoyant convective flow model with that of FLOW-3D's finite element fluid model. It was assumed that the FLOW-3D model prediction would be more accurate in terms of its capability to fluid problems of this nature and its extensive heritage in industry, and so it provided the basis for comparison of the STRAT prediction. The same thermodynamic properties and equation of state were used in both models and the liquid surface was assumed flat by imposing a zero surface tension condition to the free surface in the FLOW-3D model. In addition, the same uniform heat flux was applied to the tank wall area encapsulating the liquid volume.

The maximum and minimum temperature conditions in the bulk liquid were extracted from the analysis runs at two heat fluxes, 0.315 and 1.892 W/m^2 (0.1 and 0.6 Btu/hr-ft^2). The comparison at low heat flux is shown in Figure 4.9-9. The two heat fluxes analyzed provided more than one data point from which comparisons in model predictions could be made. Excellent agreement was obtained between

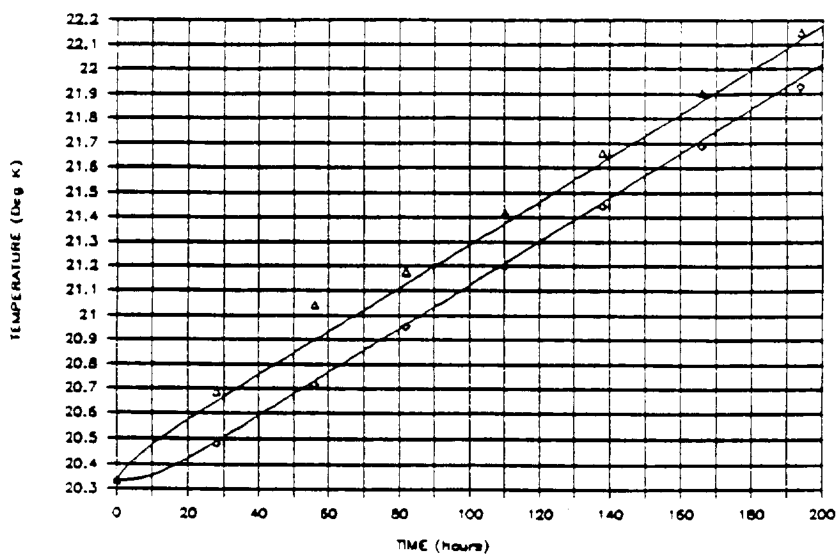


Figure 4.9-9 Comparison of STRAT and FLOW-3D Model Predictions for Low Heat Flux

the two models. The chart shows a maximum liquid temperature difference of about 0.17 K (0.3 R) at 200 hours time. The symbols on the plot are the FLOW-3D predictions whereas the continuous lines represent the STRAT temperature predictions for the minimum and maximum liquid temperatures.

The results of the FLOW-3D model show evidence that a distinct boundary layer has developed at the tank wall by virtue of the steep temperature isotherms near the wall as opposed to the flatter profiles in the bulk fluid region similar to the manner in which the boundary layer physics of the STRAT code tend to predict this phenomena. A net upward flow along the tank wall in the B.L. exists that gives way for a net downward flow in the bulk fluid. Therefore, the predictions are similar to both models for the fluid phenomena occurring from the conditions imposed.

A few significant conclusions can be made regarding the validation of the STRAT model with the FLOW-3D code. Excellent agreement was obtained for two independent sample run cases that used different heat fluxes since heating is the primary driver for fluid flow. Although these comparisons provided outstanding agreement and a means for cross-validation between analytical capabilities, applicable test data still needs to be obtained for the best possible validation of the STRAT code. The FLOW-3D predictions are believed accurate due to its extensive checkout and validation by the Flow Sciences Company and through its extensive use by its many users in industry. For these reasons, STRAT was determined to be more than adequate for predicting stratification in cryogenic tanks.

Analyses of the COLD-SAT ERD stratification tests have been conducted with the use of the STRAT code. An example of the pressure rise and temperature stratification results are presented in Figures 4.9-10 and 4.9-11, which graphically show the pressure rise and fluid temperatures, respectively. The case shown is for a 95% full supply tank at the low heat flux value of 0.315 W/m^2 (0.1 $Btu/hr\text{-}ft^2$) which is meant to represent test 1.1-2. Note the difference in temperature (stratification) that develops for the liquid in the tank at this high of a fill level.

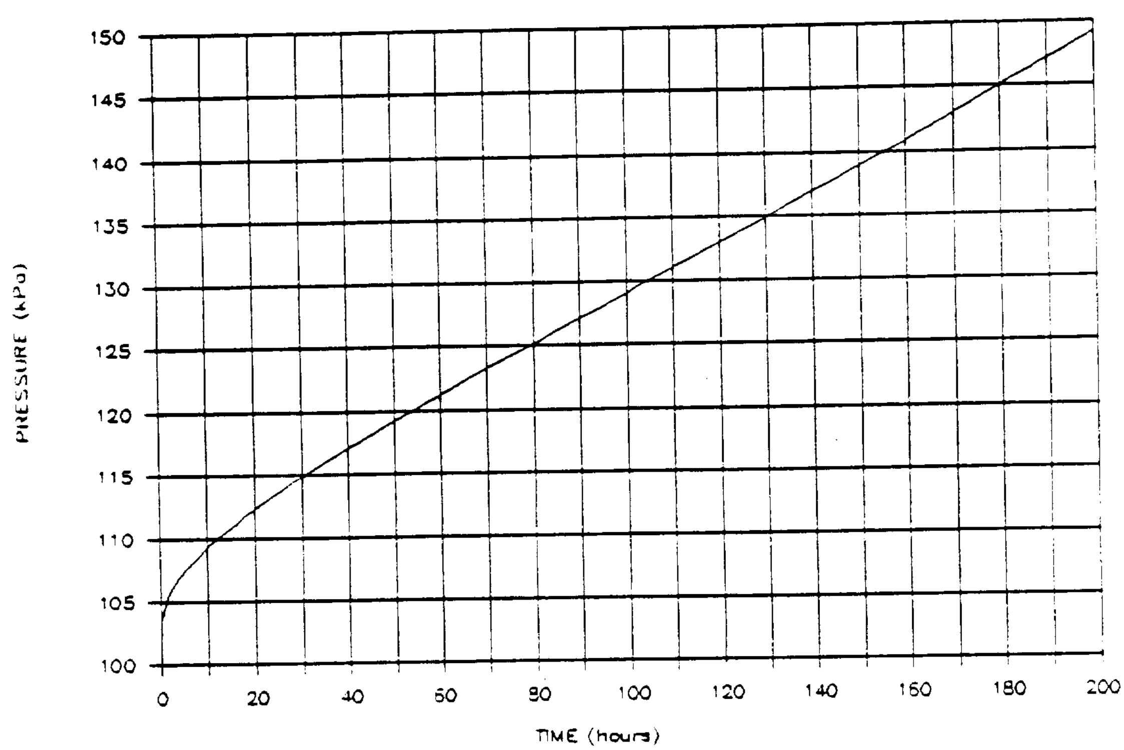


Figure 4.9-10 STRAT Supply Tank Lock-Up Pressurization Predictions

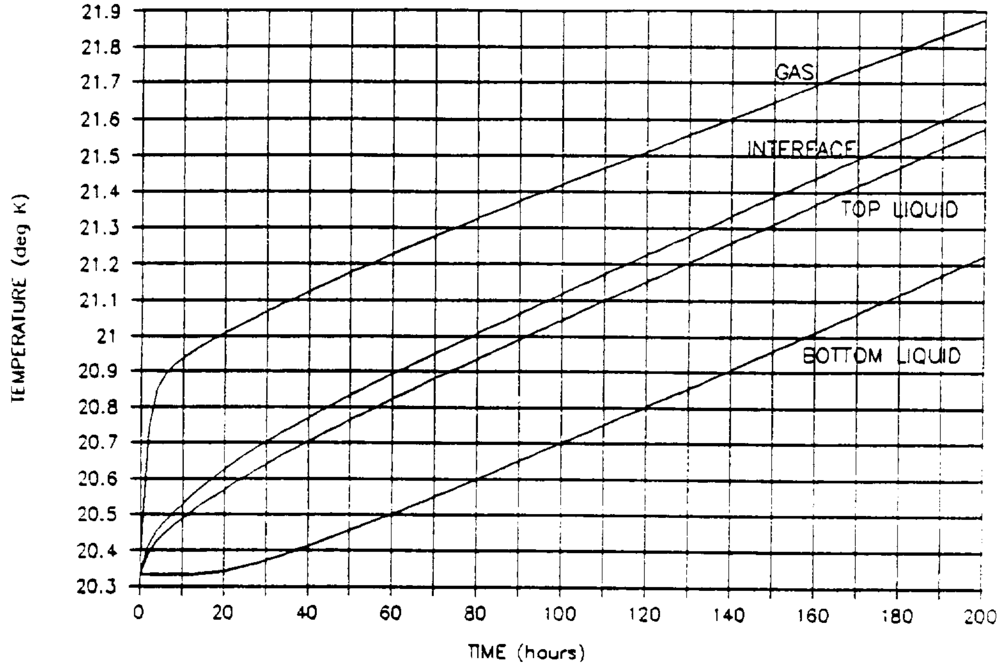


Figure 4.9-11 STRAT Supply Tank Lock-Up Stratification Fluid Temperatures

Receiver Tank Heat Exchanger Thermal Analysis - The thermodynamic vent system (TVS) heat exchanger is the primary means of controlling the tank pressure by removing heat flux from the cryogenic tank. The functional requirement of the receiver tank TVS heat exchanger is to provide passive thermal control with the use of an external wall-mounted heat exchanger.

A receiver tank heat exchanger analysis was performed to investigate heat removal capacity, required line sizes and lengths, tank wall temperature gradients, line spacing, and proposed HX tube attachment methods for the COLD-SAT receiver tanks. The assumptions were made to consider an external wall-mounted design that completely dries out at the end of its length on the tank, and one that removes a quantity of heat consistent with the required tank wall heat flux (this analysis assumed a heat flux of 1.577 W/m^2 (0.5 $Btu/hr\text{-}ft^2$)).

Since no absolute requirements for the design of the receiver tank wall-mounted heat exchangers were defined by the customer, an assumption was made to provide uniform heat exchanger wall coverage such that wall temperature gradients could be reduced to 1.1 K (2 R) or less. This assumption became one of the design requirements. This is an important requirement since high wall temperature gradients (from hot spots) could inherently contribute to stratification in the tank due to non-uniform wall heat input to the fluid. It is desirable to separate the effects of stratification and pressure control in the tanks as much as possible, which is accomplished by maintaining uniform wall temperatures.

Overall HX-to-wall conductances and contact conductances from the thermal analyses were derived for a number of arbitrary candidate heat exchanger design configurations. The computed thermal characteristics (heat exchanger conductances) of the candidate designs became the derived design requirements for the configurations analyzed. An unlimited number of possible design concepts could potentially be considered.

High resolution thermal models of the receiver tank HEX's were developed with Mini-MITAS to handle the detailed HX design variables that affect a HEX's performance in order to assess reduction of wall temperature gradients. The HX tube attachment methods and the selection of materials are variables that will affect the thermal performance of the HX design. Uniform HX coverage of tank walls can only be achieved by controlling material thermal conductivities and HX tube contact conductances. Therefore, the Mini-MITAS models of each receiver tank geometry was developed to model general HX tube networks with the flexibility to change thermal performance variables for parametric analysis and evaluation.

The high fidelity (resolution) steady-state MITAS models were developed to be used for predicting TVS heat exchanger performance of arbitrary heat exchanger networks as defined by the user. Tank wall temperature profiles and heat removal capacities were calculated from the analysis runs so that the performance of specific designs could be characterized. The models possessed the capability to define arbitrary paths and lengths of HX tube and to vary heat transfer conditions such as film coefficients, thermal conductivities, HX tubing size and contact area, and tank wall thickness and area. Each tank model is comprised of a tank grid nodal network that is interconnected by a conductor network. Receiver tank 1 has 362 tank elements and receiver tank 2 has about 218 wall elements (each tank has 24 sectors.)

The equivalent conductances for each of the HX design configurations analyzed were computed from the model variables with the assumption of infinite contact conductance between the tube and outer tank wall. The equivalent conductance is computed from a series conductor relationship for the heat transfer through the HX tube wall thickness and through the tank wall itself. The equivalent contact widths (HX length and contact width make contact area) from which the equivalent conductances are determined are shown in Table 4.9-1 below. The smaller the conductance, the longer the HX can be and the more uniform the wall coverage is for the same heat removal capability. Contact conductances are computed in a similar manner by introducing an additional conductor in series with a known contact area and assuming the same overall conductance value. These are shown in the table as well. The contact conductance is limited by the overall equivalent conductance when the contact area is large enough not to affect the heat flow (relative to assuming an infinite conductance between the HX tube and the tank wall).

Table 4.9-1 Receiver Tank Heat Exchanger Derived Contact Conductance Design Requirements

CONFIG #	HX LENGTH-m	WALL TEMP-°K MIN	MAX	Geq -W/K	Gcc -W/K	Gcc/A -W/m^2-K	CONTACT WIDTH-cm
Receiver #2 #1 Al HX SS HX	3.30 (10.82 ft)	17.3 (31.2 R)	22.2 (40.0 R)	173.5* 101.3*	277.6 406.2	6626 9698	.476* .953*
#2 Al HX SS HX	4.77 (15.64 ft)	18.3 (33.0 R)	21.7 (39.0 R)	4.30	4.33 4.40	71.5 72.7	.0082 .028
#3 Al HX SS HX	9.28 (30.45 ft)	19.2 (34.6 R)	21.1 (37.9 R)	2.11	2.11	17.9	.0021 .0070
#4 Al HX SS HX	12.1 (39.66 ft)	19.9 (35.9 R)	20.9 (37.7 R)	1.80	1.79	11.7	.0014 .0046
Receiver #1 #1 Al HX	4.89 (16.03 ft)	17.9 (32.2 R)	21.8 (39.3 R)	28.7	30.0	483.8	.053

* Heat Transfer to HX Limited by Fluid-to-Wall Convection Heat Transfer Coefficient; Values Shown are Minimum Widths for Maximum Heat Transfer

The analysis derived thermal requirements for a number of candidate HX configurations that can feed into the design of the heat exchangers. The analysis has indicated that a longer heat exchanger length is necessary and required to reduce the tank wall temperature gradients for improved stratification control of the fluid in the tank, however, these longer designs require more detailed attachment methods (less contact) based on the low heat fluxes considered. On the other hand, shorter designs require intimate wall contact yet result in higher tank wall temperature differences. The shorter designs do have one advantage in that they are less complex and can be attached to the tank wall through more conventional methods for the same heat removal capacity (such as welding).

Under the next phase of the COLD-SAT program, it will be more practical to conduct detailed parametric studies of wall-mounted heat exchanger designs once the tank designs become finalized. Possible attachment methods include insulating the heat exchanger lines and/or intermittently clipping the lines to the wall with low thermally-conductive clips. These and other viable approaches will be investigated in the next phase of the program to finalize the heat exchanger design.

Thermoacoustic Oscillation (TAO) Phenomenon Analysis - The heat leak into cryogenic tankage systems can become exorbitant if the phenomenon of thermoacoustic oscillations is allowed to occur. Such a phenomenon is known to occur primarily in liquid helium and hydrogen plumbing systems in which cold lines from a tank are connected to warm valves or lines at some length from the point of cold contact. Thermoacoustic oscillations result from a thermally-driven expansion and contraction of cold gas inside plumbing lines that is accompanied by a large magnitude of heat transfer from the warm end of the line to the cold tank. This heat leak can be on the order of many times the heat leak allowed in the tank design and therefore, must be eliminated by the COLD-SAT design.

An analysis was performed to analyze this concern in the COLD-SAT experiment plumbing for any possibilities of occurrence. A worse case analysis was assumed and theoretical TAO stability curves developed for helium and hydrogen were used for making rough order of magnitude predictions of TAO in the COLD-SAT design. The derived design requirement is to eliminate TAO concerns in the design so that the proper tank heat flux can be designed into each tank.

The analysis predictions indicated that TAO would not be a concern in the COLD-SAT tankage/plumbing design. The only plumbing suspect for TAO were the three tank vent lines which were routed to relatively warm valve panels that introduced a potential source of heat leak for the oscillating gas in the lines if TAO were to occur. The theoretical analysis predicted that the existing COLD-SAT vent line lengths were short enough to preclude the occurrence of TAO even in spite of the assumed worse case analysis conditions. The supply tank vent line length was 3.96 m (13.0 feet) long, as compared to 7.47 m (24.5 feet) required for TAO instability to occur. Likewise, the receiver tank vent line lengths were 1.07-1.37 m (3.5-4.5 feet) in length as compared to an allowed 3.32 m (10.9 feet) of length before the onset of TAO. These data are shown in Table 4.9-2 below. The conservatism in the analysis and the short vent line lengths provide a safety margin. Testing will indicate whether or not TAO is of concern in the final design.

Table 4.9-2 Derived Design Requirements for Thermoacoustic Oscillations

LENGTHS	SUPPLY TANK	RECEIVER TANKS
ALLOWABLE	7.47 m (24.5 FT)	3.32 m (10.9 FT)
ACTUAL	3.96 m (13.0 FT)	1.07-1.37 m (3.5-4.5 FT)

Thermoacoustic oscillations can occur spontaneously in gas or vapor lines containing helium, hydrogen, nitrogen, or neon in which a temperature difference exists between the ends of the tubes. The warm end is closed or restricted and the cold end is open to the liquid dewar. As already mentioned, extremely high heat transfer rates can occur as a result of the thermally-driven oscillations between the warm and cold ends of the tube.

Thermoacoustic theory has been developed for these gases subject to rapid heating and cooling which describe the stability regions for predicting TAO in plumbing geometries. An analysis was performed using the TAO theory in order to identify plumbing lines in the COLD-SAT experiment subsystem and to predict whether or not TAO is expected to occur.

The stability curves for hydrogen are a plot of temperature ratio versus a dimensionless parameter, Y_C. The temperature ratio is the ratio of the hot-to-cold end tube temperatures and the dimensionless parameter is a function of the tube geometry and the gas fluid properties. The occurrence of TAO becomes more pronounced with an abrupt change in temperature although a gradual change in temperature does not necessarily exclude the possibility of occurrence. A series of "stability" curves developed from the theory were used to make the TAO occurrence predictions for the COLD-SAT spacecraft (Ref. 4.9-7). Each curve is represented by a different hot-to-cold tube length ratio (eta ratio).

A plot of the thermoacoustic oscillation stability curves for hydrogen is shown in Figure 4.9-12 below. Curves are shown for many hot-to-cold line length ratios. The eta ratio is defined to be the ratio of the warm (hot) to cold ends of the tube that penetrates the tank. The alpha ratio is defined as the ratio of the hot end to the cold end temperatures of the tube. The parameter Yc, is a combination of fluid properties and the radius of the tube. It is defined as the tube radius times the square root of the quantity: velocity of sound at cold gas temperature divided by the cold length times the kinematic viscosity. It is expressed as:

$$Yc = r\left(\frac{C_c}{L_c V_c}\right)^{1/2}$$

where r= tube radius
C_C= velocity of sound at cold temperature
L_C= length of cold end of tube
V_C= kinematic viscosity of cold gas

A worse case eta ratio (hot to cold length ratio) of 1.0 was selected for conservatism in the analysis. An eta ratio of 1.0 indicates that the hot and cold lengths of the tube are the same.

The profile of the curves tend to open up to the upper right in the plot. The region inside of the curves is the region of instability where TAO is expected to occur. The region to the left and below the curves is the region of TAO stability, the area that the COLD-SAT plumbing will be designed to. For an eta ratio of 1.0, a minimum temperature ratio of about 5.5 - 6.0 exists such that below this value TAO will never occur. Temperature ratios for COLD-SAT could typically get above a value of 10.

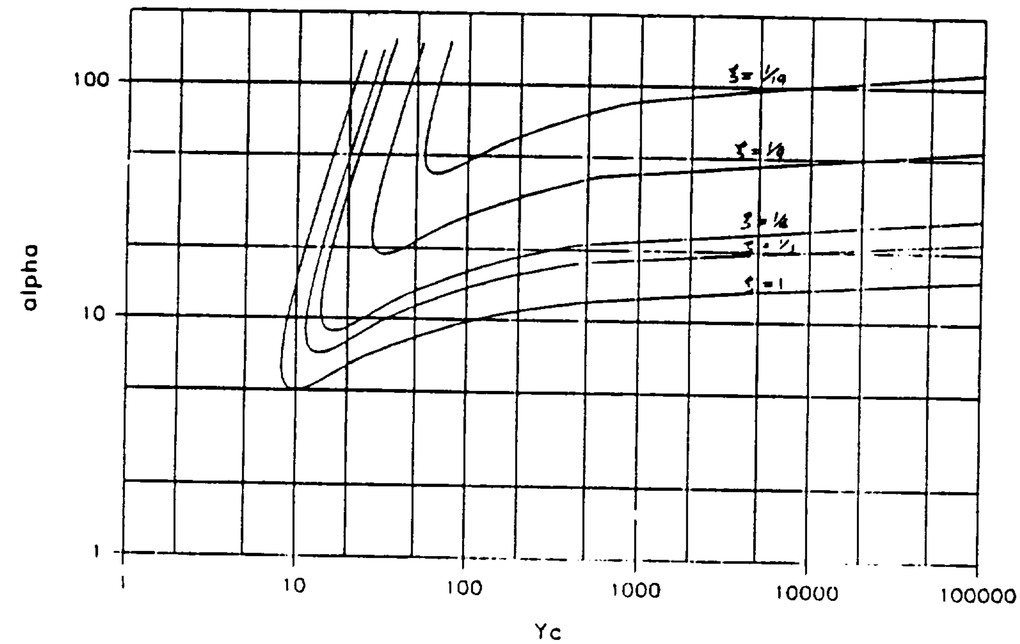


Figure 4.9-12 TAO Stability Curves for Liquid Hydrogen Based on Thermoacoustic Theory

A great deal of work has been performed by Rott and others on the development of TAO theories (Ref. 4.9-8) . The most extensive work has been conducted for helium for which there is much test data that has aided in the validation of the theories. A theory has been developed for hydrogen similar to that of helium, but no test data is available to validate the theory as of yet. Future work on hydrogen TAO testing is planned as early as spring or summer 1990 in order to obtain some real test data to validate theories. Dr. Timmerhaus at the University of Colorado is currently working these issues and plans to conduct the testing with hydrogen under a grant (# NAG3-1018) from NASA-LeRC. Once test data is obtained, the issue of TAO will be investigated further in the next phase of the program.

4.9.2 Tank Chilldown - COLD-SAT Receiver tank chilldown analyses were conducted for a spray chilldown process and for the tank wall heat exchanger chilldown process. Both chilldown processes have been shown analytically to perform adequately in order to achieve the required tank wall target temperatures prior to no-vent fill. The differences noted for each of these two processes include the heat transfer mechanisms, fluid usage, and times for chilldown.

Spray Chilldown Process - The spray chilldown process depends on the understanding of the fluid dynamics of the injected fluid and heat transfer processes occurring between the fluid (spray or otherwise) and the tank wall. As the chilldown fluid enters the tank as a spray, the small liquid droplets flash and boil at the lower tank pressure. The spray drops impact the warm tank wall and since the wall temperature is above the "Leidenfrost" temperature where drops bounce off the hot wall characteristic of film boiling, much of the heat transfer occurs by convection to the gas than by contact of the liquid with the wall. The process of film boiling imparts thrust forces to the droplets, which in turn maintains fluid motion. These thermodynamic processes add vapor mass to the tank ullage and thus raise the tank pressure. Heat transfer due to film boiling and radiation heat transfer are present to some extent with the majority of the initial heat transfer occurring by flashing of the spray droplets as long as liquid is present and the tank pressure is below liquid saturation pressure. This process occurs very rapidly and the time taken is essentially negligible. The final phases of heat transfer involve convective heating of the resulting vapor until the chilldown gas reaches near the tank wall temperature at the maximum tank pressure. This is the time intensive portion of the chilldown process. The ultimate goal in order to characterize the chilldown process will be to examine and understand these processes and the mechanisms which control their behavior.

The general energy equation describing this process for a control volume around the tank system is expressed as follows:

$$M_W C_{pW}\, dT_W/dt = Q_{EXT} - Q_{WALL} = Q_{FLUID} = m_{SPRAY}\,(u_g - u_{g\,sat} + h_{g\,sat} - h_{l\,sat})$$

M_W = Mass of wall (+ MLI + supports + hardware if affected by chilldown)
C_{pW} = Wall specific heat (function of T_W)
T_W = Wall average temperature
Q_{WALL} = Sensible heat stored in the tank wall
Q_{EXT} = Heat added from external sources (background heat leak)
Q_{FLUID} = Heat absorbed by the chilldown fluid from the tank wall and heat leak
m_{SPRAY} = Charge mass for chilldown cycle
$h_{l\,sat}$ = Incoming saturated liquid enthalpy
$h_{g\,sat}$ = Saturated vapor enthalpy
u_g = Internal energy of vapor before venting
$u_{g\,sat}$ = Internal energy of the vapor at saturation

This relationship states that the sensible heat stored in the tank wall and other affected tank system hardware is ultimately absorbed by the chilldown fluid for any given cycle. The Q_{FLUID} term encompasses all of the above mentioned fluid dynamic heat transfer effects that are being investigated in this experiment. The chilldown fluid is initially injected into the tank for each cycle as a saturated liquid at the nominal supply tank pressure. Supply pressurization or CHX operations will provide subcooled liquid to insure delivery of pure single phase fluid (liquid) from the supply tank to the receiver tanks.

Some of the heat transfer processes include liquid flashing, the heat transfer rate for drops splattering on a hot surface, the droplet breakup Weber Number for splattering, free convection heat transfer and correlations for evaporating droplet heat transfer, fluid to tank wall free convection heat transfer, forced convection vapor heat transfer, Leidenfrost temperature for film boiling correlations, spray nozzle flow for choked and unchoked flow conditions, etc. These are all of the processes affecting the spray chilldown performance of the receiver tanks. Flashing, fluid convective heat transfer, and venting processes have been considered and are simulated by the fluid and thermodynamic analyses conducted. The results of these analyses are presented in this section of the Experiment Analyses.

Figure 4.9-13 shows the schematic and the control volume entities for the energy balance of the tank chilldown process. The heating term for the tank wall heat exchanger (Q_{HX}) should be ignored since the TVS heat exchanger will be inactive for the spray chilldown process. Typical tank pressure and chilldown fluid temperature transient profiles for spray chilldown are also shown in the figure as an example. A fixed quantity of chilldown fluid is sprayed into the tank at a predetermined flow rate and allowed to absorb heat from the tank until a delta temperature of about 5% is obtained between the tank wall and the chilldown fluid. At this time, the fluid (which is still colder than the tank) is vented through the tank vent in stages resulting in additional tank cooling for isentropic cooling of the remaining gas in the tank. The process is continued until the tank wall reaches the "target" temperature of about 78 K (140 R) or less.

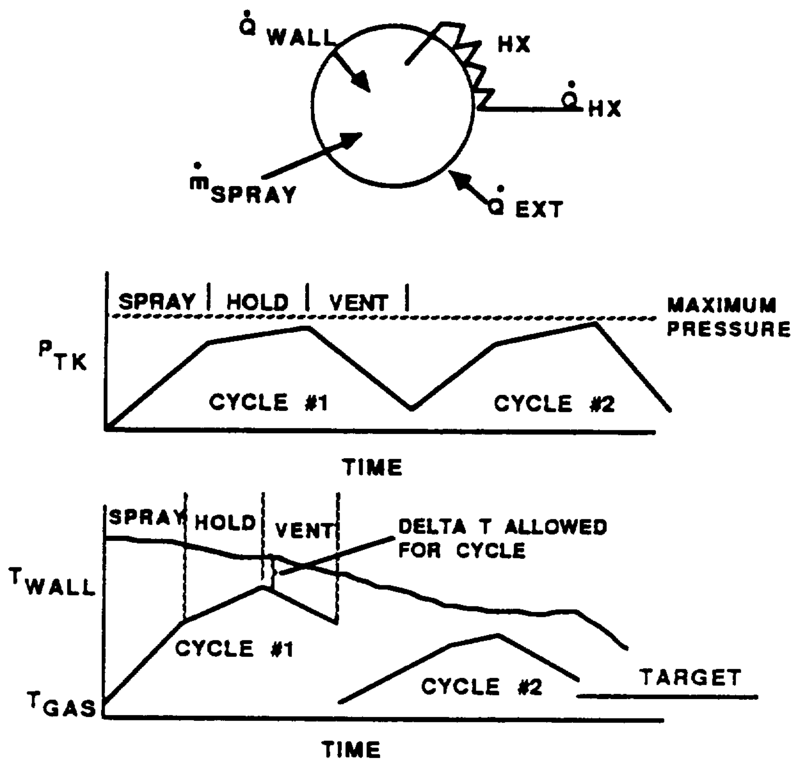


Figure 4.9-13 Heat and Mass Balance of Tankage System and the Process During Childown

The chilldown experiment and process performance has been predicted in reasonable detail using a few computer analytical capabilities for the refinement phase of the COLD-SAT program. The analytical capabilities include the use of the MMAG and NASA-LeRC developed computer codes, MMCAP, TARGET, and CRYOCHIL. TARGET computes the final chilldown temperature for each receiver tank before commencing with an adiabatic no-vent fill process. CRYOCHIL uses the target temperature as a finish point for mapping the number of chilldown cycles and chilldown fluid used for each cycle from an initial tank temperature [usually about 294 K (530 R)] given fluid and tank boundary conditions. The MMCAP model assesses the transient hold and vent thermodynamics following each charge cycle. The MMCAP model simulates the thermodynamics of the flashing, convective heat transfer, and venting processes resulting in reduced tank temperature and the time it takes to perform each of the charge-hold-vent cycles.

The analysis assumptions and conditions for TARGET, CRYOCHIL, and MMCAP are shown in Table 4.9-3. These assumptions were driven by many different inputs. The target temperature range for the COLD-SAT receiver tanks is illustrated in Figure 4.9-14. The range of target temperatures varies considerably over the 137.9 to 206.8 kPa (20 to 30 psia) fill pressure region, that is expected to be the range of fill pressures for the no-vent fill. The temperatures are lower for receiver tank 1 by about 5.6 to 8.3 K (10 to 15 R) since this tank has a higher M/V ratio. The 137.9 kPa (20 psia) values are the lowest at about 73.7 and 78.4 K (132.6 and 141.1 R) for receiver tanks 1 and 2, respectively. This is important because a single chilldown scenario will cover the range of target temperatures.

Table 4.9-3 Analytical Assumptions and Conditions

TARGET	
(1)	95% fill level during no-vent fill
(2)	minimum target temperature for 138 kPa (20 psia) fill
(3)	saturated fluid conditions following fill
CRYOCHIL	
(1)	chill to minimum target temperature for range of fill pressures (138 kPa (20 psia) minimum)
(2)	345 kPa (50 psia) maximum vent pressure
(3)	345 kPa (50 psid) vent stage pressure drop (single vent stage)
(4)	maximum initial tank wall temperature of 294 K (530 R)
(5)	charge mass attains 95% of tank wall temperature
MMCAP	
(1)	flashing and heating of each liquid charge mass initially to saturated vapor conditions
(2)	free convective wall to vapor heat transfer for stagnant fluid motion
(3)	forced convection heat transfer for persisting fluid motion case
(4)	vent system discharge coefficient based on choked flow at 345 kPa (50 psia) inlet pressure and 278 K (500 R) gas inlet conditions
(5)	tank vented to 13.8 kPa (2 psia) in last stage

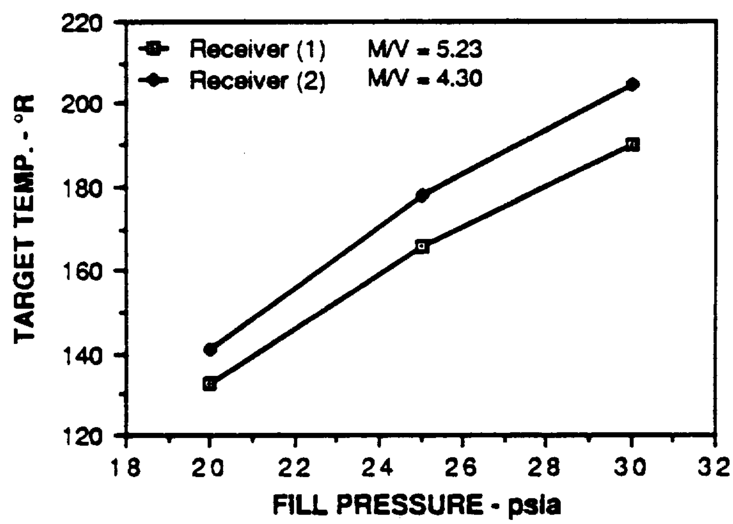


Figure 4.9-14 COLD-SAT Receiver Tank Target Temperatures

Figures 4.9-15 and 4.9-16 illustrate the reduction in tank wall temperature and the cumulative charge mass injected for each of the COLD-SAT receiver tanks. The final temperatures noted are indicative of the target temperatures for subsequent no-vent fill to 137.9 kPa (20 psia). The resulting target temperatures are higher for higher fill pressures and smaller mass-to-volume (M/V) ratios. The number of cycles and chilldown mass required greatly increases for higher M/V tanks and lower target temperatures. This is typical of the higher M/V receiver tank 1, especially since the tank wall temperature drops below 83 K (150 R) where the efficiency of the fluid used for cooling is less at the lower temperatures.

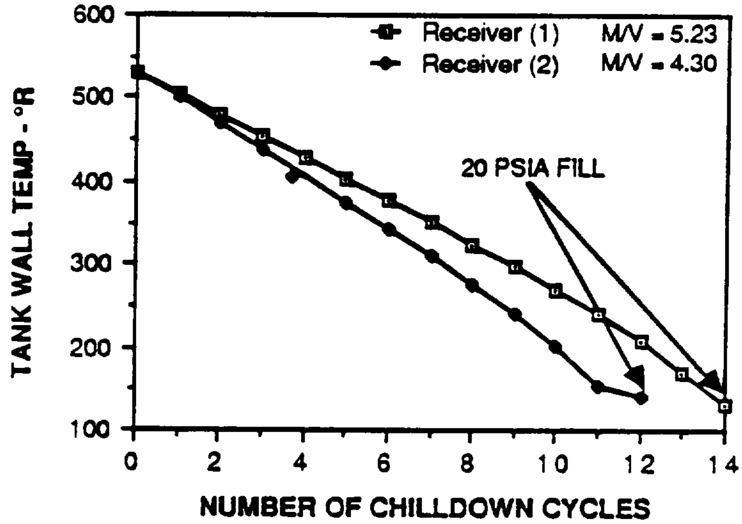


Figure 4.9-15 COLD-SAT Receiver Tank Wall Temperature During Chilldown

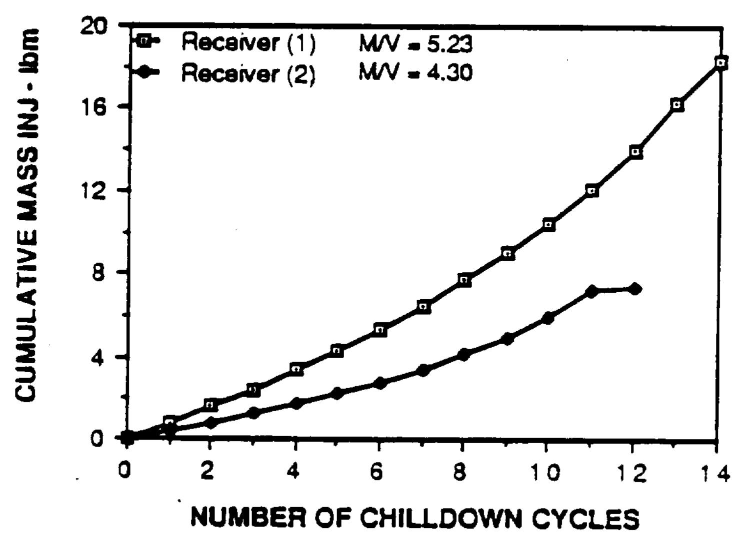


Figure 4.9-16 COLD-SAT Chilldown Fluid Usage

The MMCAP model of the two receiver tanks was used to predict the amount of time for spray chilldown. Three specific heat transfer correlations were considered with which to bound the chilldown experiment processes. These were free convection for a Nusselt Number of 6, a Nusselt No. of 32 obtained from ORS flight tank data, and forced convection heat transfer Nusselt Numbers that range from approximately 160 to 430. The free convection heat transfer correlation model was assumed to represent the upper bound worse case for chilldown time. The lower bound was represented by the forced convection correlation for laminar flow over a flat plate. The times for chilldown can be substantially reduced if a persisting fluid motion can be induced for the cooling vapor in contact with the tank wall. In reality, a persisting fluid motion may persist for a short duration relative to the whole chilldown process, unless a mixing capability is provided in the tank or fluid can be injected in spurts over the duration of each hold cycle. Fluid motion will cease due to fluid friction and the interference introduced by the internal tank hardware. The heat transfer correlations used in the MMCAP models are :

Free Convection Nusselt Number	$Nu = C (Ra)^n = 6$ (internal to MMCAP)
ORS Effective Nusselt Number (Ref. 4.9-9)	$Nu = 32$ (measured)
Forced Convection Nusselt Number (Ref. 4.9-10)	$Nu = 0.664\ Re_L^{1/2}\ Pr^{1/3}$ (ave., flat plate)

The models examined the transient behavior of the first and the second to the last cycles for each receiver tank (thus the variation in forced convection Nusselt number at different temperatures). The transient performance for all of the cycles in between was assumed to vary linearly since it would be cumbersome to analyze each cycle independently. Figures 4.9-17 and 4.9-18 show the performance of the chilldown process (times) for each receiver tank considering the above heat transfer conditions.

The time for chilldown from an initially warm tank wall temperature to the target temperature is a function of convective heating, tank M/V ratio, tank A/V ratio, and the target temperature. More chilldown time is required where free convection heat transfer dominates at low Nusselt Numbers and where the temperature difference between the tank wall and chilldown fluid decreases. The times for free convective chilldown are probably higher than would be expected during the COLD-SAT mission. The performance of the ORS data is a more realistic candidate since it does not consider a purely buoyant system representative of Nu=6. Chilldown times on the order of a few hours could possibly be attained with more, inefficient fluid usage (quicker cycles) or by imparting a persisting fluid motion in the tank.

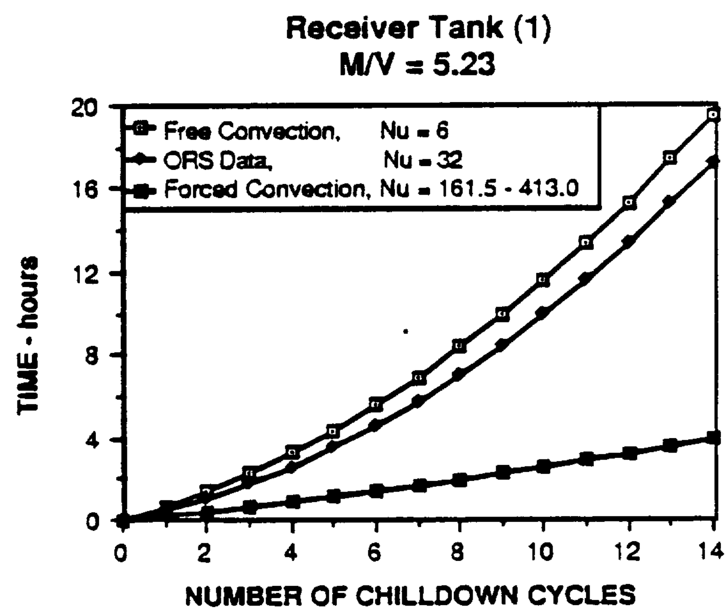


Figure 4.9-17 COLD-SAT Receiver Tank 1 Chilldown Process Performance

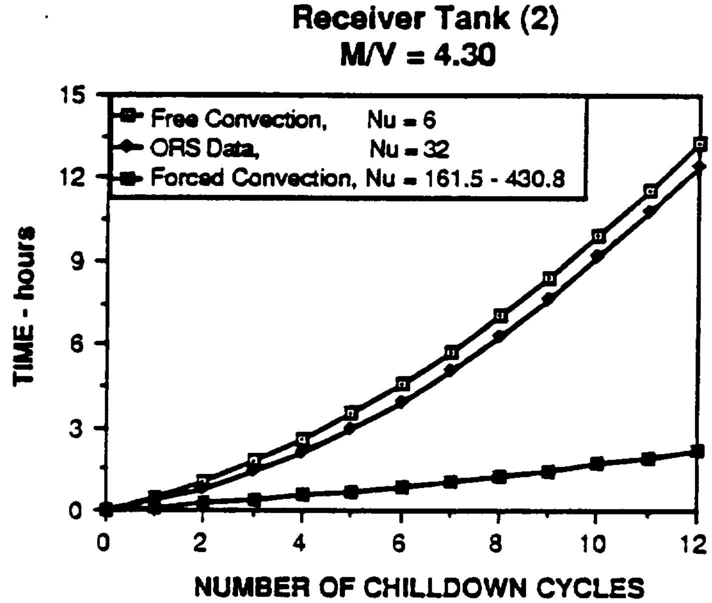


Figure 4.9-18 COLD-SAT Receiver Tank 2 Chilldown Process Performance

An increased number of vent stages during a particular cycle will optimally utilize the available cooling in the charge mass, but more time will be required to recover this added efficiency for vent stage warming of the cooled vapor. A fewer number of vent stages (one preferably) will only require slightly more fluid and reduce the chilldown time considerably. This is the approach that will be adopted by many of the tank chilldown tests on COLD-SAT.

Trade Study of COLD-SAT Receiver Tank Chilldown with Different Heat Fluxes - A trade study was conducted to determine the sensitivity of liquid hydrogen fluid consumption for chilldown while imposing two different environmental heat flux conditions, 0.315 and 1.577 W/m^2 (0.1 and 0.5 Btu/hr-ft^2). The tank wall heat flux contributes to tank wall heating during the periods of the mission between tank no-vent fills. A higher tank wall heat flux will warm the tank wall to a higher temperature, thus requiring more chilldown fluid to attain the target temperature.

The difference in fluid usage between the two heat fluxes by the receiver tanks for all phases of the COLD-SAT mission is relatively significant and amounts to about forty-three pounds of additional hydrogen for the higher heat flux of 1.577 W/m^2 (0.5 Btu/hr-ft^2). In addition, the higher heat flux contributes to increased fluid usage for thermal control (pressure control) based on the existing COLD-SAT experiment subsystem and experiment timeline. This resulted in approximately another 28 kg (62 lbm) of liquid hydrogen required for cooling. These results indicate that a 1.577 W/m^2 (0.5 Btu/hr-ft^2) tank heat flux is too high and a lower heat flux will be required for COLD-SAT. The required heat flux is on the order of 0.631 W/m^2 (0.2 Btu/hr-ft^2), high enough to eliminate concern for a VCS in the tank design and low enough to preclude excessive fluid usage for chilldown cooling and thermal control.

The chilldown fluid consumption was based on the previous TARGET, CRYOCHIL, and MMCAP thermodynamic analyses from which polynomial curve fits were established to derive chilldown fluid requirements based on initial tank wall temperatures when cooled to the target temperature. Transient warming of the tanks is allowed to occur during periods between no-vent fills when the receiver tanks are empty. The resulting transient warm-up temperatures will constitute the initial temperature for chilldown when the tank wall heaters are not used on receiver tank 2. Heating of the tank wall with environmental heat flux follows an exponential decay law. A simple computer model was developed to determine the transient heating of the receiver tanks in order to establish the initial conditions for the chilldown process. Figure 4.9-19 typifies the transient heating profile of the tank wall exposed to environmental heating, and Figure 4.9-20 shows the curve fit of the linearized exponential heating equation used for predicting the temperature of the tank wall at the start of chilldown [example is receiver tank 1 at 0.315 W/m^2 (0.1 Btu/hr-ft^2)]. Figure 4.9-19 shows that the transient heating of the tank wall follows an exponential decay relationship. When the tank wall nears the external environment temperature, then tank wall heating slows down considerably due to reduced temperature differences.

Chilldown fluid requirements for each of the COLD-SAT tests varied depending on the initial tank wall temperature. Figure 4.9-21 is a polynomial curve fit of the relationship between the initial tank wall temperature and the chilldown fluid required for charge-hold-vent spray chilldown. These curves (with the one for receiver tank 1 shown) were developed from the analysis results presented in Figures 4.9-15 and 4.9-16 to allow a simpler analysis of the chilldown fluid requirements. Most of the initial temperatures were established as a direct result of tank wall transient warm-up between chilldown tests rather than with the use of heaters (receiver tank 2). The initial temperatures of the receiver tanks, and thus the fluid used for chilling down, were largely different for the two heat fluxes analyzed. Table 4.9-4 shows the initial tank wall temperatures, the chilldown fluid used, and the fluid usage for thermal control as derived by the analysis for each of the tests baselined in the ERD (Ref 4.9-6).

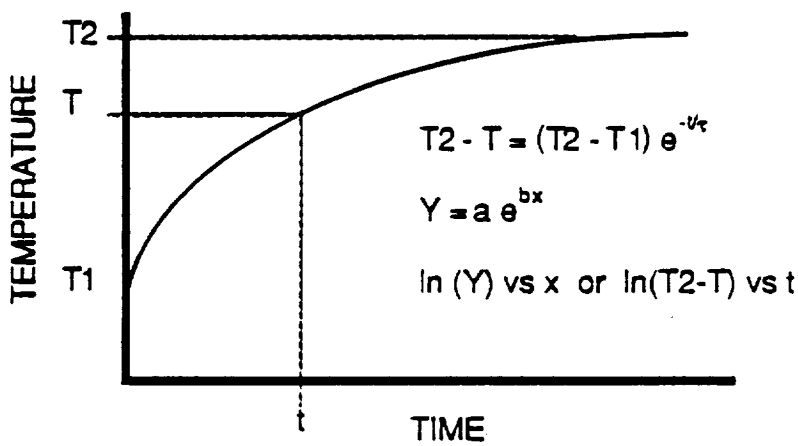


Figure 4.9-19 Transient Response Profile of the Receiver Tank Wall for Environmental Heating

<u>Tank Wall Heat Exchanger Chilldown Process (Receiver Tank 2)</u> - An analytical assessment of the tank wall heat exchanger chilldown process on receiver tank 2 has been performed. The heat exchanger thermal/fluid processes are characterized between the Fanno Line Flow and Rayleigh Line Flow analyses with liquid flashing. The Fanno Line Flow analysis assumes adiabatic flow with friction and the Rayleigh Line Flow analysis is frictionless with heat transfer to the fluid. These cases will bound the actual tank chilldown process via the tank wall heat exchanger.

The modeling approach taken used the MMCAP cryogenic system analysis program to conduct the analysis. Analysis assumptions included a constant 0.91 kg/hr (2.0 lbm/hr) heat exchanger flowrate, saturated liquid inlet conditions at 103.4 kPa (15 psia), exit conditions at 34.5 kPa (5 psia). This flowrate was more than adequate to provide cooler two-phase fluid throughout the length of the heat exchanger. The heat exchanger length is 4.33 m (14.2 feet) long with a 0.476 cm (3/16" O.D.). The heat exchanger is attached to a 46.7 kg (103 lbm) aluminum tank wall initially at a warm temperature of 294 K (530 R). The heat exchanger used for tank wall chilldown is the same one used for receiver tank 2 thermal control in the TVS system.

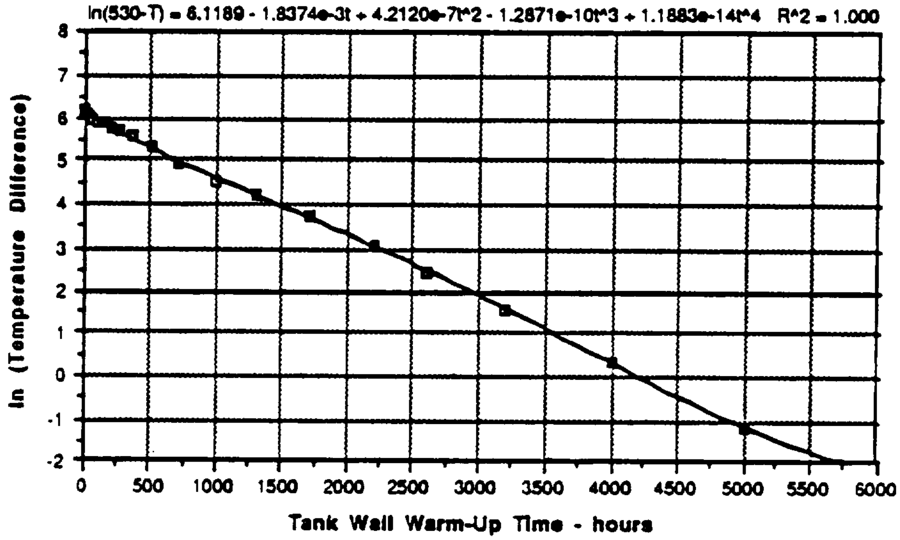


Figure 4.9-20 Transient Warm-Up of Receiver Tank with Time (Receiver 1, Low Heat Flux)

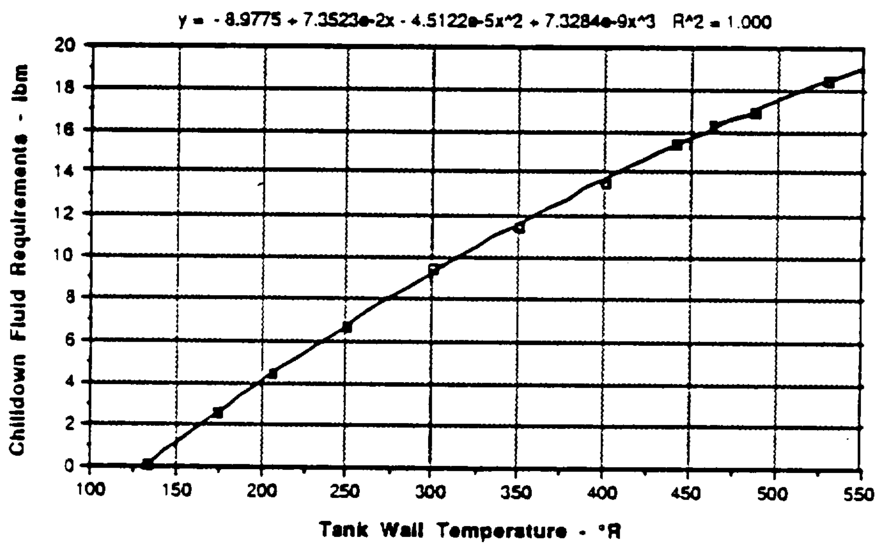


Figure 4.9-21 Chilldown Fluid Consumption as a Function of Initial Tank Wall Temperature (Receiver Tank 1)

Results of the analysis simulation are illustrated in Figures 4.9-22 and 4.9-23. Figure 4.9-22 shows the transient temperature response of the tank wall and the heat exchanger fluid at the HX exit. Note how the HX fluid temperature is generally less than the tank wall itself. Figure 4.9-23 shows the heat transfer rate to the HX from the tank wall during the chilldown process. As the tank is chilled further and the wall temperature decreases, fluid utilization becomes less efficient and a higher concentration of liquid is expelled from the heat exchanger.

Table 4.9-4 Comparison of COLD-SAT Fluid Usage for Two Receiver Tank Net Heat Fluxes, 0.315 and 1.577 W/m² (0.1 and 0.5 Btu/hr-ft²)

Sequence Order	Receiver Tank #	ERD #	Warm-Up Time-hr	Final Tank Wall Temp. - °R 0.1 B/hr-ft^2	Final Tank Wall Temp. - °R 0.5 B/hr-ft^2	Fluid Used for Chilldown - lbm 0.1 B/hr-ft^2	Fluid Used for Chilldown - lbm 0.5 B/hr-ft^2
1	1	1.3-11	N/A	530.0000	530.0000	18.41	18.41
5	1	1.3-2	374.0	289.1613	498.0564	8.69	17.35
9	1	1.3-13	445.3	314.4207	510.0971	9.91	17.76
11	1	1.3-8	179.0	198.7826	417.0806	3.91	14.37
2	2	1.3-6	N/A	530.0000	530.0000	7.50	7.50
3*	2	1.3-3	N/A	530.0000	530.0000	7.50	7.50
4*	2	1.3-10	N/A	530.0000	530.0000	7.50	7.50
6	2	1.3-9	160.5	207.7055	424.0482	1.37	6.04
7*	2	1.3-4	N/A	530.0000	530.0000	7.50	7.50
8**	2	1.3-12	37.0	215.0000	228.0995	1.57	1.94
10	2	1.3-7	276.3	274.3682	484.3219	3.21	6.89
12	2	1.3-1	205.5	236.2126	453.4368	2.17	6.46
13**	2	1.3-5	36.5	215.0000	226.5126	1.57	1.90
14**	2	1.3-1	69.0	215.0000	309.1741	1.57	4.05

Totals : (Chilldown)	82.38	125.15
(Fluid for Thermal Control)	15.47	77.35
Difference = (chill)	42.78	lbm LH2
(control)	61.88	lbm LH2
Total Fluid Difference =	104.66	lbm LH2

* heatup with tank wall mounted heaters
** heaters used to bring R(2) above target temperature
T targ (R1) = 132.6 °R
T targ (R2) = 141.1 °R

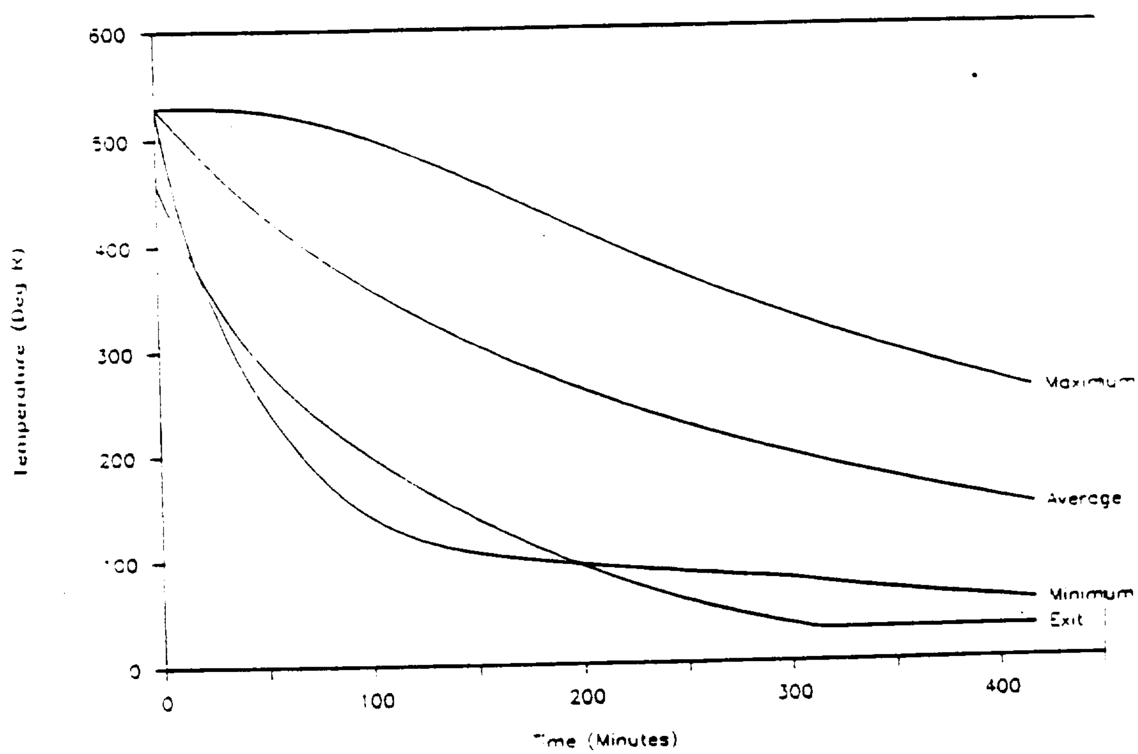


Figure 4.9-22 Receiver Tank 2 Wall-Mounted HX Chilldown Process Temperatures

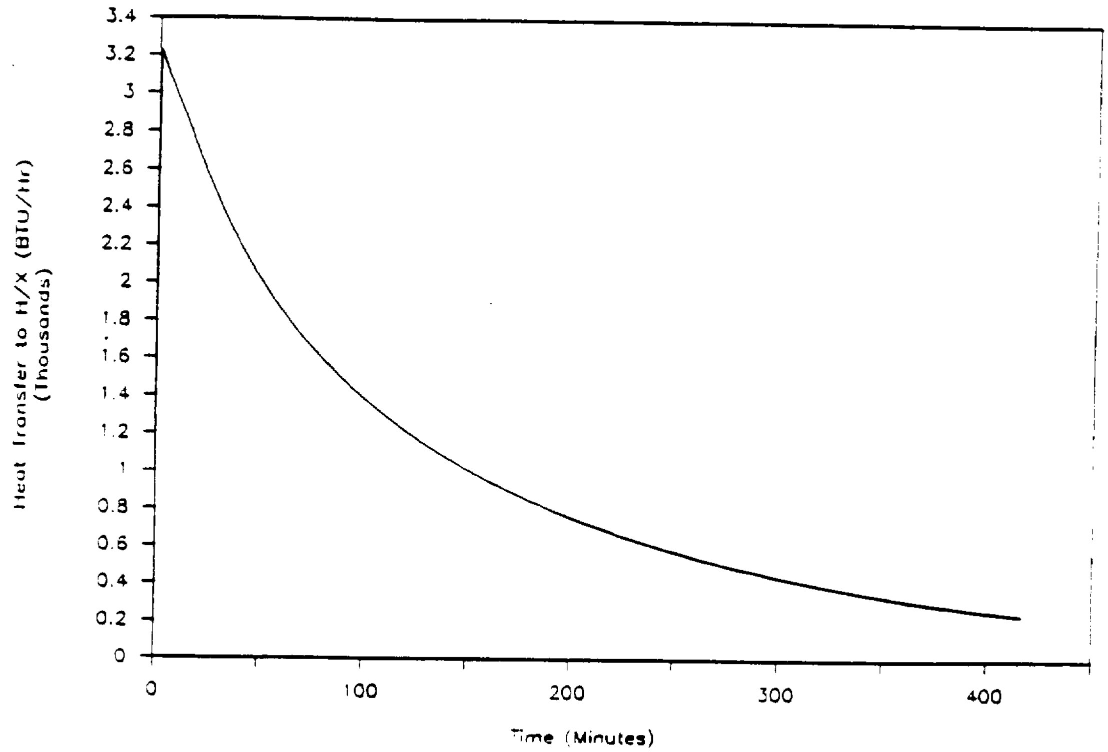


Figure 4.9-23 Receiver Tank 2 Wall-Mounted HX Childown Heat Transfer Rates

Table 4.9-5 shows a comparison of the time and fluid usage for each chilldown process assuming a complete chilldown from ambient tank wall temperature conditions. The H/X chilldown method substantially reduces the chilldown time over the charge-hold-vent process, yet requires a higher consumption of fluid since two-phase fluid exits the heat exchanger near the end of the chilldown.

Table 4.9-5 Comparison of Results for Each Chilldown Process

	CHARGE-HOLD-VENT	WALL HX
CHILLDOWN FLUID	3.86 KG (8.5 LBM)	6.35 KG (14.0 LBM)
CHILLDOWN TIME	14.4 HRS	7.0 HRS

4.9.3 <u>Tank No-Vent Fill and Refill</u>

The no-vent fill is a complex process and has proven difficult to analyze completely. To-date only the thermodynamics of the test have been modeled with any degree of confidence. The heat transfer between the ullage and the liquid is the great unknown in this instance. This value is highly dependent on the liquid position, velocity and the local acceleration environment. Therefore no one as yet has been able to predict the condensation rate of the ullage (in fact the heat transfer is usually a direct input of models). The fill discussion has been broken down into two separate tasks with a separate write-up for no-vent fill and ullage exchange, since the two fill methods have fundamental differences in approach and hardware design.

No-Vent Fill - A no-vent fill is accomplished by controlling the fluid inflow so as to preclude compression of the ullage, thereby achieving a greater fill level than would be possible under normal conditions. The no-vent fill process can be broken down into three main steps that are initial pressure rise, ullage condensation, and ullage compression. The second step is the most important in the process since the amount of ullage condensation that occurs will determine the final fill level. To accomplish the required condensation rates three different nozzle designs will be utilized; the axial, radial, and tangential nozzle systems. By varying the flow rate through each nozzle, the ullage condensation rate will be varied to see how this parameter will affect the final fill level.

The first phase of the no-vent fill is the initial pressure rise, which occurs during the first few minutes of a tank fill. This process is the result of the introduction of a liquid into the tank that is at a higher pressure than the receiver tank (103.4 kPa [15 psia] liquid into a 6.9 kPa[1 psia] tank for example). Due to the drop in pressure upon entering the tank, some of the liquid will flash generating vapor. The remaining liquid will then contact the tank wall that is initially at a target temperature greater than the saturation temperature of the liquid. Due to this contact the liquid will boil, thereby cooling the tank wall. This process will continue until the tank wall temperature is reduced to a point close to the saturation point of the liquid, at which time the boiling will cease.

The analysis of this process, is fairly straight forward and consists of performing multiple mass and energy balances on a tank that account for the mass of liquid and gas along with the thermodynamic state of each component. The energy balances also must take into account the heat transfer from the warmer wall, the work being done on the ullage by the flashing inlet liquid, and the change in fluid properties with pressure. The logic for predicting the heat transfer from the wall to the liquid is the key to solving this problem. Due to the fact that the wall to liquid temperature difference is greater than critical temperature difference for LH2 nucleate boiling over most of the cooldown process, one can assume that film boiling will be the predominate heat transfer mechanism. Two correlations (for pool film boiling on a spherical surface and for forced convective film boiling on a flat plate) can be used to predict the wall to liquid heat transfer. The use of these two correlations allows one to bound the problem since a real case will be somewhere between the two limits.

The next phase of the fill is ullage condensation. This process is related to the third phase (ullage compression) since the only difference between the two is whether there is enough heat transfer out of the ullage to allow the gas to condense. While a no-vent fill of the tank is being performed, the ullage is simultaneously undergoing condensation due to heat transfer to the bulk liquid and the inflow, and compression due to the influx of liquid. The dividing line between the two processes is when the compression effects become larger than the condensation's, at this point the tank pressure will begin to rise again.

The analysis of this process is much more detailed than the first case. Energy balances are performed on the tank with three nodes in the tank, the gas, liquid and interface nodes. Using appropriate energy and mass balances the hope is to predict the liquid and gas masses, the interface heat transfer, and thereby the ullage condensation rate. The interface node is the key to this since it is the only point at which all fluid properties are known before hand (it is assumed to always be at the saturation temperature). This node also is the point at which all heat transfer between the ullage and the liquid occurs.

Again in this analysis the heat transfer becomes the driving force behind the fill results. If there is insufficient ullage condensation (i.e. insufficient heat transfer) the net work being done on the ullage will cause the pressure to increase, leading to a cessation of the transfer. This compression process is very important since in a pressure driven flow once the pressure increases the flow rate will drop off, leading to a further reduction in ullage condensation. Therefore once the heat transfer rate drops below a set value, this effect will accelerate and may not be easy to stop.

The mixing configuration chosen for a particular test will directly affect the fluid motion and heat transfer. The configuration believed to be the best is to start the fill using tangential nozzles to provide good heat transfer with the wall, resulting in a quick pressure rise. This fast fluid motion will also tend to force the fluid to the outside wall of the tank and the ullage to the inside. This liquid motion will also begin to condense the ullage, thereby providing pressure control for the first part of the transfer. After the fluid mass has reached a predetermined value (~ 70% full) the flow will be transferred to the radial or axial spray systems. This action will be performed to ensure that the heat transfer out of the ullage will continue, since the new spray pattern will be directed straight into the ullage. This spray configuration is only assumed to work the best, thereby leading to all the other proposed tests.

To-date no model of the heat transfer between the ullage and the liquid has been able to adequately predict the ullage condensation rate, thus analysis of this most important variable will have to wait until the tests have been conducted and the data recorded. Previously developed mixing correlations and possibly others will be evaluated to see if a general model can be developed which will allow one to optimize the no-vent fill process.

Ullage Exchange - The ullage exchange technique is a method of transferring liquids in a low-g environment which eliminates problems associated with vented or no-vent fill processes. Fluid transfer with the ullage exchange technique is accomplished by connecting the supply and receiver tank fill and vent lines to each other so that there is a closed fluid loop connecting the two tanks. The supply tank has a liquid acquisition device (LAD) to deliver liquid to the tank outlet. The liquid is transferred to the receiver tank with a liquid pump. Pressure is relieved in the receiver tank as the tank is being filled by venting through the vent line. The position of the ullage is uncertain in such a process, so liquid or gas may be vented. All fluid vented from the receiver tank is collected in the supply tank. The ullage exchange process increases system heat leak due to heat transfer to the fill and vent lines and pump work to the liquid. It is possible that the increased heat transfer may raise tank pressures to unacceptable levels, therefore analysis was needed to determine if this effect would occur. This concern is compounded by the randomness of liquid/gas venting from the receiver tank which makes the amount of time necessary to fill the receiver tank unpredictable. This concern was analyzed by performing Monte Carlo simulation of the ullage exchange process (between two generic spherical tanks) (Ref 4.9-11) using the computer model 'MMCAP'. Details of the analysis are presented below.

The following assumptions were made in performing the analysis:

1) acceleration level of $1x10^{-6}$ g's
2) 2831 liters (100 ft^3) supply tank volume,
3) 283 liters (10 ft^3) receiver tank volume,
4) 15.65 kg (34.5 lbm) receiver tank mass,
5) 0.316 W/m^2 (0.1 Btu/hr-ft^2) heat flux into the two tanks,
6) 1.58 W/m^2 (0.5 Btu/hr-ft^2) heat flux into the transfer lines,
7) negligible supply tank mass (i.e. all of the heat flux goes into the fluid),
8) supply tank pressure of 137.9 kPa (20 psia),
9) a 6.89 kPa (1 psi) pressure rise across the pump at a flow rate of 45.36 kg/hr (100 lbm/hr),
10) a 50% pump efficiency, and
11) receiver tank is initially evacuated

To model this process an MMCAP input deck was generated with the following capabilities. Early analysis had shown that the flow resistance of the vent and transfer lines must be accounted for. This fact can be visualized by imagining a case where the system has a very small vent system. In this case the ullage exchange will become more like a true no-vent fill since very little mass will exit the receiver tank. To account for this parameter the lines were modeled as constant flow resistances where the flow rate is proportional to the square root of the pressure difference. By varying the ratio of transfer line to vent line resistances (i.e. varying the line sizes) different results could be achieved. The baseline case had this ratio set to a value of 1. This analysis approach was limited to single phase flow, therefore only liquid or gas was assumed to be vented at one time. Finally, the flow in the lines is assumed to be in a quasi-steady state mode since the flow transients due to pressure fluctuations cannot be modeled.

The Monte Carlo simulation was performed by randomly venting liquid or gas from the receiver tank. The randomness was implemented with three methods. The first method assumed that venting was random over the duration of the fill process so that there was an equal probability of venting liquid or gas at all fill levels. This approach is referred to as "Random Exchange". The second approach assumed that the probability of venting liquid increased as the tank became more full. This approach biased the venting so that no liquid was vented when the tank was empty and no gas was vented when the tank was full. There was an equal probability of venting liquid or gas when the tank was 50% full. This approach is referred to as "Biased Random Exchange" and was the one used in most of the simulations because it was felt that this approach most accurately represents what would happen in an actual ullage exchange. A third simulation was performed to represent a best case ullage exchange. This approach assumed that the liquid in the receiver tank remained settled during the fill process so that only gas was vented. This approach is referred to as "Settled Ullage Exchange". All three probabilities are illustrated in Figure 4.9-24, which shows the probability of venting liquid for each approach as a function of liquid fill level.

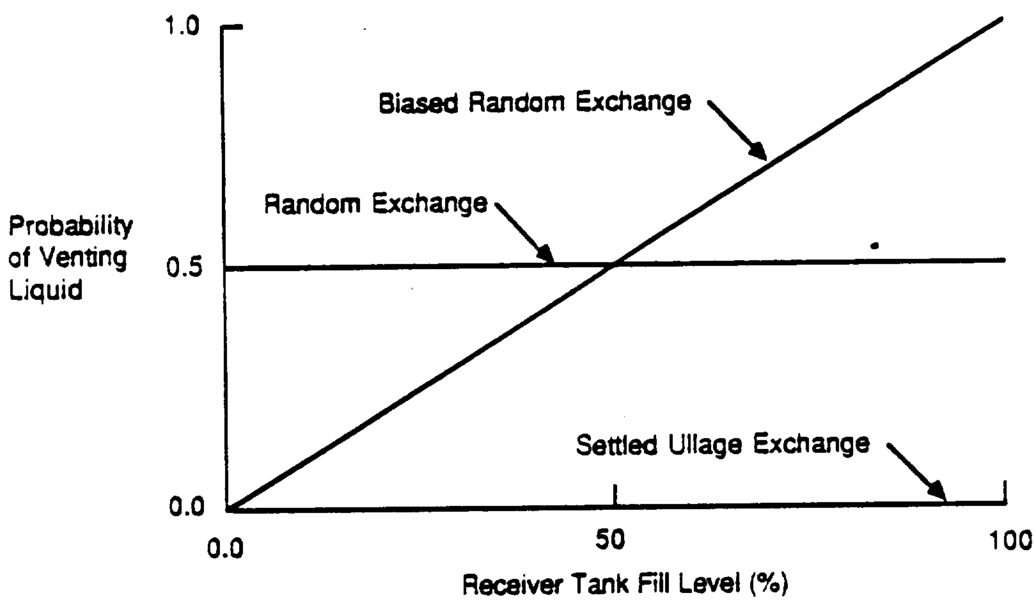


Figure 4.9-24 Venting Probability

During the analysis many cases were run to determine the effect that parameters such as receiver tank initial temperature and supply tank fill level would have on the results. The entire set of cases run are described fully in the reference, thus only the highlights will be discussed here. Several runs were performed to assess the effect that the probability of liquid or gas venting has on the results. Figure 4.9-25 presents the results of this set of analysis. Multiple runs were made for the Random cases and one for the Settled Exchange. This allowed the full effect of the randomness to be seen. The receiver tank filled in 0.44 hours in the Settled Exchange case. This benchmark was then used as a best fill case to compare other runs against. Next, 5 Random Exchange cases were run. In each case the tank filled at a nearly constant rate that did vary from run to run. Finally, three Biased Exchange fills were modeled. In each case the tank initially filled at a rate equal to the Settled Exchange, that then began to decrease as the tank became filled. After the tank had filled to approximately a 90% level the net rate had fallen to such a low amount that the process was assumed to be done. The results of this analysis has shown that the transfer line flow resistances must be accounted for in the analysis. The cases run here show a higher rate of fill than those that assumed the lines had no pressure drop. This result is obvious if the fact that it is easier to flow liquid through the vent line than gas is accounted for. Thus when liquid does enter the vent line less of it can flow, leading to a net gain of fluid in the tank.

The other parameter that drives the results is the receiver tank initial temperature. If the receiver tank is too warm at the start of the fill, the rapid boiloff of liquid will result in a pressure spike that if too large would lead to supply tank venting. To assess this effect a series of runs were performed with different receiver tank initial temperatures. Supply tank pressures for the cases are presented in Figure 4.9-26. The first two cases had temperatures of 27.8 and 55.6 K (50 and 100 R) respectively, and the runs predicted that the pressure would actually decay before beginning to rise again. The last case had a temperature of 111 K (200 R). In this run the pressure in the tank rose to a value more than double the initial one. Extreme surging was also seen in the transfer lines with the pump actually deadheading at times due to excessive receiver tank pressure.

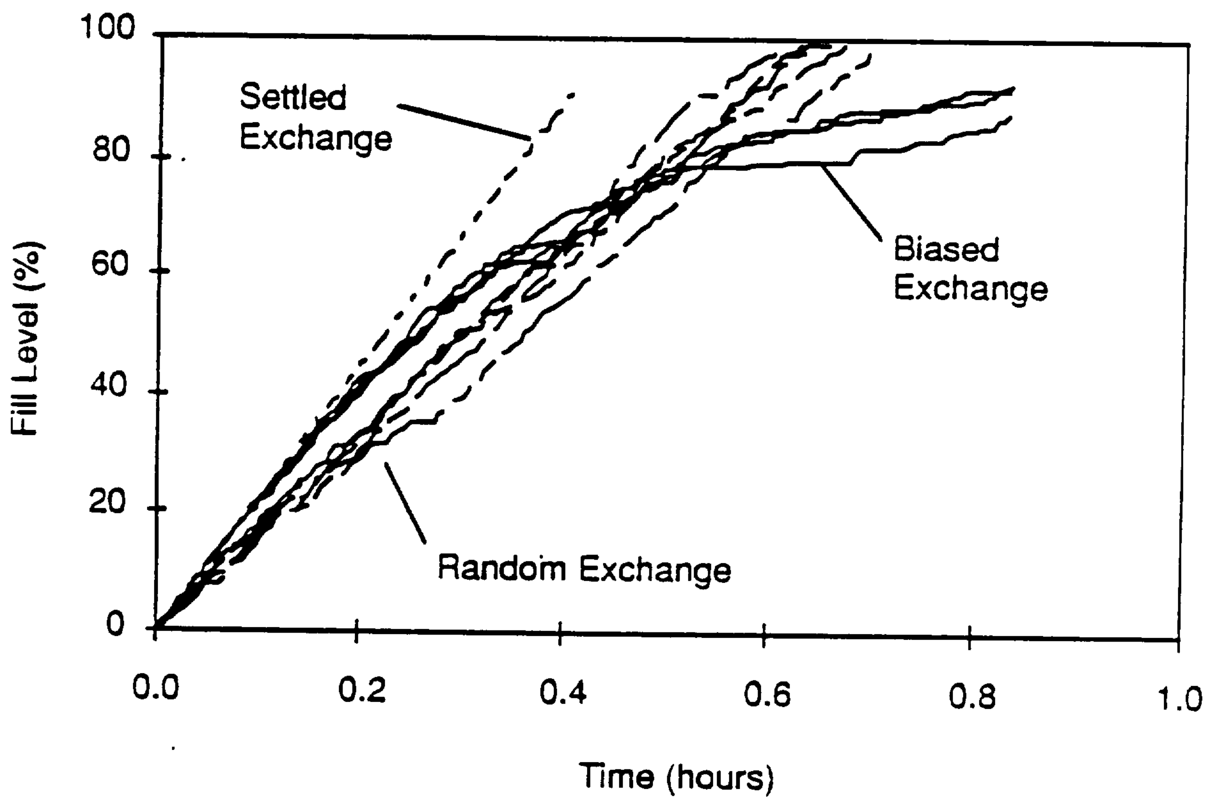


Figure 4.9-25 Ullage Exchange Fill Levels for Different Fill Scenarios

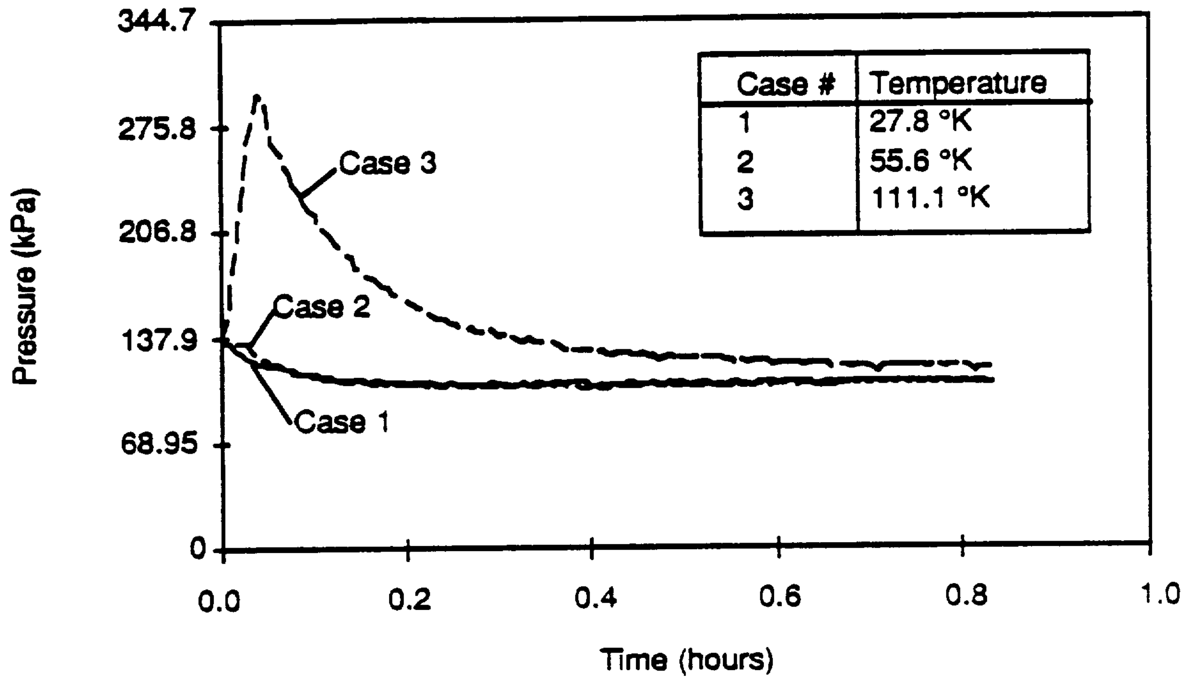


Figure 4.9-26 Effect of Receiver Tank Initial Temperature on Supply Tank Pressure

This analysis shows that the ullage exchange process can fill a receiver tank without overpressurizing the system. The results show, however, that a significant pressure increase can occur if the receiver tank is warm and it would be possible to overpressurize the system if the receiver tank was not pre-chilled. The method of modeling the venting randomness affected the filling profile of the receiver tank but did not significantly affect the pressure or temperature response of the system. This approach addressed the concerns of pressure and temperature rise during the filling process with minimum modification of the analysis tools.

4.9.4 <u>Tank Pressurization</u> - A pressurization subsystem is required in order to evaluate the pressurization process whereby pressurant shall be supplied to the COLD-SAT tanks to provide the driving force necessary for liquid expulsion from the tank for liquid transfer. The pressurization design requirements were established from specific customer directions and detailed thermodynamic analyses of the pressurization process in the COLD-SAT tanks.

The customer issued direction to evaluate the pressurant requirements for the COLD-SAT experiment subsystem pressurization experiment. The direction was very specific and called for pressurizing the tanks at different overpressure levels and specifically allocating the use of hydrogen and helium pressurant. The direction implied that all supply tank transfers are to use GH2 at two different overpressure levels such that 75% are performed at a 13.8 kPa (2 psid) overpressure for pumped transfers and the remaining 25% at 68.9 kPa (10 psid) for pressurized transfer. In addition, the customer directed that all back-transfers from the receiver tanks to the supply tank be accomplished by a 68.9 kPa (10 psid) overpressure for pressurized transfer. An equal number of receiver tank back-transfers are to use GH2 and GHe pressurant (50% each).

Analyses were conducted with the MMCAP program in conjunction with the customer direction in order to determine the pressurant quantities required to support the COLD-SAT experiment set. The pressurant quantities for experiments created a demand for numerous pressurant bottles for storage of the required pressurant as a design requirement for the experiment subsystem. The pressurant quantities, the bottle size and number of tanks are listed in Table 4.9-6 and comprise the derived design requirements. Details of the pressurant bottle design are included later on in this report.

Table 4.9-6 Derived Design Requirements for the Pressurization Subsystem

PRESSURANT	# TANKS	TANK VOLUME (EA)	PRESSURANT MASS
GH2	7	0.076 M^3 (2.7 FT^3)	7.94 KG (17.5 LBM)
GHE	2	0.076 M^3 (2.7 FT^3)	4.67 KG (10.3 LBM)

The experiment pressurization analyses were prompted as a result of reducing the experiment size and by the customer direction to pressurize at different pressure levels for pumped and blowdown transfer methods. MMCAP models were developed for each of the tanks and simulations were run for each of the cases outlined by the Technical Direction (derived requirements). The quantity of GH2 and GHe was calculated based on each of the analysis runs and the number of tests performed in the experiment set. From these quantities, the number of pressurant storage bottles required for the pressurization system design was determined from a bottle design established through consultation with SCI given their existing experience, production tooling, etc. The design established from the analysis through Structural Composite Industries (SCI) required seven GH2 and two GHe pressurant bottles, each with a volume of 0.076 m^3 (2.7 ft^3).

The analysis assumed that the pressurant was supplied at a 278 K (500 R) warm gas condition. In addition, assumed interface heat transfer conditions based on the experience and recommendations from the ORS studies were fed into the analysis. A minimum Nusselt number of 32 for quiescent periods and a value of 250 during actual pressurization or outflow processes was assumed based on the ORS recommendations.

Table 4.9-7 of the analysis results shown below outlines all of the possible tank pressurization and outflow scenarios that will be encountered during COLD-SAT pressurization experiments. The pressurant fluid quantities for each case and the number of complete transfers for each scenario are presented. The difference in the total derived quantities presented on the previous chart and the compiled totals on this chart are for short LAD outflow tests following filling of the LAD. These quantities are about 0.27 kg (0.6 lbm) for GH2 and 0.045 kg (0.1 lbm) for GHe pressurant.

4.9.5 Low-g Settled Outflow, Vented Fill, and Ullage Venting

This test series is concerned with the behavior of the fluid while in a controlled low-g environment. Control of the acceleration environment will be provided by the spacecraft propulsion system. The three separate tests that will be evaluated are an outflow without the use of an LAD, a vented fill, and a direct ullage vent to provide pressure control without the use of a TVS system. The separate tasks involved with performing the test series will be discussed in the following sections.

Settling - This process is critical to the success of all of the separate experiments in the test series. If the liquid cannot be maintained over the outlet or away from the vent, whichever is required, the test will not achieve the desired results. To achieve settling the thrusters are fired at a predetermined level and duration. The liquid interface shape and fluid position will be determined by use of the point level sensors in the receiver tanks.

Table 4.9-7 Pressurization System Analysis Results

TANK	DELTA P -kPa (Psid)	VOLUME -m^3 (ft^3)	PRESS. TYPE	PRESS. PER X-FER -kg (lbm)	NUMBER OF COMPLETE TRANSFERS*
SUPPLY	68.9 (10)	1.13 (40)	GH2	0.50 (1.10)	1
	68.9 (10)	0.57 (20)	GH2	0.31 (0.68)	4
	13.8 (2)	1.13 (40)	GH2	0.22 (0.49)	8
	13.8 (2)	0.57 (20)	GH2	0.12 (0.26)	8
RECEIVER 1	68.9 (10)	1.13 (40)	GH2	0.28 (0.61)	6
	68.9 (10)	1.13 (40)	GHE	0.73 (1.62)	2
RECEIVER 2	68.9 (10)	0.57 (20)	GH2	0.15 (0.34)	7
	68.9 (10)	0.57 (20)	GHE	0.41 (0.90)	7

* TOTAL OF 7.21 KG (15.9 LBM) FOR GH2 AND 4.33 KG (9.54 LBM) FOR He (SEE ERD DATABASE FOR ALL PRESSURIZATION TESTS)

The settling time and resultant fluid interface shape are parameters that can be complex and difficult to calculate. Many forces affect these values, but the interface shape is primarily determined by the tank Bond number. The Bond number criterion for stability of the interface is:

$$Bo_{cr} = \rho g R^2 / \sigma = 0.84$$

where: Bo_{cr} = Critical Bond Number
ρ = Liquid density (kg/m^3)
g = Acceleration (kg-m/sec^2)
R = Tank radius (m)
and σ = Surface Tension (N/m)

When the acceleration level results in a Bond number greater than the critical level the liquid will settle in the direction of the acceleration vector. For the receiver tanks, this level will be surpassed with any acceleration above 10^{-5} g's. When the Bond number is less than 50, the surface tension forces tend to impede the flow at a rate proportional to the Bond number. When the Bond number is greater than this level, the interface level rate of rise is dependent on many factors including liquid kinetic energy, the flow's Reynolds and Weber numbers and the Froude number. The regime of flow will not be encountered since the maximum Bond level that will be obtained in the receiver tanks will be ~12. The settling time will be determined from the level sensors in the receiver tanks. A prediction of the settling time could be made apriori if a FLOW-3D model were to be developed of the receiver tanks. This step has not been done as of yet, but could be performed in the future.

<u>Outflow</u> - The liquid outflow through the inlet/outlet baffle will commence immediately following the settling. This process consists of simply draining the tank and studying the effect that varying the

acceleration level has on the amount of residuals left in the tank. The test will be terminated when vapor is detected in the transfer line. This will be accomplished by use of the flow meters capable of detecting 2-phase flow.

As the liquid flows out of the tank, there is a tendency for the liquid level to distort due to the outflow. The result is ingestion of vapor in the outlet before the entire tank contents have been depleted. Through extensive testing in both one-g and in low-g drop tower tests, it has been determined that the surface distortion is characterized by the ratio of gas ingestion height to a characteristic dimension such as the tank diameter. The gas ingestion height is the distance the liquid interface is above the tank outlet when gas first reaches the outlet. This dimensionless parameter is dependent on the Froude number, the surface tension, and viscous effects. When the Bond number is greater than 25 and the Reynolds number is larger than 100, the surface tension and viscous effects disappear. A correlation for this parameter has been presented in the literature (Ref. 4.9-12).

$$h/D = 0.43 \, \text{Tanh} \left(1.3 \, Fr^{.29} \right)$$

where:
- h = Gas ingestion height (m)
- D = Tank diameter (m)
- Fr = Froude Number = $v^2 / a\,d$
- v = Outlet velocity (m/sec)
- d = Outlet diameter (m)

and
- a = Acceleration (m/sec^2)

When the Froude number becomes greater than 10 the dimensionless number reaches a constant value of 0.43. Other correlations have been developed for this relationship, but they are of a similar form.

<u>Vented Fill</u> - The vented fill will commence as soon as the tank wall temperature cools down to a point at which liquid will accumulate in the tank. This process is controlled with the motion of the liquid in the tank and the acceleration environment of the spacecraft. The experiment will be terminated when liquid is detected in the vent line.

The vented fill is a flow pattern where the fluid motion is determined by two dimensionless parameters, the Bond and Weber numbers. The Bond number analysis has previously been discussed and the Weber number is as follows:

$$We = \rho \, v^2 L / \sigma$$

where:
- We = Weber Number
- ρ = Liquid density (kg/m^3)
- v = Inlet liquid velocity (m/sec)
- L = Characteristic length, usually the tank diameter (m)

and
- σ = Surface Tension (N/m)

The key to ensuring liquid free venting is to keep the liquid interface stable during the fill process. If the incoming flow of fluid has too much momentum it will break through the liquid interface and likely be vented overboard. By avoiding this phenomena the liquid level in the tank can be made to rise in a controllable manner, preventing unnecessary venting of liquid. Drop tower tests have been conducted to determine the flow rate at which the interface will become unstable (references 4.9-13 through 4.9-15). This value is strongly dependent on tank geometry (i.e. baffled tank or not). The results of these studies are summarized in Figure 4.9-27 which presents the critical flow rate at which the interface became unstable, for different tank configurations. The impact this effect has on the design is instantly obvious. If the tank has a bare inlet the flow rate would be limited to ~3 kg/hr (6.6 lbm/hr), whereas with a baffled inlet up to 36 kg/hr (79.4 lbm/hr) could be transferred into the tank.

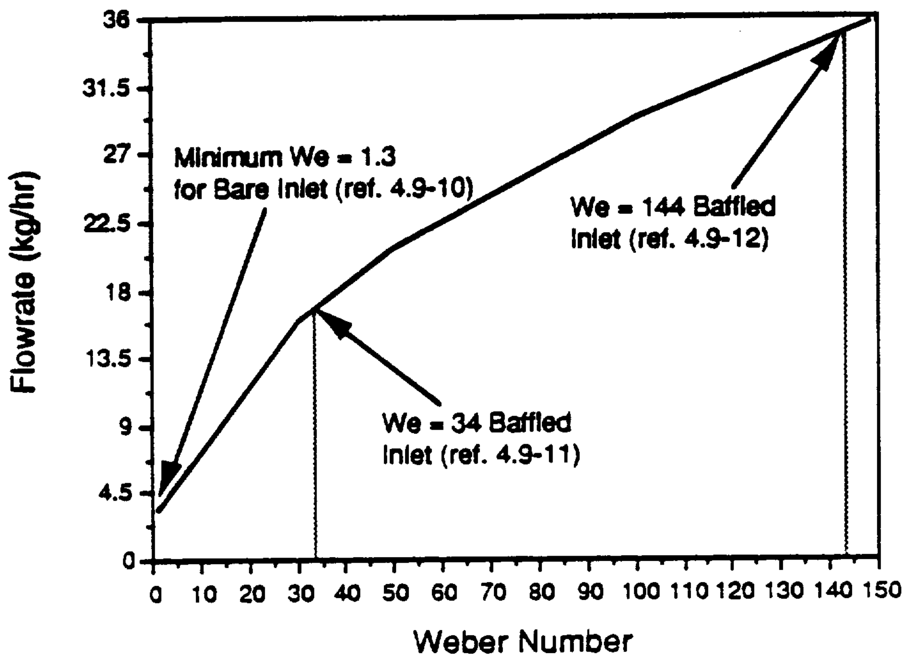


Figure 4.9-27 Critical Weber Number for Stable LH2 Interface

The analysis of the fluid motion during the fill is a complex and difficult task. Again as in settling, many factors control this flow. The model FLOW-3D could be used in this instance to predict the liquid position and velocities during this process. A detailed set of FLOW-3D models were generated to analyze this process (Ref. 4.9-16). This work was not specifically directed at the COLD-SAT design, but the results did show that the above curve can be easily scaled. There are limitations on this code though, so any heat transfer dominated effects will not be able to be predicted.

Low-G Venting - This process will be used to reduce the pressure of all three tanks without the use of a TVS system. This task will follow a settling burn of the thruster to orient the fluid away from the vent. Once the fluid has settled the vent valve will be opened to reduce the tank pressure. The initial part of the vent will be calm if the tank ullage is initially superheated. During this phase of the vent the liquid interface should rise in a predictable manner to take up the area of the tank from which the vapor has been vented. This venting case can be modeled by FLOW-3D since the interface will only be responding to kinematic forces, not thermodynamic.

For a tank that is initially at saturated conditions or once the tank pressure is reduced to a point lower than the saturation pressure of the liquid, bulk boiling will occur. Once this event begins, the position of the liquid interface will be an unknown parameter. Two possible scenarios can occur. If the boiling is very violent, the liquid will seem to explode resulting in many fine droplets of liquid that will then vent out with the gas. Another possible case is that the boiling will be less violent and the bubbles that form in the liquid will cause the liquid interface to rise, but it would remain intact. In this case the idea is to limit the vent rate to below a level at which the interface would rise to the vent, resulting in liquid venting.

The venting case can be analyzed to predict a maximum allowable vent rate for each tank fill level (Ref. 4.9-17). Studies have shown that the shape of bubbles rising in LH2 will resemble that of a cylindrical cap. For this shape bubble, the velocity through the fluid is determined by the following correlation.

$$U = 0.711 \, (a \, d_e \, \Delta\rho / \rho)^{1/2}$$

where : U = Bubble rise velocity (m/sec)
a = Acceleration (m/sec^2)
$\Delta\rho$ = Difference between liquid and vapor densities (kg/m^3)
d_e = Diameter of volumetrically equivalent bubble (m)
and ρ = Liquid density (kg/m^3)

For other shape bubbles the equations are the same, with only the constant being changed. Now, if the assumptions that the bubbles are uniformly distributed throughout the fluid and that they are of a uniform shape and volume are made the prediction of the maximum vent rate can be made. The first step is to predict the height to which the interface will raise at any given vent rate. This relation is as follows.

$$h_{l,\,max} = (V_B N + V_{l,init}) \, / \, A$$

where : $h_{l,\,max}$ = Maximum liquid height (m)
V_B = Average bubble volume (m^3)
N = Number of bubbles in liquid
$V_{l,init}$ = Initial liquid volume (m^3)
and A = Tank cross-sectional area (m^2)

By requiring that this maximum liquid height be the tank length (i.e. to ensure liquid free venting), one can determine the bubble volume and the number of bubbles (actually both values cannot be known, but the combined V N factor can be). Once these values are known, the maximum vent rate may be predicted from:

$$Q_{max} = V_B N U \, / \, h_{l,\,max}$$

where : Q_{max} = Maximum volumetric vent rate (m^3/sec)

With this model the maximum vent rate can be predicted for each case. Trade studies can be made to parametrically set the vent rate for assumed bubble diameters. This analysis method is only one way to model this process and has many limiting assumptions. Therefore it will only be used in an attempt to correlate some of the test data, not as a design tool.

4.9.6 LAD Performance

This test series is concerned with characterizing the performance of the supply and receiver tank 1 LAD's . This entails checking the liquid for the presence of vapor during an outflow. The expulsion efficiency of the two LAD's will also be determined during the COLD-SAT mission. The supply tank LAD will only provide one data point since the fluid will only be completely expelled once during the mission. The LAD in receiver tank 1 will be the primary test article for this set of experiments. The expulsion efficiency will be checked many times under varying acceleration levels.

Since the LAD of receiver tank 1 will be the primary test article for this set of experiments, the design effort has been focused on this item. The functional requirement of the liquid acquisition device (LAD) in receiver tank 1 is to provide the capability for liquid outflow in a micro-gravity environment. The customer directed that the LAD should be configured so that the device can be stressed by varying operating conditions. The design constraints were a maximum acceleration of 1.4×10^{-4} g's and a flow rate of 136 kg/hr (300 lbm/hr). The LAD analysis showed that the LAD would not meet the basic functional requirement while still being capable of being stressed by operational modifications. The low acceleration levels available on COLD-SAT could not stress the screen unless the screen were quite coarse. There is a concern that such a screen would not properly wet, thereby not meeting the functional requirement of providing low-g outflow capability. The commonly used four-channel approach would prevent meaningful evaluation of test results without some way of determining the flow distribution in the channels. Thus, the current LAD design in receiver tank 1 does not meet the customer desire to stress the LAD. It is recommended that a LAD stress test be performed on a dedicated, single channel device to preclude jeopardizing the capability to outflow in a micro-gravity environment. A single channel is recommended so that there is no uncertainty in the flow distribution.

The bubble points for several different screens were calculated for LH_2. The bubble points were compared with the maximum static head available on COLD-SAT and this relationship is shown in Figure 4.9-28. It was found that the static head was orders of magnitude smaller than the minimum bubble point. Thus, an LAD made from any of these screens would not be stressed by the available acceleration environments on COLD-SAT.

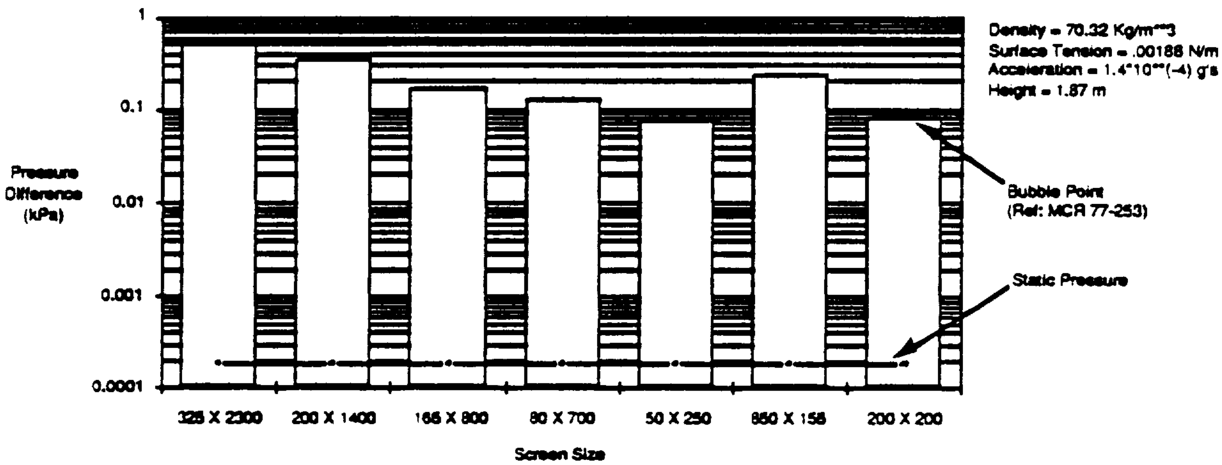


Figure 4.9-28 Comparison of Screen Bubble Point and Static Head Produced by Acceleration

The frictional pressure loss in the LAD was calculated for an LAD designed to breakdown due to friction, regardless of flow distribution. The Figure below (4.9-29) shows that the flow rate causing screen breakdown is a strong function of flow distribution in the LAD. A flow rate of 27 kg/hr (60 lbm/hr) would cause breakdown if only 1 channel is flowing whereas 109 kg/hr (240 lbm/hr) is required if all 4 channels are flowing. The LAD in receiver tank 1 has 4 channels with no way of preferentially routing the flow through the channels. Analysis of the test results would be difficult without some knowledge of the flow distribution in the device.

4.9.7 Transfer Line Chilldown

The transfer line will require periodic chilling to allow for the vapor free transfer of liquid between the supply and receiver tanks. The transfer line chilldown will be accomplished by opening the supply tank outlet valve and allowing cryogen to flow into the line. In all cases the supply tank will provide the hydrogen to chill the line, even if the transfer will be from the receiver tank to the supply tank. This choice was made for design reasons, since to use the receiver tank fluid to chill the line would require an extra valve and bypass line.

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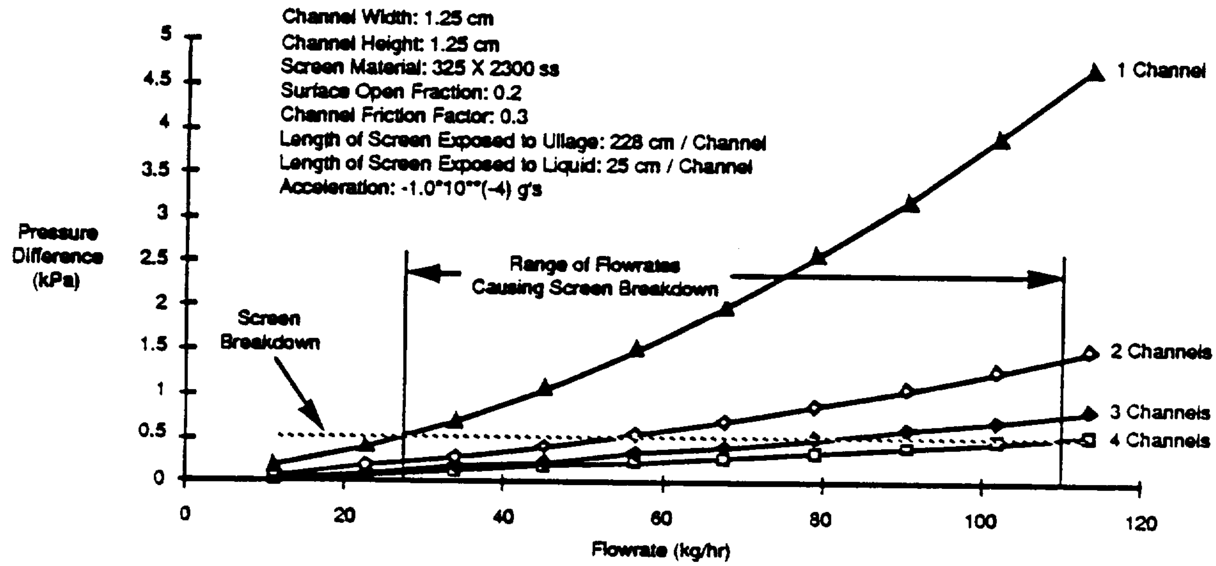


Figure 4.9-29 Pressure Drop in the Channels Under Varying Conditions

The line chilldown was analyzed to predict a hydrogen consumption value to use in the mission database. The chilldown has been considered an operational step only, therefore extensive instrumentation and analysis requirements for this test series have been deleted. Due to this fact the analysis was very crude, and also very conservative. In a cryogenic transfer line chilldown there are extreme thermal and hydrodynamic transients that occur. The flow tends to surge as the liquid front proceeds down the transfer line. This surging results in large spikes in the pressure (surges as large a 40 atmospheres have been seen in testing), and subsequent flow reversal in the line (Ref. 4.9-18). To preclude these surges two methods are employed. The first is to ensure that the fluid at the inlet is in a saturated state. This will not be easy for COLD-SAT to accomplish since the tank must be pressurized to ensure vapor free outflow from the LAD. The second measure is to throttle the flow at the valve so that the chilldown fluid is mostly gas. This method eliminates most of the pressure fluctuations and also reduces the amount of cryogen required for the chilldown. The amount of fluid needed to chill the line reduces since this method allows the wall to absorb much more of the sensible heat in the fluid.

The analysis of the process did not account for any sensible heating of the fluid. This assumption can lead to the amount of cryogen predicted to be an order of magnitude larger than that actually required. The analysis procedure consisted of predicting the amount of heat required to chill a line down to a given temperature via the equation :

$$Q = m\, C_p\, \Delta T$$

where Q = Heat removal amount (kJ)
m = Transfer line mass (kg)
C_p = Specific heat (kJ/kg-K)
and ΔT = The change in temperature (K)

For this analysis the transfer line was assumed to be 1.9 cm (3/4 inch) line with 20 gauge wall, and the length was assumed to be 15.25 m (50 feet). These values resulted in a line mass of 2.13 kg (4.37 lbm). The specific heat value for Aluminum is roughly 0.419 kJ/kg-K (0.1 Btu/lbm-R). From all of this the amount of heat required to chill the line from ambient to liquid hydrogen temperature has been calculated to be 128.7 kJ (122 Btu). To predict the amount of hydrogen required to remove this much heat, this value was simply set against the amount of hydrogen that will boil under this much of a heat load. The resultant consumption value for each chilldown has been determined to be 0.45 kg (1.0

lbm). To predict the chilldown consumption in this manner is extremely crude, but it also is very conservative. Another point of conservatism in the analysis is that the line will always be chilled from an ambient temperature. In all chilldowns, except the first one, the line will still be cold when the chilldown is initiated. Therefore even less hydrogen will be used to cool the line down in these cases than the first.

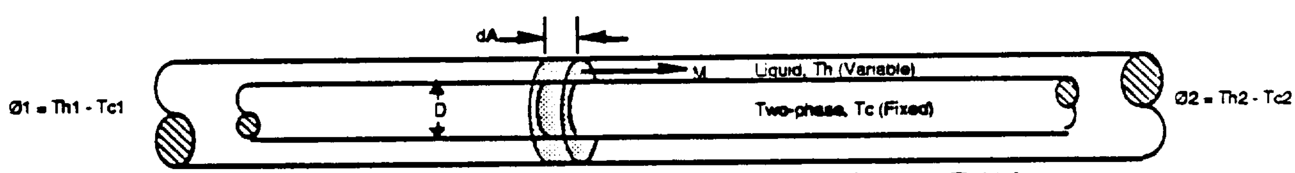
4.9.8 Liquid Subcooling During Outflow

The functional requirement of the compact heat exchanger (CHX) system is to provide active pressure control for the supply tank and thermal subcooling to outflow fluid. The customer directed that the CHX should provide sufficient heat removal capacity for a heat flux of 1.9 W/m^2 (0.6 BTU/ft2-hr), which is 6 times the nominal tank heating rate and is equivalent to 24.6 W (84 BTU/hr). It was assumed that the CHX should provide 34.5 kPa (5 psi) of subcooling to the outflow at 45.4 kg/hr (100 lbm/hr), which is equivalent to 158 W (540 BTU/hr) of heat removal.

The following assumptions were made in performing the analysis:

- 45.4 kg/hr (100 lbm/hr) liquid outflow rate
- 1.28 K (2.3 R) temperature reduction of outflow liquid
- minimum warm side inlet temperature = 20.3 K (36.6 R, corresponding to 15 psi saturated)
- maximum cold side temperature = 17.1 K (30.8 R, corresponding to 5 psi saturated)
- no fins
- constant 2-phase heat transfer coefficient = 2000 W/m^2-K (352 BTU/ft^2-hr-R) (Ref 4.9-19)
- variable single phase heat transfer coefficient, Dittus-Boelter equation
- concentric tubes with liquid in outer tube
- outside surface is insulated
- double length for conservatism.

Figure 4.9-30 illustrates the CHX configuration. The constant temperature cold-side made it possible to develop a closed form expression for the heat exchanger length based on the desired heat removal capacity of 158 W. This expression was evaluated for several different tube diameters, and the results are presented in Figure 4.9-31. From this figure the design point for the heat exchanger was chosen to be an outer tube diameter of 2.5 cm (1 inch), an inner tube diameter of 1.6 cm (5/8 inch), and a heat exchanger length of 3 meters (10 feet).



$dQ = U\,dA\,(Tc - Th)$ [Heat Transfer Between Fluids]

$dQ = \dot{M}\,Cp\,dTh$ [Liquid Energy Balance]

$L = 2 \ln(Ø1 / Ø2)\,\dot{M}\,Cp / (\pi D U)$ [Solve For Length, Including SF = 2]

Figure 4.9-30 CHX Configuration and Design Considerations

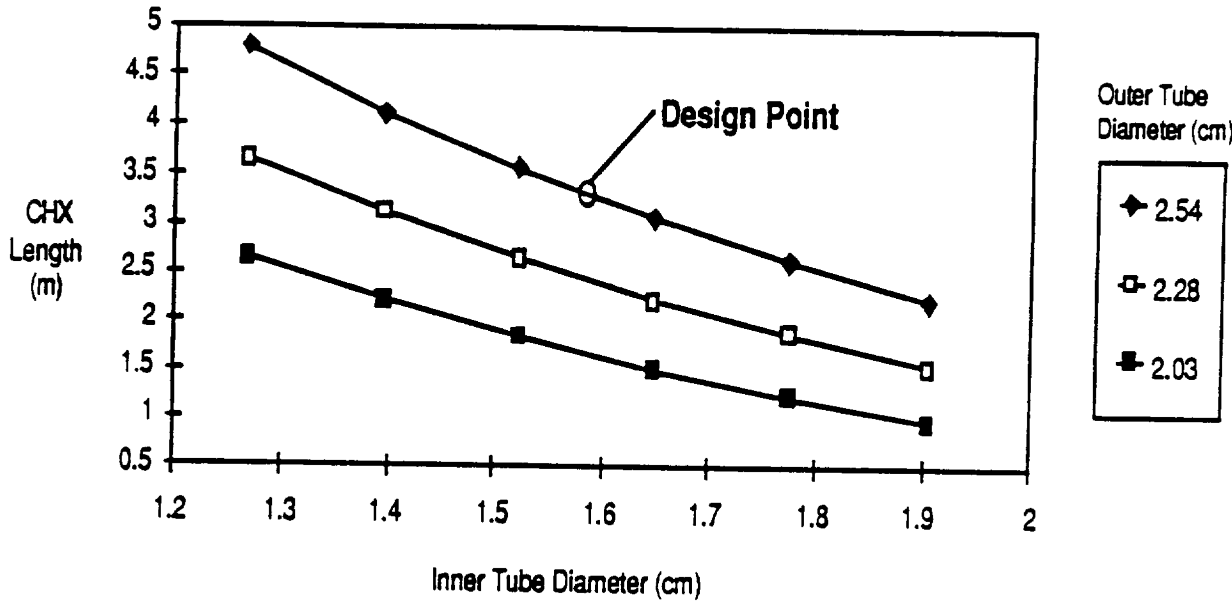


Figure 4.9-31 CHX Analysis Results

4.9.9 COLD-SAT Mission Database

The database has been developed to allow for the tracking of all of the COLD-SAT experiment consumables and to organize the test series into a logical manner. A sample print out of the database is shown in Table 4.9-8, and the complete database can be found in the final review package provided to NASA-LeRC. The database can be used to track the test number, sequence number, liquid hydrogen, gaseous hydrogen, gaseous helium, and propellant consumption, as well as determine the spacecraft weight. The titles are generally self explanatory, with a few exceptions. The column labeled pump number is used to track which pump is operating. A 1 refers to the operation of 1 mixer pump, a 2 means both mixers are being used, and a 3 refers to the transfer pump. The three columns to the right of this one track the power consumed by the heaters, the thrusters, and the pumps respectively. Also, the column labeled D/C (duty cycle) has been included to allow for the pulsing of the thrusters.

On a separate page the database can be used to track the amount of LH2 in each of the three tanks during every test. This page also tracks the true test timeline by accounting for simultaneous tests and is shown in Table 4.9-9. In addition, the last column is a cross reference between the experiment database and the valve position database.

Table 4.9-10 presents a summary of the estimated required LH2 usage for the various processes assessed in the COLD-SAT experiment set. The 100% nominal TVS flow is the flow required to balance a surface heat flux of 0.316 W/m^2 (0.1 Btu/ft^2-hr). The surface heat flux refers to the flux on the pressure vessel and not the flux on the VCS. The supply tank and receiver tank 1 baseline heat leaks and consumptions do not take into account the heat flux reduction that will occur while the TVS is operating. The higher TVS consumptions provide greater heat removal capability which may be used to reduce tank pressure or to maintain the pressure at a higher heat flux. The CHX consumptions are based on reducing the liquid saturation pressure from 103 to 69 kPa (15 to 10 psia). The transfer line chilldown quality was based on a 1.8 kg (4 lbm) Aluminum transfer line being chilled from 167 K to 21.1 K (300 R to 38 R). Only the heat of vaporization was used to provide cooling, therefore this consumption is very conservative. The tank chilldown quantities were determined from the computer codes TARGET and CRYOCHILL. The range given represents two different chilldown approaches:

full childown and partial childown. A full childown begins at 295 K (530 R and proceeds to the target temperature. Partial childowns begin at whatever temperature the tank is at the start of the test (i.e. the tank wall heaters will not be used). The LAD residuals are the volume occupied by the LAD's. The residual of receiver tank 2 is estimated to be 5% of the tank volume.

Table 4.9-8 Sample COLD-SAT Mission Database - Page 1

ERD	Set #	Seq.	ΔT (hr)	Tank	Description	g's	Fill %	Xfer Rate	Path	Pump #	Heater (W)	ACS (W)	Pump (W)	Thrust (lbf)	O/C	Prop (lbm)	ΔV (ft/s)	ΔLH2 (lbm)	dM/dt (lb/hr)	% Full	ΔGH2 (lbm)	ΔGHe (lbm)	S/C Mass (lbm)
1.1	1	1	0.5	S	Prelaunch/Ascent	1.0E+00	95	0	0	0	0.0	0.0	0.0	0	1.0	0.0	0.0	0.0	0.00	95.0	0	0	7103
1.1	2	2	144	S	Stratification	[illegible]	95	0	0	0	4.0	0.0	0.0	0	1.0	0.0	0.0	0.0	0.00	95.0	0	0	7103
1.1	3	3	1	S	Mixing	[illegible]	95	0	Axial	1	4.0	0.0	2.5	0	1.0	0.0	0.0	0.0	0.00	95.0	0	0	7103
1.1	4	4	48.4	S	TVS	[illegible]	95	0	0	0	4.0	0.0	0.0	0	1.0	0.0	0.0	8.2	0.17	93.8	0	0	7103
1.1	5	5	3.93	S	CHK	[illegible]	95	0	Axial	1	4.0	0.0	2.5	0	1.0	0.0	0.0	6.3	1.60	92.8	0	0	7095
1.1	2	6	138	S	Stratification	[illegible]	95	0	0	0	4.0	0.0	0.0	0	1.0	0.0	0.0	0.0	0.00	92.8	0	0	7088
1.1	6	7	1.37	S	CHK	[illegible]	95	0	Axial	2	4.0	0.0	5.0	0	1.0	0.0	0.0	4.4	3.20	92.2	0	0	7088
1.1	7	8	1.88	S	CHK	[illegible]	95	0	Radial	2	4.0	0.0	5.0	0	1.0	0.0	0.0	6.0	3.20	91.3	0	0	7084
1.1	8	9	26.5	S	Stratification	[illegible]	95	0	0	0	12.1	0.0	0.0	0	1.0	0.0	0.0	0.0	0.00	91.3	0	0	7078
1.1	9	10	1	S	Mixing	[illegible]	95	0	Axial	1	12.1	0.0	2.5	0	1.0	0.0	0.0	0.0	0.00	91.3	0	0	7078
1.1	10	11	4.27	S	CHK	[illegible]	95	0	Axial	1	12.1	0.0	2.5	0	1.0	0.0	0.0	6.8	1.60	90.2	0	0	7078
1.1	8	12	24.2	S	Stratification	[illegible]	95	0	0	0	12.1	0.0	0.0	0	1.0	0.0	0.0	0.0	0.00	90.2	0	0	7071
1.1	11	13	0.85	S	CHK	[illegible]	95	0	Axial	2	12.1	0.0	5.0	0	1.0	0.0	0.0	2.7	3.20	89.4	0	0	7071
1.1	12	14	1	S	CHK	[illegible]	95	0	Radial	2	12.1	0.0	5.0	0	1.0	0.0	0.0	3.2	3.20	89.3	0	0	7068
1.1	13	15	8.35	S	Stratification	[illegible]	95	0	0	0	24.2	0.0	0.0	0	1.0	0.0	0.0	0.0	0.00	89.3	0	0	7065
1.1	14	16	1	S	Mixing	[illegible]	95	0	Axial	2	24.2	0.0	5.0	0	1.0	0.0	0.0	0.0	0.00	89.3	0	0	7065
1.1	15	17	3.21	S	CHK	[illegible]	95	0	Axial	1	24.2	0.0	2.5	0	1.0	0.0	0.0	5.1	1.60	88.6	0	0	7065
1.1	13	18	27.2	S	Stratification	[illegible]	95	0	0	0	24.2	0.0	0.0	0	1.0	0.0	0.0	0.0	0.00	88.6	0	0	7060
1.1	16	19	2.32	S	CHK	[illegible]	95	0	Axial	2	24.2	0.0	5.0	0	1.0	0.0	0.0	7.4	3.20	87.4	0	0	7060
1.1	17	20	2.06	S	CHK	[illegible]	95	0	Radial	2	24.2	0.0	5.0	0	1.0	0.0	0.0	6.6	3.20	86.4	0	0	7053
		21			0						0.0	0.0			1.0	0.0	0.0			86.4			7046
		22			0						0.0	0.0			1.0	0.0	0.0			86.4			7046

Table 4.9-9 Sample COLD-SAT Mission Database - Page 2

ERD	Test #	Seq.	Start t (hr)	End t (hr)	Index	Supply Mass (lbm)	R1 Mass (lbm)	R2 Mass (lbm)	Final Fill %	Valve ID
1.1	1	1	0.0	0.5		630.0	0.0	0.0		1
1.1	2	2	0.5	144.5		630.0	0.0	0.0		2
1.1	3	3	144.5	149.5		630.0	0.0	0.0		3
1.1	4	4	148.5	193.9		621.8	0.0	0.0		4
1.1	5	5	193.9	197.9		615.5	0.0	0.0		5
1.1	2	6	197.9	335.9		615.5	0.0	0.0		6
1.1	6	7	335.9	337.2		611.1	0.0	0.0		7
1.1	7	8	337.2	339.1		605.0	0.0	0.0		8
1.1	8	9	339.1	365.6		605.0	0.0	0.0		9
1.1	9	10	365.6	366.6		605.0	0.0	0.0		10
1.1	10	11	366.6	370.9		598.2	0.0	0.0		11
1.1	8	12	370.9	395.1		598.2	0.0	0.0		12
1.1	11	13	395.1	395.9		595.5	0.0	0.0		13
1.1	12	14	395.9	396.9		592.3	0.0	0.0		14
1.1	13	15	396.9	405.3		592.3	0.0	0.0		15
1.1	14	16	405.3	406.3		592.3	0.0	0.0		16
1.1	15	17	406.3	408.5		587.2	0.0	0.0		17
1.1	13	18	408.5	438.7		587.2	0.0	0.0		18
1.1	16	19	438.7	439.0		579.7	0.0	0.0		19
1.1	17	20	439.0	441.1		573.1	0.0	0.0		20
		21	441.1	441.1		573.1	0.0	0.0		21
		22	441.1	441.1		573.1	0.0	0.0		22

The database output can be presented graphically to provide a better understanding of the trends during the mission. Figure 4.9-32 presents the amount of LH2 allocated for each experiment category. Approximately 75% of the total fluid is budgeted to class 1 experiments with the single largest allocation being given to the pressure control experiments. The large allocation for ERD 2.5 is due to the fact that this experiment set represents free venting and vented fills, both of which will use large amounts of LH2.

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Table 4.9-10 COLD-SAT Mission Database Fluid Usage Assumptions

LH2 USAGE DATA	% OF NOMINAL TVS FLOW	
Supply Tank	100%	0.041 kg/hr (0.09 lbm/hr)
	200%	0.078 kg/hr (0.17 lbm/hr)
CHX		0.73 to 1.45 kg/hr (1.6 to 3.2 lbm/hr)
Receiver Tank 1	100%	0.078 kg/hr (0.17 lbm/hr)
	200%	0.15 kg/hr (0.34 lbm/hr)
Receiver Tank 2	100%	0.045 kg/hr (0.10 lbm/hr)
	175%	0.078 kg/hr (0.17 lbm/hr)
Transfer Line Childown		
Quantity Used Each Time		4.54 kg (1.0 lbm)
Transfer Line Residuals		0.45 kg (0.1 lbm)
Receiver Tank Childown		
Quantity Used Tank 1		0.91 to 8.2 kg (2.0 to 18.0 lbm)
Quantity Used Tank 2		0.91 to 3.6 kg (2.0 to 8.0 lbm)
Lad/Tank Residuals		
Quantity Used Supply Tank		1.27 kg (2.8 lbm)
Quantity Used Receiver Tank 1		0.50 kg (1.1 lbm)
Quantity Used Receiver Tank 2		1.81 kg (4.0 lbm)

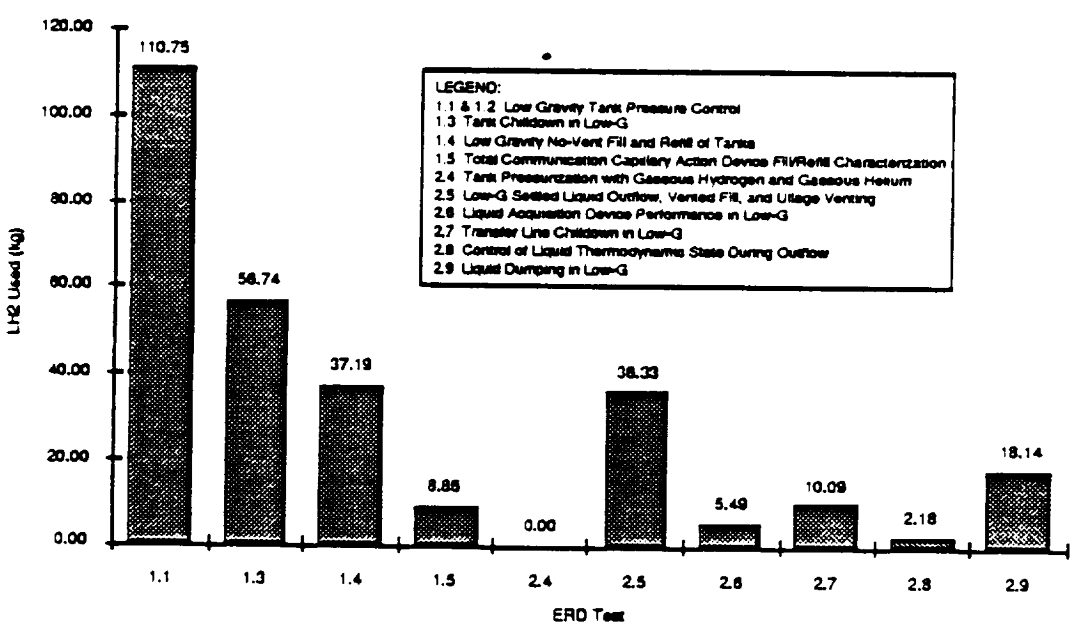

Figure 4.9-32 LH2 Allocation by ERD Number

In comparison, the database can also present the amount of liquid hydrogen available during the mission. This is presented in Figure 4.9-33. The database can track many different consumables, including the liquid hydrogen, the pressurant (both hydrogen and helium), and the propellant.

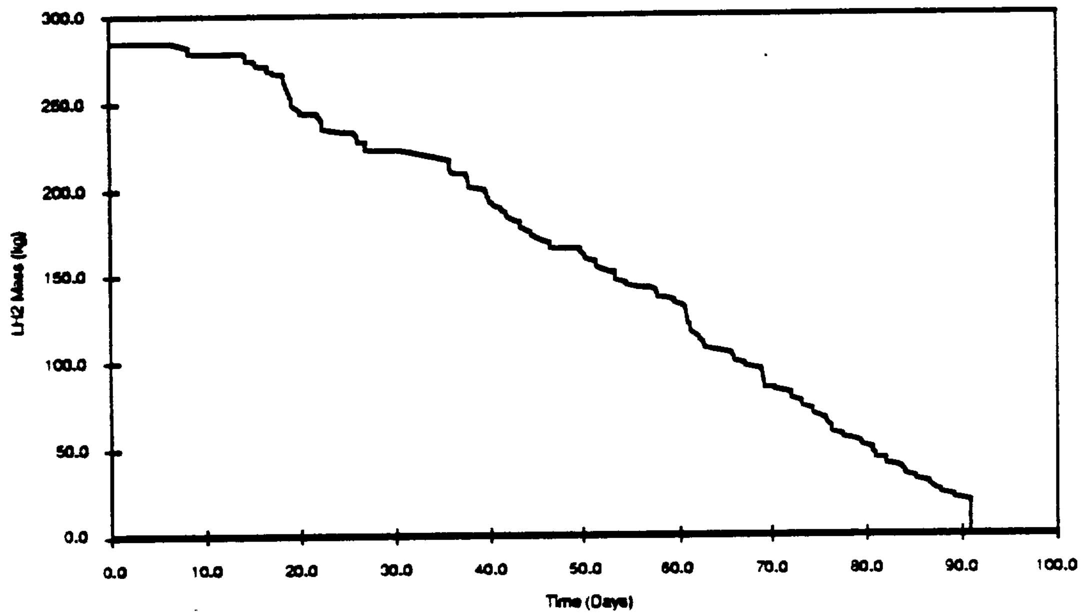

Figure 4.9-33 Total LH2 Remaining During COLD-SAT Mission

The database can also track the amount of hydrogen in each of the three tanks. This capability allows one to evaluate certain transfers to ensure that the supply tank does not have to be completely emptied to fill the receiver tank. By using this approach, we were able to ascertain that the receiver tank 1 fills had to be moved to a point earlier in the mission, since there was simply not enough hydrogen in the supply tank to fill the receiver tank fully. Figure 4.9-34 presents the the amount of hydrogen in the supply tank throughout the mission.

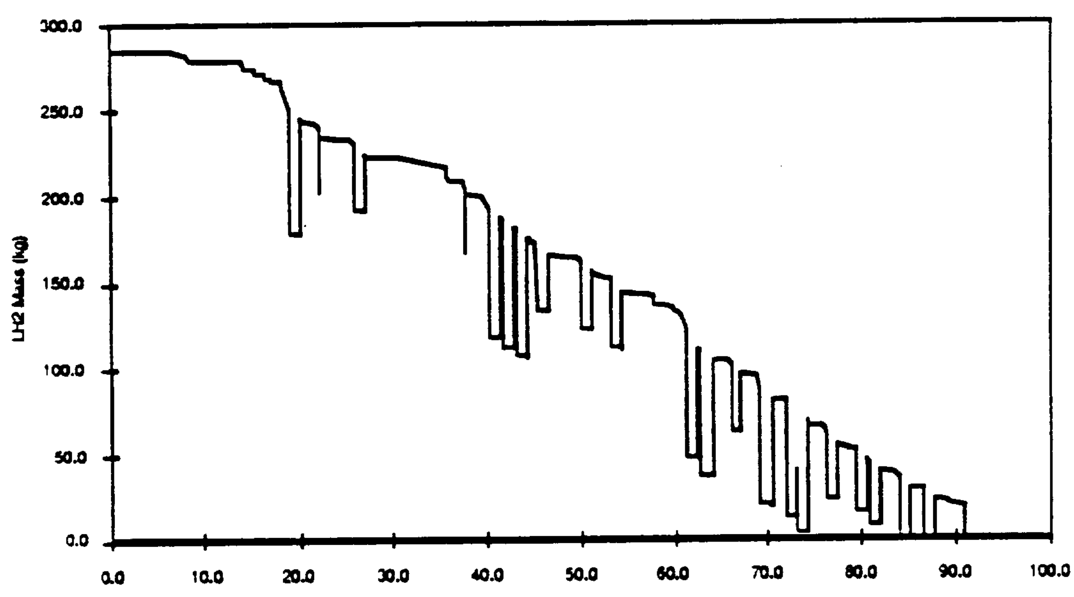

Figure 4.9-34 Amount of LH2 in the COLD-SAT Supply Tank Throughout the Mission

One last capability of the database is to be able to track the true timeline of the mission. Many of the experiments occur simultaneously (liquid outflow and a no-vent fill for example). From this data a timeline for the mission can be generated and printed graphically. A sample timeline is presented in Figure 4.9-35. Each test is presented on the y-axis, in the order of testing sequence. The horizontal bar shows the test duration in days.

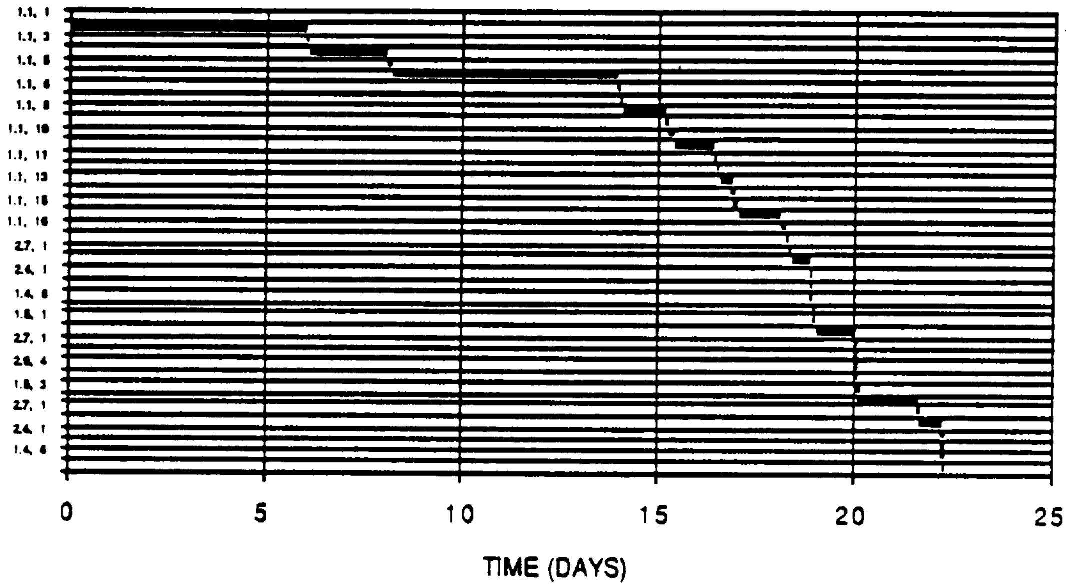

Figure 4.9-35 Sample COLD-SAT Mission Timeline

4.10 Experiment Subsystem Control and Monitoring

Control and data handling of the experiment and its subelements will be by the Remote Interface Units (RIUs) that exist within the experiment subsystem. The RIUs receive commands from the Telemetry, Tracking, & Command (TT&C) subsystem via the multiplex data bus. Commands are stored in the On-Board Computer (OBC) memory where the CU controls the relaying of commands to the experiment subsystem or any other subsystem via the data bus. Any changes/updates to the software sequencer will be uplinked to the OBC via TDRSS from the SOCC. The RIUs also control the acquisition of experiment data and provide the data to the TT&C via the data bus. The CU collects the data and provides the data to the OBC for processing, downlinking, and/or to be used by the software sequencer for experiment control. The EUs (Extender Units) extend the capability of the RIUs to acquire data. Figure 4.10-1 shows the Experiment Subsystem functional control and monitoring approach .

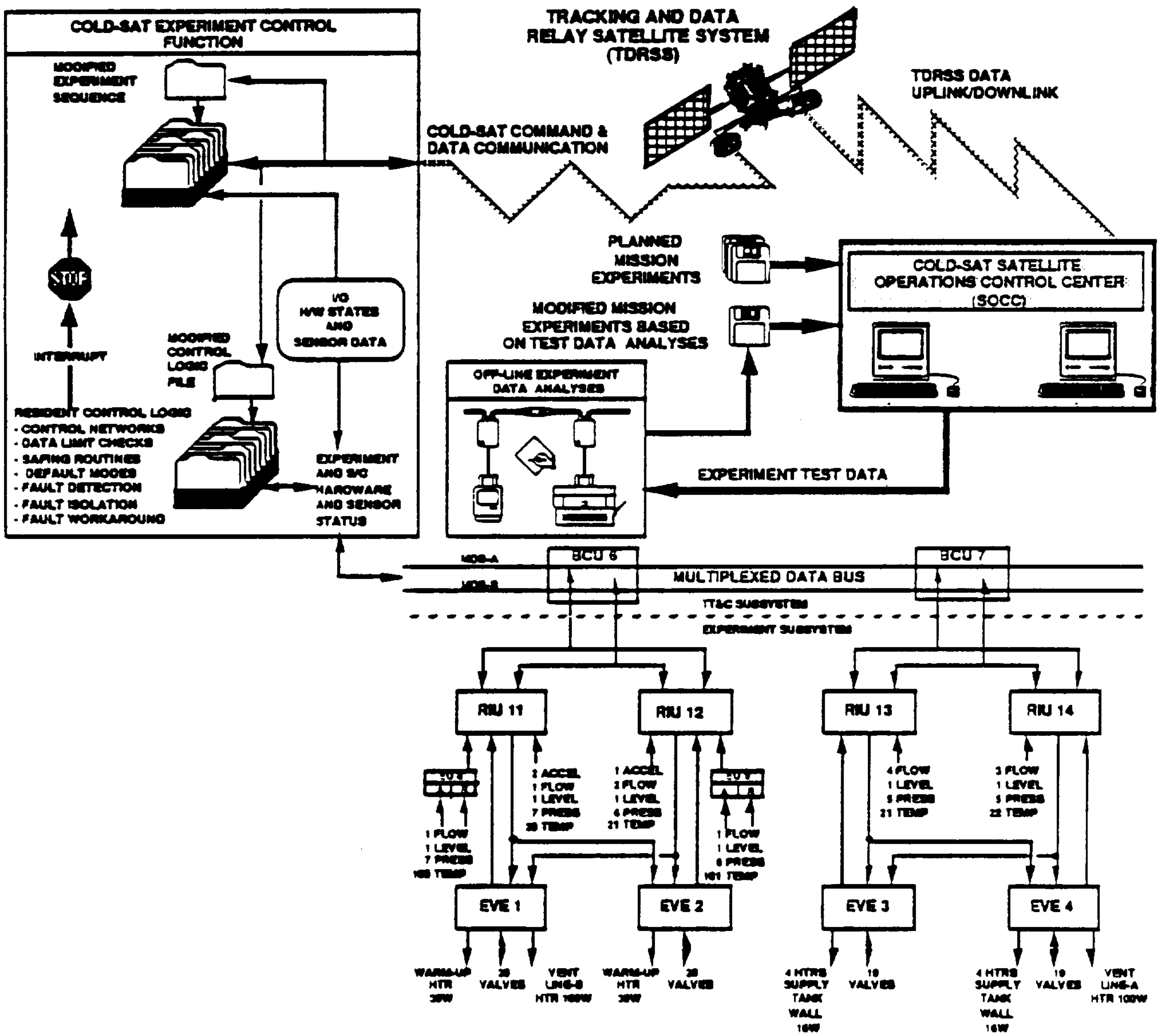

Figure 4.10-1 Experiment Subsystem Control Functional Approach

As shown in Figure 4.10-1 the experiment subsystem will utilize RIUs to process commands from the TT&C subsystem for the control of the experiment valves. The Experiment Valve Electronics (EVEs) will provide the control and data interface between the RIUs and the valves. Data acquisition will be via RIUs and EUs. Experiment sensors will be assigned to different RIUs or EUs to maintain fault tolerance.

The Experiment Valve Electronics (EVE) module is based on the Multi-mission Modular Spacecraft (MMS) Propulsion Module Electronics (PME) design. The EVEs interface with the system through a standard Remote Interface Unit (RIU). Four EVEs are used for status and control of all valves in the experiment except the ordnance valves which are handled by the Power Control & Distribution Module (PC&DM) in the Electrical Power Subsystem (EPS).

To create an EVE, all analog signal conditioners were removed from the PME design. The mother board and the circuits in the box were modified. The quantity of valve drivers and bilevel signal conditioner boards was tripled to handle 24 valves per EVE. The only change to the valve driver circuit was the output pulse duration. Figure 4.10-2 shows the EVE functional configuration.

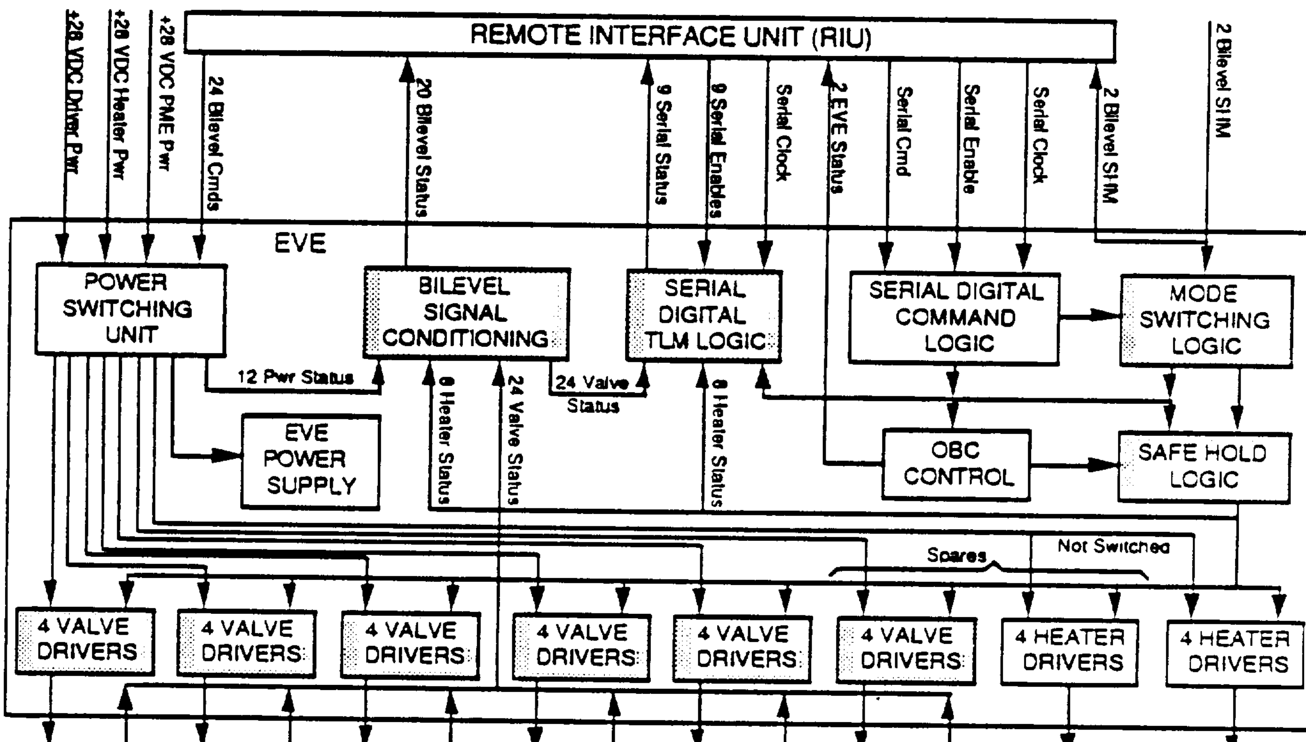

Figure 4.10-2 Experiment Valve Electronics (EVE) Functional Configuration

Control algorithms have been defined as shown in Figure 4.10-3 to perform automatic control of critical events many of which are safety related. Most pressure relief valves are complemented with venting pressure using system valving before manual relief valve and/or burst disc settings are exceeded. Approximately half of the defined control networks are associated with safety, while the rest perform various component limit cycling. Figure 4.1-3 shows the control networks on the experiment subsystem schematic. Each shows what sensors or functions that are being monitored along with the components that are effected by the operation of the control network. As other requirements are defined, the use of these algorithms will be expanded. For the most part, these functions will reside in software and will be continuously active to perform required actions should they be required.

The Martin Marietta approach to measuring temperatures in the COLD-SAT experiment involves the use of the Remote Interface Unit (RIU) and Extender Unit (EU) from the existing Multi-mission Modular Spacecraft (MMS) family. At issue is that the single 8 bit data word generated by the RIU/EU for each passive resistive temperature sensor cannot provide the desired accuracy for some temperature ranges. The amount of redesign required to convert the present system to 12 bits is considered to be too extensive. The following discussion presents our recommendation to use this equipment to get the accuracy desired with minimal impact and redesign while still using the existing 8 bit MMS bus without modification.

A list of potential problems associated with our existing baseline electronics is:

- the 3 lead arrangement must be converted to a 4-lead configuration,
- the ± 0.5 % current source error implies an identical voltage error, ± 0.5% ,which will add to other voltage error sources unless it can be compensated,
- the scanning rate limit (~ 50 sensor / sec) for accurate measurement means that the RIU multiplexing pulse time must be increased from 55 µS to 20 ms (Ref 4.10-1).

Figure 4.10-4 shows the RIU/EU as it was originally intended to be used with passive resistive temperature sensors. A command received on the Multiplex Data Bus causes the Current Source to produce a 1 mA ± 0.5 % current pulse. This 54.7 µs pulse is directed by the Current Demultiplexer to one of 16 connector pins that act both as current outputs and voltage sense inputs. The current passes through one temperature sensor and then returns to the Current Source by a path common to all 16 sensors. The current flowing through the sensor resistance causes a voltage difference to appear across the sensor. The positive side voltage, plus voltage appearing on the current/sense wire, is routed by the Telemetry Data Multiplexer to the Analog to Digital Converter (ADC) in the Telemetry Controller. The minus side reference voltage returns by a path that is twisted with the positive voltage and shielded. Seven inactive sensor returns join the active one before being routed by the Telemetry Reference Multiplexer to the ADC. The ADC converts the voltage difference to an eight bit binary word which is sent back on the Multiplex Data Bus.

The advantages of using this scheme are:

1. No development costs required.
2. Less wires penetrating the tanks.

The disadvantages are:

1. Current Source inaccuracy ±0.5%.
2. Current pulse is a very short 54.7 µs. Sensor manufacturers recommend 20 ms.
3. Because one of the sense wires also carries the current pulse, the situation is not ideal for the use of high thermal resistance manganin wire, due to its large electrical resistance.
4. Inaccurate temperature measurements.

Range	Accuracy at Range Extremes
16-31° K (28 - 55° R)	±6.94-1.28° K (12.5 - 2.3° R)
17-50° K (30 - 90° R)	±5.44-0.78° K (9.8 - 1.4° R)
17-139° K (30 - 250° R)	±5.44-1.16° K (9.8 - 2.1° R)
17-300° K (30 - 540° R)	± 9.5-2.5° K (17.1 - 4.5° R)
222-333° K (400 - 600° R)	±2.28-2.83° K (4.1 - 5.1° R)

5. Only 16 of the 64 RIU inputs (32 of 128 EU inputs) are set up for passive sensors.

CONTROL NETWORK	CONTROL NETWORK DESCRIPTION
C1 - SUPPLY TANK CHX COLD SIDE OVER PRESSURE PROTECTION	SPRAY SYSTEM SELECTOR VALVES ST4 & 5 WILL OPEN WHEN CHX PRESSURE EXCEEDS 50 PSIA. VALVES WILL CLOSE WHEN PRESSURE DROPS BELOW 40 PSIA.
C2 - RECEIVER TANK OVER PRESSURE PROTECTION	TANK PRESSURE IN EXCESS OF 50 PSIA WILL BE VENTED BY OPENING TANK VENT VALVES VV7 - VV8. VALVES WILL CLOSE WHEN PRESSURE DROPS BELOW 40 PSIA.
C3 - RECEIVER TANK (2) PRESSURE CONTROL	TVS HX CONTROL VALVES TV3 & 4 WILL BE CYCLED TO MAINTAIN TANK PRESSURE TO A SPECIFIED SETPOINT LIMIT BETWEEN 15 - 40 PSIA.
C4 - PRESSURANT REGULATED PRESSURE CONTROL	PRESSURANT FLOW TO TANKAGE WILL BE TERMINATED BY CLOSING VALVES PV1 & 2 IF TANK PRESSURE SETPOINT IS EXCEEDED BY 5 PSIA.
C5 - SUPPLY TANK CHX COLD SIDE OVER PRESSURE PROTECTION	CHX FLOW CONTROL VALVES TV3 & 4 WILL OPEN WHEN CHX PRESSURE EXCEEDS 50 PSIA. VALVES WILL CLOSE WHEN PRESSURE DROPS BELOW 40 PSIA.
C6 - RECEIVER TANK(2) WARM-UP HEATER CONTROL	WHEN PRESSURE VESSEL WALL TEMPERATURES RISE TO INITIAL WARM STARTING CONDITION HEATERS WILL BE TURNED OFF.
C7 - SUPPLY TANK OVER PRESSURE PROTECTION	TANK PRESSURE IN EXCESS OF 50 PSIA WILL BE VENTED BY OPENING TANK VENT VALVES VV5 & 6. VALVES WILL CLOSE WHEN PRESSURE DROPS BELOW 40 PSIA.
C8 - SUPPLY TANK PRESSURE CONTROL	CONTROL VALVES TV1 & 2 FOR TVS HX WILL BE CYCLED TO MAINTAIN TANK PRESSURE TO A SPECIFIED SETPOINT LIMIT BETWEEN 15 - 40 PSIA.
C9 - MID TRANSFER LINE OVER PRESSURE PROTECTION	TRANSFER LINE PRESSURE IN EXCESS OF 50 PSIA WILL BE VENTED BY OPENING VALVES TL5 - TL7. THE VALVES WILL CLOSE WHEN PRESSURE DROPS BELOW 40 PSIA.
C10 - SUPPLY TANK FLUID MIXER CONTROL	TANK JET PUMP WILL BE TURNED ON WHEN TANK FLUID TEMPERATURES VARY BY MORE THAN 3 DEG F. JET PUMP WILL BE TURNED OFF WHEN VARIATION DECREASES TO 0.5 DEG F. RADIAL AND/OR AXIAL SPRAY OPTIONS CAN BE SELECTED.
C11 - FREE VENT OVER PRESSURE PROTECTION	PRESSURE IN EXCESS OF 50 PSIA IN THE FREE VENT BEFORE OV4 IS OPENED WILL OPEN VALVES VV1 & 2. THE VALVES WILL CLOSE WHEN PRESSURE DROPS BELOW 40 PSIA.
C12 - PRESSURIZATION LINE OVER PRESSURE PROTECTION	PRESSURIZATION LINE PRESSURE IN EXCESS OF 50 PSIA WILL BE VENTED BY OPENING VALVES PV4 - PV6. THE VLVS WILL CLOSE WHEN PRESSURE DROPS BELOW 40 PSIA.
C13 - SUPPLY TANK TVS HX OVER PRESSURE PROTECTION	HX LINE PRESSURE IN EXCESS OF 50 PSIA WILL BE VENTED BY OPENING TVS CONTROL VALVES TV 1 & TV2. VALVES WILL CLOSE WHEN PRESSURE DROPS BELOW 40 PSIA.
C14 - TRANSFER LINE OVER PRESSURE PROTECTION	TRANSFER LINE PRESSURE IN EXCESS OF 50 PSIA WILL BE VENTED BY OPENING VALVES VV3 & 4. THE VALVES WILL CLOSE WHEN PRESSURE DROPS BELOW 40 PSIA.
C15 - DELETED	DELETED
C16 - RECEIVER TANK (1) TVS HX OVER PRESSURE PROTECTION	TVS HX LINE PRESSURE IN EXCESS OF 50 PSIA WILL BE VENTED BY OPENING TVS CONTROL VALVES TV 8 & 9. VLVS WILL CLOSE WHEN PRESSURE DROPS BELOW 40 PSIA.
C17 - RECEIVER TANK (1) PRESSURE CONTROL	CONTROL VALVES TV8 & 9 FOR TVS HEAT EXCHANGERS WILL BE CYCLED TO MAINTAIN TANK PRESSURE TO A SPECIFIC SETPOINT LIMIT BETWEEN 15 - 40 PSIA.
C18-RECEIVER TANK (1) OVER PRESSURE PROTECTION	TANK PRESSURE IN EXCESS OF 50 PSIA WILL BE VENTED BY OPENING TANK VENT VALVES VV10 - 12. VALVES WILL CLOSE WHEN PRESSURE DROPS BELOW 45 PSIA.
C19-DELETED	DELETED
C20-TRANSFER LINE OVER PRESSURE PROTECTION	LINE PRESSURE IN EXCESS OF 50 PSIA WILL BE VENTED BY OPENING VALVE TL2. THE VALVE WILL CLOSE WHEN PRESSURE DROPS BELOW 40 PSIA.
C21- DELETED	DELETED
C22-RECEIVER TANK (2) TVS HX OVER PRESSURE PROTECTION	TVS HX LINE PRESSURE IN EXCESS OF 50 PSIA WILL BE VENTED BY OPENING TVS CONTROL VALVES TV5 & 6. VLVS WILL CLOSE WHEN PRESSURE DROPS BELOW 40 PSIA.

Figure 4.10-3 Experiment Subsystem Control Networks

The poor accuracies shown in "disadvantage 4" primarily represent the error per count at each end of the range. They are caused by the low amplitude of the sensor output voltage at 1 mA and by the sensor's inherent nonlinear temperature - resistance characteristic. However, other sources of error associated with "disadvantages 1 - 3" become increasingly important when the sensor output problem is corrected. PRT's having appropriate resistances (up to 8000 Ω) at the high temperature end were baselined for these estimates.

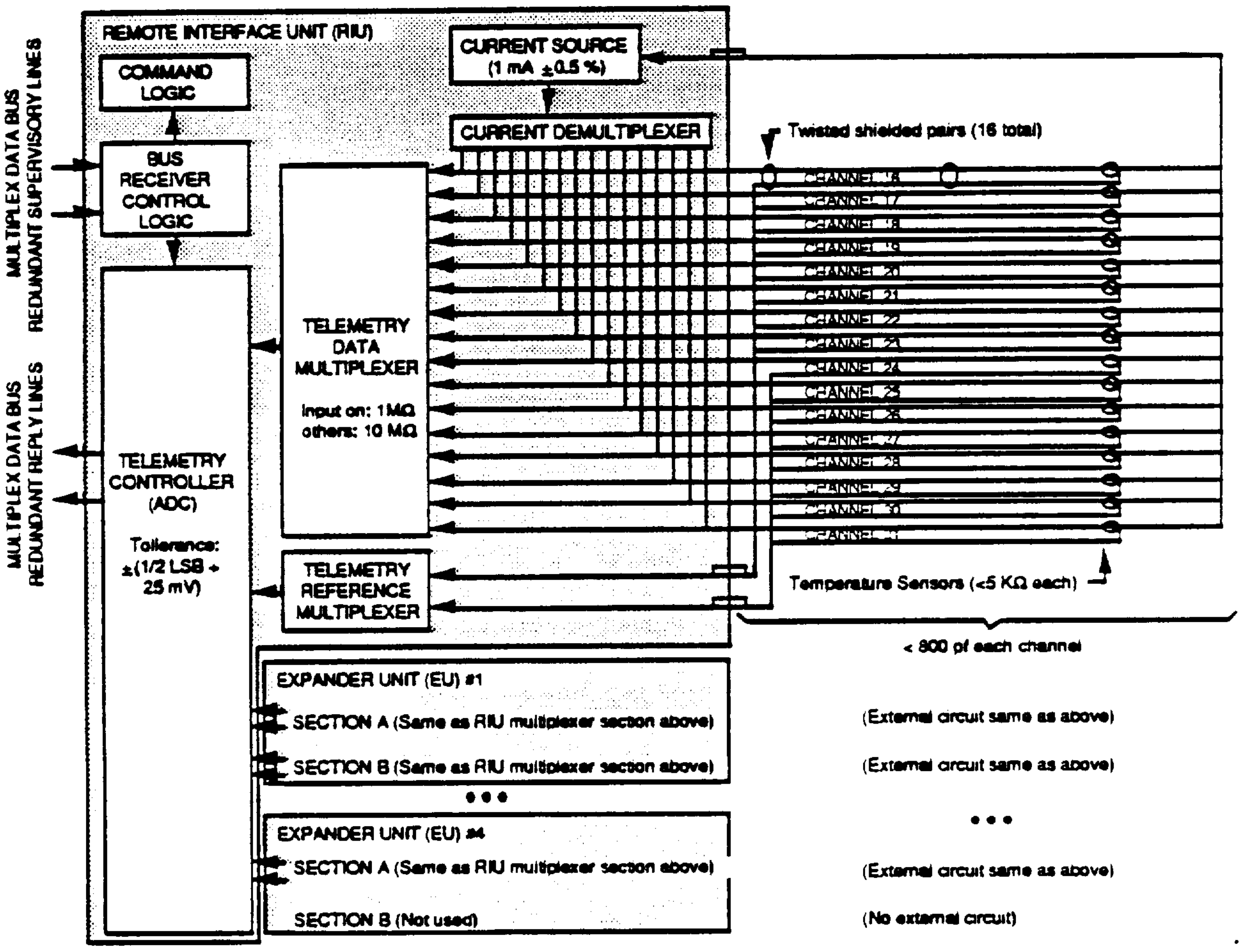

Figure 4.10-4 Existing RIU/EU Passive Temperature Sensor Circuit

Figure 4.10-5 shows a circuit with five advantages over Figure 4.10-4. They are the duration of the current pulse, four lead wires to each sensor, tighter current source control, linearizing signal conditioning, and the number of channels that can be used for passive temperature sensors.

Due to the Multiplex Data Bus timing and design, extension of the internal Current Source pulse duration is quite difficult. External current sources controlled by a separate command allow any pulse duration desired. The measurement is taken near the end of the current pulse by executing an active sensor read command. In order to read many sensors in a short time, 8 current sources drive 8 sensors simultaneously. Near the end of the current pulses 8 active sensor read commands are sequentially executed.

The use of active sensor read commands allows all 64 input channels to do temperature measurement, instead of the 16 original passive input channels. For the EU this means there will be 128 active input channels instead of 32 passive.

The advantages of using this scheme are:

1. Four lead wire configuration to each sensor.
2. Current accuracy improved from 0.5% to 0.1%.
2. Separate current and voltage sense wires.
3. Manganin wire reduces thermal loss.
4. Signal conditioning incorporates linearization to allow nearly uniform temperature error across the entire range.
5. Current pulse increased from 54.7 μs (one sensor at a time) to 20 ms (8 sensors at a time).
6. Measurement accuracy considerably improved.

Range	Accuracy at Range Extremes
16-31° K (28 - 55° R)	±0.07-0.16° K (±0.12 - 0.29° R)
17-50 ° K (30 - 90° R)	±0.14-0.16° K (±0.25 - 0.29° R)
17-139 ° K (30 - 250° R)	±0.5-0.6° K (±0.89 - 1.07° R)
17-300° K (30 - 540° R)	±1.17-1.4° K (±2.01 - 2.51° R)
222-333° K (400 - 600° R)	±0.63-0.74° K (±1.14 - 1.34° R)

The disadvantages are:

1. Moderate development.
2. Flight certification of Current Sources, Demultiplexers, Control Logic, and Signal Conditioning is required.

The primary advantage of the baseline electronics is that it already exists. We believe that it can be modified for compatibility with an existing sensor type, such as the 2000 Ω (273°K[491°R]) PRTΩ, so that the temperature measurement system meets the ± 0.14°K (0.25°R) requirement at 31°K (55.8°R). An example of a candidate sensor / signal conditioner circuit for the 15 to 31°K (27 to 55.8°R)temperature range is given in Figure 4.10-6. An analysis was performed to characterize the circuit and is contained in the Instrumentation Report (Ref 4.10-2). In this figure the transducer is a Rosemount Model 118 MF PRT and the voltage values represent calibration data points from a typical sensor excited at 1mA. The temperature vs voltage characteristic at each stage of the signal conditioner, which uses Burr-Brown components was also defined. The theoretical temperature vs analog voltage curve which would be generated by the signal conditioner was determined. A best fit equation with equal weight factors indicates a standard deviation of ± .07° K (0.13°R); the 8 bit resolution is ± .06° K (0.11°R) and the COLD-SAT requirement is ± 0.14° K (0.25°R). The worst case error analysis for optimized instrumentation requires that the current source be 1 mA ± 1μA (0.1%). The error sources can be related to 1) sensor repeatability / current source regulation, 2) the 8 bit resolution limit, 3) mathematical modelling of the sensor output linearization process, and 4) total output errors inherent in each stage of the signal conditioner. To implement a circuit which minimizes the total error involves a judicious choice of instrumentation amplifier parameters (gain and offset) such that the converter stage can operate in the most accurate part of its input range. Transformation equations have been used to determine optimum values of these parameters which are shown in Figure 4.10-6.

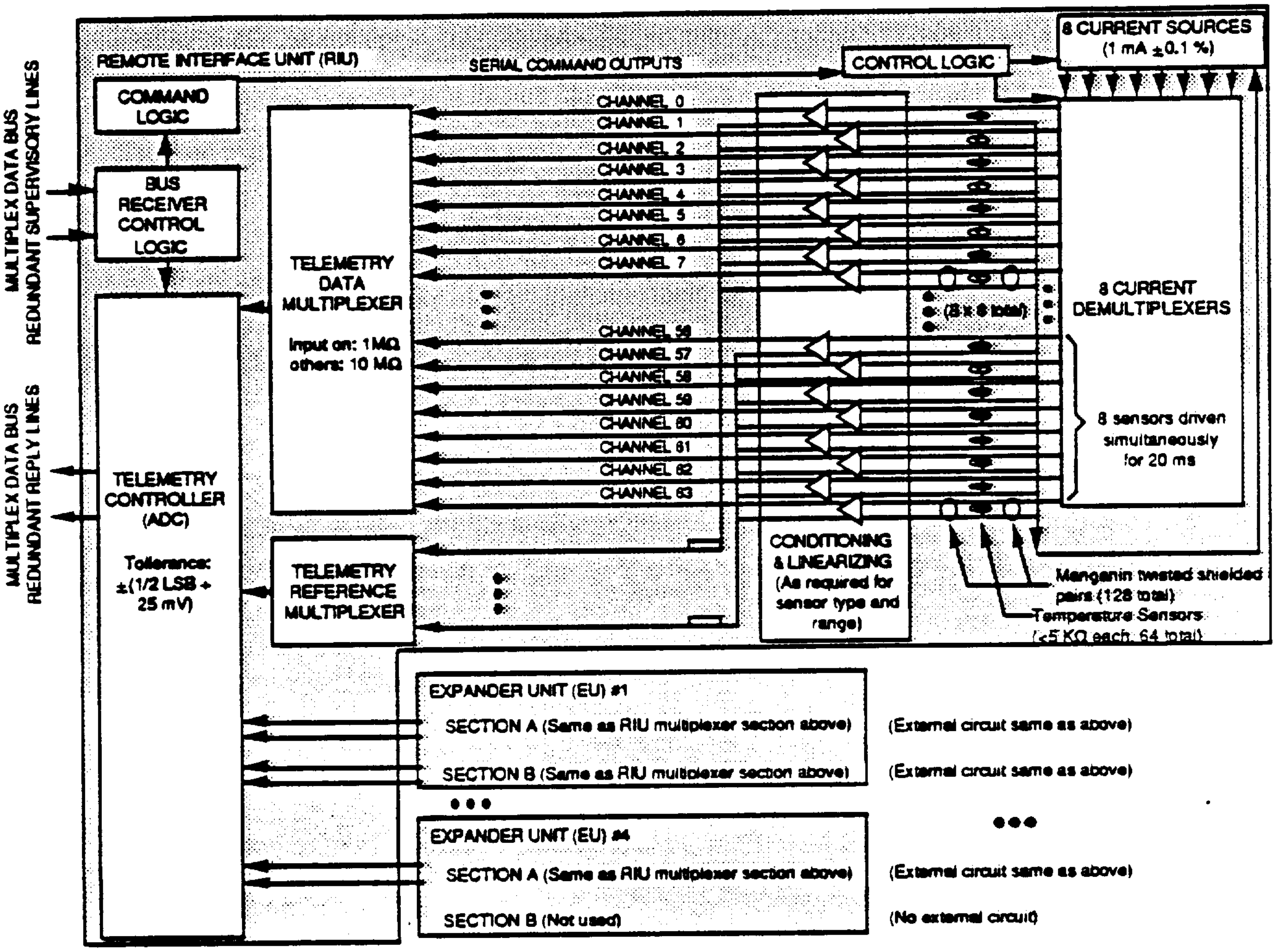

Figure 4.10-5 Recommended RIU Modification for Required Accuracy Temperature Measurements

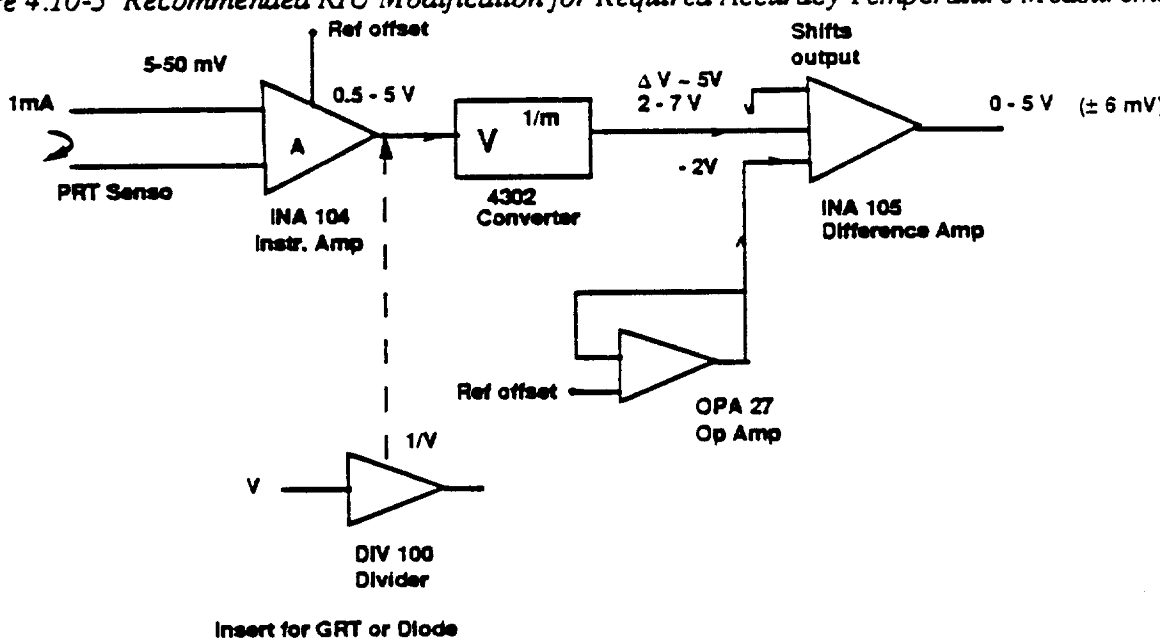

Figure 4.10-6 PRT Temperature Sensor Signal Conditioning Circuit

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Figure 4.10-7 shows the solution for those few remaining cases where the accuracy is still too low. Two channels are assigned to a single sensor. The 16.7-300°K (30 - 540° R) temperature range is broken into two sections with different signal conditioning for each. When one channel is saturated the other is within its range.

The advantages and disadvantages for this configuration are the same as for Figure 4.10-5 except that the accuracy for the 17 - 300° K (30 - 540° R) range is improved to ±0.56-0.84° K (±1.01 - 1.51° R) and fewer channels are available.

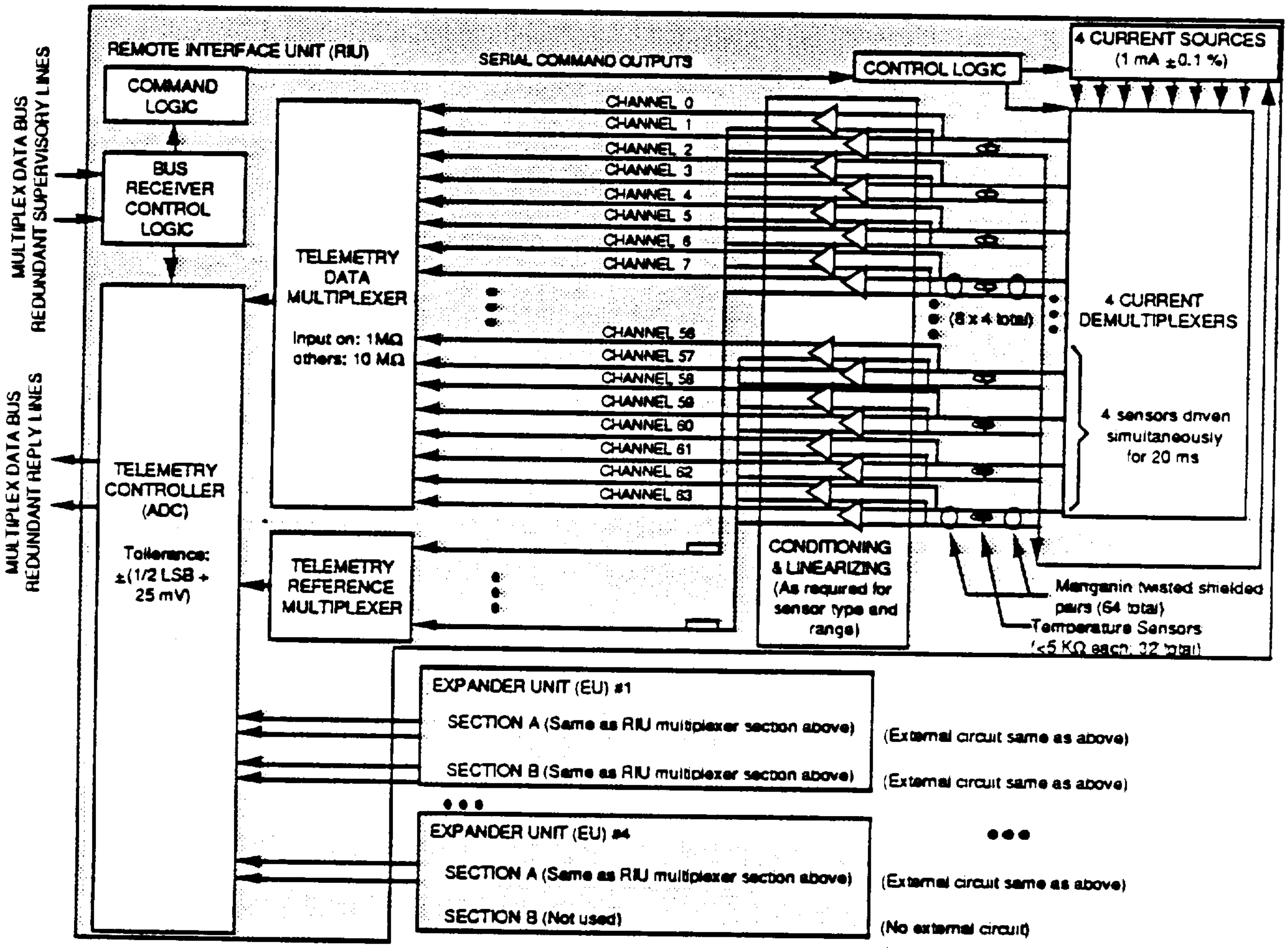


Figure 4.10-7 Recommended RIU Modification for Dual Ranging for Sensor Accuracy

Figure 4.10-8 shows the generic circuit for the RIU/EU interface of acceleration, flow, level, and pressure sensors. None of these require signal conditioning beyond that supplied with the sensor. These sensors all provide a 0-5 vdc output that is compatible with the RIU ADC. Required accuracy is attainable without additional signal conditioning. To keep the hot wire level sensors from generating more heat than necessary, their +28 volt supply should be pulsed. This requires a control circuit that receives its direction from the command outputs of the RIU. Active sensor read commands are sequentially executed near the end of the +28 volt pulse. The other sensor circuits may also be pulsed if desired.

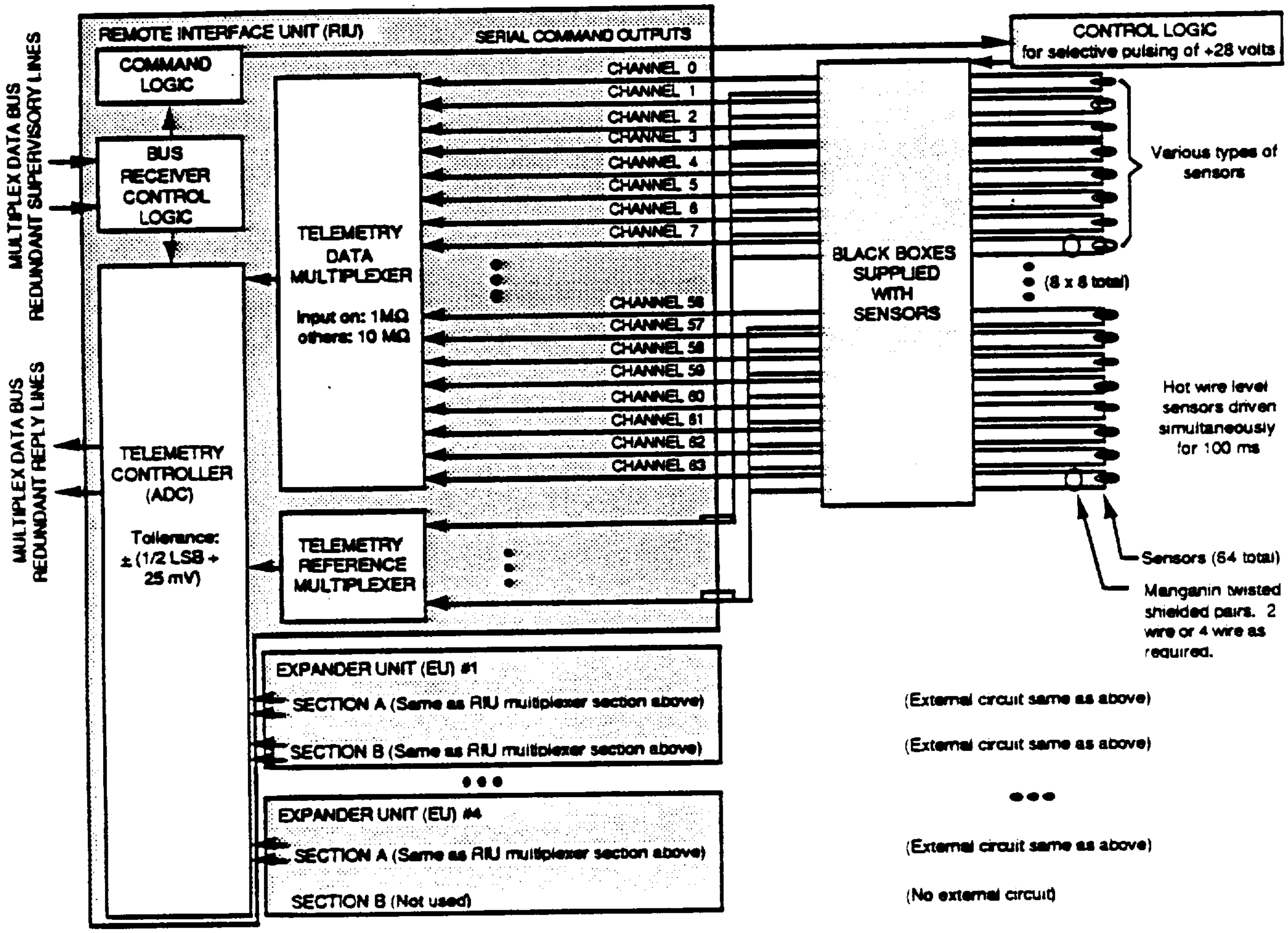


Figure 4.10-8 RIU Interfacing With Other Instrumentation Sensors

4.11 Experiment Subsystem Recommended Changes

The experiment subsystem not only must be compatible with meeting experiment set needs, but should also provide for an optimized, cost effective design that is also operationally responsive. The following are some recommendations for modifications to the experiment subsystem design:

- There is still some uncertainty of the actual pressurant use during experimentation that may be dictated by variables that cannot be controlled. Performing an LH2 recharge on-orbit would accommodate these uncertainties, provided that additional fluid was allocated in the supply tank. The number of bottles could be reduced eliminating S/C weight and complexity, as well as eliminating a GH2 loading system on the ground. Ground loading of the pressurant bottles with LH2 could be accomplished while the supply tank is being serviced.

- The receiver tanks' thermal management subsystems can be optimized without the addition of a VCS to substantially reduce heat flux so that a hydrogen use benefit can be realized. This saved hydrogen could then be allocated towards performing additional tests in numerous experiment categories.

- With range safety concurrence, a plausible LH2 ground loading scenario can be developed that would result in the elimination of the supply tank vacuum jacket which would reduce weight and complexity of the design. A foam/MLI system would replace the jacket for ground servicing of the tank using the GN2 purge of the payload fairing for additional thermal capability and to mitigate condensation accumulation. The size of the tank will have to be assessed to meet both experiment set goals and new overall satellite weight goals.

- Receiver tank 1 currently has an external wall mounted TVS heat exchanger that precludes the need to penetrate the tank wall multiple times. However, using an external wall mounted heat exchanger presents concern with whether or not it is important to provide adequate cooling to the LAD fluid. Additional assessment of LAD fluid cooling needs is required to resolve this issue.

- Desired mass-to-volume ratios require additional evaluation to achieve proper receiver tank design. The tank sizes are too small to achieve large differences without artificially adding unnecessary weight (from a structural stand point) to one of the tanks (most probably receiver tank 1). Tank sizes may also be reduced to meet new overall satellite weight goals.

- Finally, there is an issue of how to size and control the flow legs for the TVS HX in each of the experiment tanks. A higher-than-nominal TVS flow could overcontrol pressure in the tank, resulting in more of a pressure drop than desired if there is no absolute basis from which to turn the flow legs on and off. On the other hand, too little flow could allow for unwanted pressure increase. In any event, higher than nominal flow legs will have to be operated intermittently to maintain and reduce steady state pressure levels, as desired, in the tanks. Detailed analysis and ground testing of control algorithms will have to be performed to accurately characterize the existing TVS flow control designs for pressure control. VCS temperature may be another control mechanism which may add to the controllability of tank pressure.

5.1 Mission Requirements

COLD-SAT mission design requirements were derived primarily from the need to reduce the background acceleration during the experiments to less than 1 micro G. The capability to transmit experiment data and uplink command data was also considered. Launch on an ELV was baselined. A final orbital altitude of 926 km (500 nmi) was selected to provide a 500 year lifetime, in order to circumvent a detailed reentry study.

A 3 month mission is planned, based on projected consumption of the liquid hydrogen. At the end of the mission, propellants, pressurants, and remaining hydrogen will be purged from the tanks as a shut-down procedure is followed to safe the spacecraft.

5.1.1 Orbit - Launch to a circular orbit was baselined, with experiment thrust maneuvers performed to minimize the growth of eccentricity. Although circularity is not a strict requirement, it is desirable in order to maintain a more consistent experiment environment (background acceleration due to atmospheric drag varies with altitude). The drag acceleration at 926 km (500 nmi) is less than 0.001 micro G's. Refer to Figure 1.7-1 for the orbit in relation to TDRSS.

The attitude of the COLD-SAT spacecraft was selected to provide adequate solar array contact with the sun, and minimize perturbation of the experiment environment. A slow roll, pitch and yaw of the spacecraft is required as the orbit regresses and as the earth moves around the sun.

COLD-SAT mission design requirements went through several iterations to refine and improve the overall mission design. The initial orbital altitude was raised from 834 km (450 nmi) to 926 km (500 nmi) in order to provide additional margin for the final periapsis altitude. The increase to 926 km (500 nmi) results in an orbital period of 103.5 minutes. This change tends to improve the TDRSS communication availability and reduce disturbance torques, while increasing the final periapsis altitude. A second change was the reversal of the spacecraft long axis, so that the longitudinal axis aft end points toward the projection of the sun in the orbit plane.

5.1.2 Communications - The TDRSS satellite is baselined as the primary communication mode for downlinking experiment data and uplinking commands. The GSTDN network is included to provide health and status data only, as a backup to the TDRSS link. TDRSS contact is available for at least 10 minutes per orbit, and backup GSTDN contact for at least 9 orbits per day. Health and status data are transmitted through the GSTDN/DSN emergency backup link. The data is analyzed to determine whether to reinstate the operational on-board computer (OBC) or to transfer control to the redundant OBC. Finally, commands are uplinked through GSTDN/DSN to return to the nominal attitude control scheme.

The three GSTDN locations not targeted for shutdown, and the three DSN locations were analyzed for contact with COLD-SAT. Using a 5 degree minimum elevation requirement, contact with at least one station in 9 orbits per day was provided. Four of these orbits showed contact with 4 out of the 6 stations. The average contact time, 8 minutes per station, should be adequate for health and status information.

A reduction in staffing, in addition to a reduction in the number of GSTDN stations from 8 to 3 has been planned. This could mean delays of 2 to 3 hours between the time a link is requested and the time communication is actually established.

Data Storage and Transmittal Strategy

(1) Two on-board solid state recorders together provide a minimum of one day of storage capability (1.29 x 10 exp(+8) bits). The entire orbit data will be recorded at 2 kbps (103.5 minute orbit). Loss of one recorder will mean that one recorder records and plays back. There is no effect on the mission.

(2) The downlink rate has been set at 16 kbps (nominal) and 32 kbps (maximum). Typically, a ten minute per orbit contact period with TDRSS will be adequate to recover the experiment and housekeeping data and to transmit changes to the onboard sequences. However, to recover from gaps due to TDRSS scheduling conflicts or to provide continuous downlinking during critical experiment activity, additional time may be requested from the TDRSS scheduling office at GSFC.

5.2 Launch Vehicle Capabilities

No surfaces of the spacecraft may protrude through the dynamic envelope. High frequency basic structure may come close to the dynamic envelope, but low frequency structure such as solar panels and antennas must be adequately contained. Any infringements of the above practices may be negotiated with MDAC.

The Delta II - two stage launch vehicle can circularize a 4082 kg (9000 pound) payload at 926 km (500 nmi) (per the Commercial Spacecraft User's Manual). A Delta II expendable launch vehicle was selected based on a trade study of Titan, Atlas, and Delta ELV's. The Delta II is a two-stage launch vehicle with solids for additional thrust.

A Kepner-Tregoe (K-T) analysis was used to select the launch vehicle. With the K-T analysis, the candidates must first pass a go/no-go criteria. NASA LeRC identified the candidates, so this was considered the go/no-go criteria. The alternatives evaluated were based on a weighted criteria affecting system cost and the maximum technology return. Spacecraft volume was treated as the criteria to determine technology return which would be based on the maximum amount of liquid hydrogen that could be carried. The experiment K-T analysis ranked various methods of utilizing the available volume for the class I experiments. Basic features required to perform the experiments were enhanced with extra features to increase the fidelity of the experiments. The Titan III and Atlas Centaur were considered to have twice as much payload volume available to increase the amount of liquid hydrogen. Payload volume was considered separately from experiment fidelity to consider the impact of the arrangement of the housekeeping functions. Satellite cost increases caused by a larger volume (excluding the cost of larger experiment tanks) is offset by the decrease in cost of allowing easier housekeeping function placements. Launch site modification was considered a driver because Atlas Centaur was the only vehicle which had cryogenic handling facilities and equipment on the launch site. The other launch sites required modification to provide cryogenic handling. Operations complexity was included with launch modifications and was rated according to the number of stages and additional motors and the necessity to introduce LH2 into the processing flow, which Atlas-Centaur already did. Payload weight was not a discriminator, because all of the launch vehicles could meet the minimum capability to the destination circular orbit. Axial acceleration limit load factors were relatively close for each of the vehicles, and no adverse affects could be identified. Increased tank sizes also increases the technology risk. However, no available tanks meet the minimum COLD-SAT requirements for LH2. The Centaur availability risk factor was speculated as low due to problems previously experienced at KSC. Partners available to coexist with a COLD-SAT would be required for launch on a Titan III, and none could be identified. The study results determined that designing to the minimum configuration, utilizing the largest Delta II shroud volume, would allow the satellite to fit on any of the launch vehicles. Both Atlas-Centaur and Delta II had almost equal scores based on the combination of the cost analysis and the experiment fidelity analysis, therefore the Delta II was selected as the baseline launch vehicle..

The Delta II launch vehicle consists of two liquid stages and attached solid boosters. The solid boosters are separated prior to first stage separation. On orbit, the shroud is ejected and the attitude control system activated prior to second stage separation. After separation from the Delta II, the TDRSS antenna and solar arrays are deployed. After the spacecraft check-out procedure is completed, experiment operations are initiated. Experiment data is recorded each 103.5 minute orbit. The recorder data is downlinked and commands uplinked (if required) during the 10 minute contact with TDRSS each orbit.

Solar array panels and TDRSS antenna deployment follow Delta II second stage separation. The solar array panels are folded and each attached to a boom which is folded. The boom is deployed and latched after the panels are released and unfolded. The panels are rotated to align with the sun. The TDRSS antenna is also attached to a boom which is released and deployed.

5.3 Mission Analysis

5.3.1 Orbit - The orientation selected for the COLD-SAT orbit and attitude results in a continual spacecraft roll, pitch, and yaw to maintain direction of the longitudinal axis at the projection of the sun in the orbit plane. The plane of the orbit is constantly changing because of the nodal regression that results from the earth's oblation. The rate of the regression is a function of the orbital altitude and the inclination. Based on a 926 km (500 nmi) circular orbit with an inclination of 28.8 deg, the longitude of ascending node regresses at 5.4 deg per day.

The effect of nodal regression on the spacecraft attitude is demonstrated below. Assuming an initial longitude of ascending node of 0 deg, the spacecraft is pitched at 28.8 deg and the roll is 0 deg. The longitude of ascending node regresses at 5.4 degrees per day. After 16.7 days the ascending node regresses to -90 deg, causing a pitch of 0 deg and roll of -28.8 deg. After an additional 16.7 days, the ascending node is -180 deg with a pitch of -28.8 deg and roll of 0 deg. The nodal period is 67 days. Figure 5.3.1-1 is a description of the variation in orbit.

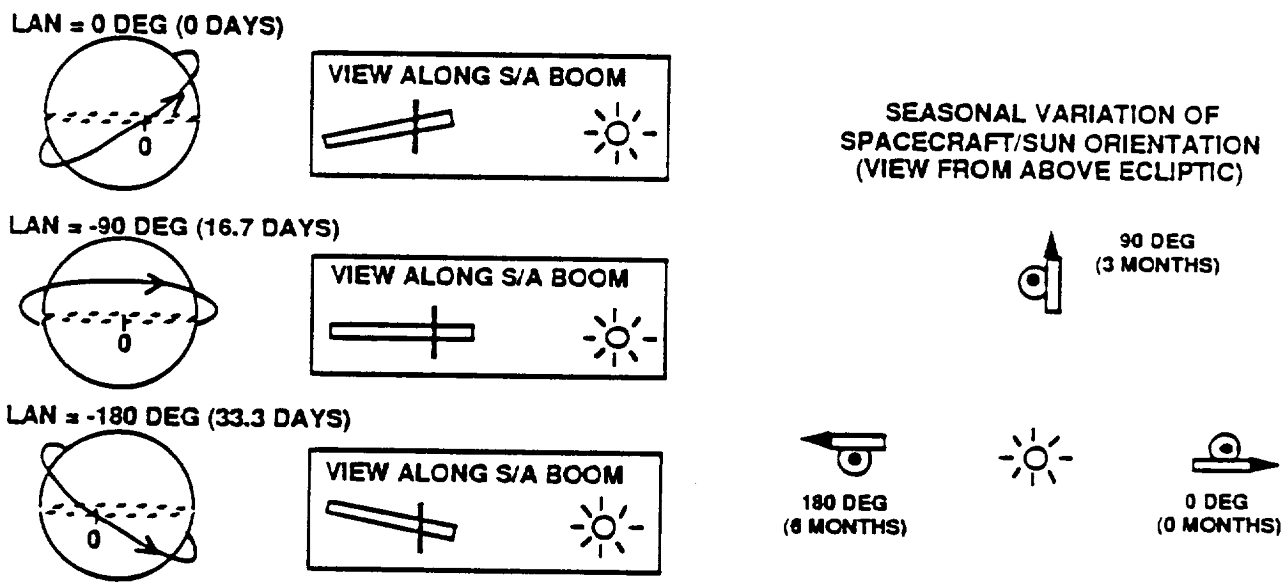


Figure 5.3.1-1 Orbit Description

A second attitude effect is caused by the motion of the earth about the sun. The variation in spacecraft yaw is illustrated by viewing the spacecraft / earth / sun geometry from above the ecliptic plane. The yaw changes 180 deg in 6 months at an average rate of 1 deg per day.

The spacecraft roll, pitch, and yaw are continuously updated by the vehicle attitude control system. This maintains constant pointing of the spacecraft longitudinal axis toward the projection of the sun in the orbit plane.

For the 40 experiments that require thrusting to achieve desired bond numbers, three thrust levels were selected: 5.6 n (1.26 lb), 1.9 n (0.42 lb), and 0.4 n (0.09 lb). Over the 90 day mission, a delta v of nearly 213 m/s (700 ft/s) is applied to the COLD-SAT orbit. This results in a growth of eccentricity, causing a reduction in the final periapsis altitude. Using a simulation that integrates the COLD-SAT orbit, it was found that eccentricity can be reduced by applying thrust reversals. Thus, by reversing the long axis of the spacecraft for certain experiments, the eccentricity of the final orbit can be reduced, increasing the final orbital periapsis altitude.

Six of the experiments were selected as candidates for long-axis reversal, based on high thrust and 1 hour duration criteria. The application of these 6 reversals significantly reduced the final orbital eccentricity. The thermal impact of 1 hr reversals is expected to be minimal. Furthermore, because the solar arrays can be articulated ±170 deg, there should be no solar power degradation during these reversals.

Initial studies examining the effect of experiment thrusting on final orbit eccentricity revealed that despite the input of significant delta v (nearly 213 m/s (700 ft/s)), the semi-major axis of the final orbit was relatively unchanged. Parametric analyses were performed to characterize this result. A relationship was discovered between low level thrust directed in the orbit plane and the orbital semi-major axis.

Based on COLD-SAT orbital conditions and thrust levels, a periodic perturbation of semi-major axis of approximately 3.7 km (2 nmi) occurred (repeating every 103.5 min). This sinusoidal effect resulted without regard to the spacecraft true anomaly or the angle between the thrust vector and orbit periapsis. Furthermore, it was discovered that the phasing of the cyclical variation in semi-major axis was dependent only on the angle between the thrust vector (vehicle long axis) and the center of the earth at thrust initiation. An initiation angle of 0 deg (nadir-pointing at thrust initiation) resulted in a semi-major axis perturbation cycle beginning at the minimum semi-major axis. An initial angle of 180 deg (thruster initiation when vehicle is pointed directly away from the earth) caused the cycle to begin at the maximum semi-major axis.

In order to continually increase the semi-major axis over the COLD-SAT mission, a strategy was adopted to delay the start of each experiment until the vehicle is within 10 deg of nadir-pointing. This provides a 5 minute window (once an orbit) to begin thrusting and in the worst case extends the mission by 3 days. Because each experiment duration is different from the 103.5 min orbit period, the semi-major axis is larger after each experiment. Figure 5.3.1-2 demonstrates the effect of reversing the spacecraft for six experiments and constraining the burn initiation times.

Experiment thrusting without timing constraints causes a slow increase in the eccentricity, while the semi-major axis remains at about 926 km (500 nmi). Reversing the spacecraft long-axis causes the eccentricity to decrease, while the semi-major axis remains at about 926 km (500 nmi). If experiment timing is optimized, the semi-major axis steadily increases, while the eccentricity is relatively unaffected. Using both techniques the eccentricity is reduced while the semi-major axis is increased.

• EXAMPLES BASED ON MARCH 21 LAUNCH AND ASCENDING NODE = 0 DEG

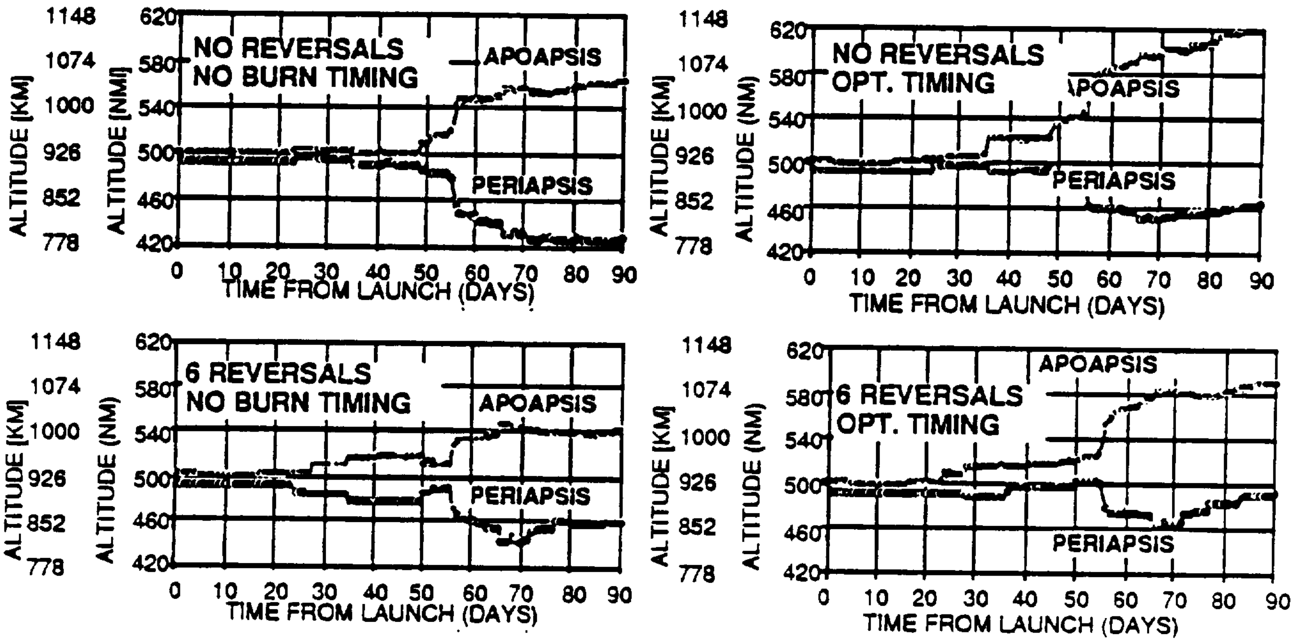


Figure 5.3.1-2 Altitude Time History

5.3.2 Lifetime - Lifetime prediction is highly dependent on the atmospheric model used. A heavier spacecraft leads to a higher ballistic coefficient, which leads to a lower altitude with an equivalent lifetime. The following results are based on circular orbits, decaying in a nominal COSPAR International Reference Atmosphere (CIRA 72 - 1972). An initial altitude of 765 km (413 nmi) corresponds to a 500 year lifetime assuming a 3175 kg (7000 lb) final mass (consumables depleted), CD=2, and a reference area of 11.15 sq meters (132 square feet). Some sources indicate atmospheric density increases of 1 to 2 orders of magnitude over nominal values can be seen during high solar activity periods. The effects of dispersions in atmospheric density and elliptical initial orbits on lifetime predictions should be investigated.

5.3.3 Sun Pointing - The time history of the solar beta angle (the angle between the orbit plane and the sun) is a result of the baseline orbit and the spacecraft attitude scheme that points the back of spacecraft long axis at the projection of the sun in the orbit plane. Figure 5.3.3-1 depicts the time history of the solar beta angle over the mission starting at a beta angle of zero degrees. The beta angle can be used to represent the solar array articulation angle for movable arrays, or the angle between the long axis of the spacecraft and the sun for fixed arrays.

The pitch attitude variation (a sinusoidal oscillation between ±28.8 deg every 56 days), is superimposed on the annual apparent sun elevation motion between ±23.5 deg. The resulting beta angle varies between ±52.5 deg. The orientation of beta angle peaks and valleys can be adjusted by modifying the launch time of day (affects the longitude of ascending node of the orbit) or the launch time of year (affects the initial apparent sun angle relative to the equator).

For a 90 day mission duration, the beta angle can be reasonably bounded by ±40 deg. This will impact the fixed solar array scenario. The beta angle range for the 6 day quiet experiment is of interest for the movable array option, because it will be fixed during this 6 day period. In the worst case the beta angle will vary 22 deg. For the best case, the beta angle will only change 2 deg. Figure 5.3.3-1 contains the solar beta angle time history based on a longitude of ascending node of 0 degrees.

A movable solar array option has been baselined for the COLD-SAT mission. However, the arrays will be fixed during quiet experiments, the longest lasting approximately 6 days. The power degradation that results from the combination of the change in beta angle during the 6 day period and the basic pointing requirements is bounded by anticipating the beta angle change. The arrays can be biased to yield a drift offset equal to half the beta angle change. Pointing requirements of 2 deg in spacecraft pitch and 2 deg in solar array articulation, yield a total pointing tolerance of 4 deg. This results in a total worst case offset of 15 deg and best case offset of 5 deg, corresponding to power degradations of 3.4 percent and 0.4 percent, respectively. The average drift offset of 10 deg yields an expected power degradation of 1.5 percent for the 6 day quiet experiment.

Solar array shadowing as a function of the boom length shows minimal shadowing [0.06 sq m. (0.7 sq ft.) or less than 1 percent] for the 2.8 deg pointing requirement, even with a very short boom length. If desired, shadowing can be eliminated completely by incorporating a 0.305 to 0.61 m (1 to 2 ft) solar array boom extension or separation distance between the spacecraft body and the solar array.

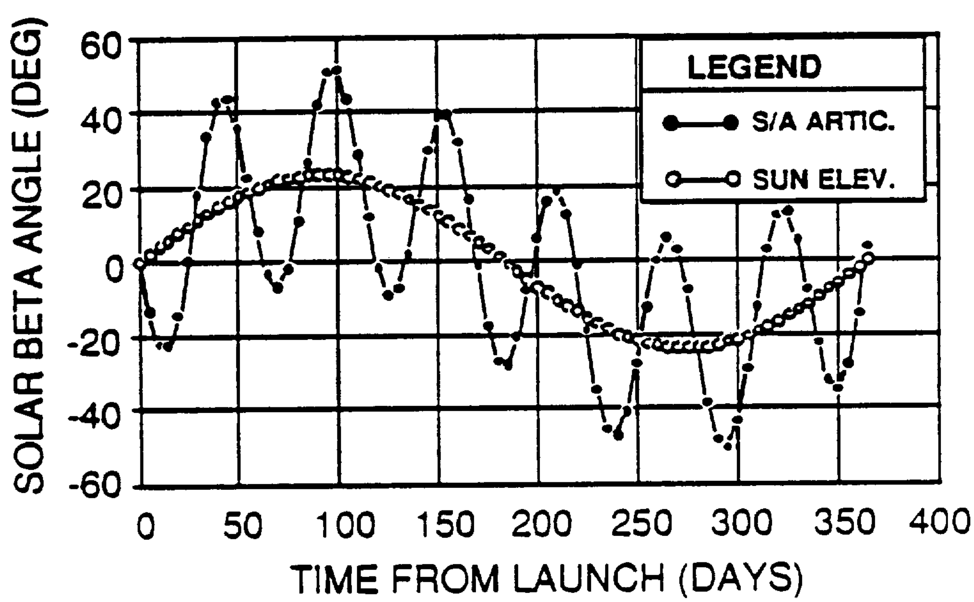


Figure 5.3.3-1 Solar Beta Angle Time history

5.3.4 Propellant Requirements - Station-keeping thrust requirements are expected to be driven by the end-of-mission periapsis altitude and the projected lifetime corresponding to this altitude. Current lifetime predictions show an ample altitude margin, requiring no propellant to raise the final periapsis altitude. However, lifetime analyses are highly sensitive to the atmospheric model. Until a more sophisticated lifetime program can be used to examine the COLD-SAT mission, a propellant allocation of 22.7 kg (50 lb) will be used for station keeping.

Attitude control thrust requirements are based on countering thrust misalignment and cg-offset errors that induce torques during thrusting experiments. Based on a simplified, two-dimensional analysis, a propellant allocation of 34 kg (75 lb) has been established, with an expected usage of approximately 22.7 kg (50 lb). This two-dimensional approach to a three-dimensional problem provides a rough approximation to propellant consumption. A high-fidelity attitude control simulation should be applied to validate these results.

Experiment thrusting has been allocated 374.1 kg (825 lb) of propellant, providing a margin of 24 kg (53 lb) over expected usage. Overall, a propellant margin of 58 kg (128 lb) or 13 percent exists for the current COLD-SAT mission.

5.3.5 Attitude Control - The control system concept is a traditional design consisting of an onboard computer and software, sensors and actuators, and interface electronics. The spacecraft attitude is determined using a sun sensor, earth sensor, and the spacecraft ephemeris which is periodically obtained from GSFC and propagated between uplinks.

Sun sensors are body-mounted with sufficient field-of-view to handle beta angles between ±52.5 deg. Horizon sensors are directed along the spacecraft ± Y-axes to ensure horizon contact twice each orbit. Inputs from the coarse sun sensor and the three axis magnetometer provide an orthogonal current coordinate system. OBC models of the desired sun position and magnetic field provide a targeted coordinate system. The attitude error between current and targeted conditions are processed through the reaction control system logic to command the thrusters. Vehicle attitude is changed and a new current attitude is established.

Peak attitude rate requirements were derived from the orbital simulation that tracks vehicle attitude as a function of sun position, orbit plane, and spacecraft position within the orbit plane. Regression of the orbital longitude of ascending node and motion of the earth about the sun, cause peak rates of 4 deg per day for roll and pitch, and 6 deg per day for yaw. Rotational acceleration about the spacecraft z-axis induces transverse acceleration in the supply tank and receiver tanks. It is desirable to maintain these induced acceleration levels less than 10(E-6) g's. Finally, attitude deadbands of 2 deg during experiments and 1 deg between experiments (to minimize gravity gradient torques) have been baselined. A limitation of 25 % ratio of transverse to axial acceleration has been established. The expected thrust vector misalignment should be between 0.1 degrees and 0.5 degrees.

The COLD-SAT spacecraft will be subjected to numerous internal and external disturbance torques. The internal torques are discussed in section 6 (dynamics). The external torques are considered as they affect the spacecraft design and mission design.

The largest external torques are due to gravity gradient and aerodynamic drag. By designing the attitude of the vehicle with the long axis of the vehicle in the orbit plane these effects are both cyclical. The total torque integrated over a complete orbit is zero, with peak torque within the capability of the reaction control wheels. Although solar pressure torque is significantly less than gravity gradient and drag torques, it builds over time necessitating continuous use of the mag torquers to keep reaction control wheels from becoming saturated.

The attitude control capabilities include reaction wheel momentum of 20 N-m-sec (15 ft-lb-sec), torque of 0.15 N-m (0.11 ft-lb), and average magnetic torque of 0.004 N-m (0.003 ft-lb), and the use of thruster off-pulsing and on-pulsing.

The small disturbance torques between experiments should be within reaction wheel and magnetic torquer capability. However, torques caused by cg-offset and thrust vector misalignment, during experiments, require thrust on-pulsing or off-pulsing.
Based on Magellan experience, the cg is expected to be balanced to within 0.127 cm (0.05 inch) with a ballast mass of less than 45.4 kg (100 lb). Thrust vector misalignment is expected to be between 0.1 deg and 0.5 deg. Finally, the interaction between the individual ACS elements is a complex process. To fully understand this interaction, the use of a high-fidelity simulation is required.

The COLD-SAT orbit and attitude scheme dictate a slow roll, pitch and yaw in order to maintain the long-axis of the spacecraft pointed at the projection of the sun in the orbit plane. As the ascending node regresses, the roll and pitch attitudes oscillate between ±28.8 deg. The peak roll and pitch rates (4 deg per day) occur as the vehicle attitudes pass through 0 deg. The yaw attitude averages 1 deg per day driven by the earth's motion around the sun. However, peak yaw rates can reach 6 deg per day due to periodic nodal regression effects. The reaction wheel and magnetic torquer elements should provide sufficient capability to handle these peak attitude rates.

For the purpose of attitude control analysis, the cg-offset and the thrust vector misalignment angle can be combined into an effective cg-offset. Thrust vector misalignment and cg-offset create a torque imbalance that imparts an angular acceleration about the spacecraft z-axis.

The angular acceleration as a function of effective cg-offset for the 3 experiment thrust levels was determined. Assuming a 1.7 m (5.5 ft) moment arm from the cg to the bottom of the supply tank, the maximum allowable angular acceleration (corresponding to an induced transverse acceleration in the supply tank of 10E-6 g's) is 3.35 x 10E-4 deg/sec^2. To meet this requirement, an effective cg-offset of 0.8 cm (0.3 in) would be required. This would constrain the thrust vector misalignment to 0.15 deg. Figure 5.3.5-1 depicts the CG offset for various thruster accelerations required for the experiments.

A highly simplified, two-dimensional analysis of a complex, three-dimensional ACS process assumed a 1.25 cm (0.5 inch) effective cg-offset, resulting in a planar rotation about the spacecraft z-axis. The torque imbalance was allowed to continue until a deadband of ±2 deg was reached. At this point, thrust pulsing was initiated to counter the torque, arrest the angular velocity, and return the spacecraft to the 2 deg deadband limit. The thruster pulsing was discontinued, followed by the torque imbalance due to the effective cg-offset, etc. Derivation of the equations describing this model showed that the ratio of the time outside the deadband to the time inside the deadband is simply the ratio of the torque inside the deadband to the torque during thruster pulsing. Therefore, a larger torque ratio (torque applied during pulsing over cg-offset torque) results in a shorter thruster pulsing time ratio.

The axial acceleration regimes of 4.7x10E-5 and 1.0x10E-5 axial g's required on-pulsing for only 1 second out of every 10 seconds, because the same number of thrusters could be used during on-pulsing as were used to generate the axial acceleration. However, the 1.4x10E-4 axial g's regime has only one-third of the thrusters used to generate the axial acceleration. As a consequence, the thrusters must pulse three times more frequently than for the other two axial acceleration regimes.

It should be noted that in each of these cases the transverse acceleration levels induced in the supply tank during thruster pulsing exceeds the desired limit of 10E-6 g's by about one order of magnitude. It should also be noted that these results may be tempered by the use of reaction wheels to dampen both the torques within the deadband limits and outside the deadband limits. To fully characterize ACS performance, the use of a high-fidelity simulation is required.

In addition to affecting rotational acceleration levels, thruster on-pulsing and off-pulsing impact ACS propellant consumption. Thruster off-pulsing results in lower than expected experiment propellant consumption, while on-pulsing causes higher than expected propellant consumption. In order to assess this consumption sensitivity, the two-dimensional approach was employed. To be conservative only on-pulsing was considered (the 4.7x10E-5 and 1.0x10E-5 axial g's regimes).

Additional propellant consumption due to thruster on-pulsing as a function of effective cg-offset using a mid-range offset of 0.01 m (0.5 inches) results in ACS propellant consumption of 22.7 kg (50 lb). Figure 5.3.5-2 depicts the propellant required for control based on different CG offsets. See Figure 5.3.5-3 for the axial thrust required for each experiment thrust regime.

<u>Safing</u> - Contingency planning for the loss of a gyro has been established with the attitude control subsystem automatically switching to a Sun Aspect Mode (SAM). In this mode, the inertial reference unit is not used for attitude control. Instead, the OBC autonomously rotates the spacecraft to locate the sun and point the solar arrays toward the sun.

The Safe Hold Mode is a backup system that is used in the event of a failure in the OBC. The Safe Hold Mode can be initiated by a ground command or by the on-board electronics when an OBC failure is sensed. The attitude control electronics (ACE) will sense the need to switch to its analog mode to control the spacecraft. The spacecraft is driven to an orientation such that the solar panels are facing the sun and the third axis is held inertially stabilized by using gyro position / rate preference and the thrusters.

The automatic transfer to the Safe Hold Mode is accomplished in the ACE by the Computer Status Monitor (CSM) electronics when it detects an anomalous pulse train from the OBC or receives a "safe hold on" command from either of the two ACE Remote Interface Units (RIU). Upon entering the Safe Hold Mode the Safe Hold Electronics (SHE) will: (a) be powered - up; (b) switch its three axis control loop outputs to the reaction wheels; (c) switch the Inertial Reference Unit (IRU) analog rate inputs to the SHE control loops; (d) switch the rate and position signals to the Propulsion Module Electronics (PME); (e) send a "safe hold enable" logic signal to the PME; (f) switch the outputs of the Coarse Sun Sensors (CSS) to the SHE control loops; (g) use the CSS position inputs and the IRU rate and position inputs to orient the spacecraft such that the normal to the solar array is aligned with the sun line; (h) convert the reaction wheel tach pulses to analog signals proportional to the wheel momentum; and (i) switch the magnetic torque drive commands to the ACE Magnetic Torquer Drive Electronics.

5.3.6 Mission Options - Propellant to raise final periapsis altitude shows that optimized burn timing saves between 18.1 to 20.4 kg (40 to 45 lb). The reversal strategy saves 13.6 to 15.9 kg (30 to 35 lbs). The most severe power loss for the articulated solar array is about 2 percent (assuming that the 6 day quiet experiment can be pre-planned to achieve the average power degradation). Conversely, the fixed array option results in a power loss of 7 percent (assuming the 90 day mission can be pre-planned to limit the beta angle variation to ±40 deg). Additionally, if the reversal strategy is employed by the fixed array option, a propellant mass savings of 13.6 to 15.9 kg (30 to 35 lbs) can be realized, but at a power system cost requiring a doubled battery capacity or a doubled battery depth of discharge.

Currently, the articulated array concept is baselined for system flexibility. However, the benefits of simplicity of the fixed array option (along with the slight power costs) are recognized.

An alternate fixed array option was explored (different from the 20 deg canted array option, where the spacecraft is rolled 180 deg to handle beta angles less than 0 deg). In this option, the long axis of the spacecraft is still in the orbit plane, but is rotated 90 deg from the current configuration so that the long axis is parallel to the projection of the sun in the orbit plane. The solar arrays are coincident with the orbit plane (initially). The spacecraft is then rolled about the long axis until the fixed arrays are normal to the sun. This option has several drawbacks. The primary concern is that the solar array boom axis is no longer constrained to the orbit plane, introducing gravity gradient torques that accumulate over time. It is expected that these torques would be within the capability of the magnetic torquers, although a detailed magnetic field model is required for verification. This option also introduces a mechanism to rotate and lock the solar arrays during deployment. Finally, the communication link analysis is slightly perturbed by this spacecraft orientation.

5.4 Mission Design Conclusions

The major COLD-SAT mission requirements are satisfied by the current configuration. Solar power degradation is minimal. TDRSS communication is more than adequate. Disturbance torques are within reaction wheel and magnetic torquer capabilities. Additionally, several simple strategies have been developed to maximize the final periapsis altitude (longitudinal-axis reversals and optimized burn timing).

EFFECTIVE CG OFFSET		
CG OFF. CM(INCH)	THRUST (DEG)	EFF. OFF. CM(INCH)
0.12(0.05)	0.1	0.56(0.22)
0.12(0.05)	0.2	0.99(0.39)
0.12(0.05)	0.3	1.40(0.55)
0.12(0.05)	0.4	1.83(0.72)
0.12(0.05)	0.5	2.26(0.89)

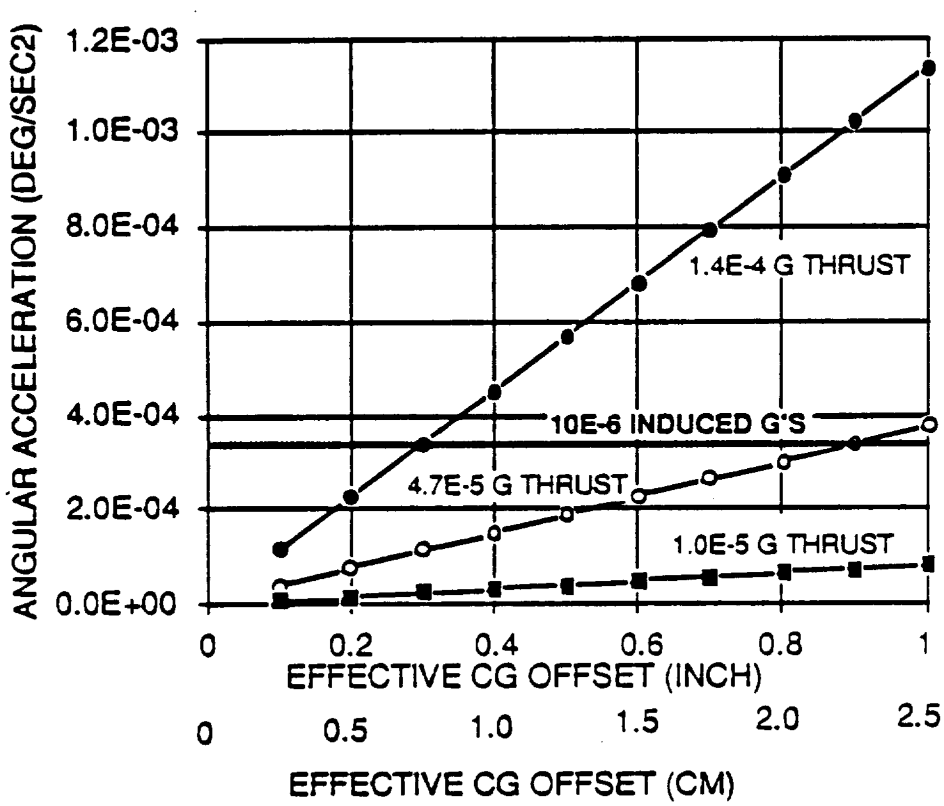


Figure 5.3.5-1. CG Offset vs Experiment Acceleration Requirements

Several areas should be targeted for further analysis. Lifetime prediction requires a highly sophisticated atmosphere model and should account for eccentricity effects. The lifetime program from NASA/MSFC should provide the required capability. Also, the current attitude control system should be analyzed with a high-fidelity simulation.

The simulation should validate the current configuration, define induced lateral acceleration levels, examine reaction wheel desaturation requirements, and provide ACS propellant consumption requirements.

The need for the 926 km (500 nmi) orbit should be examined based on the lifetime model used. The 500 year lifetime requirement was selected to avoid a lengthy analysis of the dispersion of a deorbiting spacecraft. A trade study to determine the cost of the high altitude versus the cost of the dispersion analysis should be conducted.

The articulated solar array cost versus the power available from a possibly larger fixed solar array is another trade study that was conducted. The mechanism requirements and the software costs for determining the movement of the articulated array are offset by the volume restrictions of a fixed array and the flexibility gained by the articulated array. However, the ability to eliminate external forces on the liquid hydrogen caused by the motion of the solar array is significant, but is only required during the experiment periods of no thrust (stratification) which is only done during 5 to 10% of the mission and can be accommodated by fixing the array for those time periods without significant power loss.

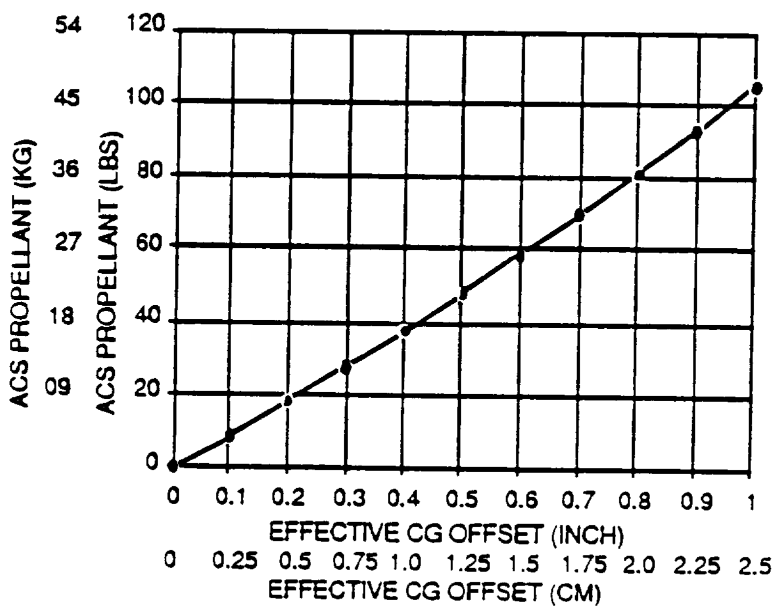


Figure 5.3.5-2. CG Offset vs Propellant Required for Control

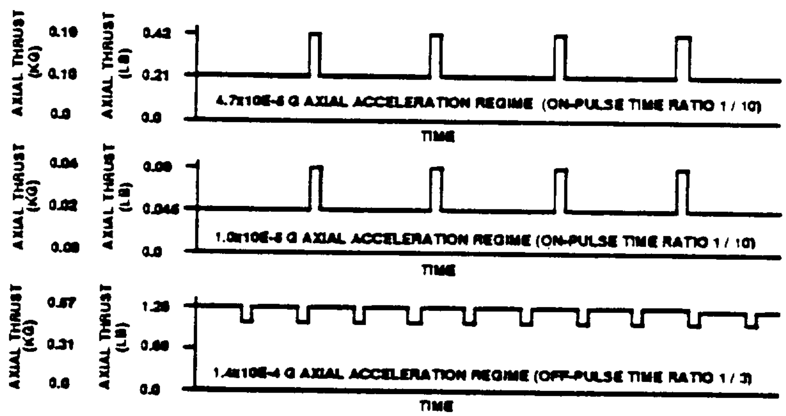


Figure 5.3.5-3. Axial Thrust Required for Experiment Acceleration Regimes

Characteristics

The satellite has characteristics similar to many inertial spacecraft designs. The driver on the design of COLD-SAT is the payload envelope permitted by the 3.05 meter (ten foot) diameter fairing and the sizing of the experiment tanks in that volume. The spacecraft design concept utilizes the entire payload fairing of the launch vehicle. The experiment tank configuration is surrounded by other subsystems' hardware. Heavier items are located at the aft end of the spacecraft to move the center of gravity further aft.

The restricted volume caused some difficulty in the design integration of the hardware and will require careful planning in the assembly of the experiment sub system at the satellite level of integration. The 3.05 meter (10 feet) fairing allows for the use of any of the ELV candidates.

The spacecraft subsystems are comprised of hardware that has existing, qualified designs. The conceptual design of the satellite has been evaluated for reliability and risk. The high reliability and low risk estimate is based on the use of spacecraft avionics presently in production, and requires minimum modifications for its electronic functions. The intent is to use the spacecraft avionics hardware with minimum modifications to their electronic functions or interfaces. Some modification to the electronics interfacing with the experiment are necessary to allow for the range of measurements and their required accuracies. The off-the-shelf hardware was selected to coexist with minimum new interface hardware and software.

The satellite fits within the shroud payload envelope of 2.54 meters (8 ft 4 in) in diameter by 5.89 meters (19 ft 4 in) in height. The satellite, with consummables, weighs 3222 kg (7105 lbs) without margin. With a 20% margin imposed, the total launch weight is 3866 kg (8526 lbs). The consummables consist of 286 kg (630 lbs) of liquid hydrogen, 433 kg (956 lbs) of hydrazine propellant, 6.8 kg (15 lbs) of GHE pressurant (for experiment and propulsion), and 8.2 kg (18 lbs) of GH2 pressurant for the experiment. The consummables are sized to provide sufficient margin to allow for minor contingencies in the mission timeline. The satellite requires an average orbital power of 1167 watts provided by a solar array and batteries. The solar array was sized for 2400 watts end-of-life. The batteries operate during peak periods and occultations.

The components from the Martin Marietta version of the Multimission Modular Spacecraft (MMS) are utilized in this concept. The capability to accept multiple Remote Interface Units and Extender Units allows for the number of measurements required by the COLD-SAT experiment. The avionics equipment has distinct heritage, and thus can be sized directly for this spacecraft. The one megabit bus provides sufficient capability to handle all of the bus traffic required by COLD-SAT. The satellite on-orbit configuration equipment bays and the propellant tank locations require that the tanks are covered with MLI. The on-board computer (OBC) has a dual function. It handles the experiment sequencing and control as well as processing the attitude control needs of the spacecraft.

The experiment subsystem will require design development for specific items of hardware defined in Section 4.8. All experiment requirements have been accommodated or revised per LeRC direction with the present design of the satellite.

6.1 Spacecraft Configuration Evolution Overview

The spacecraft has evolved over the two year study based on the driving requirement of the LH2 supply tank size. Center-of-gravity considerations also played a large part in determining the location of equipment. Every intent was made to locate electrical and mechanical hardware, involving a specific experiment tank, near that particular tank. The major change made during this study period was to include the MMS module structural containers as well as the individual electronics assemblies.

Originally it was thought that there was not enough room to include four complete modules in the given volume. The use of the GEOMOD program validated that there is sufficient room inside the shroud.

The other changes to the configuration included changing the number and size of propellant and pressurant tanks, again based on experiment requirements being reduced. Also, the Power Control and Distribution Module (PCDM) was added to house much of the electronics that was not already included in the other MMS modules. The pressure regulation scheme was changed from non-flight proven electronic regulation to a bang-bang system and then to conventional set regulation system for the high pressure required and a bang-bang system for the low pressure required. The number and the size of the thrusters changed from an original set of eight 4.45 N (1.0 lb) thrusters and twenty 0.44 N (0.1 lb) thrusters to a set of twenty 0.89 N (0.2 lb) thrusters.

The Concept Review baseline configuration was packaged within the Delta II 0.305 m (10 ft) payload fairing. It made use of the majority of the available payload dynamic envelope and allowed for the inclusion of the largest size tankage possible for both the supply and receiver tanks to provide the best compromise of available LH2 [approximately 363 kg (800 lbs)] and scaling relationships between the two receiver tanks. This concept utilized MMS hardware installed in equipment bays located throughout the satellite. Launch vehicle constraints dictated moving all of the heavy equipment as far back as possible and led to the creation of an open (MLI blanket enclosed) aft equipment bay where batteries, power boxes, propellant tanks, and valve panels were supported aft of the supply tank struts and lower ring frame which also provided for attachment/separation from the Delta II. Eight longerons provided the major structure for load carrying and support of equipment shelves and for the two receiver tanks. Equipment was installed on the top side and bottom side of the equipment shelves, as were the pressurant tanks and valve panels and associated plumbing. The interface with the Delta II was a direct mount to the top of Stage II. No payload adapter was required.

Modifications and refinements to the satellite design approach were made as a result of extending the level of design detail based on more detailed analyses of the satellite requirements to support the experiment and evolved a more cost effective and mission supporting design approach. The MMS module structures were added here and allowed for a greater off-the-shelf procurement. The experiment component panels were placed in optimum locations to be near associated tankage and plumbing interconnect/distribution systems. Propellant requirement increases changed the size of the propellant tanks and added more pressurant tanks. The solar array was resized and redesigned. A T-0 umbilical was added to support final countdown servicing.

The Preliminary Requirements Review Concept increased the supply tank capacity to 413 kg (911 lbs) of LH2. This concept utilized existing MMS module hardware installed in three existing module units. Other equipment was installed in an existing MMS likeness unit termed the PCDM. An aft equipment bay contained propellant tanks, experiment valve panels, the aft propulsion module, and various satellite interfacing electronics and avionics boxes, including the recorders which were supported on an equipment shelf above the propulsion module by the supply tank struts and lower ring frame which also provided for the attachment/separation from the Delta II. Eight longerons provided the major structure for load carrying and support of a rectangular support structure to which the MMS modules and the two receiver tanks were attached. Experiment pressurant tanks were mounted above the MMS modules. Experiment valve panels were installed as close to their respective tanks as possible, both beneath and on the sides of the MMS modules. Experiment tankage remained the same as the Concept Review concept. The interface with the Delta II remained unchanged.

The final configuration presented at the Experiment Review decreased the size of the supply and receiver tanks to provide additional volume for other equipment within the payload shroud. The TDRSS antenna boom was redesigned and relocated to provide a clear field of view. The pressurant and propellant tanks were reduced in size or number. The solar array configuration was revised from 3 hinged panels to 2 hinged panels on opposite sides of the satellite. The number of thrusters was reduced and they were all resized. The number of Remote Interface Units and Extender units was decreased after defining the measurement interface.

6.2 Structural Design

Figure 6.2-1 is a GEOMOD program-developed concept showing the satellite in the Delta II shroud. Figure 6.2-2 is the GEOMOD version of the satellite on orbit with the solar array and antenna deployed. Figure 6.2-3 is a cutaway version of the launch configuration with the experiment tanks removed to indicate structural attachment of avionics and other assemblies.

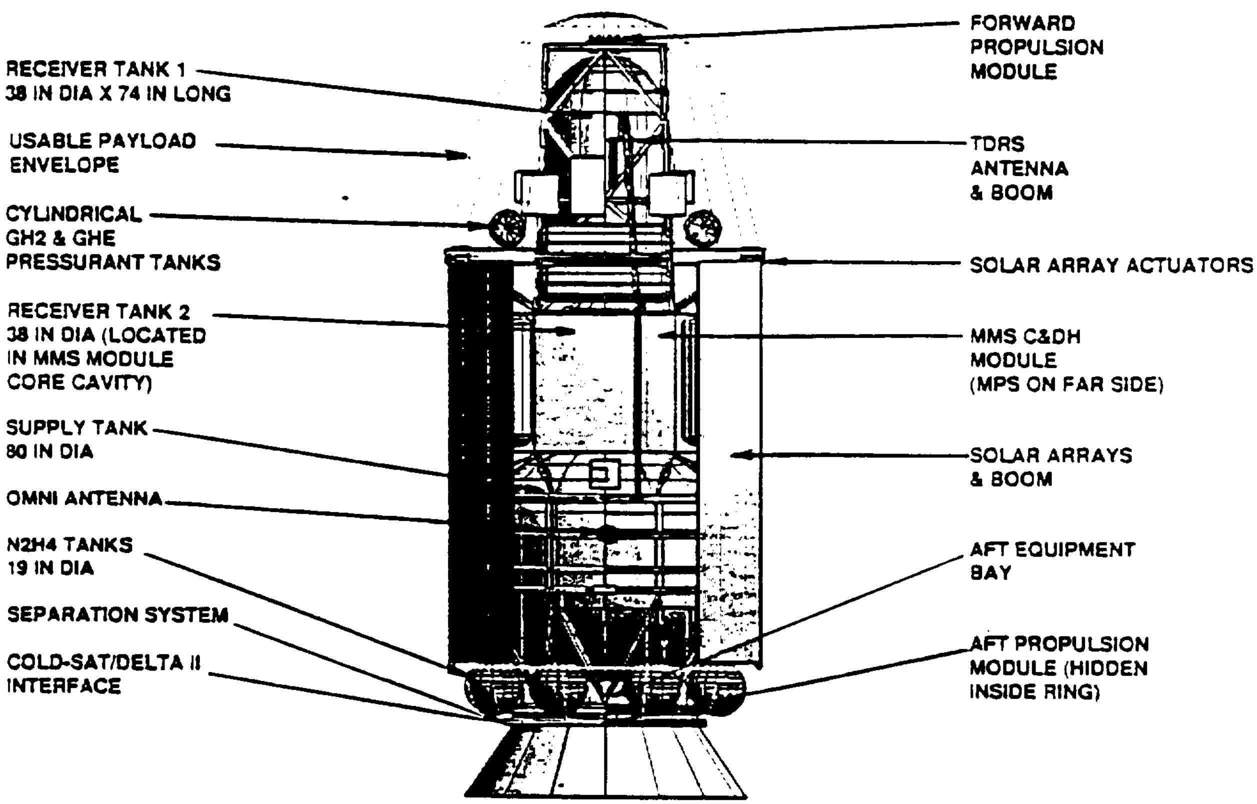


Figure 6.2-1 Satellite Configuration within the Delta II Payload Shroud

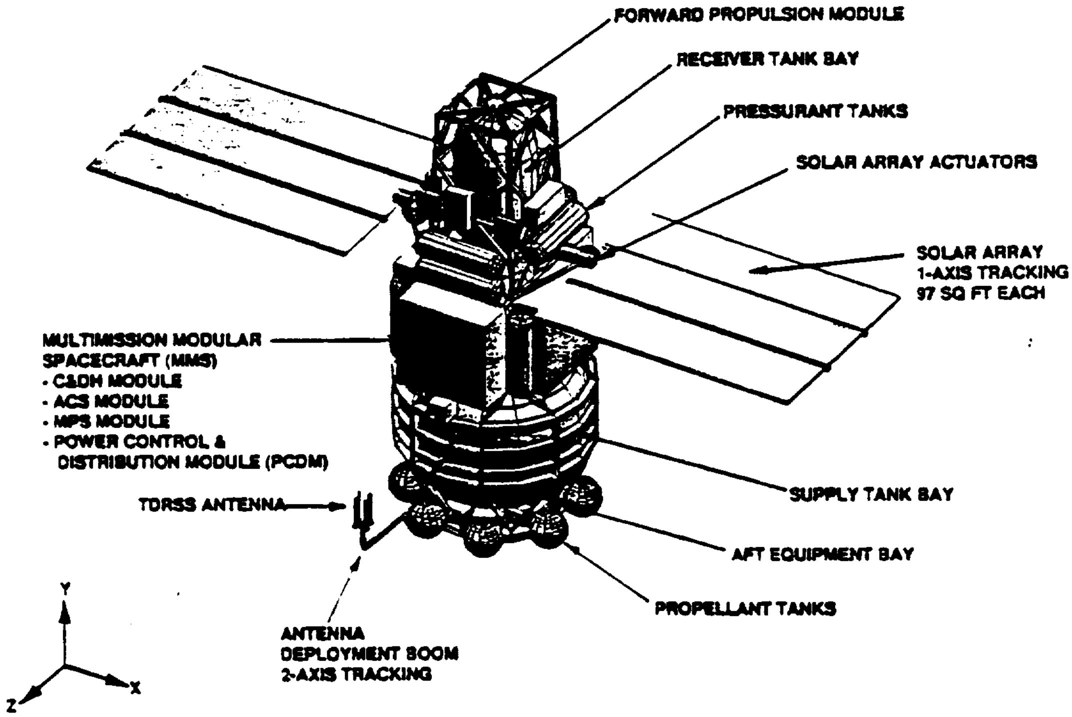


Figure 6.2-2 Spacecraft Orbital Configuration

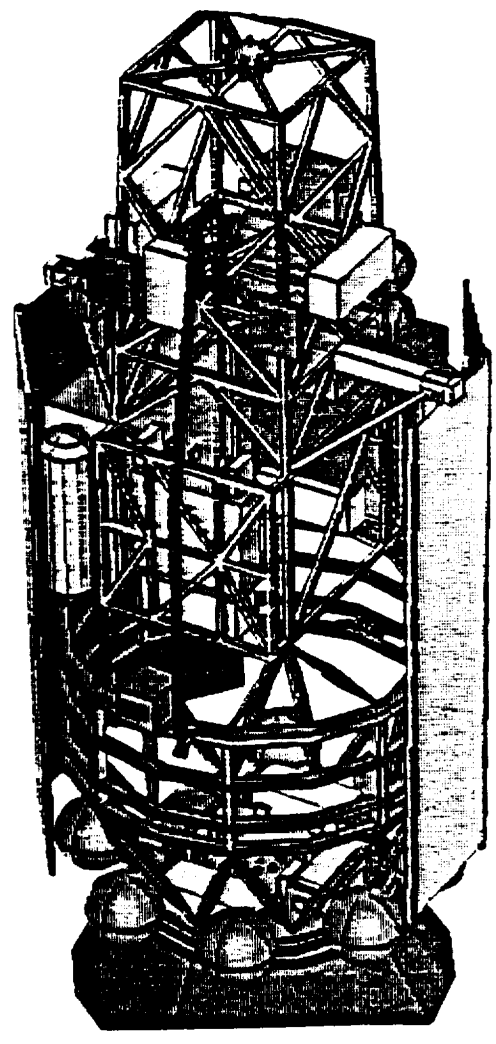


Figure 6.2-3 Cutaway View of the Satellite with Experiment Tanks Removed

6.2.1 Field of View Constraints - The field of view requirements of the sun sensors, the solar array, the earth sensors and the antennas have been observed in the design. The TDRSS antenna has been placed to avoid interference with the solar array view angle and to provide a clear field of view. The TDRSS antenna obstructions by the spacecraft body when viewing aft were eliminated by using a longer boom. To ease the design implications, a constraint has been levied to only rotate the antenna ±35° in elevation (sufficient to get at least 10 min/orbit of TDRSS time).

Solar array repositioning is required due to the changes in beta angle and the Earth's regression over time. Figure 6.2.1-1 depicts the field of view requirements.

6.2.2 MMS Module Structure - There is less risk using the MMS modules intact and not changing the mechanical interface to the boxes. However, the weight penalty for using the MMS module structure is severe ~ 18.1 kg (40 lbs) extra per subsystem. The MMS modules can fit in the envelope of the launch vehicle payload shroud in conjunction with the experiment tanks. MMS equipment mounted within their enclosures accommodates the launch c.g. requirements.

The MMS module structure provides the necessary interfaces to support and house electrical units and interface connectors. Thermal control is through the addition of a louver system and/or radiator plates depending on module-specific needs. Mounting to the spacecraft structure is via a 4-point attachment, upper and lower preload bolts, two-axis restraint socket and a three axis restraint socket. The interface connectors mate with structure for support. The connector mate on the structure is designed for easy connector mate or demate.

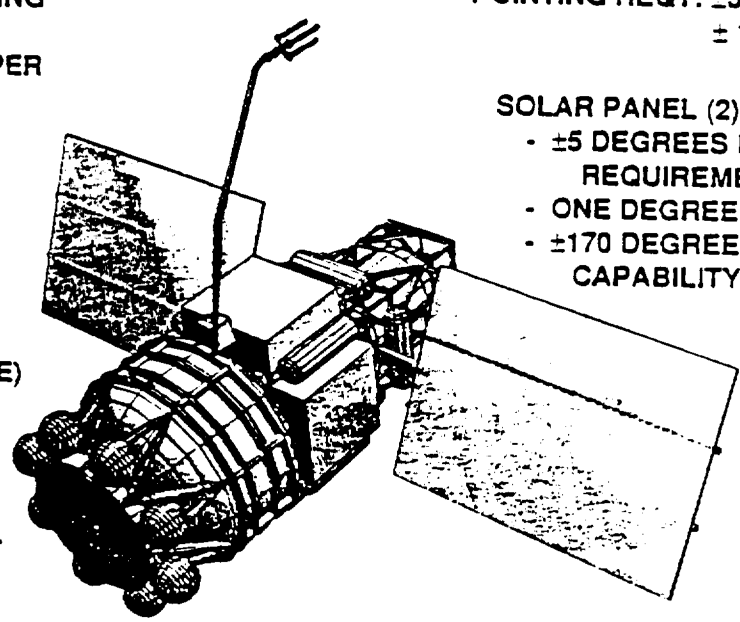


Figure 6.2.1-1 Field of View Constraints

The PCDM contains many of the assemblies required for power distribution. The PCDM is a special unit built to house equipment not included in the standard MMS complement. The dimensions of the module are the same as that of the other MMS modules. The module itself uses the basic structure of an MMS module {same size). The module uses more external connectors (8) than the basic MMS module (one or two external connectors). Mounting provisions for the module allow relatively easy removal of the module.

6.2.3 Launch Vehicle Interfaces - The launch vehicle interface consist of the Delta II Fairing, the Electrical Interface, the Umbilical, and the Separation System.

DELTA II Fairing - No surfaces of the spacecraft protrude through the dynamic envelope provided by the payload fairing. High frequency basic structure may come close to the dynamic envelope but low frequency structure such as solar panels and antennas must be adequately contained. Any infringements of the above practices may be negotiated with MDAC given the exact location.

Electrical Interface - The hardwire interface from COLD-SAT through the payload fairing boattail (bypassing the Delta II umbilical) to the blockhouse of Launch Complex 17 exists for measurements and commands. The need to activate the Attitude Control Subsystem, prior to launch vehicle separation, requires a timed signal from the launch vehicle or spacecraft.

Umbilical - Connections through the payload fairing are required for fill and drain, for purge and for vent of the liquid hydrogen and gaseous hydrogen on board the spacecraft. Two electrical umbilicals are required through the payload fairing boattail section.

Separation System - The spacecraft is attached to the launch vehicle during the launch sequence using a V-band clamp. The V-band clamp, when signaled to do so, will release by firing the pyrotechnic separation nuts. This releases the energy stored in the tension band of the clamp causing it to back away from the ring frames of the spacecraft and the launch vehicle. When the V-band clamp has released, the Delta Stage II will back away from the spacecraft accelerating to a velocity of 0.305 m/sec (1 ft/sec). The separation switch will indicate that separation has occurred. After the V-band clamp (supplied by MMAG) releases, it is captured by a restraint system which precludes the danger of it striking the spacecraft. After separation, the V-band clamp will stay with stage II, thereby not adding to the flyaway weight of the spacecraft. Figure 6.2.3-1 depicts the V-band clamp design.

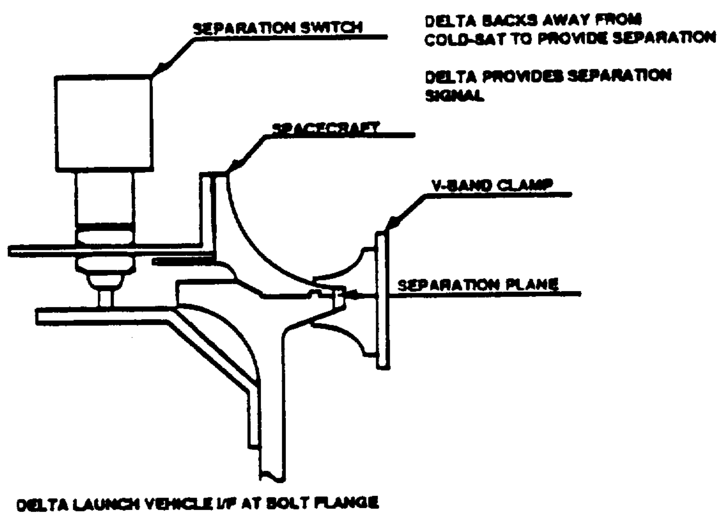


Figure 6.2.3-1 Launch Vehicle Separation System

6.2.4 Center of Gravity (C.G.) Envelope - The estimated range of spacecraft weights and C.G. locations at liftoff (stowed weight) shows that the COLD-SAT C.G. location is acceptable according to the Delta II criteria in MDAC memo A3-P923-PDES-88-93 (Ref. 6.2-1). Figure 6.2.4-1 depicts the satellite and the station locations determined from the existing station numbers assigned by the Delta II. A satellite weighing 3401 kg (7500 pounds) can have a CG below station 404. The present design of 3221 kg (7103 pounds) is well below that station at station 416.9. The satellite hardware is inside the payload fairing and is located according to the launch vehicle stations. While the volume available is restrictive, all hardware has been accommodated. The furthest aft and furthest forward c.g. locations are determined based on the consummables usage over time. The largest possible c.g. travel over the period of the COLD-SAT mission depends on the amount of consummables remaining and the tank location of the liquid hydrogen. The worst case c.g. occurs about day 75 of the mission when the LH2 remaining is located in the farthest receiver tank, with none in the supply tank.

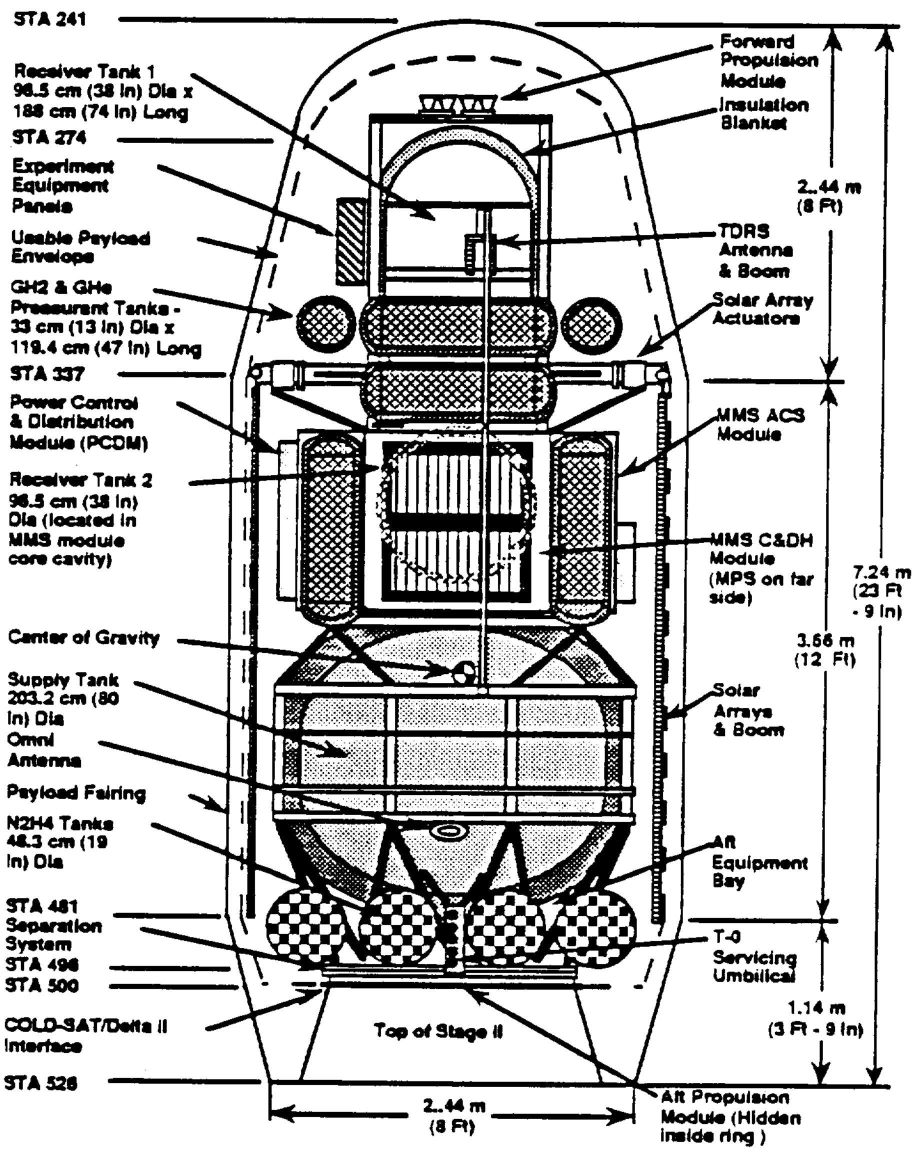


Figure 6.2.4-1 Dimensions of the Satellite within the Payload Shroud

6.2.5 Mass Properties - The summary of the satellite subsystems weights has added to these weights a 20% contingency on the total spacecraft. It is anticipated that the weight for off the shelf hardware is more than adequate without margin, since that hardware is existing and has measured weights. The estimate for the structure and the experiment subsystems are conservative, and 20% margin, in those subsystems, should also be adequate for development growth. The Delta II provides the additional weight margin since it can tolerate more than a 4082 kg (9000 pound) payload at our c.g. location. Table 6.2.5-1 contains the masses and locations of the satellite hardware and consummables.

The mass properties were calculated using a mass properties analysis program. Modification of location of hardware can easily be input to the program to determine the effect on the mass properties.

Table 6.2.5-1 Satellite Weight

GEOMOD ITEM	DESCRIPTION	STA	WT (KG)	(LBS)
	STRUCTURE SUBSYS			
8	LOWEST STRUTS(16)	474.2	53.70	(118.4)
17	MMS MODULE FRAME FACE	380.5	22.68	(50.0)
24	MMS MODULE FRAME Z	380.5	16.33	(36.0)
5	SUPPLY TANK RINGS	437.5	48.25	(106.4)
38	TOP TRUSS X	258.1	1.86	(4.1)
18	MIDDLE STRUTS(8)	412.2	16.33	(36.0)
6	SUPPLY TANK COLUMNS(8)	437.5	19.59	(43.2)
37	SOLAR PNL BOOM SUPT STRU	346.6	2.90	(6.4)
30	SOLAR BOOM	337.0	3.72	(8.2)
36	ANTENNA JOINTS	291.7	0.27	(0.6)
34	ANTENNA BOOM	351.5	2.90	(6.4)
23	FORWARD TRUSSWORK(4)	311.1	38.10	(84.0)
28	SOLAR PANEL HINGE(4)	400.0	13.24	(29.2)
35	ANTENNA BOOM BASE	421.3	0.18	(0.4)
50	MICROMETEOROID SHIELD	311.1	16.92	(37.3)
	STRUCTURAL TOTAL WT		256.98	(5[illegible])
	THERMAL SUBSYS			
	LOUVERS/COVERS	381.0		
	RADIATORS			
	MLI	417.0	17.00	(37.5)
43	HTRS, THERMOSTAT	417.0	2.72	(6.0)
	THERMAL TOTAL WT		19.72	(43.5)
	CONSUMMABLES			
56	HYDROGEN(LIQUID)	443.4	284.81	(628.0)
54	HYDRAZINE	460.0	433.56	(956.0)
58	HELIUM-EXPERIMENT	380.0	4.58	(10.1)
55	HELIUM-PROPULSION**	380.0	2.27	(5.0)
57	HYDROGEN(GAS)	NOTE 1	7.94	(17.5)
	CONSUMMABLES TOTAL WT		733.14	(1616.6)

NOTE 1:STA= (380,346.5,346.5,332.5,332.5,327.5,327.5)

GEOMOD ITEM	DESCRIPTION	STA	WT (KG)	(LBS)	DIMENSIONS(cm) (WxDxH)
	ACS SUBSYS				
40	SUN SENSOR-COARSE(2)	420.8	1.63	(3.6)	8.1x8.1x3.6
45	SUN SENSOR-FINE(2)	404.8	1.63	(3.6)	8.1x8.1x3.6
41	HORIZON SENSORS(2)	412.7	13.42	(29.6)	20.3x20.3x30.5
50	SOLAR AR DR MOTOR(2)	331.6	8.00	(17.6)	14.7x14.7x10.2
51	ANTENNA DRIVE MOTOR*	332.5	4.00	(8.8)	14.7x14.7x10.2
22	MMS ACS MODULE	381.0	167.10	(368.5)	121.9x45.7x121.9
	ACS TOTAL WEIGHT		195.78	431.7	
	POWER SUBSYS				
27	SOLAR ARRAYS	339.5	89.80	(198.0)	18.7 SQ M TOTAL
43	ORDNANCE DEVICES	417.0	0.59	(1.3)	17.8x41.5x9.9
15	BUS COUPLER UNIT(2)	492.0	1.14	(2.5)	10.2x10.2x5.1
20	MMS MPS MODULE	381.0	231.60	(510.7)	121.9x45.7x121.9
21	MMS PCD MODULE	381.0	238.60	(526.1)	121.9x45.7x121.9
59	SOLAR ARRAY GIMBALS(2)	337.0	2.72	(6.0)	
	PWR TOTAL WEIGHT		564.45	(1244.6)	
	T,T,&C SUBSYS				
15	BUS COUPLER UNIT(2)	492.0	1.13	(2.5)	10.2x10.2x5.1
9	SOLID STATE RECORDER(2)	492.0	24.94	(55.0)	20.1x27.9x17.3
33	ANTENNA(TDRSS)	380.6	3.32	(7.3)	27.9x27.9x40.6
52	ANTENNA OMNI(GND)(2)	434.2	0.87	(1.9)	0.01 SQ M
29	30 W PWR AMP(2)(TDRSS)	315.9	14.14	(31.2)	20.1x9.9x5.1
19	MMS C&DH MODULE	381.0	140.45	(309.7)	121.9x45.7x121.9
36	ANTENNA GIMBALS	392.9	2.72	(6.0)	
51	ANTENNA DEPLOY MECH	421.3	1.13	(2.5)	
	T,T,&C TOTAL WT		188.70	(416.1)	

*: INTERNALLY REDUNDANT
**: INCLUDES 0.63 KG (1.40) GHE RESIDUALS

Table 6.2.5-1 Satellite Weight Continued

GEOMOD ITEM	DESCRIPTION	STA	WT (KG)	(LBS)	DIMENSIONS(cm) (WxDxH)
	EXPERIMENT SUBSYS				
4	SUPPLY TANK	443.5	380.93	(882.0)	14 CUBIC METERS
28	RECEIVER #1	308.0	38.40	(84.7)	3.7 CUBIC METERS
16	RECEIVER #2	372.5	18.98	(41.8)	1.8 CUBIC METERS
25	PRESS BTLES(HELIUM)(2)	380.0	22.68	(50.0)	32 D x 118.1 L
31	PRESS BTLES(HYDROGEN)(7)	NOTE 9	79.38	(175.0)	32 D x 118.1 L
47	VALVE PANEL #3	312.9	11.02	(24.3)	30.8 H x 279.4 W x 12.7 D
44	VALVE PANEL #1	400.0	15.87	(35.0)	50.8 x 28.7 x 20.3
45	VALVE PANEL #2	400.0	19.73	(43.5)	50.8 x 30.5 x 20.3
46	VALVE PANEL #6	312.1	12.11	(26.7)	50.8 x 34.3 x 20.3
13	VALVE PANEL #7	380.4	29.21	(64.4)	67.9 x 58.4 x 17.8
46	VALVE PANEL #4	380.2	13.83	(30.5)	50.8 x 34.3 x 20.3
49	VALVE PANEL #5	377.2	37.46	(82.6)	67.3 x 74.3 x 20.3
53	SENSORS	NOTE 2	4.44	(9.8)	on valve panels
12	EXP VALVE ELECT. (4)	NOTE 1	103.40	(228.0)	28.9 x 64.5 x 20.3
10	REMOTE I/F UNIT(4)	NOTE 7	11.00	(24.3)	20.3 x 17.8 x 6.4
14	EXTENDER UNIT(4)	NOTE 6	5.62	(12.4)	20.3 x 20.3 x 3.6
11	FLOW METER ELECT(12)	NOTE 3	16.33	(36.0)	20.3 x 25.4 x 12.1
15	BUS COUPLER (2)	482.0	1.18	(2.6)	10.2 x 10.2 x 5.1
	TOTAL EXPERIMENT WT		831.53	(1833.5)	

NOTE 1: 4 @ 313.3,313.3,397.7,398.2
NOTE 2: DISTRIBUTED ON VALVE PANELS
NOTE 3: 10 @480 (3), 372.9, 316.0(2), 354.8, 358.9(3), 314.4(2)
NOTE: * INDICATES INTERNALLY REDUNDANT
NOTE 6: (4@400)
NOTE 7: (2@358.4)(2@400.7)
NOTE 9: (1@380,2@346.5,2@332.5,2@327.5)

LAUNCH VEHICLE CAPABILITY AT 926 KM IS APPROXIMATELY 4082 KG. BASED ON MDAC DELTA II USER MANUAL

GEOMOD ITEM	DESCRIPTION	STA	WT (KG)	(LBS)	DIMENSIONS(in) (WxDxH)
	PROPULSION SUBSYS				
7	PROPELLANT TANK(8)	488.0	73.47	(162.0)	1.32 m dia. each
25	PRESSURANT TANK(1)	380.0	11.33	(25.0)	32 D X 118.1 L
39	0.02 N (0.1-LB) THRUSTER (16)	494.9,294.4	9.52	(21.0)	16.8 x 3.6 dia
42	0.02 N (0.1 LB) THRUSTER (2 REM)(4)	453.6	3.18	(7.0)	14.7 x 3.6 dia
52	0.95 cm FD/PURGE/VENT VALVE (4)	494.0	2.00	(4.4)	
52	REGULATORS (2)	380.0	2.72	(6.0)	
52	QUAD CHECK VALVE	380.0	1.81	(4.0)	
52	LATCHING VALVE(2)	494.0	1.81	(4.0)	
52	PROPELLANT FILTER	494.0	0.46	(1.0)	
52	PRESS XDUCER(5)	494, 380	2.72	(6.0)	
52	PRESSURANT FILTER (2)	380.0	0.92	(2.0)	
52	PYRO VALVES(2)	494.0	1.36	(3.0)	
52	LINES, CABLING, MISC.	494, 380	5.00	(11.0)	
52	MIDDLE PEP	380.0	1.95	(4.3)	
52	UPPER PEP	285.0	1.95	(4.3)	
52	STRUCTURE TK SUPT & LOWER PEP	494.0	14.50	(32.0)	
12	VALVE DRIVE ELECT (PME) (2)	490.0	51.70	(114.0)	28.9 x 64.5 x 20.3
10	REMOTE I/F UNIT(2)	490.5	5.53	(12.2)	20.3 x 17.8 x 6.4
15	BUS COUPLER UNIT	482.0	0.57	(1.3)	10.1 x 10.1 x 5.1
	PROPULSION TOTAL WT		192.59	(424.5)	
	S/C DRY WT W/O EXP		1418.13	(3127.0)	
	EXPERIMENT WT		831.53	(1833.5)	
	CABLING(5% of MAX s/c wt)		170.07	(375.0)	
	S/C DRY WT		2419.73	(5335.5)	
	CONSUMABLES		733.14	(1616.6)	
	SATELLITE WT (DEPLOYED LOADED)		3152.87	(6952.1)	
	L-V ADAPTER		68.62	(151.3)	
3	V-BAND CLAMP	495.0	27.22	(60.0)	
3	RESTRAINTS	495.0	1.81	(4.0)	
2	MMC I/F	498.0	39.59	(87.3)	
	SATELLITE WT (STOWED LOADED)		3221.49	(7103.4)	
	SAT WT W/20% MARGIN		3865.79	8524.1	

6.2.6 Structure - The major structural elements of the COLD-SAT spacecraft include the following items as shown in Figure 6.2.6-1. The Delta II interface flange is an aluminum rolled ring (1). The spacecraft/Delta II separation system is a V-band clamp (2). The supply tank vacuum jacket and girth rings and ring frames are part of the support structure of the spacecraft (3). There are 16 Supply Tank support struts of aluminum with aluminum end fittings (4). The four MMS modules are supported on a frame face and frame Z structure (5). There are four GSE lifting/rotation trunnions at the top of the girth ring (6). Eight equi-spaced supply tank longerons are attached to the girth rings (7). The solar array boom is attached to the body with a support structure (8). The thrusters and supporting propulsion system hardware are supported on aft (9) and forward propulsion module panels and support structure (10). The forward propulsion module panel is made of honeycomb with aluminum face sheets (11).

The antenna deployment hinge is torsion spring loaded (12). The antenna boom is curved to fit in the shroud envelope at the desired length (13). An upper longeron / lower stringer large ring frame supports the MMS module supports and is attached to the girth ring (14). The upper structure around the upper receiver tank is a rectangular tube structure with shear panel skin (15). Eight support struts connect the large ring frame around the supply tank to rectangular tube structure with aluminum fittings (16). The solar panel is on a hinged boom (17). The gimbal design for the solar array is the same as used on the Magellan Spacecraft.

Structural responses will have a design goal of below 1 micro g. Frequency ranges will be maintained above 35 Hz in the thrust axis and above 15 Hz in the lateral axis. The satellite can experience 1.5 times the Delta II value at the C.G., affecting the lateral accelerations. Therefore, a factor of 1.5 was added to all accelerations to account for the lower frequency. The COLD-SAT load factors are:

Axis	Limit	Ultimate=Limit*2
Lateral	±5.625	±11.25
Thrust	+9.0/-0.3	+18.0/-0.6

The stress analysis included the load factors (accelerations) used for limit and ultimate load conditions, margins of safety for all structural components and pressure vessels, structural models and mass distribution used in the computer analysis. All elements of the structure and pressure vessels have positive margins of safety for limit and ultimate loads. The margins of safety for the pressure vessels are:

	Supply Tank	Receiver Tank 1	Receiver Tank 2
Limit	0.72	2.28	2.30
Ultimate	1.10	1.58	1.50
Wall Thickness	0.14	0.06 to 0.125	0.08

The tanks will be designed using fracture mechanics.

Some margins of safety are relatively high, which is a result of higher stiffness requirements for these structural components. Stress analysis has confirmed that margin exists above the ultimate loads defined by the LV requirements. The minimum margins of safety, based on yield allowables are:

Member	Limit X&Z	Limit Y&Z	Ultimate X&Z	Ultimate Y&Z
Struts	1.50 C	1.50 C	1.00 C	0.24 C
Stiffeners	3.10 C	2.90 C	1.00 C	0.95 C
Lower Ring	17.00 C	13.00 C	8.20 C	6.10 C
Transition Ring	2.90 T	2.60 C	2.70 T	1.70 T
Tank Rings	4.50 TC	4.50 TC	1.70 TC	1.70 TC
Cone Ring	93.0 T	9.10 T	4.20 T	4.10 T
Upper Struts	1.60 C	1.60 C	0.30 C	0.28 C
Column	1.20 C	1.80 C	0.11 C	0.01 C
Base Beams	2.00 C	4.00 C	0.11 C	1.50 C
Press. Bottle Struts	4.80 T	5.40 C	1.90 T	2.20 C
Solar Array Struts	16.00 T	19.00 C	9.10 C	8.80 T
Top Beams	15.00 C	19.00 C	6.80 C	7.20 C
Solar Array Beams	3.00 TC	2.50 C	1.00 TC	0.73 C
Antenna Struts	8.30 C	5.20 C	3.60 C	2.10 C
Antenna Beams	5.90 C	8.80 C	2.50 C	3.90 C
	VON MISES STRESS			
M/S	2.65	2.61	0.83	0.81

(NOTE: T=TENSION, C= COMPRESSION)

A one Micro G environment is attainable in steady state (rigid body). There is only a 2.5×10^{-7} cm (10^{-7} inch) displacement.

On-orbit transient environments cannot be kept below 1 Micro G unless an exotic isolation system is provided for the experiment tanks. It is believed that the short duration of the transient responses do not impose a restrictive force on the processes to be analyzed. No constraints are evident from reviewing the launch vehicle requirements. The required frequencies (rigid body) can be met using the correct load sizing and providing proper damping and stiffening. The load factors are very conservative for a conceptual design. Ultimate loading was changed from a factor of 1.25 to a factor of 2.0 to avoid building a test structure. Verification will be by analysis.

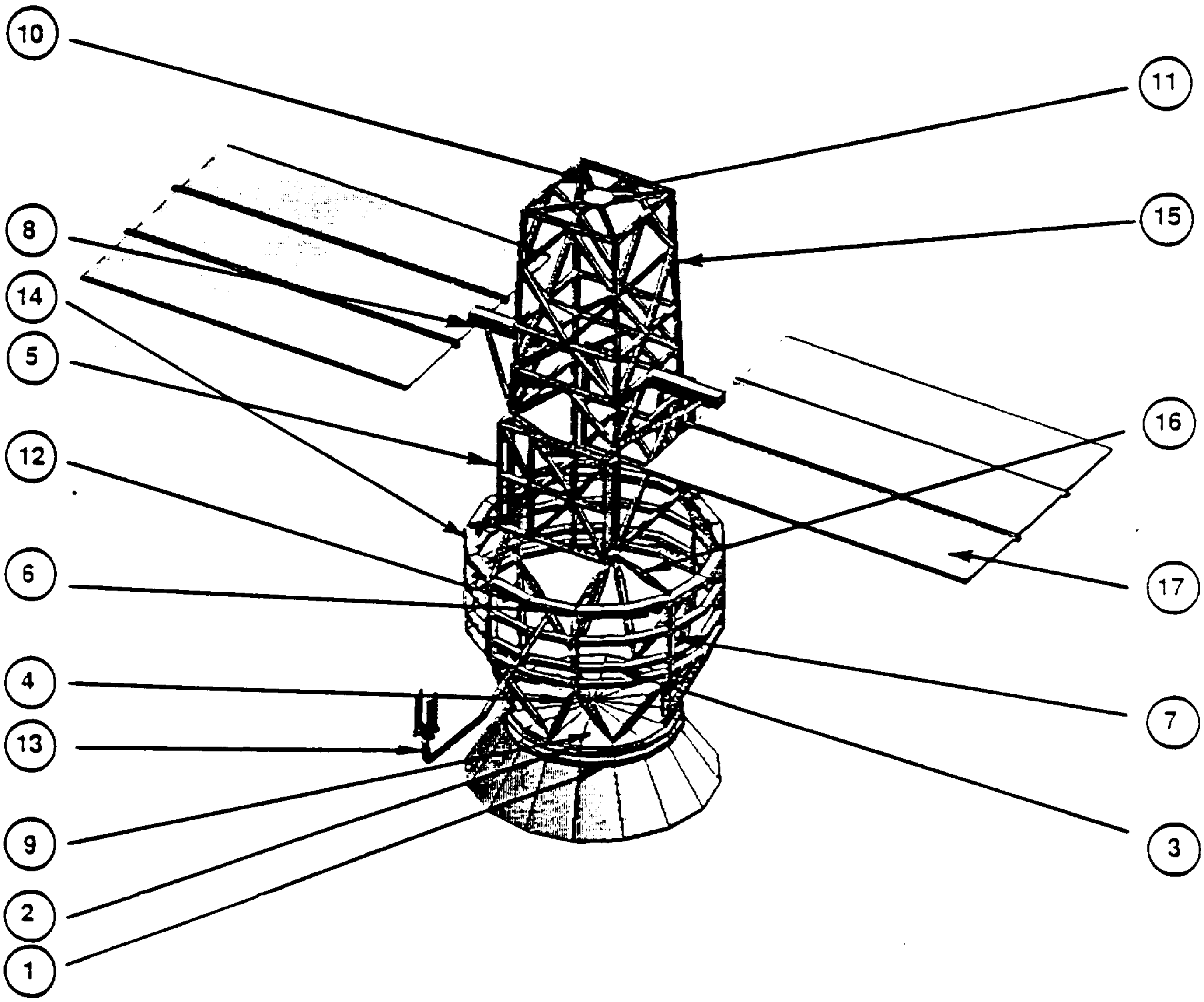


Figure 6.2.6-1 COLD-SAT Structural Subsystem Configuration Isometric

6.3 Thermal Control

As the COLD-SAT design activity proceeds, the thermal design analysis will incorporate margins for uncertainty and variations in surface properties, etc. Flight allowable temperatures for the components and equipment modules range from -159° to +135°C (-254.2 to 275 °F) external to the satellite body, from -252.7° to +77°C (422.9 to 170.6°F) for the experiment, and from -50° to +80°C (-58 to +176°F) for the avionics. Temperature predictions with thermal math models must be within the "flight allowable range". A margin of 11°C (51.8°F) is applied to the flight allowable range to determine acceptance test levels. This is consistent with Mil-Std-1540B Test Requirements for Space Vehicles. If the component is actively heated, then the temperature predictions can be within the 11°C (51.8°F) margin band below the lower flight allowable limit in Figure 6.3-1.

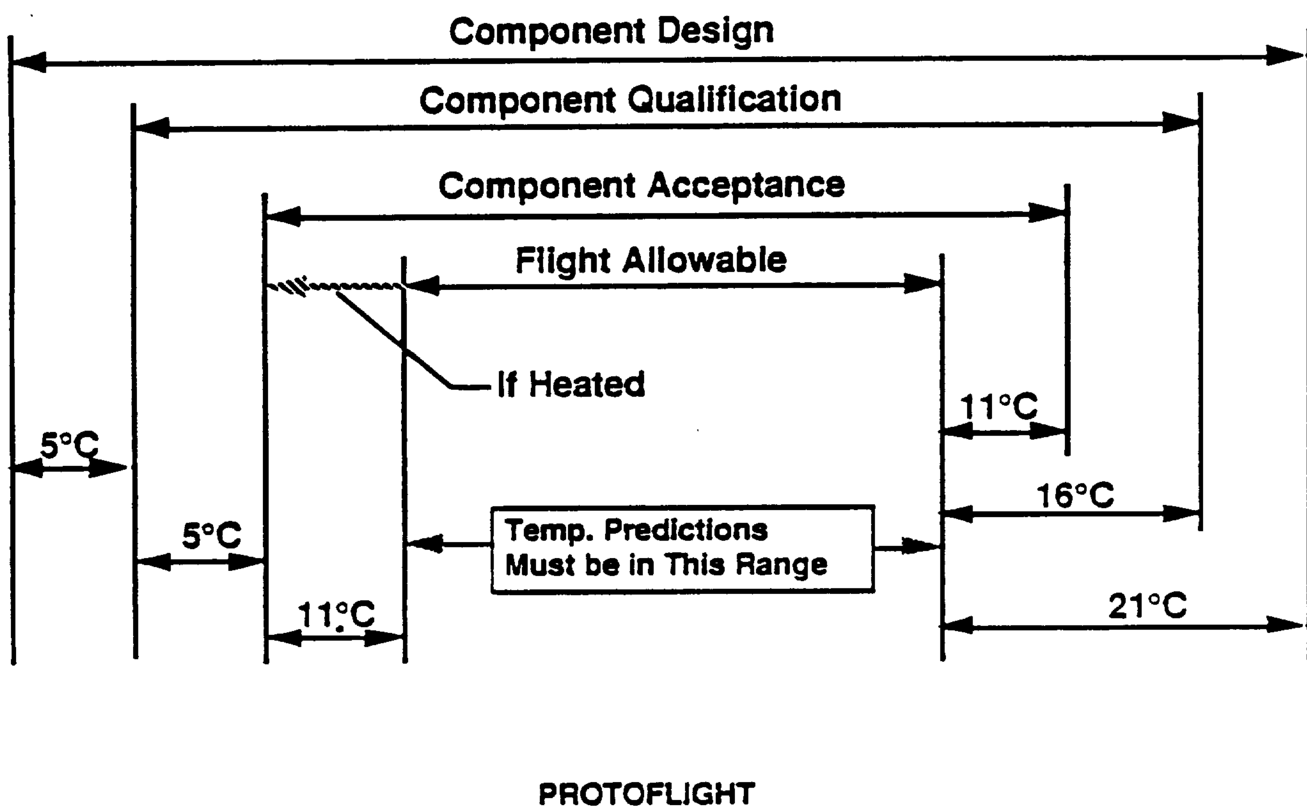


Figure 6.3-1 Flght Allowable Temperature Limits and Margins

The test levels for qualification include margins that depend on whether the qualification hardware will be flown as the flight vehicle (protoflight vehicle). Normally this margin is reduced to 10°C per Mil-Std-1540B, however for a protoflight design such as COLD-SAT this margin is reduced to 5°C. Derived requirements include those such as the vehicle orientation and heat loads.

The most restrictive thermal requirement is the need to maintain the batteries within a narrow temperature band at all times in the mission. Rotating the vehicle 180° about the Y-axis (point the longitudinal-axis in the opposite direction) can be accomplished utilizing a passive thermal design concept. The solar panels are oriented normal to the solar vector.

The longitudinal or long axis of the vehicle is fixed inertially in the orbit plane and it is always pointed parallel to the projection of the solar vector in the orbit plane, e.g. when the solar beta angle is zero the long axis points directly at the sun at all points in the orbit.

Instantaneous and orbital average heat fluxes were computed for beta angles of 0° and 52°. The beta = 0° orbit is the cold case because of the reduced time in the sun and because the vehicle's long axis is parallel to the solar vector. The beta = 52° case corresponds to the hot case because of the solar exposure time and the incident solar fluxes on the vehicle sides.

Equipment operational scenarios were examined to determine hot and cold case conditions. The key factor that drives the hot case heat loads is the operation of the TT&C components and also the operation of the experiment. The cold case scenario assumes minimal experiment and subsystem activity. Then, combined with cold orbital conditions (sun-orbit beta angle =0) the worst case heater power results. The conceptual layout of the components results in the heat loads distribution. These values were input to the conceptual thermal analysis to assess the performance of our passive thermal balance approach.

The surface geometry (TRASYS inputs) used in our conceptual design analysis defined the nodes in our thermal math model. The Thermal Radiation Analysis System (TRASYS) program was used to compute orbital heat rates and radiation exchange factors for input to our COLD-SAT thermal math model.

The model predicted preliminary temperatures for COLD-SAT using a 68-node MITAS thermal math model, with 278 conductor nodes. The results are for steady state conditions. Orbital average heat fluxes were computed for the external surfaces using TRASYS and put into this MITAS model. Individual boxes and components were not modeled at this point. Heat loads from the components were impressed on the modules and on the other mounting areas to provide this assessment of the thermal balance characteristics of this conceptual design. These preliminary results show that our approach is reasonable, e.g. our selected thermal control coatings and MLI can maintain the equipment environments in the desired ranges and has adequate heat rejection capability. Two different optical property conditions for MLI were investigated to bound the problem of thermal control. These are the minimum (α/ε=.33/.84) and maximum (α/ε=.35/.76) values that can be obtained with available off-the-shelf insulation. The minimum α/ε for white paint should be .16/.92. Table 6.3-1 lists MITAS temperature predictions from the preliminary model.

No new development is needed for the thermal control hardware. The design approach is to provide passive thermal balance of the total vehicle using thermal control coating, multilayer insulation, heaters and louvers. The existing thermal control hardware used has extensive heritage in programs such as Magellan, Scatha, etc. as well as numerous other spacecraft under classified programs. The louvers have a long heritage for their use with the MMS hardware.

Table 6.3-1 Conceptual Thermal Design MITAS Temperature Predictions

Item	Cold deg C(deg F)	Hot deg C(deg F)	Cold deg C(deg F)	Hot deg C(deg F)
	α/ε = .35/.76 max MLI		α/ε = .22/.84 min MLI	
PCDM Mounting Plate	17 (62.6)	24(75.2)	15 (5)	23(73.4)
ACS Mounting Plate	20 (68)	27(80.6)	18(64.4)	26(78.8)
C&DH Mounting Plate	23 (73.4)	38(100.4)	19(66.2)	35(95)
MPS Mounting Plate	18 (64.4)	24(75.2)	16(60.8)	22(36.4)
No. 1 Receiver Tank Radiative Environment	-15 (5)	7 (44.6)	-19(-2.2)	6(42.8)
No. 2 Receiver Tank Radiative Environment	26 (78.8)	36(96.8)	13(55.4)	30 (86)
Supply Tank Radiative Environment	24 (75.2)	33(91.4)	16(60.8)	30 (86)
Hydrazine	40 (104)	51(123.8)	17(62.6)	43(109.4)
Experiment Pressurant Tanks	-4 to -13 (24.8 to 55.4)	6 to 47 (42.8 to 116.6)	-9 to -19 (15.8 to -2.2)	0 to 28 (32 to 82.4)

Figure 6.3-2 depicts the thermal control methods to be used on COLD-SAT. The forward segment of the vehicle containing the receiver tank 1 will be coated with white paint to minimize temperatures around the tank. The experiment pressurant tanks will be individually wrapped with MLI to prevent radiation cooling to space and to moderate tank temperatures within the surrounding spacecraft environment. The four MMS modules will be wrapped with MLI with the exception of the outboard radiator surface. The heat flow dissipation will be controlled (regulated) from these radiator surfaces to the module baseplates by the module louvers. The louvers are temperature actuated and will account for variations in environmental and component heating. The batteries are located within the MPS module and will be maintained below 30 °C (86°F) by the use of a module radiator without a louver assembly. The MPS module will not require any louvers because of its higher heat dissipation rate, even in the cold case condition. The C&DH module uses heat pipes for dissipation of heat. The heat pipe contacts the electronics by a series of flow loops (legs) such that heat can be absorbed by the heat pipe and rejected by the module base. The fluid is recirculated to continue the cycle over and over.

The aft equipment located under the supply tank will be enclosed in an MLI blanket enclosure in order to maintain the equipment temperatures in their allowable ranges. The propellant tanks will be maintained within their allowable range by the use of thermostatically-controlled tape heaters to control individual propellant tank temperatures to within ±2 °C (35.6 °F). The supply tank vacuum jacket will be painted white on the outer barrel section surface that is exposed to space to minimize solar heating (low a/e ratio).

A cross section through the MMS Modules at station 381 looking aft shows the location of the louvers and MLI relative to the solar vector orientations. This conceptual design utilizes these modules because of their ability to regulate the heat flow to the module electronics in both cold and hot case heat load environments.

The modules are thermally isolated from the spacecraft structure by the use of its four point mounting system coupled with an inboard radiative barrier of MLI. They are insulated from the exterior environment with the use of MLI on the module walls and an outboard radiative surface and louver system which regulates heat flow to the module baseplates.

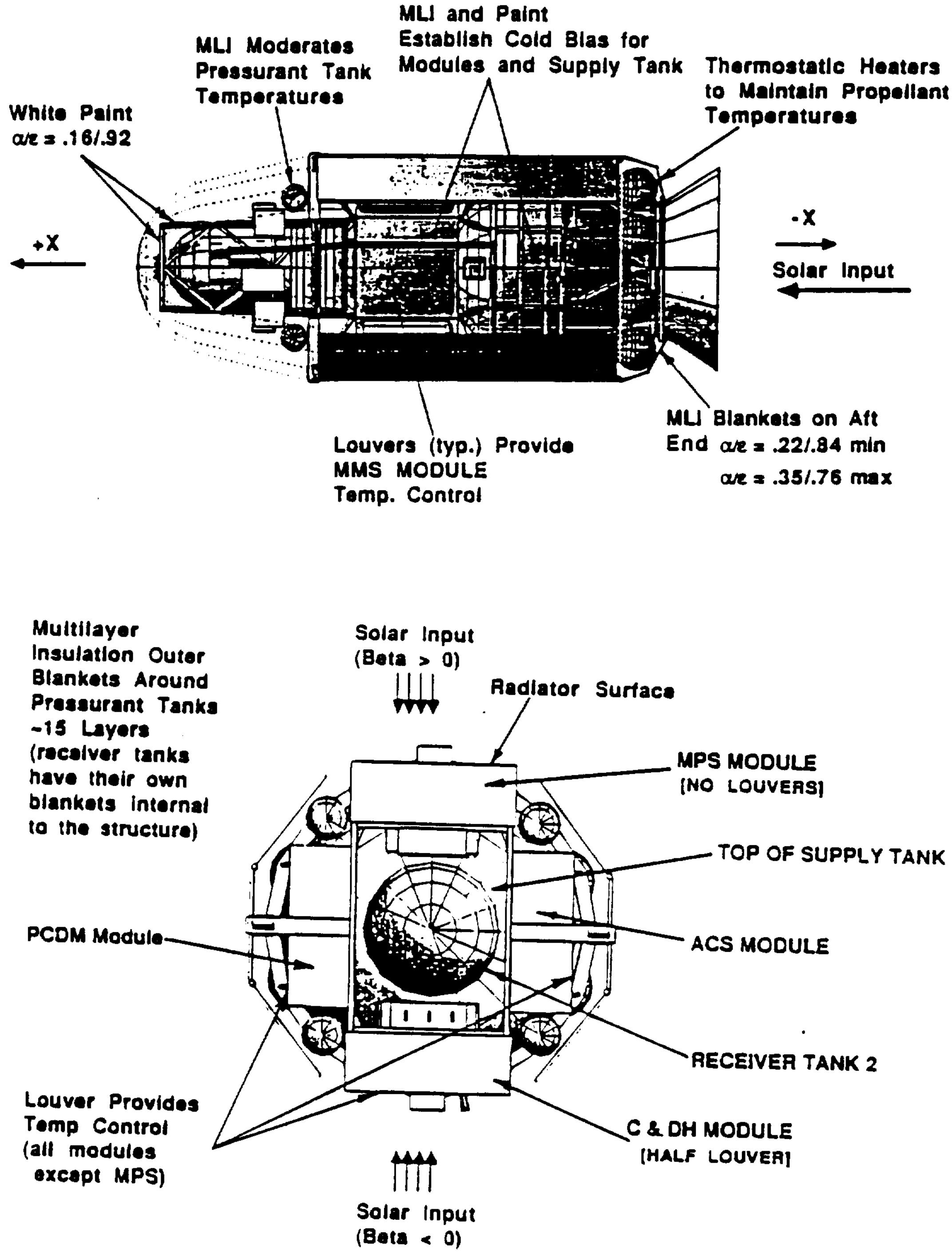


Figure 6.3-2 Thermal Control Concept

The experiment pressure bottles surround the modules for purposes of maintaining a thermal environment to assist in keeping the bottles warm.

The louvers on the individual modules are passively controlled with a bimetallic spring mechanism that automatically expands and contracts in response to the module baseplate temperature to achieve the proper opening for the correct heat dissipation rate. The maximum effective emittance of the MACS louver in the fully opened position is 0.822, and occurs at a temperature of about 19.7 deg C (67.5 °F). The minimum effective emittance of the louver occurs at about 1.3 deg C (34.3°F) for the fully closed position and has an emittance value of 0.11. A Chemglaze paint (E= 0.85) is used on the plate exterior. The louver area = 0.6 sq m (6.5 sq ft).

The heaters selected are a film type built by Tayco and used on the Magellan spacecraft. The thermostats are a snap action type built by Texas Instruments and used on Magellan. The MLI material is manufactured by Sheldahl and fabricated by Martin Marietta of aluminum mylar and dacron net.

The design approach of our conceptual thermal control system for COLD-SAT is to provide passive thermal balance of the total vehicle using thermal control coating, multilayer insulation, heaters and louvers. No orbit constraints have been determined as yet if the vehicle attitude is maintained. The 180 degree rotation of the vehicle (aft end toward the sun vector) for a few orbits does not seem to require more than the passive design concept. Flight allowable temperature limits for the COLD-SAT components and experiment hardware must be maintained for all the on-orbit phases of the mission.

6.4 Electrical Power

The electrical power subsystem controls, stores, distributes and monitors power derived from a solar array. Two modules are used, the Modular Power System (MPS) and the Power Control and Distribution Module (PCDM). The MPS supplies unregulated 28 vdc power to other MMS subsystems and to the experiment subsystem. Isolation diodes are used to prevent damage to the MPS from external power line faults. During normal operations the MPS accepts power from the solar array, controls the solar array generated power, controls the unregulated output bus voltage, and the charge and discharge of the batteries. Batteries are required to provide power during sun occultations and to supplement solar array power during peak loading. The batteries are rechargeable. A single point ground system is used with the power distribution return bus grounded to the external spacecraft structure at the spacecraft central ground point. All primary subsystem power distribution return buses are independently connected to the Power Control Unit (PCU) in the MPS and bussed within the PCU to the MPS power return bus. The onboard computer (OBC) monitors MPS parameters for control. These functions are battery under-voltage protection, battery overtemperature protection, load bus voltage, ampere hour battery charge control, computer pulse train, and battery and bus currents.

Battery charge control is achieved by time integration of the battery charge/discharge currents, computation of battery efficiency, computation of battery depth of discharge and measurement of battery voltage, compared against computed temperature compensated voltage limits. The voltage from each battery, battery temperature, sensor outputs and elapsed time with real time indicators are all used in battery charge control and welfare monitoring as well as measurements of individual battery currents and total load bus currents.

The PCU serves as the distribution point for the spacecraft loads and for battery recharge power. The PCU contains the power switching functions and current sensors for monitoring the MPS currents. The Power Regulation Unit (PRU) maximizes the utilization of the solar array energy to supply load power and battery charging, and to control battery charging.

The 50 AH batteries are Nickel Cadmium and utilize the GE 42B050AB22 cell design with the NASA standard terminal configuration. No third electrode is used.

The orbital average load was analyzed to determine the solar array and battery requirements. The unique load requirements fall on day one of the mission. Day 1 consists of four phases.

1 - Launch 2 - ACS Activate 3 - Post Deployment 4 - System Checkout:

In Phase 1 the EPS and TTCS are active in support of recording the experiment subsystem status during launch. In Phase 2 the ACS is brought on line to spin up the gyros prior to separation. The batteries provide all of the power during phase 1 and 2. Phase 3 peak power uses the solar array to recharge the batteries that have been partially depleted during launch and ascent. Phase 4 peak power includes transmitting data using the transponder and the 30 watt amplifier. Day 2 is the start of the experiment phase. Orbital average battery power during occultation in the experiment phase is 1167 watts. The orbital average power during sunlight of 2003 watts includes: Average maximum power - 1167 w + battery charging power of 886 w.

Power levels above 1167 watts would include a mix of the following:

A: Mixer Pumps on (included in orbital average)
B: 2 Thrusters (on continuous)
C: 6 Thrusters (on continuous) (included in orbital average)
D: Pulsing 2 Thrusters
E: Pulsing 6 Thrusters
F: Experiment Heaters on (included in orbital average)
G: Experiment Valve Activation
H: Transfer Pump on (included in orbital average)

A breakdown of elements within each subsystem with maximum orbital average and peak power loads was performed to generate the power requirements. Table 6.4-1 lists the load requirements averaged over an orbit for the assemblies in each subsystem. Peak power requirements are also shown. A worst case total of the peak power was calculated to provide a measure of the battery requirements.

A flight qualified MMS design concept has been utilized for the electrical power subsystem. The Modular Power Subsystem Module provides power generation, regulation and battery charging. Command & data handling for the EPS is from the T, T, & C Subsystem via the Remote I/F Units (RIUs). The Power Control & Distribution Module (PC&DM) provides protection, control & distribution of power to electrical elements external to the Subsystem Modules (AACS, C&DH, MPS). The PC&DM provides control of Solar Array & TDRSS Antenna Articulation, power to mixer pumps & control of firing NSIs. The PCDM contains the pyrotechnic initiator controller firing circuits and provisions for nominally firing simultaneous prime and redundant initiators by a single set of firing commands. Command & Data Handling is from the T, T, & C subsystem via the Remote I/F Units (RIUs). The MMS MPS module is built by McDonnel Douglas except for the Power Regulation Unit which is built by Martin Marietta for the MMMS. The PCDM is built by Martin Marietta for the MMMS. The Pyro Controller is built by Martin Marietta. Figure 6.4-1 is a block diagram of the EPS.

The solar array consists of two solar panels. Each panel is oriented by a redundant, independently controlled, single axis drive unit. The solar array is designed with multiple diode isolated parallel strings of solar cells, such that no single failure causes more than a 2% loss of the total (both panels combined) power output. The solar array power generation capability was calculated using the conditions and degradation factors for a short 6 month mission. The initial output wattage per square foot is degraded, resulting in a lower output wattage. Certain factors are over a 1 year period. The solar array is sized on the maximum orbital average power requirement, the worse-case beta angle, efficiency of the solar array & battery systems, and the ratio of the solar arrays in the shade to being in the sun. Sufficient spacing between solar cells is provided. The solar array requires a folded boom and two folds per panel to fit within the Delta II shroud. The solar array has heritage from the Magellan program.

Table 6.4-1 Satellite Orbital Average Power Requirements

DESCRIPTION	POWER PER UNIT (W)	MAX ORB AVE LOAD (W)	PEAK LOAD (W)	NOTES
ATTIT CTRL SUBSYS				
ATTITUDE CTRL ELECT(2)	59.0	59.0	140.0	1 OF 2 ON
REMOTE I/F UNIT(2)	10.8+2.9	13.7	13.7	1ACT,1STBY
EXPANDER UNIT	3.0 + 1.8	4.8	4.8	1 ACT, 1 STBY
INERTIAL REF UNIT	25.0	25.0	27.3	ALL CHANNELS OP
HORIZON SENSORS(2)	5.4	10.8	10.8	2 OF 2 ON
COURSE SUN SENSOR(2)	2.0	2.0	2.0	2 OF 2 ON
REACTION WHEELS(4)	6.83	20.5	240.0	3 OF 4 ON
TRIAXIAL MAGNETOMETERS(2)	1.7	1.7	1.7	1 OF 2 ON
MAGNETIC TORQUERS(2)	9.4	9.4	9.5	1 OF 2 ON
FINE SUN SENSORS	2.0	2.0	2.0	2 OF 2 ON
TOTAL		144.1	447.0	
ELECTRICAL POWER				
MPS				
SIGNAL CONDITIONER ASSY(2)	2.08	2.08	2.08	1 OF 2 ON
BUS PROTECTION ASSY		-		
POWER REG UNIT(6)	6.88	-	41.26	4 OF 6 ON
POWER CONTROL UNIT		-		
REMOTE I/F UNIT(2)	10.8+2.9	13.7	13.7	1ACT,1STBY
MPS INTERNAL ELECTRONICS	56.0	56.0	56.0	MAXIMUM
PC&DM				
ELECTRONIC SUBMODULES(2)	16.46	16.46	39.36	1 OF 2 ON
ACTUATOR SUBMODULES(4)	0.11	0.44	1.32	72 HRS
EXPANDER UNIT(4)	3	3	3	1 OF 4 ON
S/A DRIVE ELECTRONICS(2)	13	26	46	BOTH ON
ORDNANCE CTRL(8)		PULSED		
BATTERY CHARGING	400.59	136.27	-	
REMOTE I/F UNIT(2)	10.8+2.9	13.7	13.7	1ACT,1STBY
TOTAL		268.66	214.44	
THERMAL				
PC&DM MODULE		9	9	INTERNAL HTRS
C&DH MODULE		22	22	INTERNAL HTRS
MPS MODULE HEATERS		3	3	INTERNAL HTRS
TOTAL		34	34	
EXPERIMENT SUBSYS				
PRESSURE TRANSDUCERS	0.25	6	6	ALL ASSUMED ON
LIQUID LEVEL SENSORS	0.175	0.70	0.70	ALL ASSUMED ON
VALVES [0.6 cm & 1 cm (1/4" & 3/8")]	2.1 & 4.2	PULSED	4.2	0.6 cm = LATCH VLV; 1 cm =TORQUE MOTOR VLV
VALVES [1.3 cm & 1.9 cm (1/2" & 3/4")]	1.5 & 3.0	PULSED	3	8 TO 18 SEC TO OPEN/CLOSE
MIXER PUMPS(2)	5	5	10	1 ON; BOTH ON FOR 29 HRS TOTAL
TRANSFER PUMP	30	30	30	ON 16.5 HRS TOTAL
EXP VALVE ELECTRONICS(4)	58	58	58	1 OF 4 ON
REMOTE I/F UNIT(4)	10.8+2.9	19.5	19.5	1 ACT,3 STBY
EXPANDER UNIT(2)	3+1.8	4.8	4.8	1 ACT,1 STBY
FLOWMETER ELECTRONICS(12)	7.5	45	45	6 OF 12 ON
HEATERS: - TANK WALL(8) SUP TK	4.06	24.2	24.2	
- VENT LINE(4)	100	78	200	1 ON 36 MINS/ORBIT
- WARM-UP(2) RCVR 2	30	30	30	108 HRS
-PRESSURANT LINE	0	0	0	NOT REQUIRED
ACCELEROMETERS(2)	10.57	21.14	21.14	BOTH ON
TOTAL		329.94	456.44	
T,T,&C SUBSYSTEM				
BUS COUPLER UNIT		PASSIVE		
REMOTE I/F UNIT(2)	10.8+2.9	13.70	13.7	1ACT,1STBY
RECORDERS(2)	6 + 1.5	11.70	16	1 ON CONTINUOUS/ORBIT. BOTH ON 10' PER ORBIT
CENTRAL UNIT(2)	23.5	32.80	32.8	1ACT,1STBY
INTERFACE UNIT(2)	16.9	16.90	16.9	1ACT,1STBY
ON-BOARD COMPUTER(2)	125	125	125	1 OF 2 ON
TRANSPONDER(2)	18/36	3.67	36	1 OF 2 ON 10'/ORBIT
EXPANDER UNIT	3	3	3	1 OF 2 ON
30W POWER AMPLIFIER(2)	200	18.32	200	10'/ORBIT
TOTAL		226.16	441.1	
PROPULSION SUBSYS				
REMOTE I/F UNIT(2)	10.8+2.9	13.7	13.7	1ACT,1STBY
PROP MODULE ELECTRONICS(2)	58	58	58	1 ON AT A TIME
LINE HTRS(2)	2	0.64	2	33 MIN/ORBIT
CAT BED HTRS(20)	1	10	10	10 OF 20 ON
THRUSTERS(20)	9	54	90	MAX 14.2 HR PERIOD
VALVE HTRS(40)	1	40	40	LIFE OF MISSION
TOTAL		176.34	218.7	

ORBITAL AVERAGE BATTERY LOAD = 1167.1 W
WORST CASE PEAK LOAD = 1808.7 W

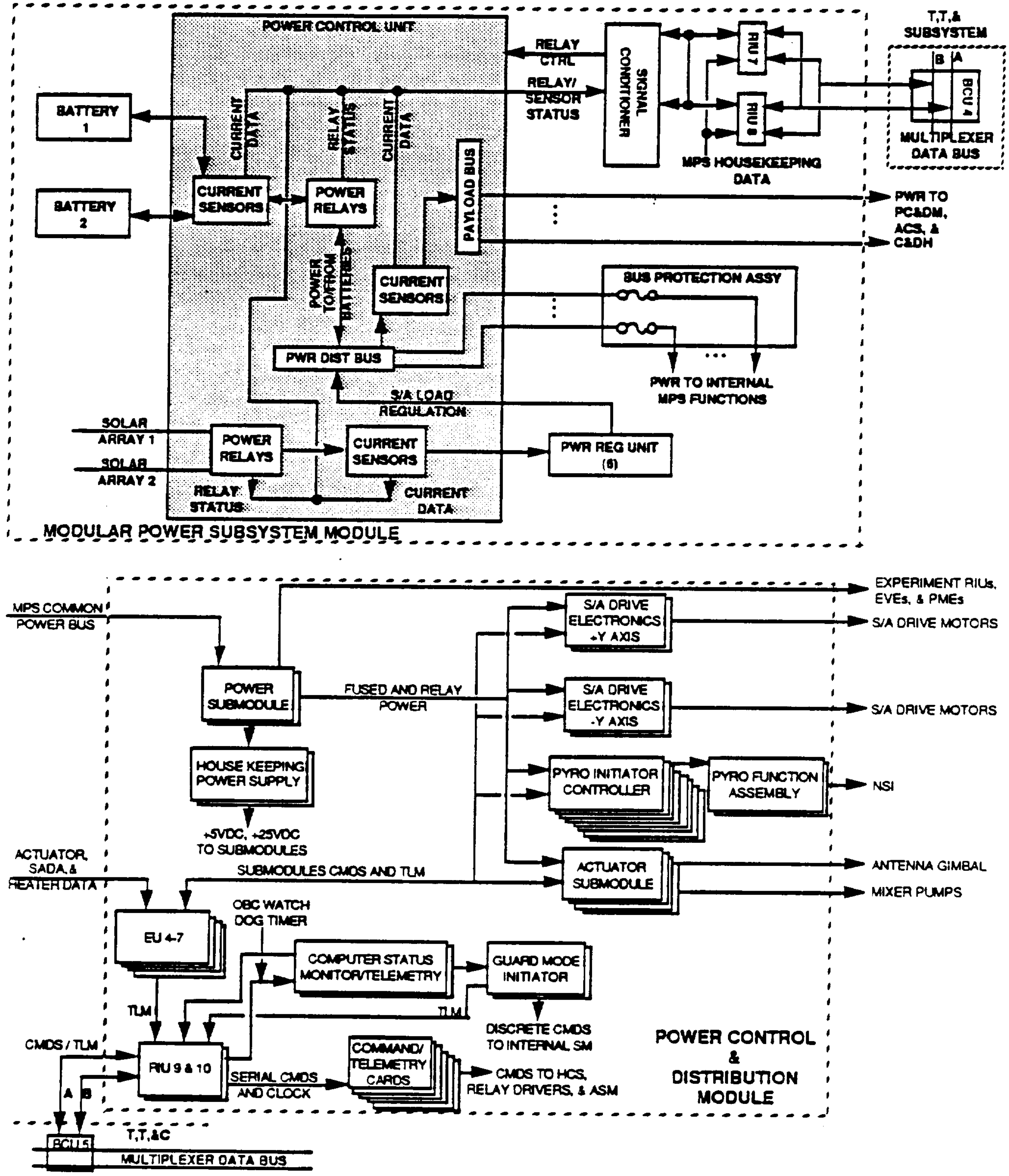


Figure 6.4-1 EPS Block Diagram

Batteries will supplement the solar arrays in the event loads exceed the capability of the solar arrays. The batteries have the capability to supply 75% of the battery rating (based on a 50 AH battery) to handle peak loads. The battery charge rate is less than 27.8 amperes. The maximum discharge is 37.5 amperes maximum per battery. The batteries selected (2-50 ampere-hour batteries) are used on the Multi-Mission Spacecraft and provide redundancy if one battery is lost. The worst case depth of discharge is 25% with two batteries operational. With one battery the DOD is 50%. The batteries are built by General Electric for the MMS.

The capability of the Electrical Power Subsystem to handle peak power loads is dependent on the capability of the batteries to supply the necessary amperage. Based on a 75% discharge capacity per battery, calculations show a sufficient margin capability of the batteries to meet peak loads.

The EPS can control up to twelve pyro initiating events. The events, functions, and pyro device is shown in the chart. The EPS provides a redundant pyrotechnic initiating controller system capable of selecting and firing up to 48 NSIs. Control commands are two steps: Arm and Fire.

6.5 Telemetry, Tracking & Command (TT&C)

The C&DH module provides a means for tracking, for ground and on-board control of all spacecraft and experiment sensor functions and for transmission of housekeeping and experiment data. To uplink commands a redundant TDRSS transponder includes receivers. The transponder transmitters are used for transmitting data. The commands are routed from the command receivers/detectors to the Interface Unit (IU) which authenticates and distributes the commands to the Central Unit (CU). The CU distributes these commands throughout the spacecraft. The IU provides an interface to the transmitters to downlink, as well as performing the telemetry selection and processing. Control and monitoring of the housekeeping subsystems and the experiment subsystems is handled by the Multiplex Data Bus (MDB) attached to Remote Interface Units (RIUs).

The MDB consists of a supervisory bus and a reply bus; each bus being redundant. The central unit (CU) within the TT&C controls the distribution of commands and the acquisition of data. Remote interface units (RIUs) in each subsystem interface to the MDB, process commands and acquire data as requested by the CU. The telemetry and command requirements of the COLD-SAT spacecraft and the experiment have been analyzed. Command requirements will fit within the one kbps uplink rate utilizing a block update concept. This allows multiple commands, which are frequently used, to be grouped together and initiated from a single block command in the uplink. The data bus rate required is 2.0 kbps which is well within the one Mbps capability of the conceptual design. The MMS data bus can handle one Mbps of information. Both commands and telemetry are channeled to the Onboard Computer (OBC) which is a Litton LC-4516E Extended version.

The RIU is the standard interface between the CUs and the various subsystems. The RIU performs the functions of remote command decoding as well as remote telemetry multiplexing required by the subsystems. The capability exists for 62 RIU taps for telemetry. The conceptual design utilizes 14 remote interface units (RIUs) and 9 extender units (EUs). The reason for the quantity of interface units and extender units is the large number of active analog channels required by the experiment subsystem. Each RIU and EU can handle up to 16 active analog channels each. The remaining spacecraft measurements are easily handled by the RIUs. Data is acquired in the form of 0 to +5 volt analog signals, passive transducer signals, bi-level signals, and serial-digital signals. These signals are converted, conditioned, and multiplexed in 8-bit types. The RIU accepts 32 bit instruction messages from the CU, recognizes its own unique address, and responds appropriately to the instruction by (a) decoding and distributing commands to the subsystem, (b) decoding and distributing selected clock signals to the subsystem, and (c) accepting, conditioning, formatting, and transmitting the subsystem telemetry data. This includes supplying all necessary control and conditioning signals to the subsystem to effect data transfer.

The expander unit (EU) provides two way communication between a subsystem and the CU via the RIU and the MDB. On command from the CU, an RIU requests telemetry data from a channel via an EU. The RIU accepts, converts, and conditions the data as necessary, then transmits it via the MDB to the CU for insertion into the telemetry downlink stream and/or input to the OBC.

The OBC is a general purpose, stored program, digital computer with a redundancy approach suitable for achieving long life in a space environment. The OBC is used for experiment control and data processing, attitude control and determination, solar array and antenna pointing, variable format telemetry, mission sequence controlling, fault detection with corrective action for critical satellite failures, and monitoring and controlling the electrical power subsystem including battery charge control. One string of the OBC redundant processing capability is active. Functional redundancy is capable of being operationally verified. The OBC is organized in four functional subdivisions: the Central Processing Unit (CPU) which provides the computational capability of the OBC; the Power Conditioning Unit (PCU) which provides dc-dc conversion and regulation; the Memory Unit which has a storage capacity of 96K words; and the Input/Output Unit which provides cross-strapped redundant interfaces to the CUs, the RIUs and IUs. The OBC provides the capability to address up to 128K (K=1024) words of memory. The OBC can accept a minimum of 16 interrupts which can be selectively inhibited. The Input/Output Unit receives 16 bit serial magnitude commands from the RIU to put into the OBC.

The telemetry, tracking and control subsystem utilizes standard MMS hardware. The conceptual design presented intends to use these components without modification. The heritage, therefore, reflects actual hardware presently being produced. Figure 6.5-1 is a block diagram of the TT&C Subsystem.

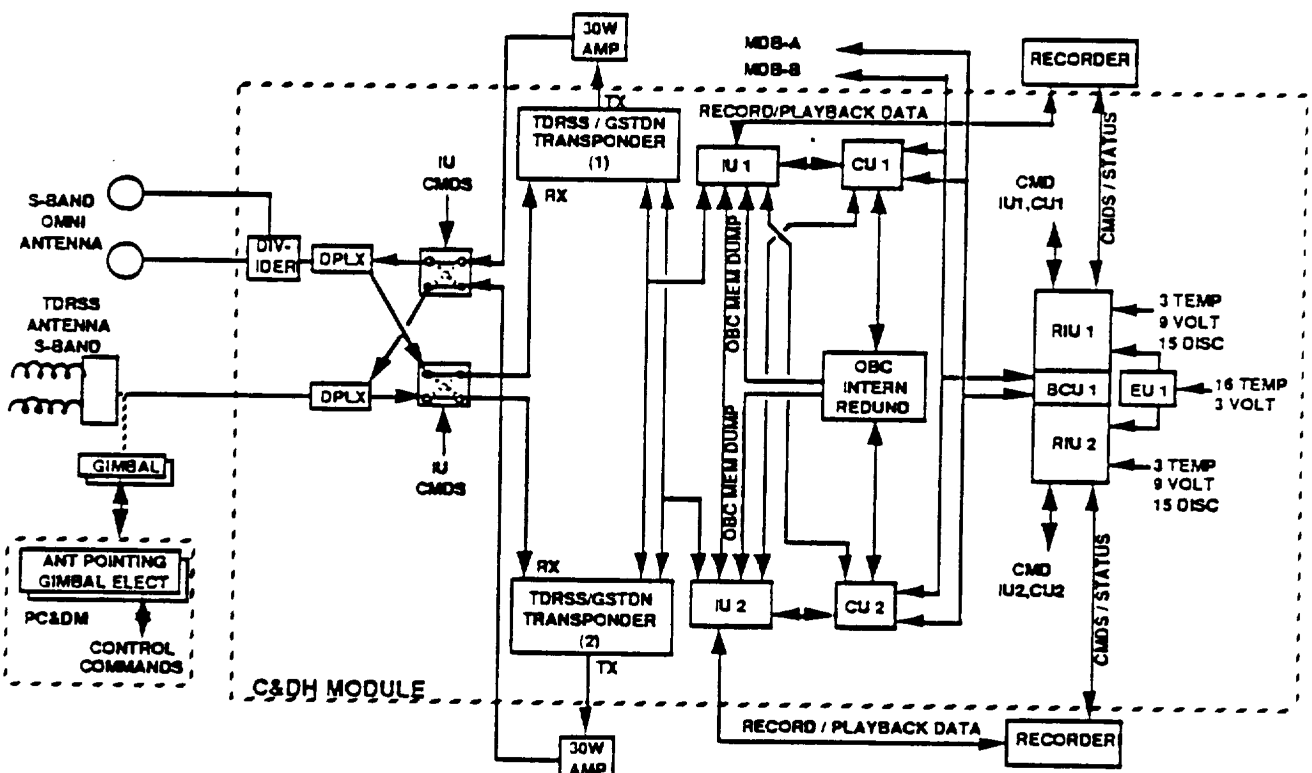


Figure 6.5-1 TT&C Block Diagram

All data is recorded. Solid state recorders are sized to hold 12 hours of data each in case of TDRSS unavailability. All orbits have at least a 10 minute TDRSS window with many having as much as a 60 minute window. The recording media for the solid state recorder is semiconductor. There are no moving parts. There is no restriction on the ratio between the record rate and the playback rate. The recorder has the capability to simultaneously record and playback. The power consumption is data rate dependent and relatively independent of the mode of operation. The recorder utilizes a first in/first out mode of operation, with two of eight channels assigned a FIFO pair. The model selected is a Fairchild SSR1-64B (to be flight qualified in 1990) which contains a 64 megabit recording capability with memory expansion in 64 megabit increments. Each memory card has 64 megabit user space. The recorder MTBF is estimated at 10 years. Status telemetry is 1 serial digital channel (8 bit word) and 4 bi-level channels and 2 analog channels. A separate battery (8.5 to 20 vdc) is required for backup when the bus is down. The 28 vdc bus input is required for operational use. This recorder is compatible with the MMS.

In a contingency mode, if one solid state recorder fails, real-time data during the TDRSS contact could still be recorded for playback. Each recorder can record and playback at the same time. GSTDN stations are visible once per orbit for 3 to 8 minutes to process emergency health & safety data. To communicate with GSTDN a 2-hour call-up time is required.

The telemetry, tracking and control subsystem utilizes the MMS hardware. Multiple remote interface units (RIU) and extender units (EU) allow control and monitor of the extensive experiment subsystem sensors and valves. Control of the experiment sequencing function and the attitude control function are both handled by the on-board computer. The data handling function is handled by the Central Unit. Handling of transponder uplink & downlink is through the Interface Unit. Loading of ground or uplinked commands will be under the control of the central unit (CU). Commands will be tagged as being required to be loaded into OBC memory or executed real time. Uplinked commands will consist of housekeeping or experiment sequences. Experiment sequence uplink events will occur once per week. The memory has been sized for a two week upload. Housekeeping commands can be uplinked every TDRSS pass as required.

The RIU, Bus Coupler, EU, CU, and IU are built by Fairchild for the MMS. The On Board Computer is built by Litton and used on the MMMS. The Near-Earth Transponder and 30W Power Amplifier are built by Motorola. The electronics and motor for articulating the antenna are built by Schaeffer Magnetics and have heritage from Magellan.

Command operations are as follows: Computer commands are sent to an RIU to control the satellite or acquire data. These commands can be realtime or delayed and can be OBC commands from the stored program, CU commands for memory load, or IU commands for memory dump. Special commands are executed by the CU to control CU operations and MDB configurations. Realtime commands can bypass the OBC. Fixed commands are used for control of the satellite or experiment elements.

The RF equipment provides the capability to communicate with ground stations or TDRSS antennas. Pointing control, in two axes, is provided for the TDRSS antenna with pointing accuracies plus or minus 5 degrees. The RF equipment acquires and phase-locks to a carrier signal and receives and demodulates the S-band signals transmitted by the TDRSS remote stations (at GSFC). The frequency of the received signal is coherently translated. The normal operating mode of the RF equipment is two receivers active and one transmitter on standby except for the 10 minute period of TDRSS downlink availability. The active transmitter is selected by the OBC initiated commands in response to stored program commands or real time commands. RF switch activation as well as transmitter activation is used to switch transmitters from primary to redundant or vice versa.

The primary communication link is via TDRSS. The antenna required by COLD-SAT will be a 4-element array antenna. Each element is of helical design with 16 turns per element. Frequency range of the antenna is 2.1 GHz (forward) and 2.3 GHz (return). The 30 watt S-band amplifier was selected because of its off the shelf availability. A 20 watt amplifier would be sufficient but was not available off-the-shelf. The amplifier, built by Motorola, is space qualified on Centaur. It amplifies the 5 watt rf output of the TDRSS compatible transmitter in the NASA Standard Transponder. It has a 10 year lifetime. It can withstand temperatures from -50 deg C to +60 deg C (-58 to 140 °F). When transmitting, the amplifier uses 200 watts maximum. The analysis of the return link indicates that with a 32 kbps downlink rate, the rf output is 45 dB with a margin of 3.5 dB. At 16 kbps, the margin grows to 6.5 dB.

The redundant communication link is via Ground Stations (GSTDN). Two omni antennas will be utilized, located perpendicular to the longitudinal-axis near the supply tank, and placed 180 degrees apart. The omni antennas will be passively coupled. GSTDN communication links will be used for return link of data only, no forward links of commands will be allowed although possible at 1 kbps.

6.6 Attitude Control

The control system concept was selected to maximize the ability to perform all of the experiment operations with a minimum of external torques on the fluid. Some operational requirements were derived to be used in conjunction with the control system operation. Reaction wheels in combination with magnetic torquers are to be used for experiments requiring a background acceleration of less than one micro g acceleration. This is to provide a minimum amount of disturbances on the experiment. When acceleration is required, forward or aft thrusters will be used to provide the acceleration and attitude control about the transverse axes. Reaction wheels will control the longitudinal axis. It is expected that the reaction wheels would be used during any quiescent period for tracking TDRSS and performing very slow maneuvers required to maintain the orbit for sun pointing. Any significant maneuvering rates will be performed using thrusters.

The control system concept is a traditional design consisting of an onboard computer and software, sensors and actuators, and interface electronics. The spacecraft attitude is determined using a sun sensor, earth sensor, and the spacecraft ephemeris which is periodically obtained from GSFC and propagated between uplinks. Nominally, an attitude update will be performed once per orbit. Figure 6-6-1 is a block diagram of the Attitude Control Subsystem (ACS).

The attitude error is corrected using thrusters or reaction wheels and magnetic torquers, depending upon the spacecraft mode of operation. The commands to the wheels, torquers or thrusters are issued by the flight software to the hardware via the interface electronics. The control system will determine the present, and desired orientation will be issued from the flight computer's control software. Accelerometers are required to provide experiment data correlation but are not needed for Guidance and Navigation. They could be used in a fault detection and isolation scheme.

Because of the nature of the COLD-SAT mission, the pointing requirements for the various mission phases are not very stringent. The toughest pointing requirement of one degree is needed during periods when no accelerations are desired on the experiment. Due to gravity gradient torques, frequent momentum desaturation would be required if one of the spacecraft axes (preferably X) was not aligned with nadir. A two degree pointing requirement is anticipated for delta-V maneuvers, during experiments with accelerations, or when control during quiescent periods is performed using thrusters.

The modes of operation for attitude control are (1) Delta V for orbit adjust, (2) Experiment (with and without thrusting), (3) Quiescent (with and without thrusting), and (4) Slew to maintain the orbit. The pointing accuracy of the solar array is a significant driver in the power subsystem design. A requirement for pointing accuracy of five degrees was selected to minimize power loss due to pointing at 0.4 percent.

In the allocation of pointing requirements to the spacecraft attitude and solar array articulation, and because the articulation is about the solar array boom -axis, the other axes show off-pointing due to spacecraft attitude only. The RSS method of combining angular offsets (applicable for small angles) yields a total pointing offset of less than 5 degrees. The coarse sun sensors are only used for acquiring the sun, not for pointing information. The fine sun sensors assist in the attitude determination and meet the one degree pointing requirement derived from the momentum buildup from gravity gradient torques. Nominally, a two degree pointing requirement is sufficient while thrusting.

The TDRSS antenna is also articulated, and also depends on spacecraft attitude as well as antenna articulation. The TDRSS antenna pointing requirement is based on the antenna beam half-width of 10.5 degrees. Antenna pointing is achieved with a two axis gimbal for azimuth and elevation. For consistency, spacecraft off-pointing was converted from roll, pitch, and yaw to azimuth and elevation. The articulation requirement levied on the TDRSS antenna can be combined with the spacecraft attitude to yield a total pointing offset of less than the 10.5 degrees beam half-width. The Schaeffer stepper drive motor operates in steps of 0.0075 degrees or less. The motor can be driven to a maximum of 2.5 degrees per second. This rate is much beyond the tracking rate requirements of the TDRSS antenna or the Solar Array. The step size assures accurate pointing capability with this motor design.

Solar array sun pointing will be maintained by a single axis drive to within +/- 5 degrees of the sunline, except during experiment quiescent tests where solar array panels will be held fixed. Constant slow pointing maneuvers will keep the satellite longitudinal axis in the orbit plane and avoid maneuvers to maintain the attitude and the orbit overcoming the regression caused by the Earth.

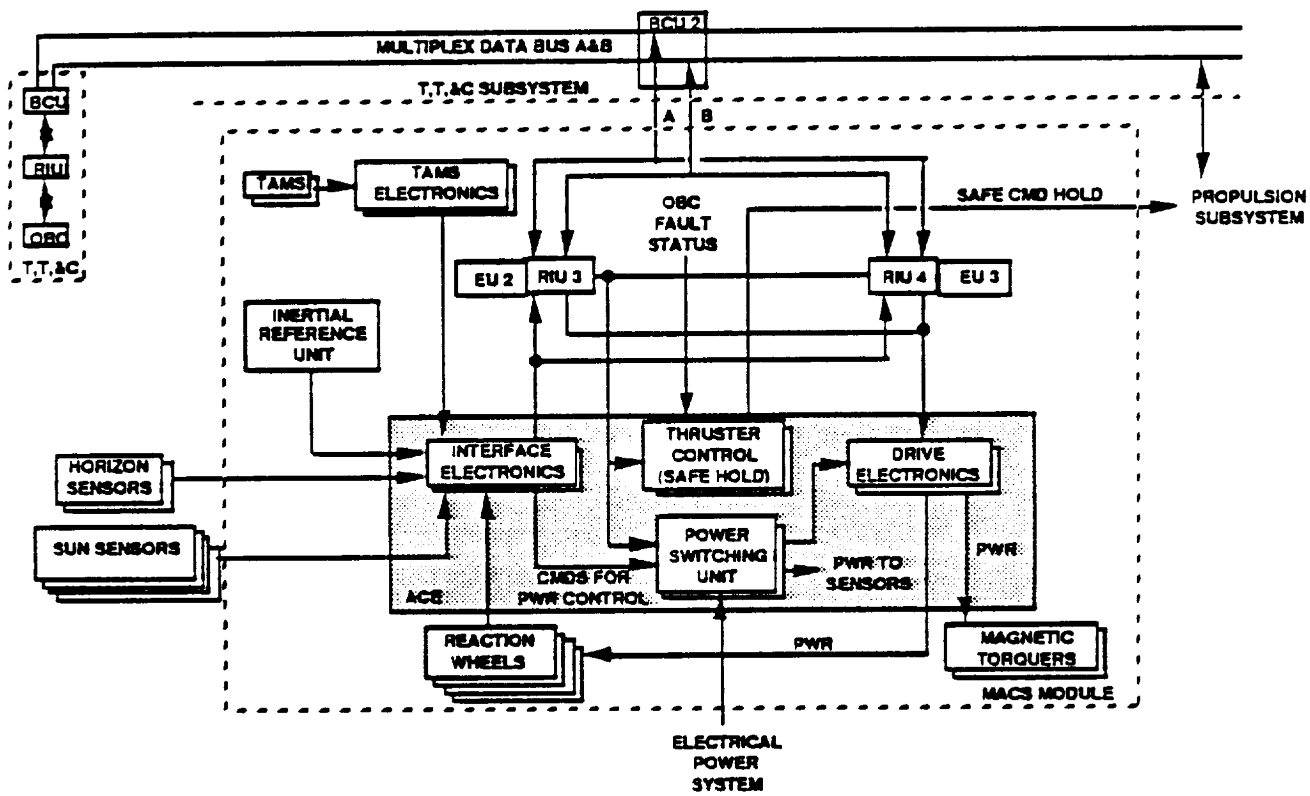


Figure 6.6-1 ACS Block Diagram

Guidance algorithms are required for performing orbit adjust maneuvers. The maneuvers are anticipated to keep the orbit near 926 km (500 nmi) to maintain orbital lifetime. Using a fixed burn time scheme should be adequate to perform the orbital adjust maneuvers although more complex and precise options exist using accelerometers or navigational aids.

Navigation is required for both the attitude determination scheme and for orbit adjust maneuvers. A simple scheme will be employed which used TDRSS or ground based tracking for the spacecraft ephemerides. The flight software will have the ability to propagate its ephemeris between uplinks. No special sensors are being added to the spacecraft for either guidance or navigation.

The spacecraft also has some rate constraints derived from the experiment requirements. For example, during experiments the rotational rates about the longitudinal and transverse axes must be less than .07 and .05 degrees per second, respectively. This is to minimize transverse accelerations and to make them as small a component of longitudinal acceleration as possible. Other rate constraints are imposed to minimize sloshing of the fluids between experiments. These requirements may change as the vehicle evolves from a concept to a design.

The attitude control electronics (ACE) employes the design from the MMS MACS module. The ACE is being considered to minimize costs in the development of the control system. Sensor data is taken and actuators are commanded via these electronics. The ACE concept includes an analog safe hold mode in the event of an OBC fault.

The control system concept was selected to maximize the ability to perform all of the experiments. Some operational requirements were derived to be used in conjunction with the control system operation. Reaction wheels in combination with the magnetic torquers are to be used for experiments requiring 1 micro g or less acceleration. This is to provide the minimum amount of disturbances on the experiment. When acceleration is required, forward or aft thrusters will be used to provide the acceleration and attitude control about the transverse axes. A reaction wheel will control the longitudinal axes.

It is expected that reaction wheels would be used during any quiescent periods for tracking TDRSS, and performing slow maneuvers. Any significant maneuvering rates will have to be performed using thrusters.

Most of the ACS hardware has heritage from the MMMS used in other Martin programs. The hardware is being manufactured today. The most recent NASA MMS hardware is on the Explorer Platform and its ACS hardware provides a heritage factor. The horizon sensor replaces the star scanner used in the MMMS configuration.

The Inertial Reference Unit selected is built by Teledyne for the MMS. The Sun Sensors, both coarse (Model 18394) and fine, are built by Adcole. The fine sun sensor has heritage from Magellan. The Horizon Sensor is built by Ithaco and has heritage from SAS-3. The reaction wheel is built by Sperry and has heritage from many explorer programs using MMS hardware. The 3 axis magnetometer is built by Schonstedt (Model SAM-63C-12). The magnetic torquer is built by General Electric (model SYS-1046S). The attitude control Electronics is built by GE for the MMS.

The disturbance torques that act on COLD-SAT will be environmental as well as internal. The gravity gradient torque causes momentum build-up in the reaction wheels and drove the requirement to keep the spacecraft longitudinal axis in the orbital plane during the long, no-acceleration experiment tests.

The aerodynamic torque also causes momentum accumulation. However, it is cyclic in nature if the spacecraft is maintaining an inertial attitude. Analysis shows the wheels cannot tolerate the momentum build-up without requiring desaturations during the experiment tests.

Solar pressure is another environmental disturbance but is small enough such that the wheels can also manage the momentum buildup without requiring desaturation. Magnetic and outgassing effects are anticipated to be negligible. The internal torques need to be assessed as the spacecraft design matures.

One of the major concerns for attitude control is fluid slosh. An interaction between the control system and the slosh frequencies could lead to gyro saturation or large disturbances on the experiment.

Typically, spacecraft will manage slosh in tanks by use of baffles. In the case of COLD-SAT, baffles can not be placed in the experiment tanks since studies are being performed to assess fluid motion and interactions. The control system will most likely employ a technique of operating at a frequency far away from the slosh frequencies.

At this point in time it is not possible to predict with accuracy the slosh or control system frequencies except that the slosh frequency was analyzed to be between 1 and 10 Hz (during on-orbit thrusting). The slosh frequency will be dependent upon the supply tank size, its geometry, fluid mass, damping characteristics, and the acceleration levels imparted on the tank. The control system frequency can only be determined given a known c.g. offset, moments of inertia, and control algorithms. Software solutions to separate control from slosh frequency include rate signal filtering or forcing control frequencies. A simulation model has been developed for use in Phase B that will predict the control system frequencies. A slosh model developed for another program will be integrated into the simulation model for COLD-SAT.

Trade studies and analyses have been performed to resolve the issues of fluid slosh, flexible body dynamics, internal disturbance torques, and fluid venting.

The degree of autonomy that the fault detection and isolation system should have will require a trade study between hardware and software costs vs reliability. The selected approach to recover from loss of attitude reference is to use the scheme developed on other MMAG programs for "Attitude Safe Hold Mode" and "Sun Aspect Mode". Experience and analyses from other similar systems such as Magellan will serve as useful information toward resolving these issues.

6.7 Propulsion

Propulsion is a required subsystem of COLD-SAT for the purposes of station-keeping, providing specified acceleration levels for experimentation, and attitude control. The requirements derived for the propulsion system are based on these functions.

Station-keeping requirements are based upon the impulse required to reorient the spacecraft between experiments in order to minimize orbit perturbations due to thrusting during the experiments. Meeting the experiments' acceleration levels is not a simple matter. Other options for performing the acceleration functions include more and different thrust levels. This option has not been investigated at this time because it is considered to require a large number of thrusters and thus add greatly to system complexity and weight. This option would, however, eliminate the need for varying tank pressure in order to achieve the desired thrust levels. The minimum size thruster available is 0.445 N (0.1 lbf). We have selected 0.89 N (0.2 lbf) thrusters for the mass of COLD-SAT.

In order to satisfy the experiment requirements for supplying the proper acceleration level(s), it is necessary to vary the thrust level of the thrusters. In other words, the various acceleration ranges of the experiments impose a requirement to be able to select various total thrust levels. This can be accomplished by selecting certain thrusters as well as varying the thrust of those thrusters between experiments. This variation of thrust is done by varying the tank pressure. Table 6.7-1 provides the correlation between acceleration requirements and thrust levels.

The system is capable of maintaining tank pressure at a given value that can be changed between experiments. The system operates by monitoring tank pressure and controlling power to the solenoid valves. The valves are commanded opened if the tank pressure falls below that desired, thus supplying more pressurant to top the propellant tanks.

Figure 6.7-1 shows the propulsion subsystem schematic for COLD-SAT. The propulsion subsystem consists of a single pressurant tank, eight hydrazine tanks, twenty 0.89 N (0.2 lbf) thrusters, valves, filters, transducers, and regulators. The pressurant tank is the same design as used for the experiment subsystem. The propellant tanks have an elastomeric diaphragm to provide positive expulsion capability and are initially loaded to a 90% fill level. The current qualified level of the tanks is 75%, but the vendor, TRW-PSI, has indicated that the higher fill level should be possible without modifying the tank design. The propellant tanks are arranged in two groups; a group of 2 tanks for low thrust experiments and a group of 6 tanks for high thrust experiments. The two groups are arranged symmetrically to prevent CG shifts during firings. The thrusters have a thrust level between 0.187 to 1.121 N (0.042 - 0.252 lbf) depending on feed pressure. Figure 6.7-2 shows the configuration of the thrusters on COLD-SAT. The thrusters are configured as close to the centerline as possible to minimize transverse accelerations. Transverse accelerations are determined by the distance from the satellite c.g.

Table 6.7-1 Experiment Accelerations and Thruster Usage

X Direction Acceleration Required (g's)	Thrust N (lbf) Required (4082 kg 9000-lb S/C)	Thrusters Used	Regulated or Set Thrust Level	Nominal Thrust	Nominal Acceleration	Max Accel. from On-pulsing	Transverse/ Longitudinal Ratio *
4.7×10^{-5} to 9.3×10^{-5}	0.09 to 0.19 (0.420 to 0.840)	(2) 0.04 N (0.2#) on constantly (1,5) 0.04 N (0.2 #) on-pulsing for control (2,3,4,6,7,8) [2 maximum]	0.05 N (0.21 lbf) 2411.5 kN/sq m (350 psia)	0.09 N (0.42 lbf)	4.7×10^{-5} g's	9.3×10^{-5} g's	10.1
1×10^{-4} to 2×10^{-5}	0.02 to 0.04 (0.090 to 0.180)	(2) 0.04 N (0.2#) on constantly (1,5) 0.04 N (0.2 #) on-pulsing for control (2,3,4,6,7,8) [2 maximum]	0.01 N (.045 lbf) 517 kN/ sq m (75 psia)	0.02 N (0.09 lbf)	1.0×10^{-5} g's	2×10^{-5} g's	10.1
9.3×10^{-5} to 1.4×10^{-4}	0.19 to 0.28 (0.84 to 1.26)	(6) 0.04 N (0.2#) on constantly (1,2,3,5,6,7) 0.04 N (0.2 #) off-pulsing for control [2 maximum]	0.05 N (0.21 lbf) 2411.5 kN/sq m (350 psia)	0.28 N (1.26 lbf)	1.4×10^{-4} g's	n/a [OFF-PULSING]	22.0 tank 1 10.1 tank 2
4.7×10^{-5} to 9.3×10^{-5} [-X ACCEL EXPERIMENTS]	0.09 to 0.19 (0.420 to 0.840)	(2) 0.04 N (0.2#) on constantly (1,5) 0.04 N (0.2 #) on-pulsing for control (2,3,4,6,7,8) [2 maximum]	0.05 N (0.21 lbf) 2411.5 kN/sq m (350 psia)	0.09 N (0.42 lbf)	4.7×10^{-5} g's	9.3×10^{-5} g's	22.0 tank 1 10.1 tank 2
4.7×10^{-5} to 9.3×10^{-5}	0.09 to 0.19 (0.420 to 0.840)	(2) 0.04 N (0.2#) on constantly (1,5) 0.04 N (0.2 #) on-pulsing for control (2,3,4,6,7,8) [2 maximum]	0.05 N (0.21 lbf) 2411.5 kN/sq m (350 psia)	0.09 N (0.42 lbf)	4.7×10^{-5} g's	9.3×10^{-5} g's	22.0 tank1 10.1 tank 2

*Worst Case acceleration requirements with two thrusters on or off pulsing
The supply tank is 1.7 m (5.5 feet) from the center of gravity
The receiver tank 1 is 3.7 m (12.0 feet) from the center of gravity
The receiver tank 2 is 1.7 m (5.5 feet) from the center of gravity

The propellant tanks are loaded by opening the service valves and filling the low and high thrust tanks. The service valves are then closed, thereby isolating the low and high thrust legs. On-orbit, the pyro valve upstream of the filter in the propellant feed line is opened, allowing hydrazine to fill the feed lines up to the thrusters. The high thrust experiments are then performed by maintaining the propellant tank pressure at 2411.5 kN/m^2(350 psi) with the pressure regulators and withdrawing propellant from the group of 6 tanks. The low thrust experiments are performed consecutively, so the pressure in the propulsion system only has to be reduced once. This is accomplished by closing the multi-function pyro valve, which isolates the group of 6 high thrust tanks, and opening the pyro valve in the pressurization line to permit pressurized outflow from the group of 2 low thrust tanks. During the low thrust experiments, the pressure in the propellant tanks is maintained at 517 kN/m^2 (75 psi) by modulating the latching valves by the regulators. The check valves in the pressurization line prevents blowdown pressurization from the group of 6 high thrust tanks. Upon completion of the low thrust experiments, the multi-function pyro valve is opened and the remainder of the experiments are performed at the high thrust level. At this point the two tanks performing low thrust operations remain manifolded to the 6 high pressure tanks and provide common high pressure propellant for the rest of the mission.

The propulsion subsystem takes advantage of an experiment set test plan which performs low thrust experiments consecutively. If the test plan would change so that the low thrust experiments are performed throughout the mission, then the propulsion subsystem would have to be modified to permit multiple changes in thrust levels. A statistically designed experiment approach may require more variation in thrust levels.

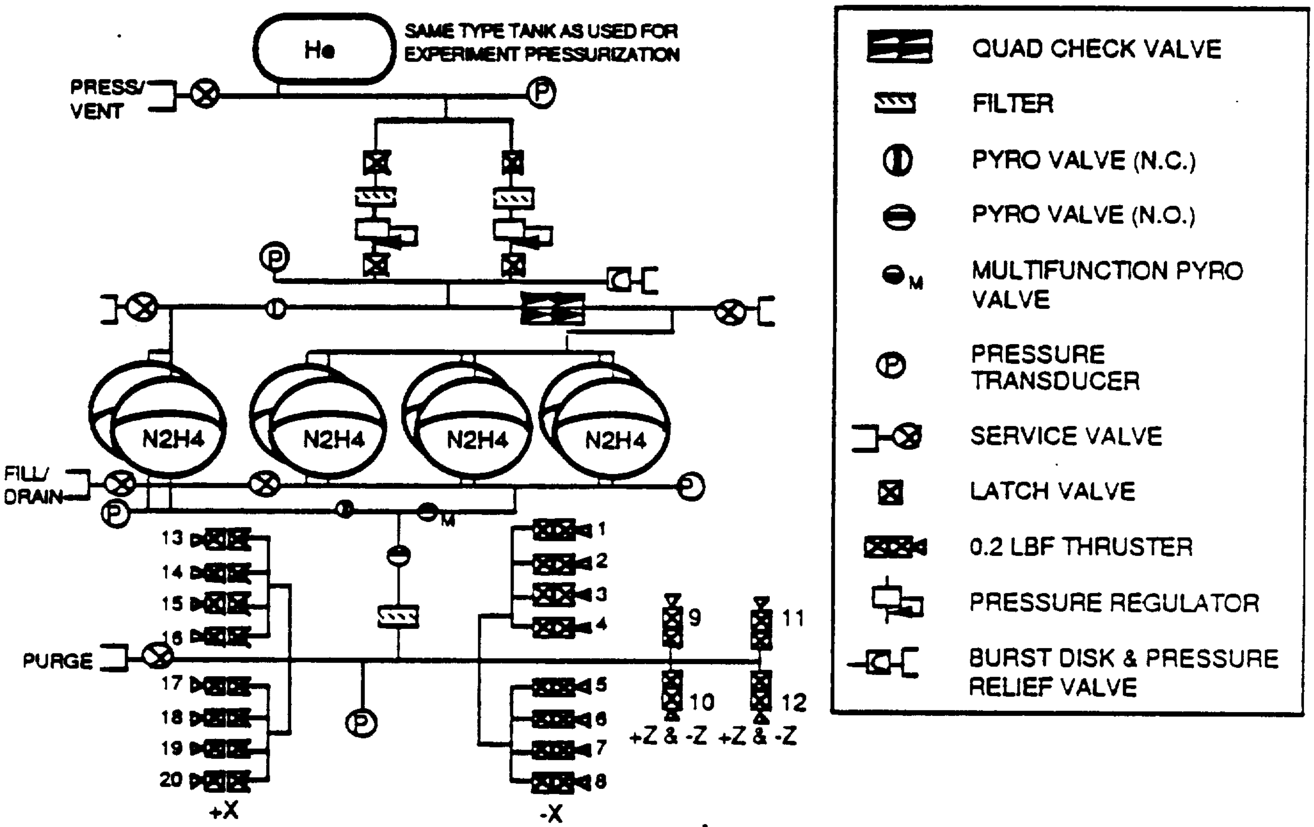
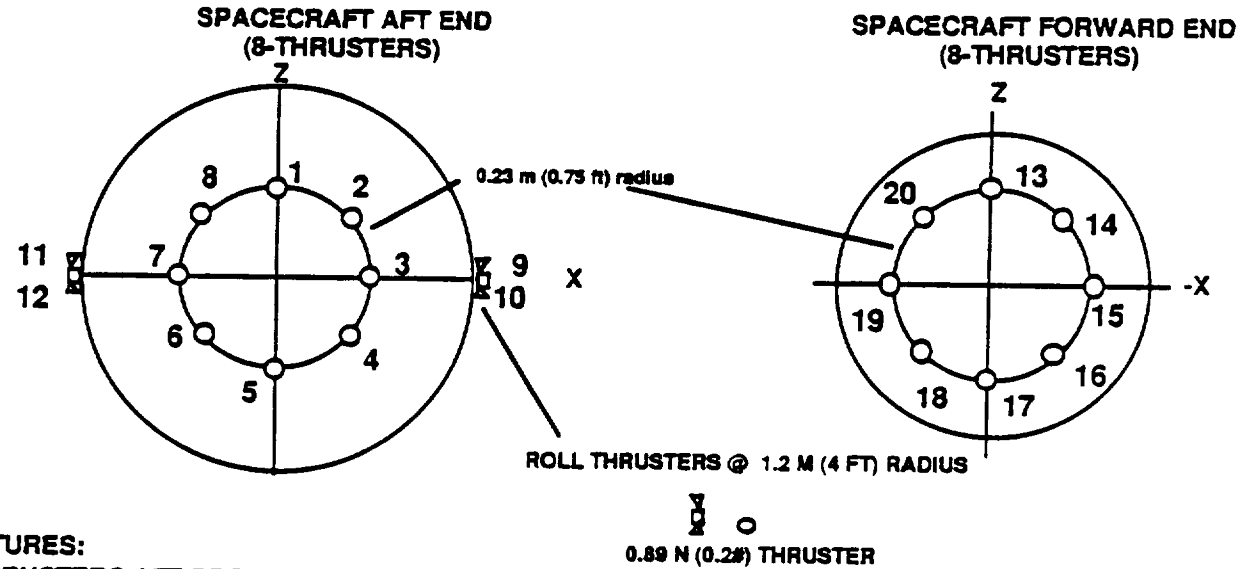


Figure 6.7-1 Propulsion Subsystem Schematic



FEATURES:
- 8 THRUSTERS AFT PROVIDE ACCELERATION & 4 DEGREE OF FREEDOM CONTROL, REDUNDANCY IS FROM 2 OF THE 8 THRUSTERS
- THRUSTERS WITHIN 1.2 M (0.75 FEET) OF LONGITUDINAL AXIS TO MINIMIZE TRANSVERSE ACCELERATION WHEN OFF-PULSING OR ON-PULSING FOR CONTROL
- PRESSURE REGULATION SYSTEM ALLOWS SELECTION OF REQUIRED THRUST LEVELS FOR EXPERIMENTS

Figure 6.7-2 Thruster Configuration

The propulsion module electronics (PME) will have the function of providing the measurement data to the TT&C subsystem. The electronics will also accept formatted commands to activate the valves and heaters of the propulsion subsystem. The PME, built by Martin Marietta, is compatible with the MMMS

The hydrazine is contained in eight diaphragm tanks. The system requires pressure regulation for maintaining a selected constant thrust level for each thruster throughout a given experiment. Two different tank pressures are required for meeting the range of acceleration requirements of the experiments. The two tank pressures of 2756 & 586 kN/m^2 (400 & 85 psi) combined with appropriate thruster firing schemes provide the flexibility needed for desired accelerations and attitude control. The system is provided with redundant main pyro valves for the propellant lines. Roll thrusters are placed in REMs (rocket engine modules) that contain two thrusters per REM.

Due to the large number of fluctuations in required experiment acceleration levels, it is unacceptable to dump pressurant each time the thrust level must decrease due to the large pressurant tanks required. One alternative is to add several different thrust levels of thrusters to the system. This would significantly increase the number of components and complexity of the propulsion system. Therefore, the compromise solution between pressurant tank size and system complexity is to independently pressurize two of the propellant tanks at 2756 kN/m^2 (85 psi) and the other six at 586 kN/m^2 (400 psi). This is accomplished by a combination of check valves and latching valves that isolate the tanks not being used in a given experiment and thus result in no pressurant needing to be dumped overboard.

The components in the propulsion system have either been flown or have been flight qualified.

The thruster patterns are at both the fore and aft ends of the spacecraft. The aft end has eight 0.89 N (0.2 lbf) thrusters (6 required) to accommodate the highest experiment acceleration requirements and allow for some redundancy in case of failure. Also on the aft end are the four roll thrusters which are 0.89 N (0.2 lbf) each. The 0.89 N (0.2 lbf) thrusters accommodate pointing the longitudinal-axis of the S/C. The eight thrusters at the front end provide negative thrust along the longitudinal axis.

The longitudinal thrusters are in patterns of eight in order to provide redundancy and to provide for control by on-pulsing. For instance, one or two thrusters would be on-pulsed if two thrusters in a pattern are already continuously firing. Off-pulsing of up to a maximum of two thrusters would be used for control where six thrusters are firing.

The major issue in the on-board propulsion system for thrusters is the steady state life of the 0.89 kg (0.2 lbf) thrusters. The function of providing low acceleration in the +longitudinal direction requires that two of the 0.89 N (0.2 lbf) thrusters on the aft end of the spacecraft handle on the order of 227 kg (500 lbm) total propellant used for the experiments. This assumes that the other six 0.89 N (0.2 lbf) thrusters on the aft end are for contingency use only (redundancy). Therefore, two thrusters must each be capable of less than 100 hours of essentially steady state operation apiece. This does not appear to present a major problem since according to Rocket Research personnel (the only manufacturer of the 0.89 N (0.2 lbf) thruster). These thrusters have been ground-tested to as much as 227 kg (500 lbm) for 500 hours of steady state operation.

The only other potential problem with the thrusters would be a result of high pulse rate (high frequency) operation. This tends to thermally cycle the catalyst bed and thus cause increased wear on the thruster. In addition, the valves may experience wear as a function of high cycle operation. The pulsed operation of the thrusters aboard this spacecraft corresponds to typical ACS thruster operation for the deadband of spacecraft attitude control. In other words, there is no high cycle or high frequency operation anticipated for the thrusters.

The ordnance valves for the COLD-SAT experiment would be supplied by Pyronetics. Their model 1420 valve was developed during and in support of the Viking Program. This valve uses redundant ordnance - any one of which would operate the valve. The valve contains dual seats of parent CRES material which is sheared upon operation to open the valve. The 1420 valve is the 1.9 cm (3/4 inch) valve which requires a pressure cartridge in addition to the NASA Standard Initiator (NSI) for activation. Pyronetics has developed and qualified many valves of various sizes which are very similar.

The N2H4 multifunction ordnance isolation valves (P/N 3325) for COLD-SAT would be supplied by Siebelair. The valves are normally open and are closed with a pyro initiation at one end of the valve. The valve is opened by a pyro initiation at the other end of the valve. In this way, the normally open valve is reopened. The multifunction capability provides a reliable and inexpensive means of switching propulsion system pressure without using latching valves. The multifunction valve is flight qualified and has flown on STS.

The GHe pressurant storage tanks will be loaded through high pressure service valves provided by Pyronetics. This valve utilizes a metal-to-metal poppet/seat design wherein the internal pressure within the system tends to assist seating the poppet. This valve also incorporates dual seals and the potential for three independent seals, if necessary. This design is utilized on many high pressure gas systems as well as storables. The valve materials are basically CRES with the seat being 15-5 PH. All seals are teflon or KEL-F.

The N2H4 tanks will be loaded through service valves provided by Pyronetics . This valve utilizes a metal-to-metal poppet/seat design wherein the internal pressure within the system tends to assist seating the poppet. This valve also incorporates dual seals and the potential for three independent seals, if necessary. This design is utilized on many high pressure gas systems as well as storables. The valve materials are basically CRES with the seat being 15-5 PH. All seals are teflon or KEL-F.

The thrusters for the COLD-SAT experiment would be supplied by Rocket Research Company. The thruster part number is MR-103C which is part of the MR-103 family of engines. The MR-103C has flown on Magellan, SATCOM, Spacenet, and G-Star. The thruster has a variable thrust capability between 0.187-1.121 N (0.042-0.252 lbf), depending on inlet pressure. COLD-SAT will use thrust levels between 0.2-0.9 N (0.045-0.21 lbf). The thrust variability permits the use of a single engine design to provide all required thrust levels. The thruster has 100:1 expansion and a dual seat, Wright Components, valve (P/N 15726). The thruster demonstrated 158,531 N-sec (35,625 lbf-sec) total impulse capability, 64,800 second continuous firing time, minimum impulse bit of 0.00445 N-sec (.001 lbf-sec) and 1033.5 kN/m^2 (150 psi) inlet pressure, and 410,000 total pulses.

The propellant tank for COLD-SAT would be supplied by Pressure Systems Incorporated (PSI), a subsidiary of Thompson, Ramo, Woolridge (TRW). The selected tank part number is 80274-1 and has previously flown on EXOSAT. The tank is spherical with a 0.48 m (19.03 inch) inner diameter. The wall material is 6Al-4V titanium. The tank uses a positive expulsion AF-E-332 elastomeric diaphragm for low-g fluid expulsion. The minimum wall thickness is 0.06 cm (0.023 inch) and the tank weight is 6 kg (13.25 lbm). The maximum operating and burst pressures are 2598 and 5195 kN/m^2 (377 and 754 psi), respectively. Normally this tank is utilized in a blowdown mode and only filled to a 75% level with propellant. Use with regulated pressurization and an initial fill to 90% is not a vendor concern although some delta qualification may be required.

The propulsion subsystem would use the same pressurant tank from Structural Composites Incorporated (SCI) as used by the experiment subsystem. The tank has a seamless aluminum liner overwrapped with a HITCO T-49 graphite/epoxy composite. The tank has a cylindrical barrel section and square-root-of-two domes. The cylindrical barrel section simplifies overwrapping, resulting in a high performance design.

The relief valves selected for the COLD-SAT application are designed and produced by Ametek/Straza Division of Ketema. The valves shall be of stainless steel construction and utilize teflon or KEL-F for seats and "O"-rings. Valve construction uses a secondary pressure pickup area which increases valve sensitivity. At valve cracking pressure the flow past the poppet flows into the secondary chamber. The secondary pressure buildup then acts over a larger diameter of the poppet thereby reducing the band from cracking to full flow. The burst disks selected for the COLD-SAT application are designed and produced by Ametek/Straza Division of Ketema. The burst disc incorporates a Belleville spring with the diaphragm. The principle of operation results in a change from increasing to decreasing force during the stroke as opposed to a coil spring which requires a uniformly increasing force to compress it. The snap over action of the Belleville results in a clean shear of the diaphragm as it is driven into a hollow punch.

The burst disk will be of stainless steel construction and will incorporate a downstream screen to trap the cut out section, thus preventing contamination of the relief valve, which is downstream of the burst disk.

The gas and liquid filters selected for the COLD-SAT GHe application are designed and produced by either Wintec or Vacco. The filters are totally welded and shall be of all stainless steel construction. The filter element is either pleated wire mesh or an etched disc, with a 25μ absolute rating. The design of the filter could permit removal of the filter element for cleaning, repair, or replacement with the filter body installed if necessary. However, since all media is filtered prior to entering the system this is not considered necessary and the filters are just added insurance to prevent any contamination from causing a problem.

The pressure transducer selected for the propulsion subsystem is the basic variable reluctance unit designed and built by the Tavis Corporation. The unit operates with a 28 vdc input and provides an output of 0-5 vdc which is linear within the pressure range of the unit.

The Sterer Engineering design for the GHe pressure regulating valve for COLD-SAT is based on the specific design utilized on the Manned Maneuvering Unit (MMU) regulator, which they developed. The MMU regulator was required to reduce 24804 kN/m^2 to 1461 kN/m^2 (3600 psig to 212 psig) with an output tolerance of ±103 kN/m^2 (±15 psi) while flowing GN2 at 1.19 to 3.74 standard cubic meters per minute (42 to 132 standard cubic feet per minute). The ±103 kN/m^2 (±15 psi) regulation tolerance applies to the GHe outlet pressure throughout the inlet pressure range and the GHe temperature range of 206 deg K to 406 deg K (-90°F to +150°F).

The GHe isolation valves (P/N 6699) were selected from Consolidated Controls Corporation. The valve is a latching, single stage solenoid valve designed to operate with a 28 VDC input signal. The valve has 34450 kN/m^2 (5000 psi) pressure handling capability and low pressure drop of 172 kN/m^2 (25 psid) at 0.14 kg/min (0.3 lbm/min) flow of helium. The valve has low internal leakage of less than 0.3 scc/s (0.02 standard cubic inches/sec) of helium. The valve is flight qualified for manned spacecraft and has flown on Apollo.

The check valve for COLD-SAT were selected from HTL. The valve is a quad package with two parallel legs, each containing series check valves. This packaging provides failed open and closed redundancy in a single unit. The package is all welded and has low pressure drop and internal leakage. The valve is flight qualified and has flown on Mariner.

6.8 Software

Flight software is divided into the four areas of Experiment Control, OBC Computations and Operations, Attitude Control, and Telemetry and Command Handling Operations.

The COLD-SAT software concept utilizes a compatible interface between test and flight and mission operations software. The flight architecture uses a high order language to shorten the design time period.

The experiment test sequences will be capable of being adjusted in flight. Sequence starts and durations will also be adjustable in flight. Attitude control pointing of the TDRSS antenna and the spacecraft will also be able to be updated.

The top level functions performed by software are

1. ACS and Experiment Control
2. Recorder Management
3. Telemetry Control
4. Redundancy Management and Fault Protection

Experiment sequence, parametric experiment data, orbit corrections, spacecraft positioning and fault recovery instructions will be reprogrammable in flight via TDRSS uplink to the spacecraft. Software estimates are provided in the table below.

	LINES OF CODE	
ACS	3650	Provides spacecraft orbit corrections and positioning for maneuvers such as solar array aiming. It is designed to accept commands uplinked via TDRSS
Experiment Control	8375	Experiment sequences instructions will be resident on-board the spacecraft. Commands will be sent via TDRSS to select the order that sequence instructions are to be performed and select associated parametric data
Recorder Management	300	Provides control of telemetry data storage on the recorder and playback of the telemetry data during active TDRSS communications to the SOCC
Telemetry Control	300	Provides control and integration into a telemetry data stream of spacecraft data and experiment data
Redundancy	300	Provides self checks of spacecraft health and means to switch to the backup on failure. Estimate is based on maximizing use of built in hardware self checks with minimal software redundancy. This will be revisited as the design progresses.
Command Acceptor	1450	Provides engineering test of the on-board software during development.
Response Generator	1750	Provides engineering test of the on-board software during development.

The software has been sized consistent with similar spacecraft subsystem requirements. The experiment subsystem software requirements provide a different sizing requirement because of the multiple sensor and control of valves requirement.

6. 9 Spacecraft Conclusions and Recommendations

The most significant concern was the payload shroud envelope. The restricted volume causes some difficulty in the design integration of the hardware and will require careful planning in the assembly flow. The use of the MMS modules eases the integration complexity. A reduced experiment set and the resulting decrease in the size of the storage tank and the propellant tanks eased any weight concerns.

An assembly and test flow has been laid out that will be within the capability to reliably assemble the satellite. It will be significantly advantageous to be able to fabricate the experiment subsystem at an off-line system level and then integrate the experiment subsystem into the satellite. In this way it may be possible to perform the thermal vacuum characterization tests in a smaller test facility.

The conceptual design of the satellite has been evaluated for reliability and risk during the concept development. The basis of the high reliability and low risk estimate is the use of spacecraft avionics that are presently in production and will require minimum modifications for its electronic functions. There is less risk using the MMS modules in tact and not changing the mechanical interfaces to the modules. The MMMS modules can fit in the shroud envelope along with the LH2 tank sizes.

The effect of acceleration forces on the experiment heat transfer and fluid motion characteristics produce transient dynamics. Damping and isolation will be used where possible to avoid self-induced accleraations on the spacecraft. An ACS fluid slosh model will be integrated into the attitude control simulation model to determine the characteristics and interactions.

Additional spacecraft simplification depends on establishing compromises to experiment requirements. As they are eased with respect to numbers of tests, amount of LH2, amount of propellant for acceleration, spacecraft attitude and pointing restrictions, etc. a lighter weight and simpler spacecraft is possible if the spacecraft simplification is allowed to drive the experiment requirements. As an example, if a simple, cost effective propulsion system results in acceleration and propellant quantity limits, the experiments should then be designed to operate within the established limits. The resulting data would then be more of a demonstration nature rather than providing model validation.

The following reflects some recommended changes that could reduce spacecraft weight and complexity. They would be implemented in consonance with recommended experiment subsystem modifications. Such combined modifications could result in a dry satellite weight of around 1814 kg (4000 lbs) or 2494 kg (5500 lbs) wet. A smaller, less expensive launch vehicle, such as the augmented Titan II, may then become a viable option that would further reduce the overall system cost. See Ref 6.9-1 for additional information on reduced size COLD-SAT options.

- Modify the propulsion system to use simple blowdown with possibly several fixed recharges for propellant expulsion. Delete the forward propulsion module that allows liquid settling over the tank vents. Only a few of these tests are currently planned and their elimination does not significantly degrade the experiment set. This change has a major impact on the capability to maintain "clean" accelerations and associated fluid regimes of interest. Reduce the number of propellant tanks using tanks as large as possible and fix the experiment set to these restrictions is also a recommendation. A major propulsion issue, that is worsened as satellite weight is decreased, is the developed thruster capability to provide very low thrust below 0.45 N (0.1 lb) to meet required experiment acceleration regimes. Further assessment in this area are required.

- Go to fixed solar arrays and accept attendant restrictions on S/C pointing and available power on experiment requirements.

- Reconfigure the MMS modules aft to accommodate ELV cg constraints to account for supply tank weight reduction from no vacuum jacket. The resulting S/C structure is greatly changed.

The ground segment consists of the ground support equipment used for test and assembly and installation of the flight hardware and software along with the operations hardware and software at the Satellite Operations Control Center (SOCC). The operations concept limits the number of personnel thus sizing the SOCC equipment. Figure 7-1 is the functional block diagram of the ground support equipment for COLD-SAT.

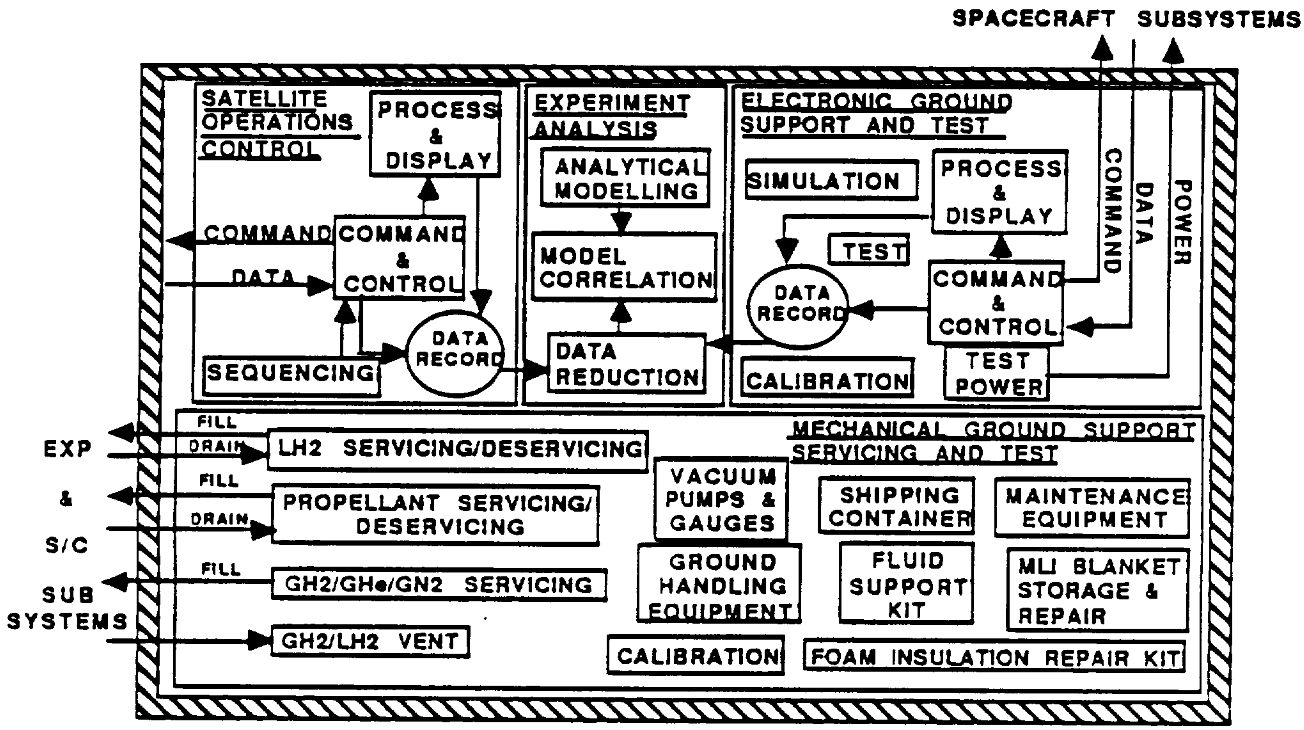


Figure 7-1 Ground Segment Functional Block Diagram

Mechanical Ground Support Equipment (MGSE) - The MGSE provides ground servicing, handling support, transportation support, and maintenance functions for the satellite. The major MGSE structural hardware items include a transporter with protective cover, handling and rotation dolly, handling/lifting slings & strongback, holding fixtures and installation tools. In addition, a separation interface test set and alignment test equipment are provided. Support equipment for the experiment and propulsion subsystem includes a propellant servicing/deservicing cart, propellant high pressure GHe pressurant servicing panel, LH2 servicing/deservicing system, high pressure GH2 experiment pressurant servicing system, high pressure GHe experiment pressurant servicing panel, experiment and propellant system leak check kits, fluid support equipment and miscellaneous calibration equipment. Figure 7-2 depicts the major interfaces with the spacecraft.

Electrical Ground Support Equipment (EGSE) - The EGSE provides command, control, calibration, simulation, ground 28 Vdc power to the satellite, and data management of the spacecraft and experiment subsystems during ground test and checkout operations. A major portion of the EGSE hardware is comprised of the spacecraft TTCS support equipment comprised of a RF test set, sun sensor simulator, articulation simulator, EPS simulator, ACS simulator, mission sequence and command generation system, monitoring system, display equipment and printer. In addition, a power distribution system, spacecraft electrical power subsystem support equipment, electronics integration test set, and solar panel test equipment are provided.

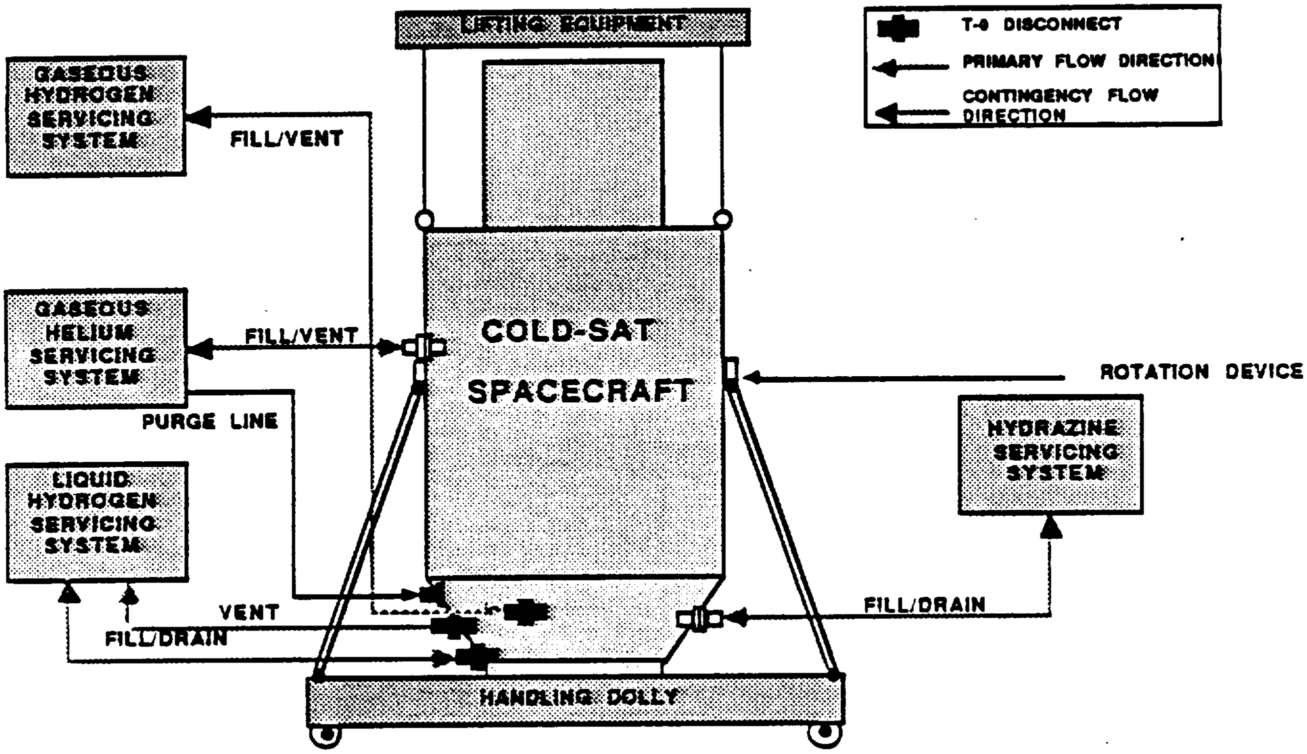


Figure 7-2 COLD-SAT MGSE Interfaces

Satellite Operations Control Center (SOCC) - The SOCC provides in-flight command, control and management of flight data (both realtime and recorded) for COLD-SAT. Operations software is included in the SOCC. The SOCC includes a router, telemetry preprocessor, data management work stations, mission planning and scheduling work stations, and personal computers for experiment monitoring and data processing. Figure 7-3 depicts the flow of data, commands, and tracking through NASCOM and TDRSS.

The spacecraft provides data through TDRSS and GSFC to the SOCC and to the GSE. The spacecraft may be commanded from the SOCC through GSFC and TDRSS, or directly from GSFC through TDRSS.

Handling equipment is provided to move and hold the spacecraft during assembly and checkout and installation at KSC.

7.1 MGSE

The mechanical interfaces with the COLD-SAT spacecraft include lines to a gaseous hydrogen servicing system, to a gaseous helium servicing system, to a liquid hydrogen servicing system and to a hydrazine servicing system. A handling dolly is required along with lifting equipment to be used while assembling the spacecraft.

Transportation - The satellite transporter along with a protective cover will be used to move COLD-SAT during the move to the facilities where integrated testing occur. The satellite will be transported by air to the LH2 thermal vacuum facility (if necessary) and to KSC.

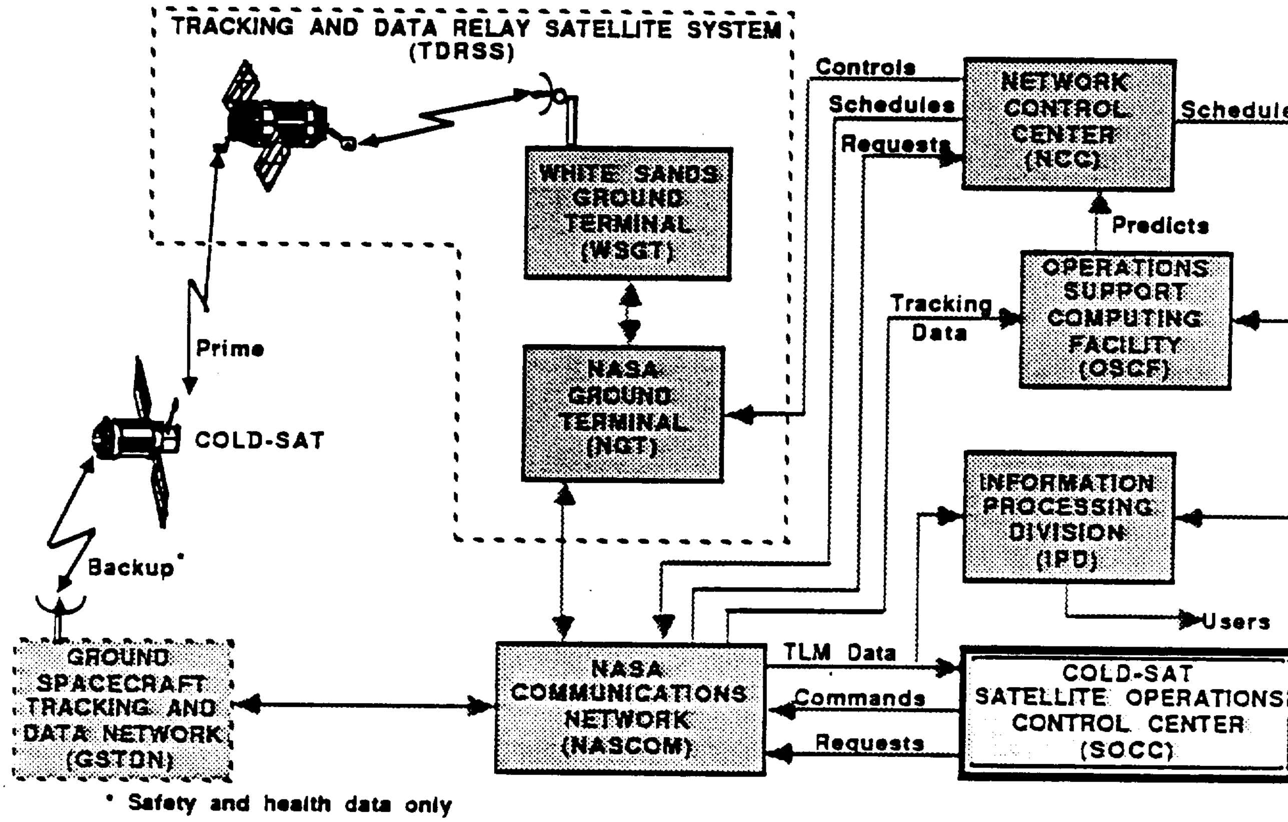


Figure 7-3 COLD-SAT SOCC to TDRSS Interfaces

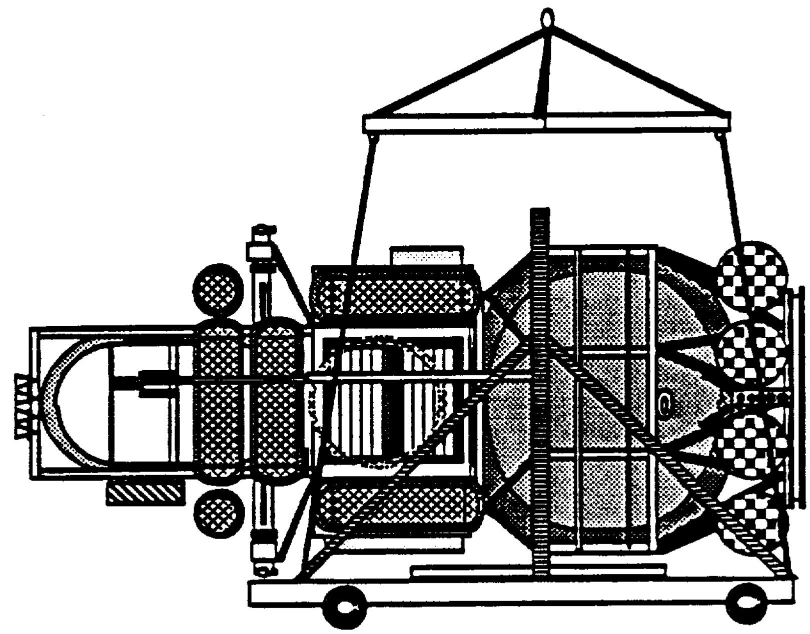
Figure 7.1-1 shows the transportation approach we have selected. Ground transportation will be used from the contractor facility to the local airport. If a suitable hazardous thermal vacuum chamber exists away from the contractor's facility air transport will be used. Air transport will be used to move COLD-SAT to the CCAFS. Ground transportation will be used for all movement at CCAFS.

One method of transportation that can be used between the contractor's facility and the thermal vacuum test facility (if this facility is not at the contractor's site) is to use the PETS or Payload Environmental Transportation System, a truck transport method belonging to NASA.

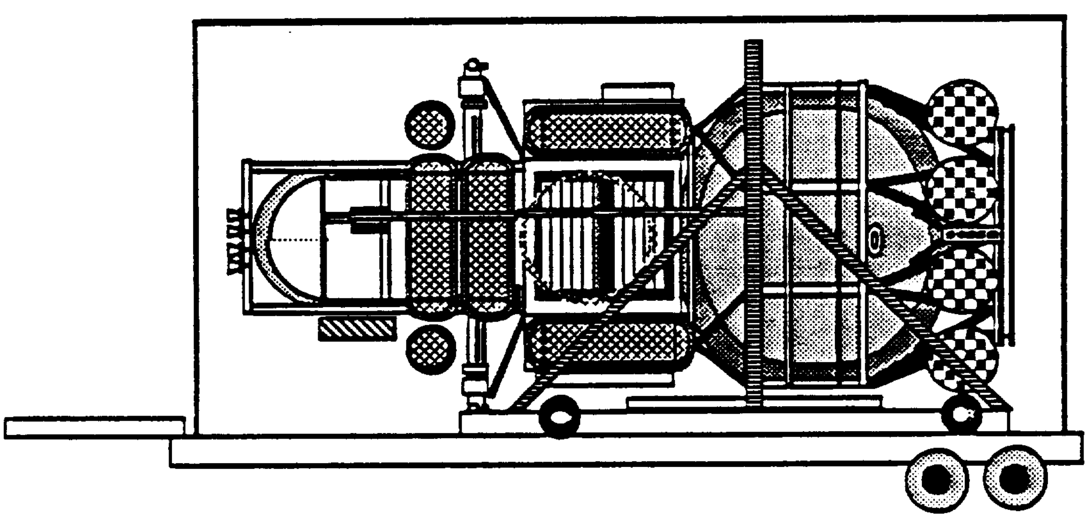
Handling - A handling dolly is required along with lifting equipment to be used while assembling the spacecraft. The dolly is accommodated in both the contractor facilities and in the KSC facilities.

A handling sling is required along with lifting equipment to be used while moving or rotating the spacecraft. The sling is accommodated in both the contractor facilities and in the KSC facilities. Handling Equipment for COLD-SAT would be built new because of the unique size and shape of the spacecraft.

PPF - The requirements for the Payload Processing Facility (PPF) are to provide for support equipment assembly, integration, and checkout, receiving inspection, and rotation, final assembly and installations, systems test and checkout, and a SOCC end-to-end test. A ground checkout and control station and personnel accommodations are required. CCAFS buildings AM,AE, and AO are suitable for COLD-SAT. The preliminary recommendation is to use building AM. Table 7.1-1 is a parametric look at the PPF requirements and the facility capabilities.



INTEGRATED HANDLING APPROACH



TRANSPORTER W/PROTECTIVE COVER

Figure 7.1-1 Transportation Concept

Table 7.1-1 Launch Site Processing Facility Requirements Summary

	PPF Requiremnts			Building AO			Building AE			Building AM			Astrotech Bldg 1			Hangar S (south)		
Dimensional	L	W	H	L	W	H	L	W	H	L	W	H	L	W	H	L	W	H
Largest Doorway	--	12'	30'	--	25'	40'	--	14'9"	38'1"	--	15'7"	34'5"	--	20'	23'	--	15'	19'
Airlock40'		15'	30'	29'	28'	48'	17'	33'	40'		none		120'	30'	24'	20'	18'	20'
High Bay	40'	40'	30'	45'	175'	48'	51'6"	43'10"	34'	63'	70'	35'	60'	40'	43' 5"	45'	55'	20'
Ground Station				79' (2)	33'	15'	28'6"	18'9"	10'	30'	26'	9'9"	30'	14'	8' 9"	22'	23'	10'
Storage													25'	22'	28'			
Offices					2586 sq ft			1119 sq ft			5225 sq ft			1188 sq ft			4184 sq ft	
Cranes																		
Capacity		5T			10T			6T			5T			10T			5T	
Hook Height		35'			48'			38'10"			36'			37'			19'	
Environmental																		
Temperature		75±5°F			75±2°F			72±3°F			75±3°F			75±5°F			72±3°F	
Humidity		50±5%rh			45±5%rh			55±5%rh			45±5%rh			50±5%rh			45±5%rh	
Cleanliness		100K			100K			10K			100K			100K			100K	
Electrical																		
Power		120vac-60a-1&3Ø 208vac-70a-3Ø			120vac-20,30,50a-1Ø 208vac-30a-1Ø 120/208-15,30,60,100a-3Ø 120vac-20a1Ø-400Hz 480vac-30a-3Ø			120vac-20a-1Ø 120/208vac-30a-1Ø 120/208vac-60a-3Ø 480vac-30,60a-3Ø			120vac-15,20,30a-1Ø 120vac-20a-400Hz-1Ø 250vac-30a-1Ø 120/208-60,100a-3Ø 28vdc available			120vac-20a-1Ø 120/208vac-60a-3Ø 480vac-30a-3Ø			120vac-15,20,30,50a-1Ø 120vac-30a-400Hz-1Ø 120/208vac-30a-1Ø 120/208vac-60a-3Ø 480vac-30a-3Ø	
Grounding		Facility Provisions			Facility Receptacles			Facility Receptacles			Facility Receptacles			Facility Receptacles			Facility Receptacles	
Commodities																		
Compressed Air		√			125/225 psig			100 psig			115/200 psig			125 psig			100 psig	
GN2		√						150/3800 psig									2200/6000 psig	
GHe		√															2200 psig	
Communications																		
Telephone		√			√			√			√			√			√	
OIS		√			√			√			√			√			√	
OTV		√			√			√			√			√			√	
Timing/Count Clocks		√			√			√			√						√	
Antennas		√			√			√			√			√			√	
Data Lines		√			√			√			√						√	
Facsimile		√			√			√			√						√	
Safety																		
Hazardous Ops Rqmnts		Lifts/Hoists			Lifts/Hoists			Lifts/Hoists			Lifts/Hoists			Lifts/Hoists			Lifts/Hoists	
Security		Standard Restricted Personnel Access			Standard Restricted Personnel Access			Standard Restricted Personnel Access			Standard Restricted Personnel Access			Standard Restricted Personnel Access			Standard Restricted Personnel Access	
Comments					Airlock Entry Could be a Problem, N2/He Sources Required, H/B Over Rqmnts			Airlock Entry/HB Ht Could be Problems, He Source Required, H/B Good Match			H/B Ht Could be Problem, N2/He Sources Rqd, H/B Good Match			Airlock Ent/HB Ht Could be Problems, N2/He Sources Required, H/B Good Match			Ceiling Hieght is too Restrictive	

The driving requirement for the choice of facilities is the overhead crane height capability. The COLD-SAT will need about 10 meters in height in the highbay.

HPF - The requirements for the Hazardous Processing Facility are to provide support equipment assembly, integration and checkout, provide for a proof pressure demonstration test, provide N2H4 servicing and pressurization, and install the Delta II Upper Stage Assembly Handling Can. CCAFS Explosive Safe Area ESA 60 Propellant Lab is the preliminary recommendation. Table 7.1-2 gives the parametric look at what is required versus what is available.

Launch Pad - The only new design equipment required for KSC operations is an LH2 and GH2 Loading and Vent System. Investigation into availability of hardware from completed programs is on-going. GH2 loading is now planned to be accomplished at the pad. This will require additional pad hardware. The modifications to Pad 17B are shown in Figure 7.1-2.

The Hydrogen loading approach features or accommodates nominal and emergency venting after LH2 & GH2 loading, topoff is easily accomplished, and launch delays/scrubs are better accommodated.

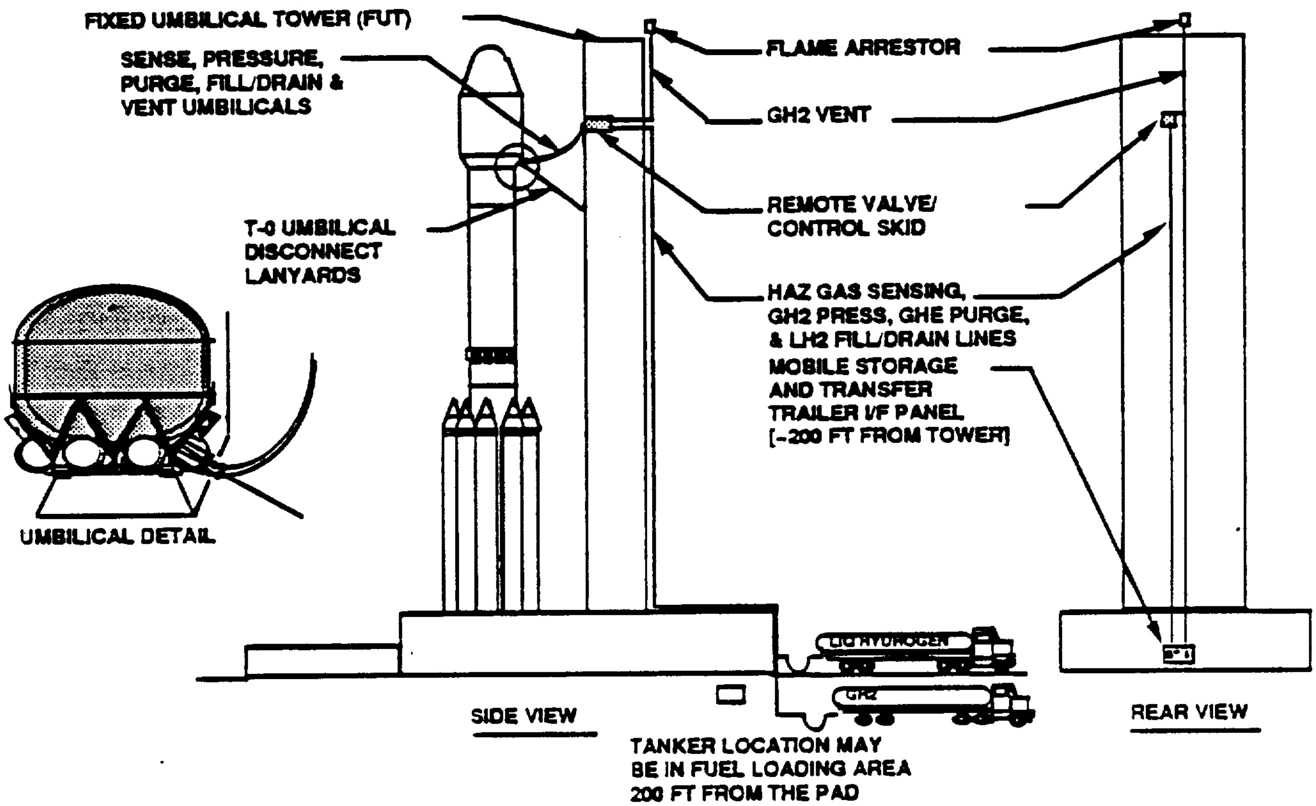


Figure 7.1-2 Launch Pad 17B Modications for Coldsat

7.2 EGSE

Using standardized components allows the use of existing support equipment no longer required for their previous missions. Martin Marietta built MMS support equipment is presently available at Martin Marietta for further design analysis.

SOCC Equipment for flight operations can be obtained, in part, from GSFC. The equipment used on Magellan for operations support might be made available thru JPL.

The user Satellite Operations Control Center (SOCC) Data Processing Facility functional traffic interfaces are command, telemetry, and tracking data through TDRSS and the functional operational interfaces are with the Network Control Center (NCC) for user utilization of the TDRSS telecommunications services.

The SOCC hardware is commercially available and similar to Magellan Operations equipment. A block diagram of the SOCC hardware is shown in Figure 7.2-1.

The following listing of hardware describes the SOCC hardware.

ROUTER
Commercial hardware - serves as gateway and formatter interfaces to GFE data transmission equipment(DTE) that interfaces to commercial long haul line vendors data carrier equipment (DCE); routes PCM to telemetry pre-processor; formats commands and requests for transfer over NASCOM to NASA or the vehicle.

Table 7.1-2 Servicing Facility Requirements

	HPF Requiremnts	PSTF	ESA 60 (SAB)	ESA 60 (PropLab)	Astrotech Bldg 2	RTG Storage Area
Dimensional	L W H	L W H	L W H	L W H	L W H	L W H
Largest Doorway	-- 12' 30'	-- 15' 30'	-- 18' 35'	-- 20' 30'	-- 20' 40'	-- 14' 14'
Airlock	-- 12' 30'	36'5" 50' 34'	48' 24' 39'	Portable Available	38' 29' 43'	none
High Bay	20' 20' 30'	36' 60' 34'	55' 37' 39'	36' 30' 30'	60' 37' 43'	42' 61' 25'
Control Room		23' 18' 12'	33' 15' 10'	33' 15' 10'	25' 15' 9' 4"	none
Storage						
Offices	None	N/A	N/A	N/A	Bldg 1	N/A
Cranes						
Capacity	None	4.5/9T	5T	10T	10T	5T
Hook Height		36'	34'	31'	37'	18'
Environmental						
Temperature	75±5°F	75±5° F	68-98° F	73±3° F	75±5° F	72±2° F
Humidity	50±5%rh	50±5% rh	35-55% rh	50±5% rh	50±5% rh	45±5% rh
Cleanliness	100K	≈100K	100K	100K	100K	N/A
Emergency Exhuast			√	√	√	
Electrical						
Power	Class I, Div II, Group B Explosion Proof 120vac-60a-1&3Ø 208vac-70a-3Ø	Explosion Proof 120vac-20a-1Ø 120/208vac-20,30a-3Ø	Class I, Div II, Group D Explosion Proof 120vac-15,30a-1Ø 120/208vac-60a-3Ø 120vac-20a-1Ø-400Hz	Class I, Div I, Group D Explosion Proof 120vac-15,30a-1Ø 120/208vac-60a-3Ø	Explosion Proof 120vac-20a-1Ø 120.208vax> 60a- 3Ø 460vac-30a-3Ø	Class I, Div II, Group C,D Explosion Proof 120vac-20a-1Ø
Grounding	Facility Provisions	Facility Receptacles	Facility Receptacles	Facility Receptacles	Facility Receptacles	Structural System
Commodities						
Compressed Air	√	200 psig	0 to 200 psig adjustable	0 to 200 psig adjustable		
GN2	√		2400 psig	2400 psig		
GHe	√			provision for 6000 psig	125 psig	
Communications						
Telephone	√	√	√	√	√	
OIS	√	√	√	√	√	
OTV	√	√	√	√	√	
Clocks	√	√	√	√		
Antennas	√	√	√	√	√	
Data Lines	√	√	√	√		
Facsimile	√		√	√	√	
Safety	N2H4Servicing	N2H4 Servicing	N2H4 Servicing	N2H4 Servicing	N2H4 Servicing	Under Investigation
Security	Standard Restricted Personnel Access	Standard Restricted Personnel Access	Standard Restricted Personnel Access	Standard Restricted Personnel Access	Standard Restricted Personnel Access	Standard Restricted Personnel Access
Comments		Good COLDSAT Match	Good COLDSAT Match	Good COLDSAT Match	Good COLDSAT Match	Not Suitable for COLDSAT due to Height Limits

TLM PRE-PROCESSOR
Commercial hardware - decommutates PCM; does real-time preliminary evaluation of data according to a set of approximately 13 algorithms; provides tape and disk storage of vehicle data as it comes in from NASCOM; also detects and displays vehicle time. Separate time code equipment displaying time to beginning of vehicle TDRSS link and time to end of TDRSS link to the vehicle; has decommutator, compressor, frame and subframe synchronizer, digital tapes, disks, terminal and 2 Ethernet ports; existing commercial off-the-shelf system similar to what will be at JPL for Magellan telemetry data pre-processing.

DATA MANAGEMENT WORK STATION
Commercial hardware - provides TLM pre-processor setup, storage of common data base (e.g. calibration curves), formats user selected data for output to plotters or line printers, has dual Ethernet ports - one to the telemetry pre-processor for setup and one to the central SOCC Ethernet for data and commands; also contains 2 plotters, 2 line printers, multiple disk drives and digital tape drives, external storage for database and experiment data storage; uses h/w similar to Magellan vehicle monitoring system Martin Marietta has developed for Magellan tracking in Denver; uses advanced

work station s/w developed in ADA for space station that has been used for national test bed, R2P2 and OSCRS.

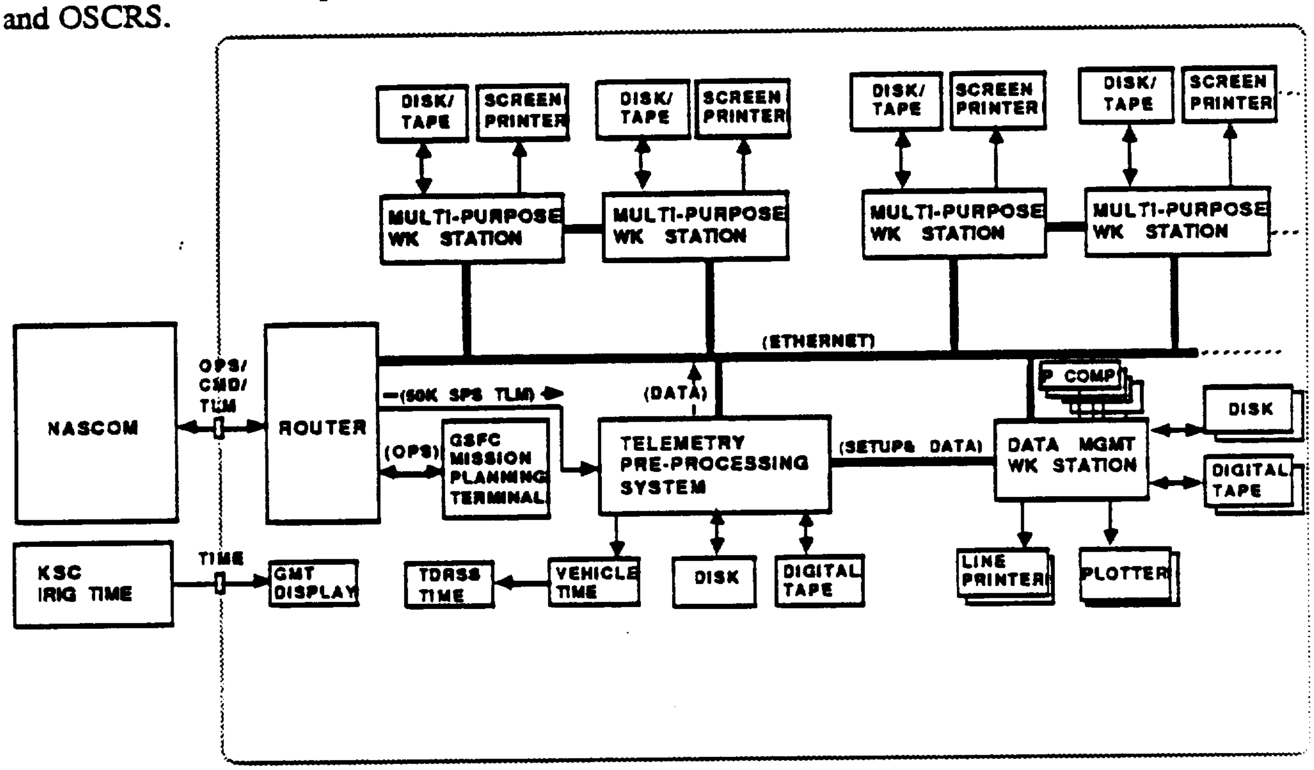


Figure 7.2-1 SOCC Configuration

MISSION PLANNING AND SCHEDULING WORK STATION
Existing GSFC mission planning terminal (MPT) system - provides dedicated communications with the GSFC network control center for TDRSS scheduling; supports planning, scheduling and mission modifications; also provides link that GSFC will use to provide SOCC mission control with attitude control corrections, burn times, etc. The intent is for GSFC to do all orbit analysis for COLD-SAT. We shall provide GSFC with vehicle parameters. GSFC will have direct access to vehicle telemetry thru NASCOM. The intent is to perform analysis regarding whether COLD-SAT should upgrade to the new user planning system under development at GSFC when it is available.

PERSONAL COMPUTER
Commercial hardware - provides user general support such as experiment data processing; includes hard disk, printer/plotter and network port to the data management work station which provides access to stored vehicle and experiment data. This is similar hardware and design to the Martin Marietta system that will be used in Denver to monitor Magellan. An enhancement will provide personal computers to data management work station interfaces so no hand data entry is required.

Electrical support equipment for processing the COLD-SAT on the ground will include that equipment in the remote Control Room located at the Processing Facility when at KSC or at the contractor's facility. Drag-on cables are used when testing is on-going. This equipment allows communication with the satellite for integration and test. Figure 7.2-3 is a block diagram of the control room EGSE.

The Near Vehicle electrical support equipment is connected to the remote Control Room EGSE located at the Processing Facility when at KSC. Drag-on cables are used when testing is on-going. Figure 7.2-4 shows the near vehicle EGSE.

The electrical support equipment has heritage from on-going Martin Marietta programs. It is derived from support equipment developed for MMMS flight hardware.

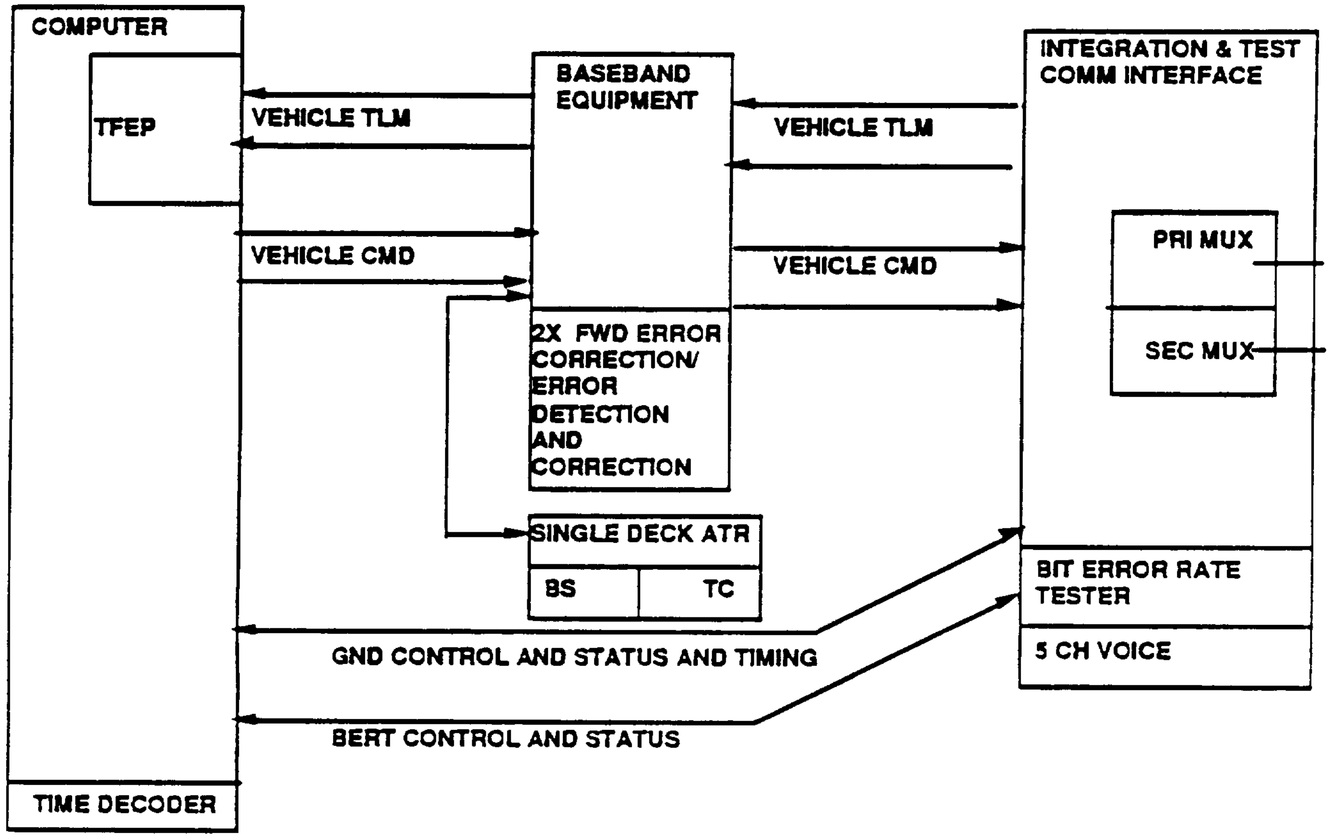


Figure 7.2-3 Control Room EGSE

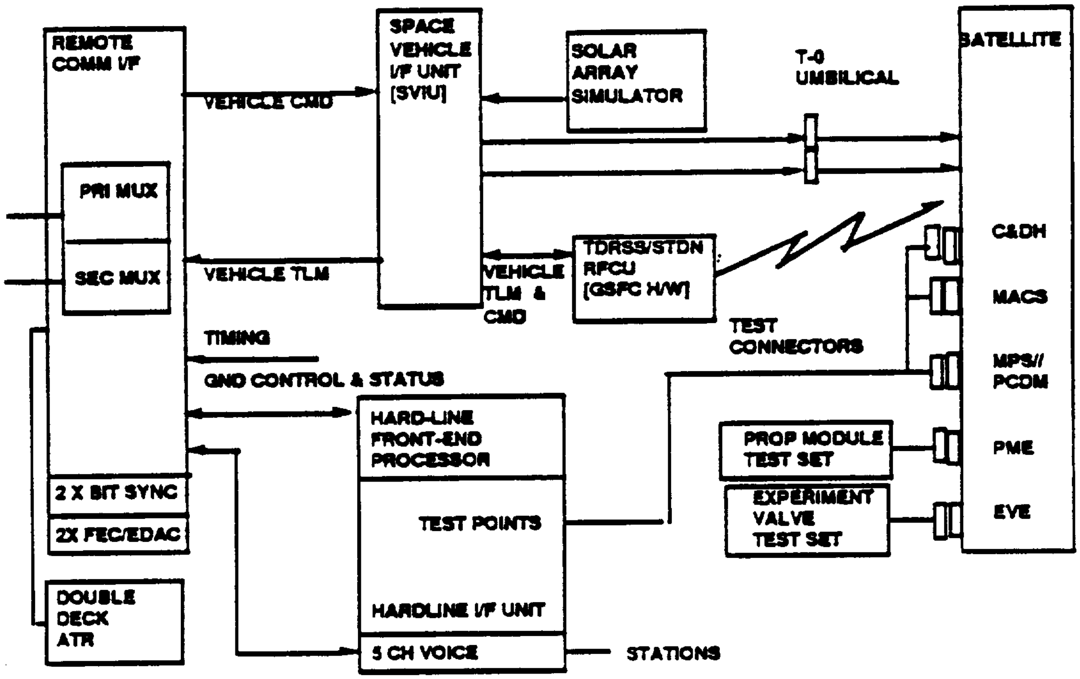


Figure 7.2-4 Block Diagram of the Near Vehicle EGSE

The following ground software is commercially available in most cases and would be used in the SOCC scenario for COLD-SAT. The amount of lines of code (LOC) required is estimated also.

ROUTER 1000 LOC
Communications executive, acts as gateway; routes NASCOM data to using SOCC s/w and formats data to be sent out on NASCOM communications.

TELEMETRY PRE-PROCESSING SYSTEM COTS
Decommutation, compression and analysis of telemetry data containing vehicle control and monitor data and experiment data; routes compressed data to the SOCC Ethernet for work station use; accepts setup from the data management work station via Ethernet.

VEHICLE CONTROL AND MONITOR 20,000 LOC
Monitor vehicle health (156 sensor & 41 effectors) using ~13 algorithms and issue responses; has COTS database at the heart of the system; uses modification of existing s/w mentioned above.

EXPERIMENT MONITOR 15,000 LOC
Real-time post test mode monitoring of experiments (471 sensors) with ~13 algorithms, will compare actual values to sequence simulation; display data and send selected data over Ethernet to line printers or plotters; issue responses to conditions; has COTS database at the heart of the system; uses modification of existing s/w mentioned above.

WORK STATION CORE 8,500 LOC
Work station, executive (5000 LOC), COTS database, output formatter and user context sensitive interactive interface (8,000 LOC and ~24 screens) uses existing advanced work station s/w developed in ADA that has also been used for National Test Bed, R2P2 and OSCRS. Existing s/w has interactive context sensitive graphics, provides features such as Help automatically displayed when a user merely touches an icon, has touch screen and pointing device interfaces, also has speech synthesis, voice

recognition and an internal expert system. Most work in adapting this system to COLD-SAT will be to delete unnecessary functions.

SEQUENCE AND SIMULATION GENERATOR 10,000 LOC
Automated creation of experiment test software similar to compiler - does syntax and semantics correctness evaluations of sequences which support 471 sensors and 222 effectors. Since actual executable sequences are stored on board the vehicle, the output is software that identifies the execution order of on-board sequences and provides variables such as time and ranges; uses COTS database with the output a listing of a file containing the model of the sequence execution, and a file that the user can transfer to the router for uplink to the vehicle.

DATA MANAGEMENT SYSTEM 5,000 LOC
Central data archive and data reduction services providing post test conversion of data to engineering units, listings, plots and graphic displays, also provides interface to personal computers for user data analyses, and includes COTS database system and COTS data reduction system.

MISSION PLANNING AND SCHEDULING - Existing
The intent is to use the existing GSFC mission planning terminal system running on the HP 1000 initially. An analysis will be performed to determine if the "user mission planning terminal system" being developed by GSFC will meet schedule requirements and will be better for COLD-SAT by reducing manpower requirements.

7.3 Ground Segment Issues and Concerns

The access tower for pad 17 has minimal space available for the controls for loading LH2 and GH2. Plumbing can be routed either internally or externally to the tower. Control of the valve complex will have to be remote. The FST electrical classification only supports H2 servicing by using the method of equipment shutdown and purging with GN2. The electrical equipment in the PAD area near the hydrogen loading equipment may need to be upgraded to avoid any ESD during loading. Some equipment can be powered down instead of modified. Modifications will take the form of providing the enclosure with GN2. The payload fairing purge also eliminates some of the hazards associated with hydrogen loading and venting.

The decision to load GH2 at the pad means additional modification for lines from the GH2 trailer to the satellite to the T-O umbilical. The T-0 umbilical for the GHe purge for a payload has never been offered as a service by Delta.

Time must be made to provide an adequate thermal conditioning of the supply tank. Time of MST removal should accommodate GH2 loading.

To avoid excessive travel expenditures, the SOCC location should take into account the home location of the flight team. Existing equipment at GSFC may make it more cost effective to operate the mission there. The percentage of flight team members from LeRC may make it desirable to locate the SOCC at LeRC. The short mission duration makes TDY expenses more economical.

The thermal vacuum testing of the spacecraft should include loaded LH2. A hazard-protection thermal vacuum facility must be refurbished or built to accommodate the satellite.

8.0 INTERFACES

Internal interfaces are defined here as those between the spacecraft and the experiment subsystem; those between the spacecraft and the ground support equipment used during test and prelaunch activities; and those between analysts and PI's and the SOCC.

External interfaces are defined here as those between the spacecraft and TDRSS, between the spacecraft and the launch vehicle, between the NASCOM and the SOCC, and between the GSE and KSC/CCAFS.

Figure 8-1 depicts the interfacing functions required to successfully complete the COLD-SAT program.

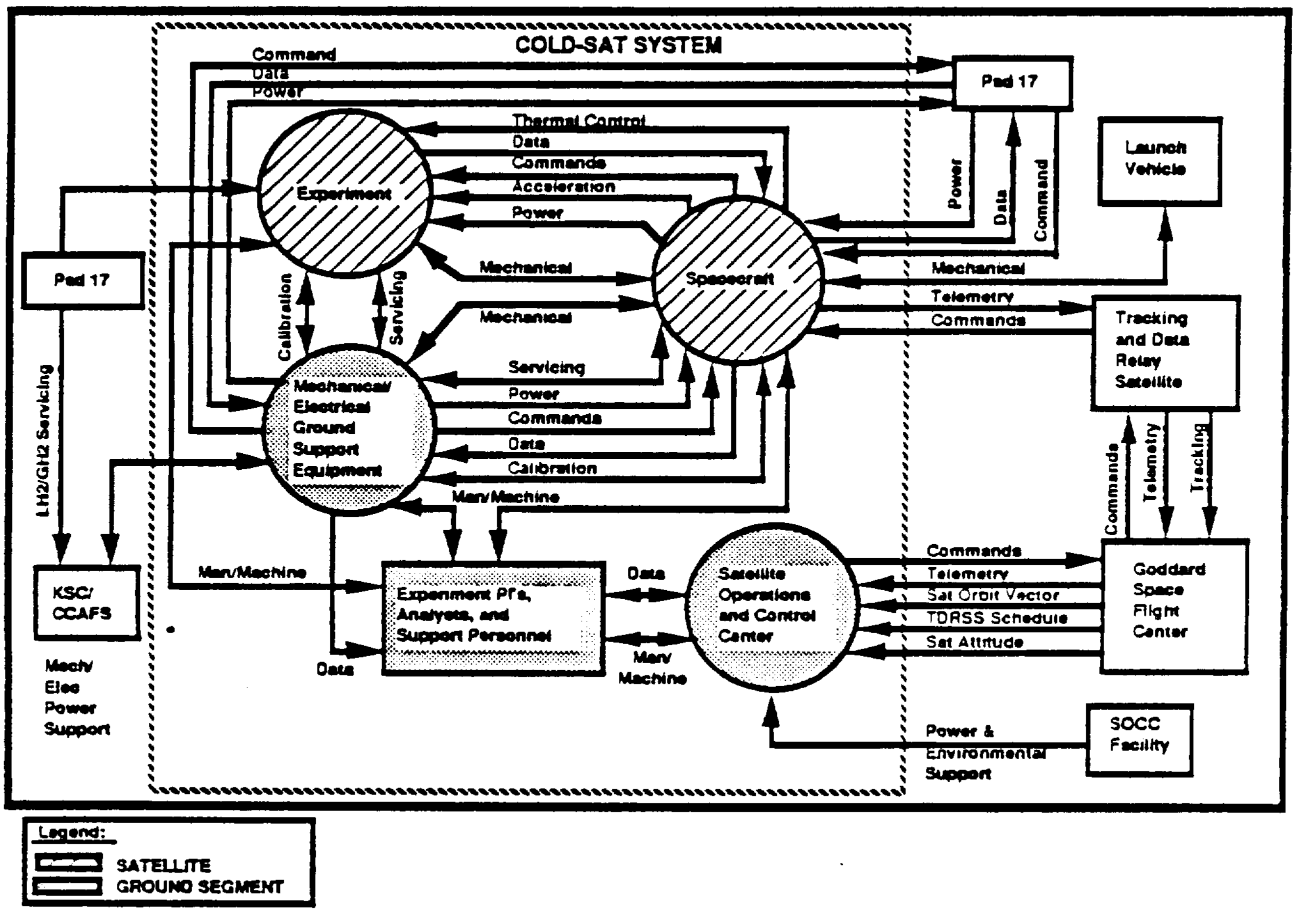


Figure 8-1 COLD-SAT External and Internal Interfaces

All environments will be defined in the system specification. Specific environments while attached to the launch vehicle, will be specified in the Spacecraft to Launch Vehicle ICD.

TDRSS interfaces will be defined in the Spacecraft to TDRSS ICD.

Mission Operations (MOS) interfaces will be defined in the MOS to TDRSS ICD. This ICD will include the agreements between GSFC and LERC specified in the Memo of Agreement (MOA) signed by GSFC and LERC.

Interfaces between the flight and ground segments of COLD-SAT include servicing and calibration support mechanical interfaces between the MGSE and the satellite; communications between the satellite and the SOCC and between the satellite and the EGSE (through TDRSS, MIL-71 or hardwire). Handling equipment attachments to the satellite are detailed in section 7.

SOCC interfaces to the satellite are through the NASCOM network supplied by GSFC. GSFC also provides the scheduling of TDRSS usage through coordination with the SOCC. Tracking data is routed to GSFC and processed for updating the ephemeris data to be uplinked to the satellite via inclusion in the command loads developed at the SOCC and sent to GSFC over NASCOM lines for uplinking through TDRSS.

8.1 External Interfaces

The external interfaces between the COLD-SAT Satellite Flight Segment and its associated Ground Segment and other supporting systems include physical, environmental, and radio frequency which are dependent on the phase of the mission. KSC/CCAFS provides mechanical and electrical support. The launch vehicle, a Delta II, provides a mechanical interface with the spacecraft. TDRSS provides the communications from the satellite to the ground. GSFC provides the communications network as well as tracking and scheduling.

Electrical interfaces prior to ELV integration are through either the T-0 umbilical or the drag-on connections to the modules and assemblies that accommodate test connections. The functions supported by these interfaces are shown in Figure 8-2 and include:

(a). Support system level testing before shipment to the launch site to verify capability and performance. Control, checkout, and monitoring functions are provided as well as servicing of experiment consumables to simulate orbital operations on the ground. Calibration functions are included.

(b). Handling and transportation functions are required during the ground processing flow and end with flight segment integration to the launch vehicle at the launch complex.

(c). Certain final assembly operations of the satellite will be accomplished at the launch site and require support interface functions including installation and checkout of the solar array, TDRSS antenna and batteries.

(d) Functional checkout and testing of the spacecraft and experiment subsystems is required during ground processing to verify flight readiness.

(e) Hydrazine propellant servicing of the spacecraft is required prior to LV integration.

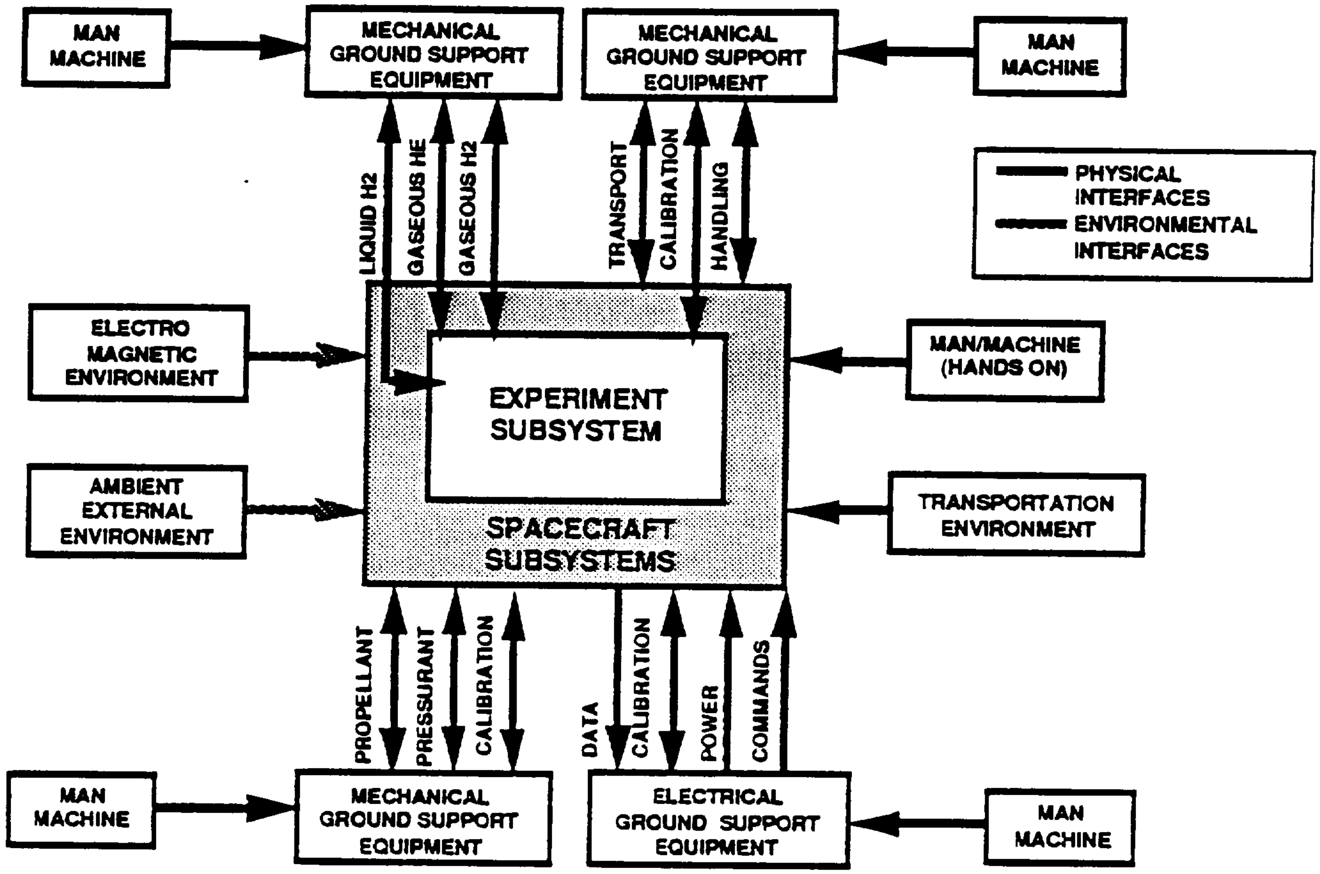


Figure 8-2 Prelaunch, Prior-to-ELV Integration, Interfaces

Ground loading carts for pressurant or liquid hydrogen can interface through ports so designated for ground fill and drain on the satellite.

Controlled environments will minimize external EMI/ESD and provide clean working conditions.

Electrical interfaces after ELV integration are through either the T-0 umbilical or the drag-on connections to the MMS modules and propulsion and experiment test sets that accommodate test connections to verify flight readiness and system integrity prior to GH2 and LH2 servicing. Experiment subsystem control is provided during GH2 and LH2 loading. The final configuration is set up through the electrical interface. Figure 8-3 depicts the interfaces after attachment to the launch vehicle.

End-to-end verification of the spacecraft uplink and downlink capability prior to launch is provided.

Ground loading for pressurant or liquid or gaseous hydrogen can interface through ports so designated for ground fill and drain on the satellite. The launch pad provides for gaseous helium loading. The launch pad will be modified to provide for hydrogen loading.

A mounting flange which is an integral part of the separation system provides the mechanical attachment of the satellite to the LV.

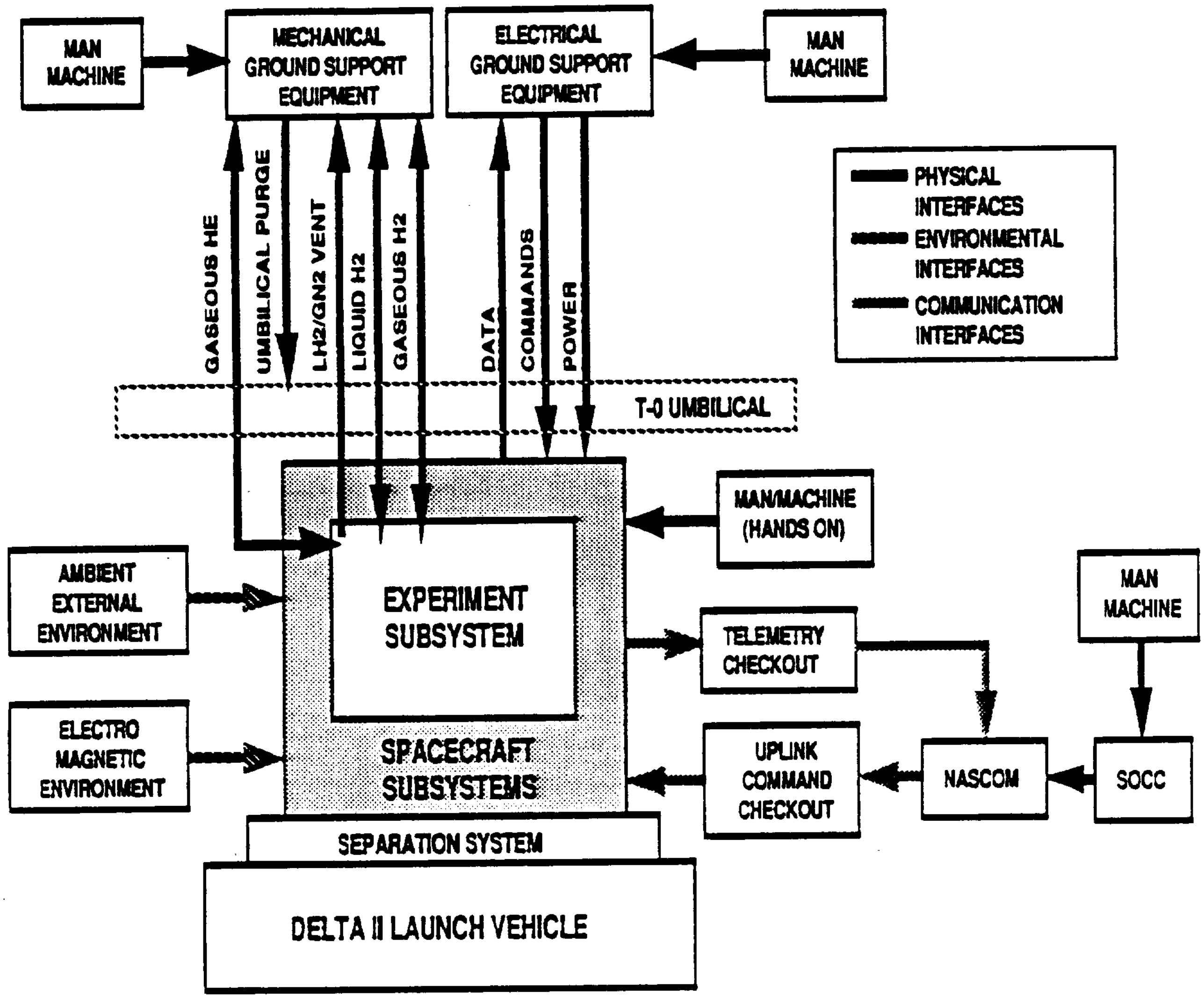


Figure 8-3 Prelaunch, After Launch Vehicle Integration, Interfaces

Controlled environments will minimize external EMI/ESD and provide clean working conditions. A GN2 purged shroud will assist in eliminating potential hazards between the hydrogen during loading and the electrical circuits activated for the COLD-SAT launch.

Ascent is defined as the period from launch to separation of the spacecraft from the launch vehicle. No electrical interfaces are available during ascent through Delta II. The initiation of spacecraft attitude control will have to be a timed signal generated on-board the spacecraft. The separation signal will be provided by a limit switch at the interface. Environments normally are most severe during this mission phase. The satellite will be designed to accommodate the environments as specified in the Delta II User's Guide and defined in the Satellite-to-Launch Vehicle ICD. Figure 8-4 shows the types of environmental interfaces during ascent.

Protection from the environments near Earth will be provided on the satellite. Specifically, the induced drag at the orbit altitude will not interfere with the on-going experiments. On orbit interfaces are depicted in Figure 8-5.

Communications will begin with the first acquisition of TDRSS for transmission of recorded launch data and the initial recorded data from the checkout of the spacecraft and the experiments. Thereafter all data will be recorded for transmission later.

8.2 Internal Interfaces

The experiment subsystem interfaces with the spacecraft for data and command through the RIUs to the TT&C subsystem. The clock reference is provided from the TT&C subsystem. Prime power is provided by the EPS. The spacecraft and experiment are integrated to form the structure of the satellite. The ACS and Propulsion subsystem provide acceleration forces on the experiment subsystem.

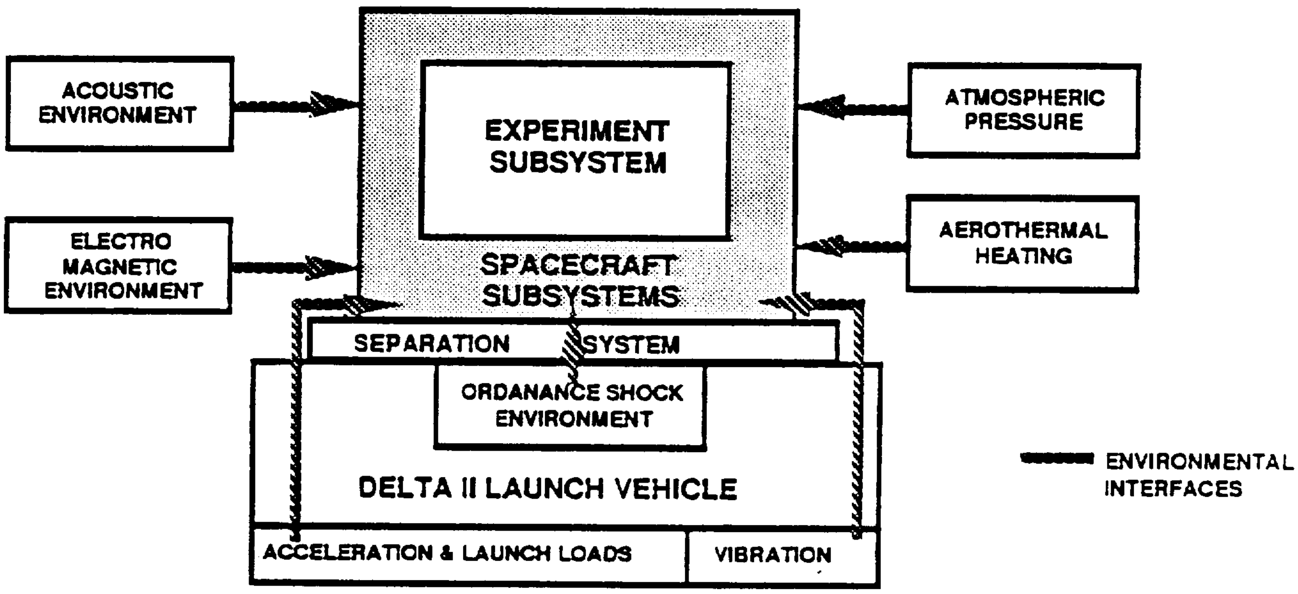


Figure 8-4 Ascent Interfaces

The satellite interfaces to the SOCC (using the TDRSS link) using an S-band carrier. A backup net through the GSTDN will be provided for emergency use only to acquire health and safety data.

Another internal interface is the one between the SOCC and the personnel assigned to COLD-SAT. The SOCC provides a quick-look capability at experiment data. It also can recover and process recorded satellite engineering data. All data received will be recorded by the SOCC. Satellite data will be time tagged such that the onboard satellite time may be correlated with UTC.

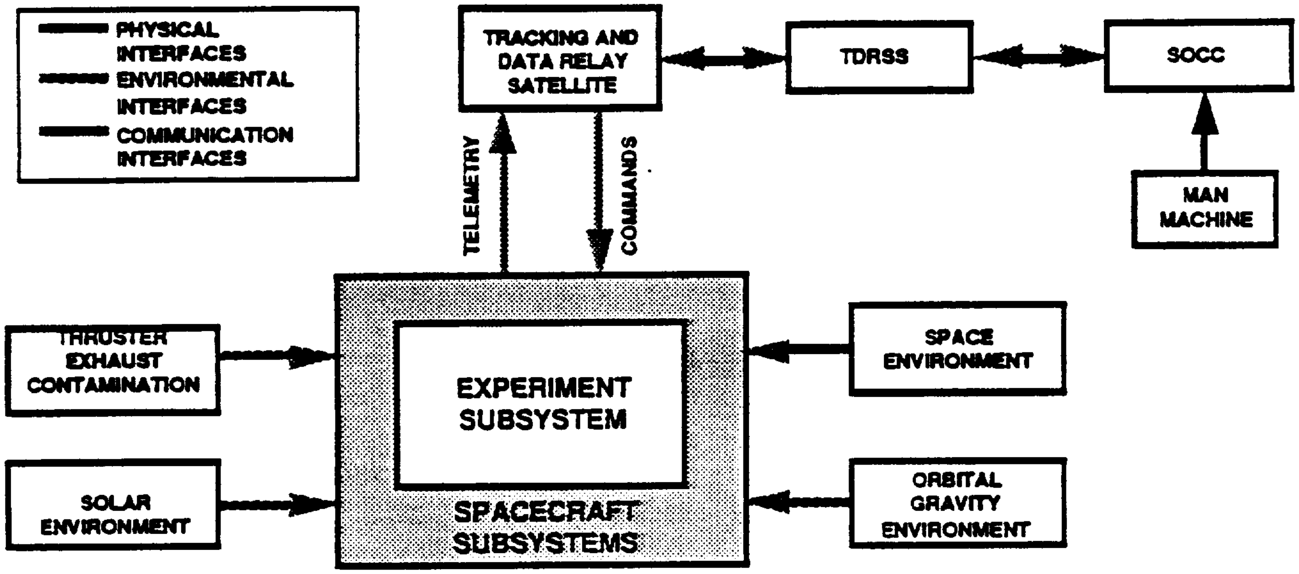


Figure 8-5 On-Orbit Interfaces

9.0 OPERATIONS

Operations Areas - Operations will be conducted at (1) the contractor facility during assembly, integration and testing; (2) the large thermal vacuum chamber facility for sequence testing of the satellite with liquid hydrogen; (3) KSC and Cape Canaveral Air Force Station (CCAFS) for satellite assembly and integration and testing after attachment on the launch vehicle, and for launch operations; and (4) the SOCC for flight operations.

Organizational Roles and Responsibilities - There are six organizations that play a part in COLD-SAT. 1). LeRC is the project management for COLD-SAT and is responsible for the selection and direction of the science team. LeRC also provides direction to the satellite contractor for design requirements, information requirements, and budget considerations. LeRC also provides the Delta II launch Vehicle. 2). GSFC provides the interface with COLD-SAT through NASCOM and the TDRSS. Link availability is provided through coordination with GSFC. 3). KSC provides the launch processing facilities. 4). AFETR provides the Delta II Launch Facility and coordinates range safety. 5). The LV Contractor provides the Delta II and its associated integration functions. 6). The Satellite Contractor provides the satellite and personnel to perform on the mission operations team. The Satellite Contractor also integrates the flight and ground systems, coordinating the requisition of any new equipment needed either at the SOCC or at the launch site.

Operations Summary - Operations can be divided into pre-mission and mission.

•Premission - Integration and systems testing at the contractor's facility, at the large thermal vacuum chamber, and at KSC/Cape Canaveral Air Force Station (CCAFS) require a control center to monitor and command the satellite and near vehicle EGSE to be utilized to connect to the remote control center EGSE. The EGSE and MGSE concept utilizes common hardware and software for use at any of the facilities. Transportation and handling hardware are discussed in Section 7.

•Mission - A series of cryogenic fluid management experiments are to be performed in low-Earth-orbit to develop the technology required to effectively manage cryogens in the space environment. The satellite used to perform this mission will employ liquid hydrogen as the test fluid, be launched on an expendable launch vehicle (Delta II), and be designed to conduct a series of experiments over a 3 month period, providing essentially low gravity data to enrich the understanding of the fluid physics of subcritical cryogens and to validate analytical and numerical models.

A circular orbit provided by the Delta II launch vehicle at 926 km (500 nmi) with an inclination of 28.8 degrees allows the satellite to remain in orbit at least 500 years and also minimizes drag on the satellite to the range of 10^{-9} g's. The longitudinal axis pointing at a projection of the sun in the orbit plane provides minimum disturbances, enhancing the sun-pointing (available power) capability. The communication capability of the satellite is enhanced by adding articulation capability. Communication using the NASA Standard TDRSS Transponder (S-Band) is provided through a switching antenna scheme. Control of on-board operations and data management is provided by an on-board computer.

9.1 Ground Processing

Ground Processing Considerations - The satellite will be serviced in two facilities at the launch site: a payload processing facility and a launch site servicing facility. The discussion of the facility requirements is in Section 7.1.

The payload processing facility will be used for 1) support equipment assembly after shipment, 2) satellite receiving, inspection and placement in a vertical position; 3) satellite final assembly and installations, 4) system test and checkout; and 5) a SOCC end-to-end checkout.

The launch site servicing facility will be used as a hazardous processing facility to 1) reassemble the support equipment, 2) provide a proof pressure demonstration test, 3) provide N2H4 servicing and pressurization, and 5) install the satellite into the Delta II Upper Stage Assembly Handling Can.

9.2 Launch Pad

Ground Servicing Considerations - Pad 17B is the desired launch site because the location of the fuel area for both pads is to the east of pad 17B. When the supply tank can be serviced with LH2 and GH2 after the COLD-SAT is integrated to the Delta II launch vehicle is a critical driver on LC-17 launch site modifications required to provide the capability to safely perform these operations. It also impacts COLD-SAT requirements for tank thermal stabilization and how the chilldown of the supply tank is going to be accomplished on the ground. Pad safety considerations and restrictions require that this servicing be accomplished in the final 8 hours prior to launch after the pad is cleared of personnel. This imposes remotely controlled LH2 and GH2 loading operations using an umbilical connected to the spacecraft via the launch vehicle fixed umbilical tower. This T-0 umbilical disconnects at launch.

Early release of the T-0 umbilical will not be accomplished since a launch abort after the release would create a situation where drain and vent access to the supply tank would only be possible by reconnecting the umbilical. This would create an unacceptable safety situation. The umbilical release with a lanyard pull system releases the umbilical by the motion of the launch vehicle as it moves off the pad. The umbilical is always in place for contingency deservicing for all pre- engine ignition launch vehicle abort situations.

Certain satellite commands are required through the T-0 umbilical. There are 30 experiment valves requiring commanding via the T-0 umbilical. They are the vent valves, supply tank valves, pressurization system valves, and transfer line valves. Housekeeping functions that require command capability include the propulsion hydrazine and pressurant valves, pyro safing, and safing commands.

Instrumentation required through the T-0 umbilical includes 115 experiment temperature, pressure and liquid level sensors, housekeeping status of the hydrazine, helium, pyros, batteries, and bus power measurements.

When the supply tank can be serviced with liquid hydrogen is a critical driver on LC17 modifications to perform this loading operation. It also impacts COLD-SAT requirements for tank thermal stabilization and how the chilldown of the supply tank is to be accomplished. If servicing has to occur after MST roll back (now at T-3 hours) then a loading approach using a T-0 flyaway umbilical is required using a LH2 servicing system attached to the Fixed Umbilical Tower (FUT). An LH2 valve complex would be mounted at the servicing level on the FUT (preferred location) or at the base of the FUT. Control would be provided remotely from EGSE. LH2 would be transferred up the FUT and then into the COLD-SAT via the T-0 umbilical. Venting would be accommodated by a vent stack with a flame arrestor located at the top of the FUT. Since the tank cannot be thermally stabilized in the three hours prior to launch, tank chilldown must be accomplished during the days prior to launch using LH2 (if safety permits) or cold GHe.

GH2 servicing has also become a critical driver on the final countdown and on MST roll back. It is estimated that it will take eight hours for GH2 pressurization to meet system temperature requirements. Countdown accommodations can be made to roll back the MST before T-8 hours. GH2 servicing of the COLD-SAT to 20670 kN/m^2 (3000 psi) would then take place via the T-0 umbilical. The safety requirements for GH2 loading are given in Table 9.2-1.

In the COLD-SAT operations for the seven days preceding launch, the significant event is the supply tank chilldown beginning at L-2 days. This chilldown will allow hydrogen servicing to be completed on the launch day. The integrated Delta II activities include removing the MST prior to hydrogen servicing and purging the shroud and FUT electronics with GN2.

Table 9.2-1 GH2 Safety Requirements

•7 GH2 tanks manifolded to a common ground servicing interface - 32 cm (12.7 in) outside diameter (31 cm (12.27 in) inside diameter), 118 cm (46.5 in) long, 11.3-13.6 kg (25-30 lbs) dry - 0.076 cubic meters (4666 cu in) volume each - 20670 kN/m^2 (3000 psi) operating pressure, 31005 kN/m^2 (4500 psi) proof pressure, 41340 kN/m^2 (6000 psi) burst pressure - 20670 kN/m^2 (3000 psi) ~ 9.1 kg (20 lbs) GH2
•McDonnell Douglas, the launch complex contractor, requires a burst to operating pressure ratio of 4 to 1 - A 2 to 1 safety factor is acceptable at the launch complex - The COLD-SAT design uses a 2 to 1 burst to operating pressure ratio
•Alternatives for operations in the HPF, transport to the launch complex, and gantry operations with less than a 4 to 1 safety factor - Pressurization not to exceed 1/4 the minimum design burst pressure prior to vehicle mate in the gantry - COLD-SAT GH2 pressurization system meets the requirements of ESMCR 127-1 and the additional requirements outlined within the MDAC Delta II Spacecraft Users Manual Safety Regulations: The electrical systems with potential GH2 exposure must meet Class I, Division II, Group B specifications.
a) Pressurizations to operating pressure require 5 minutes stabilization period prior to personnel exposure
b) Maintenance of a complete log of pressurization hold time and number of pressurization cycles
c) Submission of pressure vessel data package to MDAC concurrently with the MSPSP

The MST removal occurs at about L-6 hours. Negotiations to remove the tower before hydrogen servicing (L-8 hours for GH2) will be required. Our proposed launch day countdown has been modified, with the MST removal occurs at about L-12 hours. At L-10 hours, the electrical equipment on the FUT and the payload fairing will be purged with GN2 as a safety precaution to prevent sparks during hydrogen loading. Personnel restrictions to access to the Pad will be in force for these 10 hours prior to liftoff. Figure 9.2-1 depicts the 7 day timeline for the COLD-SAT Launch Countdown.

9.3 Flight On-Orbit

The COLD-SAT mission is planned to execute on-orbit tests and acquire sufficient data to analyze liquid hydrogen properties in low Earth orbit. The amount of data to be collected is in the range of 10 kbps which accommodates the rates of all of the sensors used in the design. At the altitude of the circular orbit selected, communication can be accomplished using either TDRSS or a GSTDN and the NASCOM network. TDRSS availability may be constrained to the actual experiment operation timeline, plus command uplink times. Sun pointing to provide solar power will be maximized

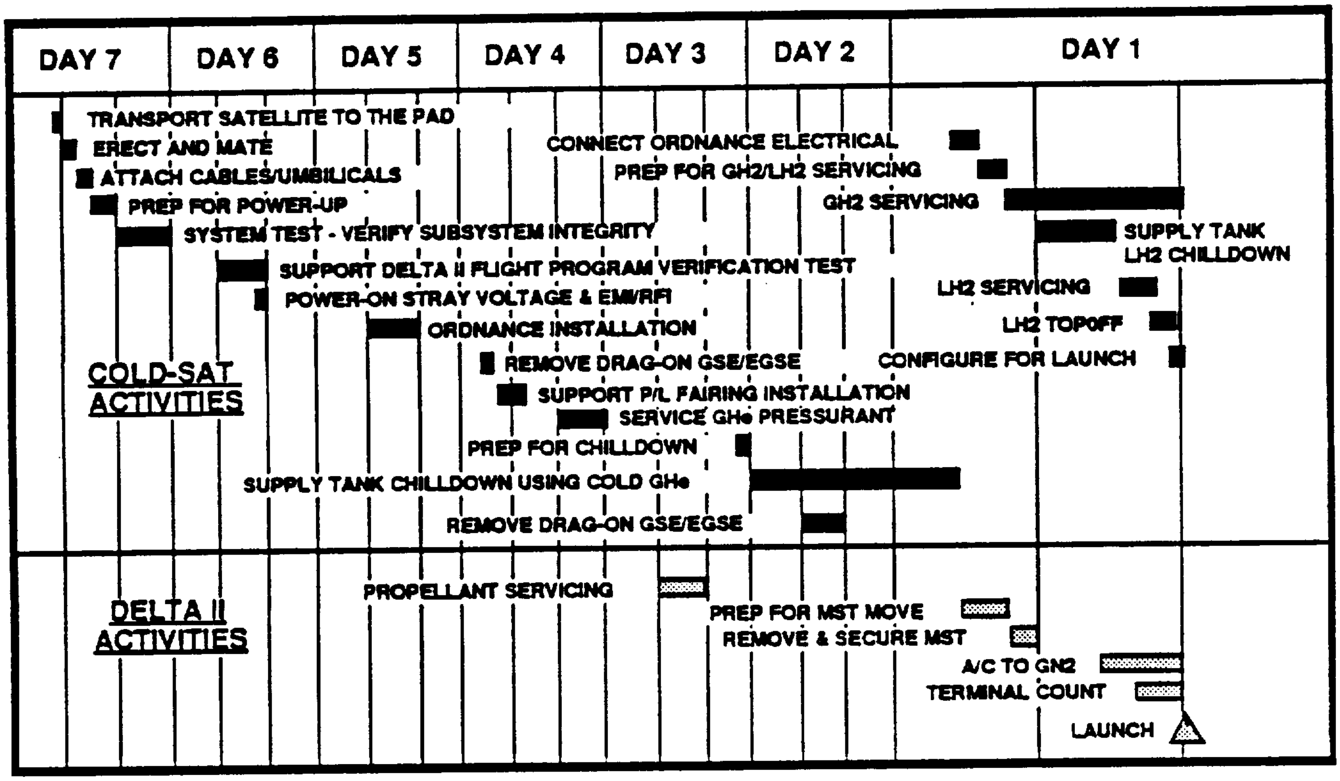


Figure 9.2-1 COLD-SAT 7 Day Launch Countdown

whenever possible to charge batteries, and power conservation will be practiced during occultations. Inertial position updates may be required after certain tests are run. The use of ACS gas will be minimized during experiments where disturbances impact the results. Uplinks, except for contingency operations, will be limited to commanding (once per week) for test sequences and routine housekeeping. Real-time changes to sequences will be limited to "GO" commands initiating on-board sequences changing experiment configurations or timing. The "GO" commands may include timing updates. Except for flight control, operations will be limited to a normal 5 day workweek. Flight controllers will monitor the satellite around the clock with predesigned contingency procedures to ensure the health of the satellite. Downlink data may be either real-time data transmitted over TDRSS or data recorded for later playback. Data taken during experiment operations will be downlinked at least the same day taken.

Experiment control sequences will be uplinked and automatically control the COLD-SAT experiment tests. The pre-programmed sequences will operate from the on-board computer which will contain the algorithms to properly condition the temperature and pressure which will be reported by the data acquisition function on the satellite. Control signals from the on-board computer to the valve drivers allow for valve control.

Because the TDRSS provides services to many users, only 10 minutes contact time per orbit will be allocated to new spacecraft. Additional time may be requested for high activity periods. Operational control of the network is the responsibility of the GSFC Networks Directorate and performed by the NCC. The user SOCC requests scheduling changes of TDRSS services.

Maximum return service using the TDRSS multiple access is 50 kbps. Forward service is either 1 or 2 kbps. In order to take advantage of all of the data from COLD-SAT, all data will be recorded and played back through TDRSS during the 10 minute contact period. Playback data is processed for scientific evaluation and long-term trend analysis of consumables. The newest data seen at the SOCC will be at best 10 minutes old unless the downlink is used for realtime instead of playback data. The MMS does not have the capability to interleave data.

The TDRSS I & Q channels were also analyzed for use - Realtime on I and playback or OBC dump on the Q channel. Although this approach is feasible, it was decided to use playback data as the primary means of data acquisition because there are no requirements for immediate action except possibly during thruster firings. If TDRSS is made available during thruster firings, we would transmit (on the multiple access channel) realtime data and delay playback data.

Timelines - The operations timeline is governed by the need to maximize the use of the liquid hydrogen to accomplish the experiment objectives. Maneuvers will be planned to work around the experiment operations. Data will be collected for the entire mission by using the onboard recorders and then downlinking as often as TDRSS permits. A detailed experiment timeline is contained in the experiment database described in section 4.10. Figure 9.3-1 depicts the accelerations required by the experiment set. Over the 90 day mission, a delta velocity of nearly 213.5 m/sec (700 ft/sec) is applied to the COLD-SAT orbit. This results in a growth of eccentricity, causing a reduction in the final periapsis altitude.

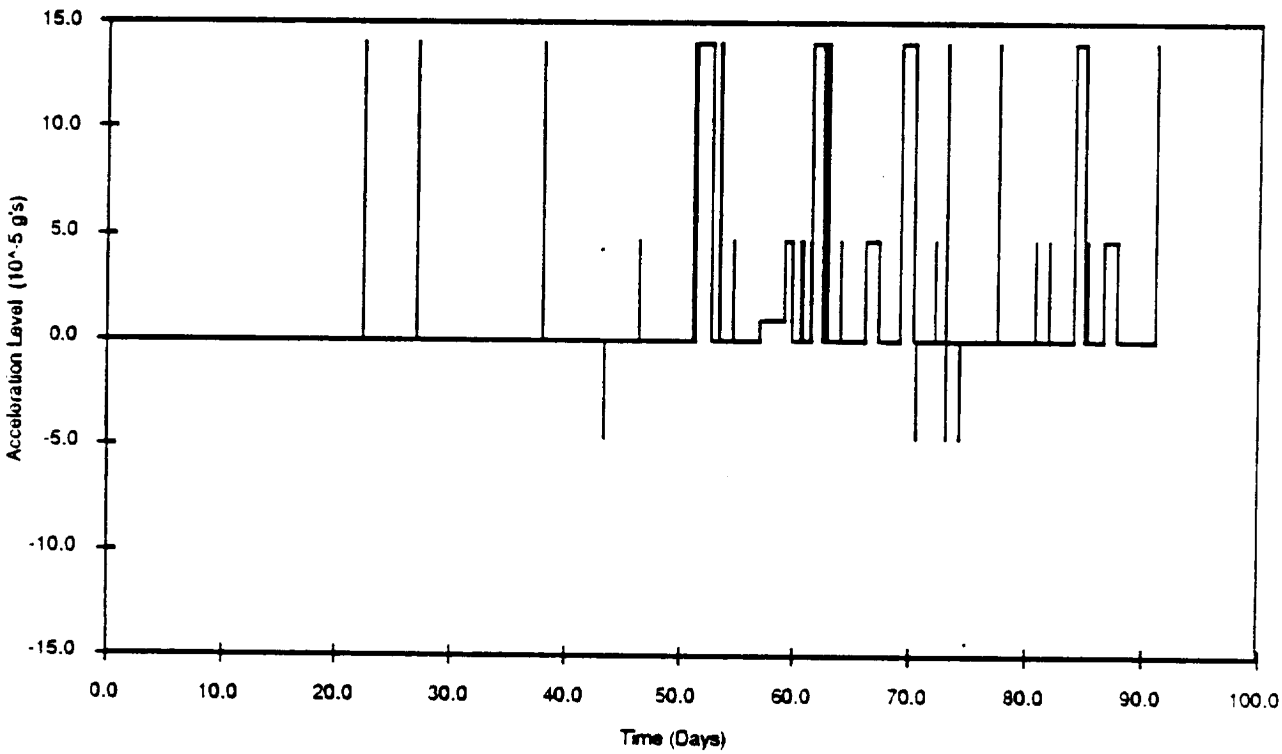


Figure 9.3-1 Satellite Acceleration Timeline

The functional flow beginning with the launch countdown until experiment checkout is shown in Figure 9.3-2.

9.4 Satellite Operations Control Center

Mission Operations Requirements - Mission operations requirements can be broken into three categories: those of 1) mission planning, 2) Mission Support, and 3) Satellite operations. Table 9.4-1 lists the requirements.

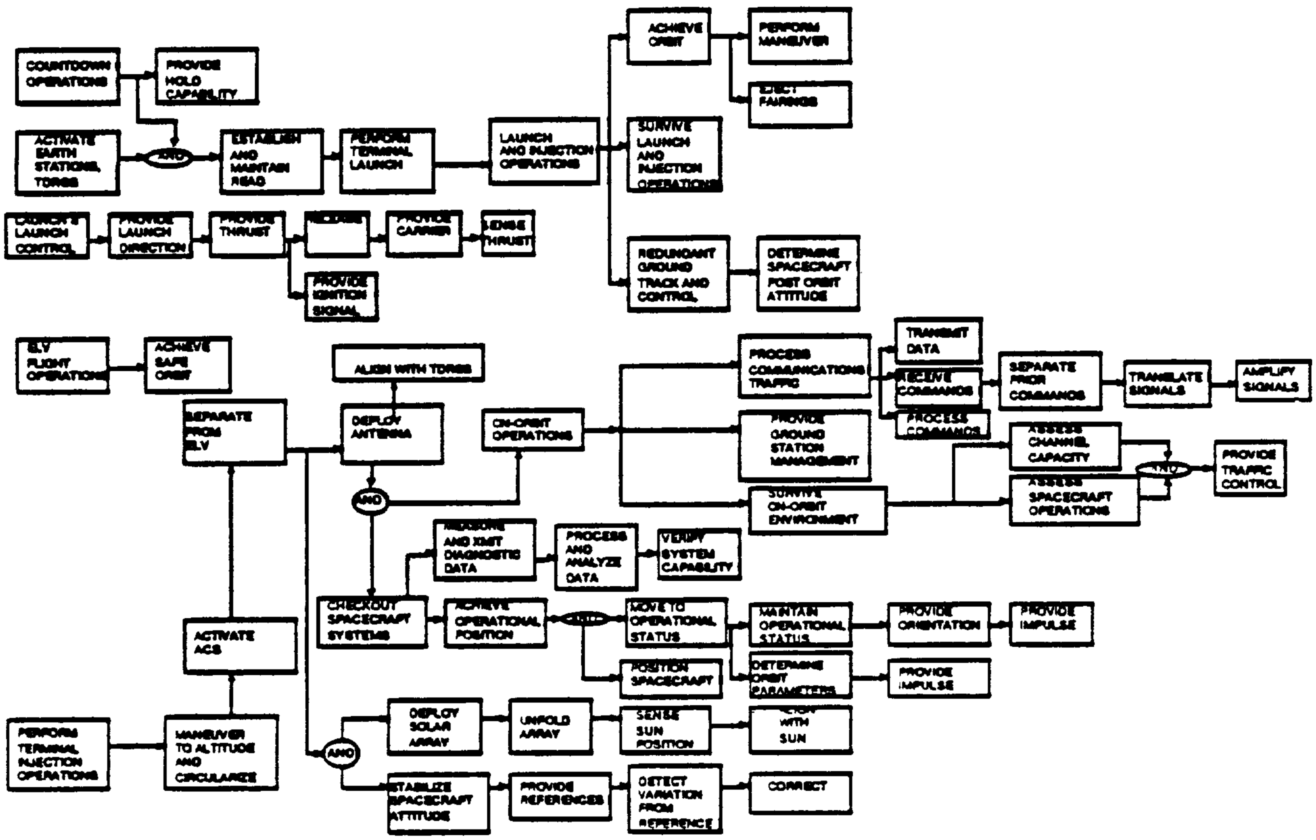


Figure 9.3-2 Functional Launch and First Orbit Operations Flow

Ground Support System (GSS) Configuration - The Ground Support System consists of the SOCC operations combined with the GSFC communications operations.

- The SOCC contains the following hardware:
  - *Experimenter Consoles to develop sequences and analyze data
  - *Experiment Database Computers and software
  - *Subsystem Engineering Analyst Consoles to analyze data and support sequence development
  - *Subsystem Database Computers and software
  - *Mission Planning Consoles to develop mission sequences and coordinate link planning
  - *Mission Operations Manager Console to coordinate conflicts and control resources
  - *Sequence/Schedule Database to develop uplink command files
- GSFC contains the following hardware:
  - *Monitor Station
  - *The navigation processing equipment
  - *The telemetry, tracking, and command equipment.

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Table 9.4-1 SOCC Operations Requirements

MISSION PLANNING

- PERFORM S/C MISSION PLANNING
- S/C ORBITAL MAINTENANCE & SUPPORT PLANNING
- S/C WEEKLY CMD GENERATION
- VERIFY CMD SEQUENCES IN S/C TEST BED
- PERFORM S/C EPHEMERIS CALCULATIONS
- CONTINGENCY PLANS
- DEVELOP MISSION PLAN
- VERIFY COMBINED MISSION PLAN/SEQUENCE OF EVENTS
- DEVELOP MISSION GND RULES & CONSTRAINTS
- COORDINATE ALL PRODUCTS WITH SOCC AND GSFC OPS SUPPORT
- PERFORM MISSION CONSTRAINTS ANALYSES
- DISTRIBUTE MISSION PLAN AND CONTINGENCY PLANS
- SUBMIT COMM SCHEDULING & OTHER SUPPORT REQUESTS TO GSFC
- DEVELOP DAY-TO-DAY TDRSS CONTACT SCHEDULES
- COORDINATE ALL PLANS & ANALYSES WITH S/S ANALYSTS
- RESCHEDULE
- PERFORM LONG TERM S/C TREND ANALYSES
- SUBMIT S/C ORBITAL UPDATE CMDS TO GSFC
- EXPERIMENT DEFINITION
- PERFORM PRELIMINARY EXPERIMENT PLANNING WITH PI'S

MISSION OPERATIONS

- MONITOR S/C HEALTH AND STATUS
- MONITOR CONDUCT OF MISSION
- ASSIST IN S/C ANOMALY REDUCTION
- ASSIST IN S/C CALIBRATION
- PROVIDE INPUTS TO & COORDINATE MISSION PLANS/TIMELINES
- MONITOR COMM LINK STATUS
- ASSIST MISSION PLANNING IN DEV. OF CONTINGENCY PLANS
- MONITOR ENFORCEMENT OF MISSION GROUNDRULES /CONSTRAINTS
- DEVELOP OPS PLANS WITH M.P.
- VERIFY COMM AVAILABILITY
- TRAIN FOR MISSION
- VERIFY AVAILABILITY OF SUPPORT
- ASSIST IN EXPERIMENT ANOMALY REDUCTION

SUPPORT

- PROVIDE S/C DATA TO ANALYSTS
- REVIEW RESULTS OF ENGR ANALYSES
- OPERATE & MAINTAIN S/C TEST BED
- PROVIDE ENGR DATA TO PI'S
- PERFORM S/C FAULT ISOLATION
- MAINTAIN SOCC H/W & S/W
- DEVELOP TRAINING PROGRAM
- DATA LOGGING AND ARCHIVING
- ADMINISTRATION,PERSONNEL,SUPPLY

Type and Quantity of Personnel Involved in Operations - The table below lists the types of personnel required at the SOCC.

1	Subsystem Analysts - for housekeeping; cross-training where possible.
2	Experiment Analysts - for pressure control, fill, class II.
3	Mission Planners - for short and long range planning
4	Science PIE's - 3 types - same as experiment analysts
5	Sequence Developers - for consecutive sequence development
6	Test and Training Manager - to develop/coordinate flight team training
7	Flight Controllers - for uplink command load development and transmission and real-time monitoring around the clock
8	Mission Operations Manager

Table 9.4-2 lists the staffing requirements over the three month mission at the SOCC.

Table 9.4-2 Operations Personnel - SOCC Staffing

ANALYST	MONTH ONE		MONTH TWO		MONTH THREE		TOTALS
	SHIFT 1	SHIFT 2	SHIFT 1	SHIFT 2	SHIFT 1	SHIFT 2	
SUBSYSTEM :							
POWER	2	1	1	1	1	1	7
TT&C	2	1	1	1	1	1	7
ACS	2	1	1	1	1	1	7
PROP	2	1	1	1	1	1	7
THERMAL	2	1	1	1	1	1	7
SOFTWARE	2	1	1	1	1	1	7
EXPERIMENT :							
PRESSURE CONTROL	2	1	1	1	1	1	7
FILL	2	1	1	1	1	1	7
CLASS II	2	1	1	1	1	1	7
MISSION PLANNERS :							
LONG RANGE	1		1		1		3
SHORT RANGE	1		1		1		3
SEQUENCE DEVELOPERS	2		2		2		6
TEST & TRAINING							1
FLIGHT CONTROLLERS	3	2	3	2	3	2	15
MISSION OPS MANAGER	1		1		1		3
TOTALS :	26	11	17	11	17	11	94

The layout in Figure 9.4-1 gives a typical setup for each mission control team member. Also shown are the personal computers for data analyses and the mission data monitor. GSFC positions are shown for completeness.

The Magellan SOCC at the Martin Marietta Space Support Building in Denver contains the mission support area (MSA) for Magellan flight operations. The area is configured for eight Sun computer stations, three high speed data lines from the Jet Propulsion Laboratory, six personal computers, a data library, a conference room, and personal offices (Contract Costs). The installation of the eight sun stations included computer and printer interconnections (GFE). Three 56 kbps, high speed, data lines were installed into the MSA (Government Leased). A library of design and test supporting documentation was set up (Contract Costs).

The cost trades associated with the location of the Magellan SOCC were:
•Send 38 people to JPL for the mission, including prelaunch training under TDY or permanent status versus the cost of leasing data lines and terminals
•The spacecraft team for launch and early mission operations for Magellan was 38 people. The number of people decreased to 32 for the remainder of the mission. TDY costs are a monthly cost per person, R&R travel, and logistics costs associated with offsite personnel.
•The cost of obtaining expertise which has left the program, in response to spacecraft problems/anomalies, is the cost to send experts offsite (time and travel) and the experts commitment to travel.

It is recognized that COLD-SAT can be operated with a smaller flight team. This makes a similar cost trade study worth pursuing in Phase B.

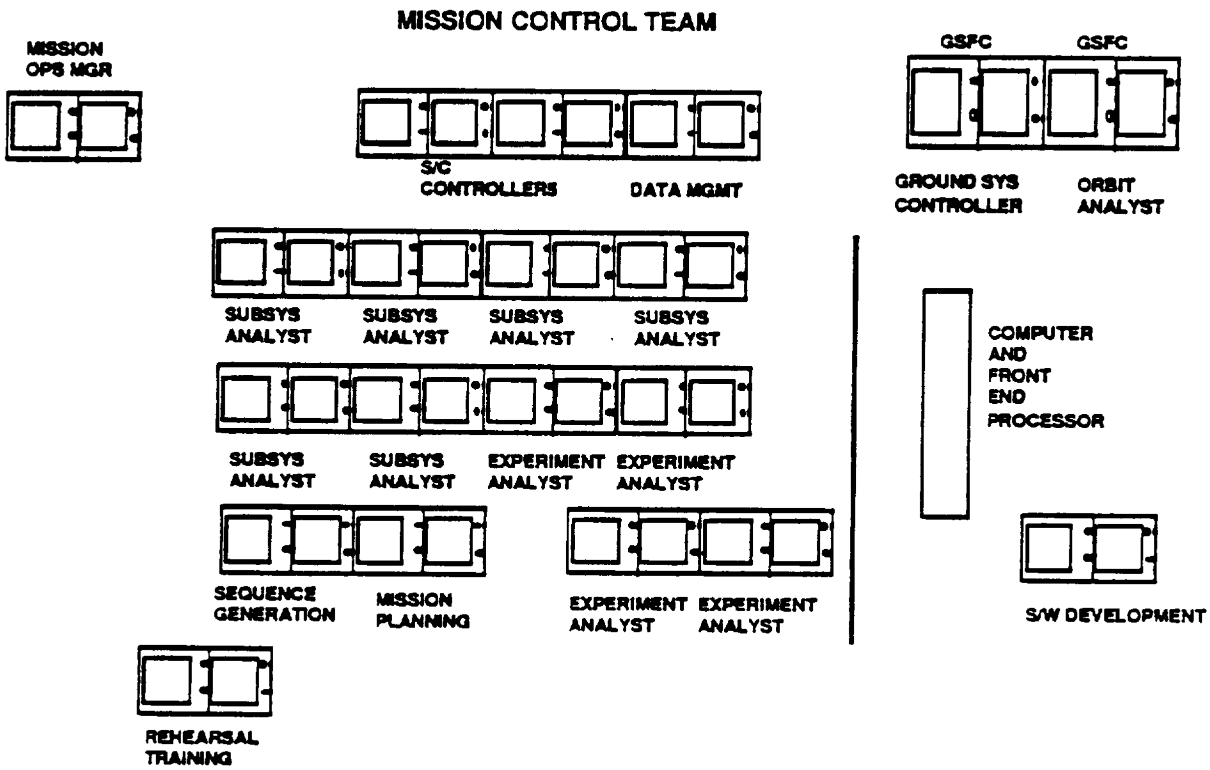

Figure 9.4-1 SOCC Layout

<u>Control System Operational Requirements and Functions</u> -

When cost effective, the control system will use previously developed system and subsystem software. Residual hardware and software will be used in implementation whenever cost effective. The operations system will be designed to sequence the spacecraft over a range of orbit attitudes and periods. Control of the altitude will be ±25 km (3 sigma) about the nominal value. The angle of inclination of the spacecraft orbit with respect to Earth's equator will be in the range of 27 to 29 degrees. The operations system will be compatible with a pointing prediction accuracy of effective range pointing error of 0.20 degrees (3 sigma). The operations system will be compatible with a pointing knowledge accuracy of effective range and azimuth pointing errors of 0.20 degrees (3 sigma). The operations system will have the capability to recover and process spacecraft recorded engineering data. Sequences will be designed such that selective playback of recorded data is not required. The operations system will accommodate a downlink data volume that allows playback of recorded data each orbit. The operations system will provide capability, including software, to support the operation of the on-board computer hardware and software. The operations system will time tag received spacecraft data such that onboard spacecraft time may be correlated with UTC to an accuracy of 5 ms (3 sigma) overall.

<u>Top Level Functional Definition of the Ground Control System</u> -

- Control COLD-SAT Orbit
- Transmit commands

•Prepare uplink command load often enough to update as requested
•Process downlink telemetry data
•Determine health of COLD-SAT
•Provide experiment data to the science community
•Track COLD-SAT often enough to control changes in the science payload and in the housekeeping functions

Partitioning of Functions into Ground and On-board Control to Assign to Facilities (SOCC and GSFC) - The operations design splits functions between ground and on-board control in order to accomplish a cost-effective mission. This partitioning is described below:

•Navigation activities will be at GSFC with orbit changes through propulsive maneuvers uplinked as command files to the on-board computer
•Command sequences will be transmitted from the SOCC through GSFC and NASCOM to TDRSS and then to the COLD-SAT Satellite.
•Command Loads will be generated at the SOCC.
•Downlink telemetry received at the SOCC from the GSFC NASCOM system will be processed to provide engineering status to the satellite analysts and science data to the experiment analysts.
•The health of COLD-SAT will be the responsibility of the satellite subsystem analysts at the SOCC. Experiment activities with potential impact on the health of the satellite will be coordinated between the analysis teams.
•Experiment data extracted from the telemetry downlinked will be accessible to both on-site (LeRC) and off-site scientists involved with COLD-SAT.
•TDRSS availability will be coordinated with GSFC and specific on-board tests will be placed to coincide with that availability where practical.

Control System Activity Approaches - Online and offline activity is provided by the ground control system.

Online Operations - The senior controller approves or disapproves problem resolutions procedures, monitors critical rescheduling and/or component reconfiguration. The controller also approves/disapproves modifications to the TDRSS contact schedule. The controller also monitors the status of the ground system and takes action to resolve anomalies/contingencies.

Data required for successful operations control includes: the status and quality of the navigation upload, the quality of the data received, the status of the downlink and uplink, the satellite status or health, and recommended contact with TDRSS.

The resource controller (GSFC) provides the status of the ground system and takes the action to resolve contingencies or anomalies. The controller also receives the status of the navigation upload and indications of communications problems and the quality of the data stream.

The Navigation controller verifies navigation upload, provides the navigation blocks, determines the quality of the navigation upload, and advises the potential of not meeting schedule.

The TT&C controller provides the status of the downlink and uplink and the status of the satellite.

Offline operations - The subsystem analysts monitor the health of the satellite and provide changes to the housekeeping of the satellite as command blocks to the sequence of events generator. Satellite on-board resources are monitored through telemetry. Sequences are reviewed to ensure sufficient power will be available. Playback times are reviewed against expected opportunities.
The experiment analysts will review the experiment resources to ensure sufficient LH_2 for the

remaining tests. The system will be capable of generating the test parameters and sequences and redesigning of tests, if necessary. Command blocks for changes to the experiment sequencing are provided to the sequence of events generator. Real-time changes will be initiated by the experiment analysts.

Mission planners determine the long range significant events required by the experiment P.I.'s and the satellite analysts. Time on TDRSS for playback of data (real-time and tape-recorded) is negotiated with GSFC. Short range planning includes up-dating the timeline and TDRSS times as required.

Definition of Operational Modes -

•Daily on-line analysis mode: Analysts will be monitoring real-time data when available and dumped recorder data otherwise during quiescent (non-test) times.

•Daily flight-controller only mode: Flight controllers will be responsible for the health of COLD-SAT in off-prime time. Analysts will be on call.

•On-board test operation mode: Analysts will monitor the experiment parameters to provide direction for real-time in-test changes. These changes will be in the nature of start commands uplinked to activate changes in either the duration of the experiment test or opening/closing of specific valves at different times in the sequence. Parameter updates will be permitted.

•Launch Mode: Uplink will only be available after separation from the launch vehicle and deployment operations have been nominally completed. No data will be monitored at the SOCC after Launch.

Contingency Operations - Contingencies will be handled by preparing scenarios for most likely anomalies and having those scenarios prepared as uplink loads available for use. Other contingencies will be handled as appropriate by the flight controller on duty by calling in the required analysts for decisions. A potential use of the development tanks is to perform the contingency procedures on the development tank system for validation prior to uplinking to the satellite.

Operational Interfaces - NASCOM circuits for voice and data will be utilized between the SOCC and GSFC. A local area network will be utilized, connecting the PC stations of the analysts with the flight controller. The flight controller will be the single point of contact with GSFC on-line operations. Personal Computers (PC s), with a local area network utilizing a common data base, will be used.

Training- All flight team members will undergo operational training on their respective consoles and software, including exercises simulating real-time mission scenarios. Cross-training of operational positions in the SOCC will be required.

Reliability, Availability, Maintainability, and Logistics Operations Concepts - Maintenance and logistics are institutionalized at GSFC for ground equipment,and include automatic fault detection and isolation. Availability is based on down time, considering the satellite, TDRSS, and external factors.

A safety program for COLD-SAT will be conducted in accordance with ESMCR 127-1, Range Safety Manual and KSC Management Instruction 1710.1, Safety, Reliability, and Quality Assurance Program. It will cover all program phases from production through deployment. A safety certification program that meets the requirements of AFETR 127-4 will be maintained.

Testing and servicing of the satellite at the launch site will comply with ESMCR 127-1. The satellite system design will provide for a safe installation and removal of pyrotechnic devices and EPS batteries at the launch site.

A hazard analysis of the COLD-SAT conceptual design was performed. A summary of the hazards identified by mission phase and by subsystem is shown in Table 10-1. The effect cause by the hazard is shown, but only to the top level category. The controls and design features which mitigate the hazards that have been identified are at a level commensurate with the design concept.

Table 10-1 COLD-SAT Hazards and Hazard Controls

Subsystem	Hazard Description	Possible Hazard Effect	Mission Phase Affected	Hazard Control
1. Experiment Propulsion and GSE	Tankage fails and leaks into the payload fairing compartment on the pad.	Fire and/or Explosion, Temperature Extremes	Manuf/Test Ground Ascent Orbit	Adequate margins and safety factors complemented with extensive ground testing
2. Experiment, Propulsion and GSE	High pressure gas pressurization ruptures/leaks GH_2 /GHe.	Fire and/or Explosion, Impingement	Manuf/Test Ground Ascent	Adequate margins and safety factors complemented with extensive ground testing.
3. EPS, ACS, TT&C	Electrical system becomes overloaded.	Fire, S/C Damage	Manuf/Test Ground Ascent	Adequate margin - Fuses
4. EPS, ACS, TT&C Propulsion Experiment	Electrical/electronic parts which can arc/spark could provide an ignition source in a flammable/explosive atmosphere within the payload fairing compartment.	Fire and/or Explosion	Manuf/Test Ground Ascent	GN2 purged compartment will be used. Satellite sealed hardware on ground.
5. All	Use of combustible materials in combination with an ignition source presents a fire hazard.	Fire, S/C Damage	Manuf/Test Ground Ascent	Material controls and review to preclude/ minimize combustivle material use
6. TT&C EPS, ACS Propulsion	EMI generated by the COLD-SAT interferes with the launch vehicle during flight.	Premature ordinance firing Electrical equipment damage	Ground Ascent	EMI design margin Adequate shielding grounding
7. Structural and GSE	Structural failure of pirmary structures, handling equipment and/or lifting equipment could cause collision damage.	Collision Injury, S/C Damage	All	Adequate margins and safety factors complemented with extensive ground testing
8. Experiment and GSE	Personnel contact with cold surfaces could result in freeze burns to the skin.	Personnel Injury	Manuf/Test Ground	Adequate insulation to minimize cold surfaces. Personnel protective equipment
9. ACS, TT&C EPS and GSE	Accidental contact by personnel with AC or DC voltage could result in personnel shock or electrocution.	Electrical Shock	Manuf/Test Ground	Adequate guards will be provided. Sealed equipment
10. All and GSE	Use of hazardous/combustible material could result in equipment damage or injury to personnel.	Fire and/or Explosion, Injury, S/C Damage	Manuf/Test Ground	Use and control of using such materials only when necessary
11. Experiment, Propulsion and GSE	Tankage, plumbing/fittings or components containing propellant fail resulting in the uncontrolled release of hazardous fluids.	Fire and/or Explosion, Injury, S/C Damage	Manuf/Test Ascent Orbit	Adequate margins and safety factors complemented with extensive ground testing
12. Propulsion ACS and EPS	Failures permit inadvertant thruster or engine operation.	Equipment Damage, Fire and/or Explosion, Injury	Ground Ascent Orbit	Isolate propellant from thruster until needed. Isolate power and commands until needed

Table 10-1 COLD-SAT Hazards and Hazard Controls Continued

13.	Propulsion Structural Experiment EPS	Premature operation of ordnance.	S/C & Equipment Damage, Fire and/or Explosion, Collision Injury	Ground Ascent Orbit	Appropriate fault tolerance and inhibits to preclude operation
14.	TT&C ACS	Improperly directed antenna radiation causes equipment damage or personnel injury.	S/C & Equip Damage Personnel Injury	All	Design inhibits, procedure discipline
15.	EPS	Battery failure causes leakage of caustic contents	S/C & Equip Damage, Personnel Injury	All	Flight qualified batteries, material margin and testing
16.	EPS	Battery rupture/explosion.	S/C & Equip Damage, Personnel Injury	All	Charge control operation precludes discipline
17.	Structrual TT&C EPS	Mechanism failure causes premature operation of deployment booms causing equipment damage or personnel injury.	S/C & Equip Damage, Personnel Injury	All	Design margins and GSE restraints
18.	Experiment/ Propulsion	On-orbit meteroid collision punctures fluid storage vessels resulting in fluid loss, a decrease or loss in experiment capability, or unbalanced thrusts.	S/C Damage	Orbit	Risk evaluation to be performed: Protection shield combined with structural panels
19.	Experiment and GSE	LH_2 trapped in lines between positive shutoff devices could expand and create overpressure conditions or line ruptures.	S/C Damage, Fire and/or Explosion, Injury, Impingement	All	Provide appropriate relief protection or procedural control to preclude trapping LH_2
20.	Experiment Thermal and GSE	Improper material (both metal and soft-good) when exposed to LH_2 and/or cryogenic temperature result in damage.	S/C Damage, Fire and/or Explosion, Injury	All	Compatibility of materials with LH_2 and cryogen temperatures, redundant shutoff/sealing devices, proper component qualification
21.	Experiment Thermal and GSE	During venting LH_2 can freeze resulting in restricted flow or blocked lines. Contents of tankage may not be completely expelled.	S/C Damage	Orbit	Preclude freezing by maintaining pressures above 2 psia. Use heater protection where required
22.	Experiment	Air or other contaminants intrude into the system which may clog or prevent component operation. Ruptures could occur.	S/C Damage, Fire and/or Explosion, Injury	Manuf/Test Ground Ascent	Proper procedure, purging and system protection to prevent intrusion
23.	Experiment	Supply tank vacuum jacket fails resulting in uncontrolled venting which dump tank contents.	S/C Damage, Fire and/or Explosion, Injury	Manuf/Test Ground Ascent	Adequate VJ margins and test approach

Table 10-2 shows the safety standards and regulations which will form the safety requirements for the design, build, test, and ground processing of the COLD-SAT system.

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Table 10-2 Applicable Safety Standards and Regulations

MARTIN MARIETTA	
M70-29, REV. 5, SAFETY ACCIDENT/ INCIDENT INVESTIGATION MANUAL, JANUARY 1984	REFERENCE ONLY
M-61-58, REV. 63, SAFETY STANDARDS MANUAL, VOLUME I, VOLUME II	COMPLIANCE (FOR TESTING HERE AT MMAG)
MARTIN MARIETTA STANDARD PROCEDURES FOR FABRICATION, INTEGRATION AND TEST ACTIVITIES	COMPLIANCE
NASA	
KHB 1700.7A, STS PAYLOAD GROUND SAFETY HANDBOOK	COMPLIANCE FOR KSC FACILITY PROCESSING
FEDERAL	
29 CFR, OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION, DEPARTMENT OF LABOR, PART 1910, LATEST ISSUE	COMPLIANCE
STATE	
NONE	
MCDAC ELV	
TBD	
DOD	
EASTERN SPACE AND MISSILE CENTER REGULATION ESMCR-127-1, 30 JULY 1984	COMPLIANCE
DOT	
U.S. DEPARTMENT OF TRANSPORTATION OFFICE OF COMMERCIAL SPACE TRANSPORTATION HAZARD ANALYSIS OF COMMERCIAL SPACE TRANSPORTATION VOLS. 1, 2 AND 3	COMPLIANCE
OTHER	
NATIONAL FIRE PROTECTION AGENCY #70 NATIONAL ELECTRICAL CODE (NEC)	COMPLIANCE
ASME BOILER AND PRESSURE VESSEL CODES, LATEST ISSUE	REFERENCE ONLY
ANSI B30 SERIES AMERICAN NATIONAL STANDARD SAFETY, LATEST ISSUE	COMPLIANCE
CHEMICAL PROPULSION INFORMATION AGENCY (CPIA)	REFERENCE ONLY

Certain COLD-SAT subsystem designs and associated operations have to comply with safety requirements which are well established. Those areas (spacecraft, experiment, and ground support) will come under the closest safety scrutiny. Other COLD-SAT areas not defined (while meeting all applicable safety requirements) have a lower level of safety concern. Table 10-3 lists the safety analysis and testing requirements for COLD-SAT.

Table 10-3 COLD-SAT Safety Analysis and Testing Requirements

- System safety Program Plan (SSPP)
- Missile System Prelaunch Safety Package (MSPSP)
- Payload Breakup Analysis
- Antenna Patterns and Power Curves
- Analysis and Testing of Electronic Equipment for Electromagnetic Interference Protection per MIL-STD-461
- Qualification and Acceptance Testing of Ordnance Subsystem
- Flight Termination System Requirement (Range Safety Analysis)

In order to verify that the COLD-SAT satellite and associated ground support equipment has been properly designed and tested from a safety standpoint, certain documentation are required (as shown in Table 10-4) which also includes ground processing, flight and mission information. Much of this data submittal is coordinated with the launch vehicle operator.

Table 10-4 COLD-SAT Safety Restrictions

- Proposed changes to a facility must be coordinated with Range Safety 90 days prior to formal meeting on the subject
- Equipment connected to a facility static ground system shall be 25 ohms or less
- An RF System shall be tested prior to arrival at the Range
- The Cryogenic System, including vacuum jacketed pipes, shall be cold shock tested
- The Ordnance System shall be tested
- Pad Electrical System -
  - For Hydrazine usage - Class I, Div II, Group C (present configuration)
  - For LH2 usage - Class I, Div II, Group B (Required upgrade for hardware on line during loading)
- Pad Hydrogen and Pressurant Loading - high factors of safety (4:1) desired for tanks (lower factors of safety required analysis)
- S/C Electrical System
- Batteries
- Satellite Lifting and Moving
- Antenna Checkout
- System Proof Pressure Check
- Hazardous Procedure Review/Approval
- Contingency Deservicing of LH2/GH2

Conclusions - Safety is a significant design driver for the COLD-SAT program. The use of liquid hydrogen at KSC requires modifications to the launch complex hardware and procedures to meet the hydrogen servicing specifications. GH2 loading was moved to the pad to avoid modification of a hazardous processing facility. The timeline was also changed to be able to power down electrical equipment on the pad earlier in the count prior to hydrogen loading. The factors of safety used in the COLD-SAT design will comply with the safety requirements of the Delta II launch facility.

The large vacuum chamber to be used for system testing while loaded with LH2 and GH2 must also meet more stringent safety requirements than the normal vacuum chambers used for spacecraft testing.

11.0 RELIABILITY

The initial reliability assessment of the Conceptual Design reflects the method used for the analysis which represents a worst-case reliability number. The reliability estimate used a six month operating time for all hardware and modeled the experiment subsystem to requiring more than half of its hardware and sensors operating throughout the mission.

The Spacecraft subsystems are comprised of existing-qualified hardware, and in this configuration we are using the avionics packaged in MMMS modules. The modules are the same as are used on another Martin Marietta program and we are using them in the same way the hardware is used on the other program. The analysis used the failure rates and reliability data from that program. The basis of the estimate includes: 1) the Experiment Subsystem hardware failure rates were derived from various space programs, 2) the Experiment Subsystem's technology development items are assumed to have been developed and qualified, 3) the avionics failure rates are based on S-level parts, and other component failure rates are from MIL-HDBK- 217.

Confidence limits for the estimated reliability have not been calculated, but the method of analysis is considered to be biased toward the lower reliability number. Therefore, the .91 estimated is attainable. Table 11-1 gives the reliability estimate by subsystem.

The single-string reliability shown is a rough estimate based on removing those components that were redundant, however the design is such that to remove some of the redundant component it would require a complete redesign. This would not decrease the program cost significantly, but it would also increase the program risk considerably.

Some single string design can be considered with a reasonable decrease in mission success probability. Single string design saves hardware costs, test costs and amplifies fault protection software. The subsystems which appear amenable to reduction in redundancy are the EPS and the ACS. Considerations in the EPS include reducing the solar array drive electronics from four units to two units; reducing the pyro initiator controller from two units to one unit; reducing the internal extender units from four units to two units. Considerations in the ACS include deleting the magnetics equipment (TAMs, Torquers, TAM Electronics). In the TT&CS, reducing the two recorders to one tape recorder would cause loss of redundancy but no loss to operational capability.

The goal is to perform the class I experiments to a mission success probability of .92. The reliability allocations shown on Table 11-2 follow the reliability estimate shown on Table 11-1 and uses the same numbers for all the subsystems except for the Experiment subsystem. The experiment subsystem contains all of the components that will require technology development and flight qualification. The design of the experiment subsystem will be new development. Therefore, we can use redundancy to achieve the allocation of .967 which should be achievable and realistic as a goal to be used for design trade-offs. The other subsystems are made up of existing hardware designs and the reliability goals will be useful only in the case of modifications to the hardware. The existing hardware reliability may be adjusted, but it could only be done on a very selective basis in order to avoid redesign and re-qualification. The cost and risk would be considered in the trade study, if reliability adjustment is warranted.

Table 11-3 lists the reliability enhancement methods that are included in our concept design. Some of the items are reliability enhancements that are not actually reflected in the reliability estimates presented. The items headed by the (*) really were not reflected in reliability probability of success numbers; these items do enhance the mission success and the technical risk factors (Section 12). The spacecraft subsystems are using existing, qualified hardware that has the redundancy hardware and software designed and validated. The reliability estimates used single failure redundant methods, however the existing system is capable of cross- strapping and therefore, can tolerate more than one failure.

Table 11-1 COLD-SAT Reliability Estimate by Subsystem

SUBSYSTEM	PROBABILITY COLLECTING ALL DATA	
	SINGLE STRING	REDUNDANT
EXPERIMENT	.507	.953
ATTITUDE CONTROL	.896	.996
ELECTRICAL POWER	.941	.988
T,T & C	.827	.986
STRUCTURE	.999	.999
PROPULSION	.896	.982
ALL CLASS I EXPERIMENTS FOR 6 MONTH MISSION	.316	.908

Table 11-2 Initial Reliability Allocations

SUBSYSTEM	ALLOCATION	
EXPERIMENT	.967	
ATTITUDE CONTROL	.996	
ELECTRICAL POWER	.988	
T,T & C	.986	
STRUCTURE	.999	
PROPULSION	.982	
ALL CLASS I EXPERIMENTS FOR 6 MONTH MISSION	.920	goal

Table 11-3 Reliability Enhancement Methods

EXPERIMENT SUBSYSTEM

-REDUNDANT COMPONENTS
*REDUNDANT PATHS FOR FLUID AND VENTS
*QUALIFIED AND SCREENED NEW TECHNOLOGY COMPONENTS
-REDUNDANT SENSORS AND DATA COLLECTION ELECTRONICS
-REDUNDANT CONTROL ELECTRONICS
*GROUND OVER-RIDE CAPABILITY FOR EXPERIMENT SEQUENCING
*SOCC CAPABILITY TO MONITOR EXPERIMENT RESULTS AGAINST ANALYSES
*FAIL SAFE CAPABILITY TO PRECLUDE LOSS OF HYDROGEN DUE TO A FAILURE
*DEVELOPMENT-PATHFINDER TANK FABRICATION AND TESTING
*PROTOFLIGHT TYPE THERMAL VACUUM TEST FOR EXPERIMENT CHARACTERIZATION

SPACECRAFT SUBSYSTEMS

-REDUNDANT SUBSYSTEMS / BOXES - PRECLUDES SINGLE FAILURE
*REDUNDANT DESIGN IS EXISTING AND PROVEN
*ELECTRONIC BOXES AND SUBSYSTEMS ARE EXISTING DESIGN - NO NEW I/F MODS
-S LEVEL PARTS AND SCREENED-UP B PARTS ARE USED
*PROTOFLIGHT ACCEPTANCE TESTING WILL BE EMPLOYED WHERE REQUIRED
*GSTDN S BAND COMM. BACK-UP FOR SATELLITE RECOVERY FROM SAFE-HOLD MODE

GENERAL PROGRAM METHODS

*TECHNICAL MANAGEMENT OF THE DESIGN, BUILD, TEST AND OPERATION OF THE SATELLITE - SPECIFY A TOTAL QUALITY PROGRAM
*TECHNICAL CHECKS-AND-BALANCE APPLICATION OF SYSTEMS ENGINEERING : TRACEABILITY OF EXPERIMENT REQUIREMENTS TO SUBSYSTEM COMPONENTS.

The reliability estimates of probability of success from each assembly type are shown in the following Tables. Table 11-4 is the thermal control subsystem heritage. Table 11-5 is the electrical power subsystem heritage. Table 11-6 is the telemetry, tracking and command subsystem heritage. Table 11-7 is the attitude control subsystem heritage. Table 11-8 is the propulsion subsystem heritage.

Table 11-4 Thermal Control Subsystem Hardware Heritage

ITEM	TYPE	HERITAGE	SOURCE/ VENDOR	RELIABILITY PROB. OF SUCCESS
LOUVERS	BIMETALLIC	MAGELLAN, MMS, CLASS. PROGS.	FAIRCHILD	.9999
HEATERS, CONTROLS	FILM TYPE	MAGELLAN, SCATHA, TETHERED SAT.	TAYCO	.9999
THERMOSTATS	SNAP ACTION	MAGELLAN, SCATHA TETHERED SAT.	TEXAS INST., ELMWOOD	.9999
MULTILAYER INSULATION	ALUM. MYLAR, DACRON NET	NUMEROUS SPACECRAFT	MATERIAL-SHELDAHL MMAG FAB.	.9999
STRUCTURE		NUMEROUS SPACECRAFT		.9999

Table 11-5 Electrical Power Subsystem Hardware Heritage

ITEM	HERITAGE	VENDOR	RELIABILITY PROBABILITY OF SUCCESS
MPS			
MODULE	MMMS	FAIRCHILD	.9996
BATTERY	MMMS	GENERAL ELECTRIC	.9999
PWR CTRL UNIT	MMMS	MCDONNEL DOUGLAS	
SIGNAL CONDITIONER UNIT	MMMS	MCDONNEL DOUGLAS	.9999
REMOTE I/F UNIT	MMMS	MCDONNEL DOUGLAS	.9999
BUS PROTECTION ASSY	MMMS	MCDONNEL DOUGLAS	
PWR REGULATOR UNIT	MMMS	MARTIN MARIETTA	.9998
PC&DM			
MODULE	MMMS	FAIRCHILD	.9968
REMOTE I/F UNIT	MMMS	MCDONNEL DOUGLAS	.9998
EXPANDER UNIT	MMMS	FAIRCHILD	.9998
PYRO CONTROLLER	MMMS	MARTIN MARIETTA	
S/A DRIVE ELECTRONICS	MMMS	BALL AEROSPACE	.9986
ACTUATOR SUBMODULE	MMMS	FAIRCHILD	
POWER SUBMODULE	MMMS	MARTIN MARIETTA	
ELECTRICAL SUBMODULE	MMMS	FAIRCHILD	.9999
HOUSEKEEPING POWER			
CMD/TLM CARDS			
COMPUTER STATUS MONITOR/ TLM & GUARD MODE INIT			
BUS COUPLER UNIT			
HEATERS AND THERMOSTATS			
PYRO SWITCHING UNIT	MGN	MARTIN MARIETTA	.9999
ARTICULATION MOTOR	MGN	MARTIN MARIETTA	.9998
SOLAR ARRAY	MGN	MARTIN MARIETTA	.9956
ORDNANCE	MGN	MARTIN MARIETTA	.9999

Table 11-6 Telemetry, Tracking, and Command Subsystem Hardware Heritage

ITEM	HERITAGE	VENDOR	RELIABILITY PROBABILITY OF SUCCESS	FAILURE RATE [F/MILLION HOURS]
C&DH MODULE	MMMS	FAIRCHILD	.9862	—
RECORDER	DEF SATELLITE	FAIRCHILD	.9998	
REMOTE I/F UNIT	MMMS	FAIRCHILD	.9999	3.30
BUS COUPLER UNIT	MMMS	FAIRCHILD	.9999	0.02
ON-BOARD COMPUTER	MMMS	LITTON	.9998	4.60
CENTRAL UNIT	MMMS	FAIRCHILD	.9996	0.13
INTERFACE UNIT	MMMS	FAIRCHILD	.9999	4.29
TRANSPONDER	LANDSAT, EXPLORER	MOTOROLA	.9996	1.73
ANTENNA ARTCC ELECTRONICS	MMMS	SCHAFFER MAGNETICS	.9999	
ANTENNA POSITIONING MOTOR	MMMS	SCHAFFER MAGNETICS	.9998	
DIPLEXER	MMMS	WAVECOM	.9984	0.06
RF SWITCH	MMMS	TRANSCO	.9940	0.23
ANTENNA: OMNI	MMMS	HARRIS	.9968	
ANTENNA:TDRSS	TDRSS	TECOM	.9969	
POWER AMP (30W)	CENTAUR	MOTOROLA		
LOUVER	MMMS	FAIRCHILD	.9995	0.29
HEATER	MMMS	FAIRCHILD	.9821	2.07

Table 11-7 Attitude Control Subsystem Hardware Heritage

ITEM	HERITAGE	VENDOR	RELIABILITY PROBABILITY OF SUCCESS
MACS	MMMS	FAIRCHILD	.9962
BUS COUPLER UNIT	MMMS	FAIRCHILD	.9999
EU	MMMS	FAIRCHILD	.9998
REMOTE INTERFACE UNIT	MMMS	FAIRCHILD	.9999
ATTITUDE CONTROL ELECTRONICS [A&B]	MMMS	GENERAL ELECTRIC	.9981
POWER SWITCHING UNIT	MMMS	FAIRCHILD	.9996
GYRO PACKAGE [IRU]	MMMS	TELEDYNE	.9969
COURSE SUN SENSOR	MMMS	ADCOLE	.9999
FINE SUN SENSOR	MGN	ADCOLE	.9999
EARTH SENSOR	SAS-3	ITHACO	.9999
REACTION WHEEL	MMMS	SPERRY	.9999
TRIAXIS MAGNETOMETERS	MMMS	SCHONSTEDT	.9999
TAM ELECTRONICS	MMMS	SCHONSTEDT	.9997
MAGNETIC TORQUERS	MMMS	GENERAL ELECTRIC	.9999
HEATERS AND THERMOSTATS	MMMS	FAIRCHILD	.9999
CONNECTORS	MMMS	FAIRCHILD	.9999

MACS - COMPUTER MODE REL. = .99021 [1 YR]
MACS - SAFE HOLD MODE REL. = .968

Table 11-8 Propulsion Subsystem Hardware Heritage

ITEM	TYPE	HERITAGE	VENDOR	RELIABILITY PROBABILITY OF SUCCESS
PROPELLANT TANK	TITANIUM SPHERE W/ DIAPHRAGM	EXOSAT	PSI/TRW	.9984
PRESSURANT TANK	AL ALLOY W/COMPOSITE OVERWRAP	MMU	SCI	.9928
0.2 LBF THRUSTER	HYDRAZINE	SCATHA, I-V	ROCKET RESEARCH	.9998
FILL / DRAIN VALVE	3/8 IN -MANUAL	MX, I-V, TOS	PYRONETICS	.9985
SERVICE VALVE	1/4 IN-MANUAL	MK II PROP MOD, MMU	PYRONETICS	.9985
RELIEF VALVE & BURST DISC	CREW SNAP ACTION W/SCREEN	MARINER 71,VO75	AMETEK/STRAZA	.9952
FILTER	25 µA ETCHED DISC	ATLAS/ CENTAUR	VACCO	.9996
PRESSURE TRANSDUCER	VARIABLE RELUCTANCE	ET, STS, TOS	TAVIS	.9900
REGULATOR PACKAGE	SINGLE STAGE	MMU	STERER	
ISOLATION VALVE	3/8 IN -PYROTECHNIC	GEMINI, LSAT, AGENA	PYRONETICS	.9999
PROPULSION MODULE ELECTRONICS	MMMS	MMAG PROGRAM	MMAG	.9999
PRESSURANT ISOLATION VALVE [LATCH]	SOLENOID	VARIOUS	CONSOLIDATED CONTROLS	.9999
RIU	MMMS	MMMS	FAIRCHILD	.9999
BCU	MMMS	MMMS	FAIRCHILD	.9999
CHECK VALVE	3/4 IN - 2 PAIR/PARALLEL QUAD PACKAGE	VARIOUS	HTL	.9999

12.0 PROJECT PLANNING

The project planning activity prepared for the COLD-SAT development addresses our approach to the detailed design and development, fabrication and test of the COLD-SAT System which includes related ground support equipment. The Phase C/D program that is outlined runs through post-mission analysis and is almost 5 years in length ending in 1997.

12.1 Technology Risks

Table 12.1-1 categorizes the elements and assigns a risk rank in the category. The rationale for our judgement is based on the heritage listed in the last column. All the spacecraft subsystems will be used without changing design or interface. The heritage is based on our finalized baseline design which uses the Multimission Modular Spacecraft (MMS) modules that are presently in production. The MMMS is a Martin Marietta version of the MMS that is presently being produced. This does not change the risk rating.

Table 12.1-2 Risk Ranking

STATE OF TECHNOLOGY CATEGORY	RISK RANGE ASSIGNED
a. USING EXISTING HARDWARE OR QUALIFIED DESIGNS	0 TO 1
b. REQUIRE NEW DESIGNS- EXISTING PROVEN TECHNIQUES ARE AVAILABLE	2 TO 4
c. REQUIRE NEW DESIGNS- AT OR NEAR THE STATE-OF-THE ART OF TECHNOLOGY	5 TO 7
d. REQUIRE NEW DESIGNS- BEYOND THE CURRENT STATE-OF-THE-ART	8 TO 10

Where : a risk factor of 10 indicates the highest degree of risk;
a risk factor of 0 indicates essentially risk free.

To perform a preliminary assessment of the state of the technology required to successfully execute the mission, we have assigned to each subsystem the risk rank shown in Table 12.1-2. In our judgement category (a) risk range specifies that the hardware is used with no modifications to the existing qualified design and includes no changes in the interfaces. The mechanical interfaces and the environments provided by the spacecraft must meet the specifications to which the hardware was qualified. A rating of "0" would only be assigned to hardware that is "on-the-shelf", built and tested.

Table 12.1-2 Risk Assessment

SUBSYSTEM	RISK FACTOR (category)		HERITAGE
Attitude Control	1	(a)	MMS/MMMS/UARS/ExplorerPlat/GRO
Electrical Power	1	(a)	MMS/ MMMS/UARS/ExplorerPlat/GRO
TTCS	1	(a)	MMS/MMMS/UARS/Explorer Plat/GRO
Thermal	1	(a)	MMS/MMMS/Viking/SCATHA/SKYLAB
Propulsion	1	(a)	EXOSAT/DSCS III/SATCOM/X-24A/SCATHA
Structure	1	(a)	Titan
Experiment	4	(b)	Component Development required
Ground Element	1	(a)	Magellan/MMMS/R2P2/GSFC/MMS
Software	3	(b)	Modify existing code

Essentially all of the risk associated with the COLD-SAT resides in the new designs associated with the experiment subsystem tankage and various supporting component elements that have to be demonstrated for LH2 use. These items have previously been defined in Figure 1.2-1 where technology needs were addressed.

12.2 Personnel Resources

The personnel required for COLD-SAT will be of two types. The spacecraft team will be contractor personnel engineers, technicians, and support specialists who have participated in the design, fabrication, assembly and testing of the satellite. The experiment team will be a mix of contractor and NASA personnel. They are scientists and engineers who understand the concepts involved with the LH2 process investigations on-orbit. They will evaluate the data and determine if the tests are set up correctly to provide the expected data. All skills required for this project are generally available in the aerospace community.

12.3 Facilities

For the most part the facilities required to fabricate, assemble and test the COLD-SAT are common to most contractors in the aerospace community and along with those at KSC/CCAFS can provide for all of the required assembly, integration, and testing required by COLD-SAT. Table 12.3-1 lists the standard and unique integration and test facilities required.

The one unique facility that is not common is a hydrogen compatible thermal vacuum chamber capable of accommodating the integrated satellite in the vertical configuration. The purpose of this test is to provide an end-to-end checkout of the system using the working media, simulate the on-orbit mission on the ground to collect a one-g data base and to exercise the entire flight and ground software together before the mission. The thermal interaction of the experiment subsystem loaded with LH2 on the spacecraft subsystems and visa versa can only be demonstrated with this type of test. The test will serve as the final acceptance test of the protoflight hardware approach being used for much of the satellite.

Table 12.3-1 Facilities Required for Integration and Test for COLD-SAT

STANDARD FACILITIES
- Facility with a Stable Platform for Model Survey
- Acoustic Facility
- Thermal Vacuum Chamber for Tank Development (LH2 compatible)
- Large Clean Room for Assembly and Integration

UNIQUE FACILITY
- Large Thermal Vacuum Chamber Facility for Integrated S/C LH2 Test
  Required- LH2 Storage, Fill, Drain and Vent Capability
  - Electrical Hazard Proofing
  - Pumping System

Figure 12.3-1 provides an overview of the COLD-SAT satellite installed in a thermal vacuum chamber and the functional interface requirements needed to accomplish LH2/GH2 testing. There are three major impacts to the chamber to accommodate hydrogen testing which include:

- Compatibility of the electrical support equipment to operate in a potentially enriched hydrogen environment.
- Compatibility of the pumping equipment to operate in a potentially enriched hydrogen environment.
- Proximity of the chamber to other facilities during hazardous operations.

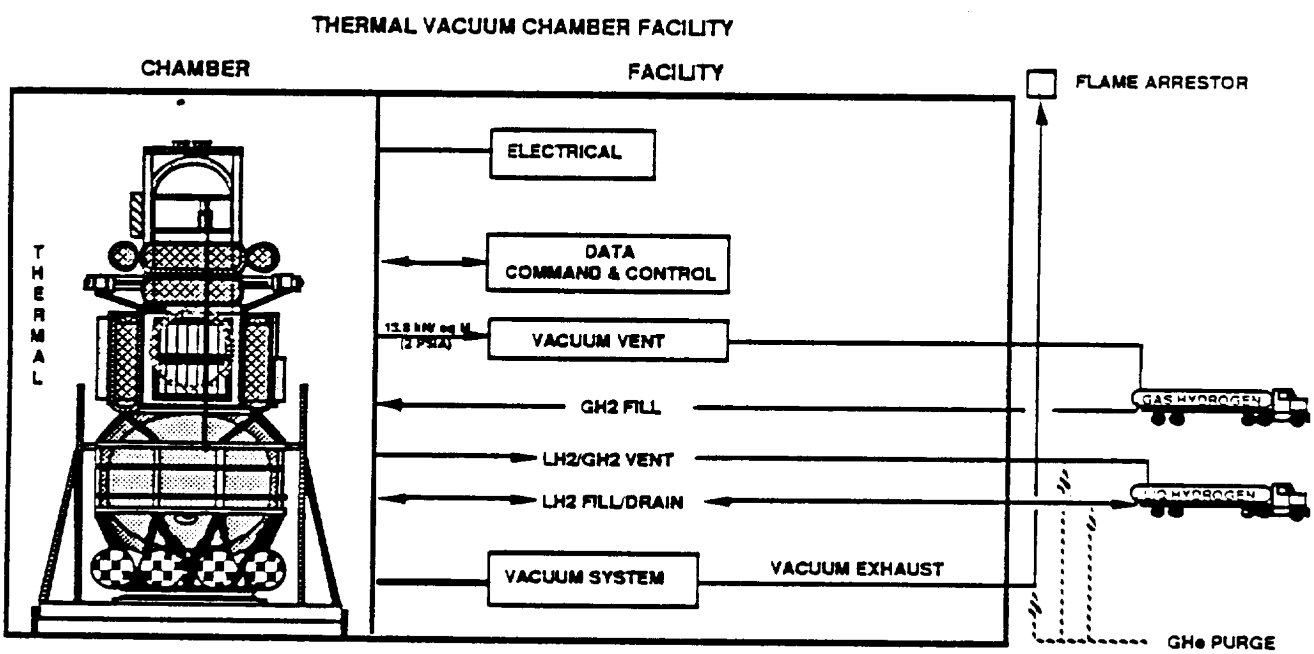

Figure 12.3-1 Thermal Vacuum Chamber Requirements for COLD-SAT Integrated Test

Impacts to the facility in which the chamber is located also is shown in Figure 12.3-1 and includes the following features:

1. Provisions for LH2 loading and contingent deservicing of COLD-SAT tankage which will mainly consist of supply tank loading.
2. Provisions for GH2 loading of the experiment subsystem pressurant tanks to 20670 kN / m2 (3000 psia).
3. An integrated hydrogen vent system which accommodates venting from:
   - the LH2 tanker
   - the GH2 tube bank
   - the COLD-SAT experiment subsystem vents
   - the chamber pumping system
4. One of the experiment vents must be maintained at space vacuum conditions of less than 13.78 kN/m2 (2 psia).
5. A GHe purge for all plumbing including the facility vent.
6. A suitable area outside the facility for tanker/tube bank placement and transfer plumbing routing.
7. Hydrogen leak detectors to monitor hydrogen concentrations in the facility in the proximity of the transfer plumbing, as well as chamber H2 detectors.

Constraints which should be placed on LH2/GH2 transfer operations include:

1. The COLD-SAT will be delivered, loaded into the chamber and removed after test in an empty condition with no LH2/GH2 on-board. Tankage may contain GHe blanket pressures.
2. LH2 will be loaded into the COLD-SAT after the chamber has been evacuated and the mechanical pumping system is off line with turbo-molecular pumps operating. The chamber may also be purged with GN2 to simulate the ELV payload fairing environment for LH2 ground servicing
3. Functional testing in the chamber will be limited to LH2 management and transfer operations which includes venting into the facility hydrogen vent. No planned venting of LH2/GH2 into the chamber will be allowed.
4. After testing is complete, the LH2 and GH2 will be off-loaded and the experiment subsystem will be purged with GHe before the chamber is repressurized.
5. If possible, chamber repressurization should be accomplished with GN2 followed by adequate air exchanges before the chamber is opened for personnel access.
6. Propulsion tankage will be filled with water or will be empty during the test.

Additional information is contained in Ref 12.3-1 relating to COLD-SAT LH2 vacuum testing.

12.4 <u>Testing</u>

The list of tests in Table 12.4-1 provides an overview for the integration and testing of COLD-SAT. The protoflight levels and durations for the tests will satisfy the verification requirements to be imposed. The COLD-SAT ground test program consists of those inspections and tests required to verify the integrity, performance, and functionality of the experiment subsystem and associated spacecraft support subsystems. Specific experiment subsystem verification consists of the following types of tests:

<u>In-line Component & Subassembly Testing</u> - These tests provide subassembly and component level testing at key points in the fabrication sequence to verify hardware integrity before performing steps that would preclude efficient repair or replacement. Tests at the component level will verify compliance with specified design requirements for the most part using off-the-shelf components that require only vendor or COLD-SAT contractor testing. For major tankage assemblies, tests include x-ray of welds, bubble point of LAD screens, dye penetrant

inspection of welds, component/subsystem LN2 cold shock, component/subsystem proof pressure tests, leak checks, instrument verification, vacuum integrity checks, cleaning, and structural proof loadings.

Qualification Testing - This type of testing is required for the most part on those parts of the experiment subsystem that require development and include the experiment tankage, pressurant bottles and various other components (see section 4.8). Our approach involves a development item for each experiment tank and a basic protoflight approach for flight tankage where testing could be accomplished on the development tanks to enhance design confidence. Design loads and design factors of safety will be intentionally conservative, where possible, to ensure sound design and preclude future safety concerns, bearing in mind restrictions created by experiment requirements for certain limitations to thermal and mass/volume relationships. As an example, pressure cycle tests can be accomplished on the development tanks, as well as a non-destructive burst test using an approach where the tank is designed not to yield at the burst pressure. The development tanks could be used in a ground test bed to evaluate LH2 processes after tank development is complete. A unique tank qualification article is not envisioned. All tank qualification testing will be accomplished on the development tank or at lower protoflight levels on the flight hardware. Redesigned RIU's and EVE's will require the development of a full qualification test approach. Where possible, component qualification by similarity of use on past flight programs will be used.

Table 12.4-1 COLD-SAT Test Program

SUBSYSTEM TESTING
- FUNCTIONAL AND PERFORMANCE
- INTEGRATION AND INTERFACE VERIFICATION (H/W AND S/W)
- ASSEMBLY ACCEPTANCE TESTING
- ASSEMBLY DELTA QUALIFICATION PROTOFLIGHT TESTING (WHERE NECESSARY)

INTEGRATION TESTING
- PROOF AND LEAK
- XRAY WELDS
- SENSOR/TRANSFER FUNCTION VERIFICATION AND CALIBRATION
- HARNESS CHECKOUT
- SENSOR/TRANSDUCER FUNCTIONAL VERIFICATION
- GSE FUNCTIONAL VERIFICATION
- INTEGRATION EXPERIMENT AND PROPULSION SUBSYSTEM
- SPACECRAFT BASELINE TEST
- GROUNDING TEST
- SUBSYSTEM TO SUPPORT EQUIPMENT
- POWER AND BUS REGULATION VERIFICATION
- SUBSYSTEM TO SUBSYSTEM INTERFACE VERIFICATION
- BATTERY CHECKOUT

SYSTEM TESTING
- MODAL SURVEY
- ACOUSTIC TEST
- PYROTECHNIC FUNCTIONAL VERIFICATION
- RF COMPATABILITY TEST
- SPACECRAFT BASELINE TEST
- WEIGHT AND CG
- SPACECRAFT LOADED LIQUID HYDROGEN THERMAL VACUUM TEST

Acceptance Testing - Such tests will be performed to certify compliance with predetermined criteria and acceptable pass/fail limits and to certify components/subassemblies to specification requirements for the purpose of ensuring proper fabrication, assembly and workmanship. Acceptance tests at the experiment subsystem and subassembly level include LN2 cold shock, proof pressure, and leak checks, etc., and consist of tests performed under other testing classifications.

Functional Tests - These tests will verify that the flight hardware is operating as designed via a series of discrete tests to verify experiment integrity, subsystem compatibility, and instrumentation functionality. Criteria and techniques necessary to perform experiment functions will be verified at both the subsystem and system levels. An example of such testing for the experiment subsystem is provided in Table 12.4- 2.

Table 12.4-2 Experiment Subsystem Testing

• EXPERIMENT SUBSYSTEM TESTING PERFORMED AT BOTH THE TANK ELEMENT AND INTEGRATED SUBSYSTEM LEVEL

- RELIEF SYSTEM VERIFICATION (MECHANICAL & ELECTRONIC)
- GHe & GH2 SYSTEMS FLOW & PRESSURIZATION CHECKS
- SUPPLY TANK GROUND CHILLDOWN & THERMAL CONDITIONING
- GHe/GH2 REGULATOR LOCKUP CHECK
- GHe & GH2 PRESSURANT BOTTLE PRESSURIZATION
- SUPPLY TANK LH2 FILL & DRAIN
- SUPPLY TANK LH2 TOPOFF
- SUPPLY TANK NON VENTED HOLD DETERMINATION
- SUPPLY TANK WALL HEATER OPERATION & STRATIFICATION CHECKS
- SUPPLY TANK TVS OPERATION
- SUPPLY TANK MIXER & DESTRATIFICATION OPERATION
- SUPPLY TANK COMPACT HEAT EXCHANGER OPERATION
- SUPPLY TANK OUTFLOW AND LAD OPERATION
- TRANSFER LINE CHILLDOWN OPERATIONS
- RECEIVER TANK TESTS
  - CHILLDOWN AND SPRAY SYSTEM EVALUATION
  - FILL CHECKS USING NO-VENT FILL
  - TVS OPERATION
  - OUTFLOW & DRAIN CHECKS
  - TANK PRESSURIZATION USING GHe & GH2
- VERIFICATION OF ORIFICE FLOW CONTROL FUNCTION
- INSTRUMENTATION OPERATION
- HEATER OPERATION
- CONTROL LOGIC & CONTROL NETWORK FUNCTIONS

Environmental and Performance Testing - This testing will verify operation over the expected extremes of thermal, vacuum, vibration, and EMI environments. These tests are system level to protoflight environmental criteria. During and after thermal vacuum environmental tests, the experiment subsystem will be operated to determine that the COLD-SAT is performing as designed over the required operating range. A complete ground based flight sequence and duration simulation using LH2 and GH2 from ground servicing through normal mission completion will be performed. This simulation in the thermal vacuum environment will serve as a validation of both flight and ground software against the flight hardware and will include separate checks of all contingency, back-up, and fault detection, as well as, off-nominal operational verification of the fault protection software. Operation of the experiment and spacecraft systems with LH2 will verify thermal compatibility between the two. Data collected from this mission simulation will provide a ground data base for math model correlation and will eventually be compared to the flight data. Testing will also be performed to verify that the flight hardware was not damaged by previous environmental testing.

The test program for COLD-SAT provides the necessary testing to verify the requirements imposed. The test philosophy is to verify using a protoflight concept where acceptance and qualification of off-the-shelf hardware is at protoflight levels and durations. Specific emphasis on safety will be maintained throughout the program. New hardware, mainly in the experiment subsystem, will be qualified using qualification units, except for the supply and receiver tanks which have development tanks which will undergo significant testing.

Minimizing the test program reduces cost significantly. The test assemblies used during COLD-SAT testing are listed in Table 12.4-3. The philosophy for conducting each type of test is also shown.

Table 12.4-3 Test Hardware for COLD-SAT and Test Philosophy

TEST ITEMS REQUIRED TO VERIFY COLD-SAT REQUIREMENTS

•PROTOFLIGHT SPACECRAFT
•TEST BATTERIES
•SOLAR ARRAY SIMULATOR
•MASS SIMULATORS FOR SPECIFIC ELECTRONIC HARDWARE

PHILOSOPHY-

COMPONENT QUALIFICATION -	•Off-the-shelf Hardware: Similarity •New/Modified Hardware: Qual at Protoflight Levels •Experiment development Items: Qual Units Except for Development Tanks
SUBSYSTEM QUALIFICATION -	•Hardware Assembled into Larger Units, such as the Propulsion Equipment, and Tested at Protoflight Levels
COMPONENT ACCEPTANCE -	•Protoflight
SUBSYSTEM ACCEPTANCE -	•Experiment Subsystem Tests, including LN2 Cold Shock; System Proof Pressure and System Leak Tests •Environmental and Performance Testing
SYSTEM LEVEL ACCEPTANCE	

Our approach to testing the supply tank pressure vessel incorporates the use of LH2 prior to installing the vacuum jacket. This will be accomplished on both the development and flight tanks. Testing the vacuum jacket for pressure integrity prior to installation is not a normal operation in that cutting, grinding, and rewelding operations to prepare the Vacuum Jacket for final installation are considered to add more risk than the test verification is worth. It is our recommendation that this vacuum jacket test verification not be considered.

Other testing on spacecraft subsystems at both the component, subassembly, subsystem, and system level after the entire integration of the experiment and spacecraft subsystems is accomplished will be performed and will include the following types of checkout:

Subsystem Integration - Such testing will verify grounding and isolation, bonding, interfacing, operating states, and selected functional capabilities. Each subsystem should have a minimum of 500 hours of operating time accumulated from all phases of the ground test program through and including pre-launch operations. Electrical/electronic flight hardware should be operated for a minimum of 300 hours prior to launch including subassembly, assembly, subsystem and system testing.

Subsystem Testing - EPS testing will provide power consumption measurements, polarity checks, AC feedthrough checks, AC amplitude and frequency verification, bus stability checks, exercising the relays that provide power to user subsystems, demonstrating that specified bus levels are maintained, and verification of the assignment of power loads. Other tests include overload protection verification, redundancy and cross-strapping checks, enable and inhibit tests, and checks for cable losses. TTCS testing will provide telemetry formats and measurement checks, power-on-reset states verification, undervoltage trip point measurements, clock synchronization, turn-on transient measurements, fault recovery testing, data handling and command interface testing. ACS testing includes simulation of flight profiles.

Systems Integration Testing - As the spacecraft bus subsystem elements are being integrated to one another testing will be accomplished that includes verification/checks for power allocation vs consumption, power distribution cable loss, power switching characteristics, ripple current measurements, power bus frequency variation and stability, power profile performance, grounding, telemetry position, timing relationships, and telemetry values and modes with all combinations of formats, including rates, memory readout, frame sync, format ID and clock. All combinations of elements of downlink telecommunications will be checked along with calibration of analog measurements, transducer operation, digital measurements verification for information content, command capability and antenna operation which include tests for uplink error detection, correction and execution, redundancy management, anomaly response, fault protection and satellite safing (including experiment subsystem safing), alignment and phasing, plugs out verification, inertial properties, temperature control, sequence verification/validation and software integration. Compatibility tests will verify compatibility to the launch vehicle, TDRSS and the SOCC.

Operating Capabilities Baseline Testing - This testing will provide, under ambient conditions, bus limits, temperature limits, long term continuous operation of the flight software, uninterrupted operation of the flight software, the capability to recover from selected faults.

System and Component Environmental Verification - This type of testing and/or verification by analysis will verify that the hardware will operate over the expected extremes of thermal, vacuum, vibration and electromagnetic environment and consists of tests such as static loads, acoustic, thermal vacuum, pyrotechnic shock, modal survey, RF compatibility and EMC/ESD.

12.5 Schedules

A top level COLD-SAT Phase B and follow-on C/D program schedule is presented in Figure 12.5-1 and reflects the current view as we understand it for the ongoing continuation of the COLD-SAT program. Critical to the ATP of the Phase C/D is the successful completion of the preliminary design Phase B where the experiment and spacecraft system requirements are baselined. This design activity ends in mid 1992 with a System Design Review (SDR) and can be followed by a formal Phase 0 safety review with the ELV operator and ETR safety. At this point the design has matured close to a Preliminary Design Review (PDR) with two contractors working independently on individual design approaches to the same set of requirements. This will allow for a very short turn around once the Phase C/D starts for a formal PDR with the single Phase C/D contractor proceeding with the favored design. Twelve months later a Critical Design Review (CDR) would be held on the completed finalized design.

The critical milestones to accomplish the phase C/D schedule in close to a four year timeframe is the very early commitment to procure long lead items. Primarily the long lead items will require new tooling and have long delivery time for basic materials and components. The date to start these procurements is at ATP where the basic tankage size, shape and configuration has to be fixed so that tank development can begin. Procurement of tank forgings for both the development and flight tanks must occur simultaneously in order to be cost effective. Final machining of the flight tank will not occur until after tank development tests are complete. After PDR commitment to procure spacecraft subsystem long lead components and assemblies must be made to meet the schedule and requires the use of an existing, mature spacecraft bus where component interfaces and compatibilities are known and proven . Our proposed S/C configuration meets these needs.

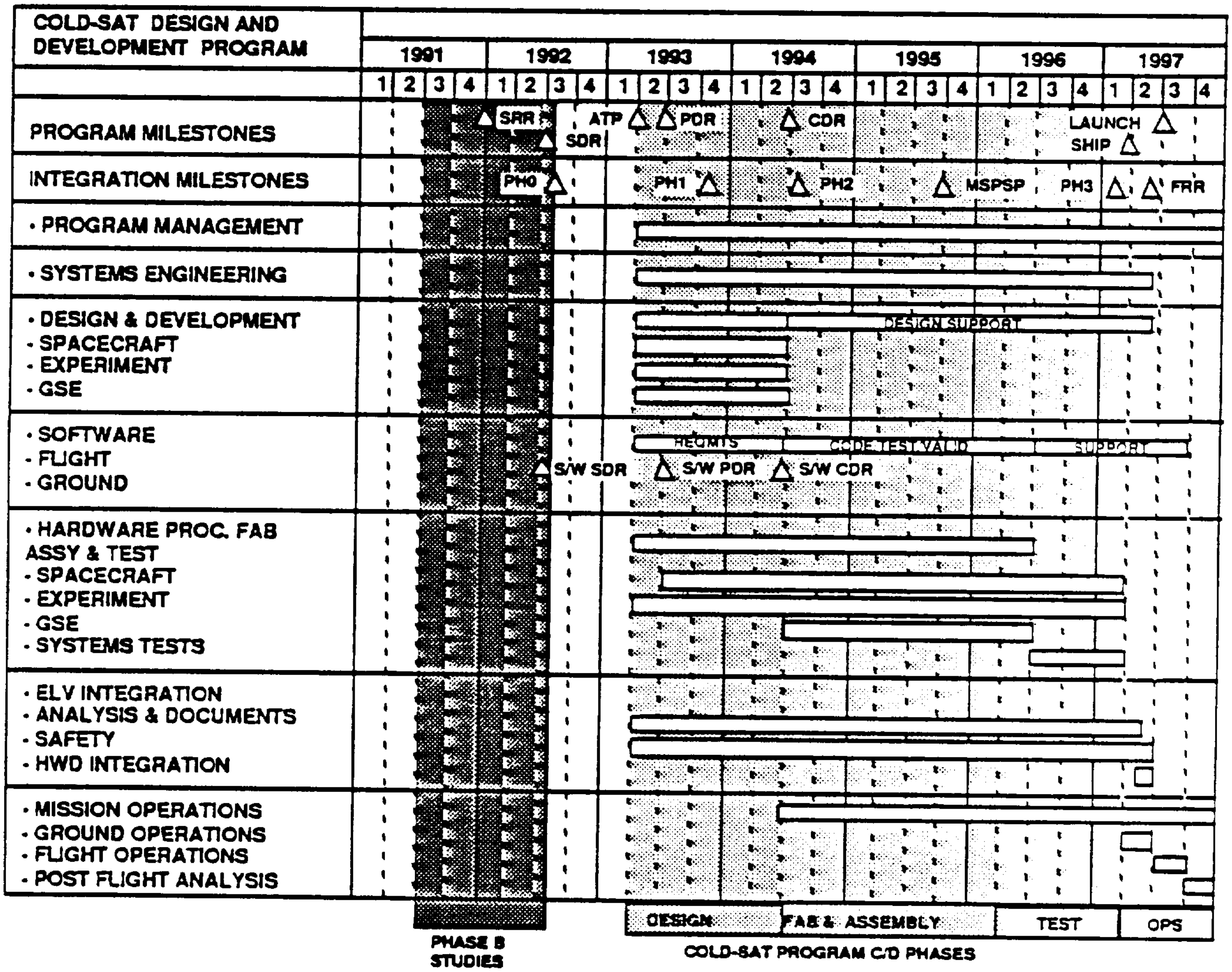

Figure 12.5-1 COLD-SAT Program Schedule

Equally critical to long lead procurement is the establishment of a supporting cryogenic technology development program that will mitigate design risk by the CDR in both component, subsystem and process investigation areas. This development is shown in Figure 12.5-2 for those areas that require such effort. Some of the component development is critical for system level characterizations. Such a component is the mixer and transfer pumps which at some point in the ground test approach will be integrated with a ground test tank that contains a mixer spray system and TVS heat exchangers and a VCS. Prior to this time, the pumps will have been qualified to operate with LH2 and the operating characteristics will have been determined at the component level. As an example the development of the mixer pump has to proceed to this point [independent of TVS development] before the combined pressure control features of both can be meshed. It is important to note that the development of experiment hardware, on-going at LeRC, must be kept up to insure availability for the COLD-SAT mission timeframe for those areas shown and must be coordinated so that the proper component characteristics are being developed.

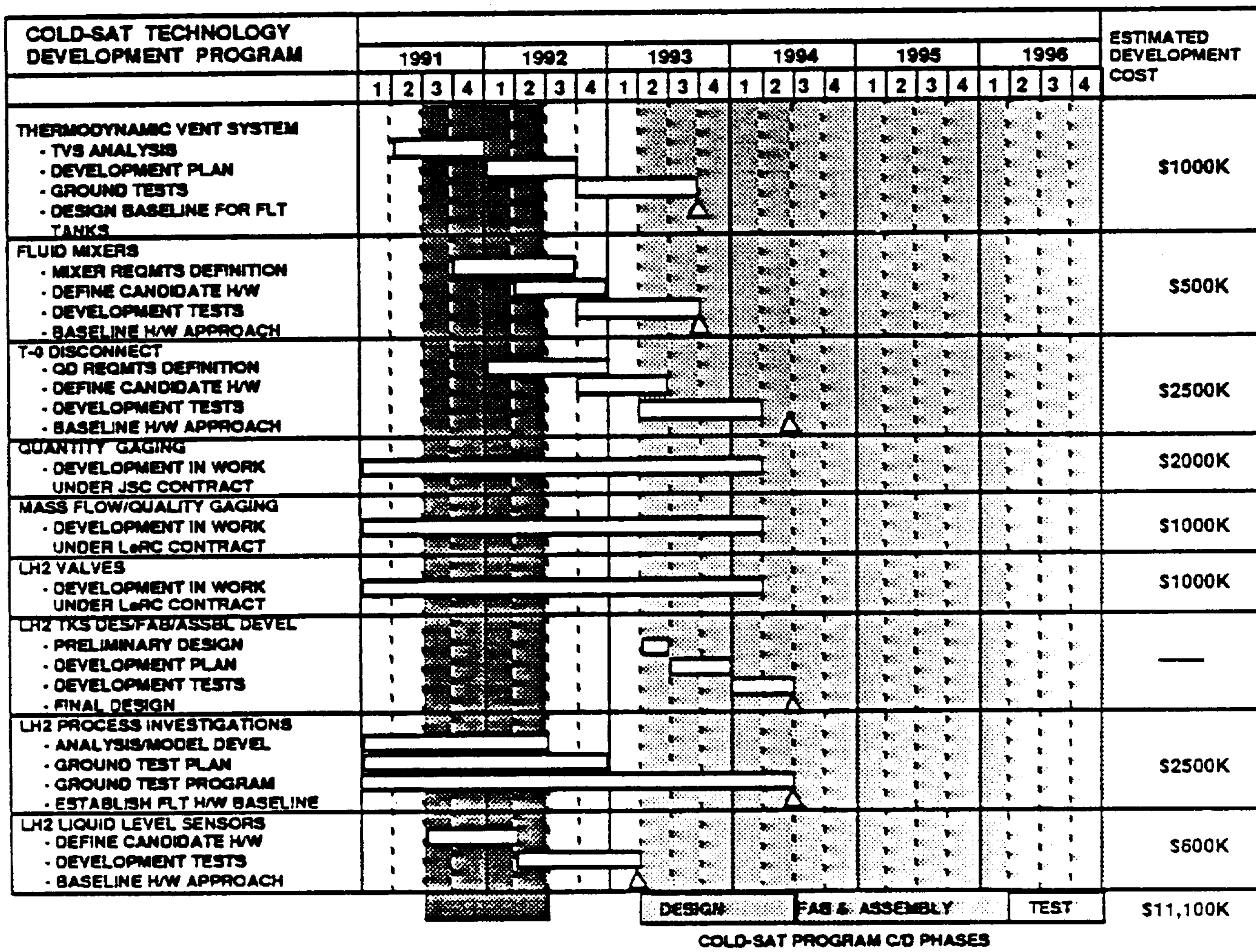

Figure 12.5-2 COLD-SAT Development Items Schedule

After CDR a twelve month manufacturing and fabrication activity precedes the assembly integration and test of the satellite experiment and spacecraft subsystems. Figure 12.5-3 is a top level summary of the assembly, integration and test flow that has been developed for the satellite. The satellite has been subdivided into three sections that can be individually processed and then integrated to one another. These consist of the following:

- Lower body composed of the supply tank and all of the components in the aft equipment bay. The aft equipment bay will be assembled and then integrated to the supply tank.
- Middle body composed of four MMS modules, structure, and all components located in the module cavity , including receiver tank 2 and certain pressurant bottles.
- Upper body consists of receiver tank 1, structure, forward propulsion module, other components, assemblies and pressurant bottles mounted above the MMS modules.

The launch operations take place at Kennedy Space Center and the Cape Canaveral Air Force Station. After delivery by air, the satellite and GSE are configured. Operations take place at the PPF and HPF prior to movement of COLD-SAT to the launch complex. The launch operations flow is shown in Figure 12.5-4. Additional discussion on GSE and ground processing operation was previously presented in sections 7 and 9, respectively.

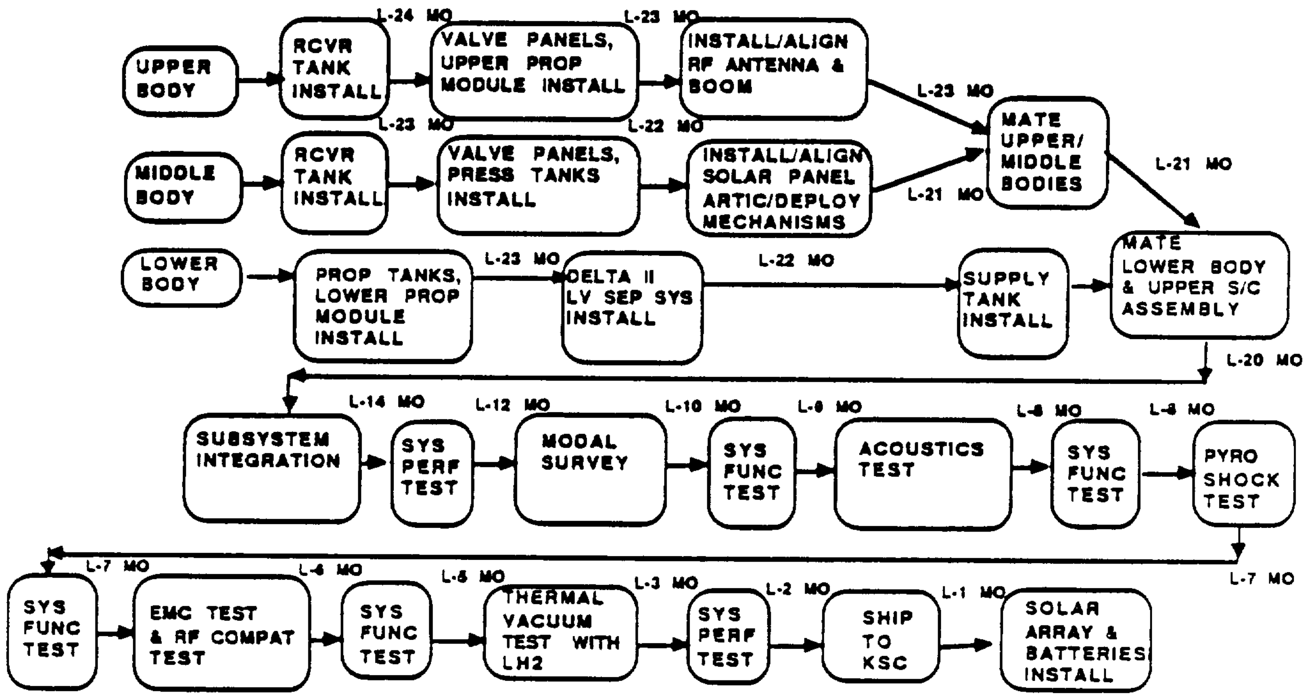

Figure 12.5-3 Flowchart of Assembly, Integration, Test, and Shipment

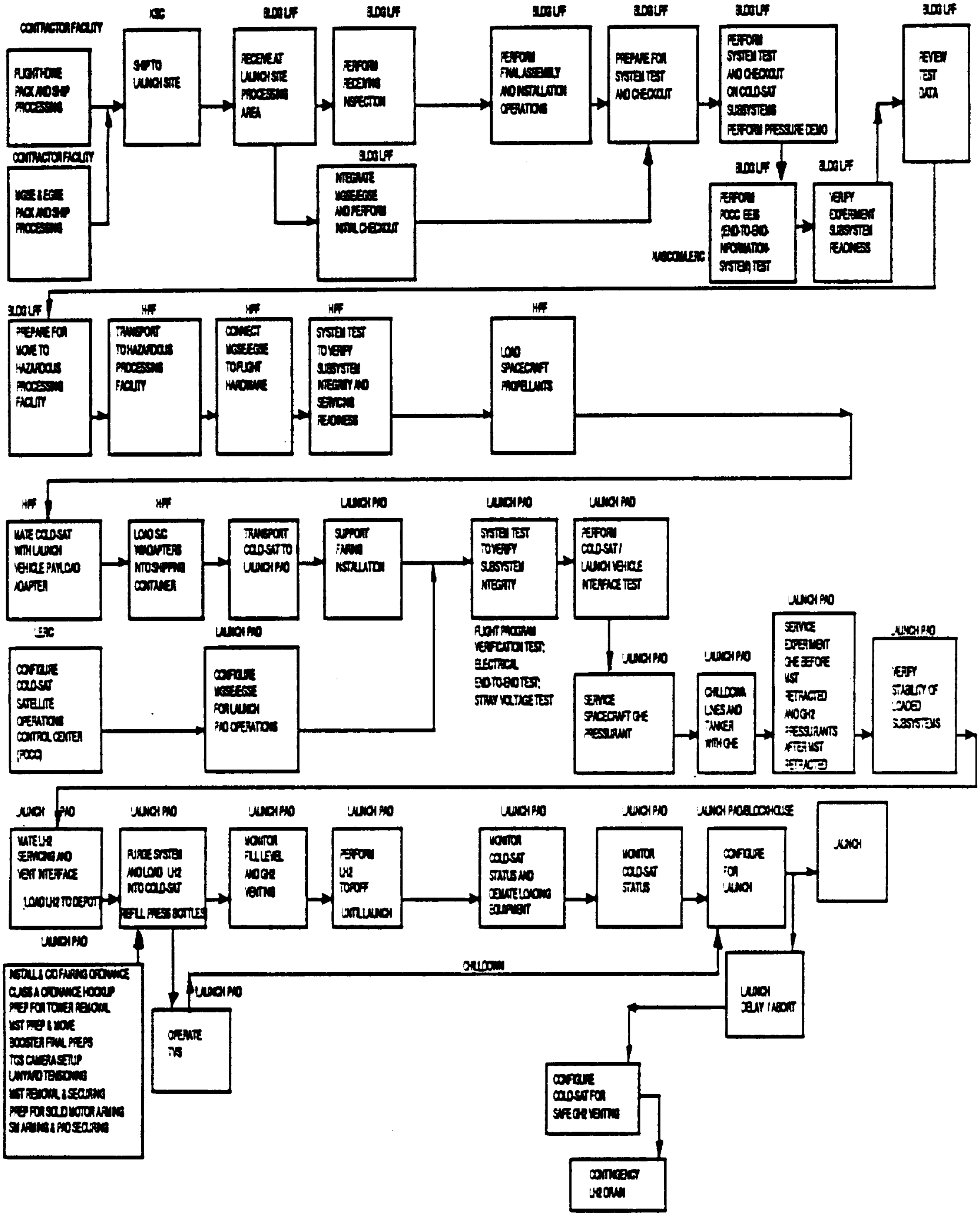

Figure 12.5-4 Launch Operations Flow

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16. Abstract

The Cryogenic On-Orbit Liquid Depot Storage, Acquisition and Transfer Satellite (COLD-SAT) is an experimental spacecraft launched from an expendable launch vehicle which is designed to investigate the systems and technologies required for efficient, effective and reliable management of cryogenic fluid in the reduced gravity space environment. Fundamental data required for the understanding and design of systems to meet this need are lacking; the COLD-SAT program will provide this necessary database and provide low-g verification of fluid and thermal models of cryogenic storage, transfer, and resupply concepts and processes. Future applications such as Space Station, Space Transfer Vehicle (STV), Lunar Transfer Vehicle (LTV), external tank (ET) aft cargo carrier (ACC) propellant scavenging, storage depots, and lunar and interplanetary missions, among others have provided the impetus to pursue this technology in a timely manner to support the design efforts.

A baseline conceptual approach has been developed and an overview of the results of the 24-month COLD-SAT Phase A Feasibility Study Program is described which includes the following: 1) a definition of the technology needs and the accompanying experimental three month baseline mission, 2) a description of the experiment subsystem, major features and rationale for satisfaction of primary and secondary experiment requirements using liquid hydrogen (LH_2)as the test fluid, and 3) a presentation of the conceputal design of the COLD-SAT spacecraft subsystems which support the on-orbit experiment with emphasis on those areas which posed the greatest technical challenge.

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