THE COLD-SAT EXPERIMENT FOR CRYOGENIC FLUID MANAGEMENT TECHNOLOGY*

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ABSTRACT

Future national space transportation missions will depend on the use of cryogenic propellants, and thus NASA-sponsored activities have addressed cryogenic fluid management technology development needs for these missions. One of the greatest needs is to conduct in-space testing to demonstrate low-gravity cryogenic fluid management concepts and to acquire the technical data base necessary to enable system design. Liquid hydrogen is the preferred test fluid due to its propellant use, the greater technical challenges it presents, and the absence of an alternative fluid having a suitable combination of thermophysical properties. The NASA Lewis Research Center has thus funded design studies of COLD-SAT, an ELV-launched orbital spacecraft that will perform subcritical liquid hydrogen storage and transfer experiments under low-gravity conditions.

There are four high-priority Class I experiments and nine lower priority Class II experiments. Although it is intended to conduct all 13, the Class I experiments control the spacecraft design and the Class II experiments are accommodated without adding substantially to the complexity and cost of the spacecraft. An Atlas commercial launch vehicle will place COLD-SAT into an initial 1300km (700 nmi) circular orbit, and the three-axis-controlled spacecraft bus will provide electric power, experiment control and data management, attitude control, and propulsive accelerations for the experiments. Low levels of acceleration will be created to provide data on the effects that low gravity levels might have on the heat and mass transfer processes involved. The experiment module that is part of the spacecraft will contain three liquid hydrogen tanks; fluid transfer, pressurization and venting equipment; and instrumentation. At launch all the liquid hydrogen will be in the largest tank, which has helium-purged MLI to prevent ingress and freezing of air on the launch pad. This tank will be loaded and topped off by the hydrogen tanking system used for the Centaur upper stage of the Atlas.

INTRODUCTION

The nation faces a future of expanding strategic, civil, and commercial space activities. Many will involve the use of subcritical cryogens, which present low-gravity fluid management challenges as well as special storage and utilization problems due to low fluid temperature. The NASA Lewis Research Center (LeRC) has thus funded feasibility studies of COLD-SAT (Cryogenic On-Orbit Liquid Depot Storage, Acquisition, and Transfer Satellite), a free-flying orbital liquid hydrogen experiment to be launched by an expendable launch vehicle in 1998. General Dynamics Space Systems Division (GDSS) and Ford Aerospace Space Systems Division are one of the contractor teams that have performed the studies. For COLD-SAT, liquid hydrogen is the fluid of choice because of its projected use as a propellant for space transportation missions and because it presents greater fluid management challenges than does liquid oxygen. Liquid hydrogen also has uses as a high-energy chemical reactant for national strategic orbital assets.

CFM TECHNOLOGY NEEDS

Cryogenic fluid management (CFM) technology needs were categorized at a NASA-sponsored workshop that addressed requirements for in-space testing.[1] The categories include liquid storage, liquid supply, liquid transfer, fluid handling, advanced instrumentation, and tank structures and materials. Table I lists CFM technology needs under these headings and indicates their criticality for performing future space transportation missions, including Initial Space Transfer Vehicle/ Lunar Transfer Vehicle (STV/LTV), the Lunar Excursion Vehicle, the Space-Based STV/LTV, the Orbital Depot, the Resupply Tanker, and Mars vehicles. For those missions affected, the criticality is Level 1 (enabling), Level 2 (high impact), or Level 3 (enhancing).

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Table I. Cryogenic Fluid Management Technology Needs.

Technology Category	Technology Criticality*					
	Initial STV/LTV	Lunar Excursion Vehicle	Space-based STV/LTV	Orbital Depot	Resupply Tanker	Mars Transfer Vehicle
Liquid storage						
• Thermal control systems						
– Degradation of material		2	2	2		2
– Effect of launch environment on thick MLI	2	2	2	2		1
– Combined Earth/orbit insulation	2				2	
– Para/ortho conversion				3		3
– Multiple/coupled VCS				2		2
• Pressure control systems						
– TVS performance	1	1	1	1	1	1
– Fluid mixing for stratification control	1	1	1	1	1	1
– Refrigeration/reliquefaction				2		2
Liquid supply						
• Pressurization system performance						
– Autogenous	3	3	2	2	3	3
– Helium	3	3				
– Mech (pumps/compressors)	2			2	2	2
• Fluid acquisition						
– Fine mesh screen LAD performance	3	3	2	2	3	3
– Fluid settling and outflow under low-g conditions	2	3	2	3	3	3
– Fluid settling and outflow under impulsive accel	3	3	3		3	3
– Impact of heat addition on LAD performance			3	3	3	
– Thermal subcooling of liquid outflow				2	2	
Liquid transfer						
• Transfer line chilldown		3	3	3		3
• Tank chilldown with spray		3	3	3		3
• No-vent fill		1	1	1		1
• LAD fill		3	3	1		3
• Low-g vented fill		2	2	2		2
Fluid handling						
• Liquid dynamics/slosh control	2	3	2	2	2	2
• Fluid dumping and tank inerting	1	1	1	1	1	1
• Earth-to-orbit transport as subcooled liquid or slush	3				2	
Advanced instrumentation						
• Quantity gauging	2	1	2	1	3	1
• Mass flow/quality metering	3	2	2	3	3	2
• Leak detection	2	1	1	2	2	1
• Liquid/vapor sensors	3	3	3	3	3	3
Tank structures and materials						
• Low thermal conductivity components	3	2	2	2	3	2
• Low-pressure tankage	3	3	3		3	3
• Composite (lightweight) vacuum jackets	3				3	
• Contamination/degradation of LAD	3	3	2	2	3	2

* Level 1 (enabling) – Specific application cannot be configured without this technology/safety-critical
Level 2 (high impact) – Technology provides significant system performance improvement or reduced operational complexity/cost
Level 3 (enhancing) – Technology provides modest system performance improvement

The criticality levels assigned to the various technology categories under these missions are based on consideration of technical feasibility, safety, operational complexity, cost, and system performance. Due to the scarcity of information on the systems for performing these missions, the assignment of criticality levels is somewhat subjective. However, it is clear that cryogenic fluid management is an important development area for these future space missions.

IN-SPACE TESTING

Testing objectives are given in Table II for the cryogenic fluid management technology categories. System developers are faced with needs for engineering data bases and validated performance models to enable design. They also require that brassboards or prototypes have certain key features demonstrated in the appropriate environments and at the appropriate systems level. In-space testing will be required to verify much of the technology needed for future space missions. Much of the testing will address systems-level behavior and control during representative operations under low-gravity conditions.

Table II. In-space Experimentation Needs.

Technology Category	Testing Objective: Engineering data base	Performance modeling	Environmental validation	System validation	In-space testing required
Liquid storage				Yes	Yes
• Thermal control systems					
– Degradation of material	Yes		Yes		Yes
– Effect of launch environment on thick MLI	Yes		Yes		
– Combined foam/MLI sys	Yes	Yes	Yes		
– Para/ortho conversion	Yes	Yes			
– Multiple/coupled VCS	Yes	Yes			
• Pressure control systems					
– TVS performance	Yes	Yes	Yes		Yes
– Fluid mixing for stratification control	Yes	Yes	Yes		Yes
– Refrigeration/reliquefaction	Yes	Yes			Yes
Liquid supply				Yes	Yes
• Pressurization system performance					
– Autogenous	Yes	Yes	Yes		Yes
– Helium	Yes	Yes	Yes		Yes
– Mech (pumps/compressors)	Yes	Yes			
• Fluid acquisition					
– Fine mesh screen LAD performance	Yes	Yes	Yes		Yes
– Fluid settling and outflow under low-g conditions	Yes	Yes	Yes		Yes
– Fluid settling and outflow under impulsive accel	Yes	Yes	Yes		Yes
– Impact of heat addition on LAD performance	Yes	Yes			
– Thermal subcooling of liquid outflow	Yes	Yes			
Liquid transfer				Yes	Yes
• Transfer line chilldown	Yes	Yes	Yes		Yes
• Tank chilldown with spray	Yes	Yes	Yes		Yes
• No-vent fill	Yes	Yes	Yes		Yes
• LAD fill	Yes	Yes	Yes		Yes
• Low-g vented fill	Yes	Yes	Yes		Yes
Fluid handling				Yes	Yes
• Liquid dynamics/slosh control	Yes	Yes	Yes		Yes
• Fluid dumping and tank inerting	Yes	Yes	Yes		Yes
• Earth-to-orbit transport as subcooled liquid or slush	Yes	Yes			
Advanced instrumentation				Yes	Yes
• Quantity gauging	Yes	Yes	Yes		Yes
• Mass flow/quality metering	Yes	Yes			
• Leak detection	Yes	Yes			
• Liquid/vapor sensors	Yes	Yes			
Tank structures and materials					
• Low thermal conductivity components	Yes	Yes	Yes		
• Low-pressure tankage	Yes		Yes		
• Composite (lightweight) vacuum jackets	Yes	Yes			
• Contamination/degradation of LAD	Yes				

FLUID SELECTION

Liquid hydrogen and liquid oxygen represent the high-energy propellant combination generally proposed for in-space transportation. For management of cryogenic fluids in space, Table III lists important thermophysical quantities and their significance. For in-space experimentation, liquid hydrogen represents the fluid of choice because it poses more severe technical challenges than does liquid oxygen.

The boiling point of the liquid is one of the most important properties to consider, as it places design requirements on the materials used in the seals, valves, pumps, and other mechanical components of the system.

Interstitial gas pressure can reduce the effectiveness of the multilayer insulation (MLI) on the tank. The interstitial gas pressure is reduced by both diffusion to space and by cryopumping once the tank chilldown is initiated. The lower the boiling point of the fluid, the more rapidly it will cryopump. Surface tension has a strong effect on the performance of the capillary liquid acquisition device and also affects ullage shape. Thermal conductivity affects mixing requirements for pressure control.

Table III. Important Fluid Properties.

Property	Significance
Normal boiling point	Affects MLI performance – Interstitial pressure – Radiation heat transfer Materials properties Reliquefier performance
Surface tension	Determines LAD bubble point Combined with density, determines ullage shape
VCS superheat/Latent heat of vap	Quantifies performance improvement gained from VCS
Latent heat X density	Affects boiloff rate, experiment duration
Thermal conductivity	Affects mixing requirements
Viscosity	Pressure drop through screens, lines, and orifices
Density	Proportional to mass of system

The purpose of a vapor-cooled shield (VCS) is to intercept incoming heat energy with the sensible heat of the boiloff vapor rather than the latent heat of the liquid. The higher the ratio of the VCS superheat to the latent heat of vaporization, the greater the performance improvement a VCS will offer.

The four nonhazardous cryogens with boiling points closest to hydrogen are helium, nitrogen, neon, and argon. Table IV compiles the thermophysical properties for both the liquid and vapor phases of these fluids, normalized after their division by the corresponding hydrogen property. Neon provides a good match to hydrogen in all the most important categories including boiling point, surface tension, VCS performance, volumetric heat of vaporization, and liquid conductivity and viscosity (except for normal helium). However, neon is 17 times the density of hydrogen, and due to weight considerations it would be limited to a very small-scale experiment.

Helium, sometimes suggested as a substitute test fluid for hydrogen, has especially low surface tension and a low enough critical pressure that rapid fluid property variation could present problems during testing.

Based on comparison of fluid properties, it has been generally concluded by technical specialists in cryogenic fluid management that in-space experimentation must be done with liquid hydrogen to provide the confidence needed to address the design of cryogenic fluid management systems for advanced space transportation missions.

NEED FOR AN ELV-LAUNCHED ORBITAL EXPERIMENT

In recognition of these technology needs, the NASA Lewis Research Center has conducted ground-based research while planning a cryogenic flight experiment. The Cryogenic Fluid Management Flight Experiment (CFMFE) was to be a subcritical LH_2 experiment performed in the cargo bay of the Space Shuttle Orbiter. Plans for it were discontinued after reassessment of payload safety criteria following the *Challenger* accident. Lewis Research Center has subsequently funded feasibility studies of COLD-SAT, a free-flying experiment to be launched by an expendable launch vehicle (ELV) in 1998 (Figure 1).

Table IV. Fluid Properties Compared to Hydrogen.

Fluid	Normal Boiling Pt	Density* (liquid)	Density* (vapor)	Latent Heat of Vaporiz	Volumetric Heat of Vaporiz	Surface Tension*	Viscosity* (liquid)	Viscosity* (vapor)
Hydrogen	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Helium	0.21	1.77	11.67	0.05	0.09	0.05	2.39	10.91
Nitrogen	3.76	11.36	3.22	0.45	5.09	4.64	12.50	4.68
Neon	1.32	17.05	6.56	0.19	3.28	2.82	8.86	4.29
Argon	4.24	19.77	4.00	0.36	7.21	6.64	18.18	6.75

Fluid	Mean Spec† Heat (vap)	Specific* Heat (liq)	Thermal Cond (liq)	Density at STP	Cp•ΔT††/ Latent Heat	Critical Pressure	Inversion Temp
Hydrogen	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Helium	0.37	0.50	0.26	1.96	7.63	0.17	0.20
Nitrogen	0.07	0.20	1.85	13.85	0.12	2.61	3.08
Neon	0.07	0.18	1.36	10.00	0.37	2.10	1.24
Argon	0.04	0.11	1.47	19.62	0.07	3.74	3.57

* Properties at normal boiling point
† Calculated from (the enthalpy at 222K and 101kPa - the enthalpy of saturated vapor at 101 kPa)/(222K - normal boiling point)
†† Numerator is [Mean specific heat (vapor)] x [222K - Normal boiling point]

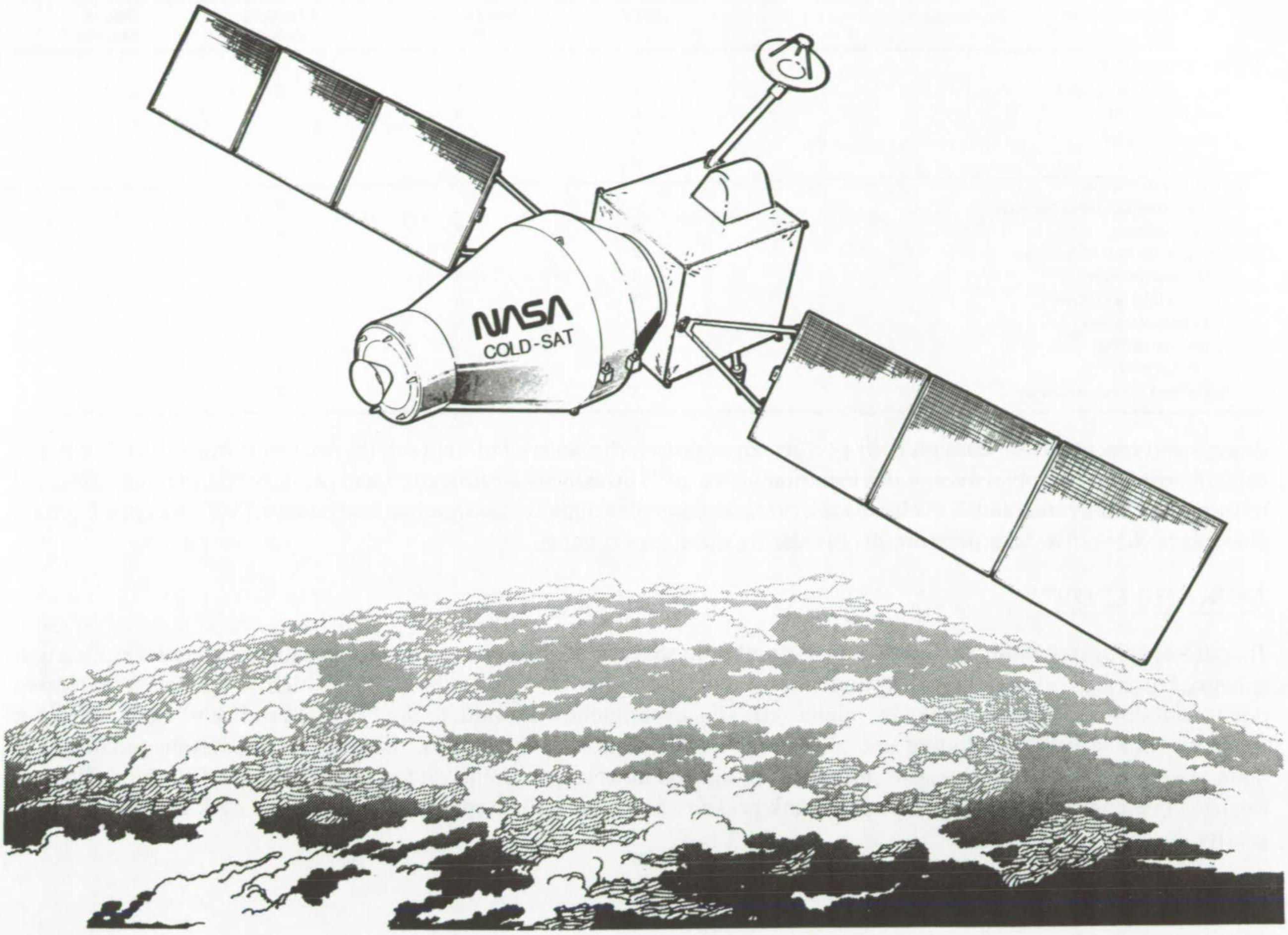

Fig. 1. Atlas-launched COLD-SAT Experiment.

COLD-SAT EXPERIMENTS

The categories of experiments being planned for COLD-SAT are listed in Table V, and are derived from the cryogenic fluid management technology needs represented in Tables I and II. The four Class I categories of COLD-SAT experiments are given the highest priority, and control the COLD-SAT system design. The nine Class II experiments are not as critical, but will be accomplished if they don't add substantially to the complexity and cost of the COLD-SAT spacecraft.

The following paragraphs contain brief descriptions of all the experiments, including a brief statement of the problem, the objective of the experiment, and the major parameters of interest. In all cases, in addition to the objectives stated, a common objective is that data be obtained to correlate with ground test data and models being used to predict the various phenomena.

PRESSURE CONTROL

Cryogenic fluids are not "storable," either on the ground or in space. A net heat inflow to the storage tank causes the fluid to warm and the pressure to rise, making venting necessary. Settled venting is the pressure control technique used on the Centaur upper stage, and it is a possible technique for some applications. However, cryogenic tanks will most likely be required on platforms, which will not allow the artificially imposed acceleration necessary for settling. Thus, an alternative approach is required.

The most promising approach for pressure control in low-g is the thermodynamic vent system (TVS). Besides maintaining tank pressure, it can also be designed to subcool the liquid in the tank. However, there are a number of alternative TVS

Table V. COLD-SAT Experiments.

Experiments	Application			
	STV	Space-based Depot	Resupply Tanker	Space Station
Class I Experiments				
Tank pressure control	X	X	X	X
Tank chilldown	X	X		X
Tank no-vent fill	X	X		X
LAD fill/refill	X	X		X
Class II Experiments				
Tanker thermal performance			X	
Pressurization	X	X	X	X
Low-g settling and outflow	X	X	X	
LAD performance	X	X	X	X
Transfer line chilldown	X	X		X
Outflow subcooling		X	X	X
Low-g vented fill	X	X		
Fluid dumping	X	X	X	X
Advanced instrumentation	X	X	X	X

designs and essentially no data on their performance, nor on the severity of the tank thermal stratification and pressure control problem. The objectives of this experiment are to: 1) investigate stratification and pressure rise in tanks subjected to various heating rates, and 2) evaluate tank pressure control techniques using active and passive TVS concepts. Figure 2 presents a qualitative tank pressure profile during these experiments.

TANK CHILLDOWN

Transfer of cryogenic fluids from one tank to another in space will be an essential feature of future space transportation systems. Since the cost of transporting material from the ground to low-Earth orbit (LEO) is high, it is essential that losses due to chilldown of receiver tanks be minimized. This experiment will evaluate the "charge/hold/vent" tank chilldown procedure in low gravity, including an evaluation of the effects of tank shape, tank mass, nozzle orientation and flowrate, mass injection profile, and staged venting on the injected mass required and on the time to accomplish the chilldown. Figure 3 presents analytical predictions of tank pressure and tank wall temperature for a typical tank chilldown in low gravity.

TANK NO-VENT FILL

Following the chilling of the receiver tank, the tank must be filled with liquid. This process can also be a large consumer of costly liquid. A procedure termed "no-vent fill" has been proposed to minimize the liquid losses that could occur in a low-g environment. It is similar to the tank chilldown procedure in that nozzles are used to inject the liquid into the tank and promote mixing and collapse of the existing vapor. This procedure has yet to be demonstrated in space. The objective of the experiment is to determine the effects of nozzle orientation, nozzle flowrates, g level, and tank fill level on the no-vent

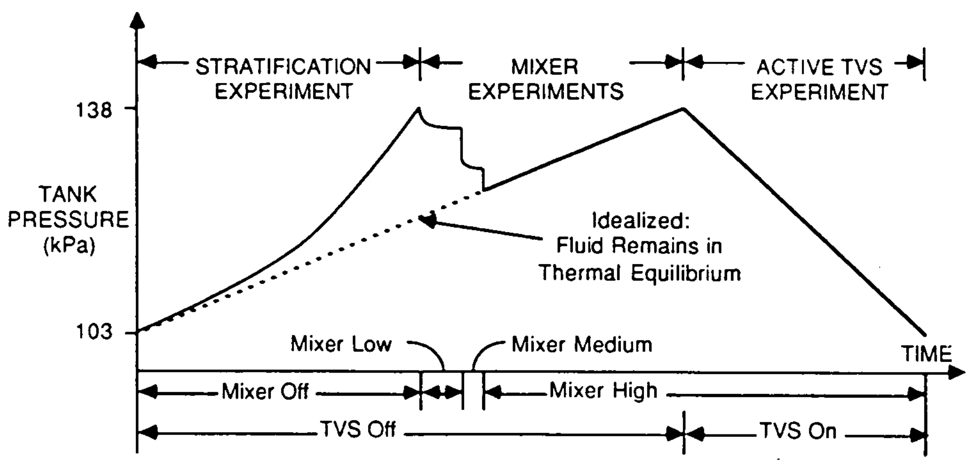

Fig. 2. Tank Pressure Profile Expected during Thermal Stratification, Mixer Destratification, and Active TVS Thermal Conditioning Experiments.

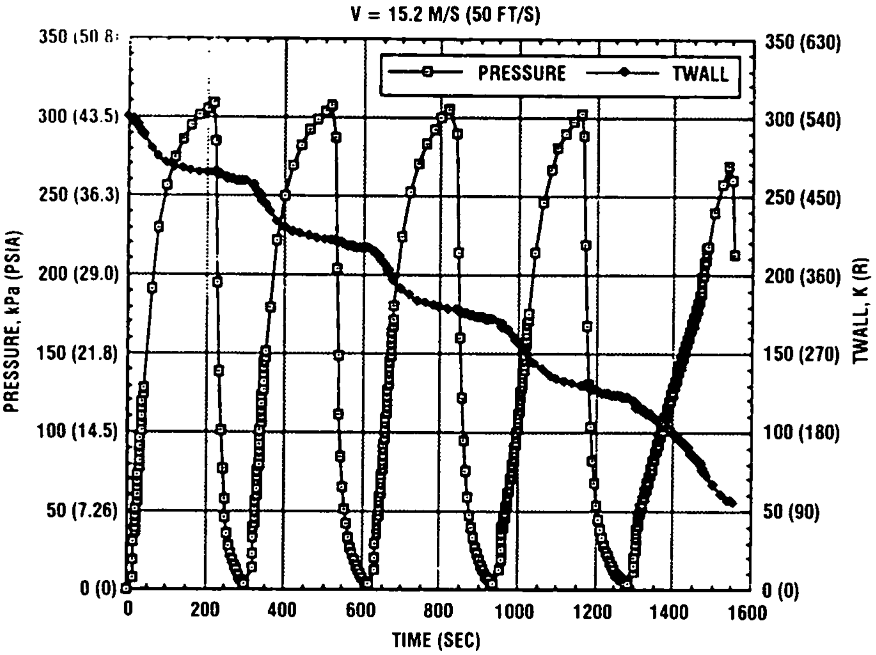

Fig. 3. Typical Charge/Hold/Vent Tank Childown.

fill process. The fill level goal is at least 95%. Figure 4 presents analytical predictions of tank pressure for a typical no-vent fill in low gravity.

LIQUID ACQUISITION DEVICE FILL/REFILL

A passive, channel-type, total communication liquid acquisition device (LAD) is an ideal system for use with a space-based cryogenic depot. Such systems have been used extensively in space, but only with storable fluids. These devices are notoriously difficult to fill in one-g, and it is anticipated that the problems could be magnified in low gravity, where the liquid could more readily wet the screen surface before trapped vapor is ejected. Two different LAD configurations will be evaluated. The objectives include determination of the effects of filling rate, LAD configuration, LAD venting through the TVS, LAD initial temperature, and tank pressurant species on the ability to fill the LAD and collapse the bubbles within.

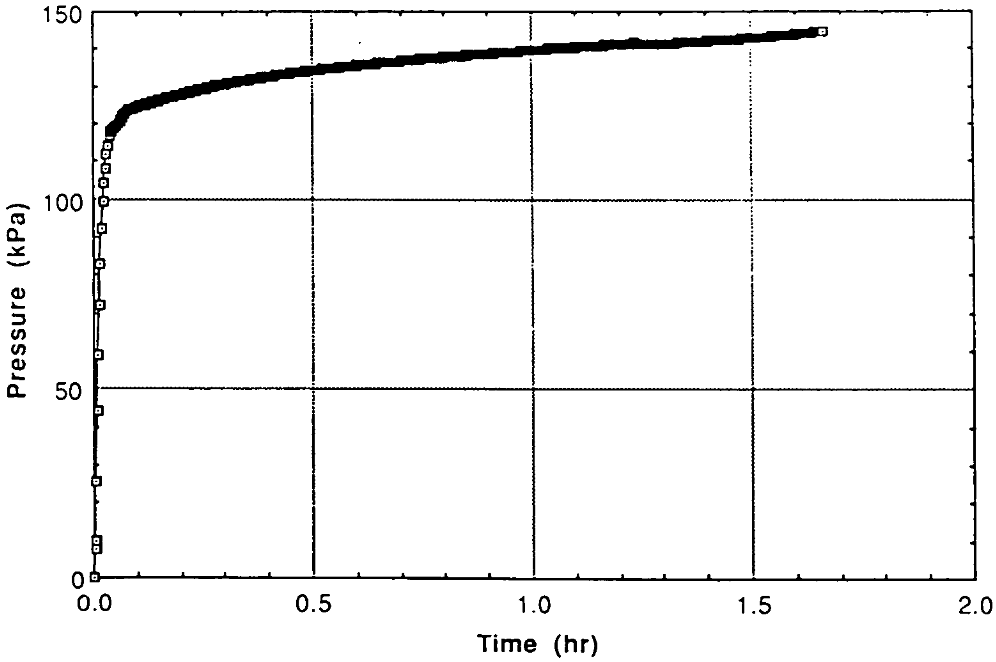

Fig. 4. Typical Tank Pressure History for No-vent Fill Process.

TANKER TANK THERMAL PERFORMANCE

The COLD-SAT hydrogen supply tank insulation system will have features characteristic of both Earth-to-orbit resupply tankers and on-orbit depots. It will have a helium-purged MLI system to prevent cryopumping of condensible gases on the ground and a VCS for absorbing more of the tank heat leak when on orbit. A major question concerning the MLI, which is quite thick (76mm (3 in.)), is whether the escape of gas during ascent may adversely affect the subsequent insulation performance. The structural and thermal performance of the system will be evaluated during the ascent phase and after space equilibrium conditions are achieved. The time required to achieve space equilibrium conditions and the measurement of the space thermal performance over an extended period of time will be investigated. Figure 5 presents analytical predictions of supply tank heating from launch until the helium interstitial pressure becomes low enough not to affect the MLI thermal performance.

TANK PRESSURIZATION

Pressurant collapse due to cooling and condensation in cryogenic tanks on the ground or when undergoing acceleration has been quantified. However, these conditions are substantially different from those for long cryogenic fluid transfers in low gravity. The objective of the experiment is to determine the amount of pressurants required for the LH_2 transfer process under varying conditions of pressurant flow, g-level, tank fill level, pressurant temperature, and tank pressure. Data will be taken to compare the performance of an autogenous hydrogen pressurization system, a stored gaseous hydrogen pressurization system, and a stored gaseous helium pressurization system.

LOW-G SETTLING AND OUTFLOW

An alternative to the use of a total communication liquid acquisition device is the process of applying a low acceleration level to settle and outflow liquid from one tank to another. This experiment will determine settling times under controlled low-gravity conditions and determine residuals at vapor pull-through for various g-levels and outflow rates. Settling under the influence of pulsed thrusting will also be tested.

LIQUID ACQUISITION DEVICE PERFORMANCE

Screened channel-type liquid acquisition devices are commonly used with storable liquids in zero gravity. New problems surface when the fluid is cryogenic and the screens are subject to premature dryout and breakdown. The performance of a LAD will be investigated under normal and adverse operating conditions. As with many of the Class II experiments, these will be integrated with the Class I transfer tests. Objectives are to evaluate the effects of a tank hot spot, g-level, and flowrate on the ability of channel-type LADs to transfer vapor-free liquid from tanks.

TRANSFER LINE CHILLDOWN

Another aspect of minimizing liquid loss in space is the optimization of transfer system chilldown. The phenomena associated with two-phase fluid flow and heat transfer inside a pipe can be gravity-dependent, and this experiment will quantify

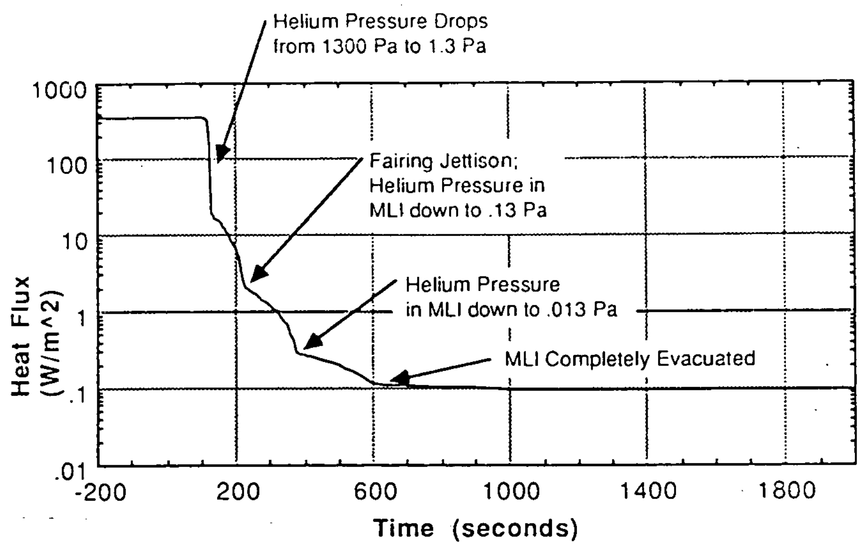

Fig. 5. Supply Tank Heating Profile from Prelaunch through Ascent.

those effects. Two different transfer lines will be tested in conjunction with other COLD-SAT transfers. The objective is to determine the flowrate, the time, and the liquid quantity required for transfer line chilldown. Both continuous and intermittent flow of the chilldown liquid will be tested. The venting of the line chilldown fluid through a tank to accomplish some degree of tank chilling will also be tested.

OUTFLOW SUBCOOLING

The subcooling of liquids in space will be required in conjunction with liquid transfers. One approach is to subcool the outflow from the supply tank as it passes through the transfer plumbing and to the receiver tank. For this purpose, a subcooling heat exchanger, cooled by throttled fluid from the supply tank, can be used. The fluid passing through the cold side of the heat exchanger is vaporized before it exits the unit, subcooling the main transfer flow of liquid. The objective of this experiment is to evaluate the effectiveness of a compact heat exchanger in subcooling tank outflow, and the use of intermittent flow of the cold side fluid in controlling the capacity of the subcooler.

LOW-GRAVITY VENTED FILL

This experiment will investigate the type of filling process used in one-g, but at a very low acceleration level. The objective is to determine the effect of g-level, inflow rate, and initial tank temperature on the ability to fill the tank without liquid ingestion in the vent. Tests will be conducted on one tank with a LAD and one without a LAD.

FLUID DUMPING

Operational scenarios are expected in which it could be necessary to dump cryogenic fluid from a tank in space, whether under emergency or planned conditions. Under such conditions freeze-up of the tank or lines could inhibit the operation. This experiment will focus on the evaluation of liquid dumping effectiveness and tank freeze-up in the two receiver tanks. Line freeze-up, which can be tested on the ground and is less gravity-dependent, will also be tested in conjunction with other transfers. The rate of dumping, tank pressurization parameters, and heater power will be determined.

ADVANCED INSTRUMENTATION

This experiment has not been defined since the instrumentation is still in the process of development. Candidates for test include a compression mass gage, as two-phase flowmeter, and other more advanced instruments. These may include leak detectors, velocimeters, liquid orientation detectors, and fiber optic/video visualization systems.

SPACECRAFT DESIGN SUMMARY

The philosophy employed for design of the COLD-SAT spacecraft has been to physically separate the experiment and bus systems to the extent possible to facilitate design, production, checkout, and assembly. Great emphasis has been placed on keeping the interfaces between the bus and experiment simple, adhering to experiment performance goals in the bus design, using flight-proven bus components to minimize development risk, and designing for high reliability. Selection of the launch vehicle is a major factor in the design of the spacecraft and the capability of the experiment. The spacecraft will be placed in a 1300km (700 nmi) circular orbit to delay eventual reentry for at least 500 years. After a study of the capabilities and costs of U.S. launchers and the experiment features they could accommodate, the Atlas I was chosen, along with the 4.2m (14 ft) diameter, 64.4m^3 (2,275 ft^3) payload fairing option. This combination provides ample lift and volumetric capacity, and the Atlas I allows the use of existing liquid hydrogen facilities and procedures, trained personnel at the launch pad, and the use of an experiment liquid hydrogen supply tank without a heavy, costly vacuum jacket. Ground and ascent venting of the supply tank is accomplished through connection to the Centaur existing flight vent system.

The COLD-SAT spacecraft, illustrated in Figure 6, is composed of two main modules, the experiment module and the spacecraft bus module. This cutaway view of the vehicle shows it in its operational configuration with the solar arrays, high-gain S-band antenna, and omni-directional S-band antenna deployed. The solar arrays are canted at a 26 deg angle to the Y-axis to keep the solar vector as close to the normal of the solar array as possible, thus permitting the use of a single-axis solar array drive. The Earth sensors mounted on the +X and –X ends of the vehicle have conical shields to protect their optics from thruster plume contamination.

A mass summary for the spacecraft is given in Table VI. A 20% mass contingency was maintained to allow for design uncertainties and future modifications. The total liftoff mass for the spacecraft, including contingencies, is 3455kg (7,617 lb), well within the capability of the Atlas I launch vehicle (4750kg (10,472 lb) capacity to 1300km (700 nmi)).

BUS MODULE

The bus module consists of the bus structure and attitude control, propulsion, electrical power, telemetry and data handling, spacecraft control electronics, and thermal control hardware.

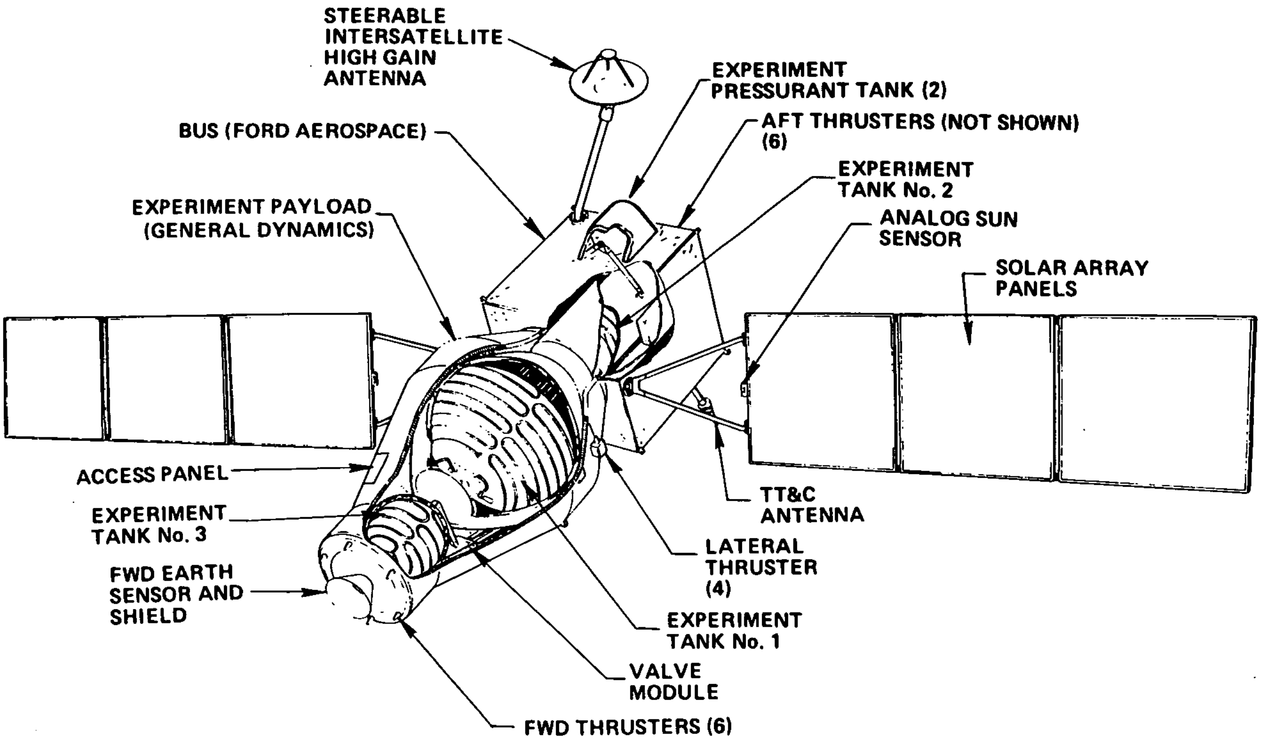

Fig. 6. On-orbit Spacecraft Configuration.

Table VI. COLD-SAT Mass Summary.

Experiment Module	1199.4kg	**Spacecraft Bus**	784.4kg
Primary structure	290.0	Structure	218.2
Fairings and supports	111.0	Mech integration	22.7
Tank 1	109.9	Electrical power	141.9
Tank 2	33.3	Solar arrays	118.9
Tank 3	16.1	Electrical integration	31.8
Fluid systems	376.4	Propulsion	68.5
Thermal control	106.9	TC&DH	86.0
Instr and control	56.8	Attitude control	76.1
Electrical	99.0	Thermal Control	20.3

Spacecraft dry mass	1983.8
Liquid hydrogen	364.5
Hydrazine propellant	530.5
20% mass contingency	575.8
Payload adapter and clamp	72.0
Total payload mass	3526.6kg

Bus Structure. The bus structure, illustrated in Figure 7, is a design adapted from Ford Aerospace's typical bus construction for a three-axis stabilized spacecraft. To efficiently package the experiment module, reduce weight, and lower the center of gravity of the vehicle, it was necessary to select a new structure based on previously flown designs. The main load structure of the bus is the central cylinder, which was enlarged to contain one of the experiment tanks and its insulation system. The bus enclosure is an aluminum honeycomb panel box supported by shear webs off the central cylinder. The experiment module is bolted to the +X end of the cylinder and a launch vehicle separation clamp is attached to the -X end. The propellant tanks, helium and hydrogen pressurant tanks, and the internal experiment tank are supported off the cylinder by struts.

Attitude Control. The three-axis stabilized attitude control system uses conical Earth sensors, analog and digital Sun sensors, and gyros as sensors. Thrusters, reaction wheels, and magnetic torquers are used as actuators. The spacecraft control electronics (SCE) provides processing of the sensor data, actuator control, automatic momentum dumping, thruster selection during maneuvers, processing and storage of commands, maintenance of ephemeris data, and the processing of atti-

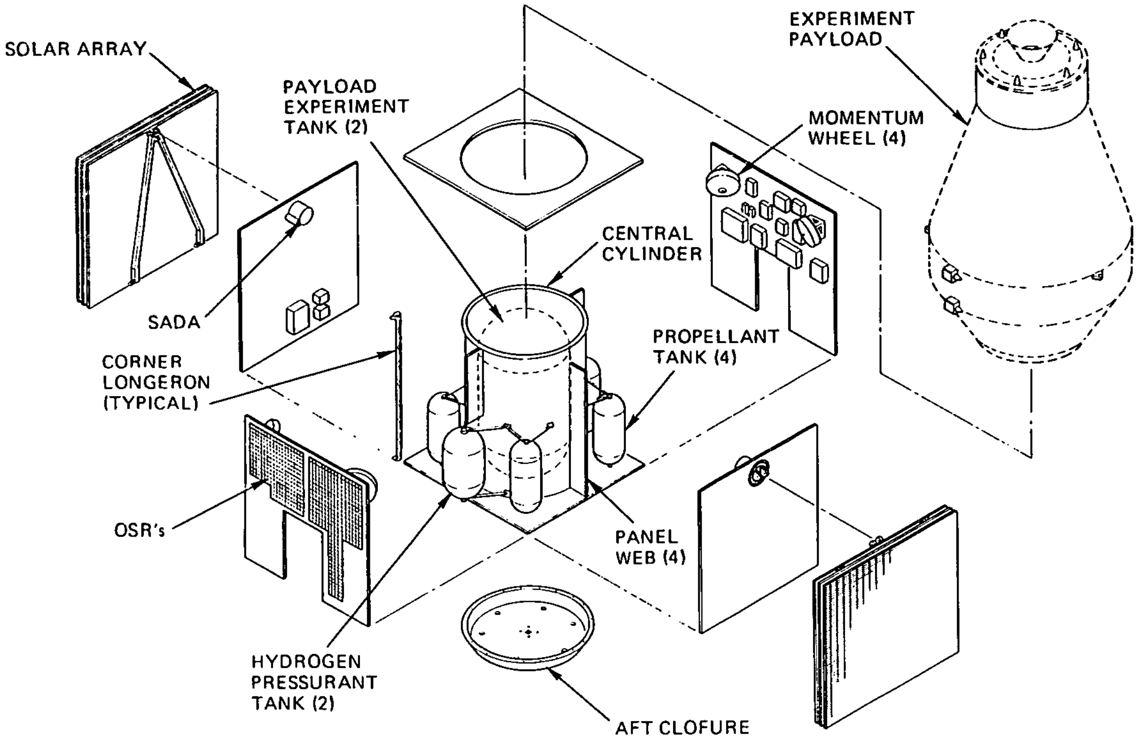

Fig. 7. COLD-SAT Spacecraft Bus Exploded View.

tude control information required by other subsystems. Three orthogonal magnetic torquers dump excess reaction wheel momentum, avoiding the use of thrusters that could possibly disturb the experiments.

Propulsion. Onboard hydrazine propulsion will provide a wide range of linear acceleration for certain experiments and also provide backup attitude control actuation. Both six +X and six -X thrusters are used for experiment thrusting so that different internal equipment can be used at each end of the experiment tanks, increasing the flexibility of the experiment design. Each of the thrusters has 0.53 Newton (0.12 lb) thrust. For each test, an appropriate number of thrusters will be used to produce nominal accelerations of either 20, 50, or 100 μg for continuous periods up to 46.5 hours. Roll control is provided by four lateral thrusters, consisting of two thruster pairs located 180 degrees apart and positioned on the cylindrical section of the experiment module.

Spacecraft Control Electronics. Under the control of the SCE, the spacecraft bus can function autonomously for up to 28 days without ground commands. Since real-time control of the experiment from the ground is not possible due to communications limitations, the SCE will control the experiment with limited autonomy for periods up to a few orbits. The SCE provides telemetry processing, command, and control for all of the subsystems. The processor analyzes the data from the attitude control system sensors and generates the necessary signals to maintain attitude for all mission phases, including pointing the spacecraft +X axis along the velocity vector for the experiments, positioning the solar arrays and high gain antenna, and maintaining attitude during thrusting maneuvers. Additionally, the SCE autonomously controls battery charge and discharge management, maintains thermal control by operating heaters, performs data acquisition and management for both the bus and the experiment, and tracks center of mass changes due to propellant and LH_2 consumption.

COLD-SAT communications provides telemetry command and ranging functions to facilitate data downlink, tracking, and ground control. The primary communications link to the ground is through the TDRSS S-band Multiple Access Service using the COLD-SAT high gain steerable antenna. Experiment and bus telemetry data will be sequentially sampled by the SCE, formatted, and stored in solid state memory for later downlink. Telemetry data is transmitted through TDRSS at 38 kbps during a 10 minimum per orbit TDRS contact time (available capacity on the S-band MA link is 50 kbps). Command data is uplinked at 1 kbps simultaneously during downlink operations for efficient use of the TDRS contact time. The uplink data capability includes functional commands and replacement software code for either the attitude control system or the experiment. Contingency communications is provided by a half-omni antenna diametrically positioned relative to the high gain antenna for a low rate data link either through the TDRSS or directly to a STDN ground station.

The SCE will control and monitor the experiment since real-time control through continuous contact with the spacecraft is not possible. A test or conditioning sequence can be initiated either with a real-time or a time-tagged command. Stored command sequences used to control each test will be resident onboard in the experiment Application Program Software. A test is initiated by identifying the appropriate stored sequence to be used and passing the desired parameters to be used in the sequence. Experiment test sequences are reprogrammable so that new or modified sequences can be substituted for the stored sequences if necessary.

Before initiating an experiment, the control system will be reconfigured in one of two ways. First, for no-thrust experiments, which require very low acceleration fields, the spacecraft will be configured to minimize all torque effects. This is accomplished by decreasing control loop gains and enabling magnetic torquers to provide wheel unloading. Second, for experiments requiring higher accelerations, thrusters will be enabled. The thruster combinations used for a particular acceleration level will be alternated during the firing to perform continual wheel unloading to prevent wheel saturation.

EXPERIMENT MODULE

The experiment module consists of structure, the three insulated experiment tanks, instrumentation sensors, pumps, valves, and associated plumbing. The experiment tanks consist of a 5.38 m^3 (190 ft^3) ellipsoidal supply tank (Tank 1), a 1.27m^3 (45 ft^3) cylindrical receiver tank (Tank 2), and a 0.62m^3 (22 ft^3) spherical receiver tank (Tank 3). Additional tank details are given in Table VII. Table VIII lists the experiments performed with each tank. The experiment structure is of aluminum honeycomb, and encloses the experiment module to provide micrometeoroid/debris protection as well as to support the tanks and other components. Some experiment equipment, including the stored helium and hydrogen gas pressurant tanks and all of the experiment support electronics, is mounted within the bus module.

The experiment module fluid system schematic is shown in Figure 8. This system is configured to provide flexibility and reliability in conducting the COLD-SAT experiments. In general, the portion shown in the lower half of the schematic is used for fluid transfer between tanks and the portion in the top half is for tank pressure control. The tanks and plumbing are designed to a maximum operating pressure of 350kPa (50 psia) with the exception of the autogenous pressurization system plumbing, which is designed for 500 kPa (75 psia), and the pressurization gas supplies, which operate up to 27.5MPa (4,000 psia).

Thermal Control. Each tank is surrounded by MLI to reduce tank heat input in orbit. A vapor-cooled shield is included in the insulation for Tank 1, which routes hydrogen from the tank to intercept heat within the insulation and vent the warmer gas overboard. At launch, Tank 1 contains all the liquid hydrogen for the experiments, while Tanks 2 and 3 are launched dry. Thus, the insulation system for Tank 1 is purged with helium on the launch pad to prevent condensation and freezing of air.

Electric resistance heaters are attached to each tank wall to augment tank evacuation and warm up between tests. The heaters for Tank 1 are distributed over most of the tank surface and specially designed to produce uniform heating at several different flux levels for the pressure control experiment.

Table VII. Experiment Tank Characteristics.

Tank No.	Designation	Shape	Size	Insulation and Shields	Internal Equipment	External Equipment
1	Supply	Elliptical heads L/D = 0.71 a/b = 1.38	V = 5.38m^3 D = 2.42m L = 1.73m A = 15.1m^2 LH_2 = 365kg at 98% full	MLI (76mm) VCS (one) He purge system Insulation fairings for equipment	Total communication LAD Wall-mounted TVS HX Mixer and compact TVS HX Pressurant diffuser	Wall-mounted heater Outflow subcooling heat exchanger Instrumentation
2	Depot (receiver)	Cylindrical, elliptical heads L/D = 1.8 a/b = 1.38	V = 1.27m^3 D = 1.02m L = 1.83m Lcyl = 1.09m A = 6.15m^2 LH_2 = 84.0kg at 95% full M/V = 54kg/m^3	MLI (38mm) Insulation fairings for equipment	Total communication LAD Wall-mounted TVS HX Axial and radial spray nozzles Pressurant diffuser Instrumentation	Wall-mounted heater Instrumentation
3	Bare (receiver)	Spherical	V = 0.62m^3 D = 1.07m A = 3.58m^2 LH_2 = 41.0kg at 95% full M/V = 47kg/m^3	MLI (25mm)	Axial, radial, and tangential spray nozzles Pressurant diffuser Instrumentation	Wall-mounted TVS HX Wall-mounted heater Liquid dump line heater

Definitions: D = diameter, L = length, Lcyl = cylindrical length, V = volume, M = mass, A = surface area, HX = heat exchanger, LAD = liquid acquisition device, TVS = thermodynamic vent system, MLI = multilayer insulation, VCS = vapor-cooled shield, a and b = major and minor axes of the ellipse of revolution forming the head

Table VIII. Experiments Performed in Each Tank.

Tank No.	Experiments Supported Class I	Class II
1	Passive pressure control	Resupply tanker performance
	Active pressure control	Pressurization*
	No-vent fill*	LAD performance
	LAD fill/refill	Line chilldown
		Outflow subcooling
		Advanced instrumentation
2	Passive pressure control	Pressurization
	Tank chilldown	LAD performance
	No-vent fill	Line chilldown
	LAD fill/refill	Vented fill
		Liquid dumping
		Advanced instrumentation
3	Passive pressure control	Pressurization*
	Tank chilldown	Settled outflow
	No-vent fill	Line chilldown
		Vented fill
		Liquid dumping
		Advanced instrumentation

* Data taken during other experiments or during fluid transfers between experiments

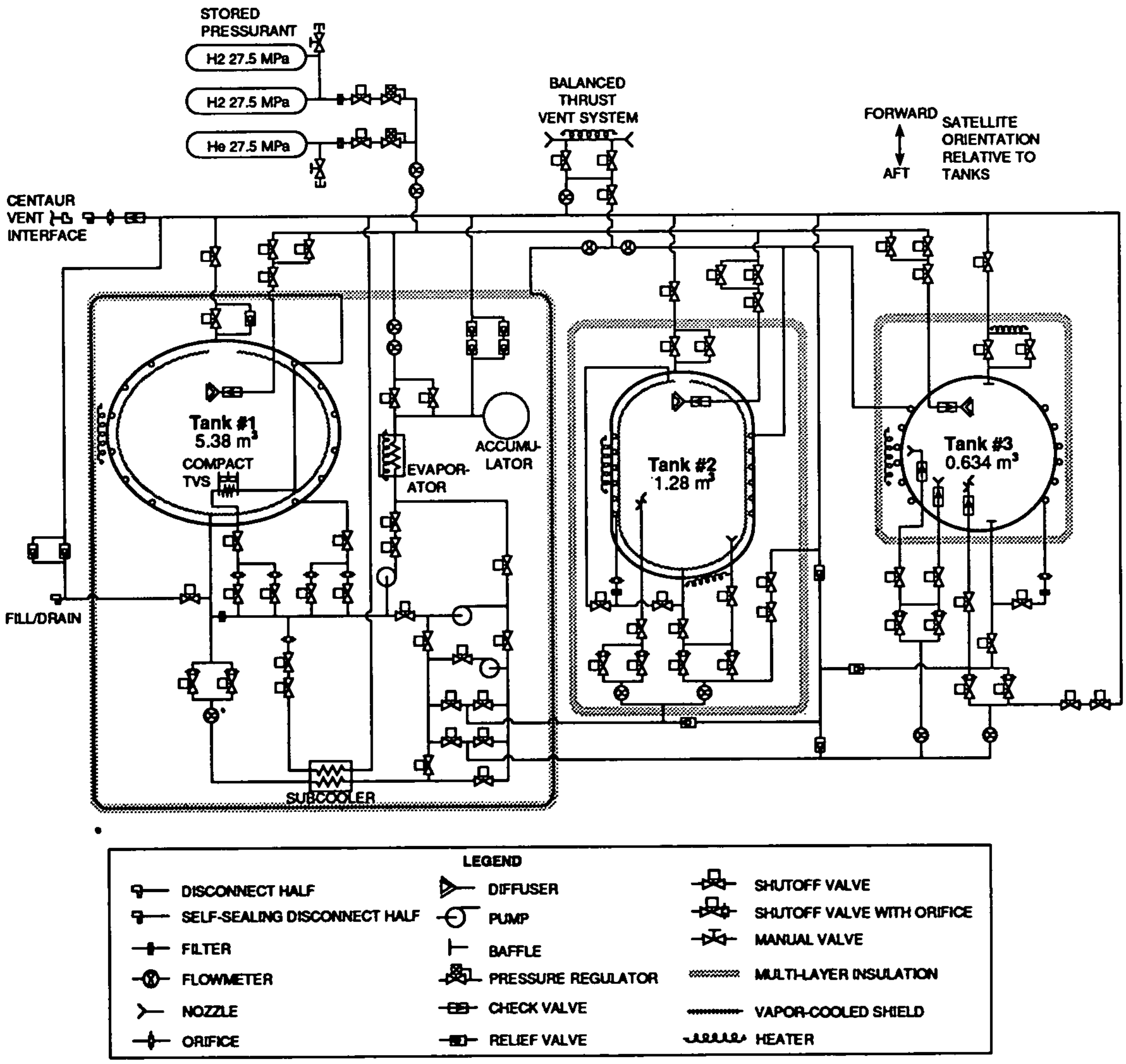

Fig. 8. Experiment Module Fluid System Schematic.

Tank Pressure Control. Tank pressure reduction (energy removal) is primarily achieved using a TVS for each tank. Each tank has tubing attached to its wall, which is used as a heat exchanger for passive TVS operation. This tubing is attached to the inner surface of Tanks 1 and 2 and to the exterior of Tank 3. Tank 1 also has a compact TVS system using a mixer to augment contact with a small heat exchanger. Each TVS is supplied through a Joule-Thomson orifice to expand and cool the flow. The TVS supplies for Tank 1 are redundant to enhance their reliability since conditioning of the fluid in this tank is central to the COLD-SAT experiments.

Each tank also has a direct vent system. Tank 1 uses this direct system to vent gas during tanking and ascent. The direct vent systems of Tanks 2 and 3 are used for tank evacuation experiments and, when the liquid has been settled, can also be used for gas venting.

Redundant valves in these vent systems enhance their reliability. Typically, three shutoff valves are arranged such that a backup valve can be used for control if the primary valve fails in any configuration (open, closed, or partway). Since the backup valves are dormant (not actuated) unless the primary valve has failed, they are much less likely to fail in another position during normal operation.

In orbit, vent flow exits the system through a balanced-thrust vent system, which directs equal amounts of flow in opposing directions to minimize its impact on attitude control for COLD-SAT. Shutoff valves near the exit control the vent line pressure to be 15–20 kPa (2–3 psia) to preclude freezing of hydrogen in the lines. An electric heater prevents freezing downstream of these valves. A heater is also provided on the Tank 3 direct vent valve module to prevent freezing during the tank dump experiment.

Tank pressurization is provided through a diffuser in each tank with flow controlled by redundant shutoff valves. The diffuser will be designed to minimize heat and mass transfer between the ullage and liquid in the tank as pressurant is introduced. Check valves are located just upstream of each diffuser to avoid the heat leak that could otherwise develop through perculation of fluid in the line.

Most pressurization gas is supplied by an autogenous system that vaporizes LH_2 pumped from Tank 1. The evaporator uses electrical resistance heating controlled to a constant outlet temperature. The generated hydrogen vapor flows through an accumulator, which provides a relatively constant pressure to the pressurization valves. Redundant relief valves protect the system from overpressure.

An independent supply of gaseous hydrogen and helium is also available to pressurize the experiment tanks. This supply satisfies requirements for certain experiments and also acts as a backup to the autogenous system.

Flowmeters are included in the pressurization and vent lines to satisfy experiment requirements. Pressurization and TVS vent flowmeters are designed to measure gas flow while flowmeters for the direct vent should be able to measure two-phase flow.

Fluid Transfer. A centrifugal pump is normally used to transfer liquid between the tanks. Transfer lines from each tank are connected to the pump module, which can, through valving, provide pumping between any two tanks in either direction. The pump arrangement is configured such that one is the primary pump and the other provides backup. Transfer flowrate is controlled by varying pump speed. Alternately, fluid transfer can be accomplished by tank pressure control using the orificed shutoff valves in the transfer lines to provide incremental flow control. Flowmeters in the transfer lines are designed to measure two-phase flow to provide experiment data.

Tanks 1 and 2 each contain an LAD for low-g liquid acquisition. An electric resistance heater is attached to Tank 2 in the vicinity of the LAD outlet to satisfy the LAD performance experiment. Tank 3 has a baffled outlet to promote the acquisition of liquid during settled outflow.

All transfer flow into and out of Tank 1 is through its LAD with forced convection within the tank being provided by the mixer of the compact TVS. Tanks 2 and 3 have various nozzles, which are used to inject flow into these tanks at different locations and orientations. Each set of nozzles is controlled independently by orificed shutoff valves. Both tanks have nozzles that are oriented axially and radially; Tank 3 also has a set that spray tangential to the tank wall. Check valves are used on the nozzle supplies to Tank 3 to reduce heat leak (similar to the pressurization system).

The transfer lines are connected to the vent system through redundant shutoff valves near Tanks 2 and 3. This allows the transfer lines to be chilled without chilling the intended receiver tank by flowing directly to the vent.

A subcooler is located in the transfer line from Tank 1. When desired, outflow cooling is provided by flowing some hydrogen through a Joule-Thomson orifice. This flow is vented overboard after absorbing heat from the flow being transferred between tanks.

Between fluid transfer operations, the liquid in the transfer lines is vented through the line childown vent only as required to relieve excess pressure. Relief valves provide backup protection from overpressure of these transfer lines. The transfer line for Tank 1 is within the vapor-cooled shield and will remain open to the tank when not in use.

Tanking. The gaseous hydrogen and helium supply bottles will be charged through the manual shutoff valves prior to close-out of the surrounding payload fairing. These valves are then closed and the connections capped to provide redundant sealing.

Prior to launch, Tank 1 is loaded with liquid hydrogen through the Fill/Drain Disconnect. The tanking flow from the ground supply is controlled by ground system valves based on the pressure and liquid level in Tank 1. Hydrogen vapor generated during chilldown and tanking will be vented through the Vent Disconnect, which interfaces with the Centaur vent line to share the ground and ascent provisions of the Centaur hydrogen tank.

Instrumentation. Table IX provides a summary of experiment measurements. The experiment data sampling rates are low to match the rate of change of the thermodynamic variables and to satisfy telemetry limitations. One acceleration will be sampled at eight samples per second. The other two accelerations and the flows will be sampled at four samples per second, and the remainder of the measurements at one sample per second or slower.

Table IX. Measurement Quantity and Distribution.

Measurement Type	Tank 1	Tank 2	Tank 3	Other	Total
Liquid/vapor detector	33	24	27	0	84
Temperature	145	79	56	47	327
Pressure	8	6	6	11	31
Flowrate	1	2	2	7	12
Fluid mass	1	0	0	0	1
Acceleration	0	0	0	18	18
Current	1	2	2	13	18
Voltage	0	0	0	4	4
Command status	31	17	17	5	70
Total	219	130	110	105	565

Temperature sensors and pressure transducers are developed and available from applications to Atlas and Centaur. The accelerometer is available from Textron. Tank liquid/vapor detectors are currently in procurement for Titan/Centaur. A two-phase flowrate/quality meter and a tank mass gage are currently being developed under NASA contracts, although alternative components should also be considered in order to reduce risk.

SUMMARY

1. Cryogenic technology is an important element of planned national space transportation missions.
2. In-space experiments are required to provide an adequate cryogenic fluid management data base.
3. Liquid hydrogen is the preferred fluid for most cryogenic testing.
4. The COLD-SAT systems-level experiment presents the opportunity to accomplish most testing objectives in a single mission.
5. The COLD-SAT experiment can be configured into a module and mated with a conventional spacecraft bus.
6. Atlas, with its liquid hydrogen upper stage, large payload fairing, and large launch margin, eases COLD-SAT design and integration.

REFERENCES

1. Aydelott, J.C., "Fluid Management Technology," *NASA/OAST In-Space Technology Experiments Workshop, Volume II – Critical Technologies, Themes 1-4,* December 1988.