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COLD-SAT, An Orbital Cryogenic Hydrogen Technology Experiment

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J.R. Schuster
General Dynamics Space Systems Division
San Diego, California

Joseph P. Wachter
Ford Aerospace Space Systems Division
Palo Alto, California

Albert G. Powers
Lewis Research Center
Cleveland, Ohio

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J.R. Schuster*
General Dynamics Space Systems Division
San Diego, California
USA

Joseph P. Wachter**
Ford Aerospace Space Systems Division
Palo Alto, California
USA

Albert G. Powers†
NASA Lewis Research Center
Cleveland, Ohio
USA

Abstract

The COLD-SAT spacecraft will perform subcritical liquid hydrogen storage and transfer experiments under low-gravity conditions to provide engineering data for future space transportation missions. Consisting of an experiment module mated to a spacecraft bus, COLD-SAT will be placed in an initial 460 km circular orbit by an Atlas I commercial launch vehicle. After deployment, the three-axis-controlled spacecraft bus will provide electric power, experiment control and data management, communications, and attitude control along with propulsive acceleration levels ranging from 10^{-6} to 10^{-4} g. These accelerations are an important aspect of some of the experiments, as it is desired to to know the effects that low gravity levels might have on the heat and mass transfer processes involved. The experiment module will contain the three liquid hydrogen tanks, valves, pressurization equipment, and instrumentation. At launch all the hydrogen will be in the largest tank, which has helium-purged MLI and is loaded and topped off by the hydrogen tanking system used for the Centaur upper stage of the Atlas. The two smaller tanks will be utilized in orbit for performing some of the experiments. The experiments are grouped into two classes on the basis of their priority, and include six regarded as enabling technology and nine regarded as enhancing technology.

Introduction

The United States is entering an era of expanded space activity that will involve space-based operations to carry out and support key space transportation missions. These missions, along with their earliest forecasted dates, include the Space Station (1997), Orbital Fuels Depot (2001), Space Transfer Vehicle (STV) (interim 1998, space-based 2001), Resupply Tanker (2001), and, in the longer term, such Pathfinder missions as lunar base support (2005) and piloted Mars expeditions (2003 – 2008).

As in the past, government and industry will carry out joint efforts to accomplish these missions, including development of new, long-lived orbital systems that depend on the use of subcritical cryogens presenting low-gravity fluid management challenges as well as special storage and utilization problems due to low fluid temperature. System developers, whether in government or industry, are faced with needs for an engineering data base, validated performance models, and brassboards or prototypes that have had certain key features demonstrated in the appropriate environments and at the appropriate systems level. Fluid management needs were recently addressed in a NASA-sponsored workshop devoted to requirements for in-space testing.[1] Table 1 lists cryogenic fluid management technology categories where data will be needed, along with an indication as to whether the technology is enabling or enhancing for each mission. Table 2 provides an assessment of in-space testing needs and indicates if the objective is to provide an engineering data base or to validate analytical performance models, appropriate environmental characteristics, and/or system-level behavior.

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 (Cryogenic On-Orbit Liquid Depot Storage, Acquisition, and Transfer Satellite), a free-flying orbital experiment to be launched by an expendable launch vehicle (ELV) in 1996. General Dynamics Space Systems Division and Ford Aerospace Space Systems Division are one of the contractor teams performing the study.

Experiments

The COLD-SAT experiments (Table 3) will be conducted using liquid hydrogen. It is the fluid of choice because of its projected use as a propellant and because it presents greater fluid management challenges than does liquid oxygen. Each experiment consists of a number of tests spanning a range of test parameters. The six Class I experiments are regarded as enabling technology for some space transportation missions and are therefore of the highest priority. These experiments

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* Senior Engineering Specialist

** Principal Engineer

† NASA Project Engineer

Table 1. Cryogenic fluid management technology needs.

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

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control the COLD-SAT system design. The nine Class II experiments represent alternative fluid management operations and data that would enhance, but not be essential for, future missions. NASA has recently published details on the COLD-SAT experiment requirements.[2]

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 may be the preferred approach for space-based vehicles. However, unique requirements such as those that were imposed on the Shuttle/Centaur vehicle may eliminate the settling option. In addition, settled venting does not take full advantage of the heat capacity that is available in the exiting fluid to reduce the net heat flow to the stored fluid. The most promising alternative, the thermodynamic vent system (TVS) concept, can also be designed for thermal conditioning of the tank fluid.

The objectives of this experiment are to develop a better understanding of the basic phenomena involved, measure

Table 2. 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
• Pump assist	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				

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self-pressurization and destratification rates, evaluate several different TVS options (active/passive, compact/wall-mounted, internal/external), and provide the data necessary to correlate measured space and ground performance with analytical models of the process.

Tank Chilldown

Transfer of cryogenic fluids from one tank to another in space will be an essential feature of the future space transportation architecture. Since the cost of transporting material from the ground to LEO is high, it is essential that losses due to chilldown of transfer systems and receiver tanks on orbit be minimized. This experiment will evaluate the "charge/hold/vent" procedure for tank chilldown, using two experiment tanks and three injection spray configurations. The objectives include evaluation of the charge/hold/vent chilldown procedure in low gravity, evaluation of the effects of tank shape and mass on chilldown time and the amount of liquid mass required, comparison of the performance of the different spray nozzle configurations, and development of data to correlate low-g chilldown analytical methods.

Table 3. COLD-SAT experiments.

	Application		
	Resupply tanker	Orbital depot	STV
Class I Experiments			
Pressure control	X	X	X
Tank chilldown		X	X
No-vent fill/refill		X	X
Liquid acquisition device fill/refill		X	X
Mass gaging	X	X	
Slosh dynamics and control	X	X	X
Class II Experiments			
Tank thermal performance	X	X	X
Pressurization	X	X	X
Low-g settling and outflow	X	X	X
Liquid acquisition device performance	X	X	
Transfer line chilldown	X	X	
Thermal conditioning	X	X	
Low-g vented fill		X	X
Fluid dumping		X	X
Advanced instrumentation	X	X	X

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No-vent Fill/Refill

The second aspect of transfer that could be a large consumer of costly liquid is the receiver tank fill process. A procedure termed "no-vent fill" has been proposed to minimize the liquid losses that could occur in a zero-g environment. This procedure has yet to be demonstrated in space, and this experiment is designed to investigate the key parameters and to optimize the operations and hardware required. The objectives include demonstration of the ability to fill a tank to at least 95% under both settled and unsettled conditions and to obtain data on transient phenomena for correlation of analytical models.

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 a one-g environment, 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 with both active and passive design features to promote vapor-free filling will be evaluated. The objectives include determination of the ability to completely fill the LAD in a micro-gravity environment, evaluation of active and passive design techniques intended to promote complete filling of the LAD, and evaluation of procedures for collapsing trapped bubbles.

Mass Gaging

Since it is not always convenient to settle the fluid in a tank and measure the liquid level to determine fluid mass, it would be convenient to have a device that could provide instantaneous mass readings in all anticipated operational conditions. Two such devices are under development by NASA, and it is anticipated that one will be sufficiently advanced such that a prototypical system could be evaluated on the COLD-SAT spacecraft. The objective will be to evaluate mass gage performance for various tank fill levels, for both settled and unsettled fluid orientations, and for various fluid motion states, including quiescent, mixing, and outflowing.

Slosh Dynamics and Control

The last of the Class I experiments is slosh dynamics and control. This technology could be particularly important for the very large tanks that will be required for space-based depots and vehicles designed for manned interplanetary missions. Both periodic and docking-type impulses will be investigated in cylindrical and spherical tanks, with and without a rigid ring baffle. The objectives are to determine fluid motion and reaction loads, evaluate baffle damping characteristics, and obtain data for correlation of low-g fluid motion analytical models.

Tank Thermal Performance

The 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 multilayer insulation (MLI) system to prevent cryopumping of condensible gases on the ground; but the MLI is thick (7.6 cm) and the system includes a vapor-cooled shield to minimize boiloff in space. The structural and thermal performance of the system will be evaluated during the ascent phase and after space equilibrium conditions are achieved. The objectives include demonstration of a thick MLI design for ascent venting, determination of the time required to achieve space equilibrium conditions, and measurement of the space thermal performance over an extended period of time.

Pressurization

Pressurization requirements for cryogenic ground tanks and space vehicles undergoing acceleration are well established. The situation is different for a cryogenic tank located in a zero-gravity environment and for the longer-term transfer operations that will be required to resupply a vehicle or tank an STV. This experiment will quantify the amount of pressurant required under various operational situations and provide much-needed data to correlate low-g pressurization analytical models. The objectives include collection of data for establishing pressurant collapse factors; comparison of the performance of autogenous, stored gaseous hydrogen and gaseous helium pressurization approaches; evaluation of the effects of dissipator design and location on performance;

and collection of data for correlation of low-g pressurization analytical models.

Low-g Settling and Outflow

An alternative to the use of a total communication device is the process of applying a low acceleration level to settle and outflow liquid from one tank to another on orbit. This experiment will evaluate various methods of liquid settling and attempt to optimize the outflow process to minimize tank residuals. The objectives are to determine settling times under controlled low-gravity conditions, determine residuals at pullthrough for low-gravity outflow, and provide data for correlation of low-gravity analytical models.

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 two LAD configurations 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 ability of channel-type LADs to transfer vapor-free liquid from tanks in microgravity, and to obtain data for correlation of analytical models of LAD performance.

Transfer Line Chilldown

Another aspect of minimizing liquid losses in space is the optimization of transfer system chilldown. The phenomena associated with fluid flow and heat transfer inside a pipe are known to be gravity-dependent, and this experiment will quantify those effects. Two different transfer line configurations, masses, sizes, and lengths will be tested in conjunction with Class I transfer experiments. Objectives include determination of times and liquid quantities required for transfer system chilldown, and collection of data for correlation of low-gravity transfer analytical models.

Thermal Conditioning

This experiment will demonstrate the ability to condition cryogenic propellants efficiently on orbit. Several different thermodynamic vent system configurations will be compared in their ability to condition the fluid in a tank in the minimum amount of time with the lowest loss of tank fluid. Objectives are to determine times and liquid loss penalties associated with conditioning, and to obtain a comparison of active and passive thermal conditioning approaches.

Low-gravity Vented Fill

This experiment will attempt to simulate the normal ground fill process but at very low acceleration levels. It is anticipated that this process, perhaps in combination with no-vent fill, might well prove to be the preferred procedure for filling space-based vehicles from a co-orbiting platform where low acceleration levels are achievable. Objectives include demonstrating combined vented fill/no-vent fill, evaluating the effects on performance of tank vent design and location, and demonstrating an inlet baffle/dissipator design.

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. This experiment will investigate dumping in various controlled and uncontrolled modes to determine whether the tank or lines will freeze up, trapping fluid in the tank. The objectives include determination of the rate and quantity of fluid removed from a tank during dump, and collection of data for correlation of low-gravity dumping analytical models.

Advanced Instrumentation

This experiment is a placeholder to provide for the on-orbit testing of unspecified new types of instrumentation. These might include two-phase flow detectors, leak detectors, velocity meters, tankage liquid level and orientation detectors, and fiber optic/video visualization of fluid orientation in tanks.

Spacecraft Configuration

After evaluating candidate launch vehicles for COLD-SAT, the General Dynamics/Ford team selected the Atlas I commercial launch vehicle, which has a 4.2 m diameter, 64.4 m^3 payload fairing, and the capability of placing over 5000 kg of payload in a 460 km circular orbit. A 460 km orbit was found to be high enough to ensure that orbital drag would be below the threshold considered acceptable on the basis of experiment tank liquid Bond number; but a higher orbital altitude may be selected to delay eventual reentry of the spacecraft. Figure 1 illustrates the payload capability of the Atlas I as a function of circular orbit altitude for a two-burn ascent.[3] The large payload fairing of the Atlas permits good-sized test tanks, an extra margin of hydrogen, and a well laid out experiment design. The Atlas lift capability provides comfortable mass margin to accommodate design changes.

Figure 2 illustrates the COLD-SAT spacecraft, which weighs about 3140 kg at launch, and Table 4 provides a weight breakdown. The experiment hardware includes three hydrogen tanks contained in an experiment module. The experiment module is mated to a three-axis-controlled spacecraft bus. The bus provides power, communications, and attitude control along with propulsive acceleration levels ranging from 10^{-6} to 10^{-4} g. Thrusters are located on the forward and aft ends of the spacecraft and on the cylindrical portion of the experiment module. This combination of thruster arrays allows propulsive accelerations for experiment purposes to be provided in both the forward and reverse axial directions and laterally. Bidirectional axial thrusting permits simplification of experiment tank internal features at the expense of modest thruster additions.

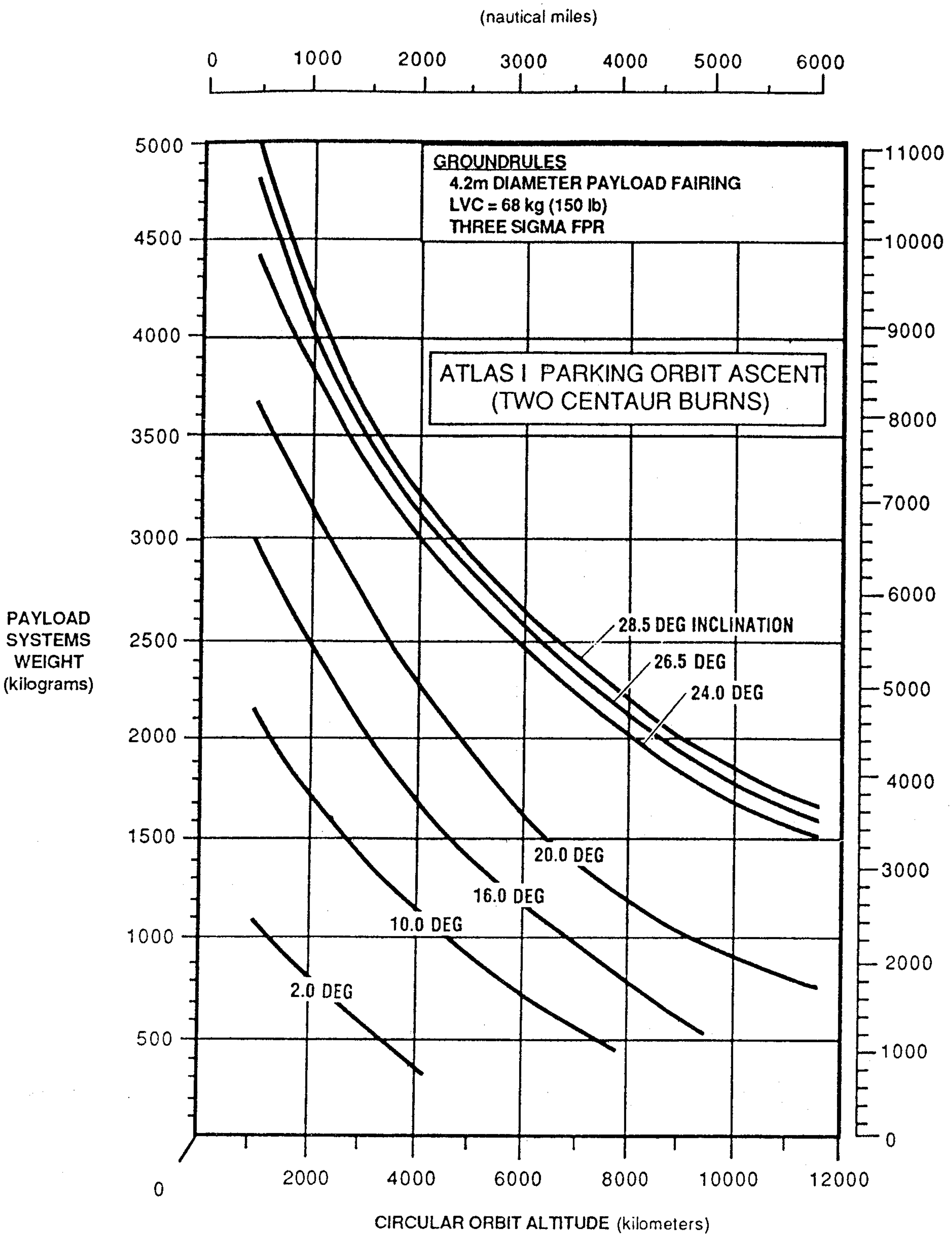

Figure 1. Atlas I parking orbit ascent payload capability to circular orbit.

Spacecraft Bus

The spacecraft bus arrangement is illustrated in Figure 3. The structure is composed of flat panels and the load-carrying central thrust cylinder. Loads from the side panels are transfered to the cylinder via structural webs. Electronic and attitude control components are located on the Earth-facing and anti-Earth panels with the solar arrays gimballed off the north and south panels. Optical solar reflectors (OSRs) are used on the bus thermal radiators. The hydrazine tanks for the bus propulsion system are located outboard of the central cylinder.

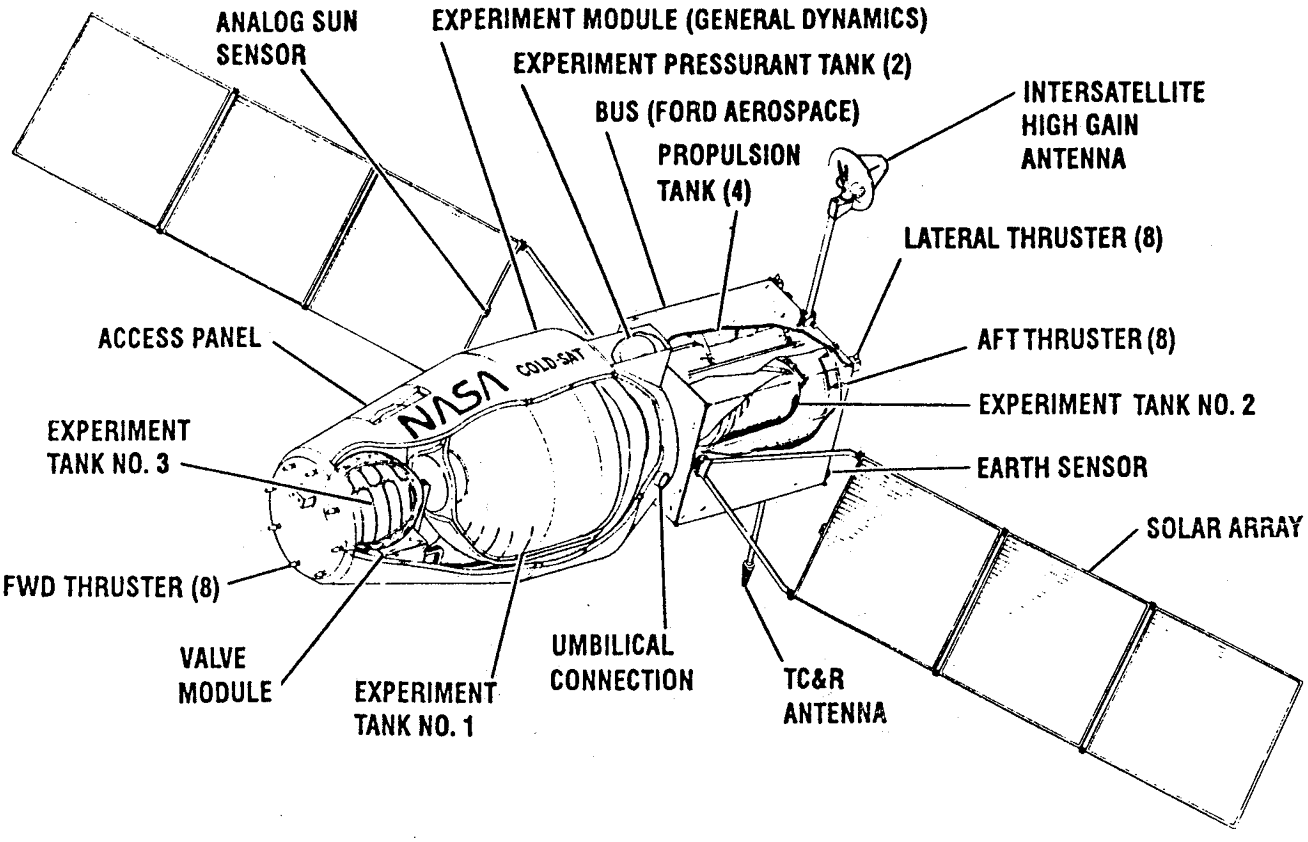

Figure 2. On-orbit spacecraft configuration.

Table 4. Spacecraft weight breakdown.

Experiment Module	**1835 kg**	**Spacecraft Bus**	**1308 kg**
Structure/shield	351	Structure	241
Tank No. 1	419	Power/Electrical	173
Tank No. 2	144	Propulsion system	68
Tank No. 3	87	Command & data handling	82
Fluid transfer system	151	Attitude control system	76
Pressurization system	88	Solar arrays	119
Data management and control	20	Thermal control	20
Electrical	37	Hydrazine	529
Liquid hydrogen	538		
Total payload with contingency	3844 kg		
Experiment module	1835		
Spacecraft bus	1308		
20% contingency	629		
Payload adapter and clamp	72		
Atlas I lift capability*	5400 kg		
Direct ascent	4900		
Two-burn ascent	5400		

* 463 km circular orbit GST0505-4

Experiment Module

The experiment module interfaces cleanly with the spacecraft bus at the end of the bus structural thrust cylinder. It contains all the cryogenic system components for performing the COLD-SAT experiments, including the liquid hydrogen tanks, hydrogen valves and other plumbing, pressurization systems, instrumentation, and some signal conditioning and electrical control components. Key interfaces with the spacecraft bus, in addition to structural interfaces, include electric power, data management, and control.

The experiment module structure surrounds the tanks and other components and provides protection against the low-Earth orbit environment, including micrometeoroids, debris, and atomic oxygen. The semi-monocoque shell consists of inner and outer aluminum skins separated by a low-density aluminum honeycomb. The experiment tanks are supported by low-conductance fiberglass struts that are attached to ring frames in the shell. Once the forward and aft portions of the shell are joined, access to the experiment module components is through the end cap panel on which the forward thruster array is mounted, and through several access doors in the shell.

Experiment Tanks. Table 5 lists the experiments to be performed in each tank. Some of the experiments must be conducted in tanks having specific equipment for those experiments. For example, the mass gaging and mixer experiments will be conducted only in Tank No. 1. However, data for many of the experiments can be obtained in more than one tank. Data can also be obtained incidental to carrying out other experimental operations. Many fluid transfers will be required,

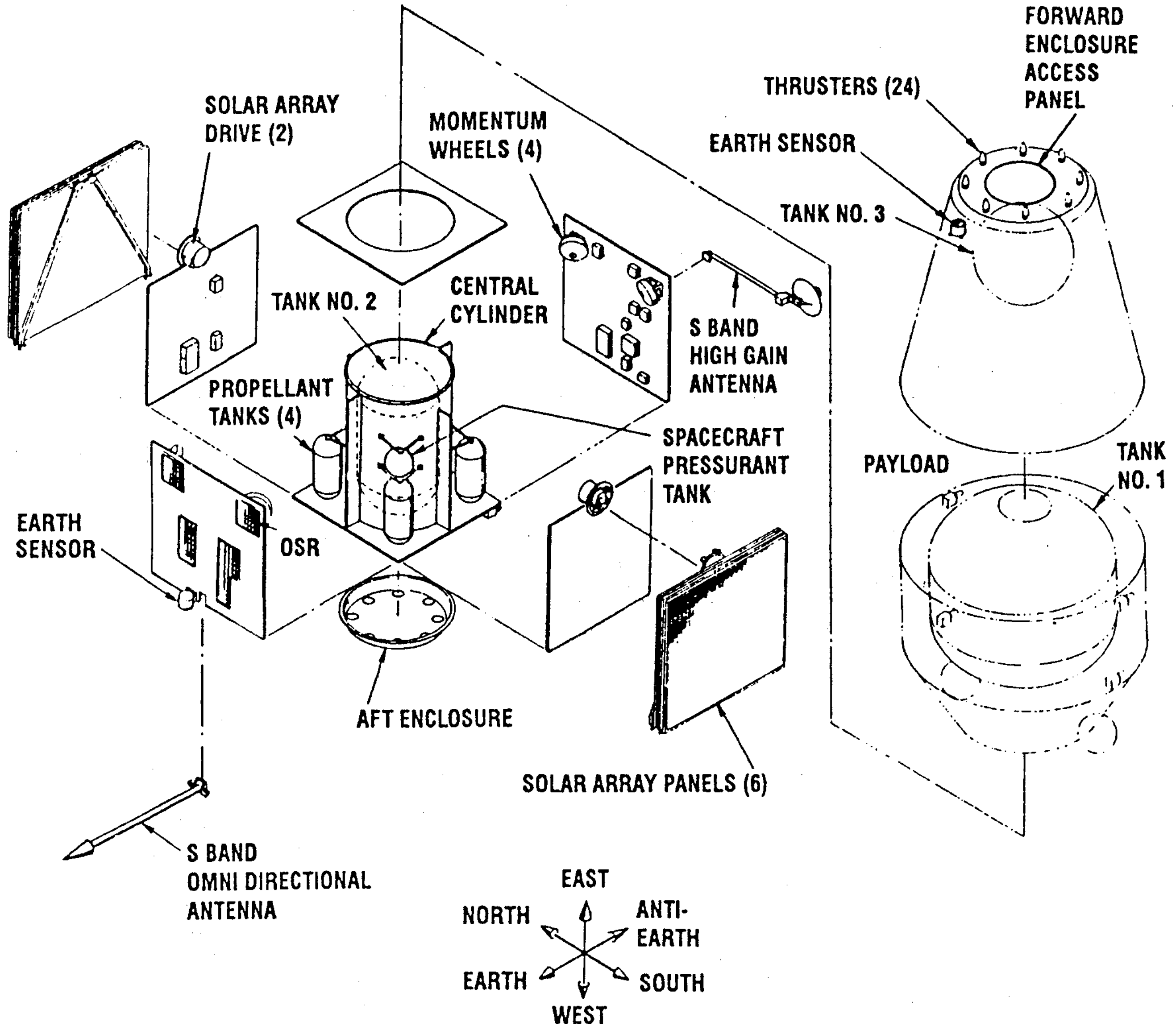

Figure 3. Spacecraft exploded view.

and each will allow acquisition of experimental data on processes such as tank pressurization, line chilldown, and tank chilldown. Table 6 provides a summary of experiment tank features.

Tank No. 2 fits inside the thrust cylinder for efficient packaging. At launch all the hydrogen is contained in Tank No. 1, which is located forward of the spacecraft bus. Tank No. 1 has helium-purged multilayer insulation, which results in a much lighter and cheaper tank than if it was vacuum-jacketed. Tank No. 3 is forward of Tank No. 1. All tanks are centered on the longitudinal axis of the spacecraft to minimize off-axis cg dispersions during the course of the experiment. The tanks are supported with low-conductance struts from the rings of the dual-layer micrometeoroid/debris shield structure. For Tank Nos. 1 and 2, the valves and other fluid transfer components are located within an insulated fairing that extends beyond the barrel of the tank. For Tank No. 3 the valves and other components are contained in an insulated module mounted off the micrometeoroid/debris shield on isolation mountings. Parallel, isolated pressurant and LH_2 transfer lines run the length of the experiment module, with branches to each tank. The ground support equipment fluid interface with the experiment is through a disconnect assembly, developed for Titan/Centaur, at the base of the experiment module. The mating half of the disconnect assembly passes through a chute in the payload fairing that closes after disconnect. Fluids are provided through a draped umbilical that has been developed for Titan/Centaur. Venting of hydrogen from Tank No. 1 prior to payload fairing separation is through a connection made to the Centaur ground/ascent vent.

Fluid System. The fluid system of the experiment module is shown schematically in Figure 4. Banks of orificed shutoff valves are used for LH_2 flow control. In order to meet experiment reliability objectives, some valve redundancy is required. The schematic illustrates the redundancy only for Tank 1 and the pressurization system.

Table 5. Experiments performed in each tank.

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

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

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Tank No. 1 contains a compact TVS heat exchanger integral with the axial flow mixer. There is a ground vent at the top of the tank and a diffuser for the introduction of pressurant during experiments. The diffuser is located in the central region of the tank to decrease the probability of the inflowing pressurant contacting liquid in the tank. The tank is protected from over-pressure by the relief valve and burst disk.

Tank No. 2 uses two sets of orificed valves to control the flow to the radial and axial nozzles, as well as to the tank inlet/outlet. The LAD can be vented through the TVS. Vent valves are located close to the tank inlets for the purpose of line chilldown prior to fluid transfers.

Tank No. 3 uses two orificed sets of shutoff valves for flow control to the tank nozzles and main inlet/outlet valve. A vent for line chilldown is included and outlet lines at the top of the tank are provided for tank dumping and settled filling.

The autogenous pressurization system consists of two 0.56 m diameter rechargeable accumulators connected in parallel. During recharge, the accumulators are first vented and then filled to approximately 20% with liquid, locked up, and pressurized to approximately 6.9 MPa with heaters. Separate high-pressure bottles of ambient temperature H_2 and He are provided for certain pressurization experiments requiring He and ortho H_2, and also for some H_2 pressurization backup. Gas meters are provided for monitoring the flow of pressurant to the tanks. Pressure in the tanks is controlled by the shutoff valves in each of the pressurization lines.

Potential valve concepts have been reviewed to identify any existing flight-qualified designs for COLD-SAT. No existing off-the-shelf designs were found that could be directly used, although several designs (including some with flight history) can be modified. These include cryogenic flow control valves, pressurization control valves, high-pressure regulators, relief valves, and cryogenic check valves.

Table 6. Experiment tank characteristics.

Tank No.	Designation	Shape	Size	Insulation & Shields	Internal Equipment	External Equipment
1	Supply	Cylindrical, elliptical heads L/D= 0.89 a/b= 1.38	$V=7.84m^3$ $D=2.49m$ $L=2.21m$ $Lcyl=0.41m$ $A=19.2m^2$ $LH_2=538$ kg	MLI (76mm) VCS (one) He purge system Insulation fairings for equipment	Total communication LAD Wall-mounted TVS HX Mixer and compact TVS HX Mass gage Pressurant diffuser	Wall-mounted heater Cooled LAD outlet Instumentation
2	Depot (receiver)	Cylindrical, elliptical heads L/D=1.8 a/b=1.38	$V=1.27m^3$ $D=1.02m$ $L=1.83m$ $Lcyl=1.09m$ $A=6.13m^2$ $LH_2=81.6$ kg*	MLI (76 mm) VCS (one) Insulation fairings for equipment	Total communication LAD Wall-mounted TVS HX Slosh baffle Axial and radial spray nozzles LAD heater Pressurant diffuser Instrumentation	Wall-mounted heater Cooled LAD outlet Instrumentation
3	Bare (receiver)	Spherical	$V=0.623m^3$ $D=1.07m$ $A=3.62m^2$ $LH_2=38.6$ kg*	MLI (51mm)	Axial, radial, and tangential spray nozzles Pressurant diffuser Instrumentation	Wall-mounted TVS HX Wall-mounted heater Liquid dump line heater

* 95% full

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

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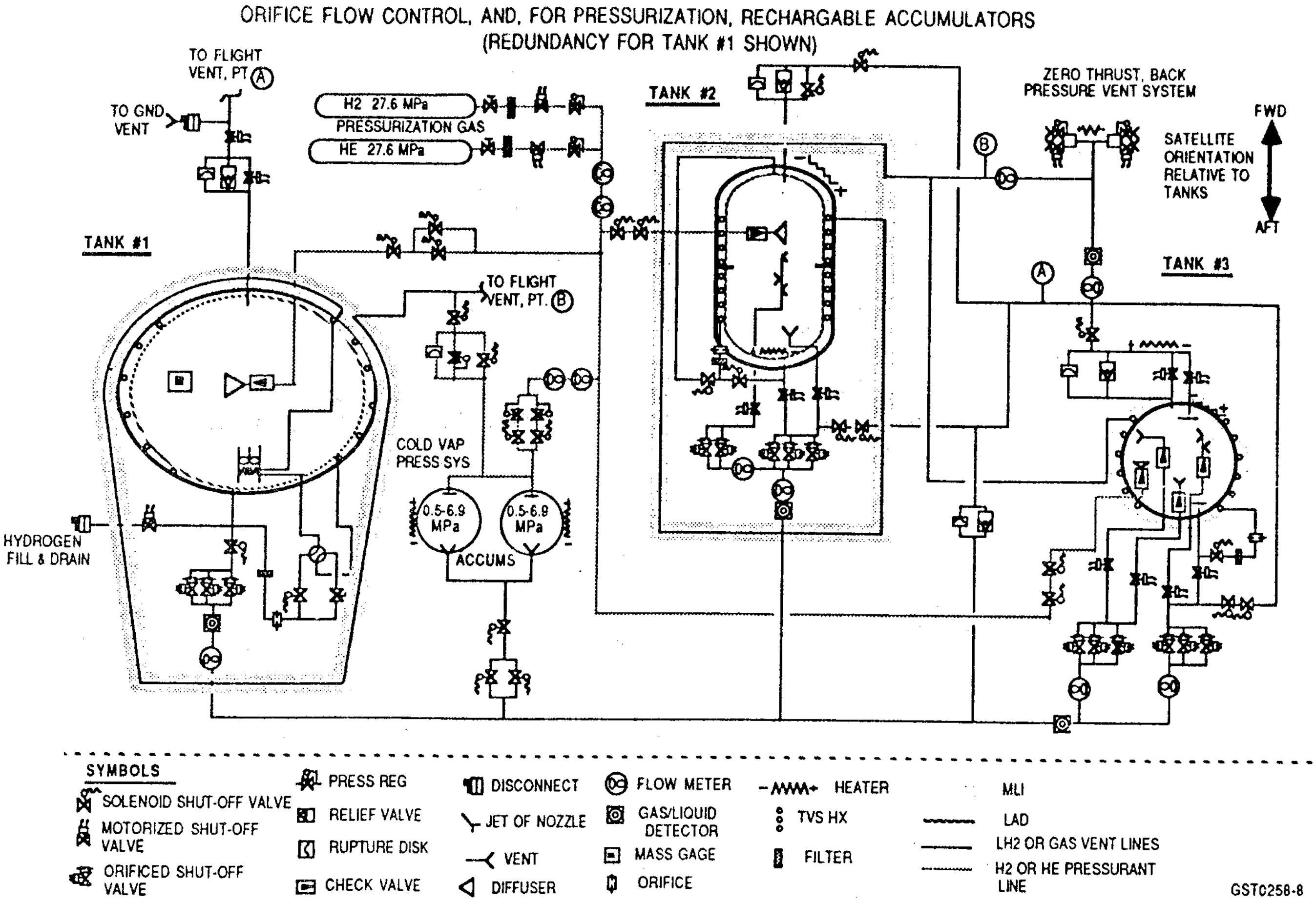

Figure 4. Experiment fluid system.

Experiment Instrumentation and Control. Table 7 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 7. Measurement quantity and distribution.

Measurement Type	Tank 1	Tank 2	Tank 3	Other	Total
Liquid/Vapor detector	33	25	26	0	84
Internal/temp	50	34	16	0	100
External/temp	44	28	35	31	138
Pressure	6	6	6	6	24
Flowrate	1	2	3	5	11
Fluid mass	1	0	0	0	1
Acceleration	0	0	0	3	3
Current	2	2	2	14	20
Voltage	0	0	0	7	7
Command status	22	25	28	8	83
Total	159	122	116	74	471

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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.

System calibration will ensure overall measurement accuracies of 1% of full scale for high-level analog and 2% of full scale for low-level analog with 8-bit encoding. As required, improvement in resolution can be obtained by a reduction in measurement range and/or by using 10-bit encoding.

Figure 5 illustrates experiment control functional elements. Autonomous experiment commands originate from the control unit memory of the spacecraft bus. Commands are transferred from the control unit to the remote terminal unit via a MIL-STD-1553B data buss. The remote terminal unit decodes the commands and distributes them to the appropriate devices. The commands actuate valves to accomplish fluid transfer, operate the tank mixer and heaters, and perform component redundancy control.

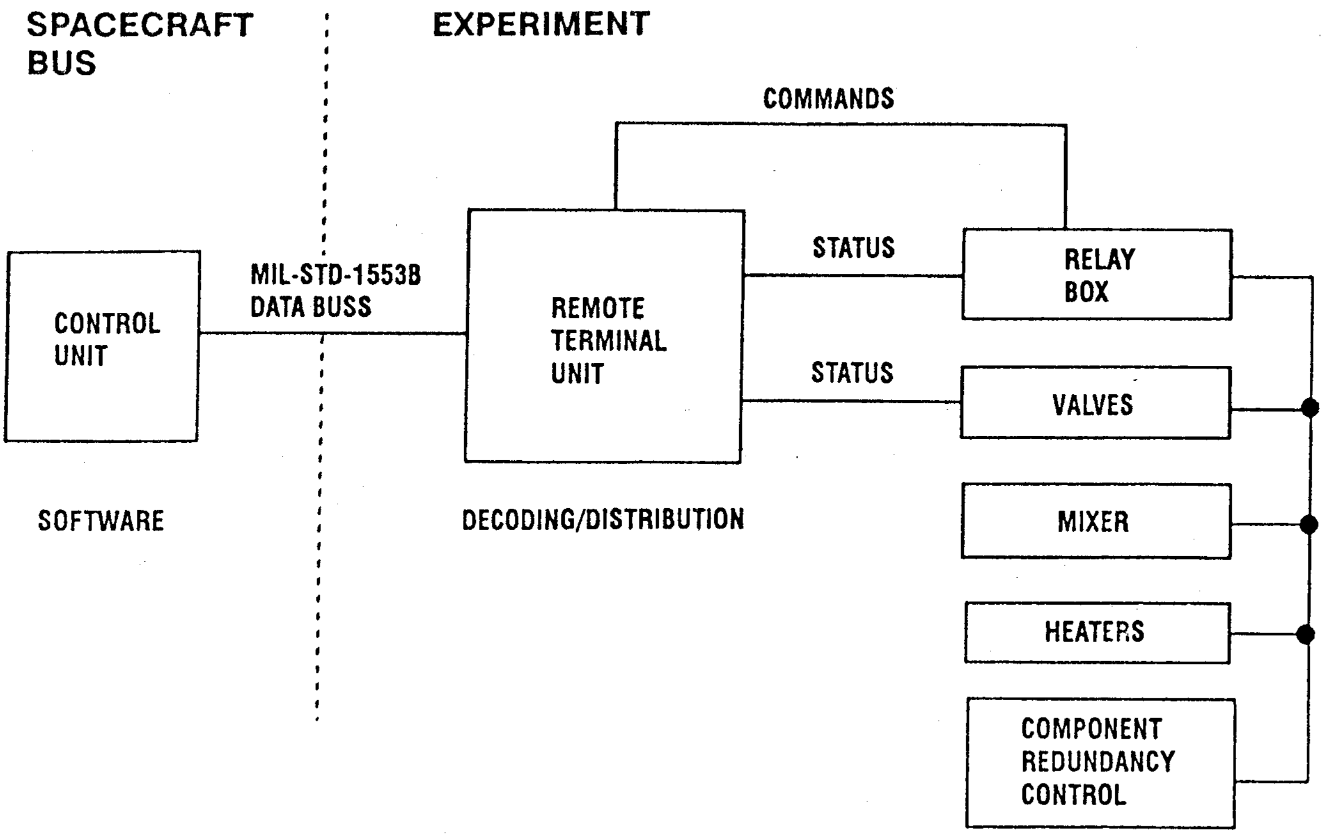

Figure 5. Experiment control.

Thermal Performance. The multilayer insulation specified for the tanks is organically coated, double-aluminized Kapton with a Dacron net spacer, providing about 28 layers per centimeter of thickness. The layers have slits to facilitate broadside venting during ascent, without substantially degrading radiative performance. Low-conductance polyphenylene oxide pins are used to anchor the layers.

The hydrogen aboard the experiment is loaded using the system that tanks the Centaur upper stage, allowing Tank No. 1 to be topped off nearly until launch. During ascent, the helium-purged MLI rapidly evacuates, reducing gas conduction effects. Only about 1.2 kg of hydrogen is lost due to helium gas conduction effects from the time of liftoff to when gas conduction becomes negligible (about 2500 sec). Outgassing effects must also be considered, as they will also contribute to initial tank heating.

Table 8 gives quasi-steady-state orbital heating and resulting hydrogen boiloff rates for the tanks. Tank heating loads include not only heat flow through the MLI but also heat flow through the structural, electrical, and fluid penetrations. The penetration heat load comprises 43 to 93% of the total heat loads for the tanks. Tank Nos. 2 and 3 will have hydrogen in them only part of the time. When the VCS is operational, hydrogen boiloff can be reduced up to 28% in Tank No. 1 and up to 23% in Tank No. 2.

Table 8. Steady-state tank heating and boiloff.

		Heat Flow (W)		
		Tank 1	Tank 2	Tank 3
Baseline MLI Configuration	Hot case	2.5	1.9	0.6
	Cold case	1.9	1.2	0.5
Baseline MLI, with VCS	Hot case	1.2	1.0	N/A*
	Cold case	0.9	0.6	N/A*
Penetrations	Electrical	1.5	1.3	3.1
	Fluid	0.2	0.6	0.5
	Structural	0.1	0.06	0.03
	Total Penetrations	1.8	2.0	3.6
Total heating load (H$_2$ boiloff, kg/day)	Hot, with VCS	3.1 (0.59)	2.9 (0.54)	N/A*
	Hot, without VCS	4.3 (0.86)	3.9 (0.77)	4.2 (0.82)
	Cold, with VCS	2.8 (0.54)	2.5 (0.50)	N/A*
	Cold without VCS	3.8 (0.73)	3.2 (0.64)	4.1 (0.82)

(For Tank 1, Tank 3; Hot case T = 239K, Cold case T = 216 K)
(For Tank 2; Hot case T = 294K Cold case T = 239K) *No VCS on Tank 3

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Conclusions

1. In-space cryogenic fluid management testing is required to support national space transportation missions.
2. COLD-SAT presents the opportunity to accomplish most testing objectives in a single mission.
3. COLD-SAT will require component development, principally in the areas of fluid system components and instrumentation.
4. Atlas, with its liquid hydrogen upper stage, large payload fairing, and large launch margin, eases COLD-SAT design and integration.

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16. Abstract
The COLD-SAT spacecraft will perform subcritical liquid hydrogen storage and transfer experiments under low-gravity conditions to provide engineering data for future space transportation missions. Consisting of an experiment module mated to a spacecraft bus, COLD-SAT will be placed in an initial 460 km circular orbit by an Atlas I commercial launch vehicle. After deployment, the three-axis-controlled spacecraft bus will provide electric power, experiment control and data management, communications, and attitude control along with propulsive acceleration levels ranging from 10^{-6} to 10^{-4} g. These accelerations are an important aspect of some of the experiments, as it is desired to know the effects that low gravity levels might have on the heat and mass transfer processes involved. The experiment module will contain the three liquid hydrogen tanks, valves, pressurization equipment, and instrumentation. At launch all the hydrogen will be in the largest tank, which has helium-purged MLI and is loaded and topped off by the hydrogen tanking system used for the Centaur upper stage of the Atlas. The two smaller tanks will be utilized in orbit for performing some of the experiments. The experiments are grouped into two classes on the basis of their priority, and include six regarded as enabling technology and nine regarded as enhancing technology.

17. Key Words (Suggested by Author(s))
COLD-SAT, Cryogenic storage and transfer; Heat transfer; Microgravity; Liquid hydrogen

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