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COLD-SAT: A Technology Satellite for Cryogenic Experimentation

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COLD-SAT: A TECHNOLOGY SATELLITE FOR CRYOGENIC EXPERIMENTATION

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ABSTRACT

NASA's Lewis Research Center (LeRC) is involved in the development and validation of analytical models which describe the fluid dynamic and thermodynamic processes associated with the storage, acquisition and transfer of subcritical cryogenic fluids in low-gravity. These technologies are considered enabling for future NASA space missions. Four concurrent studies, including one in-house at LeRC, are underway to determine the feasibility of performing model validation experiments aboard a free-flying spacecraft (S/C) called Cryogenic On-Orbit Liquid Depot - Storage, Acquisition and Transfer (COLD-SAT), using liquid hydrogen as the cryogen. This paper describes the technology requirements for the experiments, and presents the initial LeRC concepts for the S/C and an experiment subsystem comprising of cryogenic tankage (a supply dewar and three receiver tanks), gas pressurization bottles (both helium and autogenous hydrogen), their associated plumbing, and instrumentation for data collection. Experiments have been categorized into enabling/high priority Class I technologies and component/system Class II demonstrations. As initially envisioned by LeRC, COLD-SAT would have had a 1997 launch aboard a Delta-II for a six month active lifetime in a 925 km orbit with a pseudo-inertial attitude.

INTRODUCTION

The Cryogenic Fluids Technology Office at NASA LeRC is assessing the feasibility of cryogenic experimentation on a S/C, called COLD-SAT, which will be used to conduct a series of well-conceived experiments using liquid hydrogen in the reduced gravity of space. These experiments will provide low-gravity (low-g) data for those technologies that are required to develop a greater understanding of the fluid dynamic and thermodynamic management of subcritical cryogenic fluids in space. Three parallel feasibility study contracts were awarded in February 1988 to General Dynamics[1], Martin Marietta[2] and Ball Aerospace to develop alternate conceptual designs and preliminary requirements for the COLD-SAT S/C, and to provide overall program schedules and cost estimates. An in-house conceptual design activity was also initiated at LeRC. Following the period of performance of the feasibility studies, a FY92 new start is planned for COLD-SAT, which will be designed and built under contract. This paper presents a brief history of initial LeRC work in the area of cryogenic fluid management(CFM), description of the enabling and enhancing

Table 1. CFM Technology Criticality

Category	Subcategory	CFM Technologies	Criticality
LIQUID STORAGE	THERMAL CONTROL	LAUNCH EFFECTS ON THICK MLI	2
		LONG TERM SPACE ENV EFFECTS ON MLI	2
		COMBINED EARTH/ORBIT INSULATION	2
		PARA-TO-ORTHO CONVERSION	2
		VAPOR-COOLED SHIELDS	2
	PRESSURE CONTROL	THERMODYNAMIC VENT SYSTEMS	1
		FLUID MIXING	1
		REFRIGERATION/LIQUEFACTION	2
LIQUID SUPPLY	PRESSURIZATION	AUTOGENOUS	2
		HELIUM	2
		PUMPS/COMPRESSORS	2
	FLUID ACQUISITION & SUBCOOLING	FINE MESH SCREEN LAD EXP. EFF.	2
		REORIENTATION & OUTFLOW VIA IMP. ACC.	2
		REORIENTATION & OUTFLOW VIA CONS. LOW-G	2
		THERMAL EFFECTS ON LAD PERF.	1
		THERMAL SUBCOOLING	2
TRANSFER		TRANSFER CHILLDOWN	2
		TANK CHILLDOWN WITH SPRAY	2
		NO-VENT FILL	1
		LAD FILL	1
		LOW-G VENTED FILL	2
HANDLING		SLOSH DYNAMICS	1
		VENTING/DUMPING	2
		SUBCOOLED LIQUID/SLUSH TRANSPORT	2
INSTRUMENTATION		QUANTITY GAGING	1
		MASS FLOW METERING	2
		LEAK DETECTION	2
		LIQUID/VAPOR SENSORS	2
STRUCTURES		COMPOSITE VACUUM JACKET	2
		LOW CONDUCTIVITY COMPONENTS	2
		LOW PRESSURE TANKAGE	2
		LAD DEGRADATION	2

COLD-SAT IN-SPACE EXPERIMENTATION PROGRAM

COLD-SAT EXPERIMENTS	CLASS I	CLASS II	TANK
TANKER THERMAL PERF.		x	1
DEPOT THERMAL PERF.		x	2
OTV THERMAL PERF.		x	3,4
PASSIVE TVS	x		1
ACTIVE TVS	x		1
HELIUM/AUTOGENOUS		x	2,3,4
DIRECT LIQ. OUTFLOW WITH LOW-G SETTLING		x	2,3,4
LAD PERFORMANCE		x	1,2
CONTROL OF FLUID THERMO. STATE		x	1
CRYOGENIC TANK CHILLDOWN	x		2,3,4
NO-VENT FILL/REFILL OF TANKS	x		2,3,4
FILL OF LAD	x		2
TRANSFER LINE CHILLDOWN		x	5
VENTED FILL OF TANKS		x	2,3,4
TANK FLUID DUMPING		x	3
MASS GAGING OF TANK	x		1
MASS FLOW METERING		x	5

CRITICALITY: 1-ENABLING, 2-ENHANCING; TANKS: 1-ST, 2-DT, 3-OTV #1, 4-OTV #2, 5-TRANSFER LINE.

CFM technologies that form the basis of the COLD-SAT experiments, concise requirements and procedures of the in-space experiments to be performed, details of the experiment hardware and S/C subsystems for the initial LeRC design, and future plans for the accomplishment of the program.

The technology that is required to effectively and efficiently manage subcritical cryogenic fluids in the low-g space environment is crucial for the national space research and technology base and for the space missions to be initiated under NASA's Civil Space Technology Initiative and Pathfinder programs. Applications of this CFM technology are wide-spread including on-going projects like the Space Station Freedom with its operations involving life support, attitude control, power and fuel storage. Future applications include satellite servicing, initial and space-based space transfer vehicles (ISTV, SB-STV), earth-to-orbit resupply tanker, space-based weapons systems, and in the event of missions to the Moon or Mars, free-flying on-orbit cryogenic fuel depots (OOCFDs). A strong technology base is required for the design of low-g management systems for cryogenic liquids to support and enable these missions. In most cases, there is a lack of sufficient low-g verified data to effect detailed design.

Experimental and analytical research programs to provide the technology base for the design and operation of fluid systems in space have been underway at LeRC for over 25 years[3]. LeRC has developed a wide variety of hazardous experimental research facilities[3] and computational capabilities for analytical research, and as a result most of the investigations into low-g fluid management problems, especially those with LH_2, have been and are currently being conducted here. Early emphasis of the LeRC experimental program in the 1960's was to study the effects of gravity level changes on a wide range of fundamental physical processes, aimed at developing a basic understanding of low-g fluid and thermal behavior.

Subsequently, through much of the 1970's, the LeRC activity became more focused, applying the fundamental knowledge developed in the 1960's to specific mission and vehicle technology needs. In support of the Centaur vehicle development effort, studies of propellant sloshing, settling and draining, and improved tankage thermal and pressure control techniques were undertaken. The majority of the effort during the 1960's and 1970's involved studies conducted in-house using the LeRC drop facilities. This in-house experimental program was supplemented over the years by contracted numerical modeling studies of low-g fluid behavior.

The focus of the LeRC CFM program during the 1980's and beyond is in the development of experimentally verified analytical models of all the important CFM technological processes which can be used to establish design criteria for future space missions. Ground-based verification of the models is being conducted at the above referenced facilities, however, it has been realized that complete verification can only be accomplished by conducting in-space experiments. For this purpose, a contracted effort to Martin Marietta for the development of a Shuttle-attached reusable test bed called the Cryogenic Fluid Management Flight Experiment (CFMFE) was initiated in the early 1980's to conduct on-orbit cryogenic testing to obtain engineering data for model verification[4,5]. In the aftermath of the Challenger disaster, the decision by NASA not to fly LH_2 payloads such as the CFMFE on the Shuttle, led LeRC to reconfigure CFMFE and plan a free flying S/C for a launch aboard an expendable launch vehicle (ELV). This S/C was renamed COLD-SAT.

ENABLING TECHNOLOGIES

In 1979, a NASA-wide In-Space Cryogenic Fluid Management Research and Technology Ad Hoc Planning Committee was commissioned by the Office of Aeronautics and Space Technology to advise the agency on the scope of the CFM technology needs and requirements. This committee recommended that a significant number of technologies associated with subcritical CFM in space were enabling to future NASA missions and that these technologies could only be developed by conducting in-space experiments. These experiments would verify analytical models which have been developed to describe the on-orbit cryogenic storage, supply and transfer. Numerous similar reviews of the technology requirements have been performed by contracted efforts funded by other organizations[3,4]. As recently as 1987, a CFM Technology Workshop[6] was held at LeRC, with the participants identifying those technologies which require in-space experimentation. This workshop formed the basis for a comprehensive CFM technology roadmap which, in turn, formed the basis for the COLD-SAT flight experiments. There was a consensus reached by the workshop participants in terms of the technologies which needed to be developed, several of which were identified as enabling for future missions such as the ISTV and the OOCFD.

Based on a review of future NASA mission plans and technology development recommendations as made by the workshop, in-space CFM technology requirements were grouped by NASA into six general categories (Table 1). Criticality is described as enabling when a specific application cannot be configured without that particular technology. Enhancing technology provides system performance improvements or reduced operational complexity and cost. Table 1 also provides information on how these technologies are being addressed for in-space experimentation by COLD-SAT. Based on the criticality of the total CFM program technology level, experiments have been categorized into Class I enabling technologies, and Class II system/component demonstrations which will provide future missions with operational and/or performance enhancements. Orbital testing is required for the Class I and they are considered essential to the success of COLD-SAT. LH_2 was chosen as the COLD-SAT experiment fluid due to its planned use as a propellant for future NASA and DoD missions. Technologies developed for managing its challenging low-g behavior should also be applicable to other space cryogens, with the exception of LHe which has unique fluid and thermal properties. Studies have shown that if hydrogen was substituted with a different cryogen as the test fluid, because of differences in the properties required at the initial conditions from experiment to experiment, all of the objectives of a COLD-SAT type S/C will not be met.

COLD-SAT IN-SPACE EXPERIMENTATION

Among the COLD-SAT tankage (Figure 1), the supply tank (ST) has the largest volume and is a model of an earth-to-orbit cryogen transport system or "Tanker"; the next in volume tank is a model "Depot" (DT) that would be filled on orbit and will become a "source" tank for subsequent experimentation. The remaining two tanks are modeled as subscale "Orbit Transfer Vehicle" (OTV) tanks (OTV#1 and #2) and are configured differently to meet a variety of experimental objectives.

Liquid Storage. To store cryogens in space for long durations, tank heat leaks, which cause liquid boiloff, have to be minimized and tank pressures controlled. One source of heat leakage is through the tank thermal control multi-layer insulation (MLI) blankets. The impact of launch environment on thick MLI blanket performance and the degradation resulting from long-term exposure to the space environment has not been fully determined. COLD-SAT will characterize the thermal performance of a typical "Tanker" operating in storage mode, in prelaunch, launch, ascent and on-orbit environments, and the DT and OTV tanks operating in on-orbit storage environment, through the use of the COLD-SAT subscale model tanks. Additionally, COLD-SAT will evaluate the pressure controlling abilities of both passive thermodynamic vent systems (TVS), where sacrificial tank liquid subcooled because of throttling in a Joule-thompson valve is circulated through a heat exchanger (HX) on a vapor-cooled shield (VCS) or on a tank wall to intercept heat leaks, and active fluid mixing devices coupled with a TVS.

Liquid Supply. This technology area will investigate the efficiency in low-g of fine mesh screen liquid acquisition devices (LADs) to continuously supply single-phase cryogenic liquid at a required and controlled thermodynamic state to a tank outlet, a technique which is still unproven in space. Also, pressurization techniques for the discharging of cryogens from propellant tanks which were developed for rocket vehicles with high expulsion rates, have not been characterized for the low expulsion rates required here. Therefore, pressurized expulsions with a condensible gas (autogenous hydrogen) and a non-condensible gas (helium) will be performed to determine gas requirements and system performance.

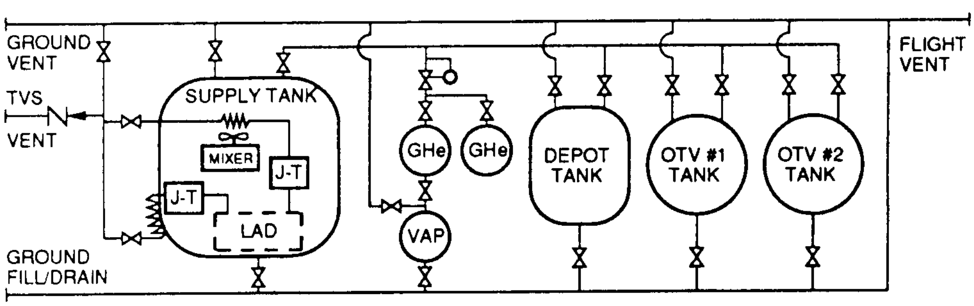

Figure 1. COLD-SAT Simplified Fluid Schematic

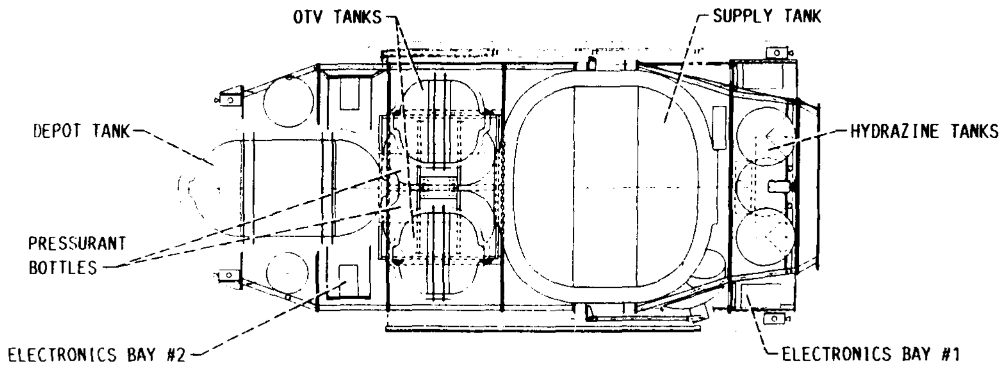

Figure 2. COLD-SAT Spacecraft Configuration for Delta-II ELV

Liquid Transfer. This technology requires the minimization of fluid losses and control of tank pressures during transfer of cryogenic liquids from one tank to another through a transfer line. A "thermodynamic" technique for transfer of fluids is the preferred approach to be investigated, and consists of alternately chilling a tank with and venting a small quantity of cryogen until the tank is cold enough so that it can be filled without venting (chilldown and no-vent fill). A "fluid dynamic" approach is also to be explored, and involves the positioning of liquid away from the tank vent by the use of a low-thrust propulsive system to provide liquid settling.

Fluid Handling. Space missions which are aborted may require that the S/C cryogenic liquids be dumped to space or returned to a storage tank. COLD-SAT will investigate the thermodynamic and fluid dynamic processes associated with the in-space dumping of liquids.

Instrumentation. In this general area, there is a recognized need for instrumentation to determine the quantity (or mass) of liquid in a tank under low-g conditions, to determine liquid mass flow rates, and to assess the occurrence and magnitude of leaks in cryogenic systems. Contractual development of a two-phase flow metering system with Quantum Dynamics and a mass quantity gaging system using the compression method with Ball Aerospace through NASA Johnson is underway.

MISSION AND OPERATIONS

The COLD-SAT description presented in this paper is based on a 3691 kg, 3-axis stabilized S/C to be launched from Cape Canaveral on a Delta-II ELV in a 925 km, 28.5^{o} inclination circular orbit, with the active testing life ending at six months upon hydrogen depletion (Figures 2 and 3). The orbit altitude has a 104 minute period, with 82 minutes of sun, and should give the S/C an estimated orbital lifetime of 500 years. This altitude provides drag acceleration of less than one micro-g to meet the experiment Bond number requirement under no thrusting. The S/C is oriented in a pseudo-inertial attitude with the negative long-axis coinciding with the projection of the solar vector in the orbit plane. This orientation was picked to minimize the solar flux impact on the ST, thereby extending the active life of the experiment by reducing LH_2 boiloff,and also to optimally use solar heating to minimize active thermal control heaters on the hydrazine tanks and the electronics located at the aft end Electronics Bay #1 of the S/C.

The fixed solar arrays generate 2400 W and are canted at a 15^{o} angle from the S/C long-axis to minimize the cosine penalty on power generation as the angle between the sun and the orbit plane varies between 0 and ±52°. Approximately fourteen times a year, when the sun crosses the orbit plane, the S/C will go through a 180° roll maneuver around the long-axis for the solar arrays to be realigned with the solar vector. Primary on-orbit attitude reference is performed with gyros to achieve a basic pointing accuracy of 1°, with roll and pitch updates using earth sensors and yaw updates with sun sensors. Primary control torque is provided by 3-axis momentum wheels which are unloaded by hydrazine thrusters, and a backup mode using sun sensors and safe-hold electronics. The data and command links are limited to a 10 minute per orbit contact through the Tracking and Data Relay Satellite System (TDRSS) using the 50 kilobits/sec (kbps) Multiple Access (MA) data link, with Ground Source Tracking and Data Network (GSTDN) capability as a backup. Telemetry data is to be stored on-board in between TDRSS contacts. Reliability design goal of Class I experiments is 0.92.

Modifications to the Delta-II launch pad will be required to service LH_2 and provide chilled GHe for precooling the ST prior to commencing pre-launch tanking operations. Mechanical and electrical ground support will be available for performing a successful integration of the S/C with the ELV. Commands to and telemetry from the S/C will be monitored at a Payload Operations Control Center (POCC) where communications and computer equipment will be housed.

EXPERIMENT TANKAGE AND COMPONENTS

Supply Tank (ST). This largest volume, 4250 L, vacuum-jacketed (VJ) tank, with a design heat leak goal of 0.063 W/m^2 and weighing 740 kg, will be the only one launched full for supplying LH_2 to the experiments (Figures 4 and 5). Its pressure vessel (PV) consists of a 96.5 cm dia. and 61 cm long cylinder enclosed by 0.60 b/a Cassinian domes to minimize the total length to 193 cm. The PV is supported by 16 alumina/epoxy tension

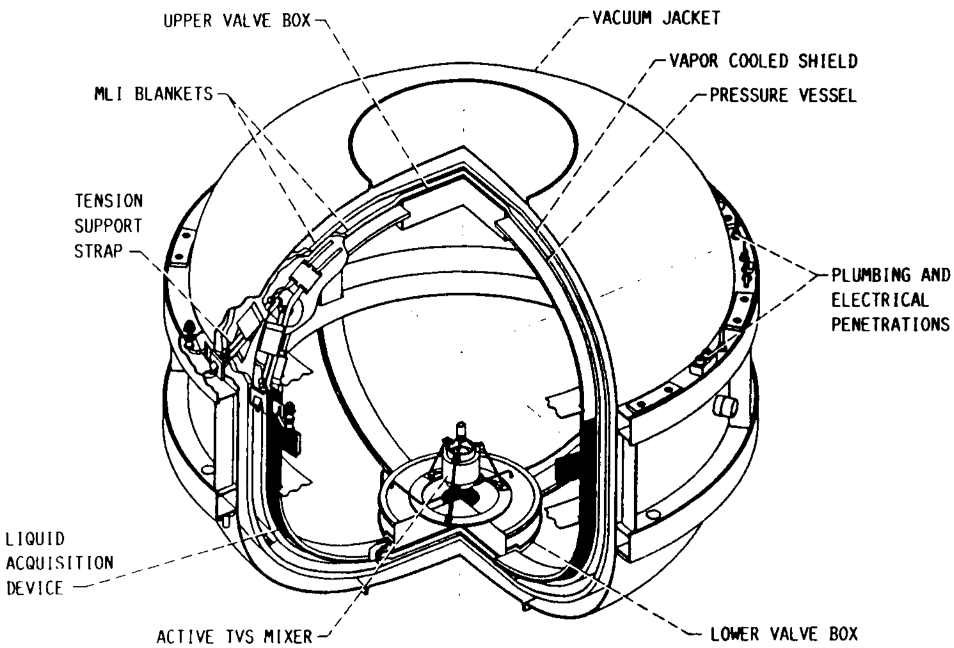

Figure 3. Supply Tank Geometry

straps, which are fixed at the PV end but can be loaded to a desired pretension by a hermetic clevis arrangement which penetrates the VJ girth rings (GR) at the other end. The 15.25 cm annulus between the PV and the VJ has a VCS with two, 2.5 cm thick double aluminized kapton (DAK) MLI blankets, one on the PV and another on the outer face of the VCS. This VCS is supported by flanges which are spring mounted on aluminum blocks bonded to the tension straps. Patch heaters bonded on the PV surface will provide the required heat fluxes for performing the pressure control experiments.

Inside the PV is a 5-channel LAD, supported by two fluid slosh damping ring baffles and two valve boxes inside the forward and aft dome of the PV, and feeds liquid to the aft valve box which has redundant latching valves to control the 1.6 cm tank liquid fill, drain and transfer line. This box also has other plumbing hardware like the J-T and check valves for the 0.65 cm TVS HXs, and supports a 2 W active TVS mixer/HX on its cover. The forward valve box contains redundant latching valves and other plumbing for the 2.5 cm vent and relief, and 1.6 cm pressurization lines. Pressurant gas flows through a diffuser inside the PV to accomplish liquid transfer. All plumbing lines penetrate the VJ through the upper and lower faces of each GR and are thermally shorted to the VCS before entering the PV. Transfer liquid is conditioned to a desired thermodynamic state by passing it through a counterflow thermal subcooler mounted as one quadrant of the horizontal LAD channel. Liquid for three TVS HX lines, for the subcooler, for passive and active TVSs and LAD experimentation, and for housekeeping needs, is obtained from the aft valve box and eventually proceeds to the HX on the VCS. Wiring harnesses leading to inside the PV pass through cryogenic hermetic connectors mounted on the four plumbing lines, joining outside the VJ and separating inside the PV, thereby minimizing the number of heat leak penetrations. Harnesses leading to the VJ annulus, pass through the GR-mounted connectors and transition to flexible ribbon cables which are epoxy-bonded to the tension straps for cooling from the VCS.

The 223.5 cm dia. and 208.25 cm long VJ has two enclosed GRs at each barrel-dome interface for reinforcement, and also to provide locations for lifting and S/C mounting. Two lip-welded grindable covers at each end of the VJ provide access through removable MLI and VCS panels to the plumbing hardware inside the PV, which also has similar lip-welded covers. The location of the plumbing inside the PV was necessary to minimize heat leaks, to ensure vacuum integrity by precluding the possibility of annular fluid leaks and to prevent vapor ingestion into the LAD from any entrapped volumes in lines. Ground pump-out is accomplished through a VJ port with a seal-off valve, burst disk and relief valve, and can be monitored through a vac-ion pump. The assembly and fabrication of the ST, though extremely complex, has been thoroughly investigated, and is too detailed to be described here. All COLD-SAT LH_2 tanks are made of AL2219-T87 and have a design pressure of 345 kPa with a factor of safety of 2.0 in ultimate.

Depot Tank (DT). This is a 990 L non-VJ tank, 92.7 cm in diameter and having hemispherical heads with a total L/D of 2. The DT will be supported from the S/C structure with seven composite fixed struts, each of which support a VCS with a 2.5 cm MLI blanket. Another 2.5 cm MLI blanket is located on the PV. A 5-channel LAD provides liquid for transfer and two TVS HXs for passive pressure control experimentation and for housekeeping, respectively. Like the ST, all TVS liquids flow to the VCS before being vented to space. Plumbing and TVS line components are all mounted on a flat plate welded in between the two PV GRs and buried under the MLI. Hermetic connectors for feeding wiring harnesses through plumbing lines are again provided. Redundant fill/drain/transfer line 1.6 cm latching valves control liquid flow to and from the sump fed by the LAD and located at the aft end of the DT. Tangential and axial spray nozzles for chilldown and no-vent fill testing are controlled by motorized stepper valves. Latching valved vent, relief and a pressurization line with a diffuser are provided. Sloshing is controlled by fluid baffles. The 129 kg tank has a design heat leak goal of 0.063 W/m^2.

OTV Tanks (OTV #1, #2). These are each nearly spherical with a 78.7 cm diameter, 0.707 ellipsoidal heads, 283 L in volume, non-VJ and without a VCS or a LAD. Liquid transfer is accomplished only by propulsive settling. Both tanks have a 1.6 cm fill/drain/transfer line with redundant latching valves, a vent/relief line with a latching valve and a pressurization line with a diffuser. Tanks are supported from the S/C structure by seven composite struts each. Tank #1 also has motorized valves to control radial and tangential spray nozzles, a TVS line for housekeeping and a 2.5 cm foam insulation with inner and outer facial aluminized mylar layers for meteoroid/debris shielding in the absence of a VCS. Tank #2 has a 2.5 cm MLI blanket with mylar layers. Plumbing components are mounted on a plate welded on the GR and insulated. Weight is about 38 kg each and a heat leak goal of 0.315 W/m^2.

Pressurant Bottles. GHe and GH_2 are each stored in two 13788 kPa, SS316 lined, 252 L, Kevlar overwrapped 61 cm diameter cylindrical bottles, with an ultimate factor of safety of 2.0 and weighing 43 kg each. GHe will be stored at close to room temperature, however, the GH_2 system being rechargeable will involve withdrawing LH_2 into a vaporizer, where it will be converted into gas by heating and then stored in accumulators. Preliminary calculations show that 10.5 kg of GHe and 5.5 kg of GH_2 will be required for all the experimentation.

Instrumentation. All the experiment tanks will have instrumentation to evaluate system performance including tank wall, TVS, and MLI temperatures, various pressures, and TVS pressure and mass flows (Table 2). The transfer line will also contain instrumentation for two phase flow detection and mass flow rate measurement. The electronics necessary to perform the experiment processes and acquire the data relevant to the experiment will interface with the S/C Power and Telemetry, Tracking and Command (TT&C) subsystems. Experiment control software will reside in the On-Board Computer (OBC) which is part of the TT&C. Due to the 10 minute TDRSS coverage limitation, all control functions will be handled autonomously by the OBC. Remote Data Units in TT&C will perform the data collection from the experiment for evaluation and control, and the OBC will operate the components in a preprogrammed manner. The electronics consist of signal conditioning boxes, flow meter electronics and data acquisition units. Numerous valves, fittings, check valves, filters, regulators, orifices, heaters, lines, flow meters and controllers, insulations systems, etc. will connect each of the tanks to a fill/vent/drain system and to the inter-tank transfer lines. Latching valves are under development by Moog.

Table 2. Experiment Instrumentation Summary

Measurement	ST	DT	OTV#1	OTV#2	Other	Total
Temperature	120	117	62	25	79	403
Liquid-vapor detection	38	50	31	15	-	134
Pressure	3	3	3	3	36	48
Flow rate	-	-	-	-	17	17
Acceleration	-	-	-	-	6	6
Liquid level	32	24	8	-	-	64
Mixer RPM	1	-	-	-	-	-
Mass gaging	1	-	-	-	-	-

Table 3. Spacecraft Weights and Reliability Goals

Subsystem	Hardware	Consumables	Reliability
Experiment	1395	315	0.959
Structure	338		0.999
Thermal	23		0.998
Power	322		0.993
Attitude Control	84		0.997
Reaction Control	99	300	0.998
TT&C	195		0.990
Software			0.985
Ballast	5		
Contingency (20%)	492	123	
TOTAL	2953 (kg)	738 (kg)	0.920

SPACECRAFT SUBSYSTEMS

Structure. COLD-SAT is configured for the 3.05 m diameter Titan-IIIC fairing which mates to a Delta-II payload attach fitting, and uses an aluminum structure consisting of rings, trusses and shear panels to support all S/C subsystems weights (Table 3). The design is modular to increase accessibility, and to provide for testing of each tank individually while being supported by its modular structure, and then being placed into its proper mounting location on the S/C. Each module has two 1.27 cm thick upper and lower interfacing circular or octagonal rings of various diameters separated by 5 cm rigid tubular struts which form trusses. All tanks are supported off these rings by struts with the exception of the experiment pressurant bottles which are held by bands on a rigid frame mounted off the rings. Electronics boxes are located on the outer walls of two Bays made of aluminum 0.3 cm hexagonal honeycomb and facesheets, reinforced by angles on edges. Hydrazine tanks are supported by struts on a honeycomb circular plate inside the Bay #1. This bay is supported off the bottom GR of the ST by rigid struts. The barrel section of the VJ acts as a primary structure, with the upper portion of the S/C supported by the upper GR. Additional plumbing supports, brackets, insulated lines and hold down devices and structural supports for valves, sensors, cables, instruments, boxes, etc. complete the structural support subsystem.

Thermal Control. As a goal, environmental fluxes have been used to obtain a passive thermal design, since most electronics boxes have a 100% duty cycle. The ST has low absorbtivity/emissivity (α/ε) ratio white paint, with an unobstructed field-of-view to maximize radiative cooling to space. Table 4 presents VJ temperatures for the two extreme attitudes, with I being the selected COLD-SAT attitude, and II is with the S/C long axis normal to the orbit plane. Electronics Bays will be covered with MLI and boxes will radiate to space through selective optical solar reflectors (OSRs) areas. Bays will have high α, high ε paint on the internal surfaces to enhance radiative coupling of the electronics to reduce heaters. Struts attaching to the VJ will be thermally isolated. The entire S/C exterior and individual tanks will be covered with MLI except for the OSR radiator areas and the ST. Solar arrays will have white paint on the rear side to minimize the cell operating temperature. The High Gain Antenna (HGA) and

Table 4. Average Orbital Vacuum Jacket Temperature, K

Spacecraft Attitude	Beta=0^{o}	Beta=52^{o}
I	200	236
II	236	233

booms will be selectively MLI covered and white painted. Individual plumbing lines will be insulated and thermally isolated from the support structure. The reaction control components will have individual heaters of about 175 W. A total of additional 100 W of active heating power is available for contingencies.

Electrical Power. This subsystem supplies 1200 W 28 V DC to the S/C and experiment loads and consists of solar arrays and rechargeable batteries, provides power conversion, distribution, control and protection, and contains interfaces for test and ground operations and other S/C subsystems that require power or provide commands and data. Two arrays with five panels each, with a 26 m^2 total area, generate 2400 W EOL peak during sunlight for S/C loads and batteries, and will be deployed during orbit acquisition by firing explosive bolts with a spring mechanism to position them. Batteries are two 40 A Ni-Cd with a 30% depth of discharge.

Telemetry, Tracking and Command. This subsystem processes S/C and experiment instrumentation data, as well as provide command and control of other subsystems. Redundant flight OBC's provide for autonomous control of the S/C and to acquire, format and process data which is sampled by remote multiplexer units located throughout the S/C and stored in an on-board data unit until an opportunity to downlink transmission to ground through the TDRSS exists. Redundant S-band transponders compatible with the TDRSS MA S-Band (SB) system, at a selectable data range between 32 and 50 kbps, will provide the telemetry, ranging, command and tracking functions using a steerable HGA which is deployed away from the S/C on a 0.92 m boom. Ground selected and controlled backup to GSTDN will be available through S/C body mounted hemispherical antennas at a 4 kbps data rate.

Attitude Control. This subsystem consists of the hardware and software elements necessary for attitude determination, orientation, and stabilization of the S/C during on-orbit operations. Primary control will be provided by software resident in the TT&C computer, and a sun-pointing safe-hold mode will be provided for by hardware in the event of a computer anamoly. S/C attitude will be determined using data from the inertial reference unit which utilizes gyros. Earth and coarse sun sensors will be used for initial attitude acquisition and reacquisition in case of anamoly. Attitude updates will be obtained periodically by using data from the earth and fine sun sensors and errors will be corrected using reaction control thrusters and/or momentum wheels. Drive electronics will be provided for the HGA gimbal and momentum wheels.

Propulsion. This monopropellant hydrazine propulsion system, operating in a 1035 to 689 kPa blowdown mode,will provide COLD-SAT with initial stabilization and orientation, 3-axis control, and five levels of acceleration environments along the S/C long axis for the experiments, ranging from 7.5 x 10^{-6} g's to 5 x 10^{-4} g's. The subsystem will consist of propellant tanks, valves, catalyst beds, heaters, thermistors, lines, pressure transducers, filters and 26 thrusters engines ranging in thrust from 0.045 to 2.27 kg, serving the dual purpose of providing the experiment accelerations and also control by firing thruster pairs creating coupled torques about the desired control axis. Four, 56 cm dia. tanks have a capacity of 345 kg of hydrazine, 250 of which are for experiments, 45 for S/C control and the remaining 50 are a 17% safety margin.

FUTURE PLANS

An important goal of the in-house feasibility study is to produce system level specifications and requirements for an actual S/C design. At present, the contractors and LeRC COLD-SAT activities are geared towards minimizing the S/C weight and cost. As a result, new design concepts are being investigated including one which involves a GHe purged ST instead of a vacuum jacketed ST, resulting in a 450 kg weight reduction. To avoid extensive and costly launch pad modifications for handling LH_2, an Atlas-Centaur is being considered as the ELV due to its use of LH_2 as a propellant and the attendant LH_2 ground loading systems. It is expected that the cost of this more expensive ELV will be offset by the avoidance of pad modification costs, while simultaneously achieving greater lift capability and fairing volume. Additional savings may be obtained by deleting one of the OTV tanks.

Results from the COLD-SAT flight experiments will be disseminated to the experimenters for correlating with analytical predictions and 1-g test data. This will allow validation of the analytical codes and models for developing design criteria to predict low-g cryogenic fluid behavior. The resulting data-base will be used in the design of future subcritical cryogen storage, supply and transfer systems.

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16. Abstract

NASA's Lewis Research Center (LeRC) is involved in the development and validation of analytical models which describe the fluid dynamic and thermodynamic processes associated with the storage, acquisition and transfer of subcritical cryogenic fluids in low-gravity. These technologies are considered enabling for future NASA space missions. Four concurrent studies, including one in-house at LeRC, are underway to determine the feasibility of performing model validation experiments aboard a free-flying spacecraft (S/C) called Cryogenic On-Orbit Liquid Depot-Storage, Acquisition and Transfer (COLD-SAT), using liquid hydrogen as the cryogen. This paper describes the technology requirements for the experiments, and presents the initial LeRC concepts for the S/C and an experiment subsystem comprising of cryogenic tankage (a supply dewar and three receiver tanks), gas pressurization bottles (both helium and autogenous hydrogen), their associated plumbing, and instrumentation for data collection. Experiments have been categorized into enabling/high priority Class I technologies and component/system Class II demonstrations. As initially envisioned by LeRC, COLD-SAT would have had a 1997 launch aboard a Delta-II for a six month active lifetime in a 925 km orbit with a pseudo-inertial attitude.

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