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NASA Cryogenic Fluid Management Space Experiment Efforts 1960-1990

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NASA CRYOGENIC FLUID MANAGEMENT SPACE EXPERIMENT EFFORTS

1960-1990

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INTRODUCTION

The history of subcritical cryogenic fluid management (CFM) technology development at NASA began in the early 1960's as the need for such technology was recognized. Two NASA centers, Lewis Research Center (LeRC) and Marshall Space Flight Center (MSFC), were active in CFM and worked independently; each approached the problem from different perspectives. As a research center, LeRC concentrated on understanding the underlying physics of fluid behavior through a series of basic experiments. As a development center, MSFC was interested in solving specific engineering problems with direct application to existing or future systems. Many design studies for CFM space experiments have been performed by both centers, but none have been built during the past 25 years. The need for CFM space experimentation has been presented many times. This essay traces the history of NASA efforts to investigate and develop CFM technology through space flight experiments.

TECHNICAL BACKGROUND

Cryogenic fluid management is a term used by NASA and its contractors to encompass the technology for handling subcritical cryogens (other than helium) in space. In low gravity, liquid does not stay at the "bottom" of a tank and the location of a liquid in a tank is not certain. For non-cryogenic liquids, bladders are a simple technology for extracting liquid from a tank. For cryogens, however, there are no satisfactory flexible bladder materials for separating liquid and vapor, and even if there were, vapor would still form on the liquid side due to heat addition. Cryogens are difficult to store because the liquids are near their boiling point (hundreds of degrees below 0 °F, much colder than ambient) and a small heat leak can cause vaporization and pressure rise. Transferring cryogens to warm tanks efficiently is also a challenge. CFM technology deals with the storage, supply and transfer of normal, subcritical cryogenic liquids in space.

Cryogens are important for space engineering for several reasons. The most important uses are as propellants and reactants. Liquid hydrogen (LH_2)/liquid oxygen (LOX) rocket propellants are very efficient (high specific impulse) and are the propellants of choice for many missions. LH_2 and LOX are also used as reactants for electric power generation in fuel cells. These and other cryogens are used in many other types of systems. The cryogenic form of desired elements is preferred because the density of cryogenic liquid allows storage of a large mass in a small, relatively lightweight tank. Liquid helium is generally considered separately from other cryogens since it has many unusual properties that allow unique solutions to fluid management problems. Supercritical storage of cryogens has been used successfully in space, but only small amounts of cryogen can be used due to the high pressures and corresponding heavy storage tanks that are involved. CFM technology is needed for large-scale future missions such as lunar bases or manned Mars exploration; these would require much larger amounts of cryogens than have been stored before.

CFM technologies can be divided into two general areas, storage and transfer. Storage problems center around controlling tank pressure as heat leaks into a tank. When vapor must be removed from a tank to reduce pressure in low gravity, the vapor is not necessarily over the vent outlet. There also is a lack of gravity-driven convection and buoyancy so that the liquid can thermally stratify and vapor bubbles can grow around hot spots in the tank. The proposed solution to the pressure control problem is using mixers to destratify the liquid and thermodynamic vent systems (TVS) to remove energy from the tank. A TVS is basically an open loop refrigeration system. The transfer problem consists of liquid acquisition (supply), chilldown of warm tanks and lines, and filling tanks. Liquid acquisition refers to removing liquid from a tank without including vapor or bubbles. This can be done by settling the tank contents with small thrusters to position liquid over the outlet or by using a liquid acquisition device (LAD) fabricated from fine mesh screen which filters out vapor from the liquid. There are other technologies important to CFM, but storage and transfer are the key areas that need space experimentation.

THE GOOD OL' DAYS

In the 1960's, NASA was forging ahead with confidence into a future that included space stations and Mars missions that were sure to follow the success of the Apollo program. It was obvious that the storage and transfer of huge amounts of cryogenic propellants would be required and that CFM technology was needed. Early estimates of Mars mission schedules projected that CFM technology was needed by the mid-1970's.

LeRC had been involved in liquid hydrogen research for rocket engine applications since 1956 when it was part of the National Advisory Committee on Aeronautics (NACA). In support of rocket research, LeRC branched out into many aspects of cryogenic engineering. In 1962, management of the Centaur program was reassigned to LeRC from MSFC where it had been managed since 1960. Centaur was the first operational, liquid hydrogen-fueled launch vehicle. This broadened LeRC interests from basic research to an operational vehicle application for liquid hydrogen technology.

LeRC had various facilities in the early 1960's for pursuing basic research in CFM technology. Insulation studies were performed in large vacuum chambers. Low-gravity testing was performed in three ways. A drop tower was used to achieve 2.3 sec of free fall. Air drag was minimized by dropping an experiment package inside a drag shield and the packages were decelerated in a sand box. The experiments were small, and 2.3 sec is long enough only to observe limited, low-gravity fluid dynamic phenomena. Later, LeRC built a larger drop facility that was essentially a long vacuum chamber sunk 500 ft into the ground. This "large" drop tower provided an essentially zero-gravity environment for 5 sec. Airplanes flying parabolic trajectories provided up to 20 sec of low gravity followed by a like period of 2-g acceleration. However, the acceleration level provided is not very low (0.01 g) and is noisy. The third type of zero-g facility was rocket based. Aerobee sounding rockets that reached altitudes of around 100 miles provided 3 to 5 min of 10^{-4} g for payload weights of several hundred pounds. Pods attached to the side of the Atlas launch vehicle (known as Atlas Scientific Passenger Pods) were ejected at high altitudes and provided up to 25 min of zero-g for payloads of up to 400 lb (ref. 1(a)).

A liquid hydrogen experiment to investigate pressure rise rates in a 9-in. diameter spherical tank was launched on a Aerobee on February 5, 1961 by LeRC scientists (ref. 10). Eight more flights (including two failures) were conducted over the next few years which focused on the investigation of the pressure response of the tank to uniform and nonuniform heat inputs (refs. 11 to 14 and 55). One Aerobee experiment (flight) also demonstrated the effectiveness of a standpipe to serve as a liquid positioning device under low-gravity conditions. Liquid hydrogen experiments were also flown on the

Atlas launch vehicle in the pod carrier. The first two experiments were not successful, but the third flight on February 25, 1964 was (ref. 15).

In October 1963, a meeting was held at NASA Headquarters for the Office of Advanced Research and Technology (OART, known as Code R from the NASA organization chart) to identify and discuss problems in zero-g cryogenic fluid management; all NASA centers were represented at that meeting (ref. 1). Code R was responsible for the development of technology like CFM and was the HQ office that LeRC personnel reported to. Presentations from the Manned Spacecraft Center (MSC, later Johnson Space Center, JSC) and MSFC covered requirements for research by the Apollo and Saturn developers. These centers worked for the Office of Space Flight (OSF) and would be the users of technology developed by Code R.

MSC requirements for CFM technology to support Apollo and for future manned space projects "such as a 400-day Mars fly-by" were presented by Jerry C. Smithson (ref. 1b):

> From a propulsion system standpoint, the problems of zero-gravity may be classified in two broad categories: 1) propellant orientation and 2) heat transfer. The primary interest of MSC at the present time is that of the effects of zero-g on the propellants. The category of propellant orientation can be broken down in the following manner: 1) expulsion, 2) measurement, 3) pressure relief, 4) slosh, and 5) transfer of fluid in a zero-gravity environment....
>
> A few specific items of interest are the following: 1) analytical methods, 2) convection in zero and low-gravity fields, and 3) propellant stratification.

G.K. Platt presented MSFC needs (ref. 1c):

> 1. Scaling: It is understood that the Bond number can be used as a gross scaling factor to determine propellant configuration and location in tanks, but in narrow corners what can be used as a characteristic length, will bubbles be caught and remain there?
>
> 2. Propellant temperature stratification: More knowledge is required concerning stratification temperature profiles and means of estimating tank pressure rise rates.
>
> 3. Venting: Studies should be made concerning mixing of stratified layers with bulk liquid during propellant settling, bubble formation, bubble size, and rise velocities during venting, sloshing at low "g", and performance of liquid-vapor separators.
>
> 4. Engine restart: More work is required on bubble recondensation rates in flowing systems due to compression and the effect on pumps of ingested bubbles.

These technology requirements remain valid today. More than a dozen LeRC researchers presented information on their work on ground and flight experimentation. The conclusion of OART was that the state-of-the-art was improving, but much additional study and testing would be needed to support space vehicle design. This was the first of many reviews to determine if the right thing was being done in CFM technology.

Launch vehicle development experiments were performed on early test flights of cryogen-fueled rockets beginning with the flight of AC-4 in December 1964 (ref. 16). AC-4 was a development flight of the Atlas-Centaur launch vehicle that was managed by LeRC and built by General Dynamics. Responsibility for Centaur was transferred from MSFC to LeRC because of Lewis' expertise in hydrogen engines and zero-g fluid management. The fourth and eighth Atlas-Centaur vehicles (AC-4 and AC-8) were used to study cryogenic fluid management during coast for engine restart. On the AC-4 flight, venting of liquid rather than gaseous hydrogen caused the vehicle to tumble out of control. Modifications made to the AC-8 vehicle controlled venting and slosh problems. The AC-8 flight in April 1966 demonstrated that propulsive settling could be used to control fluid locations, although the thrust levels used were very conservative. Some thermal data in the hydrogen tank was also obtained (ref. 18).

In July 1966, MSFC used a Saturn IB development mission (AS-203) to investigate liquid hydrogen management in the S-IVB stage. MSFC managed the Saturn program and the S-IVB was built by McDonnell Douglas. Television cameras inside the tank verified that the liquid was properly settled (ref. 17). The next month, a contract study with McDonnell Douglas was initiated by MSFC to design a cryogenic fluid research laboratory that would be put into orbit by a Saturn launch vehicle with astronaut participation for the first 7 days of a 14-day mission. This study was known as Project THERMO (ref. 19). Project THERMO marked the end of the era of actual space experiments and the beginning of decades of paper studies.

Project THERMO (Thermo and Hydrodynamic Experiment Research Module in Orbit) was to be an orbital research laboratory that would investigate CFM as a follow-on to the lunar landing program using Apollo hardware (figs. 1 and 2). THERMO would consist of a lunar excursion module (LEM) attached to an enclosed experiment structure containing several modular experiments. The effort got as far as a preliminary design in March 1967 before it was downsized to fit on an unmanned launch vehicle, such as an Atlas (ref. 20). The objective of the project was to resolve CFM technology gaps for manned Mars missions by 1971. MSFC attempted to sell the project to HQ, but "diminishing budget and low priorities resulted in a rejection of the proposal..." (ref. 41).

In November 1969, Code R invited LeRC to propose a CFM experiment to support the space station program that was being anticipated by NASA as the follow-on to Apollo. The requesting letter stated, "The final experiment must be ready for flight in January 1974" (ref. 41).

INTO THE MORASS

In January 1971, as an outgrowth of its ground-based investigations, LeRC proposed a liquid hydrogen flight experiment to Code R that would be flown on the future space shuttle. Code R (which changed names to the Office of Aeronautics and Space Technology, OAST) formed a committee with representation from LeRC, Kennedy Space Center (KSC), JSC, MSFC, and HQ to look at the need for the flight experiment. The Ad Hoc Committee on the Assessment of Reduced-Gravity Fluid and Thermal Technology recommended that flight experiments to resolve low-g technology issues be considered. The committee found that planned and potential space flight programs needed results from further research, including flight experiments, but that current needs could be met by ground-based experiments and analytical modeling.

In June 1976, LeRC had McDonnell Douglas perform a conceptual design of a dedicated flight experiment in response to a Spacelab opportunity for payloads in the shuttle payload bay (ref. 22). The experiment hardware would consist of a liquid hydrogen tank with a LAD, TVS, vapor-cooled shield, and a vacuum jacket. The low-pressure, subcritical tank design was similar to the shuttle power reactant storage assembly (PRSA) supercritical, high-pressure tanks which store hydrogen and oxygen for use in the fuel cells. PRSA-size tanks were chosen to allow the use of existing tooling and shuttle-qualified components and to provide a direct comparison between actual subcritical and supercritical systems. The experiment would investigate tank pressure control, TVS performance, liquid outflow, and LAD performance. LeRC held a competitive procurement for a Cryogenic Fluid Management Experiment (CFME) and awarded a contract to Martin Marietta in November 1978 for $1.8M to design, build, and integrate the CFME (ref. 25) onto a Spacelab pallet. At the Preliminary Design Review (PDR), HQ personnel questioned the approach of CFME. For more than $2M total program cost, they did not feel the experiment addressed enough of the required technologies. CFME consisted of a single tank which dumped its liquid hydrogen overboard (fig. 3). Code R suggested the addition of another tank to perform a transfer. Another Code R committee was formed to review the problem while CFME design progressed.

In December 1979, the In-Space Cryogenic Fluid Management R&T Ad Hoc Planning Committee recommended a facility (Cryogenic Fluid Management Facility) approach to CFM experimentation (ref. 56). A facility with a supply tank and a receiver tank that could be reflown several times with changes to its configuration seemed to offer the maximum technology return. The CFME program was modified to include transfer experiments using the CFME tank as a supply tank. Martin Marietta continued working on CFME, and LeRC let another contract with Beech for a conceptual design of a Cryogenic Fluid Management Facility (CFMF).

While LeRC was engaged in a competitive procurement for the design of the CFMF, JSC had its shuttle contractor (Rockwell) study a similar experiment concept using PRSA tanks to investigate subcritical transfer called the orbiter hydrogen transfer experiment (OHTE) (ref. 26). Nothing much came of OHTE, although Rockwell continued studying the concept under Government-funded independent research and development (IR&D) in 1982.

In September 1982, the CFMF detailed design began at Martin Marietta under contract with LeRC (refs. 27 and 28, figs. 4 and 5). As the design progressed, certain safety and integration problems surfaced. Putting a tankful of liquid hydrogen into the shuttle payload bay rightfully made some people nervous. Even if the shuttle was not the best vehicle for large liquid hydrogen experiments, it was the only game in town in the 1980's.

At the same time CFMF was being designed, LeRC was working on a version of the Centaur LH_2/LOX upper stage to be flown in the shuttle payload bay. Extreme rancor developed between LeRC and JSC over the Centaur program; the program was canceled following the Challenger disaster. LeRC was used to behaving as a launch vehicle developer while JSC wanted to treat Centaur as a payload with much stricter safety requirements. This strained intercenter relationship carried over to CFMF.

The safety problems centered around the release of hydrogen into the payload bay or the vicinity of the shuttle. Hydrogen is flammable in concentrations of 4 to 74 percent in air by volume. CFMF had to be designed so that no two failures (of plumbing components, control systems, etc.) would cause inadvertent release of hydrogen and so that it would be safe in all abort situations. This required special shuttle interfaces and modifications, such as a cryogenic vent, that limited the manifesting of the payload to certain locations in certain shuttles (refs. 43 and 44). Experiment requirements for lightweight tankage also conflicted with safety requirements for large margins in design.

LeRC and JSC spent years negotiating Shuttle manifesting and accommodations (such as fill/drain and vent lines, cooling loops, flight deck switches) for CFMF. Although supercritical hydrogen is flown on every shuttle in PRSA tanks, CFMF had to meet more stringent safety requirements than

PRSA and could not use PRSA vent provisions. This was because PRSA is part of a shuttle system while CFMF was subject to payload rules (that are somewhat vague to this date). Following the Challenger disaster, it was obvious, at the engineering level, that a hydrogen experiment on a manned vehicle did not make sense in an era where low risk was paramount and low cost was a general guideline. Work continued through 1986 on CFMF (which was renamed CFMFE because Code R preferred the name flight experiment to facility) while LeRC management tried to figure out what to do.

As end user of the technology that LeRC developed. Code R felt it was important to have the support of MSFC and wanted to find a portion of the program to give them. LeRC upper management agreed, but LeRC engineers had difficulty finding a part of the CFMF that could be given to MSFC. LeRC had a branch of its Space Experiments Division dedicated to working CFM flight experiments for years, whereas MSFC had two engineers working directly on CFM. Many ground facilities at all the NASA centers had been mothballed during the 1970's, and the people who had been working CFM at MSFC were on other assignments.

LeRC did a study of alternate fluids for CFMFE and liquid nitrogen was deemed the best replacement for liquid hydrogen. However, a liquid nitrogen experiment would only answer half the questions (since the results could not be easily applied to hydrogen) at nearly the same cost. The cost estimates had risen from the \$2.4M for CFME to \$106M for CFMFE by 1987 (Table I).

LeRC began looking at an alternate way of flying CFMFE; the facility might be launched on an unmanned Delta launch vehicle (fig. 6). This approach would be more expensive than flying on the shuttle because CFMFE would have to provide its own services, such as electric power, attitude control, telemetry and command, etc. However, the experimental return also would be much greater. The testing could go on for months instead of being limited by short, shuttle 7-day missions. The acceleration environment would be much better since the CFMFE spacecraft could be placed in a higher orbit where atmospheric drag would be much less, the spacecraft could control its thruster firings, and there would be no astronauts to induce g-jitter. The experiment hardware design could be optimized since safety restrictions would be much less severe on an unmanned vehicle.

Additional help in advocating CFMFE appeared, this time from the newly formed Office of Exploration (OEX) at HQ. The head of OEX wrote a letter of support stating, "In view of the importance of hydrogen management and transfer capability (it is an enabling capability for all, but the least ambitious of the manned exploration missions), I am requesting that the decision to exclude the CFMFE experiment package from the Cargo Bay be reviewed." (ref. 48). However, LeRC had become convinced that a hydrogen Shuttle payload was not feasible and quit pursuing CFMFE.

LeRC began working seriously on the Delta-launched CFMFE spacecraft which was renamed COLD-SAT for Cryogenic Orbiting Liquid Depot - Storage Acquisition and Transfer. Code R was looking for the word "depot" in the name to show support for future exploration programs. In February 1988, LeRC awarded three parallel Phase A study contracts on COLD-SAT to Martin Marietta, Ball Aerospace (which had bought the cryogenic division of Beech), and General Dynamics (refs. 30 to 32). In a September 1988 "Review of Advanced Studies," the NASA Administrator agreed that it made sense to put CFMFE on an unmanned launch vehicle. There was unanimous support for the need to conduct a CFM space experiment (ref. 51).

FULL CIRCLE

The late 1980's saw a role reversal for LeRC and MSFC. MSFC, which had strongly advocated Project THERMO in the 1960's, was now pushing for a shuttle experiment while LeRC had given up on hydrogen shuttle payloads and was pursuing a spacecraft along the lines of THERMO. LeRC had a significant effort in ground-based experimentation and analytical modeling. MSFC had a low level of effort in ground-based CFM technology, but they were trying to reactivate old facilities and expand their program. MSFC followed the LeRC program closely and had representation on the COLD-SAT proposal evaluation committee.

The design of COLD-SAT was carried out in parallel by the three contractors over the next 2 years. LeRC also had an in-house design effort at a low level that was free to incorporate ideas from the contractors (figs. 7 to 9). Toward the end of 1989, LeRC decided that it would present the in-house design at the COLD-SAT Nonadvocate Review (NAR) to be held in the spring of 1990 and stepped up the in-house effort. The contractors made their final presentations in March 1990. Some of the designs (especially the LeRC design) had a few remarkable similarities to Project THERMO even though the LeRC in-house design team did not know of the THERMO design.

Throughout the COLD-SAT design effort, several reviews were held with representation from other NASA centers. The MSFC position was that the COLD-SAT approach would take too long to achieve its objectives, was too expensive, and that shuttle experiments were more appropriate. MSFC was pushing various orbit transfer vehicles (OTV) and claimed to need CFM answers to support the design of these vehicles for lunar base and manned Mars missions before COLD-SAT results would be available. Code R and LeRC upper management still felt that it was important to have broad support and were interested in making a role in the program for a development center like MSFC. Early in the design phase, LeRC even offered to transfer management of the COLD-SAT project to MSFC, but MSFC did not want it. LeRC pushed for the formation of a Cryogenic Fluid Programs Coordination Committee to provide NASA-wide planning.

As the COLD-SAT design continued, LeRC management also came to believe that COLD-SAT was too expensive for Code R. LeRC was managed by Code R, however, so LeRC upper management did not feel free to go to other offices in HQ for funding. In early 1989, LeRC had decided to exercise an option clause in the COLD-SAT contract to have two contractors begin a preliminary design of a nitrogen experiment similar to CFME to be flown on the shuttle as a precursor to COLD-SAT. This experiment was called the Cryogenic Orbital Nitrogen Experiment (CONE, fig. 10). Early CONE advocacy included arguments that CONE would get early data to help in designing COLD-SAT experiments as well as lunar/Mars vehicles.

LeRC and MSFC agreed to work together to develop concepts for alternatives to COLD-SAT. LeRC had two of its contractors (Martin Marietta and General Dynamics) and MSFC had its space transfer vehicle (STV) contractor (Boeing) look at different ways of getting the needed technology, including free-flying spacecraft and shuttle experiments. A review was held at MSFC in November 1989 and at LeRC in January 1990. LeRC and MSFC agreed on the cost estimates and technology return of the alternatives, but LeRC favored a COLD-SAT or mini-COLDSAT (two experiment tanks rather than three and an overall smaller/lighter spacecraft) approach while MSFC preferred Martin Marietta's Cryogen Transfer Experiment (CTE) which was a shuttle experiment that would use liquid nitrogen as the test fluid. MSFC proposed reflying the CONE hardware (that was being designed under contract to LeRC) with a receiver tank and dubbed it the nitrogen transfer experiment (NTE).

In addition, LeRC and MSFC had increased the manpower working CFM related issues, and both centers were designing small shuttle experiments using storable fluids.

In June 1990, a NAR was held for COLD-SAT. The findings of the review committee were that the project was feasible and the total program cost estimates of $463M were reasonable. Code R (now OAET, the Office of Aeronautics and Exploration Technology) told LeRC at a meeting on October 26, 1990 at HQ that a $500M program was not acceptable, but perhaps a program in the range $200M would be. The CONE project was acceptable to Code R with a transfer experiment added. LeRC would manage the CONE-Extended project that would include the technical objectives of a liquid transfer experiment. CONE had turned into something resembling CFMF with nitrogen just as CFME had become CFMF. At the same meeting, the Associate Administrator of Code R (a former shuttle manager) expressed interest in looking into the possibility of flying a liquid hydrogen experiment on the shuttle.

CONCLUDING REMARKS

NASA's CFM technology program has been trapped in a cycle of repetitive design studies (see the chronology on page 28). Millions of dollars have been spent over the last 25 years without getting any flight data in return. The need for CFM technology development through space experimentation has been reiterated through the years by various committees and workshops. Large-scale experiments have not progressed past the design stage because of a lack of willingness to spend the amount of money required for a large space experiment in this area. Artificial timetables have been imposed depending on which future program had the most support at HQ. If a CFM project could not be completed in time to support projected lunar/Mars mission design schedules, it was not attempted, and when the lunar/Mars mission disappeared, so did the justification for timely technology development. Two questions that have perpetually greeted a finished design study are: "Will it be done in time?" and "Are we doing the right thing?" The lack of historical perspective on these questions has hindered progress in the development of CFM technology.

NASA upper management continues to return to the approach of flying liquid hydrogen payloads on the shuttle. In a search for a cheap, low-risk solution, Code R spends time and money on paper studies to reevaluate the situation for each new management team. These studies result in space experiment designs that look similar because the basic constraints on the design have not changed over the years and little, real progress has been made in the technology. Compare Project THERMO (figs. 1 and 2) with COLD-SAT (figs. 7 to 9) or CFME (fig. 3) and CFMF (figs. 4 and 5) with CONE (fig. 10). In the case of CFM technology development, history has repeated itself and likely will continue doing so.

NASA CRYOGENIC FLUID MANAGEMENT SPACE EXPERIMENT CHRONOLOGY

February 1961

First of nine liquid hydrogen experiments flown on Aerobee sounding rockets by LeRC scientists through 1965 (ref. 10 to 14 and 55)

October 1963

Zero-Gravity Fluid Behavior Review and Planning Meeting held at NASA HQ, sponsored by OART, attendees from all centers, need for CFM technology and review of current research presented (ref. 1)

February 1964

First successful Atlas pod experiment with liquid hydrogen flown by LeRC scientists (ref. 15)

December 1964

Atlas-Centaur development flight AC-4, investigated liquid positioning and attempted engine restart, LeRC managed program (ref. 16)

February 1966

Program Plan for Earth Orbital Low-G Heat Transfer and Fluid Mechanics Experiments published by MSFC (ref. 33)

April 1966

AC-8, investigated settling, slosh, engine restart (ref. 18)

July 1966

Saturn IB development mission AS-203, television cameras in S-IVB hydrogen tank, engine restart tests, MSFC managed program (ref. 17)

August 1966

Project THERMO (Thermo and Hydrodynamic Experiment Research Module in Orbit) design initiated at McDonnell Douglas under contract with MSFC October 1966 Conference on Long-Term Cryo-Propellant Storage in Space held at MSFC (ref. 3)

March 1967

"Project THERMO Final Report" design of a manned experiment to be launched on a Saturn IB (ref. 19)

September 1967

"Project THERMO Phase B Prime Final Report" conceptual design of experiments to be launched on smaller, unmanned launch vehicles (ref. 20)

March 1968

"Results of a Preliminary Design and System Integration Study of Flying Several Cryogenic and Fluid Mechanics Experiments on an Unmanned Saturn IB for Long-Term, Low-g Investigations" supported by MSFC (ref. 21)

January 1971

Preliminary Program Plan for Liquid Hydrogen Transfer Flight Experiment prepared by LeRC for OART, LH_2 shuttle experiment proposed (ref. 34)

June 1973

Report of the Ad Hoc Committee on the Assessment of Reduced Gravity Fluid and Thermal Technology to OAST recommends "dedicated flight experiments"

June 1976

McDonnell Douglas starts conceptual design of CFM experiment under LeRC contract in response to a Spacelab flight opportunity

November 1976

Special report "Spacelab Cryogenic Fluid Management Experiment" conceptual design of a LH_2 Shuttle experiment by McDonnell Douglas for LeRC (ref. 22)

August 1977

Cryogenic Fluid Management Experiment (CFME) Project Plan submitted by LeRC to OAST (ref. 35)

August 1978

CFME Project Plan approved by OAST

November 1978

CFME contracted effort with Martin Marietta begins

May 1979

General Dynamics study of Orbital Propellant Transfer Experiment under contract to LeRC

June 1979

CFME Preliminary Design Review (PDR), CFME approach questioned by NASA Headquarters

October 1979

CFME Phase 1 Flight Safety Review at JSC

December 1979

In-Space Cryogenic Fluid Management R&T Ad Hoc Planning Committee Report to OAST, recommends a multimission facility (ref. 36)

April 1980

CFME program modified to include transfer experiment

May 1980

CFME Phase 1 Ground Safety Review at KSC

August 1980

"Conceptual Design of an Orbital Propellant Transfer Experiment" General Dynamics (GDC) for LeRC (ref. 23)

April 1981

Final report "Conceptual Design of an In-Space Cryogenic Fluid Management Facility" Beech for LeRC under NAS3-22260 CFME Critical Design Review (ref. 24)

October 1981

CFME Final Report MMDA for LeRC (ref. 25)

December 1981

Orbiter Hydrogen Transfer Experiment (OHTE) final study review, Rockwell for JSC (ref. 26)

August 1982

OHTE follow-on report (STS-82-0507), Rockwell IR&D study

September 1982

Cryogenic Fluid Management Facility (CFMF) design contract begins, MMDA for LeRC

March 1983

CFMF Conceptual Design Review (ref. 27)

May 1983

CFMF Technical Interchange Meetings (TIM) at JSC/KSC

August 1983

CFMF manifesting request (STS Form 100) approved

October 1983

CFMF Phase 0/1 Flight and Ground Safety Reviews at JSC and KSC; Initial PIP review

November 1983

CFMF PDR

January 1984

CFMF Phase 1 Flight Safety Review; Integration meeting at JSC

March 1984

JSC letter to Office of Space Flight (OSF): STS cannot accommodate CFMF

June 1984

OSF letter to JSC: resume CFMF integration

October 1984

CFMF review at NASA HQ with LeRC, JSC, KSC

November 1984

CFMF TIM at KSC

February 1985

CFMF TIM at JSC on PIP and safety

May 1985
CFMF TIM at JSC on avionics

June 1985
CFMF TIM at JSC on PIP and safety; CFMF Project Plan submitted by LeRC to OAST (ref. 37)

July 1985
CFMF Interim Requirements Review

September 1985
CFMF Phase 1A Flight Safety Review, Space Station Experiment Definition: Long-Term Cryogenic Storage study contract initiated at Beech for LeRC (ref. 29)

October 1985
CFMF System Requirements Review at LeRC

December 1985
CFMF Final Report (ref. 28)

January 1986
Challenger Disaster

March 1986
Orbiter hydrogen venting study results presented by Rockwell to JSC

April 1986
CFMF TIM at KSC on safety and processing flow

May 1986
CFMFE Nonadvocate Review

July 1986
CFMFE TIM at JSC; JSC letter to LeRC on termination of CFMFE integration (ref. 44)

August 1986
LeRC letter to JSC, request reconsideration of CFMFE

November 1986
CFMFE project status review, LeRC presentation to OAST, Delta-launched CFMFE concept presented

April 1987
Cryogenic Fluid Management Technology Workshop held at LeRC (ref. 9); COLD-SAT procurement strategy presented to OAST by LeRC

May 1987
Meeting at MSFC with LeRC Management on MSFC role in COLD-SAT

August 1987

Cryogenic Fluids Technology Office established at LeRC; COLD-SAT Project Plan submitted by LeRC to OAST (ref. 38)

October 1987

COLD-SAT in-house feasibility study initiated

December 1987

Cryogenic Fluid Management overview presented to Office of Exploration (OEX); LeRC in-house meeting on MSFC role in COLD-SAT

February 1988

COLD-SAT Phase A feasibility study contracts awarded to MM, GD, and Ball supporting LeRC; Letter from OEX to OSF requesting reconsideration of CFMFE (ref. 48)

July 1988

Cryogenic Fluid Management program overview presented to OAST by LeRC

August 1988

COLD-SAT Task II contractor reviews

September 1988

COLD-SAT presentation to NASA Administrator by OAST

December 1988

In-Space Technology Experiment Workshop, Fluid Management session identifies a liquid nitrogen flight experiment to provide technology for Space Station Freedom, ISTV, and COLD-SAT

March 1989

COLD-SAT Task III contractor Preliminary Requirements Review

May 1989

Second meeting of the Cryogenic Fluid Programs Coordination Committee, MSFC agrees that LeRC should be lead center for the nitrogen pressure control experiment assuming ISTV objectives met

January 1990

Cryogenic Orbital Nitrogen Experiment (CONE) Phase A studies initiated under Task V of COLD-SAT contracts with MM and Ball; Review of COLD-SAT alternatives at LeRC with LeRC contractors MM and GD and MSFC contractor Boeing making presentations

March 1990

COLD-SAT Task IV final contractor Phase A reviews (refs. 30 to 32) First Workshop on Commercialization of Space Fluid Management held in Huntsville, AL

April 1990

Joint presentation by LeRC and MSFC to Cryogenic Fluid Programs Coordination Committee on COLD-SAT alternatives

June 1990

COLD-SAT Nonadvocate Review

September 1990

CONE Phase A completed, concept reviews held at LeRC October 1990 Head of OAET rejects COLD-SAT as too expensive, agrees to LeRC management of Extended-CONE to include transfer experiment

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TABLE I. - NASA LEWIS CRYOGENIC FLUID MANAGEMENT SPACE EXPERIMENT PROGRAM COST ESTIMATES

Program name	Year	Basis	$ Million (then year)
CFME	1978	CONTRACT	2.4
CFMF	1983	ROM	10
CFMF	1985	PDR	66
CFMFE	1987	NAR	106
COLD-SAT	1987	ROM	314.3
COLD-SAT	1990	NAR	463
CONE	1990	ROM	64.1
CONE-E	1990	ROM	76.5

Notes:
ROM - Rough Order of Magnitude
PDR - Preliminary Design Review
NAR - Nonadvocate Review

ACRONYMS

AC - Atlas Centaur
CFM - Cryogenic Fluid Management
CFME - Cryogenic Fluid Management Experiment
CFMF - Cryogenic Fluid Management Facility
CFMFE - Cryogenic Fluid Management Flight Experiment
COLD-SAT - Cryogenic Orbiting Liquid Depot - Storage Acquisition and Transfer
CONE - Cryogenic Orbital Nitrogen Experiment
CTE - Cryogenic Transfer Experiment
GD - General Dynamics
HQ - Headquarters
IR&D - Independent Research and Development
ISTV - Interim Space Transfer Vehicle
JSC - Johnson Space Center
KSC - Kennedy Space Center
LAD - Liquid Acquisition Device
LEM - Lunar Excursion Module
LeRC - Lewis Research Center
LH_2 - Liquid Hydrogen
LOX - Liquid Oxygen
MMDA (or MM) - Martin Marietta Denver Aerospace
MSC - Manned Space Center (JSC)
MSFC - Marshall Space Flight Center
NACA - National Advisory Committee on Aeronautics
NAR - Nonadvocate Review
NASA - National Aeronautics and Space Administration
OAET - Office of Aeronautics and Exploration Technology
OART - Office of Advanced Research and Technology
OAST - Office of Aeronautics and Space Technology
OEX - Office of Exploration
OHTE - Orbiter Hydrogen Transfer Experiment
OSF - Office of Space Flight
PDR - Preliminary Design Review
PIP - Payload Integration Plan
PRSA - Power Reactant Storage Assembly
R&T - Research and Technology
STS - Space Transportation System
THERMO - Thermo and Hydrodynamic Experiment Research Module in Orbit
TIM - Technical Interchange Meeting
TVS - Thermodynamic Vent System

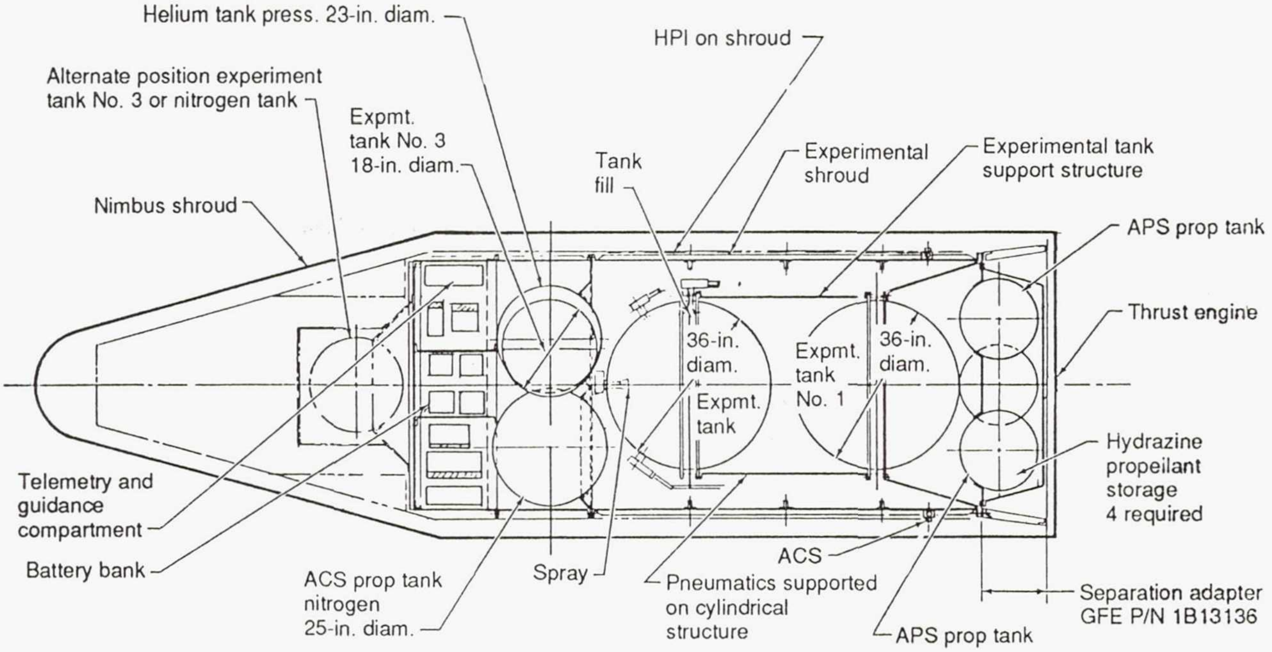

Figure 1.—Project THERMO Phase B prime layout for the Atlas Launch Vehicle.

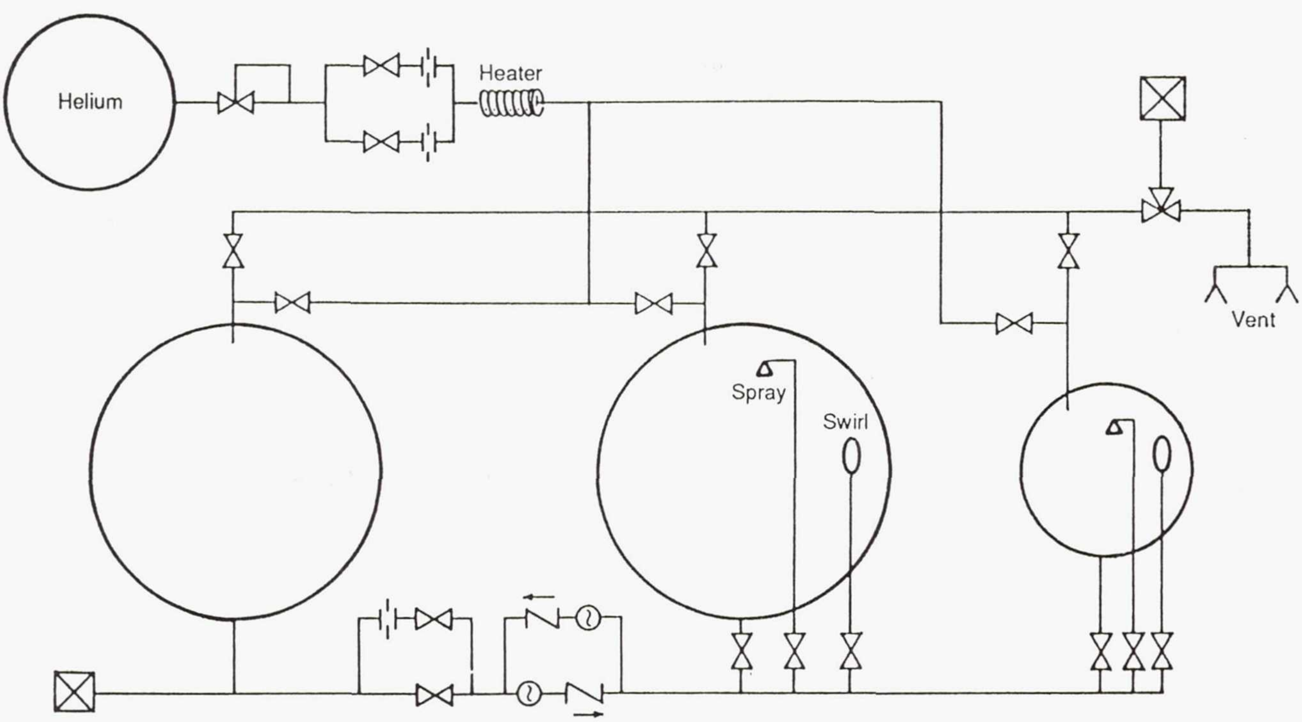

Figure 2.—Project THERMO Phase B prime simplified fluid schematic.

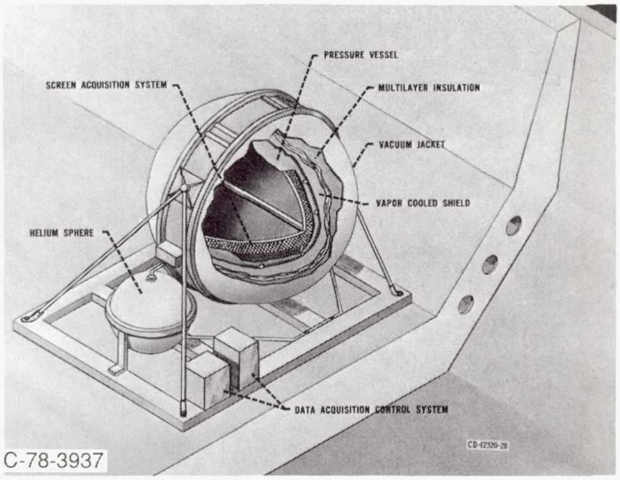

Figure 3.—Artist's concept of the Cryogenic Fluid Management Experiment (CFME).

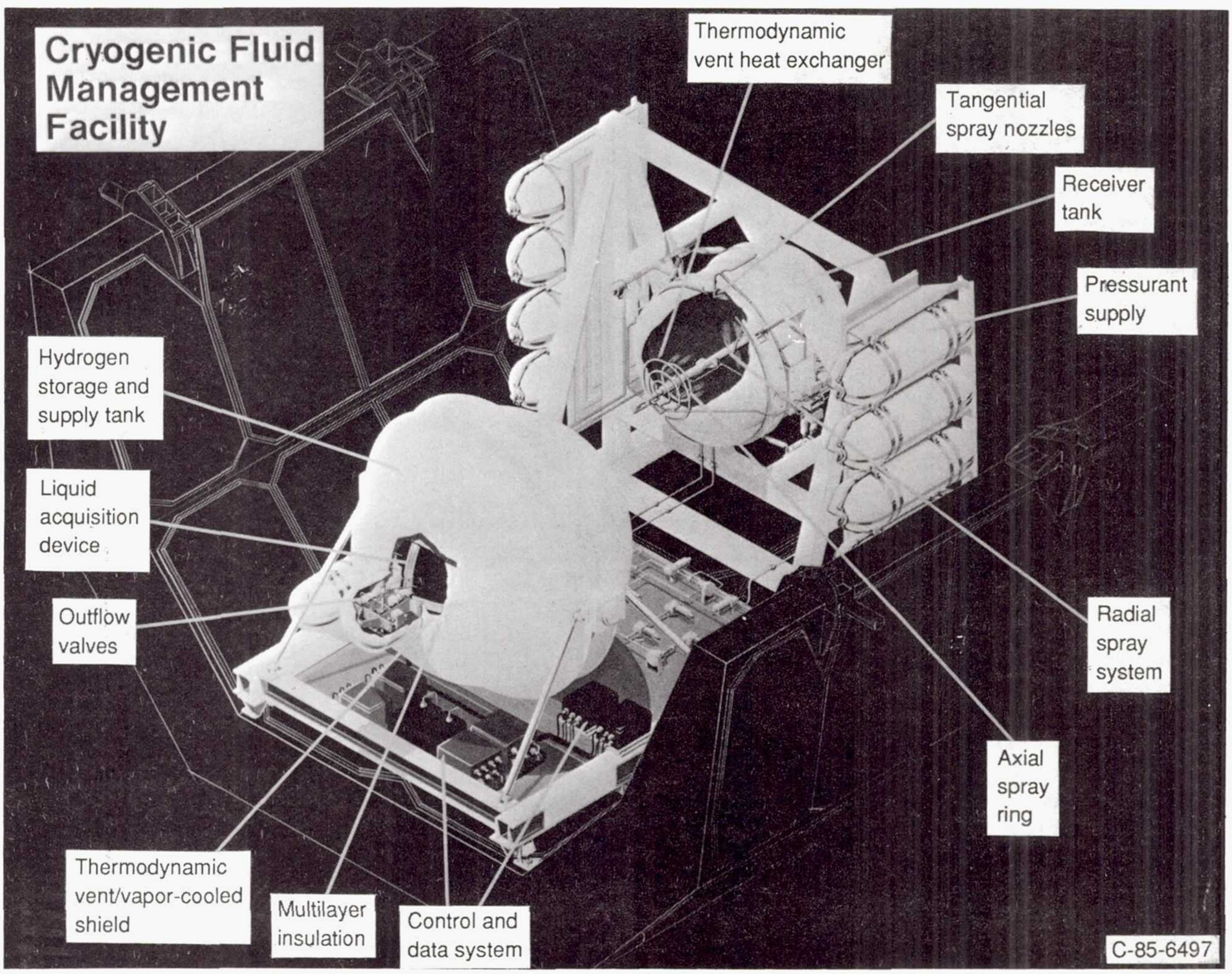

Figure 4.—Cryogenic Fluid Management Facility (CFMF) layout for spacelab pallet.

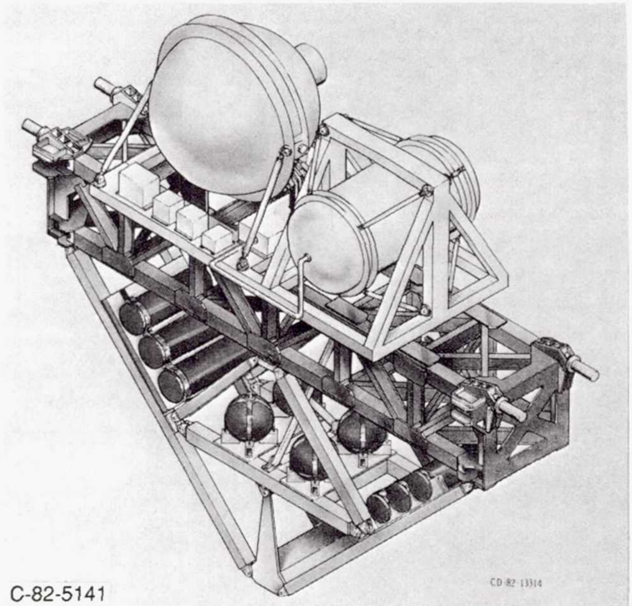

Figure 5.—CFMF layout for Truss Carrier.

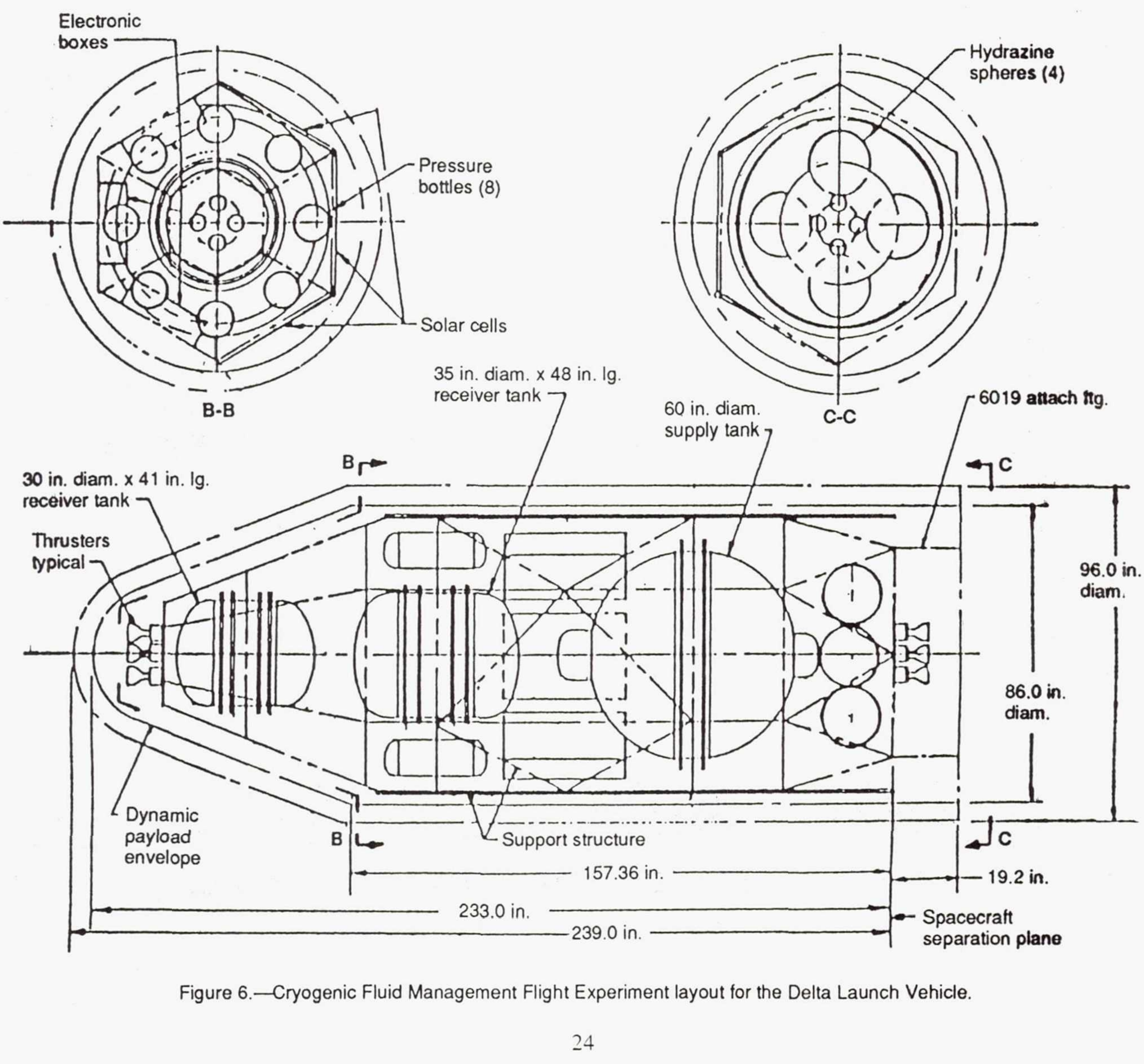

Figure 6.—Cryogenic Fluid Management Flight Experiment layout for the Delta Launch Vehicle.

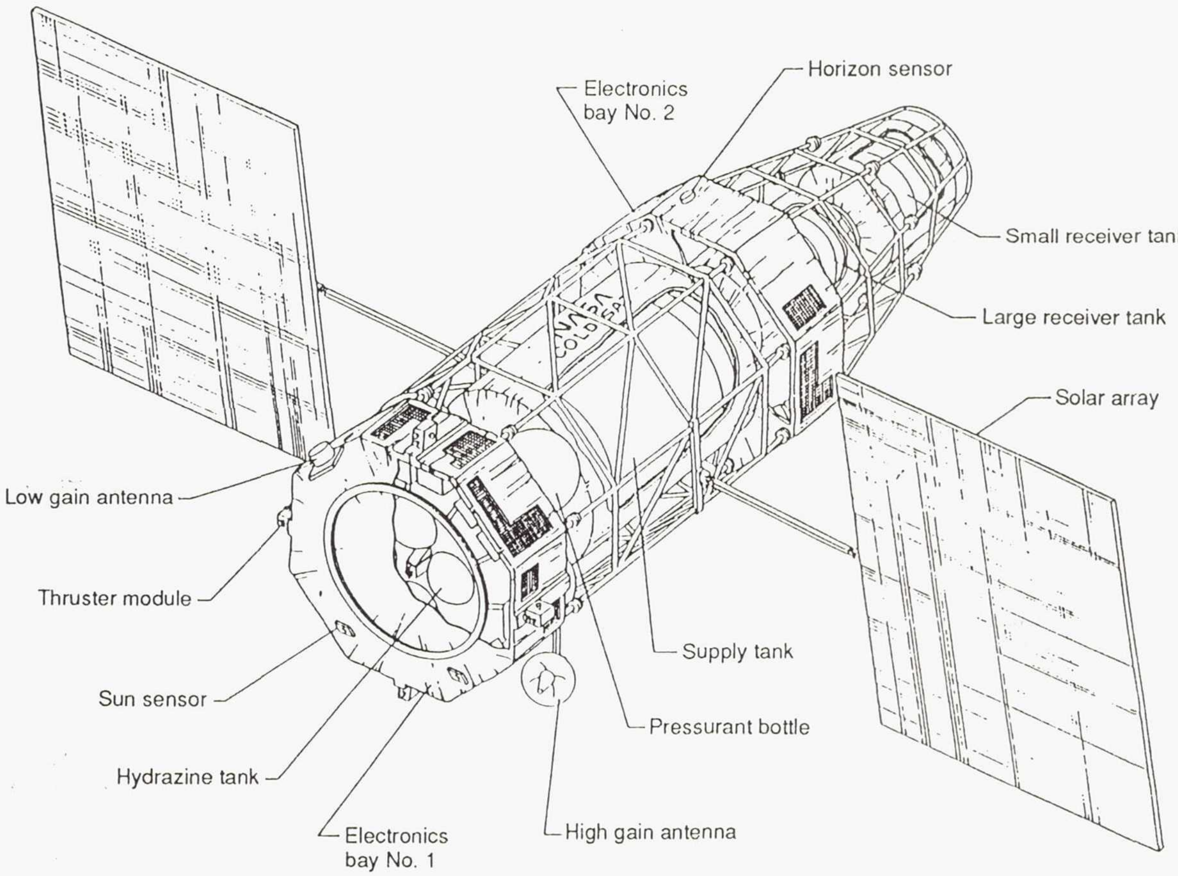

Figure 7.—Artist's Concept of the Cryogenic Orbiting Liquid Depot–Storage, Acquisition and Transfer (COLD–SAT) Spacecraft (LeRC design).

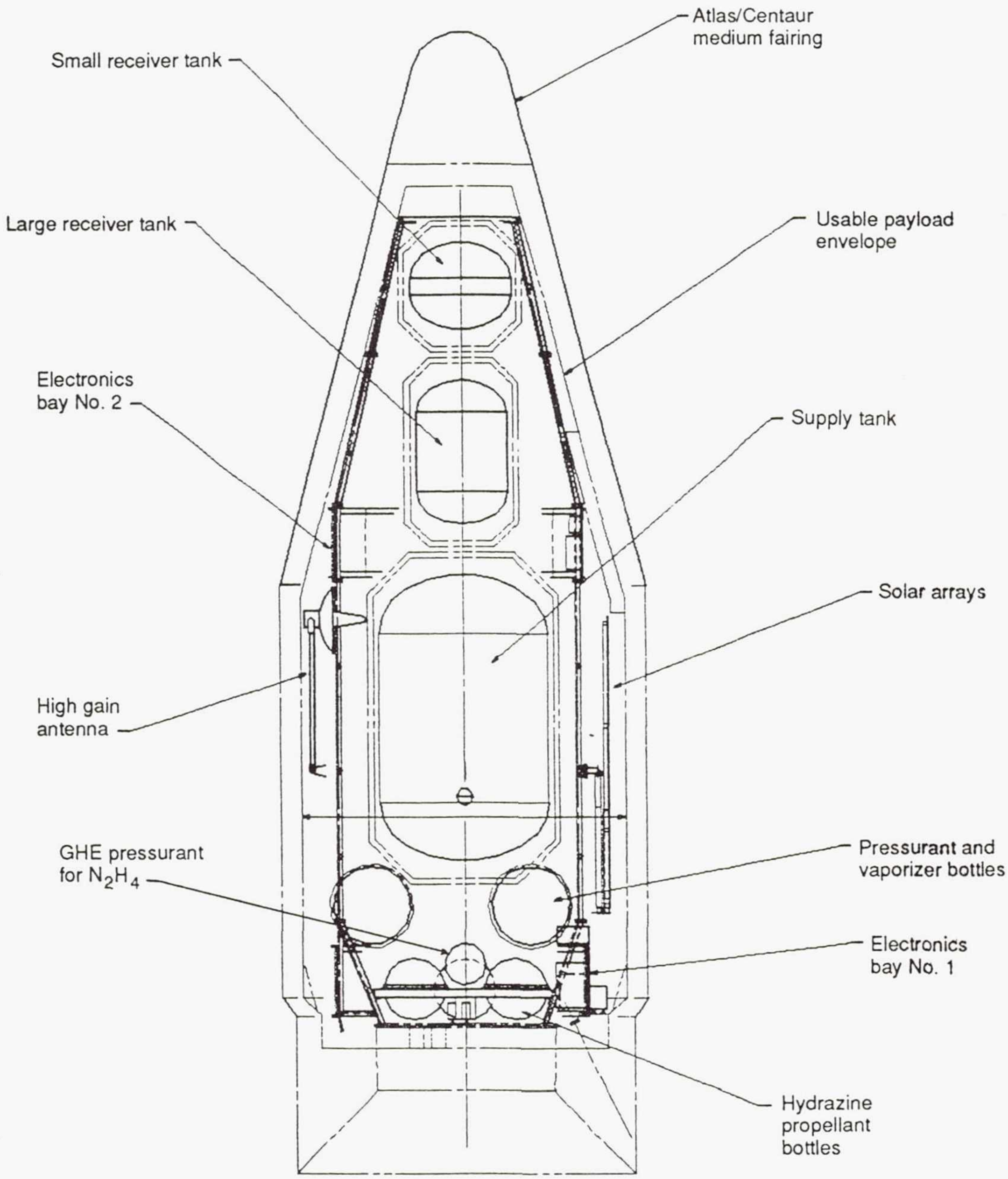

Figure 8.—COLD–SAT layout for Atlas Launch Vehicle.

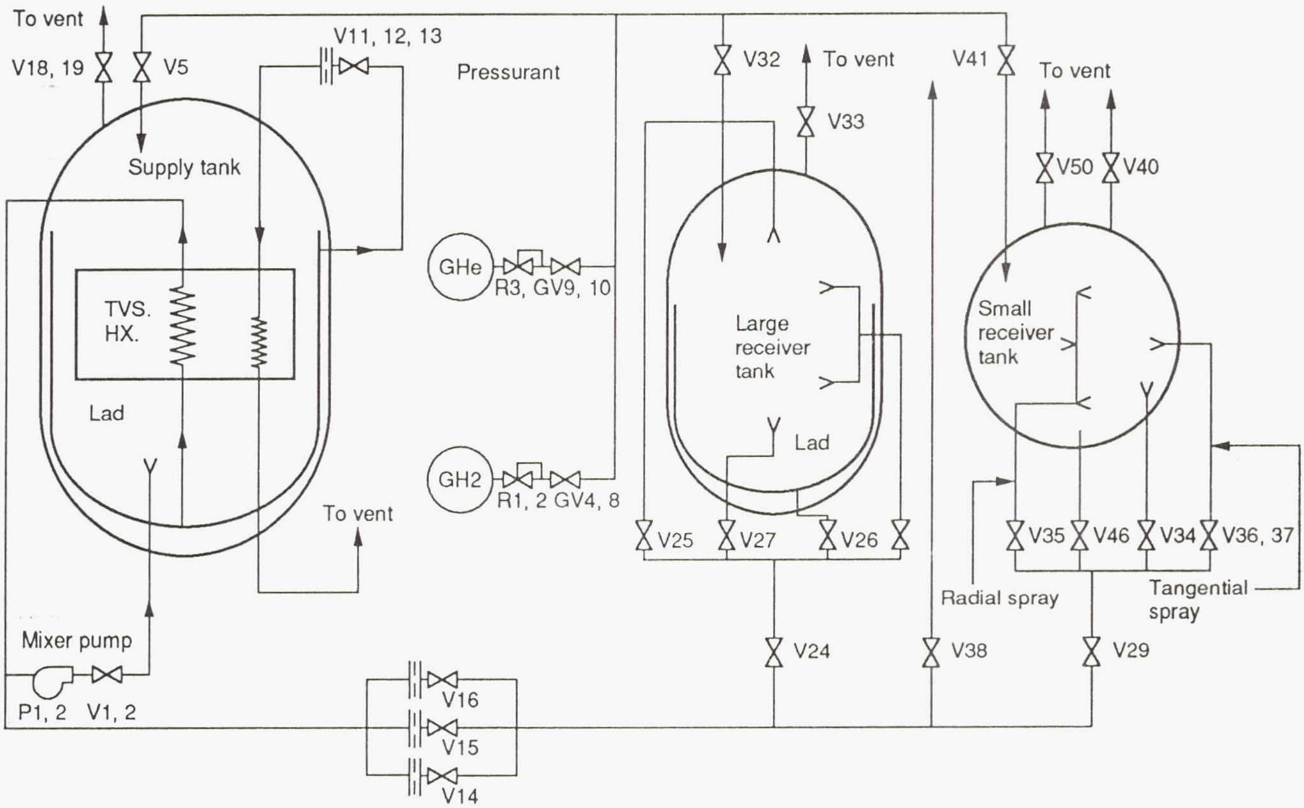

Figure 9.—COLD–SAT simplified fluid schematic.

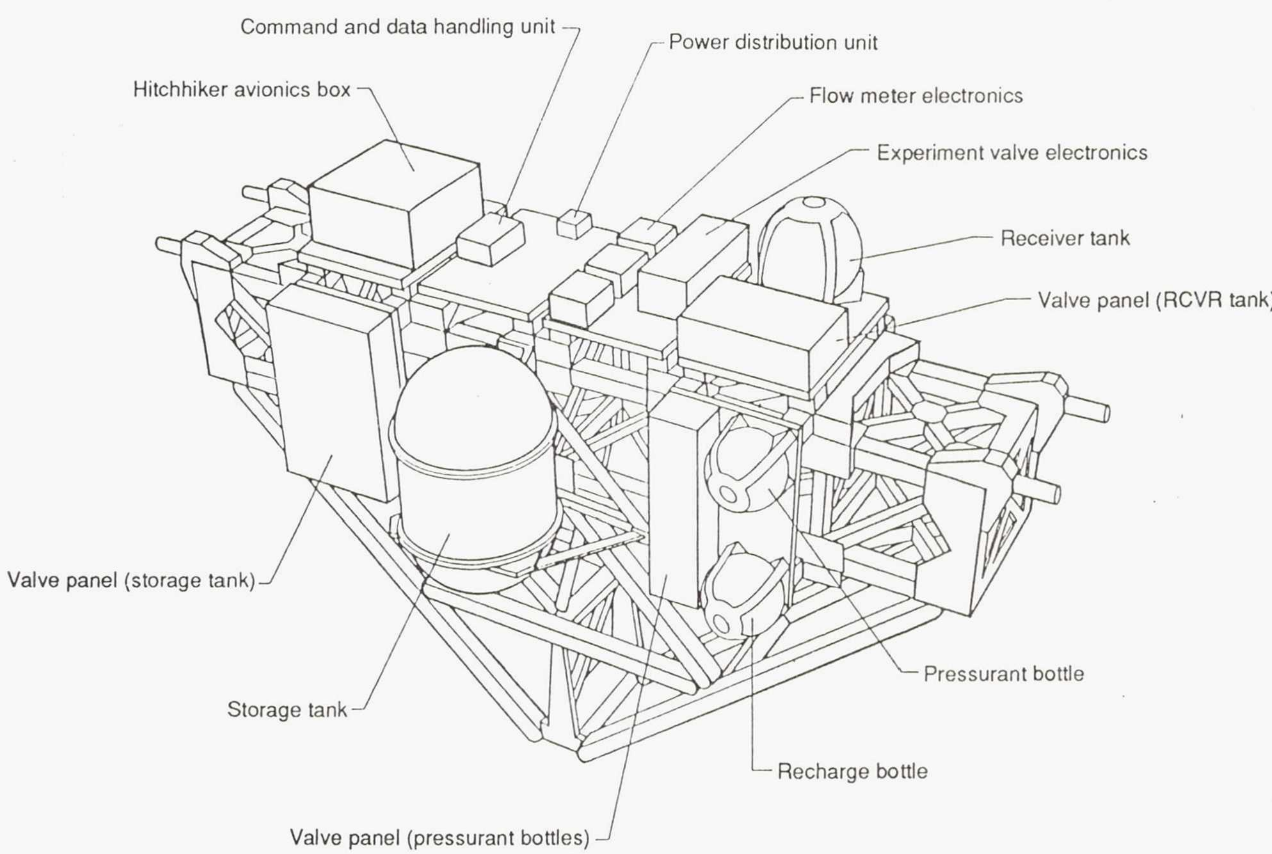

Figure 10.—Artist's concept of the Cryogenic Orbital Nitrogen Experiment (CONE).

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16. Abstract
A history of technology development for subcritical cryogenic fluid management (CFM) through space experiments is given for the period 1960 to 1990. Space experiments with liquid hydrogen were conducted in the early 1960s. Efforts since then have consisted of studies and designs of potential space experiments. A chronology of CFM space experiments and design efforts is included.

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