IN-34

33622

p.12

NASA Technical Memorandum 105197
AIAA-91-3541

Cryogenic Transfer Options for Exploration Missions

(NASA-TM-105197) CRYOGENIC TRANSFER OPTIONS FOR EXPLORATION MISSIONS (NASA) 12 p
CSCL 20D
N91-29[illegible]
Unclas
G3/34 0033622

David J. Chato
Lewis Research Center
Cleveland, Ohio

Prepared for the
Conference on Advanced Space Exploration Initiative Technologies
cosponsored by the AIAA, NASA, and OAI
Cleveland, Ohio, September 4-6, 1991

CRYOGENIC TRANSFER OPTIONS FOR EXPLORATION MISSIONS

David J. Chato*
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

E-6499

Abstract

This paper reviews the literature of in-space cryogenic transfer to propose transportation system concepts to support the Space Exploration Initiative (SEI). Forty-nine references are listed and key findings are synopsized. An assessment of the current maturity of cryogenic transfer system technology is made. Although the settled transfer technique is the most mature technology, the No-Vent Fill process transfers are the most promising and No-Vent Fill technology is maturing rapidly. Future options for development of cryogenic transfer technology are also discussed.

Introduction

As NASA prepares for a return to the Moon and a Mars landing, it has requested technologies which will enable the performance of these missions efficiently. The transferring of cryogens in the low-gravity environment of space is one of these technologies. Although the SEI baseline[1] lunar mission uses drop tanks for the main propellant supplies, it contains two such transfers; one to the Lunar Transfer Vehicle (LTV) core in low-Earth orbit (LEO) and one to the reusable Lunar Excursion Vehicle (LEV) in low-lunar orbit (LLO).

The filling of tanks with cryogens in low gravity poses several technical challenges. Chief among these are the high vapor generation rates due to the residual thermal energy stored in cryogenic tank walls, the uncertainty of liquid and vapor distributions in a tank in low gravity, and the need to keep tank operating pressure low to reduce tank mass. During a fill in a normal gravity environment, a top vent is kept open to vent the vapor generated during the fill process, thereby maintaining a low tank pressure. If the same approach is used in a low gravity environment, the ullage gas may not vent, since the position of the vent opening relative to the ullage cannot be predicted. Instead of venting vapor, large amounts of liquid may be dumped overboard. Unbalanced torques produced by venting two-phase flow, may cause the spacecraft to tumble out of control (this actually happened to Atlas Centaur 4).[2] Several approaches exist for solving these problems. The spacecraft can be placed in an artificial gravity field by continuous thruster firing to position the ullage at a vent opening, or the liquid may be injected slowly enough that it pools near the inlet. This pooling can be enhanced by baffles and/or liquid acquisition devices. One of the most promising approaches is the no-vent fill technique. The no-vent fill method uses tank chilldown, fluid mixing and spray injection to achieve a thermodynamic state in the receiver tank which allows the tank to be filled with liquid without recourse to venting. All of these approaches to orbital cryogenic fluid transfer have been under investigation by NASA for some time.

Caveat

Although the author has made every attempt to be comprehensive, the span of time and breadth of the literature make complete documentation impossible. Much of the ground work for cryogenic transfer resides internal to NASA and was prepared by workers who due to advancing age, or changing interest are no longer active in the field. If experience acts as a guide, very few NASA

---

*Member AIAA.

contracts are awarded without substantial in-house preparation and technical analysis and, just as commonly these in-house analyses are not reported. Perforce the author has been forced to rely mainly on contractor reports, NASA Technical Memoranda, and Journal Articles. Even some of these (especially contractor reports) had such limited distribution that obtaining a copy of them has proved impossible. The author is always interested in new or rediscovered documentation, and would appreciate any help in this regard. He apologizes to any whose contributions have been omitted from this paper.

Review of the Literature

Concepts for missions involving orbital fluid transfer can be found as early as the planning stages of the Apollo program.[3] Unfortunately, this author has been unable to locate any details of these missions.

One of the earliest detailed designs of an orbital fluid transfer system is found in Morgan, et al.[4] This study was in support of post-Apollo, manned, interplanetary missions and evaluated six tanker concepts. The smallest tankers were designed for launch on a Saturn V rocket; The largest tankers were for a post-Saturn rocket 70 ft in diameter. All tankers were self propelled using one or two RL10 engines. The Morgan designs for LO_2 and LH_2 tankers were based on analysis of the thermodynamics of the fill process. The baseline transfer system used a 6-in. transfer line with a 30-min transfer time. This required a 117 lb/sec flow of LO_2 and 31.6 lb/sec flow of LH_2. An analysis of the receiver tank (in this case a Saturn IIB stage) was conducted for both venting and nonvented transfer from a starting temperature of 400 R. Venting losses for the tank were 13 400 lb of LH_2 and 5620 lb of LO_2. The no-vent fill analysis indicated that a 90 percent fill could be obtained with a final tank pressure of 25 psia for LO_2 and 53 psia for LH_2. One of the recommendations of this report was to conduct a small scale orbital cryogenic propellant transfer experiment.

Nein and Arnett[5] proposed to conduct small scale experiments on boiling heat transfer, cryogenic propellant transfer, and propellant storage using a modified lunar excursion module (LEM). The transfer experiment planned to use two thin wall (0.03 in.), 3 ft by 6 ft tanks using LH_2 as a test fluid. Both vented and nonvented fills were to be conducted with a series of inlet geometries, gravity levels, and flow rates. A 350 R wall temperature was selected to limit the expected chilldown mass to 5 percent of the tank capacity. Fredrickson and Schweikle,[6] as well as Dean[7] refined the analyses of Nein and Arnett and looked at design concepts that used, respectively a manned Saturn V launch and a unmanned Saturn IB launch. In order to achieve the same overall objective but reduce the cost, Fredrickson and Schweikle[8] proposed a series of experiments with multiple expendable rockets and they changed the transfer fluid to LO_2. This transfer experiment would have required one Atlas and two Thor/Agena Launches.

Fester, Page, and Bingham[9] demonstrated 1-g nonvented fills experimentally with LN_2 and LF_2 in conjunction with liquid fluorine loading studies. Six tests were run with LN_2 in a 30 gal tank. Parameters investigated included helium concentration in the ullage and fill rate. The starting pressure was 16 psia with a 4 psia partial pressure of helium. All runs filled in excess of 90 percent, although the fill pressures were as high as 110 psia. Following the nitrogen tests, nine tests were run with LF_2 in a 165 gal tank. Again parameters were helium concentration and flow rate. Starting pressures were around 4 psia. Typical pressures at 95 percent full were between 100 and 125 psia, although, the run with no helium in the ullage filled at 14 psia. The reason given for the great difference was the ability of the incoming fluid to condense rather than compress the ullage when no helium was present. Both test tanks used a liquid nitrogen bath for insulation so the starting wall temperature was close to 140 °R. An analytical model was also presented which correlated with the experimental data fairly well.

Symons[10] along with Symons and Staskus[11] studied the stability of liquid inflow in 0-g by conducting a series of drop tower tests. The tests used various room temperature liquids and clear tanks to observe the behavior of liquid flowing into a tank. In most tests a columnar geyser of liquid was formed by the momentum of the incoming flow. The crucial question for stability was whether the geyser continued to grow in height during the fill or if the surface tension forces were sufficient to cause the geyser to collapse back into the accumulating liquid. Based on this criteria, a bounding Weber number (ratio of momentum to surface tension forces) of 1.5 (using the radius of the jet at the free surface as the characteristic dimension) was found to be the limit at which the geyser remained stable. For most fluids, this Weber number corresponds to a rather low flow rate, so, Staskus[12] undertook to determine if stability could be improved by baffling. The results indicated that for the best baffling studied (a series of stacked disks over the inlet and a ring baffle on the tank wall) the stable Weber number was 12 times greater than for the unbaffled case. Finally, Spuckler[13] looked at the effect of accelerations from 0.003 to 0.015 times the force of Earth normal gravity (g) on the inflow process and was able to correlate geyser height as a function of Weber and Bond Numbers (the Bond number is the ratio of momentum to accelerational forces).

Stark[14] studied resupply of cryogens for life support and fuel cell reactants on an orbiting space station. The baseline tank size was 42.5 ft^3. Subcritical transfer schemes were compared to supercritical transfer and tank changeout. The findings were that the subcritical transfer was the most promising approach. A detailed analysis of tank chilldown was conducted. Based on this study, it was recommended that the hydrogen tanks be prechilled prior to starting a no-vent transfer. Findings indicated that a baseline size aluminum tank would require the ability to withstand a 107 psia pressure to no-vent fill without prechill.

Sexton[15] presented a variety of tradeoffs for providing propellant to space tugs and larger vehicles that used the Space Shuttle to carry a tanker set. The selected transfer scenario used a 10^{-4} g settling thrust during the transfer. A transfer scheme was suggested which pumped the receiver tank vent gas back to the supply tank as pressurant. Since the fluid would be settled, the phase separation required for this method would be available. The trades indicated that the chill/no-vent fill approach also was feasible, however, the loss of the chill fluid made it less efficient for the system in this study.

After an extensive survey of the existing literature,[16,17] Stark[18] formulated a transfer system for support of a Shuttle-based space tug using a low-gravity transfer. Thrust levels ranged from 10^{-4} g that would be obtained by thrusting to 10^{-6} g from Shuttle drag. Analysis of the unbaffled geyser height indicate that, for reasonable inlet sizes, geyser height exceeded tank length, and necessitated the use of baffles, or no-vent transfer. The selected approach was to use baffles and a chilldown procedure to cool the tank wall to near the saturation temperature, then fill it without venting.

Heald, et al.,[19] studied transfer systems to support orbital transfer vehicles (OTV) and a space station which would use tankers and orbiting propellant depots. Vented transfer after a vented chilldown is baselined even though the gravity environment is less than 10^{-5} g. This work is noteworthy for the large size of propellant tanks to be delivered to orbit (960 000 lb of propellant within a 50-ft diameter shroud).

Merino, Blatt, and Thies,[20] along with Merino, Risberg, and Hill,[21] continued the work of Refs. 13 and 17, respectively, devising no-vent transfer schemes for the space tug and its successor, the orbital transfer vehicle

(OTV), as well as for Space Shuttle resupply. The principle advancement of these works was a transient analyses of the complete no-vent fill process. These analyses reconfirmed the difficulty of LH_2 transfer seen in the previous equilibrium analyses. As a solution to the problem of nonvented hydrogen transfer, a chilldown procedure was proposed to reduce the thermal energy from the tank walls; this thermal energy must be absorbed in the no-vent fill process. Once again in-space experimentation was proposed in Drake, et al.[22]

Cady and Miyashiro[23] analytically examined the filling of small tanks with screen liquid acquisition devices. The baseline tank was 22 ft^3. The approach analyzed was a vented fill assuming the screen acted as baffle similar to those studied by Staskus.[11] The baffled flow stability criteria led to a minimum fill time of 10.6 hr even for this small size tank. Ground and flight experiments were proposed to further investigate the approach.

In response to the need for in-space experimentation NASA Lewis Research Center added transfer experiments to its already planned cryogenic fluid management experiment (CFME) studying storage and acquisition.[24] Two studies were carried to the preliminary design level[25,26] on this program, now called the Cryogenic Fluid Management Facility (CFMF). Both of these, constrained by the 22 ft^3 volume of the CFME, proposed using multiple flights with a small scale tank for transfer and a larger tank to study chilldown phenomena. One study was selected to be carried forward to the critical design stage. The explosion of the Space Shuttle Challenger led to the cancellation of the project prior to reaching the critical design review (CDR) (increasing concerns about safety, led to the assessment that manifesting a safe liquid hydrogen experiment on the Space Shuttle would be extremely expensive). In this time frame, a conceptual study was also conducted for a larger experiment mounted on the Space Station.[27] The majority of the study was devoted to storage experiments. The transfer experiment objectives of this study were the same as the CFMF, but the greater space available allowed for use of a 45 ft^3 receiver tank.

During this time period, NASA was also studying ways residual propellant in the Shuttle external tank (ET) could be used to support OTV operations. The typical external tank has on the order of 15 000 lb propellant remaining when it is jettisoned into the Indian Ocean. Scavenging studies looked at recovering the propellant by transferring it into storage tanks in the payload bay, or a add-on carrier in back of the ET. The most attractive approach would be to use a 10^{-4} g settling maneuver to affect a rapid transfer from the ET to the storage tanks. Even though the propellant would be settled, Stefan[28] and Gilmore[29] baselined no-vent transfers. No-vent transfer appears as a option in the follow-on work at Rockwell.[30] To study the thermodynamics of scavenging (including no-vent transfer), an analytical model was developed in Louie, Kemp, and Daney.[31]

Implicit in all the scavenging studies is some form of storage depot. Fester, et al.,[32] examines how a tether might be used to settle propellent in a depot attached to the Space Station. Although vented transfer is baselined, further study is recommend due to the uncertain ability of the 10^{-5} to 10^{-4} g of the tether system to maintain liquid-vapor separation without excessive transfer times.

Another depot concept study of interest is Liggett, et al.[33] This study looked at tanks in the 100 000 to 200 000 lb total mass class. Initially, this study looked at systems which could be carried on a up-rated shuttle (capable of lifting 100 000 lb) to support orbit transfer vehicles. Later, it extended the depot concept to support Lunar and Mars missions, as well as, examining wet-launch and dry-launch depot systems. No-vent transfer was baselined for all these depots. Liggett, et al.,[34] a follow-on effort to the depot study, is of interest for the release of a revised version of the analysis code of Refs. 18 and 19 into the public domain.

After the termination of the CFMF project, NASA Lewis undertook the development of in-house models of the chill and fill process. DeFelice and Aydelott[35] undertook a detailed investigation of the chill process. A scaling relation was developed for modeling low mass-to-volume tankage (such as an OTV) with higher mass-to-volume tanks (such as the CFMF tankage). A procedure was established for calculating a "target" temperature for the high mass-to-volume tank which would have equivalent stored energy (and hence similar chilldown performance on a thermodynamic basis) to a higher temperature low mass-to-volume ratio tank. Prototype-to-model flow rate scaling correlations were developed based on the assumption that the liquid-vapor heat flux was constant. Also explored was the effect of venting chilldown gas in stages rather than all at once.

Chato[36] undertook to develop a transient model of the no-vent fill process. The no-vent fill was divided into two stages; first, a flashing stage where the tank wall is still cooling, and then a condensation stage where the tank wall is cold and the predominant problem is condensation of the vapor generated in the first stage. A parametric study was conducted of a 1500 ft^3 tank typical of OTV LH_2 tanks. Parameters investigated included the initial wall temperature, liquid inflow rate, liquid inflow temperature, and a range of assumed heat transfer coefficients for liquid-vapor heat transport. The parameters of most importance appeared to be the liquid inflow temperature and the liquid-vapor heat transport coefficients.

Without experimental data, assessment of model performance proved impossible. NASA Lewis undertook an effort to obtain experimental data on the no-vent fill process for ground-based configurations. A small rig with interchangeable 5 and 1.2 ft^3 test tanks was assembled at the NASA Lewis Cryogenic Components Laboratory to examine the feasibility of the no-vent fill process and parametrically investigate the effect of tank size, test fluids, inlet flow rates, and tank wall temperatures. Results of the testing with the 5 ft^3 tank were reported in Moran, Nyland, and Papell;[37] and were compared to an improved analytical model in Chato, Moran, and Nyland.[38] Results of the 1.2 ft^3 test were summarized in Moran, Nyland, and Driscoll.[39] Taylor and Chato[40] conducted a comparison of these tests to a further refined model along with a reassessment of the 5 ft^3 tank modeling. A large number of no-vent fills were conducted; most of them were successful. The principle reasons for failure was starting with the tank too warm, followed by loss of inflow subcooling at low transfer rates.

To obtain results more characteristic of flightweight tanks, a more limited test series was designed for a 175 ft^3 tank.[41] These tests were conducted at the NASA Plum Brook Station K-Site vacuum chamber. Design of the tests and analytical predictions for performance can be found in Chato.[42] Two spray systems were designed to try to bound the 0-g performance of spray systems. The first system was a single spray nozzle located near the bottom of the tank which would submerge quickly; this was representative of the worst case performance, since the heat transport would be force to rely on jet mixing. The second system used an array of 13 nozzles located at the top of the tank which did not submerge until the very end of the fill; this was representative of the best case due to the high heat transfer available in spray condensation. Results of initial tests are reported in Chato.[43] Nine tests were completed, six of which filled in excess of 90 percent. Top and bottom spray performances were much closer to each other than the analysis predicted. The principle reasons for poor filling was a high inlet liquid temperature caused by excessive heat leak into the transfer line at low flow rates.

Several other experimental efforts for no-vent fill have been reported in recent years. NASA's Marshall Space Flight Center

(MSFC) has conducted a series of tests using Freon 114 and converted water heater tanks using a top pipe and a bottom side inlet.[44,45] Both systems filled to fairly high levels; although, the pressure rise for the bottom inlet is considerably more rapid. Very recently, Martin Marietta Corporation has reported a series of tests on a 3 by 6 ft tank with liquid hydrogen.[46] The findings of this report, based on 14 tests, were that, although, their existing fill/drain line could only fill to around 70 percent, with the addition of an axial spray, fillings nearing 100 percent could be achieved.

In an effort to obtain 0-g data NASA Lewis defined the Cryogenic On-Orbit Liquid Depot Storage, and Transfer Satellite (COLD-SAT). The three parallel contracted efforts[47-49] that were conducted, detailed the design and analysis of hardware to conduct 0-g experiments on chilldown, no-vent fill, and low-gravity vented fill, as well as other technologies. Shifting funding priorities led to the termination of this effort in 1990.

State of The Art

Settled Transfer

Settled transfer is perhaps the best understood of the available processes. Extensive drop tower work has clearly defined Bond and Weber number requirements for inlet flow rates which will produce stable interfaces. Unfortunately, most system studies have found that this inlet flow rate is too slow for practical application at the 10^{-4} g settling rates optimum for liquid supply. Even with this relatively mature technology, there is no in-space testing or any tests with cryogenic propellants. Tests have been limited to tanks which are capable of significantly filling in 5 sec of 0-g. The largest tank tested was under 6 in. in diameter.

No-Vent Fill

No-Vent Fill has been the preferred mode for transfer since the early 1970's, due the potential for high-rate transfers. Thermodynamic analysis has indicated the feasibility of No-vent fill for LO_2 for many years. LH_2 also can be transferred by the no-vent fill method provided a chilldown stage is used to remove some wall energy. Experimental work has demonstrated the feasibility of no-vent fill transfer, assuming inlets are used which provide adequate mixing in the accumulating bulk liquid. Fairly fast transfer rates are achievable and may even benefit the process by increasing mixing and reducing residence time in the transfer line, thereby reducing performance requirements for transfer line insulation. The chief remaining issue of no-vent fill technology is how reduced gravity will effect the mixing process. Reduced gravity produces a drastic change in the fluid flow patterns and interface location. Although the 1-g data intuitively seems to bound the problem, only low-gravity testing can prove this conclusively.

Benefits of Transfer

The principle benefit of cryogenic transfer would be to allow the reuse of hardware already in orbit, thus reducing lift requirements for continuing missions. If a mission used cryogenic transfer for all propellant requirements, several additional benefits would accrue to the mission designer in the form of weight savings. Stages initially filled on-orbit can eliminate much of the structural mass required to support a tank in the 3- to 6-g launch environment. Foam and/or purge systems required to maintain cryogens in tankage on the launch pad could be eliminated from the mission stage. Transfer allows for the separation of storage and supply functions, this would allow tanks on the mission vehicle to be insulated only for the mission rather than the months required to assemble a stage on-orbit. Decoupling of space missions from ground launch can be achieved by use of transfer technology. This would allow establishment of a space-based servicing facility capable of quick turnaround missions for rescue operations. The valving and hardware requirements for implementing a cryogenic transfer are believed to be substantially simpler and safer than drop tank design requirements (two 4 to 6-in. disconnects which can be checked for leakage versus eight 17-in. Shuttle-ET style valves which must seal instantaneously when the pyrotechnic devices fire to drop the tanks).

Recommendations

When considering high rate operations between the Earth and the Moon or heavy lift operations for manned Mars missions, liquid transfer makes sense. Most of the SEI mission vehicles are highly complex and will be assembled with extensive extra-vehicular activity (EVA). With this level of investment, reuse makes sense. The only means of reusing propellant tanks (which are always a large part of any space vehicle) without returning them to the ground is to transfer propellant on-orbit. Settled transfers though fairly well understood tend to require excessive transfer times or high thrust levels. Research in no-vent fill transfers have matured this technology to the point where it should be the recommended approach.

Much remains to be done in no-vent fill research. With the current knowledge, a no-vent transfer system could be designed, but the design would be very conservative; and a flight test would probably be required to verify low-gravity performance. Work continues at NASA Lewis to understand the no-vent fill process. Currently planned testing includes studying new inlet systems, acquiring data with controlled inlet subcooling for a large size (71 ft^3) tank, and assessing high rate transfers (5000 lb/hr).

Work continues on the analytical modeling with an ultimate goal of a model which both accurately predicts performance and is conservative in nature (overpredicts rather than underpredicts pressure rise). Cancellation of the COLD-SAT experiment has left a large gap in the area of low-gravity performance data. Several approaches have been formulated to try and recover and close this gap. The furthest along is a liquid nitrogen transfer experiment for the Space Shuttle. Although LN_2 is not entirely satisfactory as a simulant of LH_2, its properties are quite close to that of LO_2. Also in the formative stages is a concept for a small scale LH_2 sounding rocket experiment. Finally, NASA Lewis efforts in the study of low-gravity fluid mixing for pressure control, which include both analytical work and experiments in space shuttle Get Away Special (GAS) cans, may provide some insight into low gravity mixing heat transfer during the fill process. As an alternative to no-vent fill, NASA Lewis, in conjunction with Martin Marietta, has recently initiated the design of a small-scale Shuttle experiment to study the use of vane liquid acquisition devices as baffles for vented transfer.

NASA Lewis is currently working to quantify the cost benefits to SEI missions of low-gravity transfer. The analysis of benefits are not straight forward, since an architecture which uses tank-changeout and expendable propellant tanks is quite different from one where the tanks are reused. Initial estimates are on the order of 10 to 15 billion dollars over the baseline architecture for just the Lunar mission. At this level of savings, even a COLD-SAT-sized experiment would quickly pay for itself.

References

1. Anon., "Report of the 90-Day Study on Human Exploration of the Moon and Mars," Nov. 1989.

2. Lacovic, R.F. et al, "Management of Cryogenic Propellants in a Full-Scale Orbiting Space Vehicle," NASA TN D-4571, May 1968.

3. Bilstien R.E., Stages to Saturn, NASA SP-4206.

4. Morgan, L.L. et al, "Orbital Tanker Design Data Study" Volume II, Lockheed Missiles and Space Co. LMSC-A748410, May 1965.

5. Nein, M.E. and Arnett C.D., "Program Plan for Earth-Orbital Low G Heat Transfer and Fluid Mechanics Experiments," NASA TM X-53395, Feb. 1966.

6. Fredrickson, G.O. and Schweikle, J.D., "Thermo and Hydrodynamic Experiment Research Module in Orbit," Douglas Missile and Space Systems DAC-60594, Mar. 1967.

7. Dean, W.G., "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," Lockheed Missiles and Space Co. LMSC/HREC A791322, Mar. 1968.

8. Fredrickson, G.O. and Schweikle, J.D., "Project Thermo - Phase B Prime," Douglas Missile and Space Systems Division DAC-60799, Sept. 1967.

9. Fester, D.A., Page, G.R., and Bingham, P.E., "Liquid Fluorine No-Vent Loading Studies," AIAA Journal of Spacecraft, Vol. 7, No. 2, 1970.

10. Symons, E.P., "Interface Stability During Liquid Inflow to Initially Empty Hemispherical Ended Cylinders in Weightlessness," NASA TM X-2003, Apr. 1970.

11. Symons, E.P., Staskus, J.V., "Interface Stability During Liquid Inflow to Partially Full, Hemispherical Ended Cylinders During Weightlessness," NASA TM X-2348, Aug. 1971.

12. Staskus, J.V., "Liquid Inflow to a Baffled Cylindrical Tank During Weightlessness," NASA TM X-2598, Aug. 1972.

13. Spuckler, C.M., "Liquid Inflow to Initially Empty Cylindrical Tanks In Low Gravity," NASA TM X-2613, Aug. 1974.

14. Stark, J.A., "Study of Low Gravity Propellant Transfer," General Dynamics, Convair Aerospace Division GDCA-DDB-72-002, June 1972.

15. Sexton, R.E., "In-Space Propellant Logistics," Vol 3., North American Rockwell Space Division SD 72-SA-0053-3, June 1972.

16. Stark, J.A. et al, "Low-G Fluids Behavior Technology Summaries," General Dynamics Convair Division, NASA CR-134746, Dec. 1974.

17. Stark, J.A. et al, "Fluid Management Systems Technology Summaries," General Dynamics Convair Division, NASA CR-134748, Dec. 1974.

18. Stark, J.A., "Low-G Fluid Transfer Technology Study," General Dynamics Convair Division, NASA CR-134911, May 1976.

19. Heald, D. et al, "Orbital Propellant Handling and Storage Systems for Large Space programs," General Dynamics Convair Division, NASA CR-151719, Apr. 1978.

20. Merino F., Blatt, M.H., Thies, N.C. "Filling of Orbital Fluid Management Systems," General Dynamics Convair Division, NASA CR-159404, July 1978.

21. Merino, F., Risberg, J.A., and Hill, M., "Orbital Refill of Propulsion Vehicle Tankage," General Dynamics Convair Division, NASA CR-159722, Feb. 1980.

22. Drake, G.L., et al, "Conceptual Design of an Orbital Propellant Experiment," General Dynamics Convair Division, NASA CR-165150, Aug. 1980.

23. Cady, E.C., and Miyashiro, H.H., "Filling of Orbital Fluid Management Systems," McDonnell Douglas Astronautics Co, NASA CR-159405, Aug. 1978.

24. Eberhardt, R.N., Bailey, W.J., and Fester, D.A., "Cryogenic Fluid Management Experiment," Martin Marietta Denver Aerospace, NASA CR-165495, Oct. 1981.

25. Eberhart, R.N., et al, "Cryogenic Fluid Management Facility Concept Definition Study (CFMF)," Martin Marietta Denver Aerospace, NASA CR-174630, Dec. 1983.

26. Willen, G.S., Riemer, D.H., and Hustvedt, D.C., "Conceptual Design of an In-Space Cryogenic Fluid Management Facility," Beech Aircraft Corporation, NASA CR-165279, Apr. 1981.

27. Jetley, R.L. and Scarlotti, R.D., "Space Station Experiment Definition: Long-Term Cryogenic Fluid Storage," Beech Aircraft Co., NASA CR-4072, June 1987.

28. Stefan, A.J., "Space Operations Center/ Shuttle Interaction Study Extension," Rockwell International Space Operations/Integration and Satellite Systems Division SSD 81-0194, Feb. 1982.

29. Gilmore, W.L., "STS Propellant Scavenging Systems Study," Martin Marietta Michoud Division, Contract NAS8-35614 DR-6, Feb. 1985.

30. Anon., "Space Transportation System (STS) Propellant Scavenging System Study," Rockwell International Space Transportation System Division STS 84-0570, Jan. 1985.

31. Louie, B., Kemp, N.J., and Daney, D.E., "Cryogenic Propellant Scavenging," National Bureau of Standards NBSIR-85/3023, Apr. 1985.

32. Fester, D.A., et al., "Tethered Orbital Refueling Study," Martin Marietta Denver Aerospace, Apr. 1986.

33. Liggett, M.W., et al., "Long Term Cryogenic Storage Facility Systems Study," General Dynamics Space Systems Division GDSS CRAD-88-003, Oct. 1988.

34. Liggett, M., et al., "COOLANT: The Cryogenic On-Orbit Liquid Analytical Tool Users Manual," Vol 1. Version 2.0, General Dynamics Space Systems Division GDSS-CRAD-88-005 Rev A., Oct. 1989.

35. DeFelice, D.M. and Aydelott J.C. "Thermodynamic and Subscale Modeling of Space-Based Orbit Transfer Vehicle Cryogenic Propellant Resupply," AIAA Paper 87-1764, June 1987 (NASA TM-89921).

36. Chato, D.J. "Thermodynamic Modeling of the No-Vent Fill Methodology for Transferring Cryogen in Low-Gravity, " AIAA Paper 88-3403, July 1988 (NASA TM-100932).

37. Moran, M.E., Nyland, T.W., and Papell, S.S., "Liquid Transfer Cryogenic Test Facility--Initial Hydrogen and Nitrogen No-Vent Fill Data," NASA TM-102572, Mar. 1990.

38. Chato, D.J., Moran, M.E., and Nyland T.W., "Initial Experimentation on the Nonvented Fill of a 0.14 m^3 (5 ft^3) Dewar With Nitrogen and Hydrogen," AIAA 90-1681 (NASA TM-103155), June 1990.

39. Moran, M.E., Nyland, T.W., and Driscoll, S.L., "Hydrogen No-Vent Fill Testing in a 34 Liter (1.2 Cubic Foot) Tank," 1991 Cryogenic Engineering Conference Preprint CD-2, June 1991.

40. Taylor, W.J. and Chato D.J., "Improved Thermodynamic Modelling of the No-Vent Fill Process and Correlation With Experimental Data," AIAA 91-1379 (NASA TM-104492), June 1991.

41. DeWitt R.L. and Boyle, R.J., "Thermal Performance of an Integrated Thermal Protection System for Long-Term Storage of Cryogenic Propellants In-Space," NASA TN D-8320, May 1977.

42. Chato, D.J. "Analysis of the Nonvented Fill of a 4.96 Cubic Meter Lightweight Liquid Hydrogen Tank," ASME Paper 89-HT-10, Aug. 1989 (NASA TM-102039).

43. Chato, D.J., "Ground Testing on the Nonvented Fill Method of Orbital Propellant Transfer: Results of Initial Test Series," AIAA 91-2326 (NASA TM-104444), June 1991.

44. Vaughan, D. and Schmidt, G., "Analytical Modelling of No-Vent Fill Process," AIAA 90-2377, July 1990.

45. Vaughan, D.A. and Schmidt, G.R., "Enhancement of the No-Vent Fill Process," AIAA 91-1842, June 1991.

46. Anderson, J.E., Czysz, P.M. and Fester, D.A., "No-Vent Fill Testing of Liquid Hydrogen," 1991 Cryogenic Engineering Conference Preprint AC-1, June 1991.

47. Bailey, W.J. et al., "Cryogenic On-Orbit Liquid Depot Storage, Acquisition and Transfer Satellite (COLD-SAT) Feasibility Studies," Martin Marietta Space Systems Co., NASA CR 185247, June 1990.

48. Schuster, J.R., Russ, E.J., and Wachter, J.P., "Cryogenic On-Orbit Liquid Depot Storage, and Transfer Satellite (COLD-SAT)" General Dynamics Space systems Division and Ford Aerospace Space Systems Division, NASA CR-185249, July 1990.

49. Rybak, S.C. et al, "Feasibility Study for a Cryogenic On-Orbit Liquid Depot-Storage,Acquisition and Transfer (COLD-SAT) Satellite," Ball Aerospace Systems Group, NASA CR-185248, Aug. 1990.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Cryogenic Transfer Options for Exploration Missions

5. FUNDING NUMBERS
WU-506-48-21

6. AUTHOR(S)
David J. Chato

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-6499

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-105197
AIAA-91-3541

11. SUPPLEMENTARY NOTES
Prepared for the Conference on Advanced Space Exploration Initiative Technologies cosponsored by AIAA, NASA, and OAI, Cleveland, Ohio, September 4-6, 1991. Responsible person, David J. Chato, (216) 433-2845.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 34

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

This paper reviews the literature of in-space cryogenic transfer to propose transportation system concepts to support the Space Exploration Initiative (SEI). Forty-nine references are listed and key findings are synopsized. An assessment of the current maturity of cryogenic transfer system technology is made. Although the settled transfer technique is the most mature technology, the No-Vent Fill process transfers are the most promising and No-Vent Fill technology is maturing rapidly. Future options for development of cryogenic transfer technology are also discussed.

14. SUBJECT TERMS
Cryogenic rocket propellants; Reduced gravity; Space exploration

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102