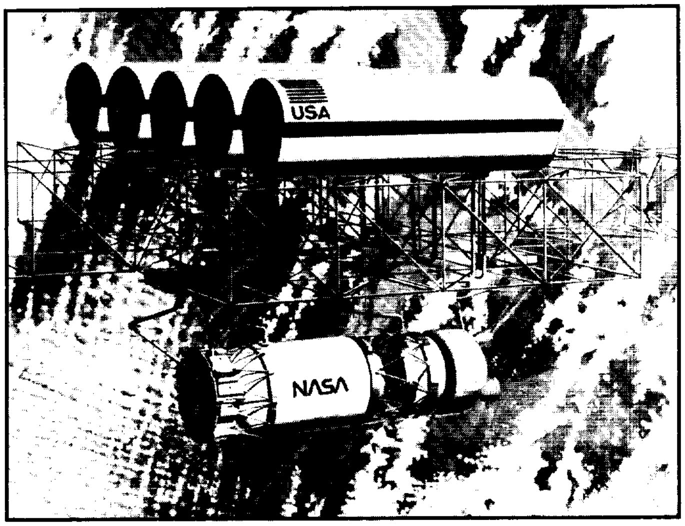
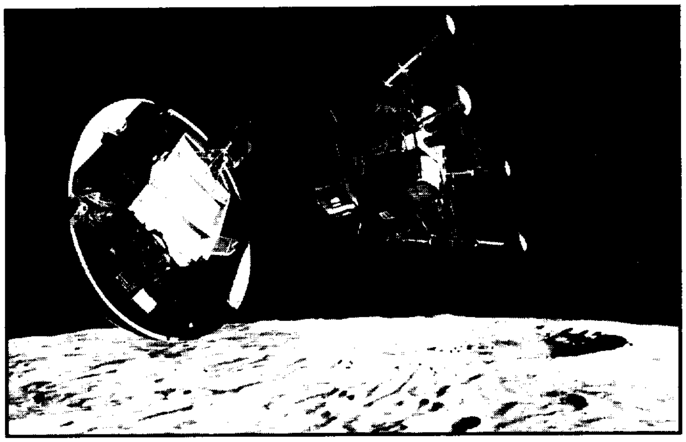
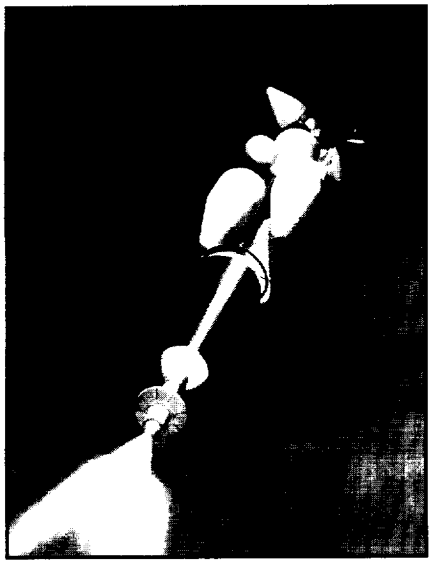
Large Scale Cryogenic Fluid Systems Testing

SPTD/CFSB







NASA Lewis Research Center's Cryogenic Fluid Systems Branch (CFSB) within the Space Propulsion Technology Division (SPTD) is developing the fluid management technology that will enable the United States to go forward with its plans for space exploration. The performance and cost advantages provided by cryogenic fluids like hydrogen and oxygen make them the optimum choice for space-mission propulsion systems. Cryogens are also likely to be used for energy storage on the moon and Mars to support manned habitats and surface exploration.

Using analytical modeling, ground-based testing, and on-orbit experimentation, the CFSB is studying three primary categories of fluid technology:

- Storage
- Supply
- Transfer

The CFSB is also investigating fluid handling, advanced instrumentation, and tank structures and materials.

The CFSB's objectives include:

- identifying the focused technologies required for the design of in-space cryogenic fluid systems
- assessing the state of readiness of the identified technologies
- determining the readiness goals required to implement the technologies
- performing necessary research and development activities to meet the readiness goals
- creating a design data base for incorporating the technology developments into a usable format for the design of actual cryogenic fluid systems.

Ground-based testing of large-scale systems is done using liquid hydrogen as a test fluid at the Cryogenic Propellant Tank Facility (K-Site) at Lewis' Plum Brook Station in Sandusky, Ohio. Ground testing permits the CFSB to provide operating procedures and partial model validation. However, final verification for most technologies must be made with on-orbit flight experiments.

The CFSB's ultimate goal is to enable the long-term storage and in-space fueling/resupply operations for spacecraft and reusable vehicles in support of space exploration.

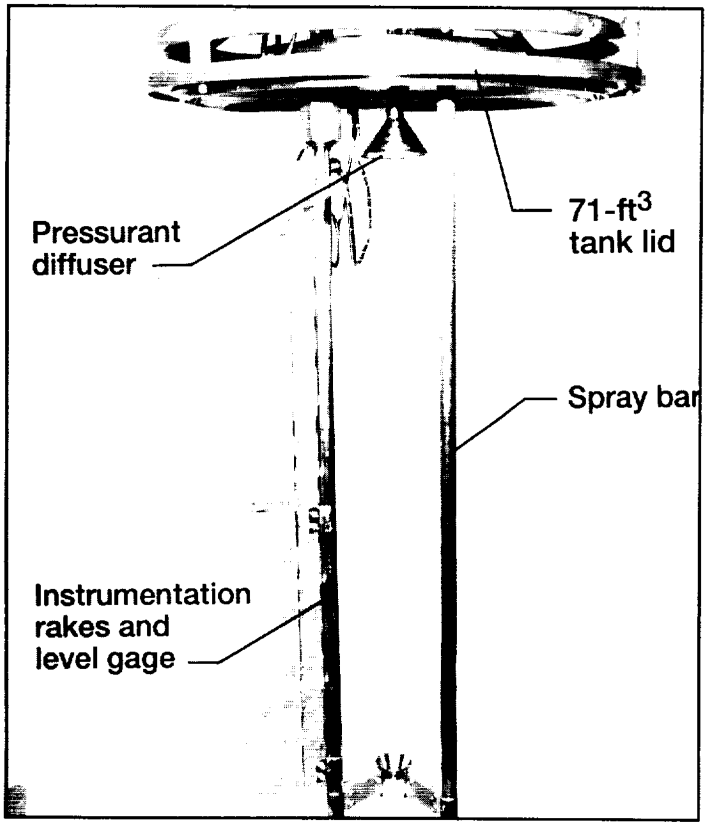
Liquid Transfer

On orbit transfer of cryogenic liquids is considered enabling to many future NASA missions, from space transfer vehicles to human exploration. The techniques required to transfer cryogens in low gravity are quite different from those used terrestrially. During a normal-gravity fill of a cryogenic storage tank, a top outlet is kept open to vent the vapor generated during the fill process, thereby maintaining a low tank pressure. However, if this technique is used on-orbit to relieve the vapor produced by the heat stored in the receiver tank wall, the uncertainty of liquid and vapor distributions in low gravity may result in the expelling of large amounts of liquid overboard. A unique process, the no-vent fill can be used in low-gravity to reduce fluid loss by keeping the tank vent closed during filling.

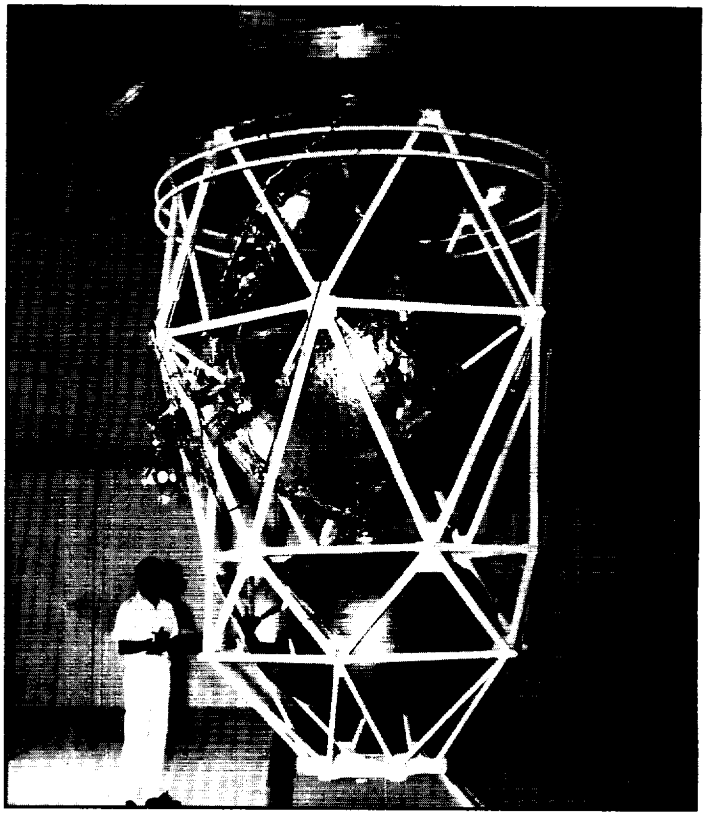
Though liquid transfer has never been accomplished in low-gravity, testing at NASA Lewis' K-Site has demonstrated the potential for the no-vent fill process to serve as an efficient solution to the low-gravity transfer problem. A no-vent fill is made possible by proper thermodynamic conditioning using an initial chilldown of the tank, with vapor-only venting. No-vent fill has only been attempted in isolated applications and experiments.

The ongoing investigation of the no-vent fill process tests various inlet spray systems, tank sizes and geometries, and inlet fluid and tank wall temperatures. Testing also examines the effects of scaling. Because of its large capacity, K-Site's vacuum chamber enables full scale testing for many applications.

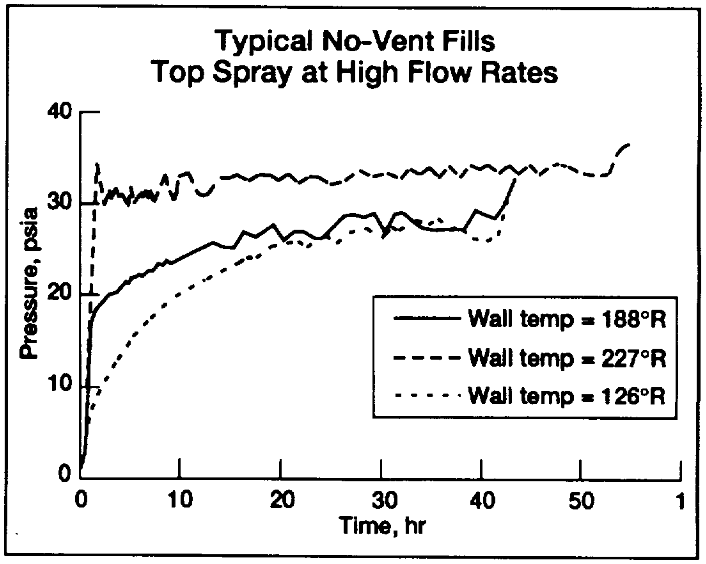
A typical no-vent fill test at K-Site uses a 175-ft^3 tank as the LH_2 supply tank and a 71-ft^3 tank as the receiver tank. Both tanks are surrounded by a 13-foot diameter cryoshroud contained in a 25-foot diameter spherical vacuum chamber. The 71-ft^3 tank has two injectors: a radial spray bar for coarse droplet spray throughout the tank; and an orifice plate located at the bottom of the tank to provide a submerged liquid jet. The orifice plate system is sized to produce a 750 lb/hr flow at a pressure drop of 5 psia. The tank's radial spray bar consists of a tube extending from the tank lid to the bottom. The tube is sealed on the bottom and the fluid exits



The lid for the 71-ft^3 tank shows the instrumentation rake, spray bar, and pressurant diffuser used in testing.



By connecting the 175-ft^3 and 71-ft^3 tanks, researchers were able to perform parametric transfer studies.



through a series of five holes drilled through the tube side walls. Flow capacity for the entire spray bar is equal to that of the orifice tube.

In a typical transfer test at K-Site, the 175-ft^3 tank is filled to greater than 85 percent. Subcooling of the liquid is controlled by using this tank to precondition liquid to bulk temperatures from 30 to 40 °R for the 71-ft^3 tank.

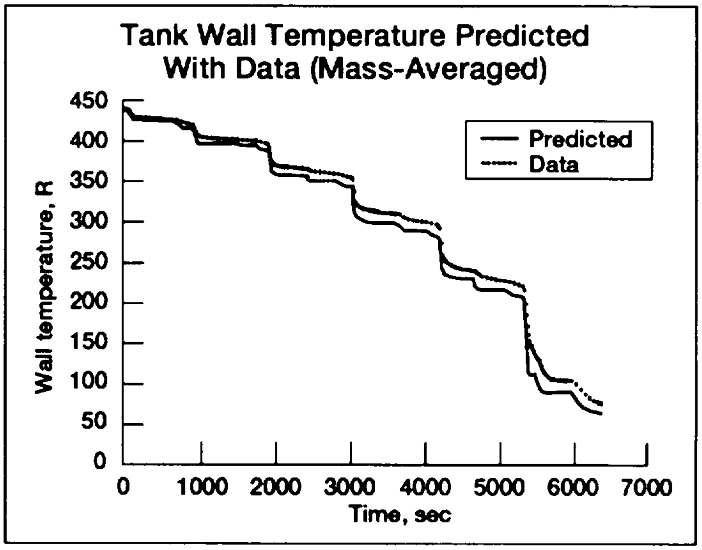
In the chilldown process, a spray system injects a calculated amount of liquid cryogen into the evacuated, warm 71-ft^3 receiver tank. The liquid initially flashes because of the tank's low pressure. The remaining liquid droplets evaporate as they contact warm hydrogen vapor or the tank wall. Convective heat transfer from the tank wall to cold vapor continues to provide cooling. As the heat transfer from vapor to the tank wall nears completion, the pressure within the tank increases, and the tank is vented. When the desired tank wall temperature is achieved through multiple tank tank cooling cycles the vent is closed and the no-vent fill can begin.

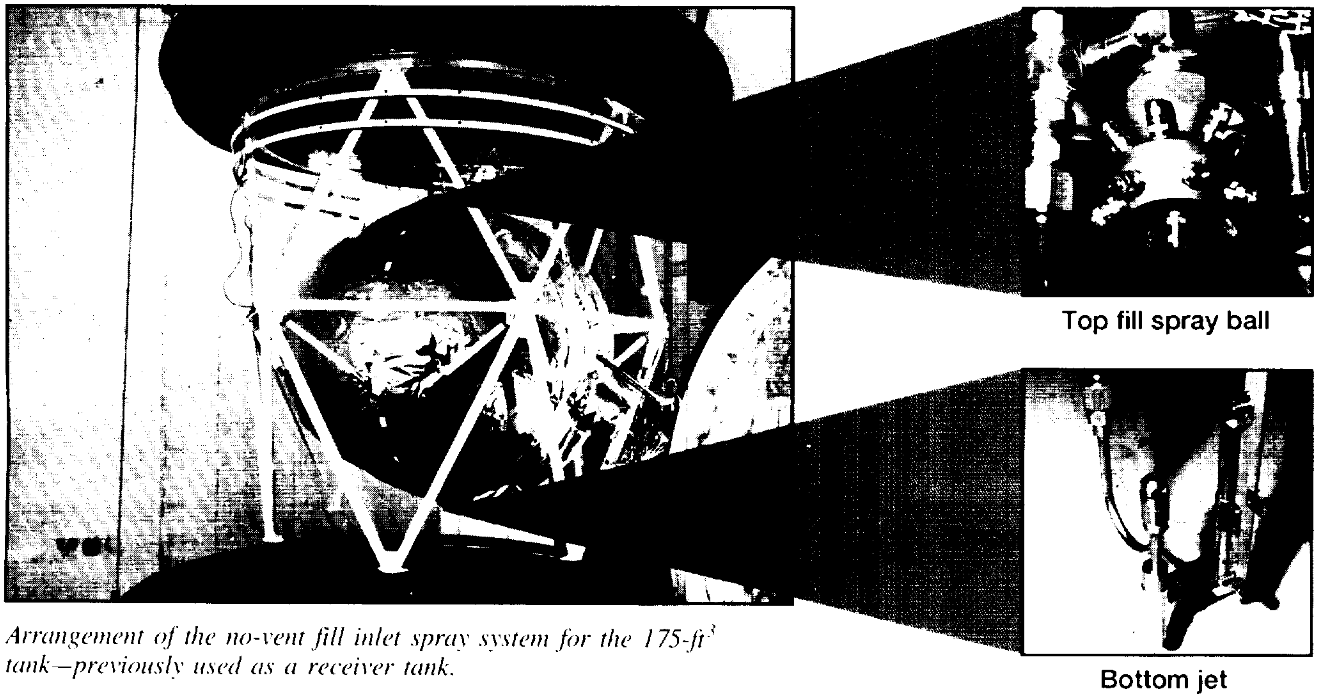
Liquid is injected by the selected spray system. Short, uninsulated lines transfer the liquid hydrogen from the supply tank to the receiving tank. Flow is stopped when the receiving tank is 95 percent full or tank pressures equalize.

The effect of several test parameters is illustrated by the comparison of pressure histories as a function of tank fill level for several test runs. Testing has found that higher liquid inlet and initial wall temperatures and lower inlet flow rates produce higher receiving tank pressures. Since the tank pressure is limited to a maximum value, the final fill level is limited by the tank pressure response.

Testing at K-Site provides the experimental data necessary for the development and validation of analytical models. The test data is being used to improve the NVFILL code, a documented code based on convective heat transfer, is an analytical model of the NVF process. The NVFILL model separates the fill process into two stages. The first stage, Liquid Flashing, is characterized by flashing and boiling and is modeled as an equilibrium energy balance between the hot tank wall and the incoming liquid flow. The second stage, Vapor Condensation and Compression, divides the tank into three nodes: gas, liquid, and interface. NVFILL then models the energy transport between them.

Low-gravity transfer of cryogenic fluids is vital to the successful operation of earth-to-orbit tanker vehicles, orbiting storage systems, space transportation vehicles, and other spacecraft. The design and test effort for 1g large-scale experimentation at K-Site provides the experience, database, and understanding necessary for a rational and astute design of flight experiments and hardware.


Tank Wall Temperature Predicted With Data (Mass-Averaged)


Top fill spray ball

Bottom jet

Arrangement of the no-vent fill inlet spray system for the 175-ft^3 tank—previously used as a receiver tank.

Thermal Control

During extended space missions, a cryogenic storage tank is exposed to a variety of extreme thermal environments. If not controlled, these environments can cause boil-off, which can result in significant losses of cryogenic fluids. The solution to this problem is lightweight, high-performance thermal-protection systems. While the system selected for future flights will be mission dependent, in most cases thermal protection will require some type of multilayer insulation (MLI).

A 25-ft diameter vacuum chamber at K-Site is begin used to study the influence of space and planetary environments on the performance of thermal-protection systems.

A typical MLI system consists of blankets made up of alternate layers of low-conductivity double silk spacing net and double-aluminized Mylar radiation shields between cover sheets of Dacron-scrim-reinforced Mylar. With MLI systems ranging anywhere from 50 to 200 layers, the MLI system can add significant weight to the cryogenic tank. However, this weight increase can be offset by the reduction of reserve fluid that would be needed to account for boil-off.

A review of the existing database for MLI technology shows that tank applied thermal performance data for thick MLI systems is not available at the external boundary temperatures these systems will encounter during various proposed missions. For example, lunar surface temperatures range between 180 and 630 °R. However, most of the experimental performance data available for MLI systems is concentrated around warm boundary temperatures of 530 °R at MLI thicknesses to 100 layers.

Thermal control testing at NASA Lewis' K-Site is producing the MLI performance data necessary to design cryogenic systems for future space flights. Insulated tanks up to 10 feet in diameter can be easily tested in K-Site's 25-ft-diameter, high-vacuum chamber. Larger scale tankage gives performance data more representative of in-space operational systems. A 13-foot by 13-foot, cylindrical cryoshroud lets researchers accurately simulate in-space and planetary thermal environments. The cryoshroud temperatures are maintained to within ± 2.0 °R of the desired set point by a closed-loop temperature control system. It is cooled by flowing liquid nitrogen or hydrogen through 1-in. diameter tubes welded to the outside surface. Resistance heaters bonded to the surface between the tubes heat the cryoshroud. To minimize the solid conduction heat input into the test tank, all plumbing and instrumentation lines entering or attached to the test tank pass through a liquid hydrogen cold guard supported off the shroud.

A typical thermal control experiment at K-Site investigates heat transfer of a liquid hydrogen tank for warm side boundary temperatures similar to the temperature variation of the lunar surface—630, 530, and 150 °R. For this test, an MLI system was designed for and installed on K-Site's 175-ft^3 tank. Nominal layer density of the insulation blankets was 45 layers/in. The insulation system contained penetrations for structural supports, plumbing and electrical wiring representative of a cryogenic spacecraft. During testing, the test tank was filled to approximately the 95 percent full level.

A simulation of the environment of a lunar-based cryogenic storage tank was established at K-Site. Lunar temperature data obtained from a surveyor spacecraft were simulated by controlling the cryoshroud's temperatures. A temperature profile of lunar sunrise, over an eight-day period, was maintained to 5 percent. Cryogenic boil off data was obtained from this transient condition to better understand the performance of the thermal protection system in such environments.

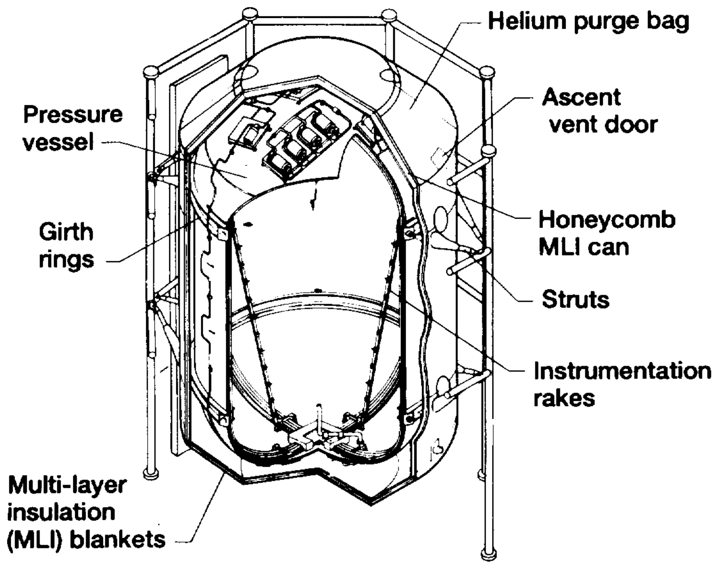
An MLI system is applied to the 175-ft^3 tank.

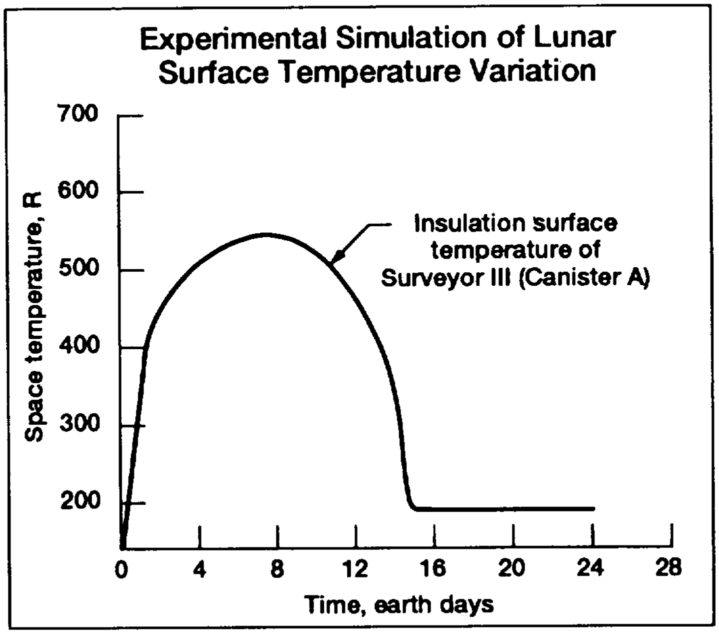
Measured with bonded strain-gage transducers, the tank and cold guard pressures were controlled, and the cold guard was held at a slightly higher pressure to prevent the boil-off flow from condensing in the vent line as it passed through the cold guard. All measurements were recorded by the NASA Lewis ESCORT-D microVAX computer system. For this test, the data was recorded once every 30 min.

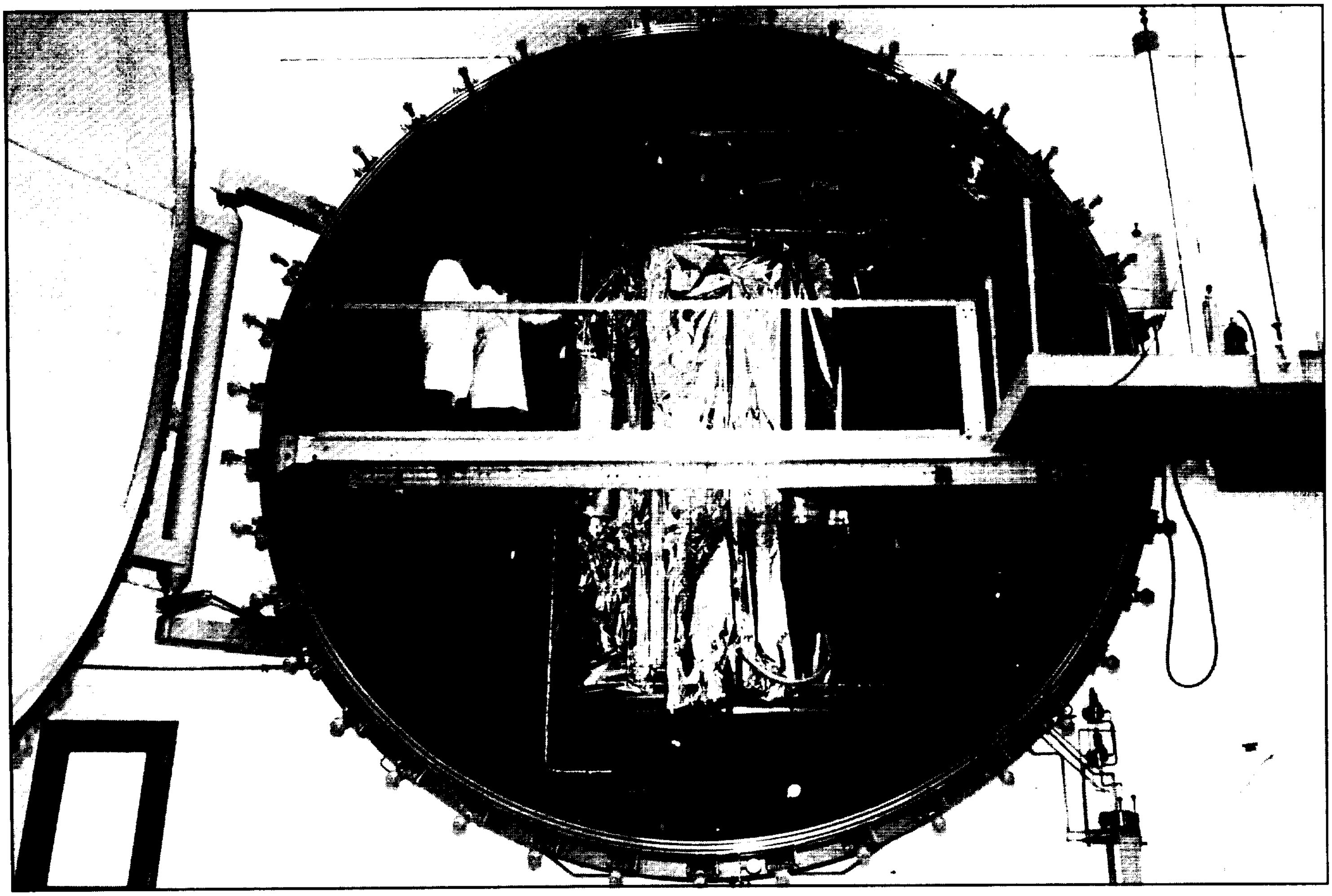
Thermocouples, platinum resistance temperature sensors (PRTS) and silicon diodes comprised the temperature transducers on this test configuration. All thermocouples on or within the insulation and on the 12 fiberglass struts were 10-mil diameter Chromel-Constantan. The evaporation rate from the test tank was metered by one of a series of four volume flowmeters.

K-Site's unique chamber will enable the development of the data base for MLI systems that will support future NASA missions. Without such a data base, space exploration would be limited.

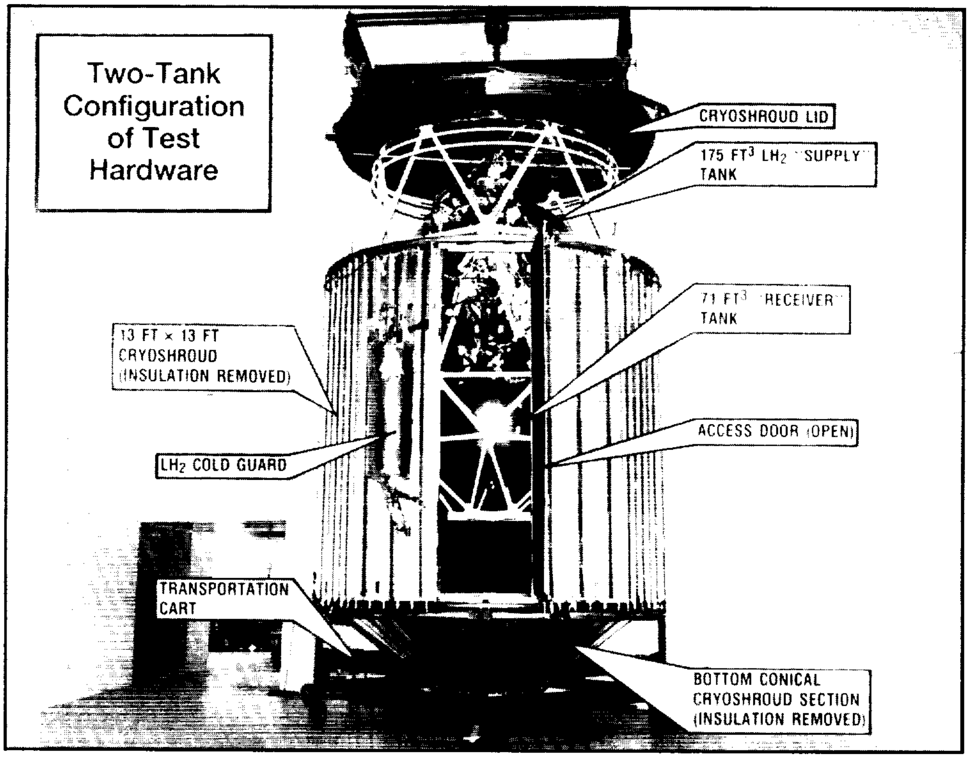
Typical Space Cryogenic Supply Tank




Experimental Simulation of Lunar Surface Temperature Variation



Once the test tank is placed in the 13-foot by 13-foot cryoshroud, the entire test rig is moved into the 25-ft vacuum chamber.



Two-Tank Configuration of Test Hardware

Test Chamber

Vacuum (bare)	5×10^{-7} torr
Vacuum (w/LH_2 cryoshroud)	5×10^{-8} torr
LH_2/LN_2 cryoshroud	−423 °F/−320 °F
Cryoshroud LH_2 flow	100 gal/hr
Chamber inside dimns.	25 ft sphere
Max. test specimen env.	13 ft cube
Side entrance opening	20 ft diam

Facility Propellant Capabilities

LH_2	26,000 gal
LN_2	15,000 gal
GH_2	300,000 SCF
GN_2	385,000 SCF
Ghe	245,000 SCF

Test Package Limits

Maximum loaded weight	16,000 lb
Maximum propellant-LH_2	10,000 gal

K-SITE

NASA Lewis' Cryogenic Propellant Tank Facility (K-Site) at Plum Brook Station in Sandusky, Ohio, is uniquely suited for large-scale testing of the storage, supply and transfer of cryogenic fluids.

K-Site features a 25-ft diameter, spherical stainless steel vacuum chamber with an internal volume of 9,500 cubic feet. The bare chamber can be evacuated to 5×10^{-7} torr. Access to the chamber is through a 20-ft diameter side opening door which is latched, unlatched, opened and closed by remote operation of hydraulic power cylinders. A 36-in. manhole opening is located at the top center of the chamber. There are two 6-in. diameter view ports for TV cameras or visual observation.

Test rigs, like the two-tank configuration pictured on the previous page, are placed in a 13-ft diameter by 13-ft high cryoshroud. The shroud uses liquid nitrogen (−320 °F) or liquid hydrogen (−423 °F) to simulate the thermal environments of deep space. The vacuum-chamber building has a roll-up access door that is 29 ft wide by 39 ft high. The facility has a totally enclosed clean-room, an attached work shop, and an overhead rail system with a 5-ton crane to handle test rigs.

K-Site has signal conditioning available for a variety of sensors with unlimited expansion capabilities. The numbers and type of sensors can be changed with each new research package. Data acquisition is accomplished by the ESCORT D, a microVAX located in the Control Building. The ESCORT D can monitor 512 channels of instrumentation. It performs all real time functions. The microVax is networked to a VAX cluster at Lewis. Data is transmitted to the cluster and then stored for post-run data processing.

The test chamber's size coupled with its ability to handle a variety of cryogenic fluids, including liquid hydrogen and liquid nitrogen, make K-Site an ideal research facility. While similar test facilities can boast certain features, K-Site has the entire package: size, vacuum, temperature control, hydrogen handling capability . . . and proven results.

Pressure Control

Thermal stratification and the resulting pressure rise in space-based cryogenic liquid tanks occurs because of the heat transfer through tank walls, volumetric heating within the stored liquid, and both mass and heat transfer between the liquid surface and the ullage. If left unchecked, thermal stratification can result in a continuous tank pressure rise, which can damage the tank and cause the loss of cryogenic fluids.

Pressure control studies are aimed at reliably predicting the self-pressurization rate caused by thermal stratification, and at more fully understanding the performance of pressure control techniques. Testing in K-Site's 25-ft diameter vacuum chamber focuses on jet-induced mixing, interface condensation, and thermal stratification/self-pressurization. A 175-ft^3 tank is used for pressure control testing, with LH_2 as the working fluid. The test tank is supported by 12 fiberglass composite struts within a 13-ft diameter cylindrical cryoshroud.

To control the pressure of space-based cryogenic storage and supply tanks, either an active, passive or hybrid thermodynamic vent system (TVS) is needed.

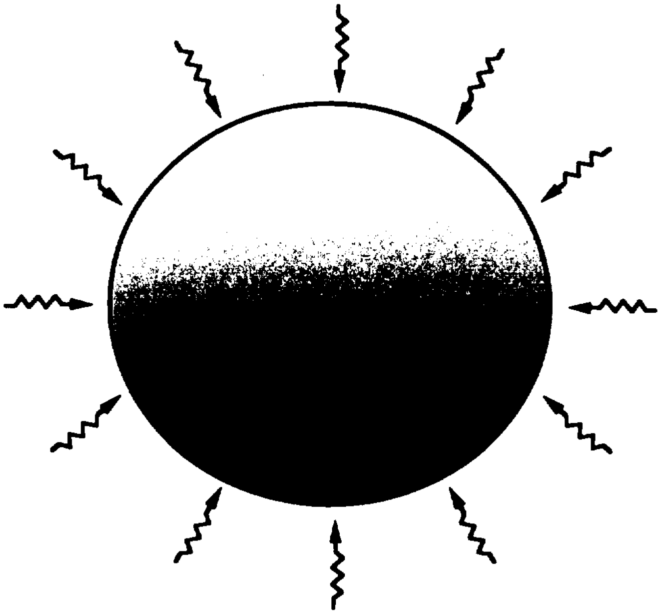
The TVS approach involves removing a small quantity of liquid from the liquid acquisition device of the storage tank. The liquid flows through a Joule-Thomson (J-T) device to a low-pressure vent. The fluid at the J-T device outlet is a low-pressure, low-temperature, two-phase mixture.

For a passive TVS, the mixture flows through heat exchangers inside the storage tank to a vent, thus providing direct cooling of the liquid cryogen in the storage tank. For an active TVS, the mixture flows through a compact, counterflow heat exchanger to a vent. Storage tank liquid is drawn through the heat exchanger by a mixer or pump and the slightly subcooled liquid is injected back into the tank—providing almost uniform cooling of the storage tank liquid.

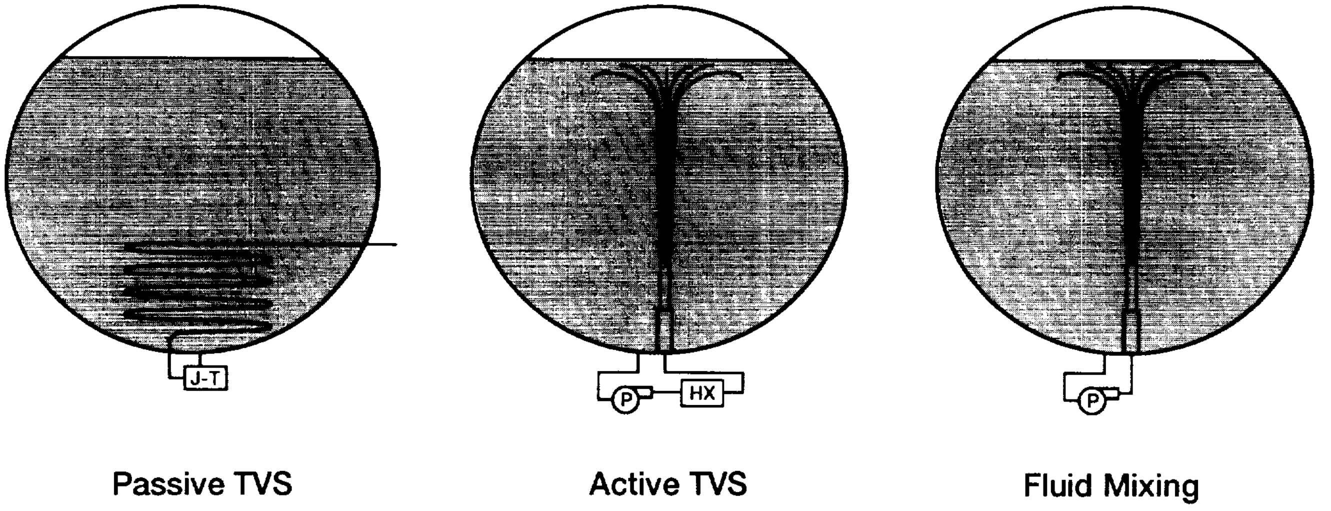
For both systems, the storage tank pressure is controlled by reducing the temperature of the liquid within the tank.

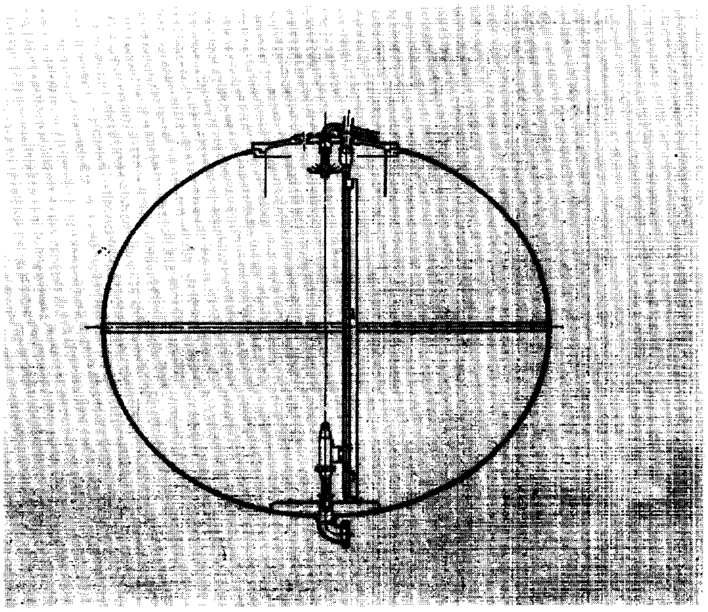
Fluid mixing can be used to destroy temperature stratification by circulating and mixing the tank fluid. Mixing induces interfacial condensation, which reduces tank pressure. Ideally, if a tank is well mixed, the fluid temperature is uniform and the homogeneous thermodynamic model, which assumes uniform temperature throughout the tank, can be used for predicting pressure change rate. However, since mixer power is required to circulate the tank fluid, a certain amount of energy is added to the system. This additional energy eventually becomes heat and increases the net fluid energy. Thus, fluid mixing only temporarily reduces tank pressure and, therefore, is of interest only for short-term storage.

The thermal stratification/self-pressurization testing at K-Site establishes the initial conditions for the jet-induced mixing test. Experiments are typically performed at 85 and 55 percent fill levels with the tank initially at a homogeneous state of 16 psia pressure. Testing ends when the tank pressure is increased by at least 8 psia.

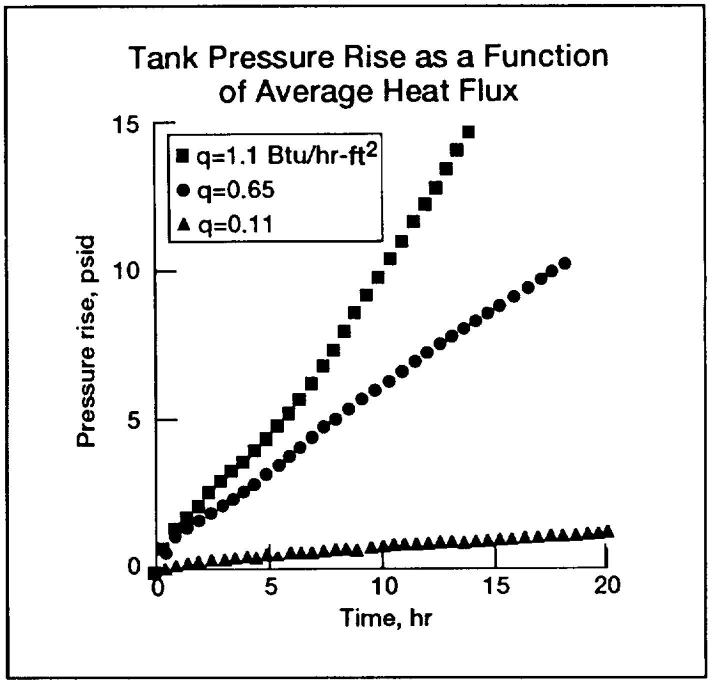


Thermal Stratification/ Self Pressurization





Jet-Induced Mixing



Tank Pressure Rise as a Function of Average Heat Flux

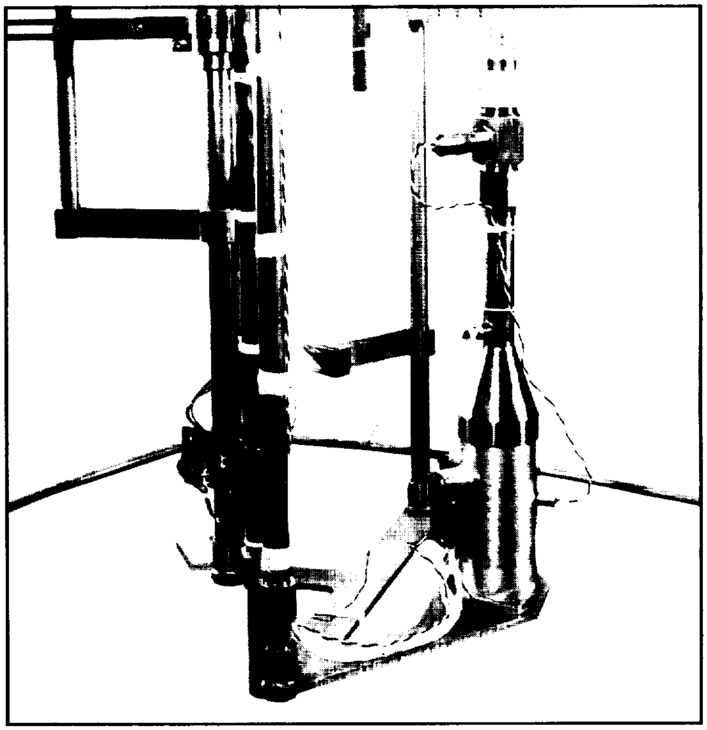
The tank pressure rise during the entire experiment is caused by both the wall heat flux into the vapor region and the mass and heat transfer processes at the interface.

Jet-induced mixing tests measure depressurization and mixing time as functions of jet flow rate and jet submergence below the interface. The range of jet flow rate is selected so that the effect of gravity on the mixing process can be investigated. The jet-induced mixing test starts immediately after each thermal stratification/self-pressurization test. The mixer is turned on at a power corresponding to the specified jet flow rate to destroy the temperature stratification and reduce the tank pressure. The jet flow rate range is selected to avoid surface breakup or significant disturbance.

Interface condensation testing measures the condensation rate of hydrogen vapor on the turbulent interface of a subcooled-liquid being mixed in a tank as a function of jet flow rate and jet subcooling. The tank is pressurized to a specified pressure increment so that the liquid is in a subcooled condition. Then the mixer is turned on at a power corresponding to the selected jet mass flow rate to generate the fluid circulation inducing vapor condensation at the interface. The tank pressure is maintained constant during the experiment by the pressurization control system and the mass of vapor condensed can be estimated by measuring the pressurant flow rate and inlet temperature and pressure.

Experimental data is analyzed for the development of simplified equations to predict the tank self-pressurization rate (due to wall heat-flux), the depressurization rate (due to jet-induced mixing), the required mixing time, and interface condensation rate.

Measurements from the normal-g experiments provide an understanding of fluid behavior in some aspects, the necessary information for design of flight experiments, and the validation of 1g analytical models which may be extended to low-g applications.



By adding a mixer to the test tank to circulate and mix the tank's fluid, thermal stratification is destroyed.

Pressurization

In the low-gravity environment of space, tank pressurization is needed to expel fluids from a supply tank to a user system. Pressurant usage in low-g is dependent on the diffusion and/or condensation of the gas, the location of the diffuser relative to the ullage, and the expulsion rate of the outflowing liquid.

Testing at K-Site is focused on developing an efficient and reliable method of tank pressurization, which is needed for liquid transfer from a long-term cryogenic storage facility in space.

An over-designed pressurant injection system will increase the pressurization system weight and its associated launch cost. An under-designed system may cause a mission failure. Thus the ability to accurately predict the pressurant requirements over a range of operating conditions plays an important role in system design. The pressurant requirement determination is made more difficult in missions where the pressurization takes place under low-gravity conditions where the liquid may not be in a settled state to the side opposite the pressurant injectors.

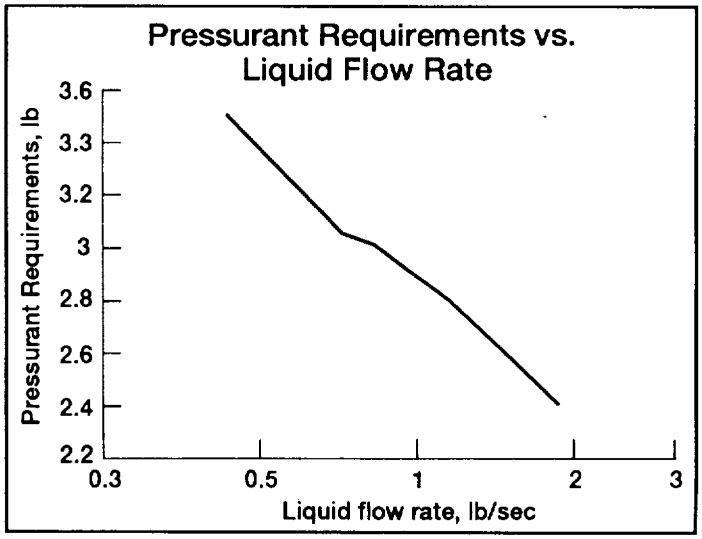
Past pressurization experiments performed in 1g environments were on propulsion-type systems with liquid expulsion rates considerably higher than those proposed for future space systems. Additional data is needed to verify the effects of any increase in heat and/or mass transfer that would occur for lower expulsion rates as a result of longer gas residence time. Pressurization testing studies the effects of these parameters.

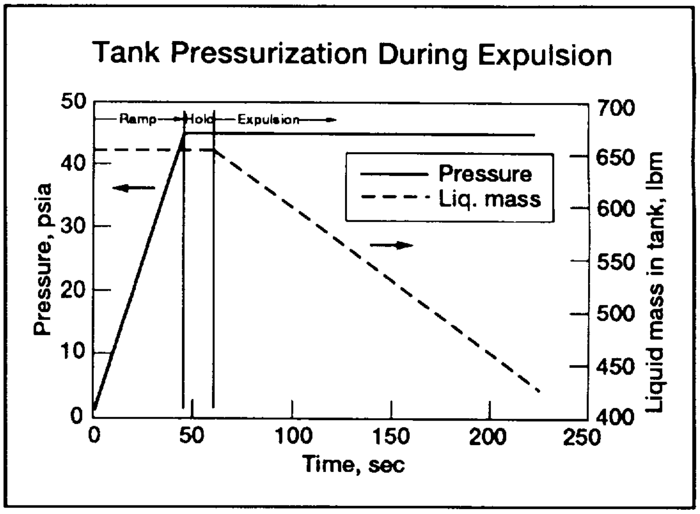
The ongoing investigation of pressurization tests low-expulsion rates, longer-duration hold times prior to expulsion, and the location of the diffuser relative to the ullage. Testing at K-Site, with its large vacuum chamber, allows these conditions to be examined in cryogenic tanks whose size correlates with actual on-orbit applications.

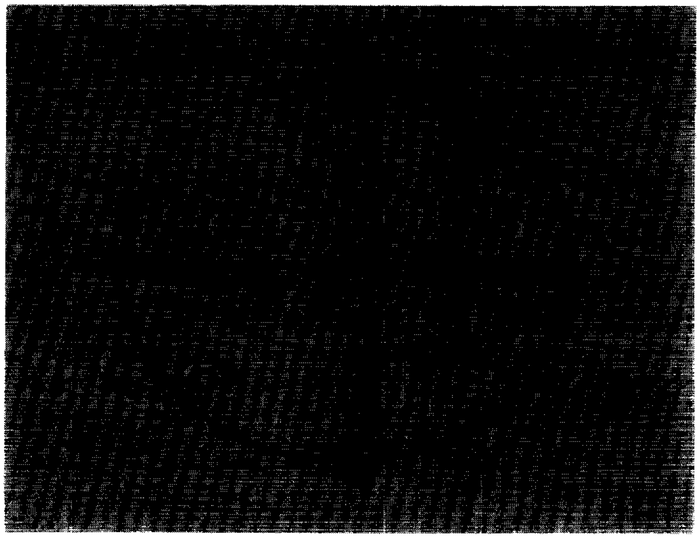
Pressurization testing at K-Site is conducted by using a 175-ft^3 tank as the pressurized supply vessel and either the 71-ft^3 tank as the receiver, or a large dewar located outside the chamber. Both autogenous (hydrogen) and helium pressurization schemes at various injection parameters (temperature, pressure, and flowrate) can be conducted at K-Site.

During typical testing, the supply 175-ft^3 tank is ramped up to the desired transfer pressure level. The pressurization rate is controlled by a ramp generator valve. The pressurant enters the tank through a cone type diffuser. The diffuser's design minimizes the gas impingement on the liquid surface. After a given hold period, the liquid outflow valve is opened and the liquid is transferred at constant tank pressure to the receiver tank. Flow terminates when either the desired fill level is obtained in the receiver tank or the transfer head becomes zero. The fill level in the supply tank just prior to transfer must be at the 85 ±2 percent position. This is to ensure that the liquid interface is located on an interface temperature rake.

Correlation of 1g experimental results with predicted analytical values partially establishes the pressurization data base necessary for the design of space-based cryogenic fuel systems.





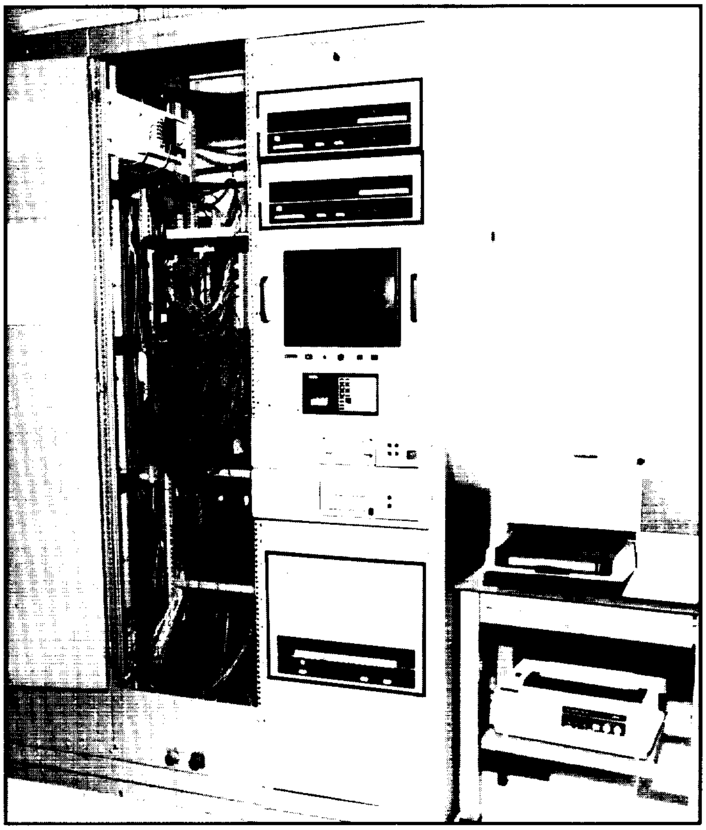


Pressurant Diffuser Assembly

Data Acquisition

A NASA Lewis Research Center-designed data acquisition system, the ESCORT D, is used at K-Site. The ESCORT D can monitor 512 channels of instrumentation. The ESCORT D configuration consists of a facility-located microVAX that performs all real time functions including: acquisition, display functions, recording, transmission, engineering unit conversions, and calculations. The ESCORT D microVax in K-Site's Control Building is networked to a VAX Cluster in the Research Analysis Center at Lewis, 50 miles away. Data is transmitted to the cluster and then stored on the cluster for post-run data processing.

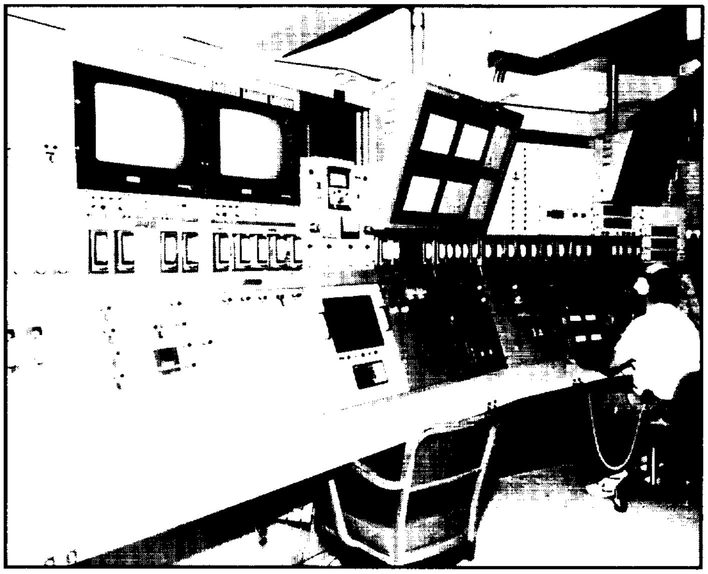
The ESCORT D system supports 6 CRT's, 3 graphic and 3 alphanumeric, for real-time monitoring of data. Data can be displayed in millivolts, engineering units, or counts. A laser printer is available for hard copies of the data. In addition to the 6 CRTs, the system has 8 individual digital displays that can also be used for displaying alphanumeric data. The data system supports RS-232-C and IEEE488 interfaces. The data system also has capabilities for digital to analog contacts, TTL contacts, and the limit contacts that can be used for alarms.

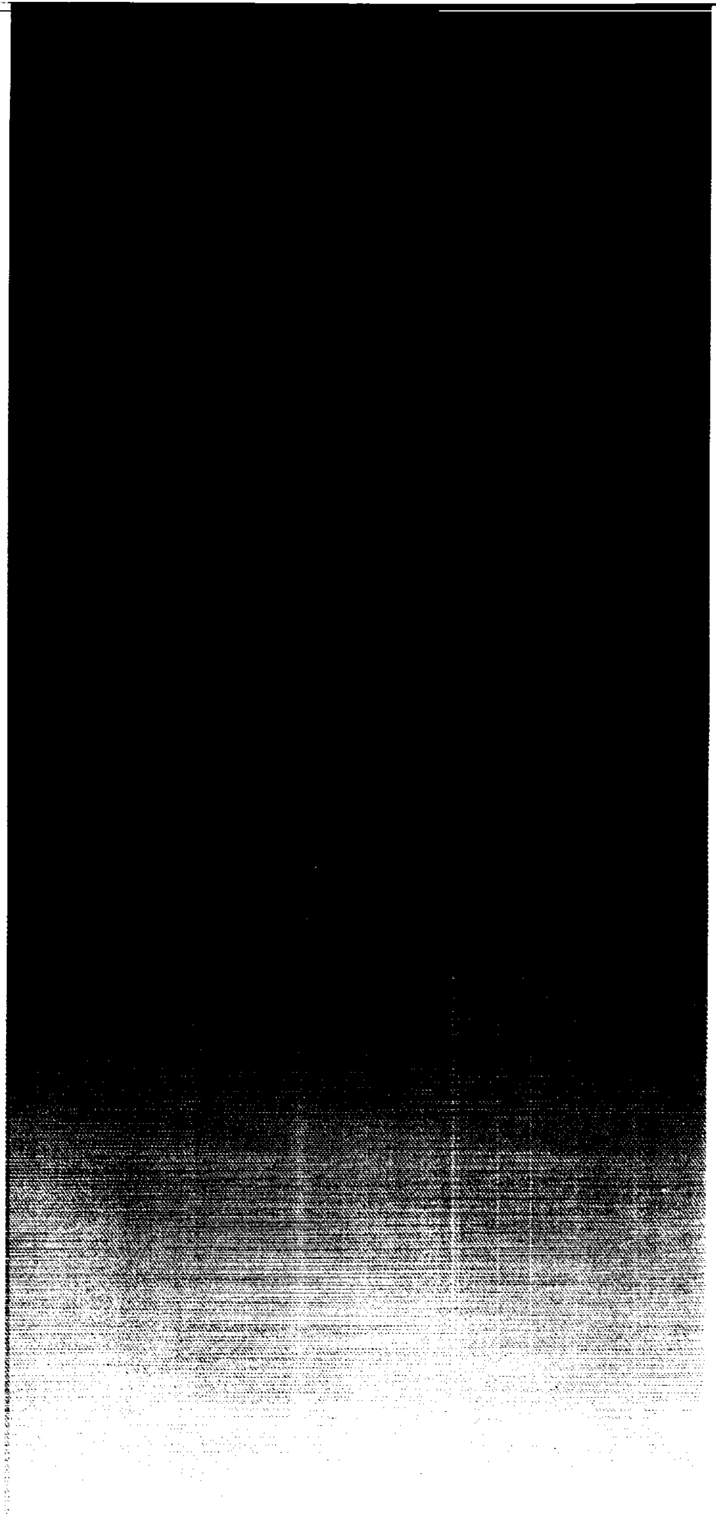


Instrumentation

K-Site has signal conditioning available for a variety of sensors with unlimited expansion capabilities. Temperature sensors used are thermocouples, RTDs, and silicon diodes from cryogenic temperatures to 170 °F. Strain gage and capacitance pressure transducers are also used to measure a wide range of pressures. Capacitance probes and silicon diodes are used to measure liquid level. Flow is measured using both turbine flowmeters and mass flowmeters. Complete vacuum instrumentation is available from 10^{-11} to 10^{-3} torr. A mass spectrometer and oxygen analyzer is also available for facility measurements. The numbers and type of sensors can be changed with each new research hardware configuration.

- 200 channels for thermocouples
- channels for platinum resistance temperature sensors
- 50 channels for strain gauge type transducers
- 50 channels for silicon diode temperature sensors
- 20 channels for transducers which provides operations information
- 2 channels of closed circuit television
- 4 channels for turbine type flowmeters
- 300-channel scanner system (data logger for system setup)
- Complete vacuum instrumentation for coverage to 10^{11} torr plus redundancy





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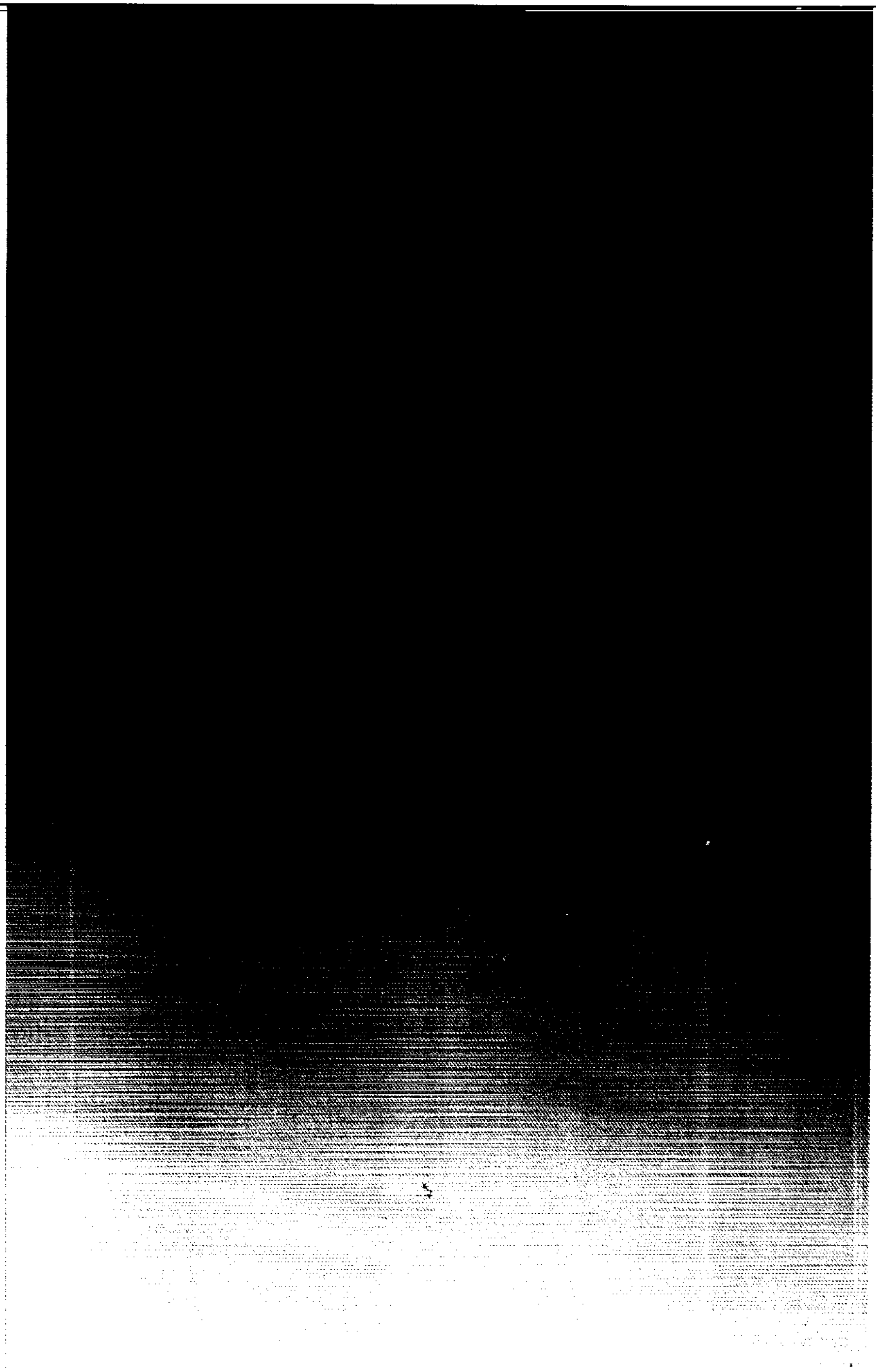

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