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A REVIEW OF CRYOGENIC TECHNOLOGY ASPECTS OF SPACE FLIGHT

By

Charles C. Wood and H. G. Paul
Propulsion Division
Propulsion and Vehicle Engineering Laboratory
NASA/George C. Marshall Space Flight Center
Huntsville, Alabama

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INTRODUCTION

The propulsion systems of rockets using liquid oxygen and, more recently, the stages of Centaur and the Saturn moon rocket burning liquid oxygen and hydrogen have drastically increased the consumption of these cryogens. Their high propulsive efficiencies have caused these exotic liquids to be abundantly produced on an industrial scale. Development of the V-2 Rocket during World War II increased liquid oxygen production approximately tenfold. Figure 1 shows a greater jump in liquid hydrogen usage during the 1950's when liquid hydrogen rocket engine development started. Cryogen usage in rocket propulsion created many new techniques and deeply stimulated many fields of cryogenic technology.

Cryogenic technology of rocket engine and stage development is broad. The principal systems and subsystems related to cryogen usage in rocketry are illustrated in Figure 2. This paper emphasizes cryogenic technology in stage development. The impact of cryogens on stage configuration is simply illustrated in Figure 3.

PROPELLANT FEED SYSTEM

Cryo-propellants of proper quality must be fed to rocket engines for adequate performance. For that purpose propellant circulation systems and local subcooling techniques provide tightly controlled

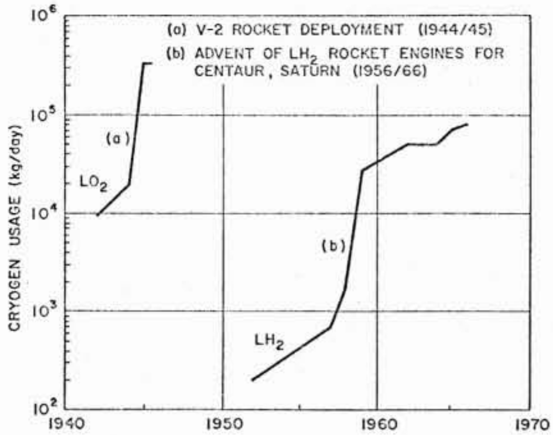


Fig. 1 History of Cryo-Propellant Usage (LO_2, LH_2)

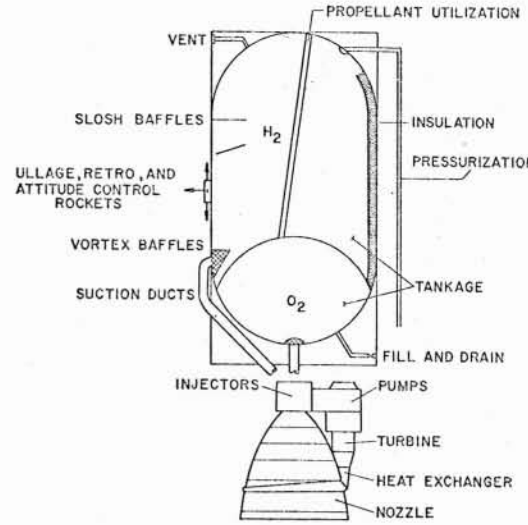
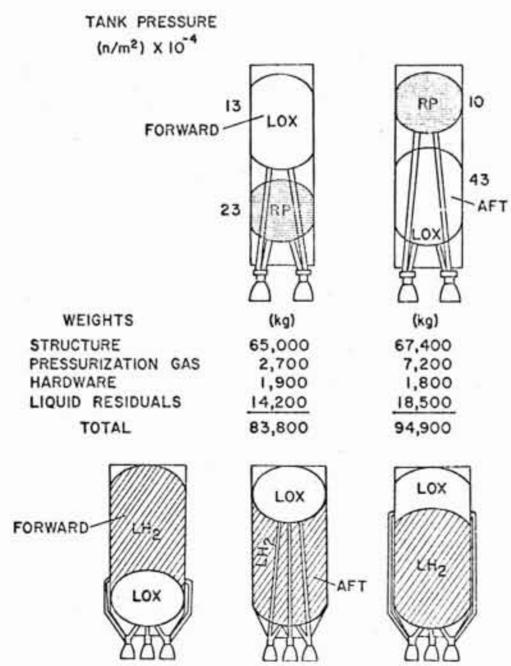


Fig. 2 Principal Rocket Systems Affected by Cryogens



WEIGHTS	(kg)	(kg)
STRUCTURE	65,000	67,400
PRESSURIZATION GAS	2,700	7,200
HARDWARE	1,900	1,800
LIQUID RESIDUALS	14,200	18,500
TOTAL	83,800	94,900

Fig. 3 Impact of Cryogenic Propellants on Stage Configuration

propellant inlet temperatures during the rocket engine start transient. Tank pressurization provides steady state pump inlet pressures for offsetting pressure losses, propellant temperature rise, etc. Cryogenic aspects of terminal drainage of temperature-stratified propellants, internal tank thermodynamics of pressurants, and localized propellant chill are reviewed as related to space technology.

Cryo-Propellant Stratification

Heat flux across a propellant tank wall establishes boundary layer flow along the internal wall; heated fluid collects near the liquid surface and an axial temperature profile develops (Figure 4). Stratified propellants increase tank venting and also stage weight by creating "unuseable residuals". Accurate prediction of propellant stratification is important, though complex, since boundary layer flow can be laminar, turbulent, or boiling. Gravitational effects and tank geometry also must be considered. A widely used semi-empirical method is based on classical boundary layer flow depositing fluid into various temperature strata through which estimated temperature profiles are faired (Reference 1). The method is adequate for gravity fields greater than one g (Figure 5), but is relatively untested for low gravity. A more recent stratification analysis uses a matrix-model solution of the Navier-Stokes equations (Reference 2). Predicted temperature and velocity fields are shown in Figure 6; analytical solutions are limited to laminar boundary layers. References 3 and 4 report other research.

Cryo-Propellant Pressurization Thermodynamics

Controlled tank pressurant flows are mandatory for weight, system design, and reliability considerations. Pressurant flows mainly depend upon tank pressure level, pressurant inlet temperature, heat input, and internal heat and mass transfer. Pressurant flows can be dependably predicted. A widely used method applies parameters shown in Figure 7 and digital computers (Reference 5). Needed empirical coefficients were determined with test data derived from configurations shown in

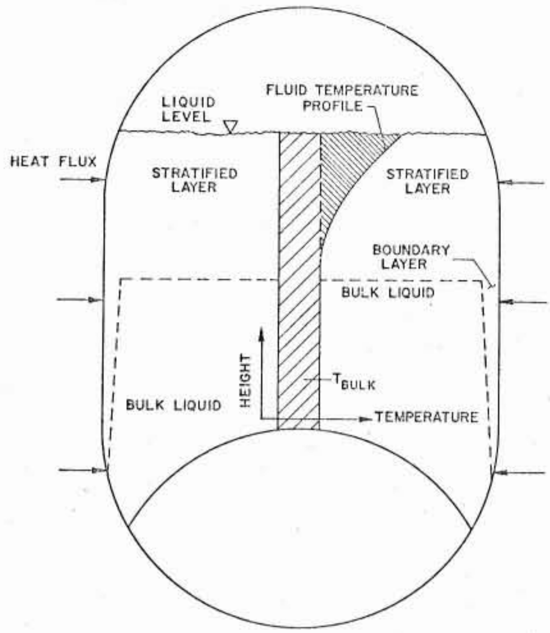


Fig. 4 Fluid Stratification Illustration

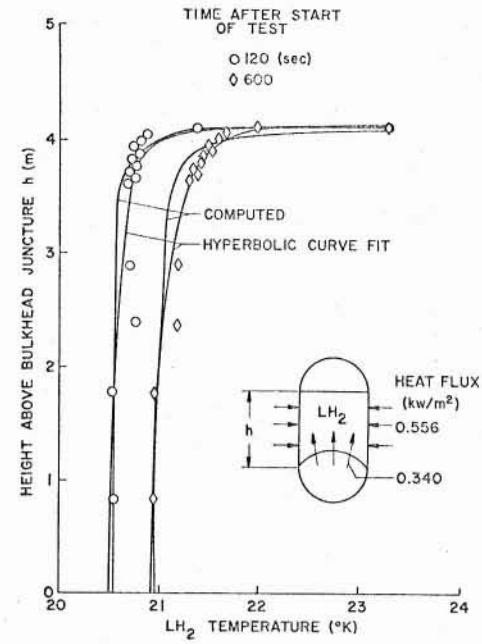


Fig. 5 Measured Temperature and Computed LH_2 Stratification Temperature Utilizing Empirical and Curve Fit Methods

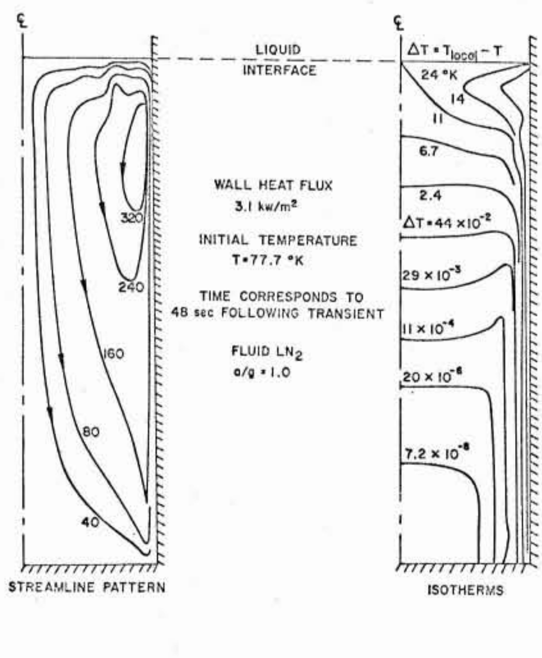


Fig. 6 Two-Dimensional, Transient Laminar Streamline Pattern and Isotherms in a Partially Filled Liquid Container

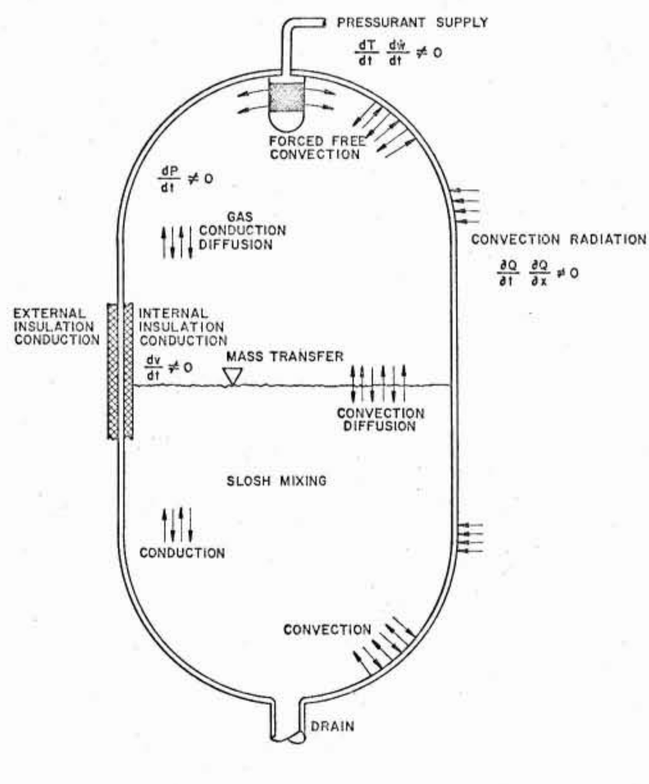
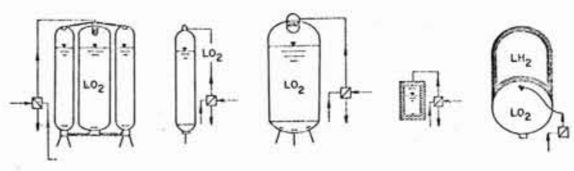


Fig. 7 Schematic of Heat and Mass Transfer Conditions in a Propellant Tank

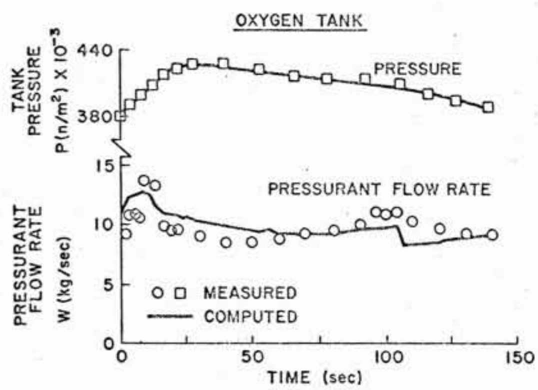
Figure 8 (Reference 6). Measured and predicted pressurant flow rate and tank pressure compared in Figure 9 agree within approximately 10 percent. Earlier studies are reported in Reference 7 and 8. The various prediction methods are compared in Reference 6.



PARAMETER	A	B	C	D	E
INITIAL ULLAGE VOLUME (%)	2 - 30	5-30	3-7	5	4.5
PRESSURANT	O_2	O_2, He	O_2, He	GN_2	He
TANK PRESSURE $(n/m^2) \times 10^{-3}$	415	101-415	138-276	101-415	318
TIME OF DISCHARGE (sec)	150	150	150-300	150-400	478
PRESSURANT TEMPERATURE (°K)	444	205-444	255-533	283	222-147
TOTAL VOLUME (m^3)	257	39	88	0.07	43
DIAMETER (m)	1 AT 2.67 4 AT 1.78	1.98	3.96	0.31	6.61
L/D (APPROX.)	7	6	2	3	0.45

Fig. 8 Tank Configurations and Test Parameters

Fig. 9 Measured and Computed Oxygen Pressurant Flow Rate and Tank Pressure Over Operating Time



Cryo-Propellant Conditioning

Propellant temperature differences between the bulk, feed duct, and rocket engine pump inlet must be minimized to eliminate fluid geysering hazards and engine start failure. Design principles, thermally insulated components, cryogen circulation systems, and localized subcooling techniques provide the required cryo-propellant temperatures. The data correlation of Figure 10 (Reference 9) permits the selection of geyser-free systems. Often, however, imposed constraints necessitate other design solutions, preferably, free of potential failure. A natural recirculation system satisfies this requirement; its performance can be accurately predicted (Figure 11, Reference 10).

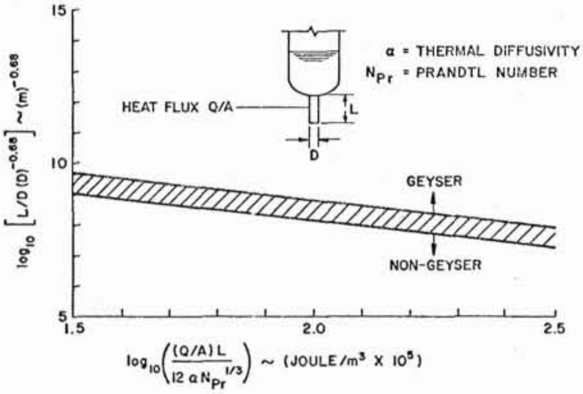
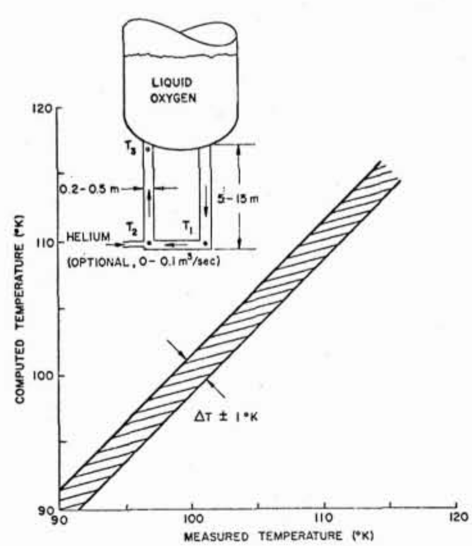


Fig. 10 Fluid Geyser-Non-Geyser Correlation

Fig. 11 Measured and Computed Fluid Temperatures for Liquid Oxygen Circulation System



Frequently, cryo-propellant temperatures are controlled by injecting a non-condensing gas into the propellant at the desired location. The degree of cryogen subcooling depends on injection gas, temperature, rate, and duration. Methods for predicting subcooling of liquid oxygen and hydrogen and related test data are published in Reference 11 through 13. Predicted and measured cryogen cooling are compared in Figure 12.

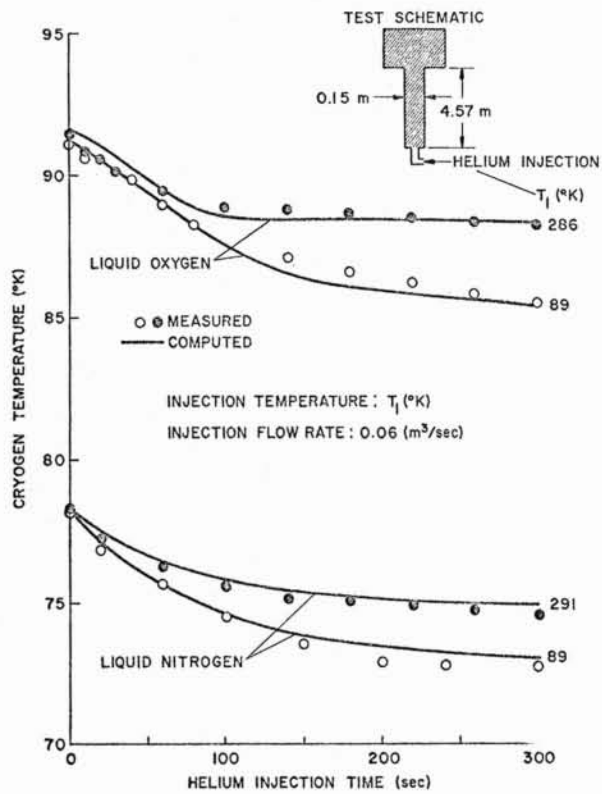


Fig. 12 Measured and Computed Liquid Oxygen and Nitrogen Subcooling Through Helium Injection

CRYO-PROPELLANT STORAGE

Present space flight operations require cryogen storage durations of a few hours, but future flight operations will require cryogen storage durations of one year or more. Long duration cryogen storage requires advanced insulation and technologies such as zero leakage fluid components, liquid separation and trapping devices, stratification destructors and possibly vapor reliquefiers, and controlled propellant state (slush or subcooled). Insulations for both short and long missions and fluid leakage are discussed.

Insulation - Short Term Storage

Figure 13 tabulates thermal insulation used on the hydrogen tanks of some space vehicles and largely summarizes present insulation technology. References 14 through 17 report most insulation research.

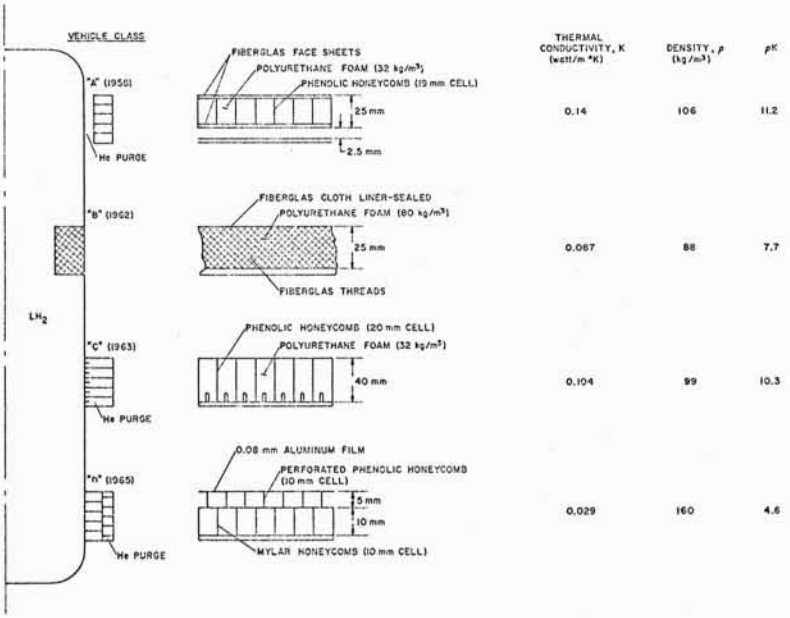


Fig. 13 Summary of Various Space Vehicle Hydrogen Tank Insulations for Short Duration Storage

Case A insulation is jettisoned at altitude and is more efficient than implied; jettisoning, however, is complicated. Hydrogen and helium (pressurant gas) permeate internally located insulation (Case B) and deteriorate insulation and stage performance. External insulation (Case C) requires a helium purge for eliminating cryo-pumping hazards. Residual helium also deteriorates insulation and stage performance. The external insulation (Case D) consists of isolated cells. Unlike other insulations, rupture or helium penetration of these cells deteriorates insulation performance only in the affected area. This concept has been tested (Reference 16) but needs further development.

Insulation reliability and trouble-free operation during ground checkouts, captive firings, and prelaunch are important and require conservative designs. Furthermore, to achieve success a high degree of quality control must be applied during manufacturing and installation on a cryogenic tank.

Insulation - Long Term Storage

A development objective is to limit loss of liquid hydrogen for large containers of approximately 250,000 pounds capacity to 5 percent per year; thus, thermal insulation performance of present-day stages must be improved by several orders of magnitude for long duration space missions.

Evacuated lightweight multi-layer reflective foils, as used in railway and truck dewars, are being applied. The evacuated heavy wall containers used commercially are unacceptable for flight and must be replaced by lightweight, flexible designs. Insulations, either evacuated on the ground or during flight in space, are considered. Regardless of insulation type, satisfactory thermal performance in space requires an insulation internal pressure less than 10^{-5} torr. A major problem for the ground evacuated insulation is the development of a flexible, lightweight, evacuated container. Major problems for the insulation evacuated during space flight are thorough ground purging and timely insulation pressure reduction to 10^{-5} torr.

Significant research in many areas is reported in References 18 through 23; however, thermal test data from potential flight tankage have only recently been obtained for modest storage duration objectives. A typical test tank is illustrated in Figure 14; measured thermal performance of applied insulation in a simulated space environment was worse than estimated by a factor of three. Improved thermal performance and predictions can be obtained through refinements in design and

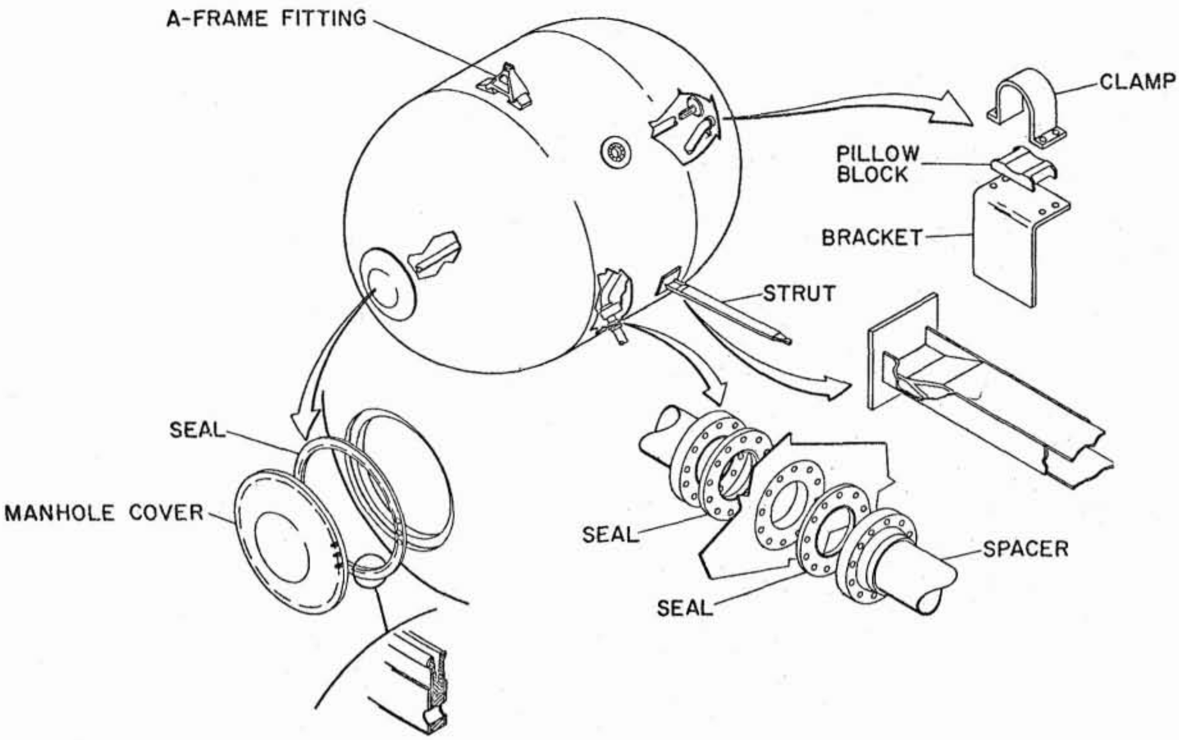


Fig. 14 Typical Tank From High Performance Insulation Development Program

analysis; however, insulation technology for extended storage requires additional efforts.

Cryo-Propellant Component Leakage

Besides evaporation of cryo-propellants, losses caused by leaking components, such as shutoff or vent valves, shaft seals, threaded or flanged fluid connectors gain importance for extended space flight. Cryo-propellant leakage can be expensive and cause functional failures and even loss of a mission. Problems are generally encountered with the leak-tight sealing of moving parts in cryogenic flow control components if one-shot burst diaphragms are not applicable. During their development phase, cryogenic flow components require careful monitoring and elimination of leakage. Leakage losses for various leak rates and storage time are given in Figure 15; research efforts to advance this technology appear in Reference 24 and 27.

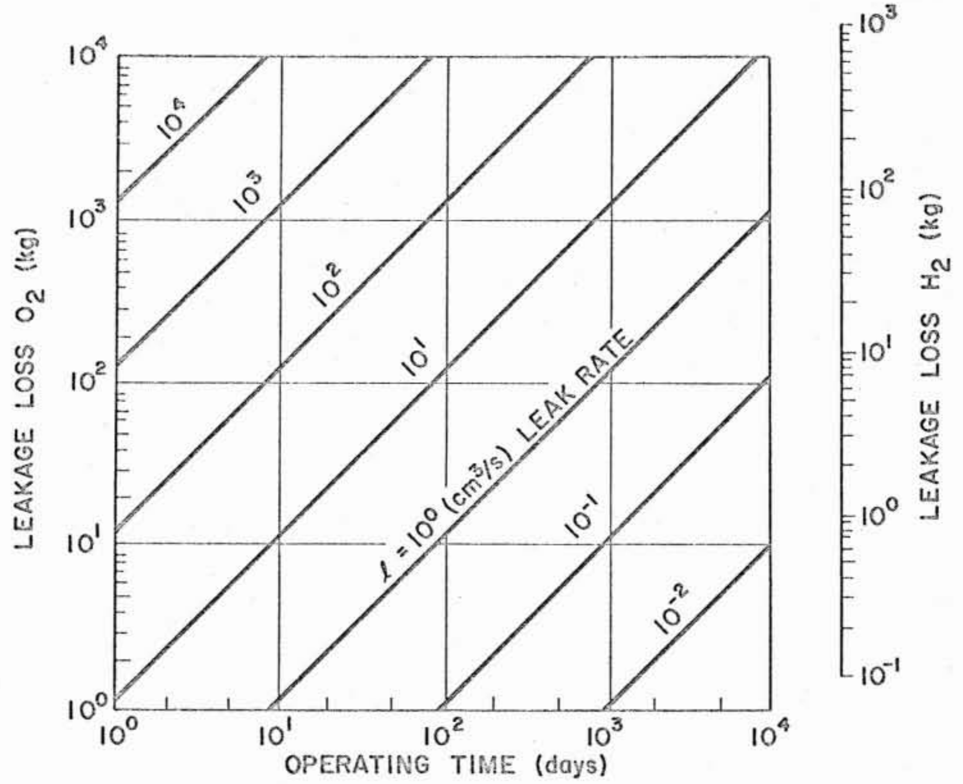


Fig. 15 Oxygen and Hydrogen Leakage Loss for Different Leakage Rates and Operating Times

REDUCED GRAVITY AND CRYOGENIC PROPELLANTS

While coasting under low gravity, liquids must not be vented from space vehicle propellant tanks. Reliable vapor separators trapping liquids inside the tank do not exist; therefore, other methods for venting only vapors are required. Propellant location in zero g is controlled by surface tension forces and is predictable (Figure 16); however, the zero gravity equilibrium fluid configuration can be delayed or prevented by forces imparted during powered flight, orbital insertion, and orbital flight. Such forces can result from propellant sloshing, deflection of the vehicle structure, thermally induced boundary layer flow, small drag forces, etc. Results from research in these and related areas are reported in Reference 28 through 32. These and other such topics as behavior of hydrogen inside pressurized tanks, venting of hydrogen, pressure increase for insulated containers, thermal stratification, and minimum acceleration for settling propellants have been recently studied in an Orbital Flight Experiment with test duration over several hours. Vehicle accelerations of approximately 4×10^{-5} and 6×10^{-4} g were maintained after insertion into orbit. The lower acceleration was maintained during the major portion of the experiment by continuous venting of vapor from the hydrogen tank. The orbital experiment objectives are illustrated in Figure 17. Selected results are discussed herein; Reference 28 reports complete flight data.

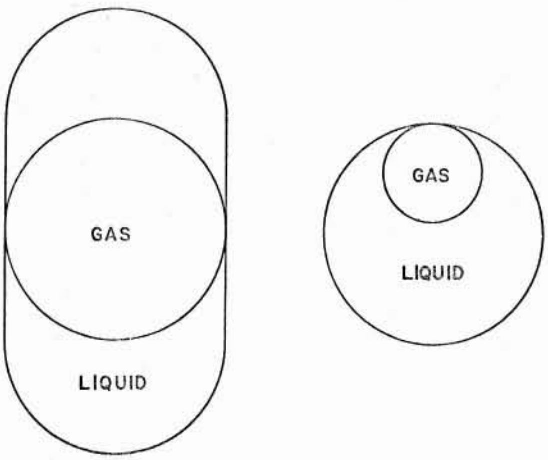


Fig. 16 Fluid Configuration in Zero Gravity

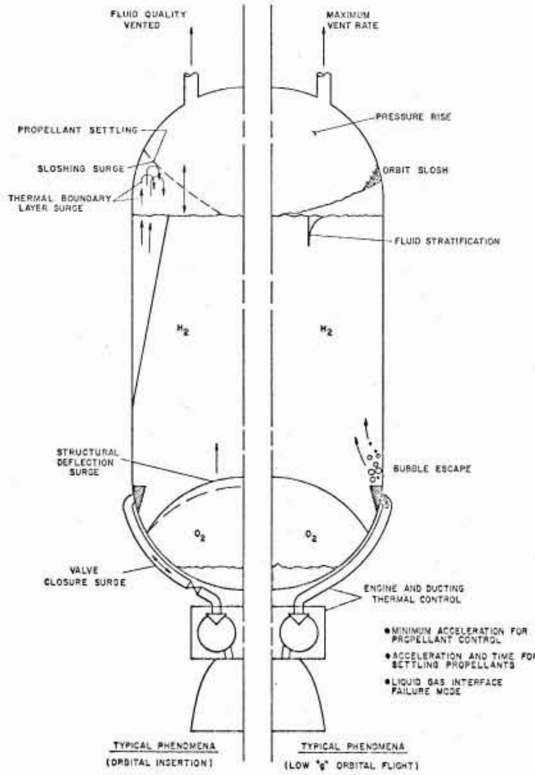


Fig. 17 Typical Phenomena Investigated in Low-g Flight Experiment

Low-g Liquid Dynamics (Orbital Insertion)

Propellant sloshing amplitude near slosh baffles was damped; first mode sloshing amplitude at rocket engine cutoff was 3 inches. Theory predicts slosh wave amplification for reduced longitudinal vehicle acceleration. A vertical liquid travel of 127 inches was calculated, which corresponds to a vehicle acceleration decrease from

3.5 to 6×10^{-4} g at engine cutoff. The flow pattern which developed immediately after orbit insertion is shown in Figure 18. A propellant forward motion of 140 inches was observed. Motion ceased 1 minute after engine cutoff. Individual contributions from such sources as fluid sloshing and boundary layer velocity are not identifiable. Liquid disturbances were not noted 77 seconds later when vehicle longitudinal acceleration decreased from 6×10^{-4} to 4×10^{-5} g. One hundred and fifty seconds after engine cutoff, propellants were relocated below the tank baffle and an axial acceleration of 4×10^{-5} g sufficed to keep propellants settled. Though specific fluid damping parameters were not obtained, the information gained is valuable.

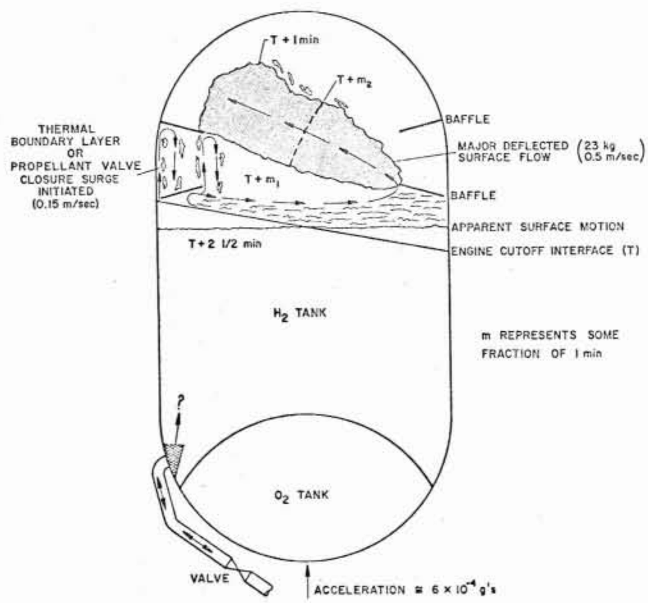


Fig. 18 Reconstructed Fluid Motions for Approximately A Two Minute Period Commencing with Engine Cutoff

Low-g Cryogen Venting

An excessive vent rate of a cryogen causes the liquid to enter a metastable state. Persistence of this metastable state depends upon such parameters as rate of depressurization, liquid purity, and number of nucleation sites inside the container. One of three phenomena can result:

Boilover - Surface evaporation and vapor formation at the nucleation sites may proceed rapidly enough to satisfy the changing equilibrium conditions. Since low bouyant forces prevent vapor bubbles from escaping, the liquid volume expands (Figure 19).

Bumping - Sudden liquid eruption can occur if boilover does not remove superheat in a liquid. Bubbles of almost molecular size may form within the superheated liquid; the bubble pressure may eventually become excessive and the bubbles so numerous that the bubbles unite with almost explosive force. The magnitude of this phenomenon has been observed but never measured.

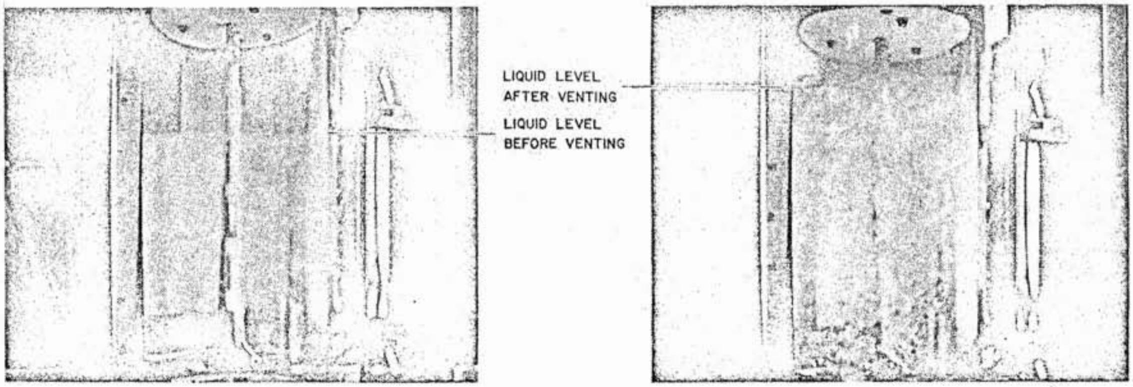


Fig. 19 Behavior of Hydrogen Prior to and During Tank Venting at Zero Gravity (Boilover Phenomena) - Data From Drop Tower

Bumping and Boilover - Both boiling modes could occur in large containers of pure liquid; since much of the bulk liquid would be independent of container boundary nucleation sites, liquid superheating is more likely to occur. Beginning 100 seconds or less after each vent initiation of the orbital hydrogen experiment (Figure 20), liquid globules one to several inches in diameter were propelled forward. Although visibility was impaired, the surface rose approximately 1 foot.

These data are used to establish maximum cryogen container vent rate, which is important for stage design.

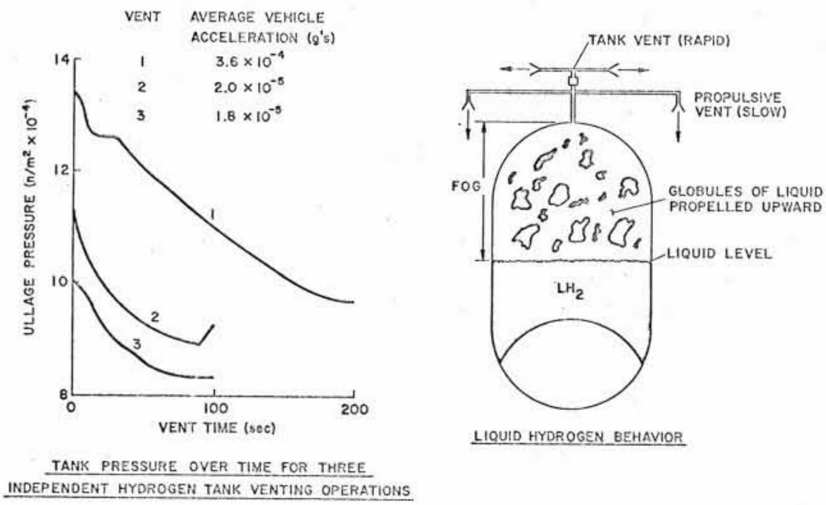


Fig. 20 Liquid Hydrogen Behavior During Rapid Tank Venting in Reduced Gravity for Varying Vehicle Acceleration (Liquid Hydrogen Orbital Experiment)

Low-g Cryogen Tank Pressure Rise

Tank pressure rise for a closed container was measured during a 1-1/2 hour coast period. Initial and final pressure and temperatures within the tank are shown in Figure 21. The existence of a thermal boundary layer flow and stratification are apparent. The lack of ullage gas heating data in a reduced gravity environment resulted in pressure rise predictions less than measured. Standard free convection equations (Reference 33) actually predict heat transfer to the ullage gas within 20 percent of measured values. Nucleate boiling along walls adjacent to the liquid negates free convection equation usage in the liquid region; however, the measured thermal boundary layer thickness agrees with the boundary layer thickness calculated by procedures of Reference 1.

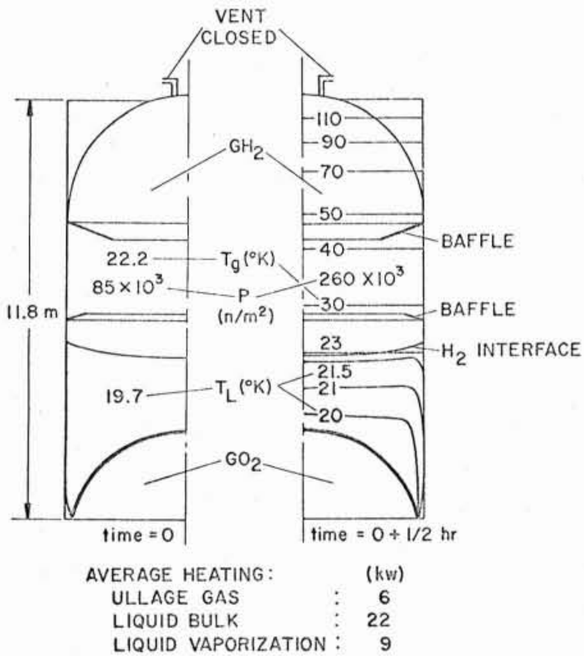


Fig. 21 Initial and Final Temperatures and Pressures of Liquid and Gaseous Hydrogen for the Pressure Rise Test Conducted in Low Gravity

CONCLUSION

Cryogenic technology for space applications has advanced within the past decade; however, potential missions utilizing cryogens for a year or more are most demanding on technology and require significant advances, particularly in high performance insulation, other media for enhancing storage, and understanding and controlling the behavior of cryogens in reduced and zero-g environments.

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