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CRYOGENIC THERMAL CONTROL TECHNOLOGY SUMMARIES

December 1974

By
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16. Abstract

This report presents a summarization and categorization of the pertinent literature associated with cryogenic thermal control technology having potential application to in-orbit fluid transfer systems and/or associated space storage. Initially, a literature search was conducted to obtain pertinent documents for review. Reports determined to be of primary significance were summarized in detail. Each summary, where applicable, consists of; (1) report identification, (2) objective(s) of the work, (3) description of pertinent work performed, (4) major results, and (5) comments of the reviewer (GD/C). Pertinent figures are presented on a single facing page separate from the text. Specific areas covered are; (1) multilayer insulation of storage tanks with and without vacuum jacketing, (2) other insulation such as foams, shadow shields, microspheres, honeycomb, vent cooling and composites, (3) vacuum jacketed and composite fluid lines, and (4) low conductive tank supports and insulation penetrations. Reports which were reviewed and not summarized, along with reasons for not summarizing, are also listed. Low-g fluid behavior and fluid management systems technology are presented in companion reports (NASA CR-134746 and NASA CR-134748) under this same contract.

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FOREWORD

This report was prepared by the Convair Aerospace Division of General Dynamics Corporation in partial fulfillment of Contract NAS3-17814. The contract was administered by the Lewis Research Center of the National Aeronautics Space Administration, Cleveland, Ohio. The NASA Project Manager was Mr. John C. Aydelott.

A summarization and categorization is presented of the pertinent literature associated with cryogenic thermal control technology having potential application to in-orbit fluid transfer systems and/or associated space storage . Low-gravity fluid behavior and fluid management systems technology data are presented in companion reports under this same contract.

In addition to the project manager, Mr. John A. Stark, Messrs. F.O. Bennett and K. E. Leonhard contributed to the preparation of this report.

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1.0 INTRODUCTION

This report presents a summarization and categorization of the pertinent literature associated with cryogenic thermal control technology having potential application to in-orbit fluid transfer systems and/or associated space storage.

The initial task was to conduct a literature search to obtain pertinent documents for review. The following sources formed the basis for this search.

a. Convair Library and Cryogenic Group files.

b. "Bibliography of References - Space Storage of Cryogenic Propellants," (Report B-777) prepared by the Cryogenic Data Center, NBS, covering the period 10 June 1974 back through 1959.

c. NASA-computer tape search covering low-g considerations for the period 30 September 1974 back through 1969. Key words used in this search are presented in Appendix C.

d. Defense Documentation Center (DDC) search of the unclassified literature for the period 3 June 1974 back through 1969.

e. Secondary sources from reports reviewed.

Reports which were determined to be of primary significance are summarized in Sections 2 through 5. Each summary, where applicable, consists of; (1) report title, author(s), organization doing the work, identifying numbers and date, (2) objective(s) of the work, (3) description of pertinent work performed, (4) major results, and (5) comments. The thoughts expressed by the objective, pertinent work performed, and major results sections are those of the author. The thoughts of the reviewer (GD/C) are presented in the comments section. Pertinent figures are presented on a single facing page separate from the text. Units used in the summaries are those from the basic report; i.e. dual units were only used if they were in the report being summarized. Where a reference is cited within the summary, the author(s) and date were used in place of a reference number. Uncommon abbreviations, acronyms and nomenclature are defined in the individual summaries, while general definitions and nomenclature are presented in Appendix C.

The summaries are organized by category and date, with the most current work appearing first. Also, a listing of all summarized reports alphabetically by author is presented in Appendix A.

The categories into which the summaries are divided are listed below, along with a brief description of the work covered in each.

a. Multilayer Insulation (MLI) - covering analyses, evaluation, development, design, fabrication and testing of MLI systems with and without vacuum jacketing.

b. Other Insulation - covering various types of foams, shadow shields, microspheres, honeycomb, vent cooling and composites.

c. Fluid Lines - covering analysis, design and test of vacuum jacketed and composite lines and associated liners and joints.

d. Tank Supports and Penetrations - covering the effects on tank heating of insulation penetrations and the design and test of low conductive support struts.

Reports which were reviewed and not summarized, along with reasons for not summarizing, are listed in Appendix B. The following ground rules were used in selecting specific reports for summarization.

a. Only the thermal control required for storage and/or transfer of cryogenics was considered which has potential application to in-orbit transfer systems and/or associated space storage. Systems only applicable to atmospheric operation such as Batting, Dyna Quartz, etc. were not included.

b. Under "Other Insulation Systems" were included new and novel approaches to thermal control.

c. The report must have provided data required for current design and/or added something important to the knowledge required to provide a complete picture of the current state-of-the-art.

d. Emphasis was on the most recent work; however, reports were not summarized if they were just a rehash of other work. If they were primarily connected with other work they must have provided useful consolidations, additions or evaluations.

e. Fluid tankage itself and associated structural details were not included.

f. Monthlies, Quarterlies and classified reports were not summarized.

g. Reports which are not generally available were not included, such as symposium papers where only those in attendance may have copies and internal company documents, such as Independent Research and Development (IRAD) reports.

2.0 MULTILAYER INSULATION

Covering analyses, evaluation, development, design, fabrication and testing of MLI systems with and without vacuum jacketing.

DESIGN AND DEVELOPMENT OF PRESSURE AND REPRESSURIZATION PURGE SYSTEM FOR REUSABLE SPACE SHUTTLE MULTILAYER INSULATION SYSTEMS
Walburn, A.B., GDC, CASD-NAS-74-032, NAS8-27419, August 1974

OBJECTIVE. - To develop and test a pressure and repressurization system for reusable multilayer insulation (MLI) systems.

PERTINENT WORK PERFORMED. - Property and performance data are presented as a result of a literature survey of purge system materials and component hardware. Purge system approaches were defined and two concepts were evaluated. One configuration was selected for manufacturing and testing, incorporating a purge bag laminate of FEP and epoxy/fiberglass. An analysis of purge gas flow requirements was made on a 2.21m (87 in.) diameter oblate spheroid test tank. MLI gold coating thickness requirements were investigated based on a layer transmittance of 0.5%. Purge bag manufacturing tests were conducted to develop fabrication techniques. Pressure cycling tests were performed at 450K and 200K and acoustic loading tests were performed. Tests were run to verify the purge pin gas injection concept for purging MLI. The final system design consisted of the test tank, fiberglass purge plenum (fairing), Superfloc MLI lay-up in 24 gore sections (2 blankets), flat end blankets, and a fiberglass purge bag with a rigid penetration panel for fluid loop hardware and instrumentation fittings. Purge pins for distributing gas between the MLI layers were mounted on the fairing. The total system was subjected to 100 simulated shuttle mission cycles including tanking, ground hold equilibrium, launch, space residence, entry and detanking. System design data are presented in Table 1.

MAJOR RESULTS. -

1. A potential purge bag weight saving of 17% is possible if DuPont PRD-49 material is substituted for the 181 fiberglass material.
2. The total helium mass required to purge the MLI of 99% of the condensible gases decreases with increasing purge flow rate.
3. The total gold thickness requirement on each reflective shield of the Superfloc MLI for the test system is 800 Å to achieve a radiation transmission of 0.5%.
4. Approximately 5 minutes are required to purge the test tank prior to cryogen filling.
5. The actual measured density × conductivity (ρk) product for the complete cryogenic storage system was 6.44×10^{-5} Btu · lb/hr ft^{4}F (Table 1).
6. The reusablity of the new goldized Kapton Superfloc MLI system was demonstrated by repeatedly subjecting the cryogenic storage system to the simulated environments of the Space Shuttle flight cycle.

Table 1. Superfloc MLI System Design and Performance Data 221 cm (87 inch) Convair Aerospace Tank

DESIGN DATA

TANK

Surface Area:	14.12 sq meters (152 ft^2)
Capacity:	4.95 cubic meters (175 ft^3)
Support System:	3 pairs of Epoxy/Fiberglass tubular struts arranged in "V" patterns.
Material:	2219-T62 Al Aly
Thickness:	1.95 mm to 3.94 mm (0.077 in to 0.155 in)
Fill, Drain and Vent:	Co-axial tube assembly. 6.35 cm (2.50 in) O.D. outer tube. 3.81 cm (1.50 in) O.D. inner tube. Material; 6061-T4 al aly, 304L CRES and Epoxy/Fiberglass.

FAIRINGS

Configuration:	Frustrum of cone at forward and aft end with stiffened flat panel at small end of cone. Ring type section at girth area. Fairing at girth seals with struts.
Material:	Epoxy/Fiberglass
Accessories:	Removable forward flat panel for access. Incorporates MLI support pins and purge pins.

MLI SYSTEM

Type of MLI:	30 gauge (0.00076 cm) double goldized Kapton Superfloc. 12 layers/cm (30 layers/inch) lay-up density. 0.00971 kg/m^2 (0.001986 lb/ft^2) per layer.
Face Sheets:	Beta glass scrim coated with pyre M.L. (preformed). 0.0888 kg/m^2 (0.0182 lb/ft^2). 0.00173 cm (0.007 in) average thickness.
Blankets:	22 core sheets and 2 face sheets/blanket. 0.523 rad (30°) preformed gores. 12 gores per blanket layer.
Quantity of Blanket Support Pins:	48 Epoxy/Fiberglass material
Quantity of Twin Pin Fasteners:	158 for outer blanket layer. 86 for inner blanket layer. Polyphenylene oxide (PPO) material.
Quantity of Coupler Pin:	24 for inner blankets. 24 for outer blankets. Coupler pin is a twin pin adapted for interconnecting the MLI blankets to the support pins. Heat leak path for two coupler pins is equal to one twin pin.
Seam Lengths:	40 meters (131 ft) per blanket layer.
Total Lay-Up Thickness:	3.82 cm (1.50 in)
Weight (Incl. Fasteners):	14.0 kg (30.8 lb)
Average Area:	16.5 sq meters (178 ft^2)

PURGE DISTRIBUTION SYSTEM

Quantity of Purge Pins:	43 PPO material.
Type of Purge Pins:	Slotted tubular type.
Gas Flow Path:	Tubular manifold supplies plenum chambers formed between tank and fairings. Plenums feed purge pins.
Purge Volume Between Tank & Bag:	2.42 cu meters (85.5 ft^3)

PURGE BAG ASSEMBLY

Fwd and Aft Bag Sections:	2 plys of 181 Epoxy/Fiberglass sandwiched between two FEP films.
Penetration Panel:	Multi ply lay-up of Epoxy/Fiberglass with one FEP film layer on inboard surfaces.
Joints Between Sections:	Bolted flange types.
Weight:	43.23 kg (95.31 lbs)

PURGE AND REPRESSURIZATION FLUID LOOP HARDWARE

Vent:	15.25 cm (6.0 in) motorized butterfly valve.
Bleed:	5.07 cm (2.0 in) motorized gate valve.
Emergency Relief:	2.54 cm (1.00 in) spring loaded poppet valve.
Supply:	0.952 cm (0.375 in) solenoid poppet valve.
Controls:	Two diaphram type pressure switches.
Weight:	11.20 kg (24.65 lbs)

THERMAL PERFORMANCE DATA

292-22K	Predicted Heat Leakage (watts)	% of Total	Measured Heat Leakage (watts)
MLI	3.08		
Seams	2.76		
Pins	2.43		
Penetrations	3.25		
Residual Gas	0.18		
Struts	0.50		
	12.20	100	12.60

Heat Flux:	.76 w/m^2 (.242 Btu/hr-ft^2)
Effective Conductivity, K_{eff}:	85.6 μw/m-k (4.92 × 10^{-5} Btu/hr-ft-R)
MLI System ρK Product:	1.78 mW-Kg/m^4-K (6.44 × 10^{-5} Btu-lb/hr-ft^4 R)

OXYGEN THERMAL TEST ARTICLE (OTTA)
Chronic, W. L., et al, Beech, ER-15961, NAS9-10348,
August 1974

OBJECTIVE. - To design and fabricate a prototype cryogenic tank for the long-term storage of propellants in space.

PERTINENT WORK PERFORMED. - A double-walled, spherical, aluminum, 91-inch I.D. vessel was designed and fabricated. The inner pressure vessel is supported by a system of glass/epoxy filament wound circular rings. An insulation system consisting of 46 layers of silverized Mylar/silk net was installed around the tank. Boiloff vapor was flowed through channels attached to two aluminum shields located between the third and fourth, and 18th and 19th layers of the MLI (counting from the cold wall). The external shell was fabricated from rigid aluminum (Figure 1). The inner vapor-cooled shield was called a "boiler shield", its function being to vaporize any liquid which was expelled from the pressure vessel. A thermal analysis of the storage system was made prior to test. The insulation performance was represented by constant effective emittances of 0.01, 0.0016, and 0.0016 for the 3-, 15-, and 28-layer blankets, respectively. Predictions of heat flux, pressure rise, and liquid expulsion rates were made. The quantity of cryogen in the tank was determined by a BLH Electronics, Inc., load cell system. The load cell was found to be highly sensitive to the ambient temperature, registering a 4-pound weight change per degree of temperature change. Tests were performed with LH_2, LN_2, and LHe.

MAJOR RESULTS. -

1. Measured thermal performance of the storage system was 2.5 times better than originally predicted.

2. Measured boiloff rates at equilibrium for LH_2 and LN_2 were 0.5 and 2.5 pounds per day, respectively. Corresponding average heat flux values were 0.022 and 0.042 Btu/hr-ft^2, respectively.

3. It was felt that the problem of silver coating tarnishing could be controlled during system fabrication.

4. No deterioration of the silk net spacer material was observed after 18 months of testing.

5. The effect of the vapor-cooled shields on thermal performance was determined during a test with liquid helium. When the boiloff vapor bypassed the shields, heat flux rose by a factor of 8.6.

COMMENTS. - There are no photographs in the final report, and there is no discussion of insulation blanket fabrication and layup. Test hardware and procedures are not adequately covered.

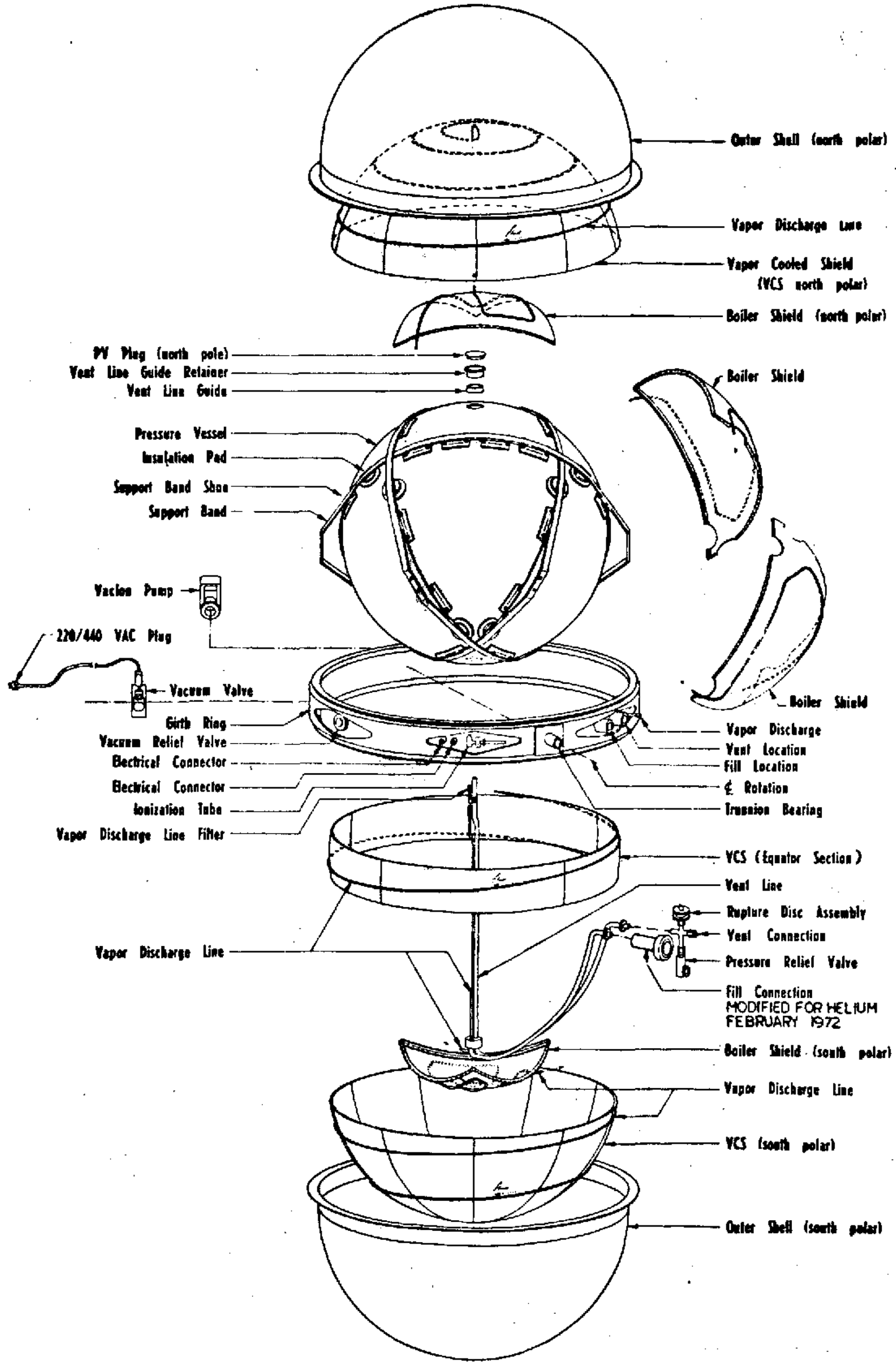


Figure 1. Oxygen Thermal Test Article

BASIC PERFORMANCE OF A MULTILAYER INSULATION
SYSTEM CONTAINING 20 TO 160 LAYERS
Stochl, R. J., NASA-LeRC,TN D-7659, April 1974

OBJECTIVE. - To obtain experimental heat transfer data on a multilayer insulation (MLI) system containing a large number of layers, and to determine whether semi-empirical equations can be used to predict heat transfer as a function of number of layers.

PERTINENT WORK PERFORMED. - A double aluminized Mylar/silk net MLI system was spirally wrapped on a 30-inch diameter double-guarded calorimeter (Figure 1) to an equivalent depth of 160 layers. The materials were tensioned during wrapping and Dacron string was taped to every tenth layer to support the material. Thermocouples and pressure sensing tubing were added during wrapping. The procedure involved performing a space equilibrium thermal performance test with this configuration, and then unwrapping the material and performing similar tests with 100, 60, 40 and 20 layers. A tare run was made to identify miscellaneous heat leaks to the measuring tank, and sufficient data were taken to permit corrections for non-radial flow, both longitudinally and laterally (due to the spiral wrap).

MAJOR RESULTS. -

1. Tank ullage pressure and system source temperature were controlled to within 0.0002 psi and 2.0 degrees F, respectively.
2. The average measured interstitial pressure of 4.5×10^{-5} torr resulted in a calculated gas conduction heat transfer contribution of 24 percent.
3. Measured and corrected normal heat fluxes decreased exponentially with number of layers (Figure 2) with approximately 75 percent of the total reduction (from 20 to 160 layers) occurring at 60 layers.
4. Predicted fluxes were within ±7 percent of measured values for all tests except 160 layers. The discrepancy in the latter test was probably due to the large corrections required for lateral conduction.
5. The semi-empirical relations were deemed adequate for predicting heat flux as a function of number of layers.

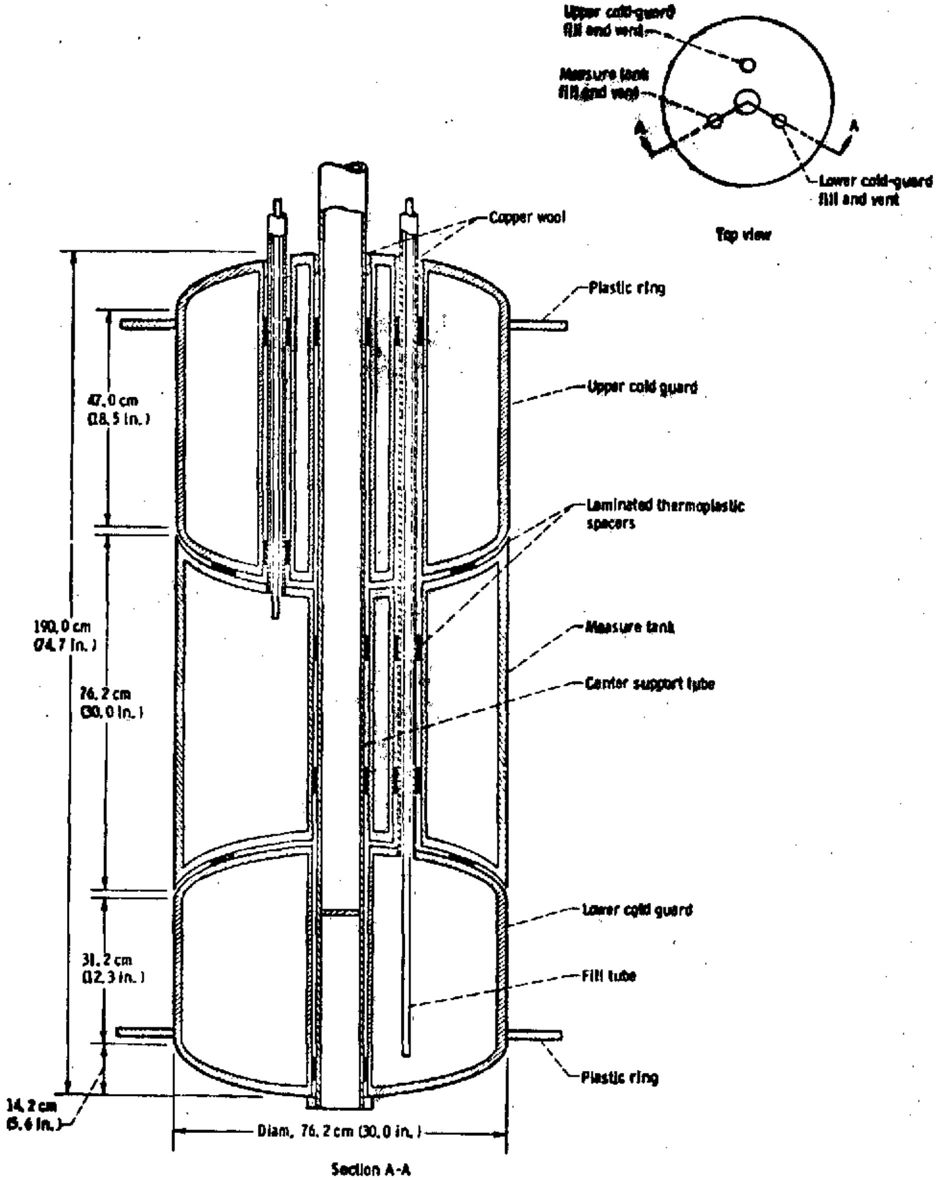


Figure 1. Doubly Guarded Cylindrical Calorimeter

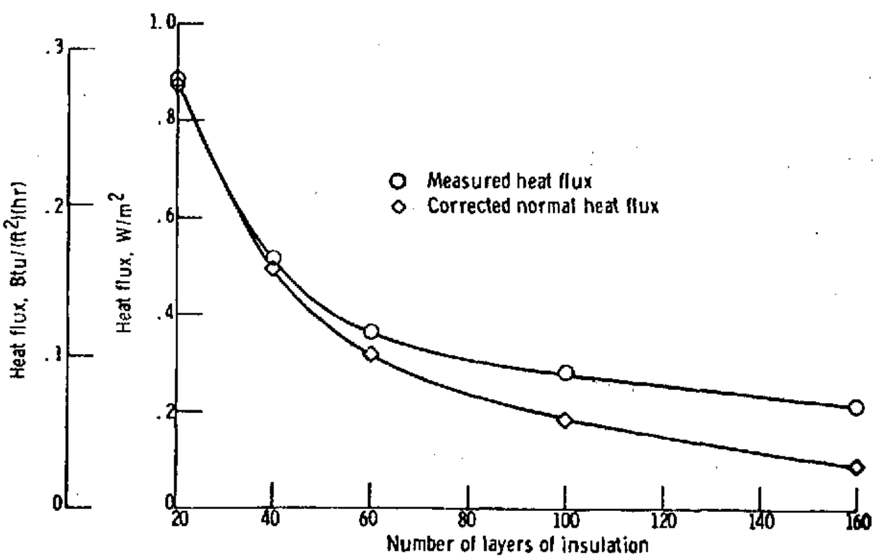


Figure 2. Heat Flux as Function of Number of Layers of Insulation

INVESTIGATION OF HIGH PERFORMANCE INSULATION APPLICATION PROBLEMS: Fredrickson, G.O., MACDAC, MDC-G4722, NAS8-21400, Aug. 1973.

OBJECTIVE. - To design, demonstrate fabricability, and experimentally determine the performance of a practical, flightworthy, multilayer insulation (MLI) system for a Modular Nuclear Vehicle (MNV) LH_2 propellant tank.

PERTINENT WORK PERFORMED. - The definition and development of the MLI system was accomplished in a three phase program: 1) Flightworthy MLI system design for a MNV; 2) Design and fabrication of a large tank MLI system test article; 3) large tank MLI system testing. Phase I included all studies to define and develop a flight-type MLI concept: design, manufacturing methods, component development, materials characterization and selection, and thermal and structural testing. During phase II the selected system was adapted and applied to the existing 105 inch diameter NASA-MSFC calorimeter. A test program was defined. As shown in Figure 1, the insulation composite (reflectors and separators) was assembled between reinforced face sheets. Assembly was accomplished with Nylon fasteners that penetrate through the panel. Two layers of panels were used in the test system. Panels were attached to the structure at their upper end with grommets which fitted over studs mounted on the tank. All panel joints were butt type and fastened together with lacing and Velcro tabs on their exterior and interior, respectively. In phase III the MLI was tested utilizing the 105 inch tank. The test program consisted of two basic MLI performance tests: evacuated equilibrium and prelaunch to orbit simulation. Purge system tests were planned and designed. These tests were cancelled after difficulties were experienced during the purge bag installation.

MAJOR RESULTS. -

1. Tests of the insulation system indicated that the applied thermal performance represents a state-of-the art advancement
2. The conductivity × density (ρk) performance was experimentally determined on the 105 inch diameter NASA-MSFC calorimeter. The result was 4.6×10^{-5} Btu-lb/ft^4 hr F.
3. Structural integrity in a launch dynamic environment was demonstrated with separate tests of representative panel segments.
4. Study results show that sufficient technology is now available to design and apply a perforated 15-gauge DAM (double aluminized Mylar) - B4A Dacron net MLI system to spacecraft for a tank temperature as low as -300°F. The MLI system design, at this stage of development however, is not optimum.
5. Additional effort is needed in the areas of joint design, perforations, and purge preconditioning.

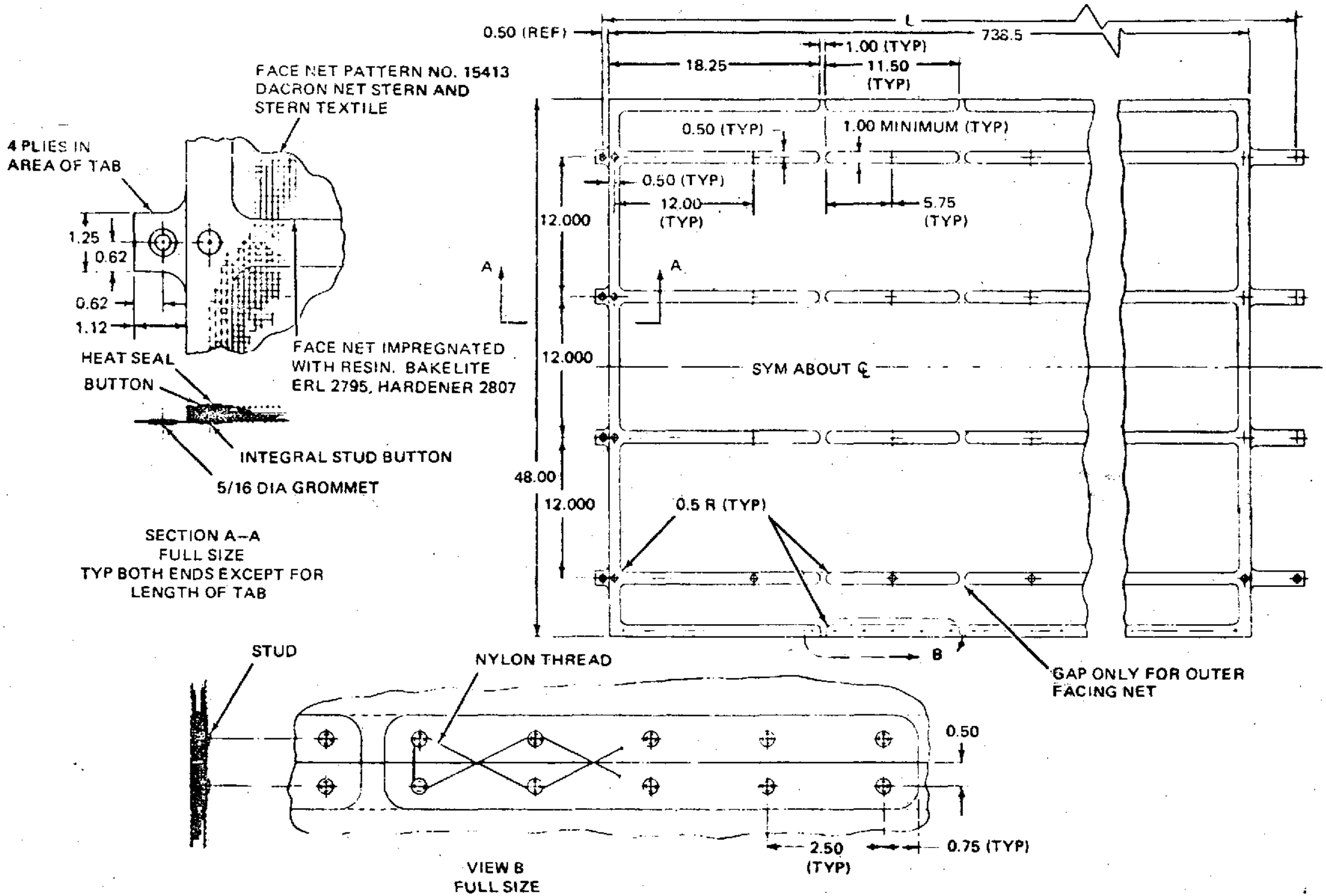


Figure 1. Prefabrication Panel Configuration

REUSABLE LIGHT WEIGHT MODULAR MULTI-LAYER INSULATION FOR SPACE SHUTTLE

Burr, K. F., Linde, NASA CR 121166, NAS3-14366, July 1973

OBJECTIVE. - To determine if the Self Evacuating Multilayer Insulation (SEMI) (Fig. 1) System could be adapted to space shuttle orbiter vehicle cryogenic tankage.

PERTINENT WORK PERFORMED. - The SEMI system investigated consisted of a flexible vacuum casing enclosing alternate layers of reflective thermal radiation shielding and space material. A gas condensible at LH_2 temperature provided the self-evacuating mechanism within the panel. This system was previously developed for a one flight vehicle. Through material substitutions, alteration of the system was sought which allows it to withstand the higher surface temperature and the 100 flight life expectancy. The system fabricated and tested consisted of a vacuum casing type 300 S Mylar film bonded with room temperature vulcanizing (RTV) rubber adhesive. Open-cell polyurethane foam and glass matting was used between double aluminized Kapton and Mylar radiation shields. The condensible filler gas was GN_2. Small scale materials evaluation and screening tests were performed to simulate the 300° F temperature and 100 flight cycle condition. Subscale insulation system tests were conducted to evaluate thermal and mechanical cycling effects on insulation panels. Fabrication techniques were demonstrated on large scale panels.

MAJOR RESULTS. -

1. Small scale screening and subscale panel tests demonstrated the insulation's potential for withstanding 100 flight cycles.

2. Considerable development work is required to ascertain reproducibility in materials and systems behavior, develop reliable manufacturing techniques, and to generate accurate system design data.

3. A single layer casing concept can simplify fabrication panels.

4. Provisions must be made for space evacuation of the panels on each flight to prevent excessive pressure rise upon panel warm up.

5. Type 300 S Mylar and 732 RTV adhesive materials provided best overall performance from a cycling and handling standpoint.

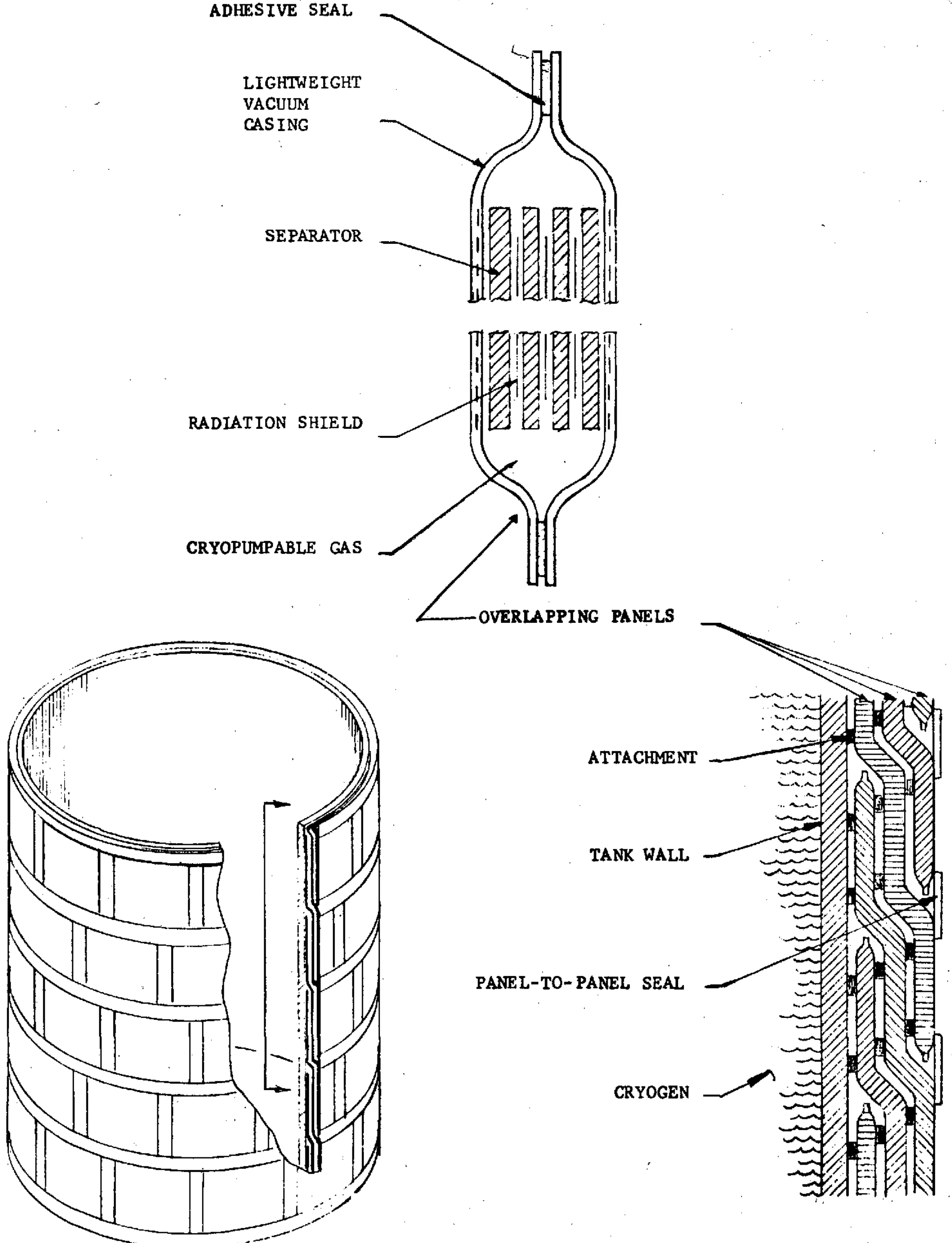


Figure 1. SEMI Panel Shingle Arrangement Installation

LIGHTWEIGHT EVACUATED MULTILAYER INSULATION SYSTEMS FOR THE SPACE SHUTTLE VEHICLE
Barclay, D.L., et al, Boeing, NASA CR-121105, May 1973

OBJECTIVE. - To develop a high performance evacuated insulation system for the on-orbit cryogenic propellant tanks of the Space Shuttle orbiter.

PERTINENT WORK PERFORMED. - Design and analytical studies were conducted optimizing structural design, insulation system, and cryogen storage method (vented or non-vented). Trade-off studies were conducted on shell construction methods and the various component arrangements (pressure vessel, vacuum jacket, support system, insulation, plumbing, etc.)for a range of tank length-to-diameter ratios. Thermal analyses of the effects of gas leakage were conducted, and the weight penalty associated with an on-board vacuum pumping system was determined. The outgassing characteristics of candidate vacuum shell materials were investigated. Non-destructive proof tests and vacuum acquisition tests were performed. Three multilayer insulation (MLI) system configurations, including double aluminized Kapton (DAK) with Dacron net spacer, a combination of DAK and double aluminized Mylar (DAM) with Dacron net, and DAK with Tissuglas spacer, were considered for this application.

MAJOR RESULTS. -

1. The combined DAK-DAM/Dacron net MLI system was selected. The DAK is used in the outer few layers due to high temperatures (350F) encountered during entry (Figure 1).

2. Due to relatively high outgassing rates, organic materials should not be exposed to the vacuum annulus.

3. A procedure for reevacuating the vacuum annulus during ground turnaround will be necessary to prevent gradual degradation of system thermal performance with time.

4. Minimum overall system weight is achieved with boron/epoxy, low L/D spherical tanks, (Figure 2) and with non-vented storage of cryogens.

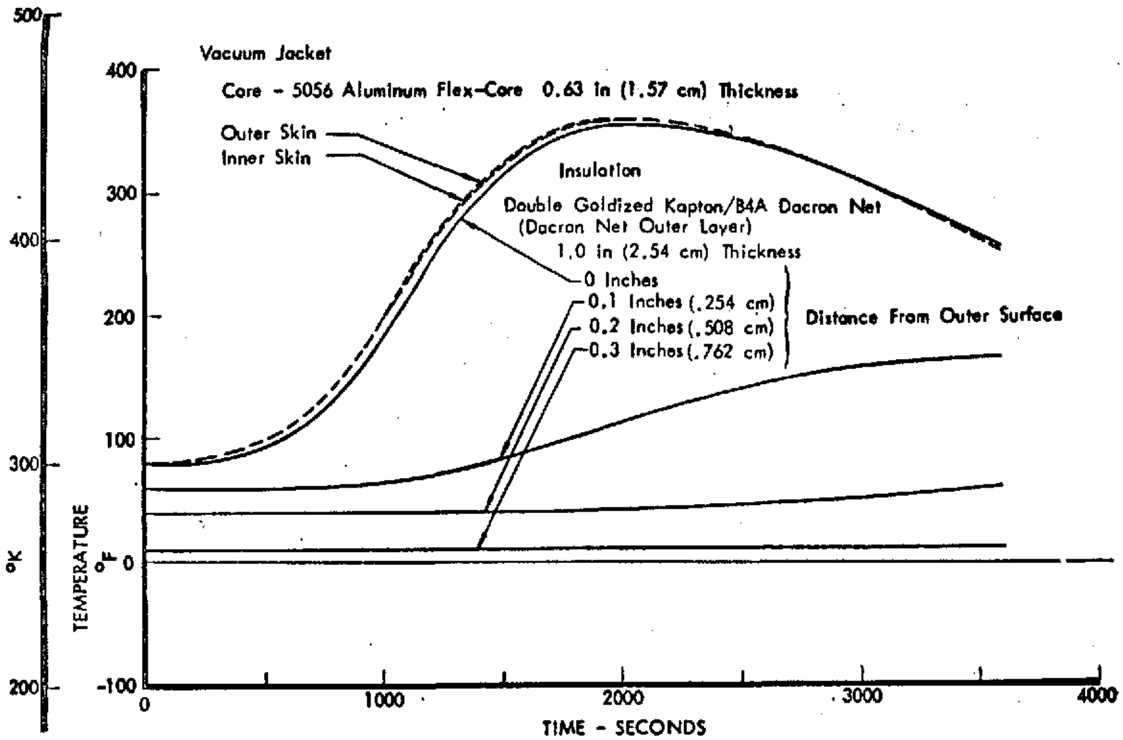


Figure 1. VACUUM JACKET AND INSULATION REENTRY TEMPERATURES

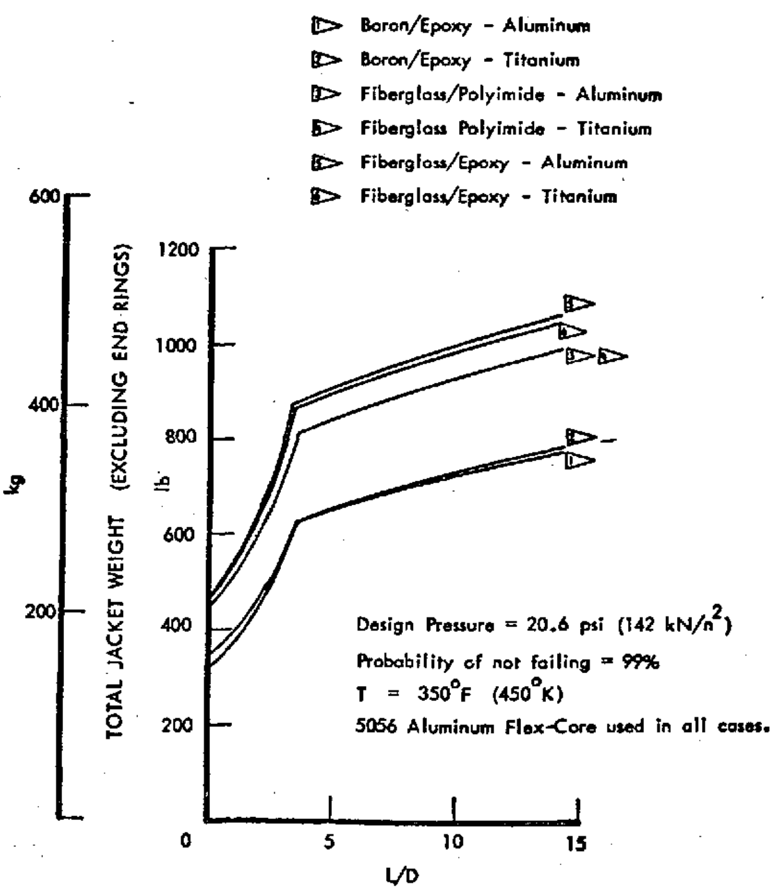


Figure 2. LO_2 VACUUM JACKET WEIGHT VS L/D FOR SIX FACE MATERIALS AND 5056 ALUMINUM FLEX-CORE (METAL OUTER SKIN)

EFFECT OF ENVIRONMENT ON INSULATION MATERIALS
Parmley, R. T. et al, LMSC, NASA CR 120978, NAS3-14342,
February 1973.

OBJECTIVE. - To obtain and evaluate data on environmental exposures of various insulation materials to provide both a quantitative and qualitative description of the degradation to certain physical and thermal properties.

PERTINENT WORK PERFORMED. - Materials tested included multilayer insulation (MLI) radiation shields and spacers, adhesives, polyurethane foam, glass fabric, paints, Teflon film, and Velcro fasteners (Table 1). Environment exposure conditions were vacuum, high temperature (200F), humidity, humidity plus salt air, water immersion, and gaseous propellants (oxygen and fluorine). Tests performed (where applicable) included weight and density determination; emittance, absorptance, and reflectance; flexibility; adhesion; tensile, shear, compression, and peel; ignition; and outgassing. Data are presented in both tables and graphs in handbook form.

MAJOR RESULTS. -

1. Gold coated films are more resistant to attack by salt air and high humidity than are aluminum coated films.
2. In most cases gold coatings provide greater protection to the substrate than aluminum.
3. Gold and Kapton outgas less than aluminum and Mylar, respectively.
4. Dacron net exhibited the fewest property changes of the spacers tested (silk net, nylon net, Tissuglas).
5. Environments having the greatest effect on material properties were high temperature (200F) at one atmosphere or vacuum, salt air, and fluorine.
6. Fluorine ignition occurred with all materials except double aluminized Mylar, single aluminized Kapton, double goldized Mylar, silk net (with sizing), glass cloth, Goodyear adhesive, and Teflon film.

Table 1. Identification of Test Materials

Radiation Shield Materials

Test Material*		Test Material Source	Applicable Purchase Spec.
Film Coating	No. of Sides Coated		
Mylar-Aluminum	1	National Metallizing Div., Standard Packaging Corp., Granbury, New Jersey 08512	LAC 22-4402
Mylar-Aluminum	2		LAC 22-4402
Kapton-Aluminum	1		LAC 22-4413
Mylar-Gold	1		LAC 22-4402 + Addendum A
Mylar-Gold	2		LAC 22-4402 + Addendum A
Kapton-Gold	1		LAC-4413 + Addendum A

* Nominal thickness 0.25 mils (6.4×10^{-3} mm)

Insulation Spacer Materials

Test Material	Test Material Source	Applicable Purchase Spec.	Nominal Thickness mils (mm)
Silk Net			
"Illusion Silk Net," approx. 1/16 in. Hexagonal Mesh	John Heathcoat Company, 108 W 39th Street New York, New York 10018	None	5 (0.13)
Nylon Net			
1/16 x 3/32 in. Hexagonal Mesh	Sears Roebuck & Co. (Any local store)	None	9 (0.23)
Tissuglas			
Style 600	Pallflex Products Corp., Kennedy Drive Putnam, Connecticut 06260	LAC 26-4382	0.6 (1.52×10^{-2})
Dacron Net			
(.0024 lb/ft^2) B/2A, 198 meshes/in.^{2}	Apex Mills 49 W. 37th Street New York, New York 10018	None	6.7 (0.12)

Ground Hold Insulation Materials

Test Material	Test Material Source
Beta Fiber Fabric (6.3 oz/yd) Style 15035 Finish 9362	J. P. Stevens & Co., Inc. 1185 Avenue of the Americas New York, New York 10036
Narmco 7343/7139 Adhesive	Narmco Materials Div. Victoria & Placentia Streets Costa Mesa, California 92627
Goodyear Pliobond Adhesive 4001/4004	Goodyear Tire & Rubber Company Adhesive Dept. 1745 Cottage Street Ashland, Ohio 44805
Polyurethane Foam (2 lb/ft3), BX-250-A	Nopco Chemical Division of Diamond Shamrock Corp. 60 Park Place Newark, New Jersey 07101 (Blown foam supplied by North American Rockwell Corp.)

Miscellaneous Insulation Materials

Test Material	Test Material Source	Applicable Purchase Spec.	Nominal Thickness mils (mm)
Velcro Fasteners 100% Polyester 1-in. wide, white HPB-12-1-100 Hook HPB-12-1-100 Loop	The Hartwell Corporation 9035 Venice Blvd Los Angeles, Ca 90034	None	-
Teflon Film TFE	E. I. du Pont, de Nemours & Co., Inc., Wilmington, Del 19898	AMS 3651 NPS 22-302	10 (0.25)
Thermatrol Paint (2A-100)	Lockheed Missiles & Space Co. (LMSC) Sunnyvale, Ca 94088	LAC 37-4294 101 (Lockheed Process Bulletin 55)	-
3M Co. Series 400 Black Paint with primer, DuPont 65-3011, Dark Gray	Reflective Products Division 3M Co., 3M Center, St. Paul, Minnesota 55101	None	-
Paint Substrate			
Epoxy Glass	LMSC	MIL-P-18177C	16 (0.41)
Aluminum, 6061-T6	LMSC		20 (0.51)

CRYOGENIC INSULATION DEVELOPMENT

Leonhard, K.E., GD/C, GDCA DDB 72-004, NAS8-26129, July 1972

OBJECTIVE. - To develop an insulation system, based on the Superfloc concept, capable of adequate performance for 100 mission cycles, and capable of withstanding extremes of -423 and +300° F.

PERTINENT WORK PERFORMED. - Typical reusable space vehicles were reviewed to establish a set of thermal and structural parameters which were used in the development of a reusable MLI system for LH_2 tanks. The materials studied were materials for radiation shields, spacers, MLI blanket face sheets, fasteners, purge bags and adhesives. Acceptance tests were performed including manufacturing tests, cryogenic dip tests, thermal expansion and cycling tests, compression and recovery experiments and thermal performance tests. MLI component development included blanket attachments and supports. Structural tests were conducted to verify the component designs. A thermal analyzer program was modified to permit an analytical evaluation of the heat flow through a MLI system from ground hold through boost to space environment. Analyses were performed to predict the concentration of a purge gas in an MLI system. Helium tests were conducted to verify the analysis and purge components were studied for hardware development. Twelve MLI purge and repressurization systems were identified, design layouts made and evaluated. A preliminary design of the selected system "Internal Fairing and Purge Bag With Complete Gas Distribution," was established for the MSFC 105 inch Calorimeter (Figure 1). The thermal performance of this insulation was theoretically determined.

MAJOR RESULTS. -

1. Kapton material, goldized on both sides with Dacron fiber tufts as the spacers, was selected as the radiation shield.

2. The thermal conductivity of Superfloc was measured to be 1.37×10^{-5} BTU/hr ft °F at 30 layers/inch.

3. The thermal analyzer program was modified to predict MLI interstitial gas pressure and the thermal resistance of the interstitial gases.

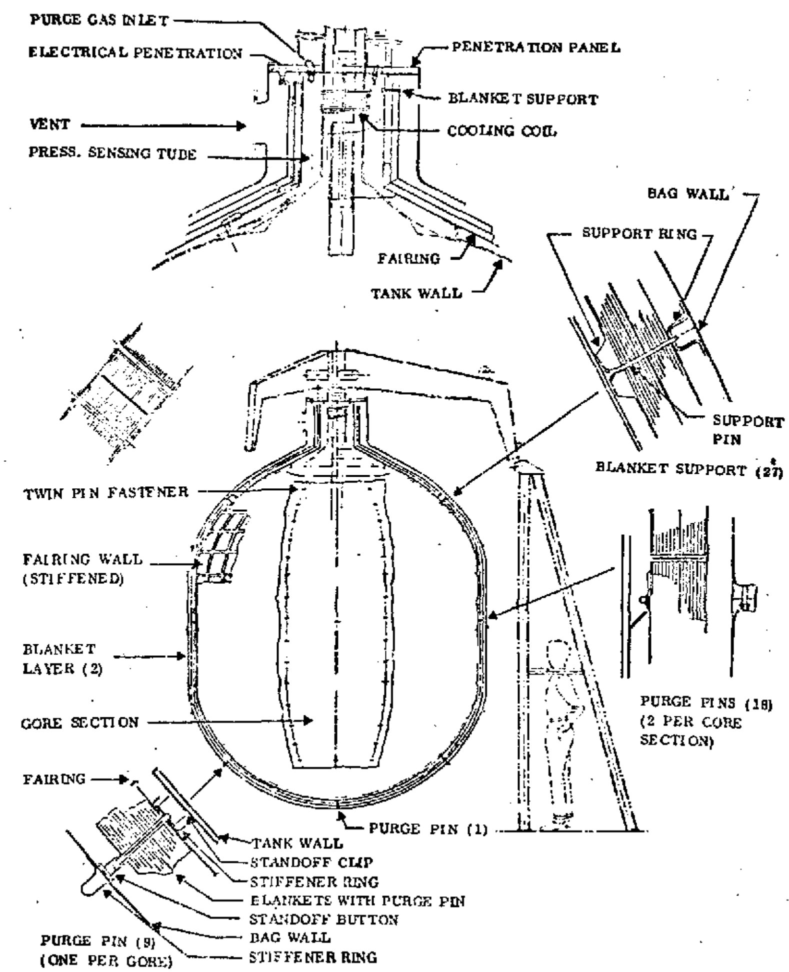
4. A 30 layers/inch Superfloc system with a vent valve of 2 inch diameter evacuated the MLI to 1×10^{-4} torr in 290 seconds.

5. A MLI system utilizing an internal fairing, purge bag and a complete purge gas distribution system was the selected system (Figure 1). The design characteristics and thermal performance are shown in Table 1.

Table 1. Superfloc MLI System Design and Performance Data. 105 Inch MSFC Calorimeter.

	DESIGN DATA	
Tank Surface:	300 ft^2	
Tank Capacity (LH_2):	450 ft^3	
Type of MLI:	30 gauge DGK Superfloc density 30 layer/inch. Calorimeter $K = 1.37 \times 10^{-5}$ Btu/hr ft °F; 0.00216 lb/ft^2; ρ = .778 lb/ft^3; $\rho k = 1.066 \times 10^{-5}$ Btu-lb/hr ft^4°R	
Face Sheet:	Beta glass scrim coated with Pyre M.L. enamel, goldized both sides, 2.602 oz/sq yd (.0182 lbs/ft^2), .007 in. av. thickness	
Purge Bag:	2 plys of Epoxy/PRD-49	
Fairing:	Epoxy/PRD-49	
Blankets:	2 blanket layers, 28 core sheets and 2 face sheets/blanket	
Gore Section:	40° gore, 9 required per blanket layer	
No. Support Pins:	27 total	
No. Twin Pin Fasteners:	345 per blanket layer PPO material	
No. Purge Pins:	28 total (PPO material)	
Length of Seams:	146 ft/blanket layer	
MLI System Layup Thickness:	3.75 inch	
MLI Weight:	197.5 lbs; or .66 lb/ft^2	
MLI Volume:	97 ft^3	
MLI Average Area:	318.4 ft^2	
System Density (ρ):	2.04 lb/ft^3	
Purge Gas Vent Valve:	2 in. dia.; Venting to 10^{-4} torr: 290 seconds	
	THERMAL PERFORMANCE	
530-37°F:	Heat Leakage (Btu/hr)	Percent of Total
Seams	2.77	11.7
Pins	9.81	41.5
MLI, Liquid Region	9.04	38.2
MLI, Dome Region	2.04	8.6
Entire System	23.66	100.0
Heat Flux:	0.0742 Btu/hr ft^2	
Effective Conductivity, K_{eff}:	5.0×10^{-5} Btu/hr ft °R	
System ρK Product:	10.2×10^{-5} Btu lb/hr ft^4 °R	

Figure 1. 105 Inch MSFC Calorimeter Superfloc Insulation System



SATURN S-II ADVANCED TECHNOLOGY STUDIES, CRYO STORAGE THERMAL IMPROVEMENT
Schwartz, R.,NAR, SD71-263, NAS7-200, February 1972

OBJECTIVE. - To develop a NARSAM (North American Rockwell Singly Aluminized Mylar) MLI system suitable for a reusable application vehicle, and install it on the NASA 105-inch diameter calorimeter to be furnished by and tested at NASA/MSFC.

PERTINENT WORK PERFORMED. - Detailed analyses of MLI effective thermal conductivity (k_e) were made, including degradation due to pins, butt joints and shield perforations. A complete 105-inch tank thermal model was developed and predictions of space-hold heat flows for the various components were made. Analyses were performed of heat leaks during the LH_2 fill transient, tank Y-ring temperatures, purge system performance and insulation venting and outgassing. A structural analysis of the insulation and purge systems was also performed. Material pumpdown characteristics (Figure 1) and thermal conductivity (Figure 2) were determined.

The embossed, perforated NARSAM MLI was cut into 22.5 degree gore sections and fabricated into five-layer blankets (Table 1). A total of 18 blanket layers were installed on the tank (total of 90 insulation layers) resulting in a thickness of 1.5 in. An internal purge manifold was attached to the tank, an aluminum support screen was positioned on standoffs, the insulation blankets were layed up on the screen, an external "tension membrane" net was installed, and an external purge tube framework was mounted and covered with a fiberglass reinforced Kapton polyimide bag (Figure 3). Three vent valves were installed and two differential pressure switches were added to protect the system against overpressure during transients.

MAJOR RESULTS. -

1. A full-scale flight-configured MLI cryogenic insulation system, complete with purge system and associated hardware, has been subjected to detailed analysis, designed, fabricated, and installed on a 105-inch diameter tank.

2. The predicted thermal conductivity (5.0×10^{-5} Btu/hr ft F) and conductivity-density product (8.8×10^{-5} Btu-lb/hr ft^4 F) of the installed NARSAM system are competitive with the best MLI systems tested to date on a large scale tank.

COMMENTS. -

As of June 1974 the NARSAM - insulated 105-inch tank has not been tested by NASA/MSFC. Thus, the design analyses and performance predictions have yet to be verified by test.

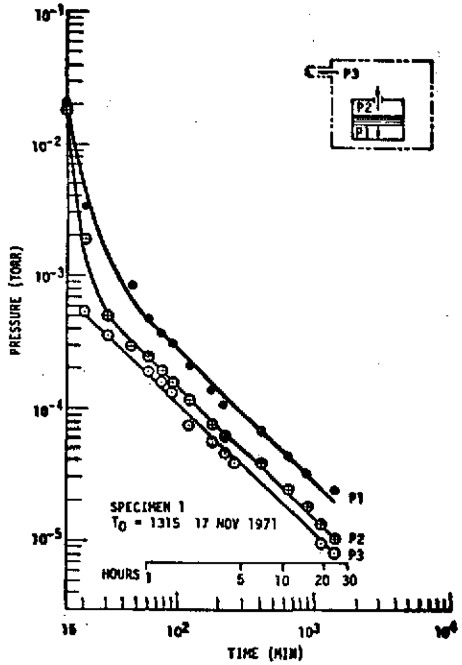


Figure 1. Pumpdown Characteristics of "As Received" Material.

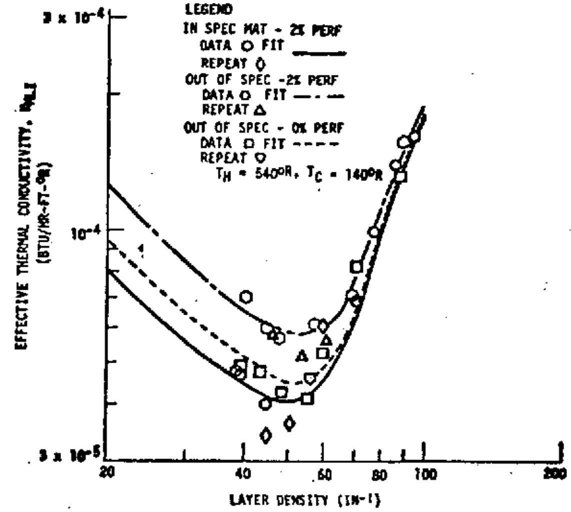


Figure 2. NARSAM-2 Flat Plate Calorimeter Data.

Table 1. NARSAM-2 MLI System Physical Characteristics.

NARSAM-2	Mylar Substrate Thickness Aluminum Thickness Layer Density ($\bar{N}$) Aluminum Surface Emittance (ϵ_{AL}) after Embossment and Perforation as Installed on Tank Percent Area Perforations Density of MLI Only (ρ_{MLI})	0.25 mil > 250 Å 60 Layers/in. <0.045; inner 1/3 layers <0.065; outer 2/3 layers 2 1.38 lb/ft^3
Natural Lay (On 105-inch tank)	Number of Layers on Tank Number of Layers per Module Number of Modules Number of Segments Around Tank Periphery Thickness of MLI Number of 0.214 Inch Diameter MLI Supports (12 mil wall) Density of MLI Including Outer Tension Membrane Weight	90 5 18 16 1.5 inches 156 1.75 lb/ft^3

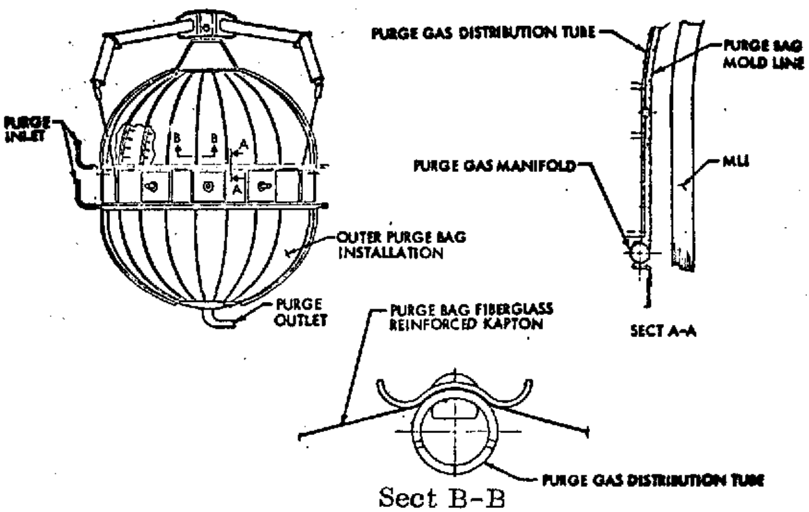


Figure 3. Outer Purge Bag.

LATERAL HEAT TRANSFER IN CRYOGENIC MULTILAYER INSULATION
Tien, C.L., et al, Univ. of California, Advances in Cryogenic Engineering, Vol. 18, 1972

OBJECTIVE. - To examine existing theories and present new analytical interpretations and experimental data.

PERTINENT WORK PERFORMED. - The paper examines existing theories and measurements of lateral heat transfer characteristics in an attempt to clarify and improve the current understanding. New analytical interpretations and experimental data are presented and earlier measurements by other investigators are analyzed. The physical system under investigation consists of two parallel conducting and radiating plates of finite length but infinite width at temperatures T_1 and T_2. The lateral heat transfer between the two ends is governed by the interaction of the lateral radiation tunneling between the two plates and conduction along the two plates. In order to obtain definite measurements an apparatus was set up and experiments were performed. The results consisted of two sets of data. The first set was obtained using thick sheets of blotting paper as the spacers. The thermal resistance of this paper is much larger than that of the aluminized Mylar shield; therefore, the measured lateral thermal conductivity corresponds to the shield thermal conductivity. The second set of data was obtained with densely packed Dexiglas spacers (twelve between each shield). It is shown that the densely packed Dexiglas system completely eliminates the radiation contribution. The measured shield conductivity was used to predict the effective lateral thermal conductivity, including radiation in accordance with the analysis performed in this program. An attempt was also made to compare the prediction with measurements reported in the literature.

MAJOR RESULTS. -

1. Numerical calculations based on simplified nodal techniques have shown good agreement with approximate analytical solutions.

2. Measured shield conductivity can be used to predict the effective lateral thermal conductivity (including radiation) in accordance with the equations developed in this program.

3. A comparison between calculated and measured values of effective thermal conductivity of (1) double aluminized Mylar with or without Dexiglas spacers, (2) crinkled, single aluminized Mylar, (3) double aluminized Mylar with Nylon net spacers is presented in Table I, II and III, respectively.

Table 1. **Comparison between Calculated and Measured Values of Effective Thermal Conductivity of Doubly Aluminized Mylar with or without Dexiglas Spacer**

	T_1, K	T_2, K	Measured k, W/cm-K	l	N	Measured k_e, W/cm-K	Predicted k_e, W/cm-K	Error, %
With no spacer	91.99	77.88	4.10	14.84	0.068	4.11	4.98	−21.4
	118.98	78.33	4.86	14.84	0.124	8.54	6.29	26.3
	149.85	79.24	5.75	14.84	0.210	13.99	8.11	42.0
	201.44	80.52	7.20	14.84	0.407	23.56	11.95	49.3
	246.71	82.81	8.50	14.84	0.633	35.66	16.49	53.8
With one layer of Dexiglas	121.74	77.85	4.91	23.71	0.161	6.33	6.74	−6.5
	129.64	78.00	5.14	23.71	0.186	6.95	7.23	−4.0
	149.69	78.22	5.68	23.71	0.260	9.12	8.54	6.3
	192.58	79.30	6.92	23.71	0.453	12.98	12.10	6.8
	247.74	80.41	8.44	23.71	0.791	19.91	18.21	8.5

Table 2. **Comparison between Calculated and Measured Values of Effective Thermal Conductivity of Crinkled, Single Aluminized Mylar**

T_1, K	T_2, K	k, W/cm-K	l	N	Measured k_e, W/cm-K	Predicted k_e, W/cm-K	Error, %
299.4	140.0	1.57	24.03	2.80	6.98	7.76	−11.5
202.8	139.4	1.48	24.03	0.92	4.26	4.56	−7.0
121.1	87.8	1.29	24.03	0.23	2.52	1.99	21.0
163.3	87.8	1.34	24.03	0.53	3.13	2.61	16.6
67.2	43.9	1.22	24.03	0.04	1.60	1.34	19.3
104.4	43.9	1.24	24.03	0.15	1.89	1.52	19.6
202.2	140.6	1.48	7.59	0.92	3.91	3.95	−1.0
267.2	177.8	1.57	7.59	1.98	5.11	5.61	−9.8

Table 3. **Comparison between Calculated and Measured Values of Effective Thermal Conductivity of Doubly Aluminized Mylar with Nylon Net Spacer**

T_1, K	T_2, K	k, W/cm-K	l	N	Measured k_e, W/cm-K	Predicted k_e, W/cm-K	Error, %
139.0	78.0	1.29	6.42	0.35	2.67	2.05	23.1
221.0	78.0	1.41	6.42	1.29	4.75	3.05	35.7
228.0	156.0	1.51	6.42	1.33	6.15	4.79	22.1
286.0	186.0	1.59	6.42	2.48	8.87	8.05	9.2
356.0	212.0	1.66	6.42	4.58	14.03	13.47	4.0
137.0	78.0	1.29	10.30	0.13	2.30	1.59	30.9
220.0	78.0	1.40	10.30	0.51	3.60	2.33	35.3
219.0	147.0	1.48	10.30	0.47	4.23	3.00	29.1
290.0	194.0	1.59	10.30	1.02	6.11	4.29	29.7
359.0	222.0	1.66	10.30	1.85	9.03	6.93	23.3

DESIGN IMPROVEMENT, QUALIFICATION TESTING, PURGE AND VENT INVESTIGATION, FABRICATION AND DOCUMENTATION OF A GAC-9 INSULATION SYSTEM
Shriver, C. R., et al, Goodyear, GER-14915 S/9, November 1971

OBJECTIVE. - To determine the purge and vent characteristics of the GAC-9 (Goodyear) insulation system.

PERTINENT WORK PERFORMED. - This report summarizes the research, development, and testing that were accomplished during the contract effort. Most of the work was directed toward determining the purge and vent characteristics of the GAC-9 insulation system. Design improvement studies involved investigation of perforated aluminized Mylar radiation shields, methods of drop thread* mechanization and laboratory tests to obtain purge and gas flow characteristics parallel to and across the layers of GAC-9 insulation. The laboratory tests were conducted on 30 cm (12 inch) diameter cylinder and disc specimens to obtain basic engineering data on purge gas flow through GAC-9 insulation. These data were required to design and demonstrate a purge system for the GAC-9 insulation on a 76 cm (30-inch) diameter calorimeter. Additional testing was conducted on a 94×122 cm (37×48 inch) GAC-9 insulation panel assembly comprising two panels that butt-jointed together. Subscale tank tests were performed utilizing the 76 cm (30 inch) diameter double guarded calorimeter for cryogenic tests to verify laboratory flow test results and demonstrate a purge system design. Other work included thermal conductivity testing using a 15 cm (6 inch) diameter flat plate calorimeter, thermal conductivity tests of a simulated penetration on the 76 cm (30 inch) diameter calorimeter, and a feasibility study of techniques for mechanization of insulation panel drop thread installation.

MAJOR RESULTS. -

1. Flow coefficient measurements obtained from laboratory tests of helium purge gas flow parallel to the layers of GAC-9 insulation compared favorably with flow coefficients obtained theoretically.

2. For large scale GAC-9 insulation panels, the capability of venting purge gas broadside as well as parallel to layers (via joints) will be beneficial to the rapid reduction of insulation internal pressure.

3. Subscale tank tests for ground hold and space conditions verified the ability of GAC-9 insulation to be purged with gaseous helium during ground hold and vented during ascent and space conditions.

4. The insulations performed their function with no evidence of deterioration.

5. LH_2 boil-off versus time for the GAC-9 insulation is presented in Figure 1.

*The function of drop threads is to hold the layers of the GAC-9 panel together during panel trimming and handling.

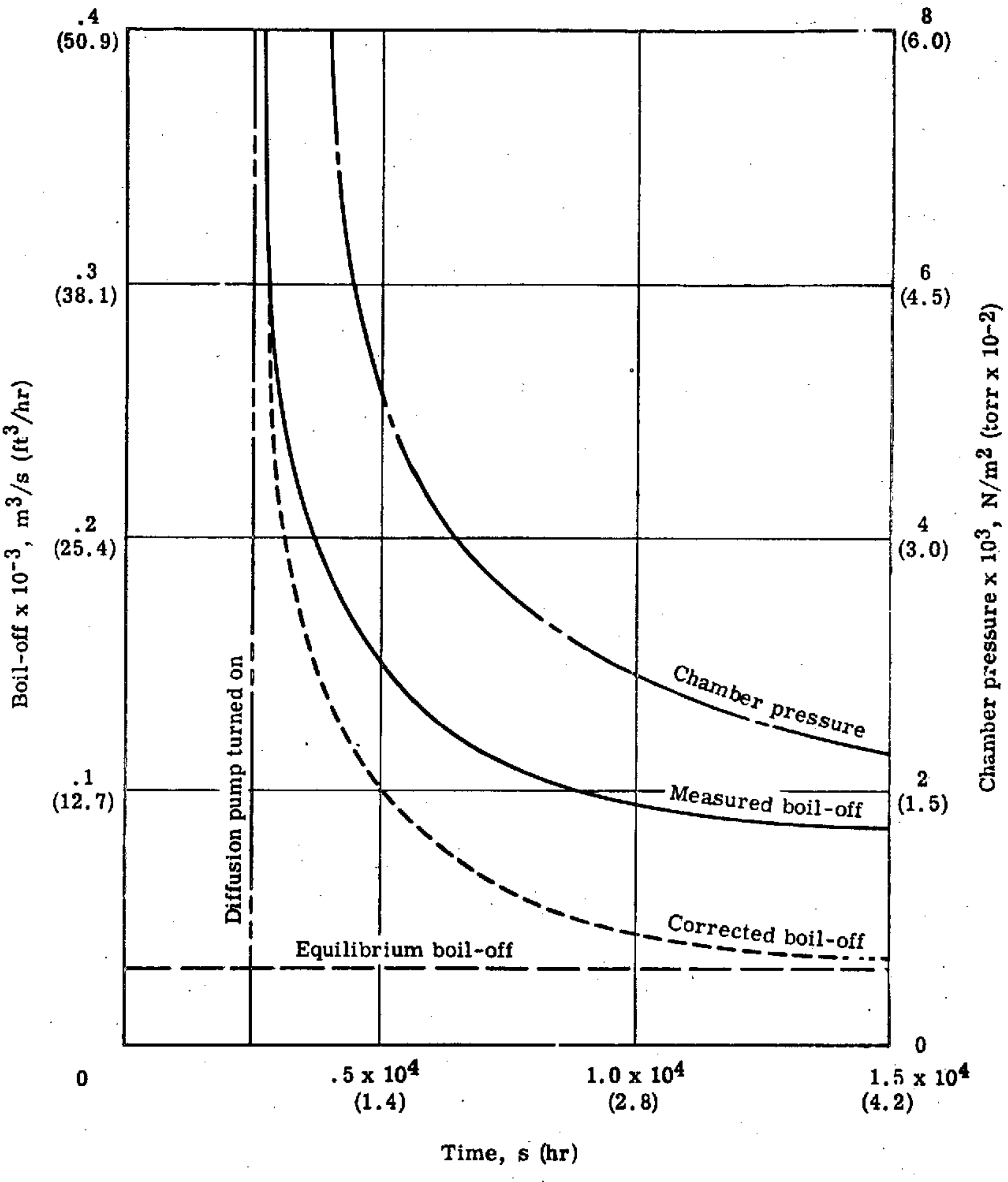


Figure 1. LH_2 Boil-Off Versus Time - GAC-9 Insulation System Test No. 4.

TRANSIENT THERMAL PERFORMANCE OF MULTILAYER INSULATION SYSTEMS DURING SIMULATED ASCENT PRESSURE DECAY
Sumner, I. E.,Maloy, J.E., NASA-LeRC, TN D-6335, July 1971

OBJECTIVE. - To measure ground hold, launch transient, and space hold heat fluxes for three MLI composites during a simulated Saturn V launch vehicle ascent pressure decay.

PERTINENT WORK PERFORMED. - A 30-inch diameter double guarded cylindrical calorimeter was used to obtain steady state and transient heat flux and pressure decay data on three insulation systems.

1. 30 layers of DAM/Dexiglas over a 0.5-inch thick fiberglass mat sublayer
2. 30 layers of DAM/silk net over a 0.75-inch thick fiberglass mat sublayer.
3. 30 layers of DAM/Dexiglas over a 0.75-inch thick polyurethane foam sublayer.

In each case the MLI and sublayer were separated by a vapor barrier, and a Dacron net tension membrane was wrapped around the MLI (Figure 1). Attempts at rapid evacuation after purging the fiber sublayer with GHe and the MLI with GN_2 (having a lower conductivity) were unsuccessful due to N_2 condensation on the vapor barrier. Therefore GHe was used in both areas. Repeatability was hard to achieve. Interstitial pressure was measured by large L/D tubes and the data were corrected for thermomolecular pumping effects. A series of valves and pumps was used to duplicate the Saturn pressure decay profile. A typical result is shown in Figure 2. Curves of pressure versus time, heat flux versus time, and both steady state and transient heat flux versus pressure are presented.

MAJOR RESULTS. -

1. Due to thermal effects,a fibrous sublayer would have to be "substantially overdesigned" to avoid GN_2 condensation.
2. Comparisons of steady state and transient heat flux as a function of interstitial pressure indicated that a quasi-steady-state heat transfer condition existed at each point during pumpdown.
3. Tests with the foam system were more successful. Ground hold fluxes were lower and there was no significant structural degradation due to thermal cycling.
4. Higher integrated heat flux for the foam system (Figure 3) is due to excessive foam sensible heat changes resulting from non-optimization of foam thickness.
5. Interstitial pressure decayed rapidly to 10^{-2} torr but required approximately 2 hours to drop to less than 10^{-3} torr.

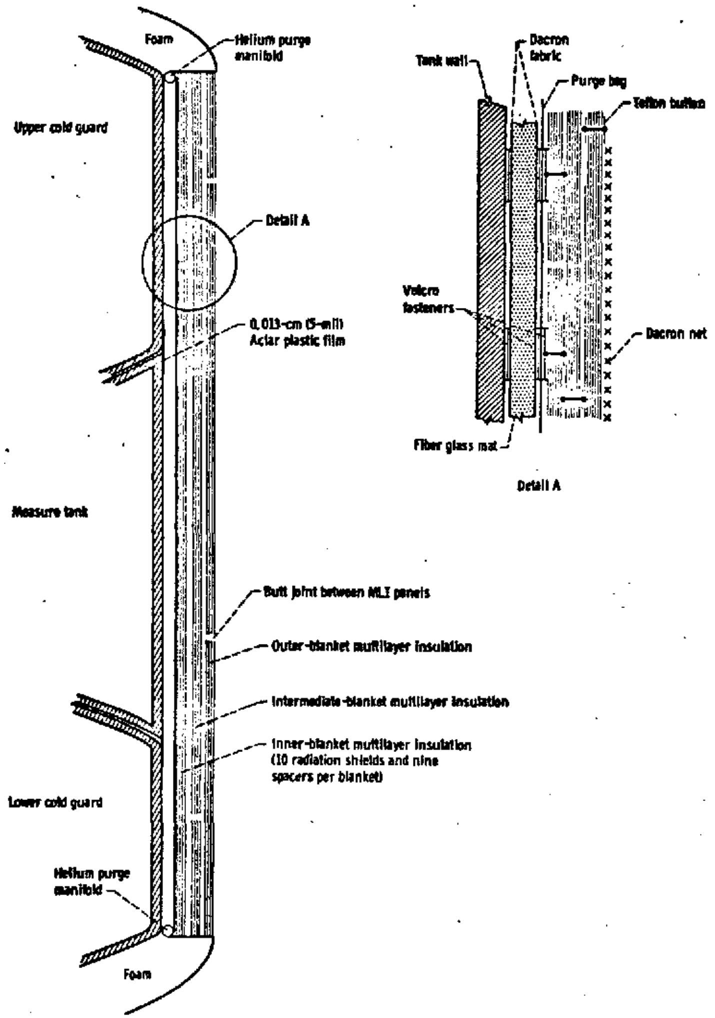


Figure 1. Installation of multilayer insulation (MLI) system on cylindrical calorimeter

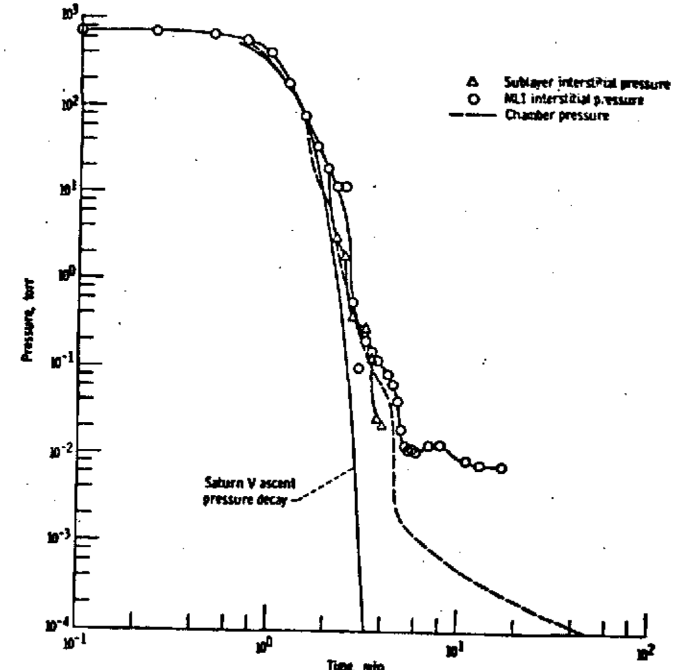


Figure 2. Pressure as function of time for aluminized Mylar/silk netting/ fiber glass sublayer insulation system. Helium purged for ground hold.

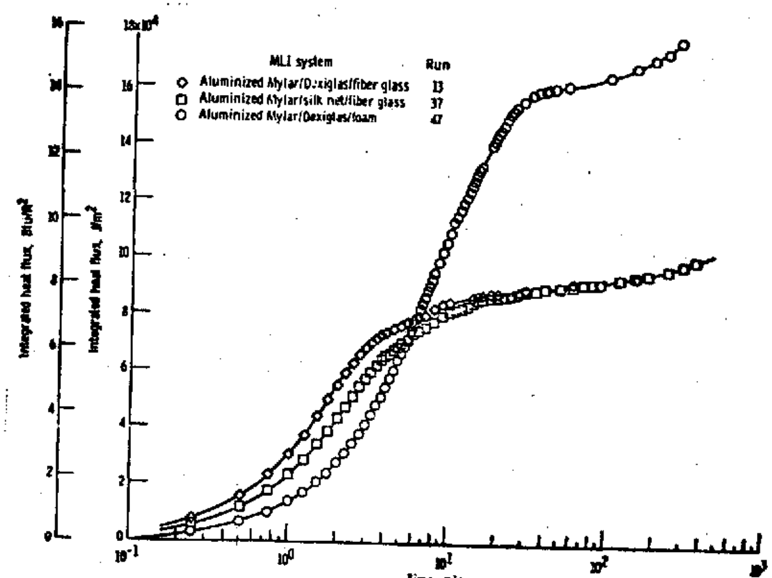


Figure 3. Integrated heat flux as function of time for helium-purged multilayer insulation systems.

STUDY OF THERMAL CONDUCTIVITY REQUIREMENTS
VOLUME I, II and III
O'Neill, M. J., McDanal, A.J., LMSC, HREC-6189-1, NAS 9-26189, June 1971

OBJECTIVE. - To analytically and experimentally determine the thermal conductivity of various insulation materials.

PERTINENT WORK PERFORMED. Thermal conductivity and compression tests were conducted for six multilayer insulation (MLI) materials to obtain temperature - dependent thermal conductivity data and compressibility versus layer density data. The MLI materials tested were double-aluminized Mylar (DAM) and Tissuglas, DAM and Goodyear Aerospace Company GAC-9 white foam, DAM and Dacron net, Superfloc, DAM and Nomex net, and DAM and CEREX (Monsanto) spunbond Nylon. Empirical correlations were developed which fit the previously defined surfaces (carpet plots). An analytical and experimental study was conducted to develop a new MLI composite by utilizing a net spacer which was nearly as optimum a spacer as possible. Experimental data obtained during the test program included physical density measurements and the response of each composite to mechanical loading. The range of test temperatures was -200 to +200 °F and the layer density range included all practical values of layer density. A subscale cryogenic tank with a MLI composite was analyzed and tested to determine the applied thermal conductivity of the MLI. The analytical predictions were made prior to the tests and were used in the development of the test plan and selection of instrumentation.

MAJOR RESULTS. -

1. The test calorimeter used, operated with unprecedented accuracy (Table 1).
2. The test automation system functioned with great ease and economy.
3. A new and untried spacer material, CEREX, was located and tested with encouraging results.
4. Double aluminized mylar (DAM) was chosen as the reflective shield to be used with the six spacers because of its extremely good thermal radiation properties.
5. The analytical technique used in the subscale tank pre-test prediction was correct.
6. Conducting tests at variable rates by using a heater to control the flow rate allows the asymptotic $\dot{Q}_{MLI}$ to be determined and used to calculate applied thermal conductivities.
7. Cooling the vent line top did not completely eliminate the vent line heat leak for the tank considered.

THERMAL DATA FOR SUPERLFOC

Layer Density $\bar{N}$ (Layers/in)	Chamber Pressure (Torr)	ΔT (°F)	Mean Temperature (°F)	Thermal Conductivity (K x 10^5) (Btu/hr-ft-°F)	Density x Thermal Conductivity (ρK x 10^5) (Btu/hr-ft-°F) (lbm/ft^3)	Probable Error ± (%)
80	2.0×10^{-9}	47.0	-202.3	1.93	3.65	0.924
80	1.0×10^{-8}	50.9	- 66.1	5.42	10.24	6.51
80	6.2×10^{-7}	26.1	96.8	10.24	19.36	0.988
80	5.2×10^{-7}	36.7	199.0	17.07	32.26	7.53
160	1.5×10^{-8}	24.8	-194.6	2.78	10.51	1.51
160	2.4×10^{-8}	49.8	- 68.3	5.13	19.37	1.53
160	3.0×10^{-7}	32.0	94.9	8.72	32.93	1.52
160	4.0×10^{-7}	34.5	197.8	11.31	42.73	1.69
200	3.0×10^{-8}	21.4	-190.5	2.43	11.48	1.85
200	1.6×10^{-7}	37.4	- 58.4	6.65	31.41	1.86
200	3.0×10^{-7}	26.4	96.9	10.01	47.29	1.86
200	3.3×10^{-7}	36.5	198.2	15.03	71.00	2.05

THERMAL DATA FOR DAM/DACRON NET

Layer Density $\bar{N}$ (Layers/in)	Chamber Pressure (Torr)	ΔT (°F)	Mean Temperature (°F)	Thermal Conductivity (K x 10^5) (Btu/hr-ft-°F)	Density x Thermal Conductivity (ρK x 10^5) (Btu/hr-ft-°F) (lbm/ft^3)	Probable Error ± (%)
120	6.0×10^{-7}	20.6	-193.0	1.36	5.14	1.12
120	8.0×10^{-7}	34.9	- 56.2	1.95	7.37	1.27
120	6.0×10^{-7}	23.4	86.9	8.62	32.65	1.90
120	8.0×10^{-7}	38.8	198.9	20.18	76.44	2.92
160	6.0×10^{-7}	39.5	-200.8	1.77	10.71	1.54
160	3.0×10^{-7}	49.0	- 61.5	2.65	16.02	1.88
160	3.5×10^{-7}	34.9	97.1	5.23	31.66	1.64
160	4.5×10^{-7}	38.3	198.8	9.92	60.03	1.74
200	8.0×10^{-8}	29.4	-197.7	1.96	14.83	1.62
200	1.5×10^{-7}	23.5	- 62.8	2.77	20.92	1.97
200	2.0×10^{-7}	17.0	87.8	4.53	34.22	1.95
200	7.0×10^{-7}	33.6	198.5	10.15	76.70	1.83

THERMAL DATA FOR DAM/CEREX

Layer Density $\bar{N}$ (layers/in)	Chamber Pressure (torr)	ΔT (°F)	Mean Temperature (°F)	Thermal Conductivity (K x 10^5) (Btu/hr-ft-°F)	Density x Thermal Conductivity (ρK x 10^5) (Btu/hr-ft-°F) x (lbm/ft^3)	Probable Error ±(%)
75	3.5×10^{-6}	41.0	-190.1	2.29	8.27	1.45
75	5.6×10^{-6}	50.3	0.4	4.42	15.97	1.63
75	6.0×10^{-6}	36.9	198.8	13.03	47.07	1.87
100	1.4×10^{-8}	40.4	-186.8	3.10	14.91	1.91
100	1.0×10^{-7}	43.9	7.2	5.11	24.58	1.90
100	2.4×10^{-6}	29.7	194.0	18.49	88.92	2.23
150	*$\leq 8.0 \times 10^{-6}$	32.2	-182.1	4.21	30.33	2.78
150	*$\leq 8.0 \times 10^{-6}$	35.6	- 17.8	7.07	50.93	2.78
150	*$\leq 8.0 \times 10^{-6}$	27.5	198.8	23.54	169.56	2.86

*Exact pressure reading was not obtained due to faulty pressure gage.

LIGHT WEIGHT MODULAR MULTI-LAYER INSULATION
Nies, G.E., Linde, NASA CR-72856, NAS3-12045, June 1971

OBJECTIVE. - (1) To design a full scale, lightweight self-evacuating multilayer insulation (SEMI) system for liquid hydrogen tankage considering thermal and structural loads, and (2) to design and fabricate a scale model of the full scale system for thermal and structural evaluation tests.

PERTINENT WORK PERFORMED. - A SEMI system was designed for a tank 10 feet in diameter by 20 feet in length with hemispherical heads. The structural and thermal loadings imposed on the insulation system were determined during the design phase. A scaled down model of the full size insulation system was designed and fabricated. The insulation system consisted of CO_2 filled panels composed of seven layers of open cell rigid polyurethane foam spacers and six aluminized Mylar radiation shields enclosed in an aluminized Mylar composite casing. The scale model insulation system was of a three layer design with panels circumferentially wrapped on the cylindrical portion. The forward bulkhead and simulated shirt section was insulated with panels installed in a polar shingle fashion. Subscale testing performed to evaluate system components included vibration testing of 12 in. by 18 in. panels; quality control checks on casing materials, foam spacers, and radiation shields and evaluation of Velcro attachments. Thermal testing of the model system was performed at NASA Plumbrook. Dynamic tests were conducted at NASA Goddard Space Flight Center. The dynamic testing was a combined acceleration, vibration, acoustic and launch vacuum profile evaluation.

MAJOR RESULTS. -

1. The system performed as designed with the thermal performance being the same when measured before and after the dynamic tests.
2. A heat flux of 1.3 BTU/hr-ft^2 was measured for both tests in the space condition.
3. The performance was slightly better than that predicted by the computer program using flat plate data, corrected for panel edge effects.
4. During dynamic testing, pressure build-up behind the panel (of an unknown cause) resulted in casing failure on two panels, and minor damage to one of the panels.
5. Except for the indicated damage, the system functioned nominally in both mechanical and thermal performance.
6. The SEMI system of cryopumpable pre-fabricated panel insulation is applicable to hydrogen tankage.
7. The calculated full scale insulation performance is shown in Table 1.

COMMENTS. - Methods of satisfactorily sealing must be developed if the SEMI system is to be successfully applied, especially if a reusability requirement exists.

TABLE 1

CALCULATED FULL SCALE INSULATION PERFORMANCE

	AVERAGE HEAT FLUX Btu/hr.ft^2 (Watts/M^2) Compressed @ 1 atm.	Uncom-pressed	TOTAL HEAT LEAK Btu/hr. (Watts) Compressed @ 1 atm.	Uncom-pressed
I. Computer Analysis [a]				
A. Best Performance				
(1) Circumferential-12 panel	7.05	.53	3177.4	236.9
(2) Head - 3 panel system	7.95	.54	701.4	47.1
TOTAL	7.2(22.7)	.53(1.67)	3879.8(1138.0)	284.0(83.3)
B. Realistic				
(1) Circumferential-18 panel	7.30	.60	3286.2	270.0
(2) Head - 6 panel	8.28	.61	731.1	53.7
TOTAL	7.45(23.5)	.60(1.89)	4017.3(1177.0)	323.7(94.8)
C. Poorest Performance				
(1) Circumferential-18 panel	7.30	.60	3286.2	270.0
(2) Head - 12 panel	8.96	.82	791.5	72.5
TOTAL	7.58(23.9)	.64(2.01)	4077.7(1195.0)	342.5(100.4)
II. Flat Plate Data (NAS 3-7953) [b] (CR 72363 - pg.13) PT-6 Configuration				
TOTAL	6.47(20.4)	.13 (.41) @ .01 psi	3480(1020.0)	70.0(20.5)
III. Calorimeter (Ref. CR 72363)				
Total - Computer [a]	-	.45(1.42)	-	242.0(71.0)
Total - Test	10.0 [c] (31.5)	.63(1.97)	5384.0 [c] (1580.0)	339.5(99.5)

(a) Based on normal conductivity numbers computed from flat plate data.

(b) Flat plat data does not account for edge losses therefore numbers are the theoretical low limit for this insulation.

(c) Calorimeter data for the compressed case was not obtained at steady state conditions.

EXPERIMENTAL EVALUATION OF A PURGED SUBSTRATE MULTILAYER INSULATION SYSTEM FOR LIQUID HYDROGEN TANKAGE
DeWitt, R.L., Mellner, M.B., NASA-LeRC, TN D-6331, May 1971

OBJECTIVE. - To perform additional ground-hold and space-hold thermal performance tests of a composite insulation system developed by LMSC under contract NAS3-4199.

PERTINENT WORK PERFORMED. - The test configuration consisted of (1) an 82.6 inch diameter spherical test tank (Figure 1), (2) an 0.5-inch thick fiberglass mat covered with an Aclar bag, and (3) various numbers of 10 layer blankets of 0.25 mil double aluminized Mylar radiation shields separated by Dexiglas spacers (Figure 2).

A total of seven space-hold thermal tests were performed. The effects of removing and reinstalling blankets, adding blankets, and multiple thermal cycling on system performance were investigated. Five ground hold tests were made with GHe in the substrate and GN_2 in the MLI, and one test with GHe in both areas.

MAJOR RESULTS. -

1. Thermal cycling had no "serious" effect on system space-hold thermal performance (Figure 3).

2. Space-hold tests after removing and reinstalling the three MLI blankets showed a 55% increase in heat flux.

3. Of the heat flowing through the insulation during space hold testing approximately 12 percent is due to radiation and 88 percent to solid conduction (Figure 3).

4. Successful use of GN_2 open purges around a LH_2 tank is difficult. GN_2 condensation and outgassing resulted in unexpectedly high heat fluxes.

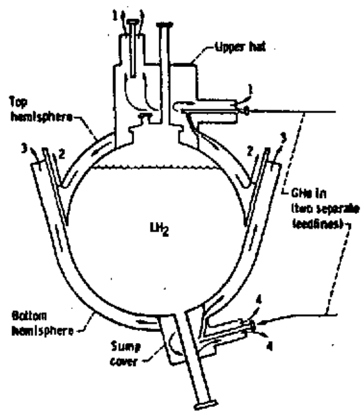
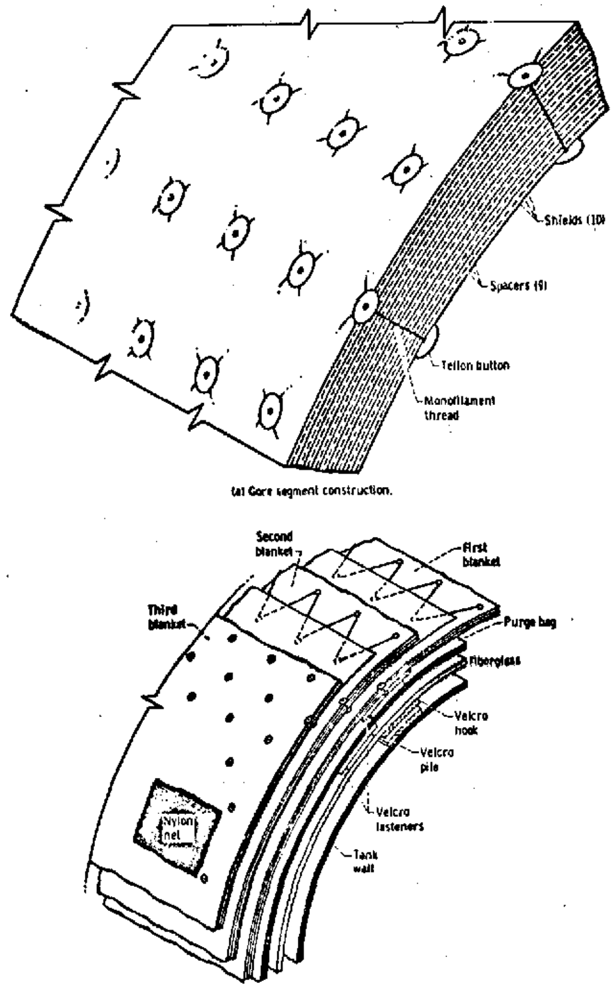


Figure 1. Schematic of 82.6-inch tank



(b) System cross section on tank hemisphere.

Figure 2. Insulation system construction.

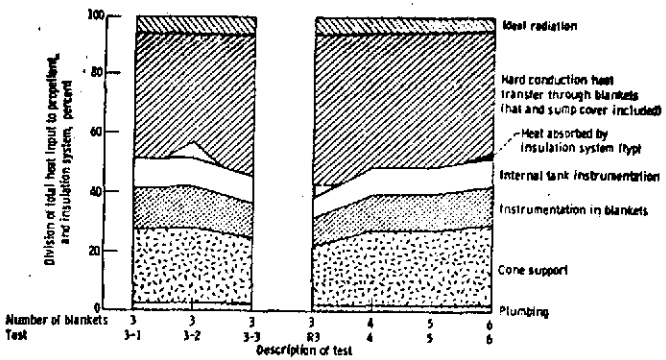


Figure 3. Distribution of total heat input (with ideal radiation) to propellant tank, space-hold condition.

THERMAL PERFORMANCE OF MULTILAYER INSULATIONS
Keller, C. W., LMSC, NASA CR-72747, NAS 3-12025, April 1971

OBJECTIVE. - To investigate the thermal performance of multilayer insulations (MLI) which may be used for the long term storage of cryogens in space.

PERTINENT WORK PERFORMED. - The total scope of work (data, results and conclusions) was presented in two volumes. Both volumes are summarized below. The first volume, NASA-CR-72605, task I and II, covers the analytical and experimental studies to assess the thermal performance of four multilayer insulations: double aluminized Mylar/silk net, double goldized Mylar/silk net, crinkled single-aluminized Mylar and double aluminized Mylar Tissuglas. Heat flux and optical property measurements were obtained for a wide range of variables including number of layers, compressive loads, thickness and boundary temperatures. Equations were developed which characterize the thermal performance of each insulation. During the final task, the double-goldized Mylar/double silk net MLI system was selected, fabricated, and installed on a 4-ft diameter calorimeter and tested in a vacuum environment. Thermal performance tests were conducted for hot boundary temperatures of 500° R and 610° R and for cold boundary temperatures of 140° R and 37° R. Each combination of these temperatures was imposed on 20, 10 and 5 shield thicknesses of the composite system in place on the tank. Results of these tests were correlated with the predictions.

MAJOR RESULTS. -

1. All four insulations exhibited reproducibility of heat flux as a function of applied pressure within ±20%.
2. Reproducibility of heat flux as a function of layer density was found to be within ±30% for the silk net and Tissuglas systems and ±80% for the crinkled system.
3. It was found that for a 30 day mission the Tissuglas system was optimum if the design layer densities were achieved. The goldized Mylar/silk net was optimum if the actual layer densities exceeded the design values by 30% or more.
4. The predicted values of the test results using double goldized Mylar/silk net insulation were within +50 to -30% of the measured heat-flux values (Table 1).
5. It appeared that MLI density has significantly changed between test runs by gas flow forces imposed during evacuation and repressurization cycles.

Table 1. Comparison of Measured and Predicted Heat Flux Values for the Tank Calorimeter Tests

Utilizing Double-Goldized Mylar/Silk Net

Test Run Number	Total Number of Shields	Boundary Temperatures[(a)] T_H °R (°K)	T_C °R (°K)	Preliminary Predicted Av. Heat Flux[(b)] q_{P1} Btu/hr ft²	(w/m²)	Final Predicted Av. Heat Flux[(c)] q_{P2} Btu/hr ft²	(w/m²)	Measured Av. Heat Flux[(d)] q_M Btu/hr ft²	(w/m²)	Preliminary Comparison $100(q_M/q_{P1}-1)$ (Percent)	Final Comparison $100(q_M/q_{P2}-1)$ (Percent)
1	20	501(279)	137(76)	0.335	(1.056)	0.345	(1.087)	0.447[(e)]	(1.409)	+33	+30
2	20	615(342)	137(76)	0.552	(1.740)	0.585	(1.844)	0.879[(e)]	(2.771)	+59	+50
3	20	502(279)	36(20)	0.340	(1.072)	0.369	(1.163)	0.343	(1.081)	+ 1	- 7
4	20	611(340)	36(20)	0.562	(1.771)	0.597	(1.882)	0.719	(2.266)	+28	+20
5	10	499(277)	137(76)	0.422	(1.330)	0.439	(1.384)	0.510	(1.608)	+21	+16
6	10	611(340)	137(76)	0.722	(2.276)	0.776	(2.446)	1.085	(3.420)	+50	+40
7	10	496(276)	36(20)	0.435	(1.371)	0.458	(1.444)	0.650	(2.049)	+49	+42
8	10	612(340)	36(20)	0.732	(2.307)	0.805	(2.537)	1.078	(3.398)	+47	+34
9	5	489(272)	137(76)	0.610	(1.923)	1.106	(3.486)	0.900	(2.837)	+48	-19
10[(f)]	5	611(340)	137(76)	1.140	(3.593)	2.003	(6.313)	1.532	(4.829)	+34	-24
11	5	506(281)	36(20)	1.720	(5.421)	1.571	(4.952)	1.522	(4.797)	-12	- 3
12	5	615(342)	36(20)	1.140	(3.593)	2.112	(6.657)	1.520	(4.791)	+33	-28

Notes:

(a) Nominal T_H values were 500 and 610°R (278 and 339°K); nominal T_C values were 140 and 37°R (77 and 20°K); values shown were measured at equilibrium test conditions

(b) Based on nominal boundary temperatures, pre-test layer densities, and total number of shields

(c) Based on measured boundary temperatures, average pre-test and post-test layer densities, and corrected number of shields

(d) Based on measured boiloff flowrates and the insulation surface area at mid-thickness

(e) Data shown were corrected for effect of vacuum chamber pressure above 1 x 10^{-5} torr

(f) Data shown are for rerun of this test

MULTILAYER INSULATION PANELS
Lofgren, C. L., Gieseking, D.E., Boeing, NASA CR-72857, NAS3-14179, April 1971.

OBJECTIVE. - To fabricate a panelized insulation system for three separate tanks.

PERTINENT WORK PERFORMED. - Phase I consisted of the design and fabrication of tools for fabricating MLI panels for a 87.9 inch hydrogen tank, a 69.3 inch FLOX tank, and a 54.5 inch liquid methane tank. Thirty glass/polyester resin and glass/high temperature resin tools were fabricated. During phase II, preparatory work was conducted on the MLI blanket components prior to fabrication of the production panels. This work included (1) forming of the aluminized Mylar without degradation of the aluminized surface, (2) forming of the MLI cover material into a female mold, and (3) forming of silk net spacer material by wetting, stretching, and retaining it over a contoured male tool until dry. Phase III consisted of the fabrication, assembly, inspection and delivery of the MLI systems. The Schjeldahl X-850 cover sheet was formed by thermal vacuum means using an infrared lamp bank. The aluminized Mylar was thermally vacuum formed by assembling alternate layers of positioning "cloth" and reflective shields and sealing them in a pillow in the forming tool. The silk netting was formed as described above. The formed inner shell of the alternate plies of 2 silk netting layers and one aluminized Mylar shield were applied over a mandrel until 15 radiation shields and 16 separator plies were applied. The final trim was made using trim templates. Button pins and grommet washers were used to complete the assembly.

MAJOR RESULTS. -

1. The program was successful in that it extended the state-of-the-art in cryogenic MLI from hand layup on the unit to an interchangeable panelized system.
2. The systems had consistent density and dimensional accuracy.
3. The systems were designed to be easily removed and replaced in the field with a minimum of technical assistance.
4. Forming of the Schjeldahl X-850 structural shell material was the most significant accomplishment of material development.
5. Softening of the sizing of the silk net spacer material with water allowed the material to drape and conform to the compound contour without wrinkling.
6. Aluminized Mylar can be formed to the required contour but not without degradation of emissivity.

THERMAL ANALYSIS OF CUSTOMIZED MULTILAYER INSULATION ON AN UNSHROUDED LIQUID HYDROGEN TANK

Johnson, W.R., Cowgill, G.R., NASA-LeRC, TN D-6255, March 1971

OBJECTIVE. - To determine analytically the spacehold thermal performance of various multilayer insulation (MLI) configurations on the upper half of a liquid hydrogen tank.

PERTINENT WORK PERFORMED. - The hypothetical vehicle assumed was sun-oriented, with the LH_2 tank in the shadow of the vehicle payload (Figure 1 and 2). Various configurations were evaluated to determine the optimum combination of the concepts. The CINDA-3G* computer program was used in the analysis. The physical data required for solving the heat flow equations were 1), the geometric radiation view factor between any two surfaces of the enclosure, 2) the surface emissivities, 3) surface areas and the temperatures of all surfaces. The MLI was arbitrarily divided into 10 annular segments from the polar cap to the equator of the tank (Figure 3). For specified temperatures on all 10 segments of the MLI, a net heat flow into the MLI was obtained. The model used to compute the heat flow through the MLI itself was the 45° wedge portion shown in Figure 3. Since the MLI was completely symmetrical over the top half of the tank, the computed thermal performance of the wedge portion was multiplied by 8 to obtain the results for the entire top half of the tank.

MAJOR RESULTS. -

1. The space-hold thermal performance of a constant thickness MLI can be significantly improved by
   - (a) Using a variable MLI thickness over the surface of the tank
   - (b) Using several high-lateral-thermal conductivity shields
   - (c) Increasing the MLI surface emissivity in certain areas
   - (d) Eliminating any shroud around the LH_2 tank
   - (e) Continuously orienting the vehicle such that the payload is between LH_2 tank and the sun.
2. Reduction in MLI system weight
3. Improvement in venting capability of the MLI during vehicle ascent
4. MLI can be easily fabricated and installed on the tank.

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*Chrysler Improved Numerical Differencing Analyzer for Third Generation Computers.

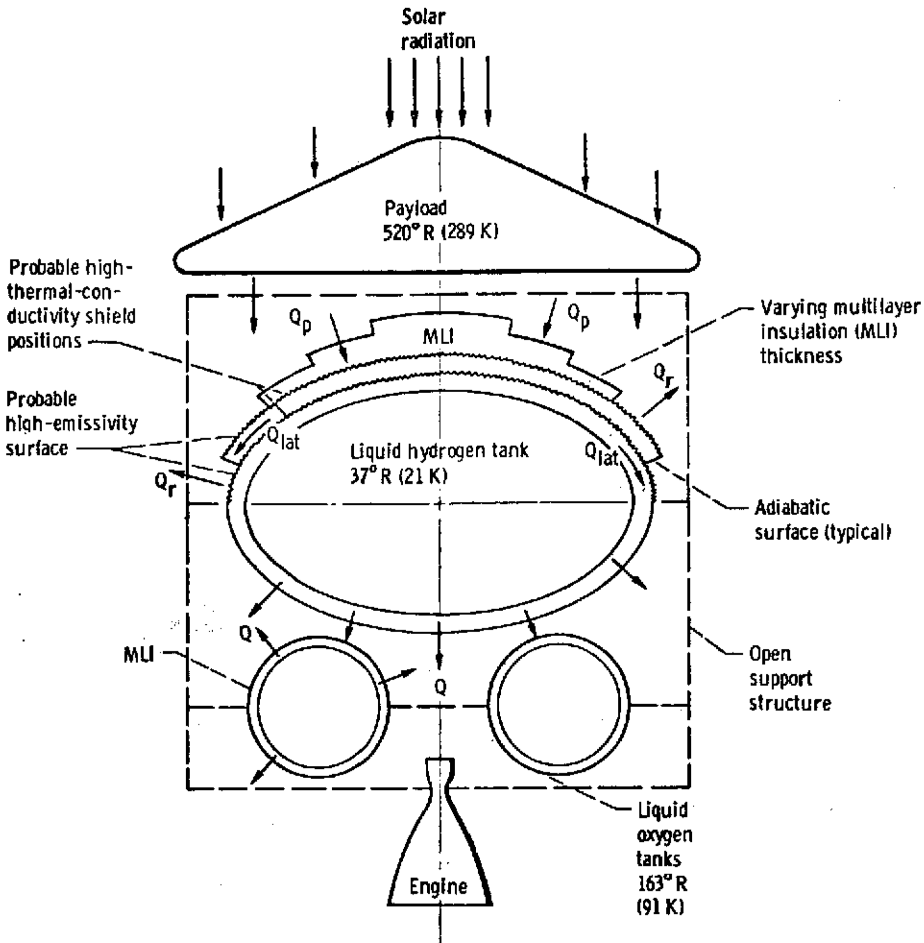


Figure 1. Vehicle Configuration

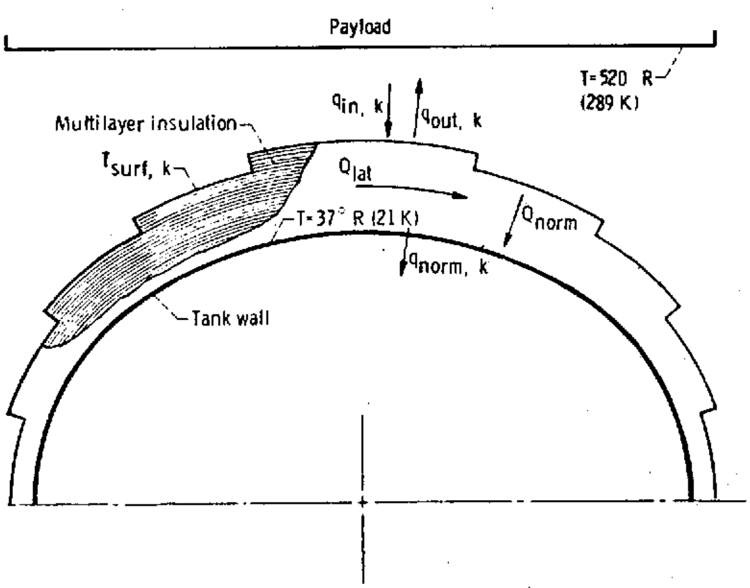


Figure 2. Cross-sectional View of Model

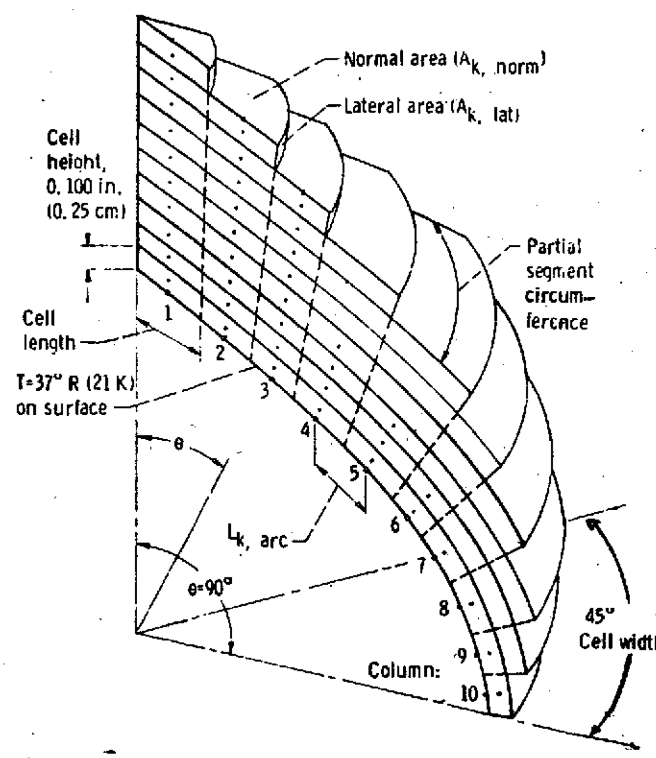


Figure 3. 45° Segment of Multilayer Insulation Divided Into Cells

FLIGHTWORTHY, HIGH PERFORMANCE INSULATION DEVELOPMENT
Leonhard, K.E., (GD/C), Hyde, E.H., (NASA-MSFC), "Cryogenic Technology" Magazine Vol. 7, No. 1 Jan-Feb., No. 2 Mar-Apr 1971.

OBJECTIVE. - To review the development of flightworthy multilayer insulation (MLI) systems.

PERTINENT WORK PERFORMED. - Basic MLI materials which have been used by the government and industrial organizations were reviewed and listed in Table 1. The radiation shield material most commonly considered was double aluminized mylar in two thicknesses 0.25 and 0.15 mil and an emissivity between 0.02 and 0.03. The spacer materials investigated included Silk and Nylon netting, Dexiglas, Tissuglas, Dacron fibers and crinkling of the radiation shields. The ability of insulation systems to resist compression and to permit rapid evacuation of interstitial gases was studied.

Five MLI systems which have been developed and tested on large scale tanks are shown in Table 2 and their performance is summarized. In order to compare the results it was necessary to recalculate the thermal performance based on common hot and cold temperatures of 525°R and 40°R, respectively. New development programs were directed toward developing of a reusable MLI system.

MAJOR RESULTS. -

1. From Table 1, the value of the "ρk" product of Superfloc was the lowest for all materials compared.
2. One disadvantage of the aluminized coated plastics was that moisture has deleterious effects on aluminized plastics. However, with proper GN_2 and GH_e purging during storage, this material was acceptable for "one shot" applications.
3. Purging of MLI either with hot GH_e or GN_2 reduces outgassing.
4. Test results indicated that below a compressive load of 2.5×10^{-2} psi, Superfloc was the most effective spacer. It has 97% recovery.
5. The greater the radiation shield spacing, the better the evacuation.
6. Table 2 gives the results of the systems tested. The table shows that the ρk of double aluminized Mylar (DAM) with Dacron needles (Superfloc) was the lowest.
7. Goldized films may be required for reusable applications since gold is more resistant to degradation due to moisture effects than is aluminum.

Table 1. Basic Candidate Insulation Materials

Configuration	Radiation Shield		Spacer		Density ρ		Conductivity, K	ρK
	Mat'l	Mil	Material	Mil	Layers/In.	lb/cu ft	(540°-140°R) Btu/hr ft °R	(Btu-lb/hr ft⁴ °R)
I. Composites								
1. Dbl-aluminized Mylar/silk net	DAM	0.25	2 layers silk net	6.0	50	2.82	2.5×10^{-5}	7.1×10^{-5}
2. Dbl-aluminized Mylar/nylon net	DAM	0.25	Nylon net	9.0	80	3.36	1.7	5.7
3. Dbl-aluminized Mylar/Tissuglas	DAM	0.25	Tissuglas	0.6	100	3.24	1.4	4.5
4. Dbl-aluminized Mylar/Dexiglas	DAM	0.25	Dexiglas	2.8	60	3.67	2.8	10.3
5. Crinkled dbl aluminized Mylar/ Tissuglas	DAM	0.25	Tissuglas	0.6	60	1.94	3.9	7.6
6. Dbl-aluminized Mylar open-cell Freon blown foam	DAM	0.25	Polyurethane Foam		22	2.17	7.4	16.1
7. Goodyear dbl-aluminized Mylar/foam	DAM	0.25	Foam		21	1.67	6.0	10.0
II. NRC-2	AM	0.25	Integral		40	0.91	2.6	2.4
III. Dimplar	AM	0.50	Al	0.5	21	1.03	13.1	13.5
IV. 1. Hastings-dbl alum. Mylar embossed	DAM	0.25	Integral		128	2.79	3.3	9.2
2. Hastings gold-coated one side	GM	0.25	Integral		68	1.84	3.7	6.8
V. Superfloc 3/8-in. tuft spacing 0.090 in. tuft size	DAM	0.25	Integral		30	0.86	2.5	2.2

Table 2. Multi-Layer Insulation Performance Comparison.

Company	Tank (in.)	Insulation System	Number of Layers	X (in.)	Test ΔT (°R)	System Density (lb/ft³)	K Meas. Cond't-ivity Btu/hr-ft-°R ×10⁵	Test ρK ×10⁵	ρK 525 -40 ×10⁵	N̄ Layers per in.	Calorimeter K ×10⁵	Calorimeter ρ lb/ft³	Calorimeter ρK ×10⁵	Date of Report
Convair	87.61 74.5	D-A-M Superfloc Tk. Mtd. 1/4 Mil	44 Rad 4 Face Sheets	1.5	525 140	1.21 with Attach	6.8	8.2	8.2	30	2.7 (3.0)*	0.65	1.8	Dec. 1969
MSFC	105.0	C-S-A-M Crinkled Al. Mylar Tank Mtd. 1/4 Mil	48	0.75	470 40	1.5 No Attach	16	24.0	32	70	3.6	1.5	5.4	Mar. 1967
Lockheed	109.7	D-A-M Tissuglas Tank Mtd .15 Mil	105 DAM 100 TG	0.7	209 40	3.3 No Attach	1.74	5.9	16	150	2.0	3.3	6.6	Feb. 1968
McDonnell Douglas	72 Dia 144 Lg	D-A-M Dimp. Shroud Mtd. .50 Mil	11 Flat 10 Dimp	1.5	510 294	.66 No Attach	52	31	31 19	14	7.4	0.6	4.42	Dec. 1968
Lockheed	82.6	D-A-M Dexiglas Tank Mtd 1/4 Mil	30 DAM 27 Dexi-glas	1.1	400 123	1.93 With Attach	15	29	56	25	5.8	1.3	7.5	Nov. 1966

(*) MSFC Flat Plate Calorimeter Data

CRYOGENIC INSULATION DEVELOPMENT (PHASE II)
Leonhard, K.E., GDC-DDB69-002, NASA 8-18021, December 1969.

OBJECTIVE. - To develop and design a light weight, structurally sound, four-inch thick super-insulation system for the NASA/MSFC 105-inch diameter calorimeter.

PERTINENT WORK PERFORMED. -

A number of multilayer insulations (MLI) were considered, each consisting of low emittance radiation shields separated by a low conductive spacer material. The insulation selected for the design was 0.25 mil double aluminized Mylar with the layers separated by small tufts of Dacron needles (Superfloc) bonded to one side of each shield (Figure 1). Blanket to blanket and blanket to tank attachment methods were developed to achieve a thermally and structurally effective MLI system. The rigid twin pin fastener (Figure 2) was chosen for its strength, positive layer density control and lower heat leaks. Schjeldahl X-850 face sheet material (Dacron scrim bonded between aluminized Mylar) was added to each side of the insulation blanket to carry structural loads. Blanket tensile and vibration tests were conducted to check MLI and fastener integrity. The effect of a rapid gas evacuation was determined in a rapid pump down test. A 25-inch diameter subscale test tank was insulated with four, 30-layer, 1-inch thick blankets having cap sections and 60-degree gore sections. Plaster tooling was manufactured and used during the lay-up of the shields. The 25 inch tank test program included a pre-thermal test, a structural test (combined environments of vibration, acceleration and temperature) and a post thermal test to determine any degradation.

MAJOR RESULTS. -

1. Thermal and structural test results are presented in Figure 3.
2. Reasons for selecting Superfloc radiation shields are lowest "ρk", superior interstitial gas evacuation characteristics, highest fabricability ranking, ease of installation, low outgassing characteristics.
3. Since thermal and structural test results were identical to theoretical calculations and no damage or change occurred to the blanket during test, it was concluded that adequate manufacturing procedures had been practiced.
4. The Superfloc insulation system is highly qualified for cryogenic tankage and the design is available for the 105 in diameter calorimeter.

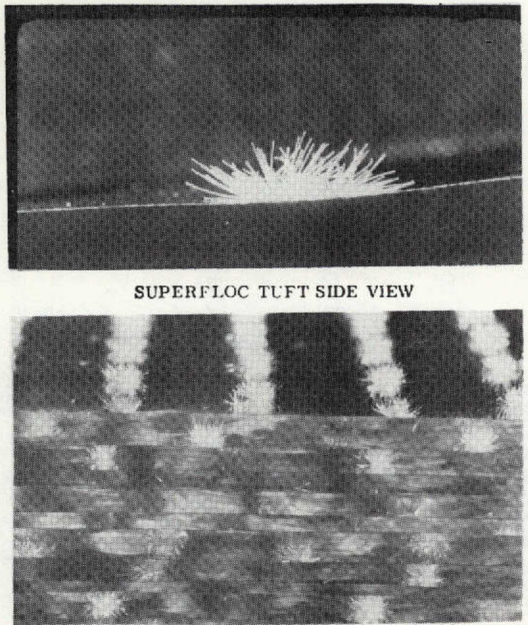
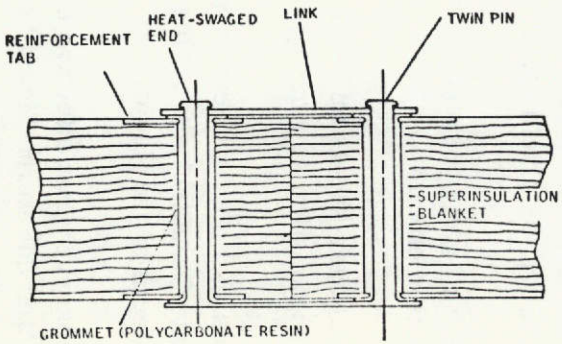
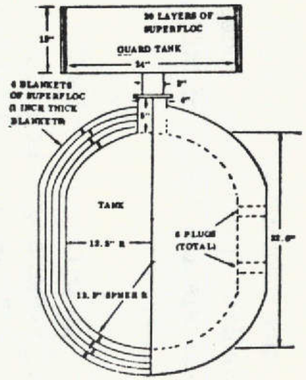


Figure 1. Stack of Superfloc Radiation Shields.



TWIN-PIN FASTENER

Figure 2. Blanket Attachment Techniques.



TANK SYSTEM PARAMETERS

Tank Volume: 7.2 ft^3
Tank Surface Area: 18.3 ft^2
Fairing Area: 0 ft^2
Cryogen: LH_2
Penetrations Thermally Guarded

INSULATION SYSTEM PARAMETERS

Insulation System: Superfloc
Nominal Thickness: 4.0 inch
System Density: 1.0 lb/ft^3
Average Area: 23.8 ft^2
Configuration: six 60° gores
two hemispherical end caps
Number of Blankets: 4
Seam Length:
Blanket #1: 29.3 ft
Blanket #2: 30. 9 ft
Blanket #3: 32.6 ft
Blanket #4: 34.1 ft
No. of Support Pins: 6
No. of Support Pin Grommets: 24
No. of Seam Pins With Grommets: 316
No. of Purge Pins: 0

THERMAL ANALYSIS

Ullage Pressure: 14.7 psia
Source Temperature: 535°R
Sink Temperature: 40°R
Performance:
Total Heat Flux: 0.185 B/hr ft^2
Insulation: 17%
Seams: 24%
Pins: 59%
Penetrations: 0%
Heat Flow Rate: 4.4 Btu/hr
Mass Flow Rate: 0.023 lb_m/hr

THERMAL TEST

Before Centrifuge Test
Duration: 38 hours
Cryogen Mass: 28.5 lb
Vacuum Pressure: 2.7×10^{-6} torr
Ullage Pressure: 14.7 psia
Heat Flux: 0.19 Btu/(hr ft^2)
Heat Flow Rate: 4.6 Btu/hr
Mass Flow Rate: 0.024 lb_m/hr
After Centrifuge Test
Duration: 72 hours
Cryogen Mass: 28.6 lb
Vacuum Pressure: 2.8×10^{-6} torr
Ullage Pressure: 15.3 psia
Heat Flux: 0.18 Btu/(hr ft^2)
Heat Flow Rate: 4.3 Btu/hr
Mass Flow Rate: 0.023 lb_m/hr
Ground Hold Test
Cryogen Mass: 19 lb
Chamber Pressure: 14.7 psia
Ullage Pressure: 14.7 psia
Heat Flux: 50 B/ hr ft^2
Mass Flow Rate: 6.2 lb/hr

STRUCTURAL TEST

Test Conditions:
Sink Temperature: 160°R
Maximum "g" Load: 17.2 g's in 250 sec
Maximum Vibration Load: 16 grms
Pumpdown: 1 torr in 70 sec
Signs of Structural Degradation: None

Figure 3. Summary of the 25-inch Test Tank Program NASA Contract NAS8-18021.

THE USE OF MULTILAYER INSULATION ON THE LM VEHICLE
Tawil, M.N., Caloger, P., Grumman, AIAA Paper No. 69-609.
June 1969.

OBJECTIVE. - To determine an evaluation parameter which would accurately predict insulation performance, to develop standardized installation procedures, and to define significant design parameters for analysis and design of MLI for the flight vehicle.

PERTINENT WORK PERFORMED. - The evaluation parameter selected, effective emittance (ϵ_e), is defined as $\epsilon_e = Q/A\,\sigma\,\left[T_h^4 - T_c^4\right]$ where Q is heat flow, A is area, σ is the Stefan-Boltzmann constant and T_h and T_c are hot and cold side temperatures. Two test panels were fabricated. A baseline ϵ_e was obtained for a continuous blanket of crinkled, 0.25 mil, SAM, under vacumn conditions and then the effects of various modifications to the blanket were determined (Table 1). Modifications investigated included Mylar thickness, crinkled vs. uncrinkled, metallizing both sides, Kapton vs. Mylar, attachment devices, seams, vent holes (Figure 1), and the effect of increased gas pressure (Figure 2). Other items investigated included techniques of reducing MLI blanket flammability, effect of liquids on layers, and means to cope with thermal shrinkage of the blankets.

MAJOR RESULTS. -

1. Tests indicated no significant effect on thermal performance (ϵ_e) due to Mylar film thickness (0.15 or 0.25 mil),shield spacing characteristics (crinkled or uncrinkled), or shield metallization (one side or both).

2. Interstitial gas pressure must be reduced to 5×10^{-5} torr to eliminate gas conduction effects.

3. Kapton cover sheets on DAM insulation layers render the blanket assembly "non-combustion supporting."

4. Liquids that get between the layers cause severe heat shorts. Apparently no amount of ambient air drying or ambient evacuation will remove or alleviate the effects of the liquid.

5. The observed test effective emittance of 0.0116 was 70% greater than that predicted due to the "ideal" conditions existing in the subscale tests (loose fit, no stretching, well vented, simple configuration, etc.)

COMMENTS. -

No data are presented to corroborate the blanket flammability statement.

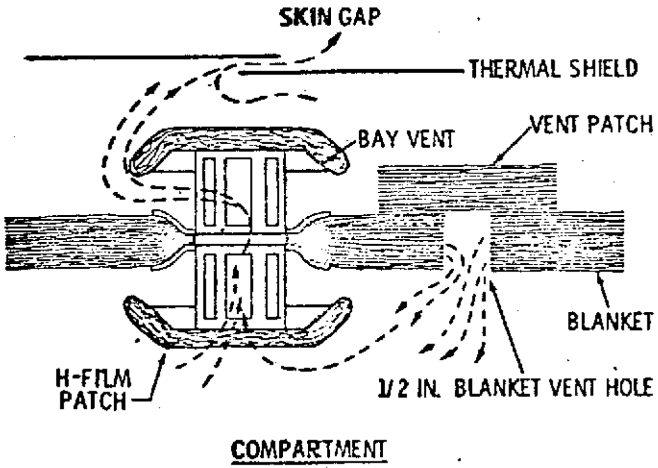


Figure 1. Bay and blanket venting during launch.

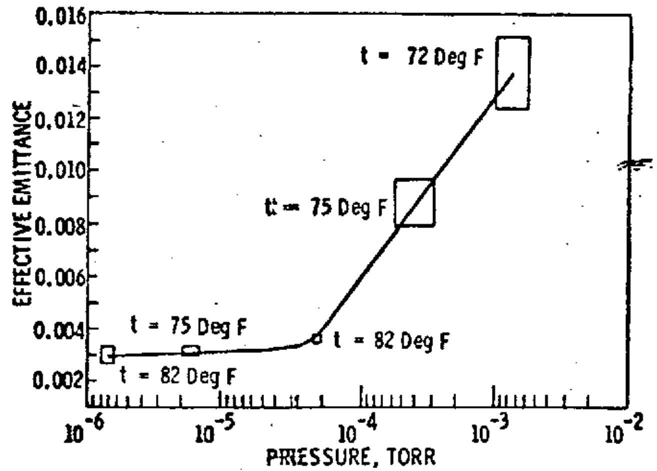


Figure 2. Effect of gas pressure on effective emittance.

Table 1. Component contributions to overall effective emittance.

Type of Seam or Blanket Penetration	Total Number of Penetrations or Total Length of Seam	Contribution to ϵeff. (One Linear Ft. of Seam or one Penetration Per Sq. Ft. of Blanket)	Total Contribution to Stage ϵeffective
Basic Blanket [618 sq. ft.]	-	-	0.00300
Aft Bay and midsection type standoff	357	0.00341	0.00197
Cabin Type standoff	172	0.00159	0.00044
Guidance area type standoff	30	0.00400	0.00020
Five inch dia. patch over 1/2" dia. thru hole	160	0.00044	0.00011
TM-2 type bay vent (figure 1)	59	0.00395	0.00038
Standard 2 inch folded seam ("drugstore wrap")	437 linear feet	0.00104	0.00074
		Overall ϵeffective	0.00684

INVESTIGATION REGARDING DEVELOPMENT OF A
HIGH PERFORMANCE INSULATION SYSTEM
Lockheed Missiles and Space Co., K-17-68-5, NAS8-20758,
July 1968

OBJECTIVES. - To perform the initial phase of development for a thermal protection system on the Modular Nuclear Vehicle (MNV).

PERTINENT WORK PERFORMED. - Nine candidate multilayer insulation composites were tested for thermal performance on a calorimeter. The data were evaluated and comparisons made on the basis of weight (resulting boiloff and insulation weights), and sensitivity of heat flow to compressive load occurring during ascent. The crinkled Mylar-Tissuglas composite was designed into insulation assemblies and installed as blankets (4×36 ft) on the cylindrical section and gore segments (4-ft max width) on the dome sections of the tank. Experimental outgassing studies were conducted on the 3 top ranked insulation composites to determine whether outgassing of the material could degrade insulation performance. Tests were conducted on full width blankets that demonstrated ease of evacuation and structural integrity during purge gas evacuation occurring in ascent flight. Five candidate tank support structures were designed. Stress, thermal, producibility, and cost data were compared to determine the best support structure for the tank. Utilizing calorimeter test results, effective thermal conductivity (k_e) equations were derived for various insulation systems (Table 1).

MAJOR RESULTS. -

1. The resulting relative rankings together with evaluations of the ease of fabrication and assembly (a subjective ranking), compatibility with a nuclear radiation environment, and costs led to selection of the following as the three highest ranked insulation composites:
   - Double-aluminized crinkled Mylar with Tissuglas spacers
   - NRC-2 (single-aluminized crinkled Mylar)
   - Superfloc (double-aluminized Mylar with discrete Dacron fiber spacers)
2. Use of three blankets was recommended for the Mars Departure Stage, each blanket 0.4-in thick. The design insulation layer density is 30 layers/in.
3. During outgassing tests it was found that the only important outgassing constituent is water vapor. At temperatures below 430R outgassing rates are so low that they could not be measured.
4. The best tank support structure was found to be a lightweight titanium semi-monocoque cone.
5. One-inch overlap of MLI blankets was shown to permit safe evacuation.

Table 1. Superinsulation System Equations

Double-Aluminized Mylar-Silk Netting (2 layers)	$k_e = 1.13\times10^{-9}\bar{N}\,T_m + \frac{\sigma\,(T_h^2+T_c^2)\,(T_h+T_c)\,t}{(N-1)[(2/\epsilon)-1]}$
NRC-2	$k_e = 5.90\times10^{-12}(\bar{N})^2\,T_m + \frac{\sigma\,(T_h^2+T_c^2)\,(T_h+T_c)\,t}{(N-1)\,[(1/\epsilon_a)+(1/\epsilon_b)-1]}$
Superfloc	$k_e = 3.23\times10^{-11}(\bar{N})^2 T_m + \frac{\sigma\,(T_h^2+T_c^2)\,(T_h+T_c)\,t}{(N-1)\,[(1/\epsilon_a)+(1/\epsilon_b)-1]}$
Double-Aluminized Mylar-Nylon Net (1 layer)	$k_e = 6.0\times10^{-11}(\bar{N})^{1.4}\,T_m + \frac{\sigma\,(T_h^2+T_c^2)\,(T_h+T_c)\,t}{(N-1)\,[(2/\epsilon)-1]}$
Double-Aluminized Mylar-Dexiglas	$k_e = 4.58\times10^{-12}\,(\bar{N})^2 T_m + \frac{2.7\,\sigma\,(T_h^2+T_c^2)\,(T_h+T_c)\,t}{(N-1)\,[(2/\epsilon)-1]}$
Dougle-Aluminized Mylar-Tissuglas	$k_e = 1.83\times10^{-12}(\bar{N})^2 T_m + \frac{1.7\,\sigma\,(T_h^2+T_c^2)(T_h+T_c)\,t}{(N-1)[(2/\epsilon)-1]}$
Dougle-Aluminized Crinkled Mylar-Tissuglas	$k_e = 4.6\times10^{-12}\,(\bar{N})^2\,T_m + \frac{1.7\sigma\,(T_h^2+T_c^2)\,(T_h+T_c)\,t}{(N-1)[(2/\epsilon)-1]}$
Double-Aluminized Mylar-Open-Cell Foam	$k_e = 1.26\times10^{-14}\,(\bar{N})^{5.1}\,T_m + \frac{\sigma\,(T_h^2+T_c^2)(T_h+T_c)\,t}{(N-1)\,[(2/\epsilon)-1]}$
Double-Aluminized Mylar-Closed-Cell Foam	$k_e = 3.5\times10^{-15}\,(\bar{N})^{5.7}\,T_m + \frac{\sigma\,(T_h^2+T_c^2)(T_h+T_c)\,t}{(N-1)\,[(2/\epsilon)-1]}$

k_e = effective thermal conductivity
$\bar{N}$ = no. of radiation shields/unit thickness
T_m = mean temperature
σ = Stefan Boltzmann constant
T_h = hot temperature
T_c = cold temperature
N = no. of radiation shields
t = thickness of insulation
ϵ = emissivity

STUDY OF ATTACHMENT METHODS FOR ADVANCED SPACECRAFT THERMAL CONTROL MATERIALS
Kordsmeier, N. H., Jr., McKellar, L. A., LMSC,
NASA-CR-73219, NAS2-4252, May 1968

OBJECTIVE. - To develop attachment methods for a thermal control composite system.

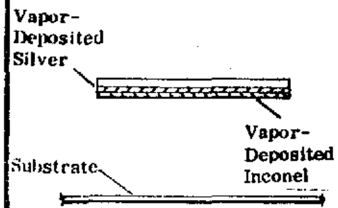
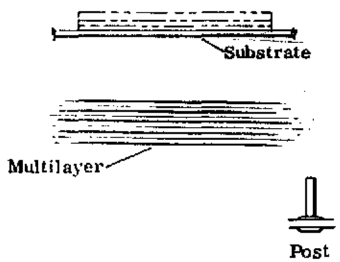
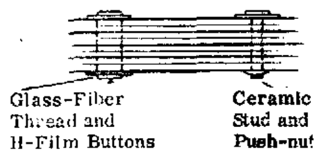
PERTINENT WORK PERFORMED. - An investigation was made to develop attachment methods for a thermal-control composite system comprised of optical solar reflectors (second-surface mirrors) and multilayer insulation. Basic systems design constraints were: (1) Systems must be removable for access to vehicle skin, (2) nonmagnetic materials must be used in the construction of the composite, (3) attachments should not appreciably degrade thermal conductivity of the MLI, (4) composite system must withstand long-term exposure to high temperature (700F) and vacuum environment, (5) structural integrity must be sufficient to withstand loads imposed during an Atlas-Agena launch, and (6) application techniques must be usable on cylindrical and flat shapes.

Various techniques for attaching the composite system were evaluated (Table 1). Two composites were fabricated utilizing different attachment methods and were subjected to environmental conditions anticipated for a near-solar spacecraft mission. Both composites employed optical solar reflectors in combination with aluminized polyimide-Tissuglas multilayer insulation. However, substrates to which the reflectors were applied differed. In one case, reflectors were bonded integrally to the MLI whereas in the other case reflectors were bonded to an aluminum expanded-metal substrate which was attached subsequently to posts mounted through the multilayer insulation.

MAJOR RESULTS. -

1. The composite attachment methods developed under this program offered potential for use as thermal protection of storage tanks for cryogenic propellants.
2. The thermal control materials (second surface mirrors and multilayer insulation) and attachment techniques will withstand forces imposed by an Atlas-Agena launch and orbit sequence and can operate successfully in the temperature range of -100 to 700F.
3. Escape of entrapped air within multilayer blanket assemblies during vehicle ascent has no detrimental effect on either design method.
4. Optimization of attachment techniques for both thermal control composites should be accomplished with respect to weight reduction and ease of installation.

Table 1. Matrix of Attachment Techniques

Elements of Composite System	Candidate Attachment Methods	Limitations: Element	Limitations: System
I. Second-Surface Mirrors to a Substrate	1. Mechanical attachment: metallic track, clips, tabs	1. Loose in holder, subject to thermal warpage	1. Compromises thermal efficiency
	2. Weld to inconel: mirror backing	2. Not sufficient film thickness to weld	2. Not replaceable if mirror is shattered during handling
	a. Ultrasonics		
	b. Brazing		
	3. Adhesive: mirror to substrate	3.	3.
	a. Silicones	a. Temperature limited to 700-800°F	a. Requires application technique
	b. Double-backed polyimide tape, silicone adhesive	b. Temperature limited to 500-600°F	b. Requires application technique
	c. Ceramic cements	c. Attack mirror surface	c. Degrades reflective properties
II. Mirror Substrate to Multilayer or to Posts Attached to Vehicle	1. Tabs welded onto underside of screen or foil. Wire threaded through tabs and twisted onto bonded posts	1. Must have clearance between mirror substrate and multilayer to attach wires	1. Time consuming to assemble; bonded posts tend to shear off during handling and installation procedures
	2. Snapon cap welded to underside of screen or foil fits over post	2. Must apply pressure to mirror and screen; post must be made from ceramic or glass to reduce heat loss	2. Alinement critical for installation; design of receptacle to be made from ceramic/glass difficult
	3. Mirrors attached to top layer of multilayer		
	a. Adhesives or double-backed tape	a. Difficulty in bonding mirrors to assembled multilayer blanket	a. Mirrors no longer removable for possible replacement
	b. Welded to top layer of multilayer	b. Existing welding techniques not applicable to polyimide film and mirrors	b. Weight causes multilayer to sag and tear during loading unless strong thread used
	4. Mirror substrate attached to top layer of multilayer		
	a. Metallic Velcro fasteners	a. Velcro material magnetic	a. Interference with experimentation/communication equipment
	b. Thread onto multilayer buttons	b. Clearance required to tie down to buttons	b. Buttons shear off due to load imposed by mirrors
III. Multilayer Insulation	1. H-film buttons, glass-fiber thread, silicone-reinforced thread, wire thread	1. Thread chaffing during handling	1. Threading and knotting time; high thermal conductivity for metallic threads
	2. Ceramic studs moored by metallic push-nuts	2. Weight of studs	2. Increased thermal conductivity; tends to tear through multilayer
	3. Teflon buttons and thread	3. Temperature limited to 500°F.	
	4. Sewing blankets together	4. Compresses multilayers together	4. System not readily removable or replaceable
	5. Cylindrical or longitudinal wrap	5. Must be performed at launch site	5. System not readily removable or replaceable
IV. Multilayer to Vehicle Skin	1. Nylon Velcro fasteners to multilayer and vehicle skin		1. Some alinement of Velcro fasteners necessary for installation
	2. Metallic clips or snaps to multilayer and vehicle skin	2. Clips not weldable to aluminized multilayer	2. Alinement for installation critical
	3. Bond bottom of multilayer to vehicle skin	3. Difficulty in bonding to aluminized multilayer	3. System not readily removable or replaceable

PROPOSED FASTENING METHODS

ADVANCED STUDIES ON MULTILAYER INSULATION SYSTEMS
Arthur D. Little, Inc. NASA CR-72368, NAS3-7974, January 1968

OBJECTIVE. - To predict and measure the heat flow in a multilayer insulation with a pipe penetration and determine the thermal performance of an MLI system that was warehoused for one year.

PERTINENT WORK PERFORMED. - The program was conducted in two tasks. Task I was a study of the influence of a pipe penetration 6 inches in diameter and 17 inches long on the heat flow through a 10-shield evacuated multilayer insulation. Two environmental temperature conditions, three free-end temperature conditions, and two internal surface emittance configurations were considered. The MLI was placed on a 4-foot diameter tank calorimeter, and tests were performed in a 5-foot-diameter space-simulation chamber.

The experimental program was performed in conjunction with an analytical program for the prediction of the penetration heat flow performance and wall temperature distributions; this led to the establishment of a mathematical model to simulate the conductive and radiative heat transport mechanisms. The results were compared with the results obtained with the experimental model.

Task II was performed to determine the stability of the thermal performance of a five shield MLI after a one-year warehouse storage period. The MLI consisted of five double-gold-coated Mylar shields and six spacers, each consisting of two layers of silk netting. It was fabricated onto a 4-foot-diameter tank calorimeter, and the heat flux was measured under NASA Contract NAS3-6283 (CR-54929). The thermal performance of this system was again measured under the current contract after one year of storage.

MAJOR RESULTS. -

1. The major portion of heat transfer is by wall conduction and internal radiation. Heat flow from the environment to the pipe through the MLI is of secondary importance.

2. The mathematical model produced excellent prediction of wall temperatures and heat flow (Figures 1 and 2) up to a penetration end temperature of 540°R. For the 750°R end temperature the heat flow was 25% less than the measured heat flow (due to the uncertainties associated with the conductance and interior surface emittance).

3. The reduction of interior wall emittances produced substantial reduction in penetration heat flow.

4. The thermal performance of a reasonably protected MLI system is not affected by storage in a shop or warehouse environment for a one year period.

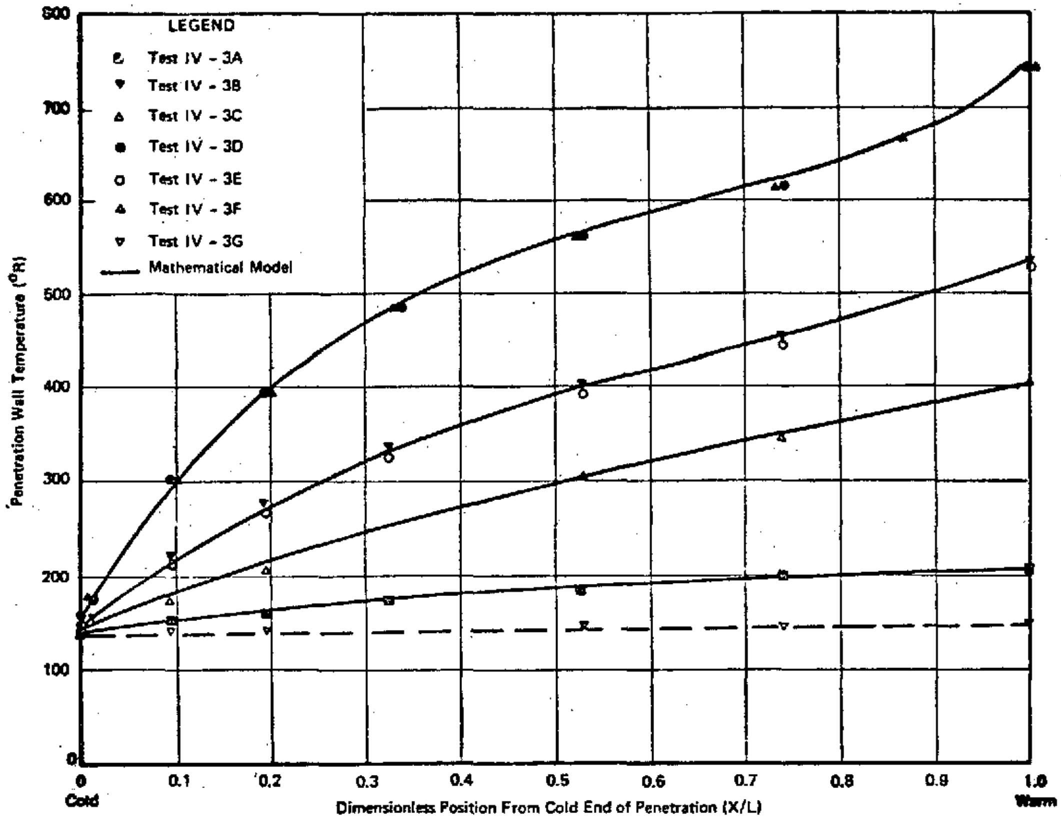


Figure 1. System No. 16, Penetration Wall Temperatures for Test Series IV-3

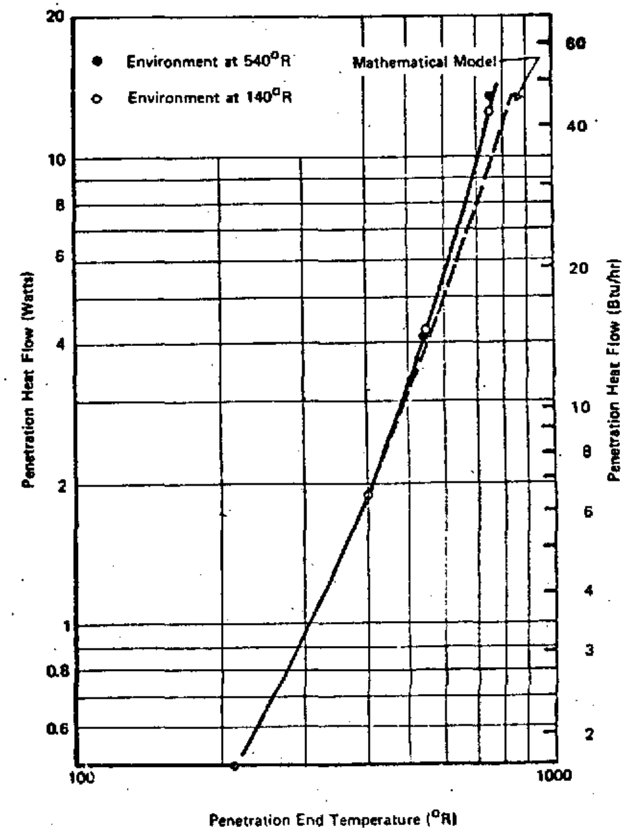


Figure 2. System No. 16, Penetration Heat Flow vs End Cap Temperature, Test Series IV-3

A STUDY OF THERMAL CONDUCTIVITY REQUIREMENTS
Hale, D. V., et al, LMSC, HREC-1134-1,
NAS 8-21134, October 1967

OBJECTIVE. - An experimental study was conducted to determine accurately the relationship between "apparent" thermal conductivity and temperature for various high performance multilayer insulation (MLI) materials and a high density foam over a range of temperature from -50 to 200°F.

PERTINENT WORK PERFORMED. - To obtain the temperature-dependent data, a steady state heat flux was passed through a one-inch thick insulation specimen with a very small temperature drop through the insulation (≈10° F). To assure accurate test results with this small temperature differential, a cylindrical calorimeter was developed which virtually eliminated extraneous heat losses. The insulation samples tested were 1/4 mil single aluminized Mylar (SAM); 1/4 mil double aluminized Mylar (DAM) with 30 mil polyurethane foam; 1/4 mil DAM and Dacron needles; and rigid urethane foam. Three calorimeter configurations were studied to determine a design which would give the best overall results. They were (1) circular disc, (2) sphere, and (3) long cylinder. The two major considerations were accuracy of the final results and ease of fabrication. The test model configuration chosen for insulation application was the long cylinder. The thermal conductivity of the specimen insulation was measured by maintaining a given temperature drop through the insulation specimen with a known heat-flux being generated by electrical heaters. A probable error was calculated for each data point obtained (Table 1). This error analysis substantiated the validity of the test results.

MAJOR RESULTS. -

1. A technique was conceived and an apparatus successfully operated which enables precise curves to be generated for thermal conductivity versus temperature for MLI.
2. Thermal conductivity is a strong function of temperature and pressure.
3. Radiation between layers was a major portion of the total heat transferred.
4. Where no spacer is present, the thermal conductivity did not appear to be a function of previous conditioning such as length of time pumped down and previous heating.
5. Where MLI spacers are used there was a definite hysteresis.
6. When heated to 200°F the specimens appeared to have "baked out" the entrapped atmospheric gases, thus reducing substantially the contribution of conduction to the apparent thermal conductivity.
7. The results obtained from the three multilayer insulation specimens tested correlated well with the theoretical predictions.

Table 1. Measured Thermal Conductivity of Test Specimen

TEST RESULTS FOR CRINKLED SINGLY ALUMINIZED MYLAR SPECIMEN

Data Point No.	Temperature (°F)	ΔT (°F)	Pressure (torr)	Thermal Conductivity ($\times 10^5$) (Btu/hr-ft-°F)	Maximum Probable Error ± (%)
1	99.3	9.9	$\leq 8 \times 10^{-6}$	8.06	8.36
2	119.4	49.2	$\leq 8 \times 10^{-6}$	8.48	10.2
3	6.0	11.0	$\leq 8 \times 10^{-6}$	3.87	26.7
4	207.6	17.1	$\leq 8 \times 10^{-6}$	18.1	9.13

TEST RESULTS FOR DOUBLY ALUMINIZED MYLAR AND FOAM SPECIMEN

Date	Temperature (°F)	ΔT (°F)	Pressure (torr)	Thermal Conductivity ($\times 10^5$) (Btu/hr-ft-°R)	Maximum Probable Error ± (%)
7/14/67	76.0	9.8	$\leq 8 \times 10^{-6}$	12.7	11.6
7/18/67	104.9	10.1	$\leq 8 \times 10^{-6}$	14.1	14.6
7/20/67	154.0	10.5	$\leq 8 \times 10^{-6}$	30.8	9.38
7/24/67	4.1	8.7	$\leq 8 \times 10^{-6}$	3.16**	81.7
7/26/67	55.8	10.9	$\leq 8 \times 10^{-6}$	8.14	8.35
7/26/67	72.3	11.4	$\leq 8 \times 10^{-6}$	11.3	8.27
7/28/67	198.6	11.2	$\leq 8 \times 10^{-6}$	30.1	8.58
7/31/67	*	270.0	$\leq 8 \times 10^{-6}$	5.10	8.31
8/1/67	174.7	13.2	$\leq 8 \times 10^{-6}$	18.4	18.4
8/2/67	132.6	12.4	$\leq 8 \times 10^{-6}$	9.62	10.81
8/4/67	74.9	10.3	$\approx 2 \times 10^{-6}$	6.03	26.4
8/4/67	75.0	9.8	1×10^{-4}	8.30	21.2
8/5/67	72.0	transient	1×10^{0}	1185.	≈50
8/5/67	74.2	9.3	6×10^{-3}	10.7	13.3
8/19/67	-46.5	9.2	$\leq 8 \times 10^{-6}$	4.68	27.1

* $T_{hot} = 76.6°F$, $T_{cold} = -193.8°F$

**This point was unreliable due to large heat stored term (as indicated by error analysis).

TEST RESULTS FOR SUPERFLOC SPECIMEN

Data Point No.	Temperature (°F)	ΔT (°F)	Pressure (torr)	Thermal Conductivity ($\times 10^5$) (Btu/hr-ft-°F)	Maximum Probable Error (%)
1	-50.2	9.2	$\leq 8 \times 10^{-6}$	3.68	19.5
2	7.9	9.7	$\leq 8 \times 10^{-6}$	6.19	12.5
3	139.4	10.2	$\leq 8 \times 10^{-6}$	13.0	9.82
4	196.3	12.2	$\leq 8 \times 10^{-6}$	19.8	8.35
5	71.4	11.8	$\approx 2 \times 10^{-6}$	11.2	9.10
6	78.0	11.7	10^{-3}	15.4	10.9
7	79.3	11.7	10^{0}	682.	8.26
8	≈75	transient	5×10^{2}	9270.	≈50

TEST RESULTS FOR A RIGID URETHANE FOAM SPECIMEN (Isonate Foam)

Data Point No.	Temperature (°F)	ΔT (°F)	Pressure (torr)	Thermal Conductivity (Btu/hr-ft-°F)	Maximum Probable Error (%)
1	119.1	12.5	2×10^{-5}	.0277	≈15
2	117.7	13.3	4.2×10^{-3}	.0261	≈15
3	89.5	15.8	10^{0}	.0263	≈15
4	85.5	14.0	5×10^{2}	.030	≈15
5	208.0	8.7	$\leq 8 \times 10^{-6}$	.0302	≈15
6	-18.3	8.3	4×10^{-5}	.0259	≈15
7	26.9	6.8	$\leq 8 \times 10^{-6}$	.0267	≈15
8	77.4	8.9	$\leq 8 \times 10^{-6}$	.0268	≈15

ADVANCED STUDIES ON MULTILAYER INSULATION SYSTEMS
Arthur D. Little, Inc. NASA CR-54929, NAS3-6283, June 1966

OBJECTIVE. - To obtain basic design information for evacuated multilayer insulation systems and to evaluate their thermal performance experimentally.

PERTINENT WORK PERFORMED. - The studies were both analytical and experimental; dealing with the performance of the insulating media in various environments. The program included three tasks: (1) Use of a previously developed emissometer to evaluate the emissivity of radiation shield materials, (2) Operation of a flat plate thermal conductivity apparatus to evaluate spacer materials, to obtain MLI penetration heat leak data and to study the effects of perforations on transient heat flow, and (3) To perform a series of insulated calorimeter tank experiments. An environmental chamber was fabricated and samples were exposed in the chamber to humid air, carbon dioxide and salt air for 50 and 100 hours. Emittance measurements were taken after these exposure periods. The flat plate tester was used to measure heat fluxes of MLI samples at compressive loads in the range between 0-15 psi. Performance degradation caused by penetrations was measured, utilizing two MLI systems, three sizes of penetrations and two materials for penetrations. Seven MLI systems were designed, fabricated and tested on the insulated test calorimeter (Table 1). The thermal performance was measured in a vacuum chamber to simulate space conditions.

MAJOR RESULTS. -

1. The coatings which were selected in the emissometer program were aluminum, gold, copper and silver.

2. Emittances of each metal had different degrees of stability when exposed to high humid air, CO_2 and salt environments. Grouped in order of decreasing stability were aluminum, gold, silver and copper.

3. At zero compression the heat flux through a sample radiation shield perforated with 0.040 in dia holes (2% open area) was twice as high as the heat flux through an unperforated shield.

4. At 15 psi compression, perforated and unperforated samples conducted the same amount of heat flux.

5. Agreement in the insulation heat fluxes measured with a tank calorimeter and with a flat plate tester was good.

6. From tests conducted with He gas in a five shield MLI blanket, a gas accommodation coefficient of 0.65 was established for a ΔT of -320 to 80F.

Table 1. Tank Program – Multilayer Insulation Performance Summary

Insulation System Description						Test Data					
System[1][2] No.	Shield Materials	Spacer Materials	Application Method	Other	System Weight[3] (lbs/ft²)	Test No.	Ave. Vac. (mm Hg)	Measured Heat Flux (Btu/hr ft²)	Ave. Baffle Temp. (°F)	Adjusted Heat Flux[5] (Btu/hr ft²)	Kp Product (Btu-in-lb/hr ft⁵ °R)[6]
1	Aluminum foil, 2 mil	Screen, vinyl coated Fiberglas 1/8 x 1/8 in. mesh, 1 layer per spacer	Ends: pressure formed shields and formed spacers; Sides: gored shields and spacers	–	.236	I-3D2, 3[4] I-7	0.4×10^{-6} 1.0×10^{-6}	0.66 0.44	79 40	0.66 0.61	.00467 .00345
2	1/4 mil polyester film aluminized one side	Screen, vinyl coated Fiberglas 1/8 x 1/8 in. mesh, 1 layer per spacer	Ends: slitted shield circles formed spacer; Sides: gored shields and spacers	–	.104	I-4A, B, C, D	4.0×10^{-6}	0.80	48	1.02	.00266
4	Aluminum foil, 1/2 mil	Screen, vinyl coated Fiberglas, 1/8 x 1/8 in. mesh, 1 layer per spacer	Ends: pressure formed shields and formed spacers; Sides: gored shields and spacers	–	.131	II-1A	0.7×10^{-6}	0.37	48	0.47	.00158
5	1/4 mil polyester film aluminized two sides	Screen, vinyl coated Fiberglas, 1/8 x 1/8 in. mesh, 1 layer per spacer	Ends: slit shield circles and formed spacers; Sides: gored shields and spacers	Urethane foam substrate, 1/2 in. thick, foamed in place, outer vapor barrier	.104	II-9A	1.3×10^{-6}	0.71	68	0.78	.00228
6	1/4 mil polyester film aluminized two sides	Nylon netting, 1 layer per spacer	Ends: slit shield and spacer circles; Sides: gored shields and spacers	–	.025	II-7	1.2×10^{-6}	1.04	74	1.11	.00072
7	1/4 mil polyester film aluminized two sides	Nylon netting, 1 layer per spacer	Outer five layers formed into blanket; Ends: slit circles; Sides: gored	System made up of System No. 5 with 5 layer blanket type system added	.047	II-8	0.7×10^{-6}	0.78	73	0.83	.00110
8	1/4 mil polyester film aluminized two sides	Glass fabric, Style 104 2 layers per spacer	Ends: circles for both shields and spacers; Side: slit shields, purse string spacers	–	.059	III-1A	1.3×10^{-6}	0.52	81	0.53	.000920
9	1/4 mil polyester film aluminized two sides perforated 1.88%	Glass fabric, Style 104 2 layers per spacer	Ends: circles for both shields and spacers; Side: slit shields, purse string spacers	Urethane foam substrate Same as System No. 5	.059	III-2A	3.0×10^{-5}	1.06	83	1.04	.00186
11	1/4 mil polyester film aluminized two sides	Silk netting, 2 layers per spacer	Ends: circles used for both shields and spacers; Sides: slit shields, purse string spacers	Urethane foam substrate Same as System No. 5	.023	III-4A, C	2.0×10^{-6}	0.48	80	0.48	.000331
12	1/2 mil polyester film silver coated two sides	Silk netting, 2 layers per spacer	Ends: circles used for both shields and spacers; Sides: slit shields, purse string spacers	Urethane foam substrate Same as System No. 5	.032	III-5A	2.0×10^{-6}	0.31	79	0.31	.000300
13	1/2 mil polyester film silver coated two sides	Silk netting, 1 layer combined with Scott foam strips except outer spacer 1 layer silk only	Ends: circles used for both shields and spacers; Sides: slit shields, gored spacers	Urethane foam substrate Same as System No. 5	.038	III-6B	2.0×10^{-6}	0.33	80	0.33	.000377
14	1/4 mil polyester film gold coated two sides	Silk netting, 3 layers per spacer except outer spacer is 1 layer	Ends: circles used for both shields and spacers; Sides: slit shields, gored spacers	–	.028	III-7	2.0×10^{-6}	0.33	80	0.33	.000273

Notes:
1. All systems contain 5 radiation shields except for System No. 7 which contain 10 shields.
2. Insulation surface area is approximately 40 square feet.
3. Insulation weight given is for multilayer only and does not include foam present on Systems 5, 9, 11, 12, and 13.
4. Test performed with liquid hydrogen in calorimeter, all others performed with liquid nitrogen.
5. Measured heat flux adjusted for warm boundary temperature of 80°F.
6. Kp product is based on measured value of heat flux.

BASIC INVESTIGATION OF MULTILAYER INSULATION SYSTEMS
Black, I.A., et al, ADL, NASA CR-54191
NAS3-4181, October 1965.

OBJECTIVE. - To study analytically and experimentally the performance of the insulating media and environments.

PERTINENT WORK PERFORMED. - The program was conducted in four tasks: (1) A series of experiments to measure the efficiency of insulations, (2) A series of tests to determine the heat leak through various insulation materials, (3) The design, construction and operation of an emissometer to determine the total emittance of materials for multilayer insulation, and (4) Analytical studies to support the other three tasks. To rapidly screen various insulations and to determine effects that occur under mechanical loads (0-2 psig), three thermal conductivity apparatus were employed. Promising insulations were selected from the conductivity tests, fabricated and tested on larger scale calorimeter tanks. Effects of penetrations were studied, experimental data analyzed and compared with predictions. An emissometer was fabricated and used to determine the emittance of materials. Also the increase in emissivity due to surface contaminants or imperfections was studied. Several theoretical studies were conducted to determine gas conduction in MLI systems, radiation transfer by closely spaced shields, radiative heat transfer through seams and penetrations, the thermal radiation incident on space vehicles, venting of MLI systems during ascent and the optimum design of thermal protection systems.

MAJOR RESULTS. -

1. Insulation with fine netting spacers were superior, based on the ρk (density $\times$ thermal conductivity) product, but were inferior with respect to foam or matted fiber spacers when subjected to compressive loads.

2. Surface treatment of the aluminum (smooth or embossed) had no apparent effect on the insulating qualities of the radiation shield.

3. Perforations on a crinkled aluminized polyester film insulation caused the heat flux to increase by about 20%; whereas, perforations of the same size in aluminum radiation shields combined with netting spacers caused the heat flux to increase by more than 150%.

4. Heat fluxes measured on the upper half of the test tanks were larger than those on the lower half.

5. Heat fluxes obtained with multilayer insulations are about 5% higher when using LH_2 as the test fluid compared to LN_2.

6. Effects of mechanical loads and density on heat flux through multilayer insulation are presented in Figures 1 and 2.

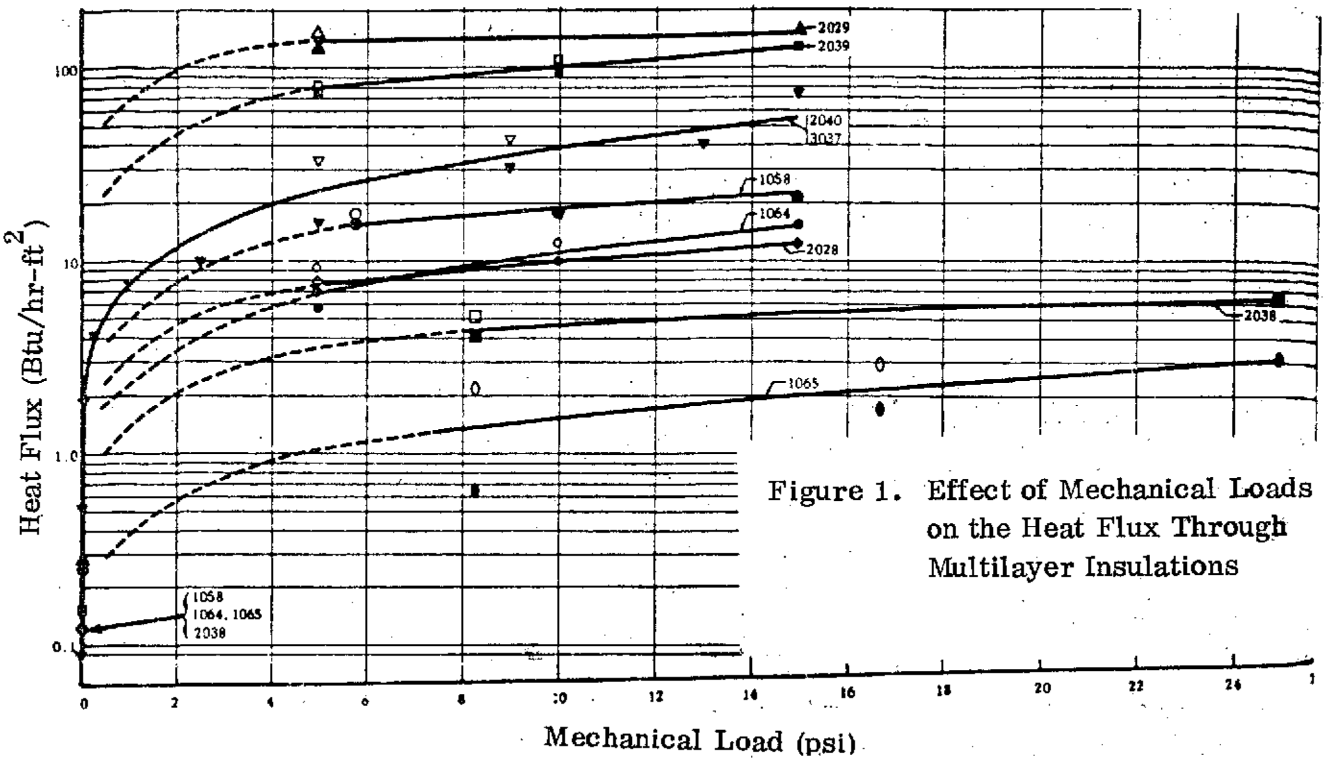
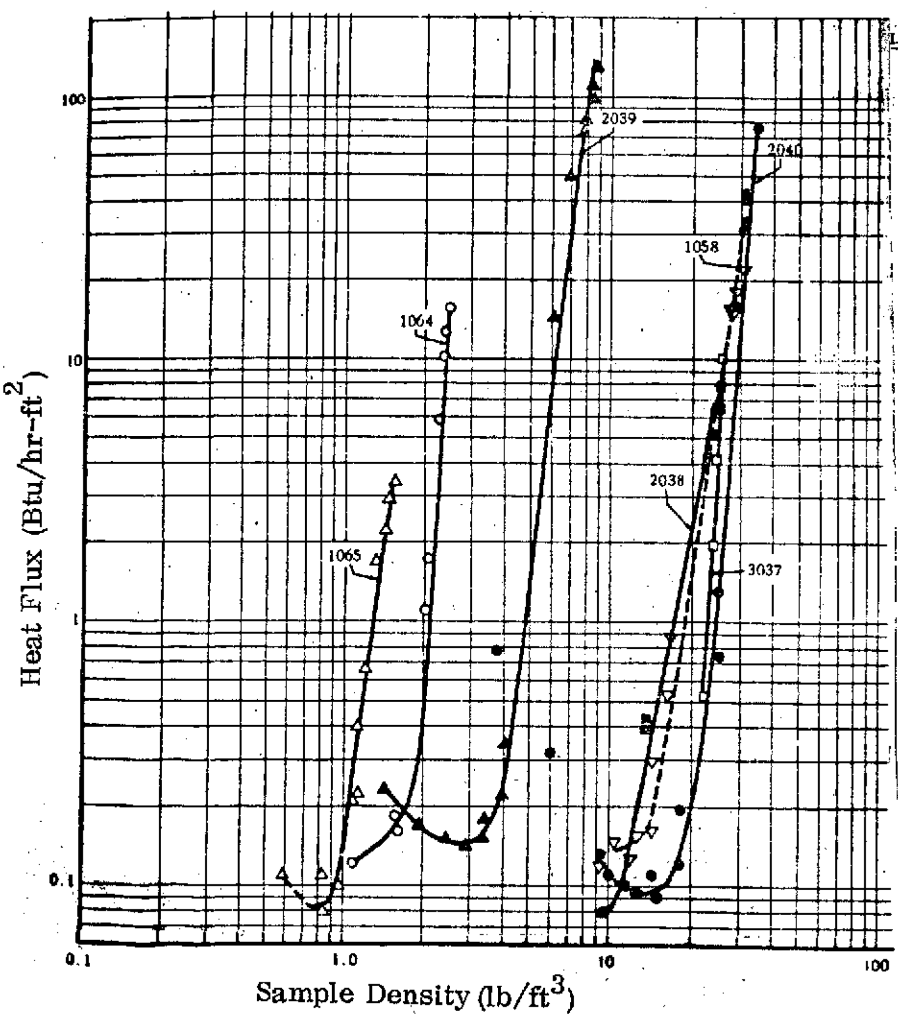


Figure 1. Effect of Mechanical Loads on the Heat Flux Through Multilayer Insulations



LEGEND

System	Sample No.	Description
XI	2029	(10) Embossed Aluminum 0.0005" (11) Fiberglass Cloth (3 ea.) 0.004"
XV	2039	(10) Aluminized Polyester Film 0.00025" (11) Nylon Net 0.007"
XIV	2040	(10) Aluminum 0.002" (11) Nylon Net 0.007"
XIII	1058	(10) Aluminum 0.002" (11) Fiberglass Mat 0.020"
XVI	1064	(10) Aluminized Polyester Film .00025" (11) Polyurethane Foam 0.02" x 2.7 lb/ft^3
X	2028	(10) Embossed Aluminum 0.0005" (11) Fiberglass Mat 0.014"
XII	2038	(10) Aluminum 0.002" (11) Fiberglass Mat 0.02" (11% Support)
XVII	1065	(10) Aluminized Polyester Film 0.00025" (11) Polyurethane Foam 0.02" x 2.7 lb/ft^3 (11% Support)

Figure 2. Effect of Density on the Heat Flux Through Multilayer Insulations

3.0 OTHER INSULATION

Covering various types of foams, shadow shields, microspheres, honeycomb, vent cooling and composites.

INTERNAL INSULATION SYSTEM DEVELOPMENT

Gille, J.P., MMC, NASA CR-121102, NAS3-14384, May 1973

OBJECTIVE. - To design, fabricate, install, and test a reusable internal gas-layer insulation system for liquid hydrogen tanks.

PERTINENT WORK PERFORMED. - Based on work of earlier programs an internal, gas layer insulation system was designed, installed, and tested on a 6 ft diameter aluminum tank. The insulation system consisted of a 1 inch thick Kapton polyimide honeycomb material bonded to the inside tank wall with a silicone adhesive (Table 1). Fiberglass batt filler plugs are installed in the honeycomb and a 2-mil Teflon facesheet is bonded to the honeycomb with a silicone adhesive. The face sheet was dimpled to reduce thermal stress at cryogenic temperature. The facesheet was perforated, one hole per cell, using a soldering iron with an 0.035-in diameter needle. The specific weight of the installed system was 0.75 lbs per square foot. Prefabricated insulation panels are fitted into the tank and cutouts are made to accommodate internal hardware. After an initial boiloff test the system was subjected to a total of five pressure/temperature cycles (10 psig, 350F) to determine the effect on system integrity (Table 2).

MAJOR RESULTS. -

1. The initial thermal performance tests resulted in an average heat flux of 349 Btu/hr ft^2, as predicted.
2. Heat flux measured after completion of the five pressure/temperature cycles was twice that of the initial test.
3. A large number of face sheet tears were found at the completion of testing, apparently due to inadequate dimpling. Some debonding occurred in the core and between the core and face sheet.
4. Purge test results indicate that sweep purging is just as efficient as pressure cycle purging in eliminating condensible gases before fill and in inerting the system after use.

TABLE 1. - SELECTED INSULATION MATERIALS

Component	Material	Manufacturer
Core Ribbon	500-gage Kapton Film (Type H)	Dupont
Facesheet	200-gage Teflon FEP Film (etched both sides)	Dupont
Core Node Adhesive	RTV-156	General Electric
Core-to-Facesheet Adhesive	RTV-560 with 0.25% DTD*	General Electric
Core-to-Metal Adhesive (and grout compound)	RTV-560 with 0.25% DTD*, 5% RTV-9811, and 1 to 2% Cab-O-Sil	General Electric Cabot
Primer on Core, Facesheet, and Metal	DC-1200	Dow Corning
Filler Material	PF-105-450 Fiber-glass Batting	Owens-Corning
*Dimethyl Tin Dilaurate curing agent.		

TABLE 2. SUMMARY OF TEST PARAMETERS

Event	Boiloff Rate Measurement									Temperature/Pressure Cycle				
	Duration		Liquid Level %	Average Tank Temperature				Vent Rate		Maximum Wall Temperature		Maximum Pressure		Liquid Level, %
				Lower Dome		Barrel (to liquid level)								
	k-sec	hr		°K	°F	°K	°F	kg/sec	lb/min	°K	°F	N/m²	psig	
1 Boiloff Rate No. 1	3.6	1	90	188	-121	254	-2	3.14×10^{-2}	4.15					
			60	179	-137	255	-1	2.33×10^{-2}	3.08					
Temperature/Pressure Cycle No. 1										446	343	73,766	10.7	90
2 Temperature/Pressure Cycle No. 2										465	375	72,387	10.5	87
Temperature/Pressure Cycle No. 3										466	379	69,630	10.1	60
Boiloff Rate No. 2	1.5	0.42	65	179	-139	252	-6	3.33×10^{-2}	4.4					
			50	174	-147	259	7	3.02×10^{-2}	4.0					
Temperature/Pressure Cycle No. 4										456	361	68,947	10.0	52
3 Temperature/Pressure Cycle No. 5										458	364	69,630	10.1	77
Boiloff Rate No. 3	6.9	1.9	40	163	-167	257	3	2.52×10^{-2}	3.33					
			10	163	-167	254	-3	1.04×10^{-2}	1.38					
4 Boiloff Rate No. 4	7.5	2.1	90	152	-186	261	10	6.4×10^{-2}	8.43					
			50	155	-181	259	6	3.42×10^{-2}	4.53					
			20	154	-182	255	-2	1.52×10^{-2}	2.01					

INSULATION COMMONALITY ASSESSMENT (PHASE I)
Schroeder, C. J., NAR, SD72-SA-0157-1, NAS7-200, February 1973

OBJECTIVE. - To assemble and organize all data on cryogenic insulation system materials and designs generated under the Saturn S-II programs in an effort to minimize redundancy in future space programs and to assure selection of an optimum design for a specific application.

PERTINENT WORK PERFORMED. This report supplies background data on the various insulation materials and systems used on the Saturn S-II (Figure 1) and studied for S-II derivative and related technologies. It is intended to be used as a handbook, guiding a designer through the various stages of system selection; requirement, design, materials, analysis, and qualification testing with tables illustrating problems and solutions (Table 1). Data on mission profiles as well as ground and flight environments are presented. The requirements for subsystem design are outlined including flight temperature, pressure, and vibration. Various aspects of insulation system design are discussed. Materials discussed include foam-filled and unfilled honeycomb, spray-on foam, pour foam, cork bonded over foam, and multilayer insulation. The particular problems of cryogenic transfer lines and high-temperature protection systems are discussed separately. Principles and techniques of thermal, structural, and dynamic analyses are presented. Various insulation materials used on the S-II and their thermal properties are shown in graphical form. Other sections of the document discuss reliability, safety and qualification test methods.

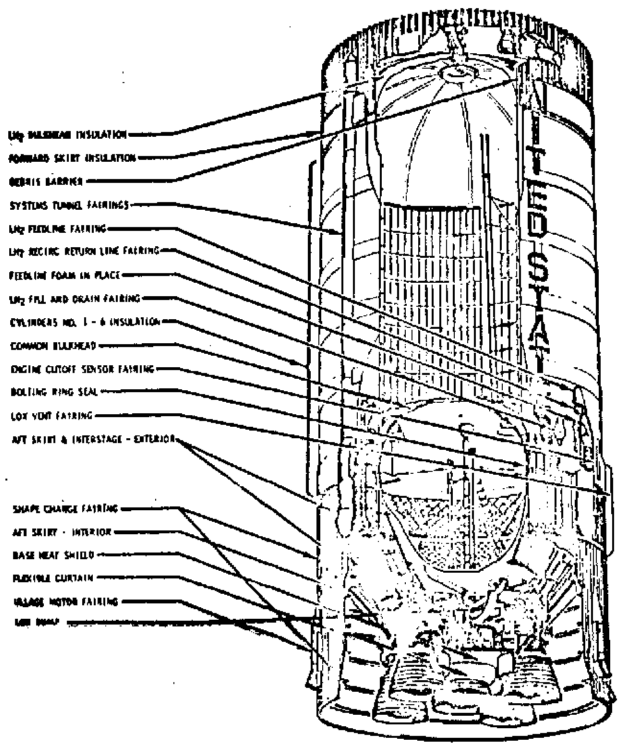


Figure 1. Saturn S-II Stage

Table 1. Insulation Problems and Solutions

Problem	Solution
Debond between outer facing sheet and honeycomb core during manufacturing test and on stage	1. Double tape adhesive in thickness to provide better filleting around edge of honeycomb core 2. Increase pressures to preclude bridging of non-uniform areas in honeycomb
Selection of outer laminate thermal compatibility	Select outer laminate with properties to match deflections imposed by primary structure; the dimples which result from the applied vacuum during fabrication are helpful in relieving thermal stresses
Effective closeout bond (local multi-contour surfaces and bonding to Tedlar)	Initial design over closeout area was effective seal but difficult to install; design changed to silicone adhesive which was easy to install but failed when subjected to cryogenic temperature because of gaps in the honeycomb/foam substrate; final solution was to use wet layup design (Detail A of Figure 6.1.1.1-1)
Inspectability (complex contours and hidden bond lines); Handling of Tedlar (wrinkles and pinholes)	Prepare designs to exclude areas where bond lines were not inspectable after cure; utilize special handling procedures and protective devices

SPACE SHUTTLE STRUCTURAL TEST PROGRAM CRYOGENIC TANK STRUCTURE/INSULATION TEST

Roodhouse, B.O., et al, GD/C, 549-3-092, NAS9-10960, March 1972

OBJECTIVE. - To design, fabricate, and test a subscale, flightweight, LH_2 tank incorporating a reusable polyphenylene oxide (PPO) foam, internal, open-cell gas layer insulation system.

PERTINENT WORK PERFORMED. - The insulation system selected for insulating the tank was PPO foam, an anisotropic material with elongated, open cells in the lateral (thickness) direction. The 1.8 inch thick foam was vacuum heat-formed on tools matching the internal contour of the tank. Special tools were used to install the panels in the tank with a two percent residual compression thereby eliminating the need for bonded butt joints (Figure 1). The panels were bonded to the tank wall with Silane-modified Crest 7343 polyurethane adhesive. Balsa wood closeouts were used between the foam and internal protrusions, and on faying surfaces. The instrumented tank was subjected to 100 simulated vehicle trajectory cycles involving tanking with LH_2, pressurization (from 1 to 60 psig), detanking, and heating (from ambient to 250F for the first 50 cycles, and from ambient to 300F for the second fifty cycles) (Figure 2).

MAJOR RESULTS. -

1. Structural integrity of the tank/insulation system was substantiated by its survival of proof pressure and cyclic environmental tests.
2. The high pressure levels in the subscale tank produced strains in the insulation material and adhesive bond line equal to or greater than those proposed for the flight vehicle.
3. No insulation system thermal degradation was experienced after 100 pressure, temperature, and tanking cycles.
4. An average insulation system ground hold heat flux of 155 Btu/hr ft^2 was measured.
5. Upon completion of the test, some cracking of the balsa wood closeout material was found, and some Teflon tape strips were found in the tank outflow filter.

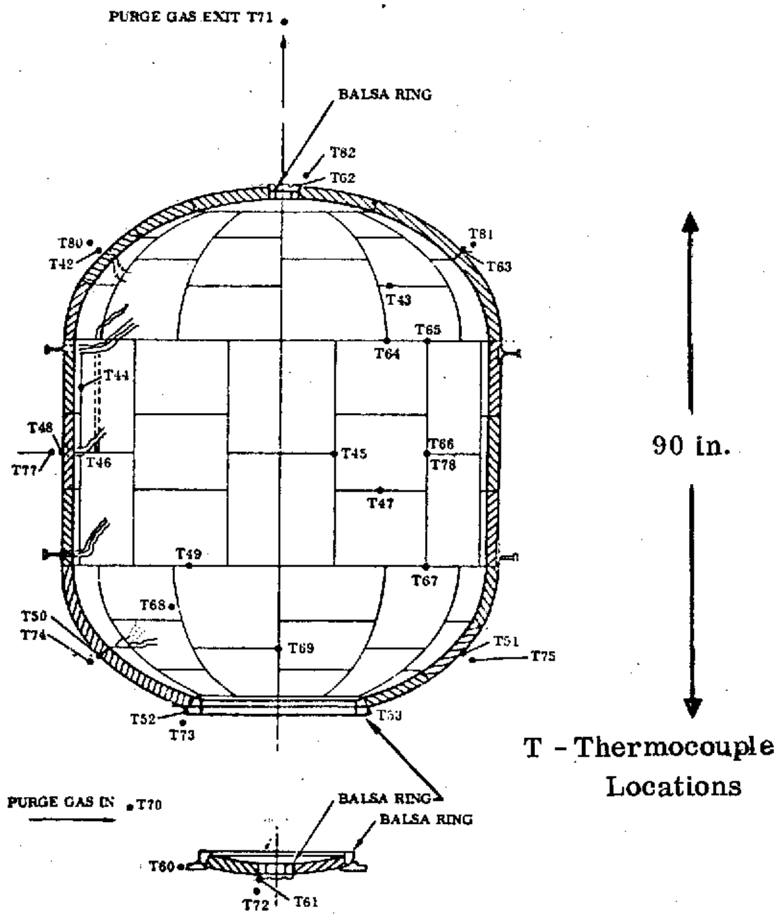


Figure 1. External Tank Surface and Purge Gas Thermocouples

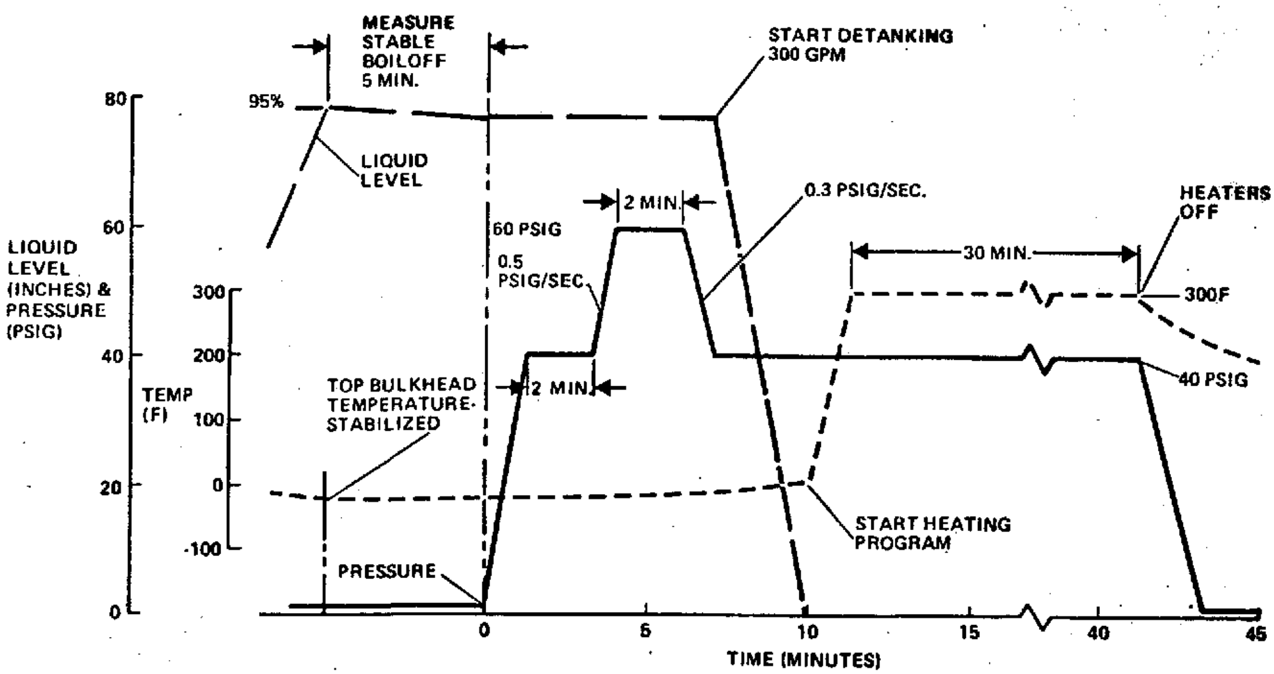


Figure 2. Life Cycle Performance Criteria, 300°F Tests

HEAT TRANSFER IN MICROSPHERE CRYOGENIC INSULATION
Cunnington, G. R. (LMSC) and Tien, C. L. (Univ. of Ca.),
Advances in Cryogenic Engineering, Vol. 18, 1972

OBJECTIVE. - To determine the characteristics of a new high performance insulation system consisting of micron-sized hollow glass spheres.

PERTINENT WORK PERFORMED. - The thermal performance of a microsphere insulation, with emphasis placed on the understanding of basic heat transfer mechanisms involved, was investigated. Both analysis and measurements are reported. A simple approximate analysis was conducted to demonstrate the interplay of various physical and system parameters and the magnitude of conduction and radiation contributions. A series of heat transfer tests was conducted to evaluate the thermal performance of hollow glass spheres for application to evacuated cryogenic insulation. Parameters of sphere size, surface optical properties, temperature, and compressive load were investigated and comparisons made between experimental results and the analytical treatment. Heat transfer measurements were performed using a 40.6 cm diameter double-guarded flat plate type calorimeter having a 16 cm diameter measuring section. The types of spheres investigated were (1) uncoated spheres, (2) aluminum-coated spheres, (3) hemispherically aluminum coated spheres and (4) a 50% by weight, mixture of 44 to 135 μm aluminized spheres and uncoated spheres. Equations describing the total heat transfer were developed from the experimental data for each type of insulation.

MAJOR RESULTS. -

1. The metallized microspheres offer a promising insulation for cryogenic applications.
2. Although heat transfer rates of microspheres are two to four times greater than those of installed multilayer insulation, the thermal isotropy and ease of use make them a candidate for some applications.
3. The use of half-coated or mixtures of coated and uncoated spheres is thermally more effective than the use of fully coated spheres for temperatures below 300°K (Fig. 1).
4. While the metallic coating increases conduction, it significantly reduces radiation, and this effect is of major importance at higher temperature where radiation predominates.
5. For very low temperature, the conduction-predominant region, the metallic coating is detrimental.
6. The effect of compression on heat flux for a 50% mixture of coated and uncoated spheres is shown in Figure 2.

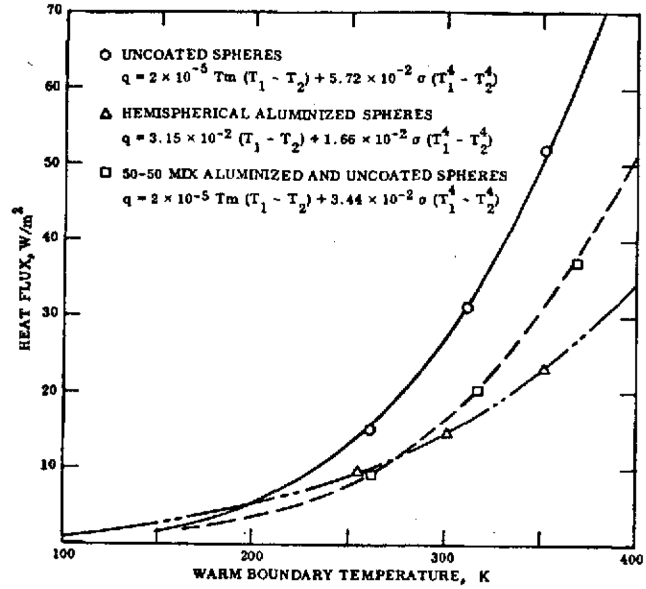


Figure 1. Influence of Metal Coating on Microsphere Heat Flux for 5.84-mm-thick Layers

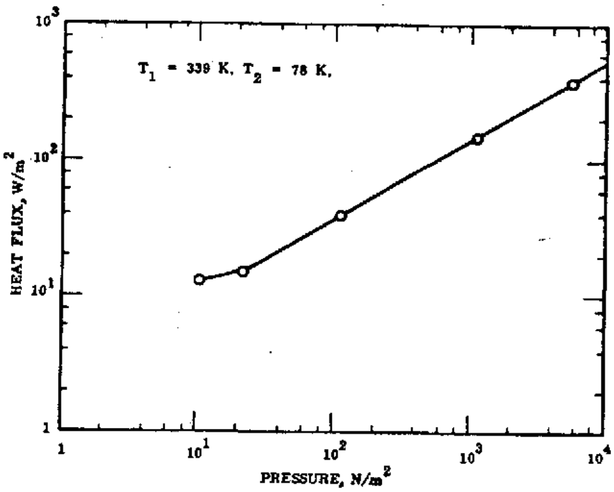


Figure 2. Effect of Compressive Pressure on Heat Flux for 50% Mixture of Coated (12.2 mm) and Uncoated Spheres

SATURN-II ADVANCED TECHNOLOGY STUDIES, IMPROVED CRYOGENIC FOAM INSULATION: Schwartz, R.; NAR, SD71-262, NAS7-200, December 1971

OBJECTIVE. - To provide data on cryogenic foam insulation systems having better temperature (to 300F) and loading capabilities than the system currently in use on the S-II stage.

PERTINENT WORK PERFORMED. - Nine polyurethane and four isocyanurate foam compositions were selected (Table 1) as candidates for evaluation, together with twelve primers and four permeation barrier materials. An extensive series of screening tests were run on the candidates including, where applicable, flammability, thermal aging, thermal shock, compression, helium permeation, and tensile monostrain. Subsequently foam/primer/barrier composites were produced and subjected to salt spray, thermal soak and shock, and tensile monostrain. Based on the results of these tests, three foams, two primers, and one barrier material were selected for a more comprehensive development program. Thermal cycling between - 300 and 300F, tensile monostrain in LN_2 and LH_2, thermal shock, thermal conductivity (Figure 1) and large panel tests were performed. For internal application additional configurations such as those shown in Figure 2 were analytically evaluated.

MAJOR RESULTS. -

1. None of the thirteen bonded, poured, or sprayed foam candidates, met the requirements for internal application, while four were considered feasible for external application.
2. A mechanically-attached "floating" foam block concept (Figure 2) was judged best for internal application.
3. The spray foam configuration was found to be best for external application.

Table 1. Literature Search-Foams

VENDOR	DESIGNATION	TYPE FOAM	DENSITY LB/FT^3	MIXTURE RATIO A/B*	PROCESSING TEMPERATURE
GENERAL PLASTICS	GP3903	POLYURETHANE	3	50/50	+ 120 F
GENERAL PLASTICS	GP3904	POLYURETHANE	4	52/48	+ 120 F
WHITCO CHEMICAL	#0037/38	POLYURETHANE	5	50/50	+ 125 F
WHITCO CHEMICAL	#0039/40	POLYURETHANE	2	50/50	+ 125 F
COOK PAINT & VARNISH	COOK 902	POLYURETHANE	3	50/50	+ 105 F
3M CORP	3M31405	POLYURETHANE	2	50/50	RT
REICHOLD CHEMICAL	R-2	POLYURETHANE	2	50/50	RT
EMERSON-CUMMINGS	ECCO - FOAM FPH-12-2H	POLYURETHANE (POUR)	2	50/50	RT
UPJOHN - CPR	CPR 421	ISOCYANURATE	2	66.7/33.3	RT
AMERICAN POLYMER	API 520	ISOCYANURATE	3	66.7/33.3	RT
GROVES SPECIALTIES	TC-4	ISOCYANURATE (POUR & SPRAY)	4	66.7/33.3	RT
GENERAL PLASTICS	GP3104	ISOCYANURATE (POUR & SPRAY)	4	66.7/33.3	NA
NOPCO	8X251	POLYURETHANE (POUR)	3	50/50	RT

*A = RESIN COMPONENT
B = POLYOL COMPONENT

RT - ROOM TEMPERATURE

NA - NOT APPLICABLE

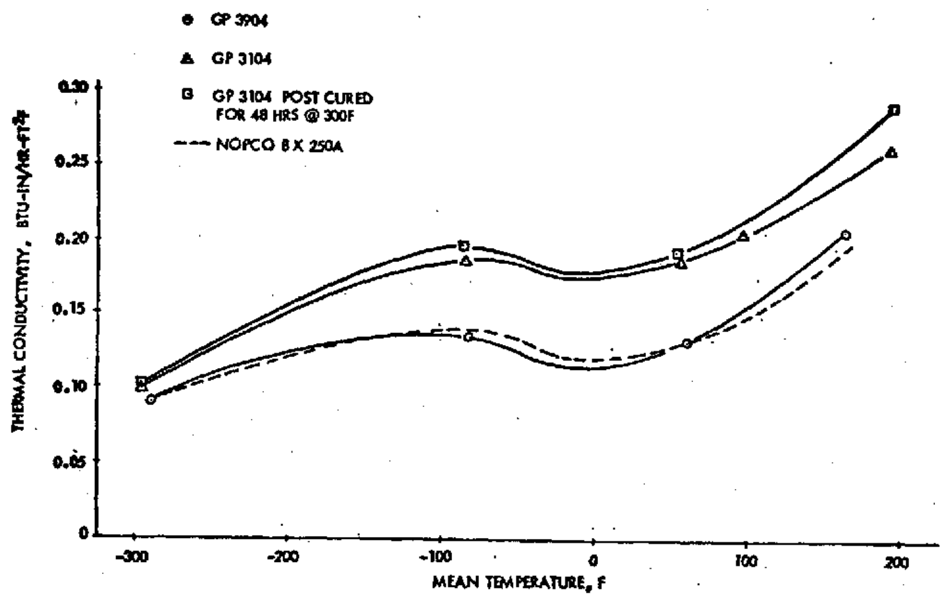
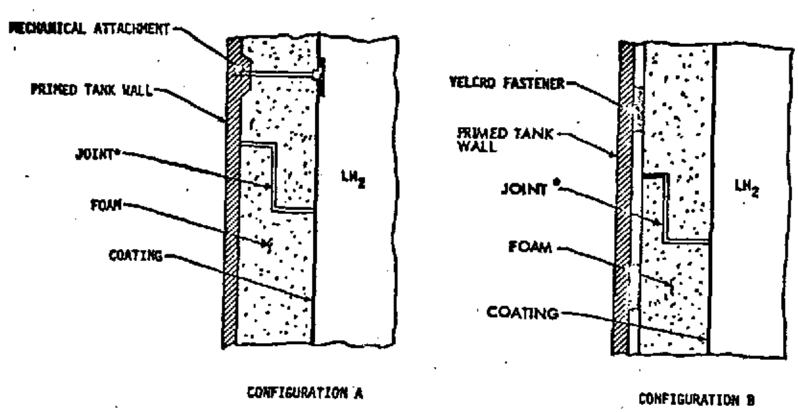


Figure 1. Thermal Conductivity Test Results GP 3904 & GP 3104



*JOINT MAY BE BONDED OR MAYBE DESIGNED AS SLIP JOINT

Figure 2. Configuration No. 4 Mechanically Attached Blocks (Internal Insulation)

INSULATION SYSTEMS FOR BOOSTER MAIN CRYOGENIC TANKAGE

Bradshaw, R.D. et al, GD/C 76-549-1-102, NAS9-10960, June 1971

OBJECTIVE. - To evaluate candidate internal insulation systems for use on the main propellant tanks of the Space Shuttle booster vehicle.

PERTINENT WORK PERFORMED. - Selected candidate insulation systems were a honeycomb/perforated face sheet open-cell system (Figure 1), the polyphenylene oxide (PPO) open-cell foam, a modified S-IVB fiber-reinforced foam system, and a modified S-II spray foam system (Figure 2). These materials were evaluated on the basis of development and operational costs, weights, thermal performance, reusability and reliability. A trade-off of tank pressure schedule and thermal residuals was included. The PPO foam system, 0.9 inch thick, was chosen for the LH_2 tank based on these criteria. For the LO_2 tank, the utilization of a ground hold nitrogen purge system made the selection of an uninsulated tank the most promising choice. Here no difficulty with thermal residuals exists, thus heat flux is not a limiting parameter. Details of the insulation systems and of the thermal residuals optimization analysis are presented.

MAJOR RESULTS. -

1. Due to the presence of an external TPS, an external cryogenic insulation system was not feasible. Consequently only internal systems were considered.
2. Gas layer insulation was preferred over the sealed foam systems since it is not stressed by pressure cycling of the cells. That is, it has a higher reliability as a reusable system.
3. PPO foam was selected for the LH_2 tank due to its lower overall cost, its potential reliability due to its simplicity and its not being sealed, and its lower weight.
4. An 0.9-inch foam insulation thickness results in propellant thermal residuals being less than those due to the trapping of the propellants in lines.
5. Purge requirements to avoid ice or frost formation are in excess of currently available launch facility flowrates.

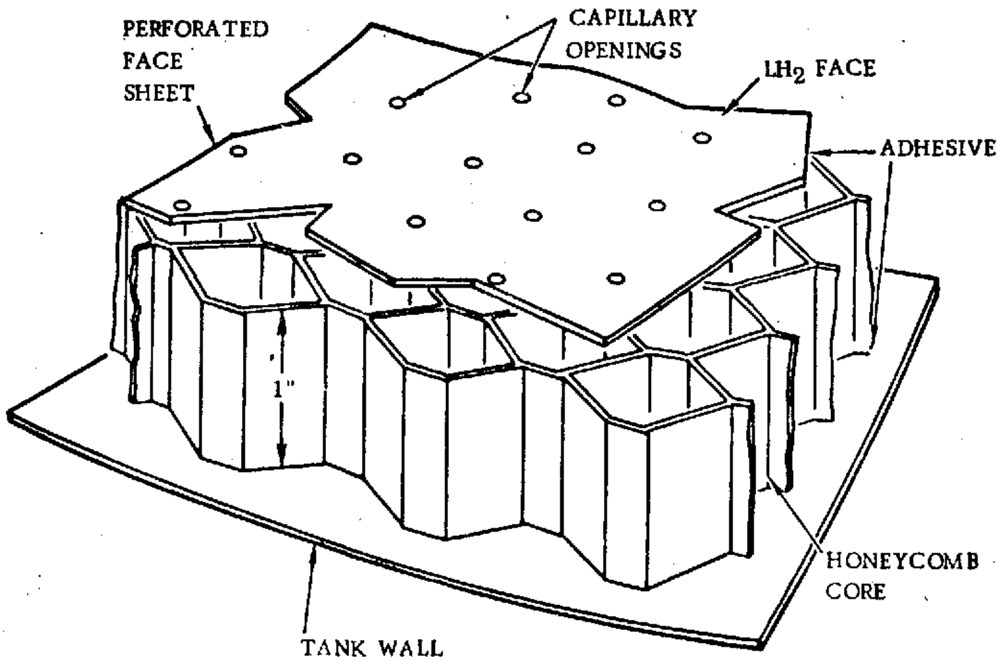


Figure 1. Details of Martin Capillary Gas Layer Insulation System

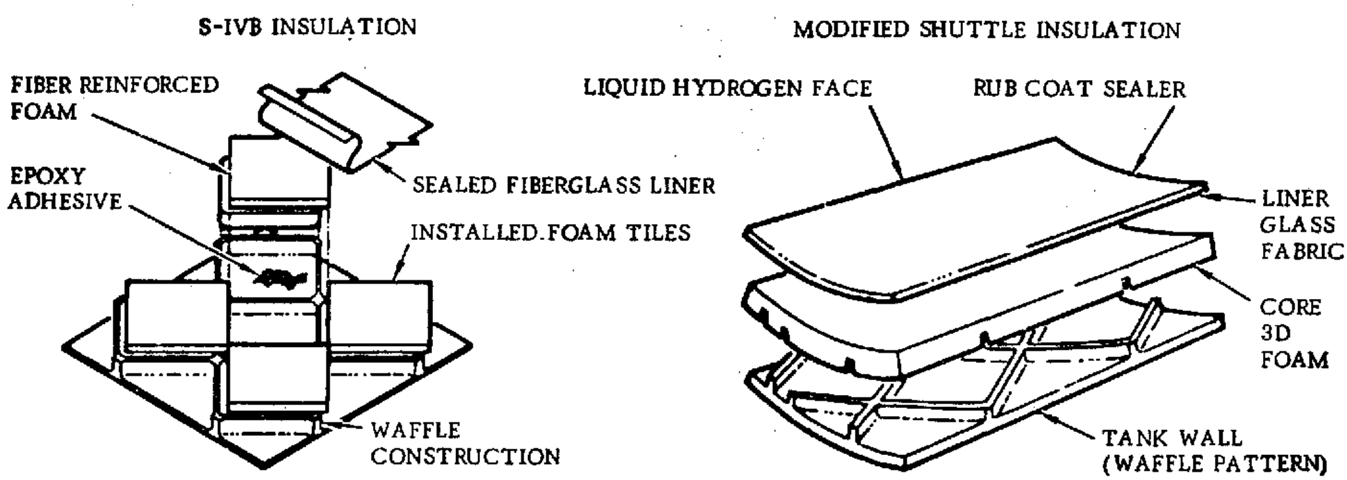


Figure 2. MACDAC Sealed Composite Insulation Concept

DESIGN AND FABRICATION OF SHADOW SHIELD SYSTEMS FOR THERMAL PROTECTION OF CRYOGENIC PROPELLANTS
Arthur D. Little, Inc., NASA CR-72595, NAS3-10292, Nov. 1969

OBJECTIVE. - To design and fabricate a shadow shield system for the long-term thermal protection of a LH_2 propellant tank.

PERTINENT WORK PERFORMED. - The design was based on the results of a previous ADL analytical study (NASA CR72369) in which several conceptual designs were evaluated for a spaceborn upper-stage configuration in which the shadow shields were located between a sun-oriented, 10-foot-diameter payload and LH_2 tank. In this program, six shadow shield systems were evaluated and two of these selected and fabricated for delivery to NASA-LeRC. The two chosen configurations both utilized two double-sheeted shadow shields located between the payload and the tank, and twelve (1) fiberglass or (2) titanium payload support struts. A test apparatus was designed and fabricated and delivered to NASA-LeRC to evaluate the two selected models. The evaluation was based on total system weight (weight of shadow shield plus weight of vaporized propellant) and the inherent reliability based on mechanical and operation complexity. The concepts evaluated included space - erectable systems, ground - erected systems (fixed) and systems which provide for solar-vector misalignment. The vehicle chosen as a representative configuration was 10 feet in diameter with an 1160 lb capacity LH_2 tank suspended within the vehicle structure. The payload was assumed to be at a constant temperature of 520°R with a mass of either 1500, 2500 or 4000 lbs. The overall arrangement of the shadow shield system, the calorimeter tank and the 8 ft.-diameter cryoshroud are shown in Figure 1.

MAJOR RESULTS. -

1. Conceptual designs and analysis indicated that shadow shield systems with fixed payload support structures could be designed to have a small mass penalty and a small payload-to-tank spacing.
2. LH_2 boiloff mass for compact, fixed structure concepts can be made small by using several, low emittance, low conductance shadow shields, spaced between payload and LH_2 tank and by reducing the conductive heat flow to the LH_2 tank.
3. The results of the analysis showed that both systems would result in LH_2 boiloff during a 10,000 hour sun oriented portion of the mission which is small compared with the estimated boiloff during ascent and earth orbital operation.

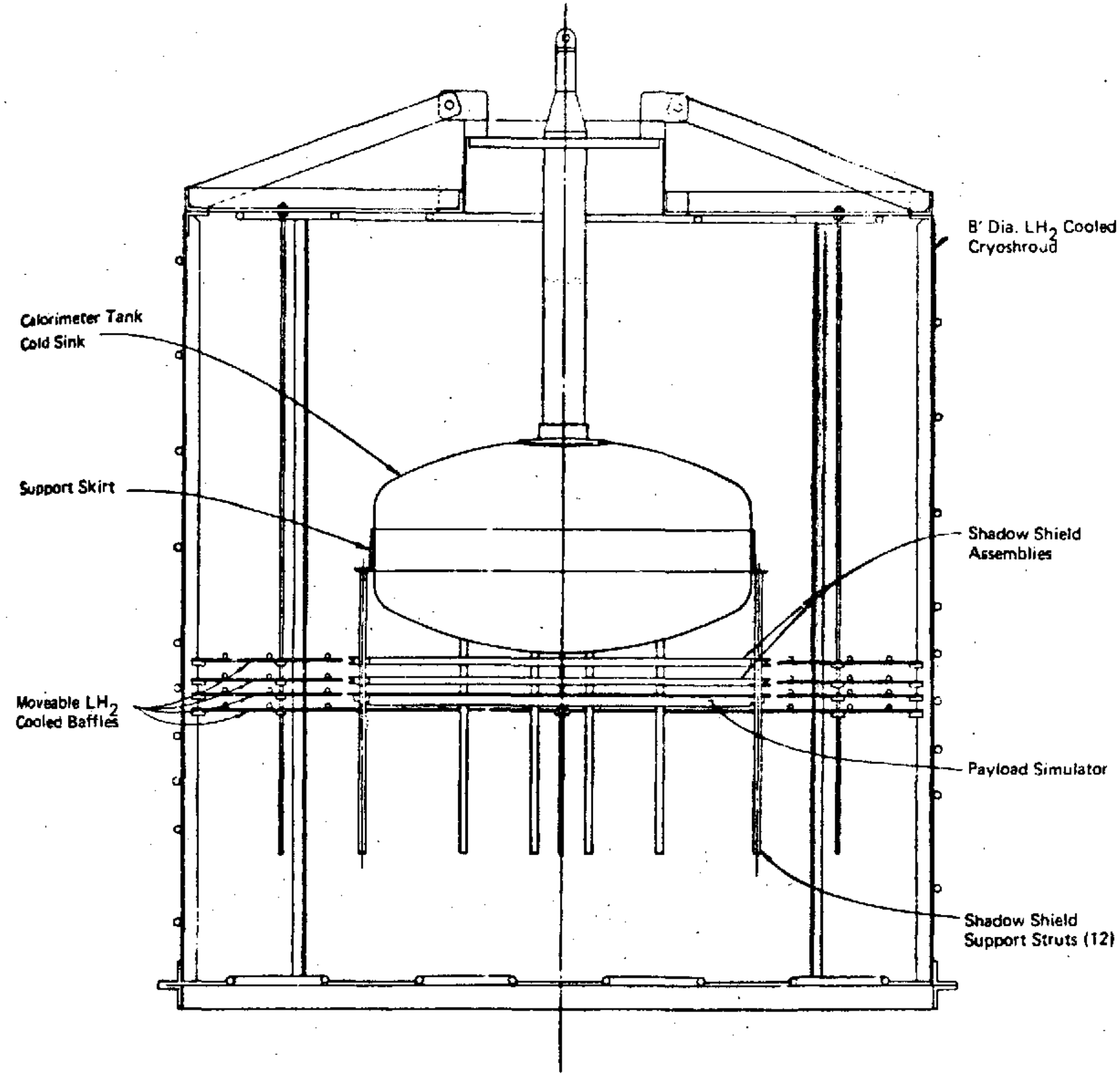


Figure 1. 8' Cryoshroud and Shadow Shield Assembly

DEVELOPMENT OF ADVANCED MATERIALS FOR INTEGRATED TANK INSULATION SYSTEM FOR THE LONG TERM STORAGE OF CRYOGENS IN SPACE
Gille, J. P., MCR-69-405, NAS8-21330, September 1969.

OBJECTIVE. - To analytically and experimentally evaluate concepts for using vented hydrogen gas to reduce heat flux to LH_2 tanks during long term storage in space.

PERTINENT WORK PERFORMED. Using the Saturn S-IVB stage as a reference vehicle, analyses were made of the effect of using the hydrogen boiloff gas to intercept incoming heat to the tank through the three principle paths; tank support structure, connecting plumbing, and insulation system. Non-metallic materials were evaluated for use in the support structure, and thermal conductivity tests of candidate materials were performed. A four-foot diameter tank was insulated with 20 layers of double aluminized Mylar (DAM) nylon net multilayer insulation (MLI) and placed in a shroud insulated with 40 layers of DAM/net MLI (Figure 1). A tube/fin heat exchanger assembly was mounted between the two MLI systems. Space equilibrium tests were run both with and without boiloff gas in the heat exchanger.

MAJOR RESULTS. -

1. Based on analytical predictions, heat entering a cryogenic tank through the plumbing system can be reduced by up to 50% by using vent gas cooling.

2. Due to low heat flux and structural complexity, vent gas cooling of the tank support system is not warranted.

3. Composite materials can reduce structural support heat leaks by 60% or more compared with titanium.

4. A thermal test of a vent-cooled insulation system indicated a 67% reduction in the heat flow through the tank-mounted MLI system, but only a 19% reduction in total heat flow to the liquid hydrogen.

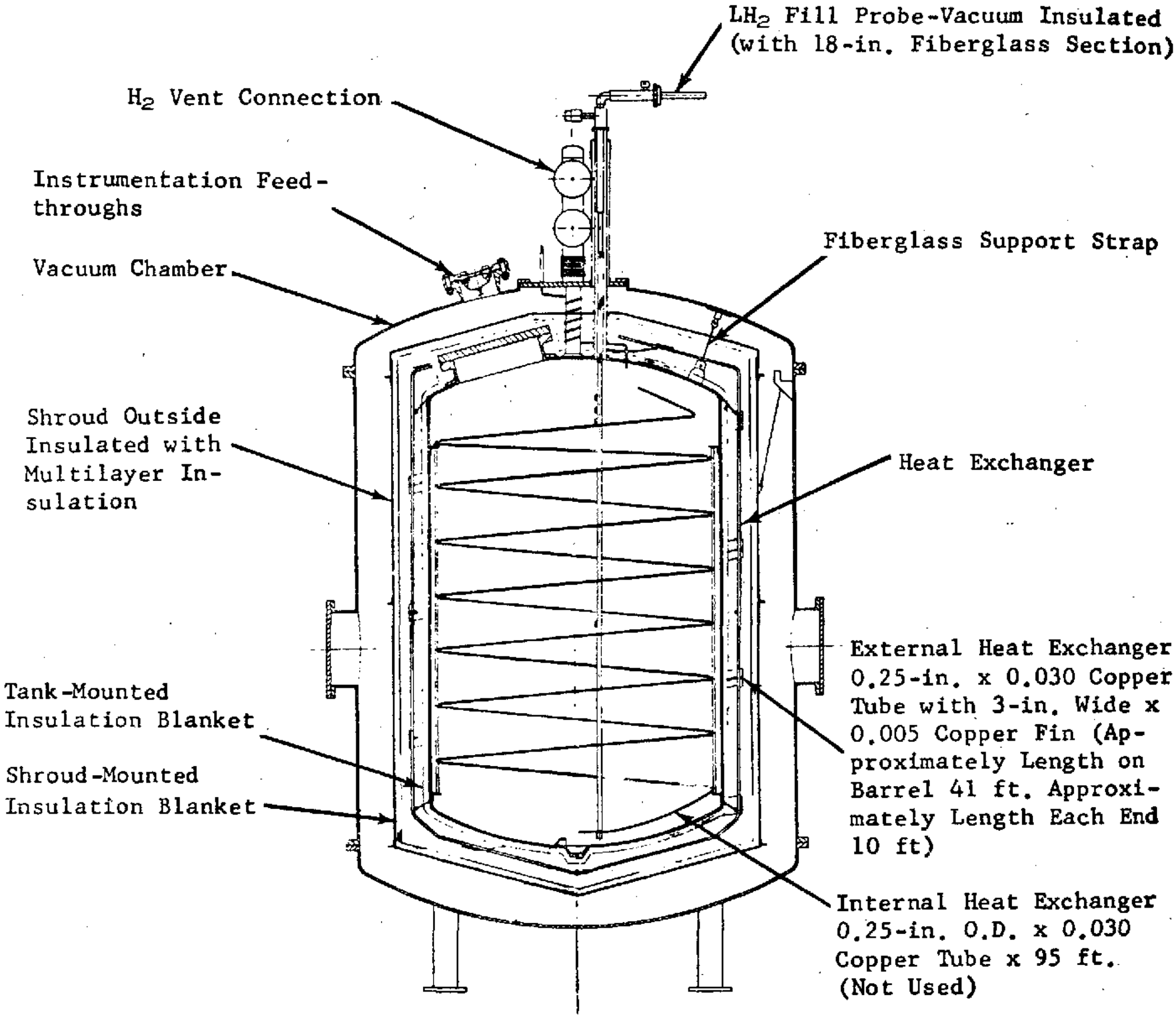


Figure 1. Integrated Tank Insulation System Test Installation

AN ANALYTICAL AND EXPERIMENTAL DEVELOPMENT PROGRAM FOR INFLATABLE SOLAR SHIELDS
Doughty, R.O., GD/FW, FZA-441, NAS8-21132, May 1969

OBJECTIVES. - To establish design criteria required for the development of inflatable solar shields, and to subsequently conduct a systematic analytical and experimental program leading to the fabrication and testing of scale model shields.

PERTINENT WORK PERFORMED. - This report presents the results of an analytical and experimental program to develop a lightweight inflatable solar shield which can be folded and packaged in a small volume for transportation into space, subsequently deployed and inflated to a large volume, and rigidized to form a structurally stable piece of space hardware. The program comprised four phases: (1) Materials development and testing, (2) structural, thermal, and operational criteria formulation, (3) scale model testing and (4) design criteria synthesis and orbital experiment definition. The materials development and testing phase of the program involved the evaluation of various candidate materials for solar shield application. An extensive series of tests was conducted to determine mechanical and thermal properties. Criteria were formulated regarding the structural, thermal and operational design of solar shield models. The scale model tests were designed to provide experimental verification of the deployment, inflation, rigidization, structural, and thermal characteristics of the solar shield design concepts. The program included both spherical models and tubular components of truss type structures. Particular emphasis was placed on the evaluation of load carrying capacities of spherical models. A synthesis of design criteria was made to provide a relatively condensed description of basic requirements involved in the design, fabrication and utilization of a solar shield.

MAJOR RESULTS. -

1. The materials investigation resulted in the development of a flexible, lightweight material that can be partially machine fabricated, folded and packed in a very small volume, stored for a prolonged period under controlled temperature conditions, then deployed from the storage cannister, inflated, and rigidized (open cell polyurethane foam, bonded to aluminized, Mylar/ aluminized film, impregnated with a monomeric compound).

2. The material properties of the foam composite shell (tensile, compressive and flexural yield stresses) were found to be well within the range required for use as the load carrying material.

3. The spherical solar shield is the most desirable configuration from both thermal and operational performance standpoints.

4. The solar shield is an effective means for protecting cryogenic vehicles from direct solar energy.

5. Typical solar shield configurations are presented in Figure 1.

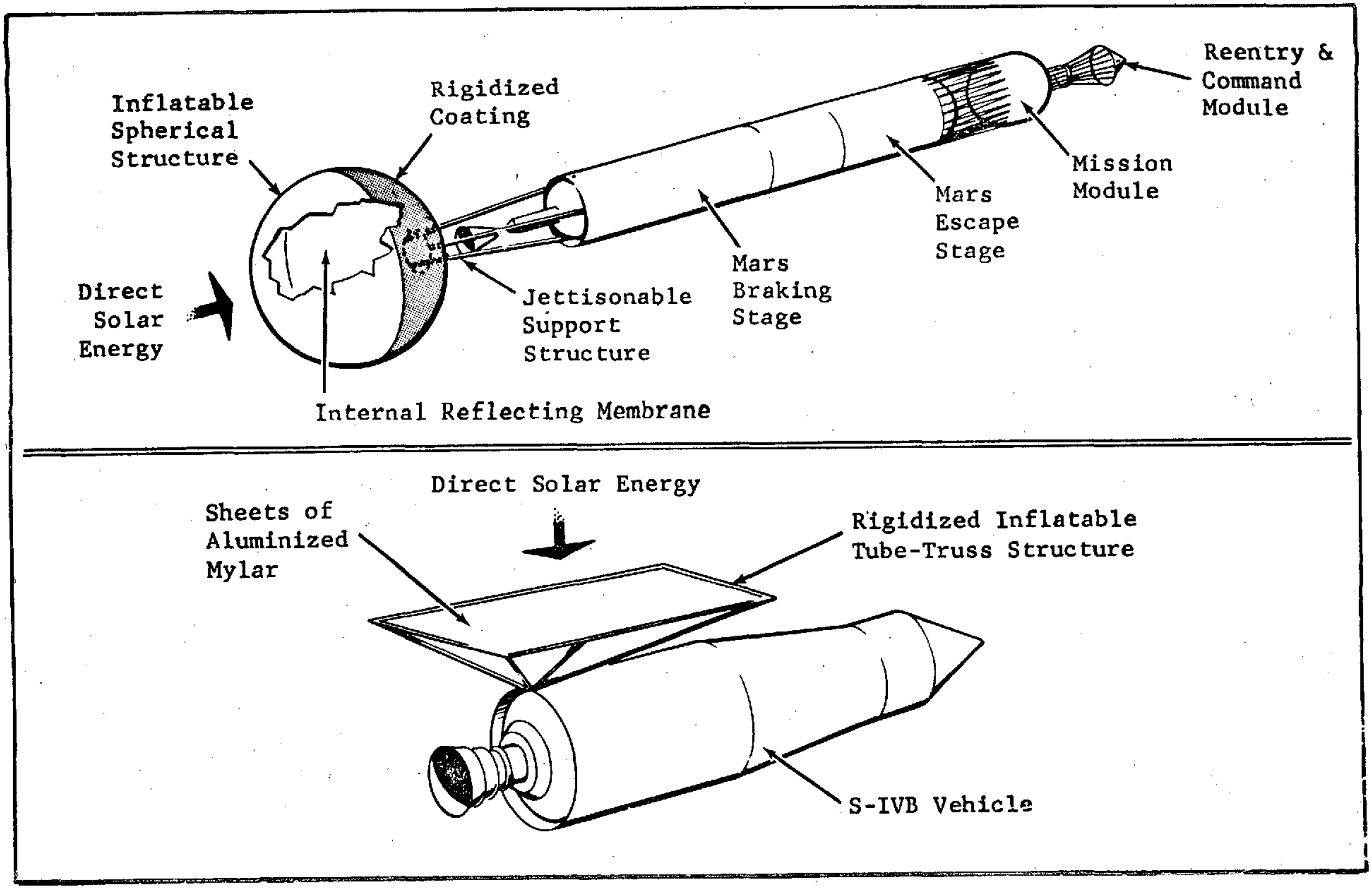


Figure 1. Typical Solar Shield Configurations

EXPERIMENTAL STUDIES ON SHADOW SHIELDS FOR THERMAL PROTECTION OF CRYOGENIC TANKS IN SPACE
Knoll, R.H., Bartoo, E.R., NASA-LeRC, NASA TN D-4887, November 1968

OBJECTIVE. - To analytically and experimentally determine the thermal performance of various configurations of shadow shields.

PERTINENT WORK PERFORMED. - Experimental data were obtained on the performance of both idealized and practical flat-disk shadow shields used to reduce radiant heating between two bodies in a low temperature vacuum environment. The experiments included the effects of shield spacing, number, emissivity, lateral conductance, and targeting (high emissivity coatings on annular rings of shields) on thermal performance. A lightweight shield concept was evolved that consisted basically of a circumferential ring with shield material stretched and secured to one or both sides of the ring (single-or double-sheeted). Experimental data were also obtained on the performance of tubular structure members for shield support. Finally, an integrated system for a hypothetical space vehicle and mission was designed, scaled down and tested to examine the interaction between shields and their necessary supports. Shield-support interactions were determined for systems with the shields pinned in place, welded in place, and welded in place with the shields and struts selectively coated. Although no analysis was made on the shield support interactions, it was determined that a separate analysis of the shields and supports could be extremely helpful in determining how and where the shields should be connected to the support members.

MAJOR RESULTS. -

1. The experimental data, in general, agreed closely with an analytical model which assumed diffuse surfaces with non-uniform radiosity.
2. The experimental shield temperatures, for the low emissivity ($\epsilon=0.03$) shields tested, tended to be lower than predicted due to neglecting the directionally-dependent, non diffuse properties of the shield material.
3. The targeted shield tests demonstrated that selective coating of annular areas of a shield can provide an effective method of controlling the shield-temperature profile.
4. The use of a peripheral ring with a shield material stretched over and secured to it (single-sheeted shield) provided a practical lightweight method of constructing a shadow shield.
5. Selectively coating the scale-model system significantly lowered the temperatures of the shield struts and pointed out a means of lowering the overall heat transfer rate.
6. Heat transfer rate between payload and upper half of the hydrogen tank of a hypothetical vehicle is shown in Figure 1.

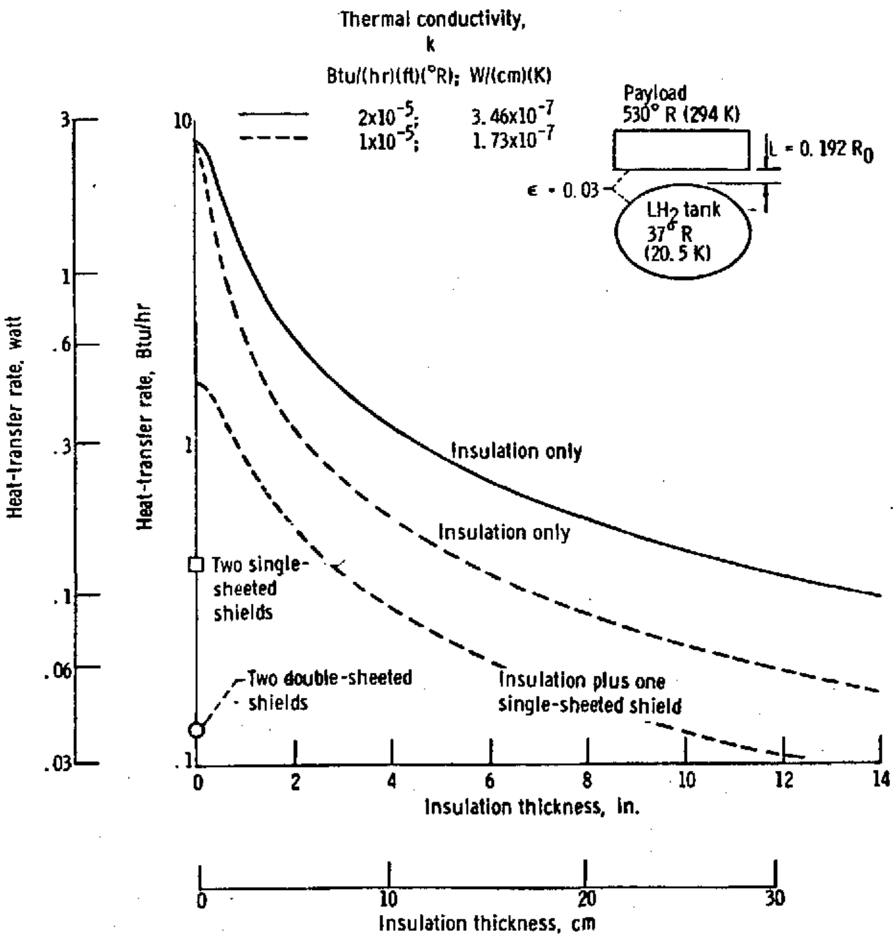


Figure 1. - Heat-transfer rate between payload and upper half of hydrogen tank of hypothetical vehicle as function of insulation thickness and thermal conductivity. Insulation surface temperature and thickness are uniform over entire upper surface of tank.

DEVELOPMENT OF A LIQUID SHROUD CRYOGENIC SUPERCRITICAL PRESSURE STORAGE SYSTEM
Lundeen, R., Bendix, NASA CR-1048, NAS 9-4634, May 1968

OBJECTIVE. - To design and fabricate a cryogenic storage system for space flights of long duration.

PERTINENT WORK PERFORMED. - A cryogenic storage system which employs the use of a shroud unit to preserve cryogens was designed and fabricated. This shroud concept provided a means of using a secondary fluid to act as a refrigerant and thus greatly reduced loss of primary fluid contained in the inner vessel. Two separate shroud designs were investigated during this period of development. The integrally-mounted shroud system (Figure 1) has the secondary fluid surrounding and in contact with the outer surface of the inner vessel, while the isothermally-mounted shroud system (Figure 2) has the secondary fluid contained within the shroud itself. The program further explored the use of a vapor-cooled discrete radiation shield as a means of reducing heat loss of the stored fluids. The cryogenic shroud test program consisted of (1) liquid nitrogen venting tests, vapor cooled and non-vapor cooled, (2) liquid hydrogen venting tests, vapor cooled and non vapor-cooled and (3) pressure buildup in the inner vessel with liquid hydrogen in both vessels. A pressure build-up test in the inner vessel was performed with the shroud filled with liquid hydrogen and vented through the vapor-cooled shield.

MAJOR RESULTS -

1. The shroud system was shown to be an effective design for both pre-launch and in-flight standbys.

2. The isothermally-mounted shroud system presents fabrication and assembly complications which are not offset by weight and thermal advantages, when compared with the integrally-mounted shroud design.

3. The use of a vapor-cooled discrete radiation shield proved highly effective when used with the shrouded cryogenic storage design in that it maximizes the utilization of the vented secondary shroud fluid.

4. It was found that a hydrogen-shrouded helium storage system represents an improved method of storing helium at high densities as well as eliminating loading problems currently experienced with conventional helium storage systems.

5. The cryogenic shroud tank vented heat leak test results and the effects of vapor cooling are shown in Table 1.

Table 1. Cryogenic Shroud Tank Vented Heat Leak Tests

INNER VESSEL		SHROUD		SHIELD	TEST PERIOD HR.	AMBIENT TEMP °F	AVE. HEAT LEAK, BTU/HR.		
FLUID	PRESS. PSIA	FLUID	PRESS. PSIA				INNER VESSEL	SHROUD	TOTAL SYSTEM
LN_2	14.7	LN_2	14.7	NON VAPOR-COOLED	24	65	3.05	4.95	8.0
-	-	LN_2	14.7	VAPOR-COOLED	15	78	-	6.89	-
-	-	LN_2	14.7	VAPOR-COOLED	10	70	-	6.07	-
LH_2	14.7	LH_2	14.7	NON VAPOR-COOLED	20	65	-	-	4.2
LH_2	14.7	LH_2	14.7	VAPOR-COOLED	40	58	-	-	3.0

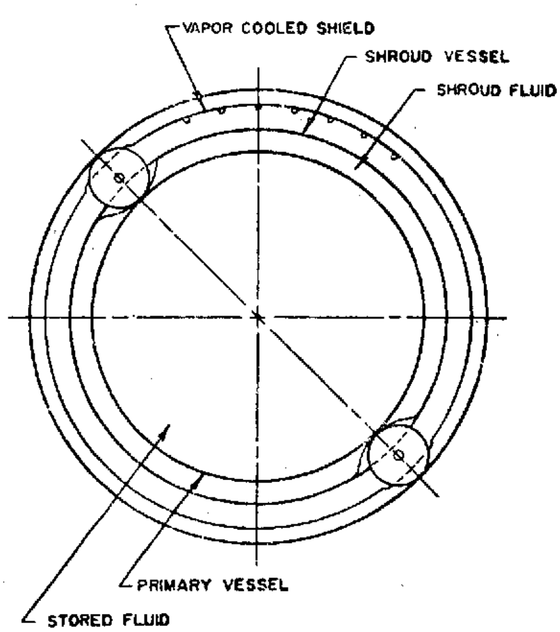


Figure 1. Integrally-Mounted Shroud Design

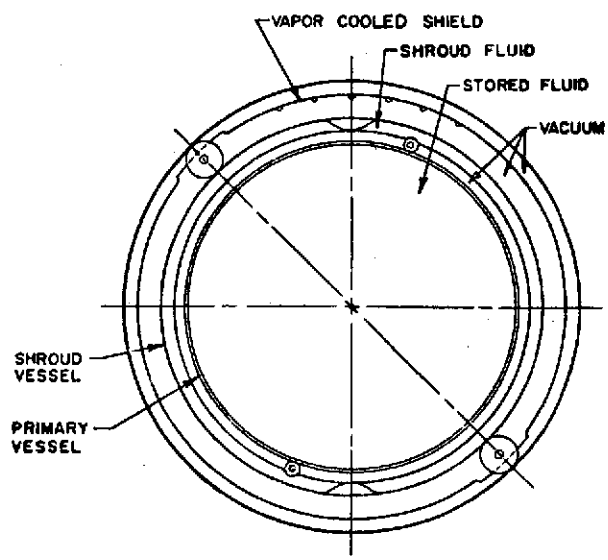


Figure 2. Isothermal-Mounted Shroud Design

SEALED-FOAM, CONSTRICTIVE-WRAPPED, EXTERNAL INSULATION SYSTEM FOR LIQUID-HYDROGEN TANKS OF BOOST VEHICLES: Hacker, P.T., et al; NASA-LeRC, TN D-2685, March 1965

OBJECTIVE. - To determine a lightweight LH_2 tank ground hold insulation system which would withstand the launch environment.

PERTINENT WORK PERFORMED. - A comparison of candidate insulation materials (foam, corkboard, balsa, powders, multilayer) and configurations (external purged, external sealed, internal sealed) led to the selection of an external, constrictive wrapped, bonded, low density polyurethane foam insulation system (Figure 1). A typical Atlas-Centaur launch trajectory was used to develop heating rates. Foam materials were subjected to flat-plate calorimeter and oxygen impact sensitivity tests prior to evaluation on a subscale tank. Conductivity and aerodynamic heating tests were performed. Finally a system was designed, fabricated, and installed on a full-size Centaur tank (Figure 2). A fiberglass roving wrap was applied over the insulation at a 2 psi normal pressure. Two ground hold tests were performed to measure liquid boiloff at constant pressure and nonvented tank pressure rise. A final, detailed inspection of the insulation system was made.

MAJOR RESULTS. -

1. To provide thermal performance equivalent to that of the jettisonable panels, a foam thickness of only 0.4 inch was required.
2. The overall installed weight of the system was only 0.16 pound per square foot.
3. Although the weight of the jettisonable system is approximately 15 times heavier than that of the nonjettisonable system, the payload capability of the vehicle with the jettisonable insulation is more than ten percent greater (Table 1).
4. The average measured thermal conductivity of the installed system was 0.10 Btu-in/hr ft^2R.
5. Several small blisters in the insulation, caused by small leaks which permitted air to cryopump into the insulation, apparently had no measurable effect on insulation performance.
6. For the pressure stabilized tank configuration, it appears that a bonded insulation system plus a constrictive wrap actually increases rather than decreases the buckling resistance of the tank.

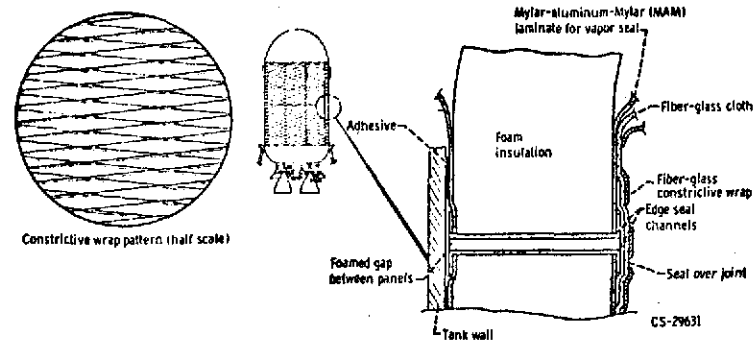


Figure 1. Lightweight Externally Sealed Insulation System

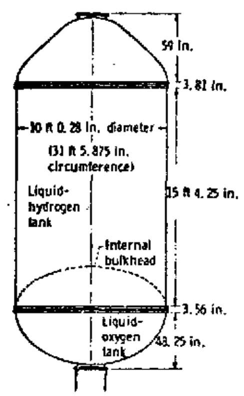


Figure 2a. Outline of dimensions of full-scale tank used for installation of insulation system.

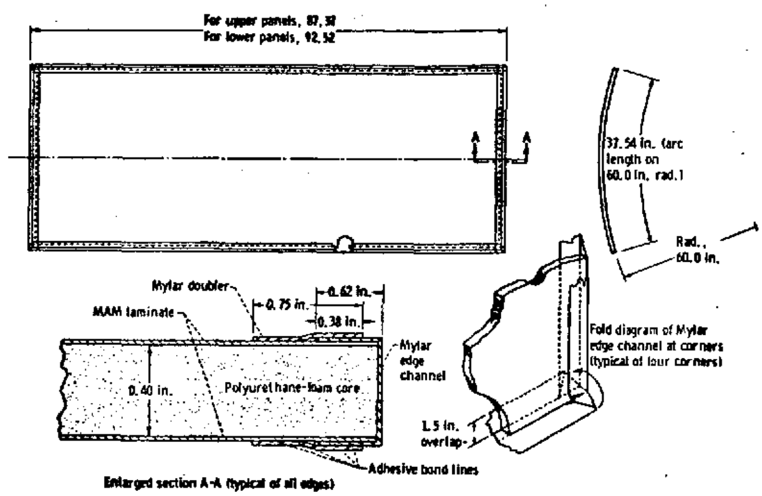


Figure 2b. Insulation Panel Details

Table 1. Comparison of Jettisonable and Nonjettisonable Insulation Systems

	Weight, lb	Payload loss factor	Payload loss, lb
Sealed foam, constrictive-wrapped, nonjettisonable insulation system			
Insulation	[a]81.3	1.0	81.3
Jettisonable fairings[b]	30	.058	1.7
Maximum fuel boiloff at 0 to 173 sec[c]	37.0	.23	8.5
Maximum fuel boiloff at 173 to 250 sec[d]	16.0	.42	6.7
Maximum fuel boiloff at 250 to 675 sec[e]	15.3	.66	10.1
Total payload loss, lb	----	-----	108.3
Typical jettisonable insulation system			
Insulation	1200	0.058	69.6
Nonjettisonable weight[f]	9.0	1.0	9.0
Maximum fuel boiloff at 0 to 173 sec[c]	11.3	.23	2.6
Maximum fuel boiloff at 173 to 250 sec[d]	7.7	.42	3.2
Maximum fuel boiloff at 250 to 675 sec[e]	14.1	.66	9.3
Total payload loss, lb	----	----	93.7

[a]Includes 2.6-lb allowance for foam fairing to cover wiring harness required on Centaur vehicle.

[b]Fairing to provide aerodynamic shield over fuel boost pump required during atmospheric portion of boost trajectory. It can then be jettisoned.

[c]Jettisonable insulation jettisoned at 173 sec.

[d]First-stage sustainer engine cut off at 250 sec.

[e]Centaur engines burning.

[f]Part of helium-purge system and equipment for jettisoning insulation system cannot be jettisoned.

EXPERIMENTAL STUDY UNDER GROUND-HOLD CONDITIONS OF SEVERAL INSULATION SYSTEMS FOR LIQUID HYDROGEN FUEL TANKS OF LAUNCH VEHICLES
Perkins, P.J., Jr., NASA-LeRC, TN D-2679, March 1965

OBJECTIVE. - To experimentally investigate three external liquid hydrogen tank insulation systems under ground hold conditions to determine feasibility for application to flight-weight tanks.

PERTINENT WORK PERFORMED. Three insulation systems were applied to 32-inch diameter aluminum test tanks: sealed corkboard, 20 lb/ft^3 and 0.25-in. thick, bonded to the tank; sealed and evacuated 2.5 lb/ft^3 polyurethane (poly) foam, 0.15 in. thick, held in place with a constrictive nylon tape wrap (Figure 1); and sealed and evacuated poly foam with a liquid nitrogen film sprayed on the external surface. An uninsulated tank, with and without a natural accumulation of ice and frost, was included for comparison. The corkboard system [density (ρ) × conductivity (k) = 8.6 Btu-lb/hr ft^{4}F] is considerably less efficient than the poly foam system [ρk = 0.2 Btu·lb/hr ft^{4}F], but was included for its superior high temperature characteristics. An orifice meter was used to measure boiloff rate and the tank wetted area was determined from capacitance probe measurements.

MAJOR RESULTS. -

1. The corkboard system cracked and suffered 50 percent delamination from the tank wall. Its overall effective thermal conductivity was determined to be 0.02 to 0.022 Btu/hr ft F (Table 1).

2. The wrapped poly foam system produced an effective conductivity of 0.0083 Btu/hr ft F at a mean temperature of 235 R, as predicted.

3. Spraying liquid nitrogen on the external surface of the poly foam resulted in an 80 percent reduction in heat flux from 156 to 30 Btu/hr ft^2 (Figure 2).

4. Heat fluxes for the uninsulated tank were on the order of 8100 Btu/hr ft^2 for the air liquefaction condition and 4000 Btu/hr ft^2 when ice and frost accumulated on the wall.

5. The specific weight of the wrapped poly system was 0.26 lb/ft^2 compared with 0.53 lb/ft^2 for the corkboard system.

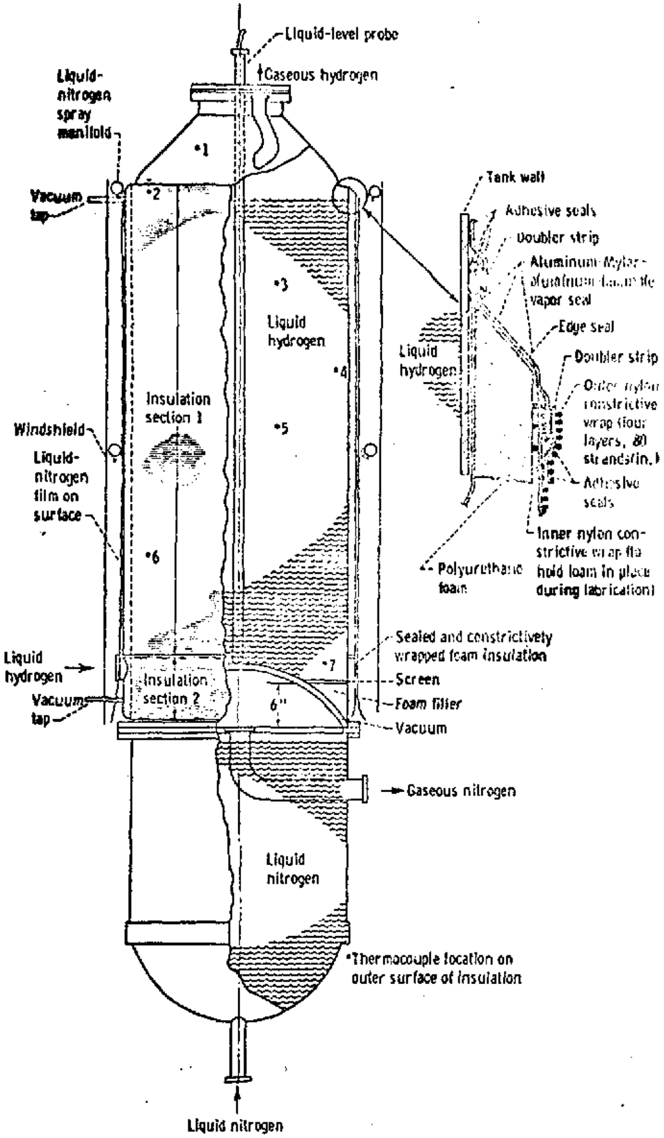


Figure 1.- Details of sealed and constrictive-wrapped polyurethane foam insulation system applied to propellant tank 2 and of liquid-nitrogen spray system. Insulation system weight, 0.25 pound per square foot.

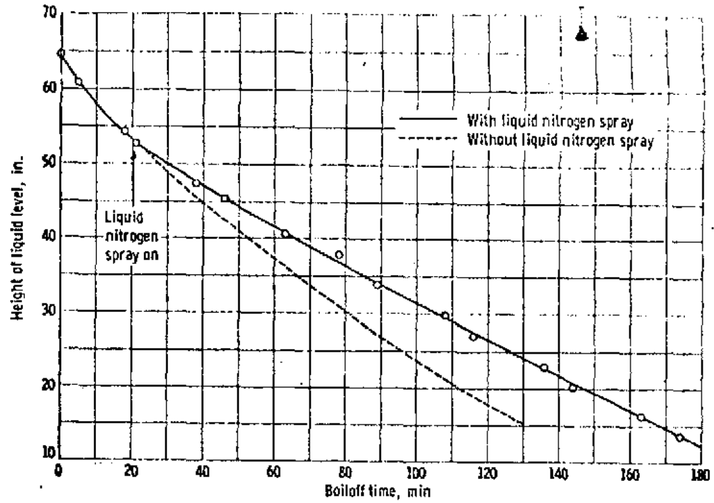


Figure 2.- Change in liquid level during boiloff of liquid hydrogen from sealed-foam-insulated tank with and without liquid-nitrogen spray over insulation.

TABLE 1. - THERMAL PERFORMANCE OF INSULATED AND UNINSULATED TANKS

Insulation type	Test	Average outside surface temperature, °F	Representative temperature difference across insulation, ΔT, °F (a)	Arithmetic mean insulation temperature, °R	Total heat inflow rate, Q_T/A_w, Btu/(hr)(sq ft)	Overall heat-transfer coefficient, h_a, Btu/(hr)(sq ft)	Apparent thermal conductivity, K_a, (Btu)(in.)/(hr)(sq ft)(°R)
Corkboard - insulated tank (1/4 in. thick)	1	-83	335	227	325	--	0.24
Sealed and constrictively wrapped polyurethane-foam-insulated tank (1/4 in. thick)	1 2 3	-25 -32 -80	393 386 338	238 235 211	156 156 102	-- -- --	0.10 .10 .08
Liquid nitrogen sprayed over sealed foam	1	-317	101	93	30	--	0.07
Uninsulated tank (condensing air on surface)	1	-340	78	--	8120	16.3	----
Uninsulated tank (layer of ice and frost on surface)	1	-380	38	--	3960	8.0	----

[a]Inside temperature of -418° F assumed for saturated liquid at tank pressure of 20 lb/sq in. gage.

4.0 FLUID LINES

Covering analysis, design and test of vacuum jacketed and composite lines and associated liners and joints.

TOPICAL REPORT, LIGHTWEIGHT THERMALLY EFFICIENT COMPOSITE FEEDLINES PRELIMINARY DESIGN AND EVALUATION:
Spond, D.E., et al, MMC, NASA CR-134631, NAS3-17796, June 1974

OBJECTIVE. - To develop lightweight, thermally efficient composite feedlines for the cryogenic space tug propulsion system.

PERTINENT WORK PERFORMED. - Six liquid hydrogen feedline concepts (Table 1) were developed consisting of composite and all-metal vacuum jacketed and non-vacuum jacketed concepts. The non-vacuum jacketed feedlines incorporated purged and non-purged multilayer insulation (MLI) systems. The latest technology developments in the areas of thermally efficient vacuum jacket end closures, standoffs, radiation shields in the vacuum annulus, thermal coatings and light weight dissimilar metal flanged joints were incorporated in the design concepts. The design concepts included straight line sections, curved sections, elbows, tees, flanged joints and gimbal installations. All concepts were evaluated on the basis of thermal performance, weight, cost, reliability and reusability. Various multi-layer insulation (MLI) systems were investigated for the LH_2 feedlines. The objectives were to find a system of low weight, readily purgeable during ground operations, easily installed on the feedline, thermally acceptable for insulation performance over all phases of the mission and reusable with minimum degradation and maintenance for the life of the vehicle. The total feedline system weight was determined by adding the feedline hardware weight and the weight of the LH_2 losses.

MAJOR RESULTS. -

1. The study showed that the Space Tug propulsion system LH_2 feedline weight can be improved by 26 lbs.by using composite tubing.

2. Composite feedlines exhibited superior damage resistance which makes them desirable from reliability, reusability and maintainability aspects.

3. The Dacron flock (Superfloc) between the radiation shields was selected over other spacer materials, e.g. foam, glass fabric, crinkled film, silk and nylon screen.

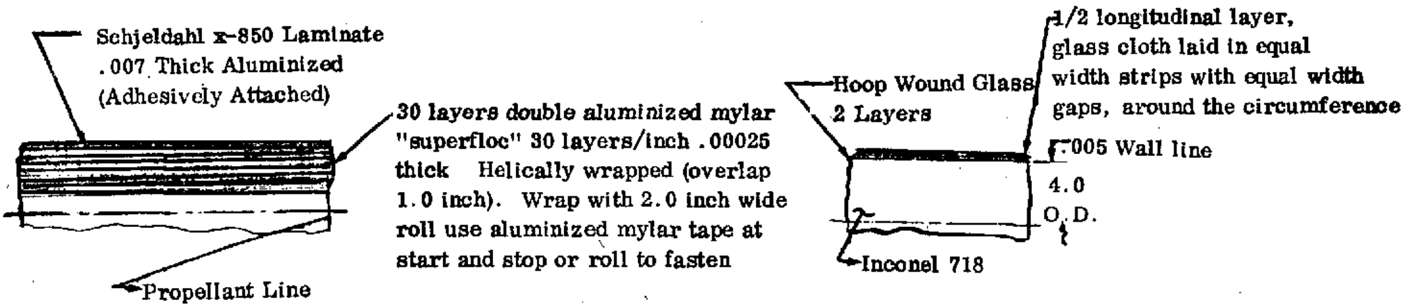
4. S-glass or graphite were the most promising overwrap materials.

5. The selected feedline design concept was a dry non-vacuum jacketed composite line utilizing MLI (Figure 1).

COMMENTS. - An apparent discrepancy exists in Table 1. Boiloff weights should be lower for vacuum-jacketed lines than for non-jacketed lines.

Table 1. Feedline Design Concepts

	Feedline Weight kg (lb)	Boiloff Weight kg (lb)	Total kg (lb)
1. Vacuum Jacketed Metal (Wet):	29.4 (64.9)	35.6 (78.6)	65.0 (143.5)
2. Vacuum Jacketed Composite (Wet):	21.3 (46.9)	35.0 (77.3)	56.3 (124.2)
Weight Saved by Composite Design:	8.1 (18.0)	0.6 (1.3)	8.7 (19.3)
3. Non-Vacuum Jacketed Metal (Purged MLI - Wet):	14.6 (32.2)	3.6 (8.0)	18.2 (40.2)
6. Non-Vacuum Jacketed Composite (Purged MLI - Wet):	10.8 (23.9)	3.0 (6.7)	13.8 (30.6)
Weight Saved by Composite Design:	3.8 (8.3)	0.6 (1.3)	4.4 (9.6)
4. Non-Vacuum Jacketed Metal (MLI - Dry):	14.1 (31.0)	6.2 (13.8)	20.3 (44.8)
5. Non-Vacuum Jacketed Composite (MLI - Dry):	10.3 (22.6)	4.1 (9.1)	14.4 (31.7)
Weight Saved by Composite Design	3.8 (8.4)	2.1 (4.7)	5.9 (13.1)



Insulation (TYP Both Concepts)	Feedline
MLI Insulation System: 1/4 Mil (.0025) thick double aluminized mylar, 30 layers helically wrapped over line from a 2.0 wide spool with 1.0 overlap. Fasten start and stop with aluminized mylar tape. Wrap outside with Schjeldahl X-850	4.0 Outside diameter .005 Wall Inconel 719 Overwrapped 2 1/2 layers, 8 - glass hoop, 1/2 longitudinal & hoop

Figure 1. Non-Vacuum Jacketed Composite Feedline Concept (Concept 5)

VACUUM JACKETED COMPOSITE PROPULSION FEEDLINES
FOR CRYOGENIC LAUNCH AND SPACE VEHICLES
Spond, D.E., et al, MMC, NASA CR-134550,
NAS3-16762, March 1974

OBJECTIVES. - To develop light weight vacuum jacketed feedline concepts, using thin metallic liners that provide leak-free service in cryogenic propulsion systems.

PERTINENT WORK PERFORMED. - An analysis program assessed thermal, structural, weight and fabrication parameters, and formed the basis for tubing design. Thin metallic liners were selected as the primary load carrying numbers. Twelve tubes of two different inside diameters (5 and 15 in) were fabricated in 3 different types of each size. The liners were overwrapped with glass fibers impregnated with a resin matrix. The tube fabrication included liner welding, joining of the liners to end fittings, instrumentation installation, overwrapping, curing and leak checking. The inner line and the vacuum jacket were joined by welding. The tubes were subjected to leakage, pressure cycling, temperature cycling, pressure surge, acoustic and burst tests. Several lines became separated from the overwrap and failed. A single tube of a modified vacuum jacket design using a 0.012 in thick metal liner was fabricated. The vacuum jacket was overwrapped. This tube passed all tests successfully.
An extremely light weight tension membrane concept was designed, fabricated, tested and evaluated.

MAJOR RESULTS. -

1. A feedline design concept was developed that is adaptable to a wide range of aerospace vehicle requirements.
2. Bonding of the vacuum jacket liner to the composite overwrap resulted in premature failure of several lines.
3. A redesign, which was not dependent on bonding was successful.
4. Weight savings of over 50% were attainable for vacuum jacketed composite feedlines when compared to conventional configurations and materials of construction.
5. A tension membrane concept is a strong candidate for vacuum jacketed feedlines.
6. Based on the results of this program, the recommended vacuum jacketed composite line (Figure 1) consists of an 0.013 in. INCONEL 718 liner, overwrapped with a 58-68R resin system.

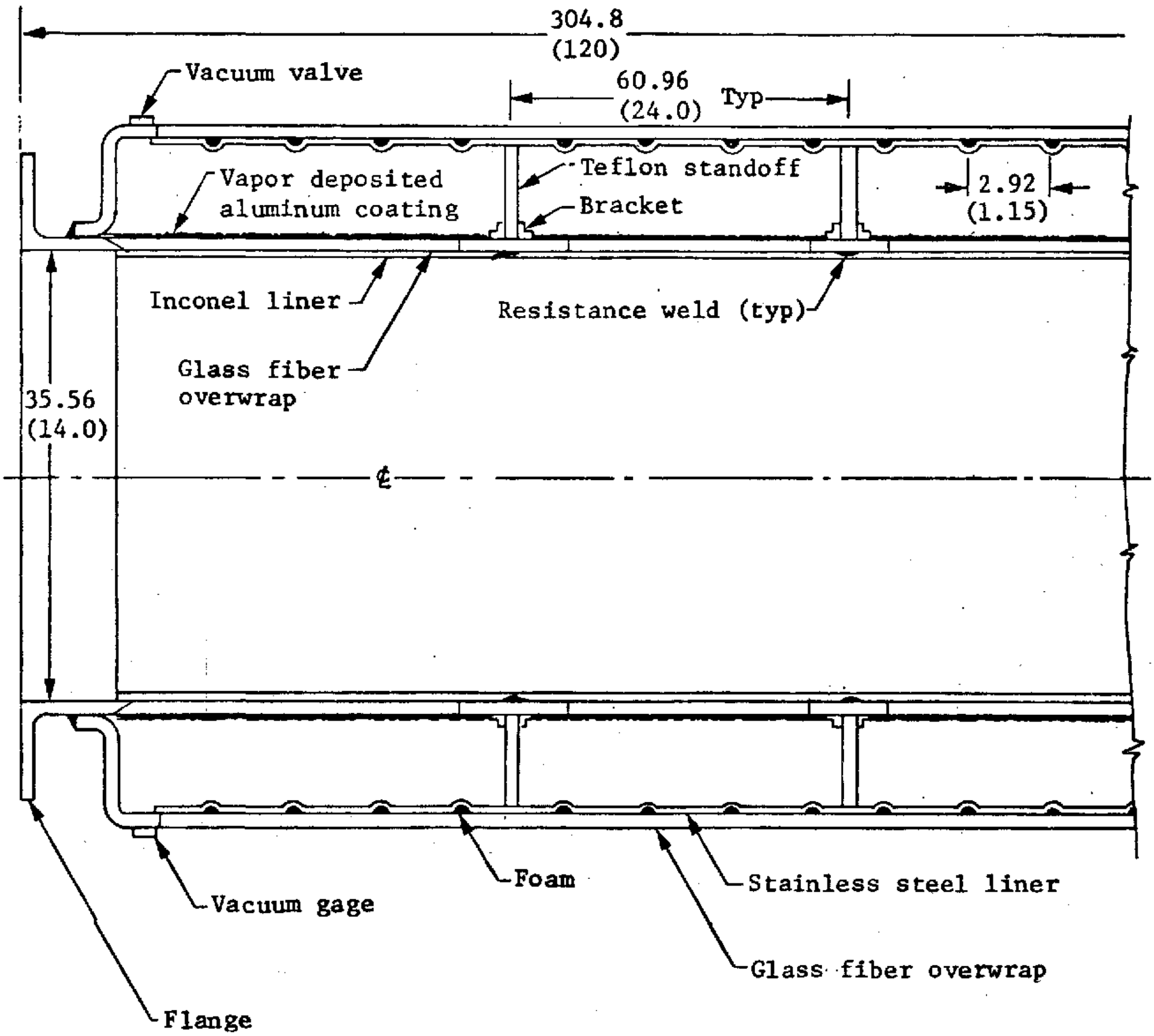


Figure 1. Recommended Vacuum Jacketed Composite Line

COMPOSITE PROPULSION FEEDLINES FOR CRYOGENIC SPACE VEHICLES
Hall, C.A., et al., MMC, NASA CR 121137
Vol. I and II, NAS3-14370, August 1973

OBJECTIVE. - To develop lightweight composite feedlines and attendant fittings for use as cryogenic plumbing on space vehicles.

PERTINENT WORK PERFORMED. - An analytical program assessed thermal, structural, weight and fabrication parameters and formed the basis for the line design. Ultimately, thin metallic liners 0.003 to 0.011 in. thick were selected as the primary load-carrying members. These liners were overwrapped with glass-fibers, impregnated with a resin matrix suitable for cryogenic service, to strengthen the liners. Tests were performed to aid in selecting materials. Tensile tests were performed on composite segments. Metallographic analyses evaluated the end fitting configurations. A 15 in. diameter specimen, 36 in. long was fabricated and used as a test bed.

Next, the 11 tubes required for test, ranging from 2 to 15 inch, were fabricated. Tube fabrication included liner welding, joining of the liners to end fittings, instrumentation installation, overwrapping and curing, and leak checks.

The main engine lines were subjected to tests including pressure and temperature cycling, torsion, bending and burst. The LOX main engine line was destroyed during post-overwrap proof testing. The Orbit Maneuvering System (OMS) lines were subjected to tests including chilldown, steady-state flow, steady-state heat input in the insulated and uninsulated configuration, thermal and pressure cycling, radial thermal conductivity, vibration and application of pressure to failure.

MAJOR RESULTS. -

1. The results verify the advantage of using glass fiber composite lines in cryogenic propellant service.
2. The advantages are low thermal flux, lightweight (Table 1) construction, low heat soakback from engines, rapid chilldown, high strength and handling ease.
3. Cost increase is moderate.
4. Design concepts are adaptable to a wide range of aerospace vehicle requirements.

Table 1. Weight Savings Obtainable by Use of Composite Lines in the Space Shuttle

DESCRIPTION	SECTION CODE	DIAMETER cm (in.)	LENGTH cm (in.)	PHASE B CONFIGURATION				COMPOSITE CONFIGURATION					WEIGHT SAVINGS/ SECTION kg (lbs)	NUMBER OF SECTION	TOTAL WEIGHT SAVINGS kg (lbs)
				MATERIAL	WALL THICKNESS cm (in.)	END FITTING	SECTION TOTAL WT. kg (lbs)	LINER MATERIAL	LINER THICKNESS cm (in.)	END FITTING	END FITTING TOTAL WT. kg (lbs)	SECTION TOTAL WT. kg (lbs)			
Booster Main Engine LOX Feedline	3A	56 (22)	305 (120)	2219-T87 Aluminum	0.203 (0.080)	Conoseal-Al	34 (75)	Inconel	0.0165 (0.0065)	SS Conoseal SS Buttweld Transition	10 (22) 1.13 (2.49)	26 (58)	8 (17)	2	16 (34)
	3A	56 (22)	305 (120)	" "	0.203 (0.080)	" "	34 (75)	21-6-9	0.0165 (0.0065)	" "	1.13 (2.49)	26 (58)	8 (17)	2	16 (34)
	3A	56 (22)	305 (120)	" "	0.203 (0.080)	" "	34 (75)	304L	0.0480 (0.0189)	" "	3 (7)	39 (87)	-5 (-12)	2	-10 (-24)
	3A	56 (22)	305 (120)	" "	0.203 (0.080)	" "	34 (75)	Aluminum	0.0655 (0.0258)	Al Conoseal Al Buttweld Tran.	2 (3.74)	23 (50)	11 (25)	2	22 (50)
	3A	56 (22)	305 (120)	" "	0.203 (0.080)	" "	34 (75)	Inconel	0.0165 (0.0065)	Al Conoseal Al Buttweld Tran.	2 (3.74)	17 (37)	17 (38)	2	35 (76)
Booster Main Engine LOX Manifold	4A	56 (22)	152 (60)	21-6-9 SS	0.318 (0.125)	Buttweld	67 (148)	Inconel	0.0445 (0.0175)	Buttweld Transition	23 (10)	18 (40)	49 (108)	2	98 (216)
Booster Main Engine LOX Feed Ducts	1 & 2 or 6 & 7	38 (15)	185 (73)	21-6-9 SS	0.203 (0.080)	Conoseal SS Buttweld	43 (94)	Inconel	0.0290 (0.0114)	SS Conoseal SS Buttweld Tran.	7 (15) 0.98 (2.16)	16 (36)	26 (58)	12	312 (696)
Booster Main Engine LOX Fill & Drain	1 & 2A	25 (10)	310 (122)	21-6-9 SS	0.089 (0.035)	Buttweld	18 (39)	Inconel	0.0180 (0.0071)	Buttweld Transition	0.60 (1.26)	9 (19)	9 (20)	1	9 (20)
Booster Main Engine LH_2 Feed Ducts	1 Eng. 2 & 3	30 (12)	94 (37)	21-6-9 SS	0.091 (0.036)	Conoseal SS Buttweld	12 (26)	Inconel	0.0076 (0.0030)	SS Conoseal SS Buttweld Tran.	5 (12) .35 (0.78)	8 (17)	4 (9)	2	8 (18)
Booster LH_2 Fill & Drain	1 & 2A	25 (10)	305 (120)	21-6-9	0.081 (0.032)	Buttweld	16 (35)	Inconel	0.0076 (0.0030)	Buttweld Transition	0.62 (1.36)	6 (13)	10 (22)	1	10 (22)
Orbiter Main Engine LOX Feedline	1A	46 (18)	808 (318)	2219-T87 Aluminum	0.127 (0.050)	Conoseal Al Conoseal SS	53 (116)	Inconel	0.0152 (0.0060)	SS Conoseal SS Buttweld Tran.	8 (17.3) .73 (1.62)	40 (89)	13 (27)	2	26 (54)
Orbiter Main Engine LH_2 Feedline	2	30 (12)	163 (64)	21-6-9	0.127 (0.050)	Buttweld	16 (35)	Inconel	0.0076 (0.0030)	SS Buttweld Tran.	1 (2.16)	4 (9)	12 (26)	1	12 (26)
Orbiter OMS LOX Feedline	2	7 (2.65)	381 (150)	21-6-9	0.041 (0.016)	Buttweld	3 (5.71)	Inconel	0.0076 (0.0030)	SS Buttweld Tran.	0.07 (0.15)	2 (3.94)	1 (1.77)	1	1 (1.77)
Orbiter OMS LH_2 Feedline	2	10 (3.9)	1460 (575)	21-6-9	0.050 (0.020)	Buttweld	18 (40.3)	Inconel	0.0076 (0.0030)	SS Buttweld Tran.	0.13 (0.28)	10 (21.63)	8 (18.67)	1	8 (18.67)
ACPS LOX Feedline	2A	3 (1.16)	79 (31)	2219-T87 Aluminum	0.07 (0.028)	Buttweld	0.15 (0.32)	Inconel	0.0076 (0.0030)	Buttweld Tran.	0.06 (0.12)	0.20 (0.44)	-0.05 (-0.12)	1	-0.05 (-0.12)
ACPS LH_2 Feedline	3B	4 (1.43)	56 (22)	2219-T87 Aluminum	0.07 (0.028)	Buttweld	0.13 (0.28)	Inconel	0.0076 (0.0030)	Buttweld Tran.	0.06 (0.14)	0.20 (0.44)	-0.07 (-0.16)	1	-0.07 (-0.16)

VACUUM-JACKETED DUCTING TECHNOLOGY INVESTIGATION
Leonhard, K.E., GD/C, CASD-NAS-73-002, NAS8-27504, June 1973

OBJECTIVE. - To perform an investigation to improve vacuum-jacketed ducting for space environments at LH_2 temperatures.

PERTINENT WORK PERFORMED. - The objective was accomplished in four tasks. Task I was a state-of-the-art review of vacuum-jacketed ducting. LH_2 feed system requirements for the booster and orbiter of a reusable space vehicle were established based on 100 missions of 4.5 minutes per mission. Various types of vacuum-jacketed and foamed LH_2 ducts such as S-II, SIVB and Centaur stages were evaluated. The evaluation included state-of-the-art duct segments, vacuum jacketed supports, flanges, gimbal joints, end-closures, rupture discs, jacketed bends, external supports, slide joints and instrumentation ports. The rating was based on heat leakage, pressure drop, weight, structural integrity, cost, fabrication and assembly, maintainability and reliability. All designs were scaled up to a common diameter of 14 inches. Detailed designs of components for the advanced duct system were made and evaluated in the same manner as for the state-of-the-art components. Ten cryogenic test specimens were designed and test results were predicted. These specimens included five duct sections using state-of-the-art techniques and components and five using the advanced techniques and components. The first specimen of the advanced duct was manufactured and a proof pressure test performed. The specimen failed during this test. The outer vacuum jacket was redesigned and new manufacturing procedures were established. A cryogenic flow loop test unit was designed to evaluate the thermal performance of all test specimens.

MAJOR RESULTS. -

1. The basic duct design of the selected state-of-the-art test specimen consisted of a straight shell section of a vacuum duct, 14 in. diameter, 120 in. long. The outer jacket was fabricated from 321 CRES 0.140 in. thick and 15 in. inside diameters. A radiation blanket (two layers of Dexter paper alternated with aluminum foil) was installed between the inner duct and outer jacket.

2. The modified basic duct design of the advanced test specimen consisted of a straight section of vacuum jacketed duct, 14 in. diameter, 120 in. long. The outer jacket is a composite shell utilizing a 0.025 in. thick CRES inner face sheet, 0.30 in. thick Nomex honeycomb and a four-layer fiberglass outer face sheet. The radiation blanket consists of Schjedahl x-850 face sheets and 8 layers of double aluminized Mylar Superfloc.

3. Predicted boiloff rates (lb/hr) of the basic duct designs were 3.89 lb/hr for the state-of-the-art duct and 0.63 lb/hr for the advanced design duct.

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LIQUID HYDROGEN SUCTION LINE INSULATION RESEARCH AND DEVELOPMENT.
Leonhard, K.E., GD/C, GDC-DDB66-007, NAS8-20167, July 1966.

OBJECTIVE. - To evaluate liquid hydrogen suction line concepts and recommend methods for reducing heat leaks in future transfer lines and components.

PERTINENT WORK PERFORMED. - Various advanced suction line schemes, including prevalves, flanges, supports and bellows were analytically and experimentally evaluated. For each concept, heat leaks were determined and the necessary experiments performed to verify both the theoretical performance as well as the physical feasibility of the proposed schemes. Eight preliminary suction line systems were evaluated from which two (a "dry" and "wet" line configuration) were selected to be representative models. The heat transfer calculations were base on a ground hold temperature of 60°F, a boost phase temperature produced by a Saturn trajectory and a 400°R surface equilibrium temperature in space. Design computations included the determination of optimum line weights and operating pressures. The cooldown process was also analyzed with and without internal coatings. A total of eleven basic superinsulation systems designed for lines, prevalves, bellows, flex-joints, flanges, and supports were considered. The three most promising multilayer insulation (MLI) systems were selected for a detailed computer analysis. The experimental program included thermal and structural testing to determine the performance of multilayered insulation systems applied to suction lines and components and line cool down tests of internally coated and uncoated lines.

MAJOR RESULTS. -

1. Titanium - Ti-5A1-2.5 SN,ELI was chosen as an optimum line material because of its favorable strength to weight ratio.
2. Analytical predictions were closely matched by test performance.
3. The use of a low conductive section of pipe, just down stream of a prevalve, is not advantageous because of the large internal radiation heat leakage into the tank.
4. The Kel-F coated pipe cooldown rate is faster than for the uncoated line at all fluid velocities; it is independent of flow rate for the regions considered.
5. Increasing flow rates shorten the cooldown time of the uncoated pipe as expected.
6. A rigid vacuum jacket duct system with external stiffening and internal radiation shields was selected for a 5 to 24 hour mission (Figure 1). For a long term mission, the purged, shingle, multilayer insulation system was recommended (Figure 2).
7. Suction line sections which are subjected to aerodynamic heating should be protected by a fairing.

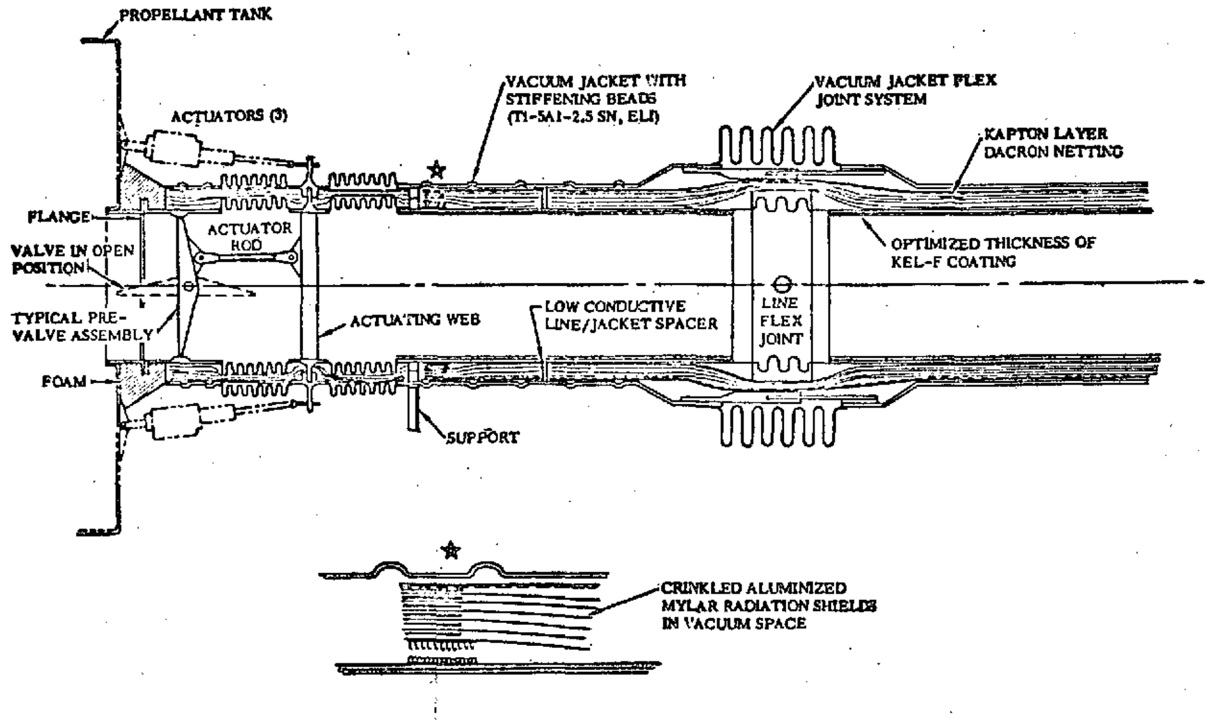


Figure 1. Rigid Vacuum Jacket Suction Line for Missions of 5 to 24 Hours

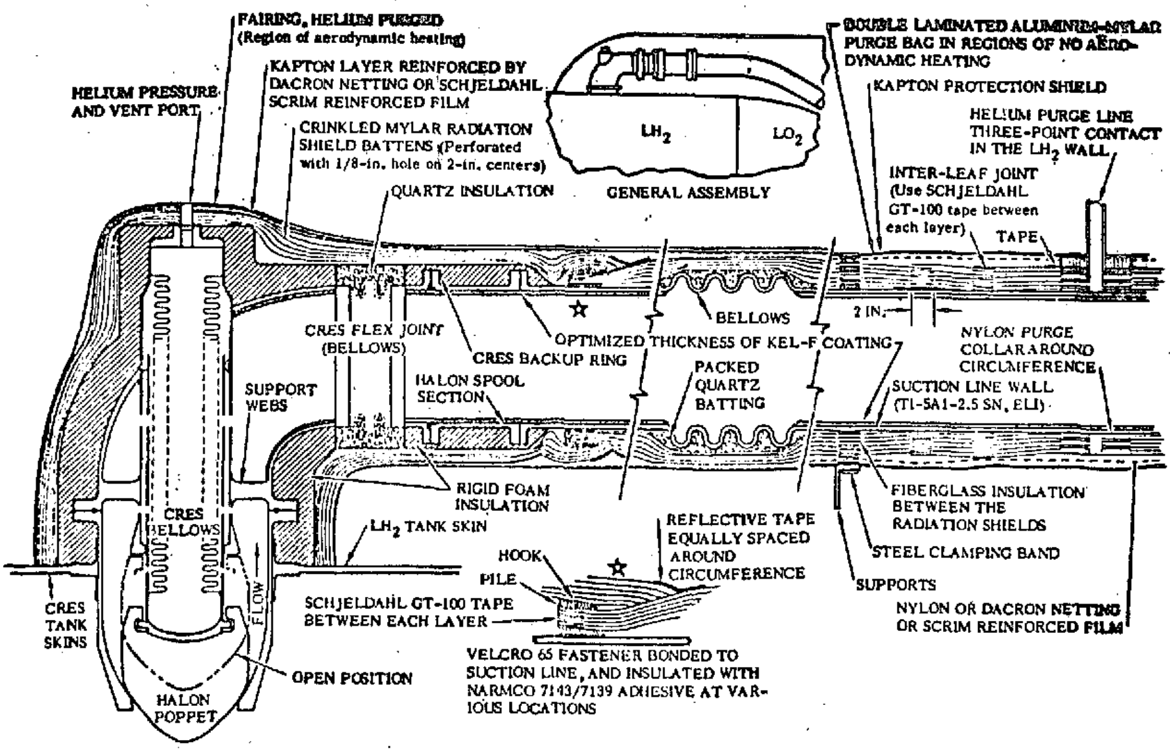


Figure 2. Purged Shingle Insulated Suction Line for Long-Term Missions (Several Months)

5.0 TANK SUPPORTS AND PENETRATIONS

Covering the effects on tank heating of insulation penetrations and the design and test of low conductive support struts.

C - 2

FIBERGLASS SUPPORTS FOR CRYOGENIC TANKS
Keller, C.W., LMSC, NASACR-120937, NAS3-12037,
October 1972

OBJECTIVE. - To develop a low heat leak, filament-wound fiberglass strut with integral end fittings. The strut must exceed the load capabilities of any metallic strut.

PERTINENT WORK PERFORMED. - The program was conducted in 4 tasks. In task I a parametric analysis was performed to assess structural and thermal capabilities of filament-wound fiberglass struts for a wide range of lengths and loads. Parameters selected included strut wall configuration, stiffener material, composite thickness, column length and outside diameter. Longitudinal heat leak due to conduction and radiation was determined. Inert weights and propellant boil off weight for representative mission durations were computed. Six promising designs were selected for a detailed study. Preliminary design drawings were established. Based on an evaluation of the resulting data, four of the six candidates were selected for fabrication and tested during the task 2 experimental screening program. Detailed drawings were prepared for each of the four selected candidates. Three struts each of four selected designs were fabricated to verify that all design and manufacturing requirements could be achieved, and to provide short-column specimens for test. These specimens were potted at each end with epoxy, instrumented with strain-measurement transducers and tested to failure in compression. In task 3 preimpregnated glass fiber-epoxy materials, titanium internal and fittings and caps, and CRES rod and fittings were procured and the strut hardware produced. Eight struts each of three selected configurations were fabricated for task 4 test specimens. Two or more specimens were tested in compression, in tension and cyclic loading modes. Each specimen was tested with one end submerged in LN_2 (Table 1) using a dynamic test machine.

MAJOR RESULTS. -

1. During this program, a low heat leak, filament-wound fiberglass strut was developed with a strength-to-weight ratio in tension and compression exceeding that of any metallic strut of equal size.

2. Monocoque cylinders and/or ogives are either optimum or can be used with negligible system weight penalties.

3. Inert plus boil-off weights for filament-wound fiberglass struts are significantly lower than for metallic struts.

4. The concept of integrally wrapping metallic end fittings with longer fibers to achieve axial load transfer has been verified.

5. Titanium end fittings with rolled external threads provide longer fatigue-life capabilities than do those with internal threads.

Table 1. Summary of Full-Scale Strut Test Results

SPECI-MEN NO.	CONFIGURATION DESCRIPTION	TOTAL LENGTH (IN.)	O. D. AND NOM THICKNESS AT MIDSPAN (IN.)	NO OF END ROVINGS	ECCENTRICITY AT MIDSPAN (IN.)	TEST MODE	PREDICTED ULT LOAD, P_P (LB)	FAILURE LOAD, P_F (LB)	MARGIN $100\ (P_F/P_P - 1)$ (PERCENT)	NO. CYCLES AT FAILURE
111-1A	MONOCOQUE	24.0	1.5 BY 0.020	146	0.078	TENSION	7660	7780	+1.6	1
111-1H	CYL				0.062	TENSION	7660	8040	+5.0	1
111-1D					0.005	COMP	2810	3290	+17.1	1
111-1E					0.037	COMP	2375	2680	+12.8	1
111-1G					0.038	COMP	2370	2600	+9.7	1
111-1B					0.053	CYCLIC	2250C/7660T	1910C/3870T	(N. A.)	209
111-1C					0.058	CYCLIC	2220C/7660T	1600C/3980T	(N. A.)	283
111-2E	MONOCOQUE	19.0	1.5 BY 0.027	274	0.018	TENSION	14,320	12,960	-9.5	1
111-2G	CYL				0.003	TENSION	14,320	13,790	-3.7	1
111-2A					0.018	COMP	5380	6740	+25.3	1
111-2B					0.019	COMP	5350	5950	+11.2	1
111-2C					0.006	CYCLIC	5830C/14320T	4500C/10030T	(N. A.)	210
111-2D					0.004	CYCLIC	6000C/14320T	4360C/10080T	(N. A.)	207
111-3F	MONOCOQUE	36.0	2.5 BY 0.022	306	0.065	TENSION	16,010	15,350	-4.1	1
111-3G	OGIVE				0.062	TENSION	16,010	15,625	-2.4	1
111-3A					0.038	COMP	3820	3950	+3.3	1
111-3B					0.034	COMP.	3920	4450	+13.5	1
111-3C					0.032	COMP	3940	3720	-5.5	1
111-3D					0.019	CYCLIC	4120C/16010T	3020C/7545T	(N. A.)	2509
111-3E					0.024	CYCLIC	4040C/16010T	2940C/7150T	(N. A.)	5761

PENETRATIONS THROUGH MULTILAYER INSULATION SYSTEMS, O'Neill, M. J., LMSC, Proceedings of Cryogenic Workshop at NASA-MSFC, March 1972

OBJECTIVE. - To review the state-of-the-art in analysis and design of penetrations through MLI blankets for cryogenic systems.

PERTINENT WORK PERFORMED. - The importance of careful consideration of the effect of penetration heat leaks on overall insulation system thermal performance is illustrated. Analysis of fluid line penetration effects requires simultaneous consideration of conduction in the wall and in the highly anisotropic MLI, convection between the wall and the venting gas, internal multiple-reflection radiation down the line, and enthalpy change of the flowing fluid. A generalized nodal model is described which includes these effects and sample penetration heat leak data are presented as a function of pipe insulated length, outside diameter, wall thickness, vent gas flow rate, and pipe warm end temperature (Figure 1). The analytical model accuracy was verified by test data taken with a 20-in. diameter test tank.

A technique for experimentally determining the heat flow due to penetrations is described. An insulated cryostat with an electric resistance heater is installed in a vacuum chamber. A calibration curve of boiloff mass flow rate as a function of heater power is obtained. Subsequent mass flow data from penetration tests can be used with the calibration curve to determine the heat flow contribution of the penetration.

MAJOR RESULTS. - It was determined that a thorough analysis of the effects of penetration heat leaks on overall system performance is very important, and should include all modes of heat transfer through the penetration.

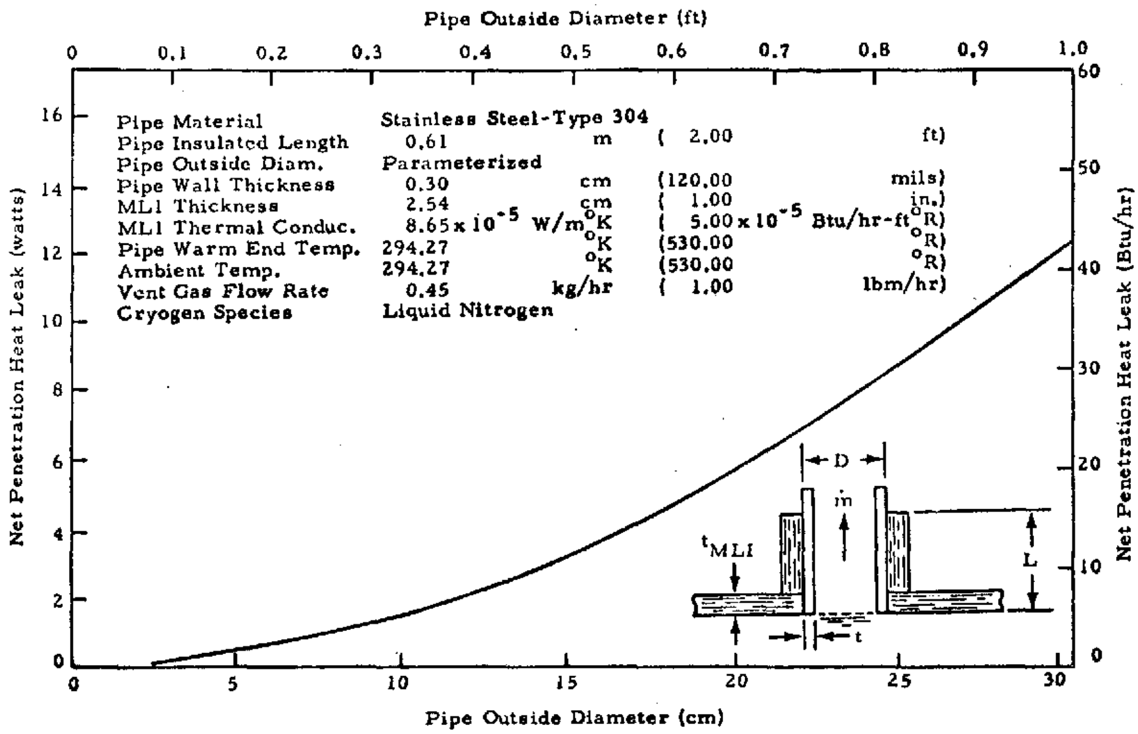


Figure 1. Example of Analytical Data - Net Penetration Heat Leak as a Function of Pipe Outside Diameter

CRYOGENIC TANK SUPPORT EVALUATION
Bullard, B.R., LMSC, NASA CR-72546, NAS3-7979,
December 1969

OBJECTIVE. - To experimentally determine the thermal performance of six different tank support concepts.

PERTINENT WORK PERFORMED. - An experimental evaluation was made of the thermal performance of six tank support concepts that had been selected as most promising from a total of twelve, on the basic of an analytical evaluation performed under Task I of this contract. Task I details are presented in NASA CR-72538 (Bullard, 1969). The six concepts tested were; (1) fiberglass strut (Figure 1), (2) titanium strut with stacked washers (Figure 2), (3) thermal disconnect titanium strut (Figure 3), (4) cooled titanium strut (Figure 4), (5) fiberglass semi-monocoque cone and (6) fiberglass honeycomb cone. A stress analysis was performed on each of the six concepts to determine the material thickness and structural weights. Constituent sizes and material gauges obtained from the stress analysis were input to the thermal analysis, and the boiloff and insulation weights were determined as a function of time for each tank. Test articles were fabricated to provide thermal simulation within the selected size range (5 to 15 ft. dia. tanks). The test articles were installed on a cryostat and the heating rates measured under a variety of boundary conditions. Both LN_2 and LH_2 were used for the cold boundary temperatures. The outer temperatures were nominally 440°R and 540°R. Thermal guards were provided to eliminate heating along the lateral surfaces of the test article. The experimental results were compared to analytical models from Task I.

MAJOR RESULTS.

1. The experimental program indicated that the fiberglass strut support concept offers the most promise for cryogenic tank supports within the sizes considered in the program.

2. In LN_2 the measured heat rates for the fiberglass strut at source temperatures of 430 and 530R were 0.248 and 0.341 Btu/hr, respectively. Corresponding values in LH_2 were 0.250 and 0.367 Btu/hr.

3. The overall program indicated that for ellipsoidal propellant tanks between 5 and 15 ft., point type supports result in lowest weight penalty.

4. In general, the experimental performance of the fiberglass strut, the cooled strut and the two continuous support concepts was slightly superior to that predicted in Task I.

5. The experimental heat rates through the disconnect concept were approximately three times the analytical prediction.

6. The experimental data on the stacked washers indicated that interface resistances were as much as ten times lower than those used for the analysis.

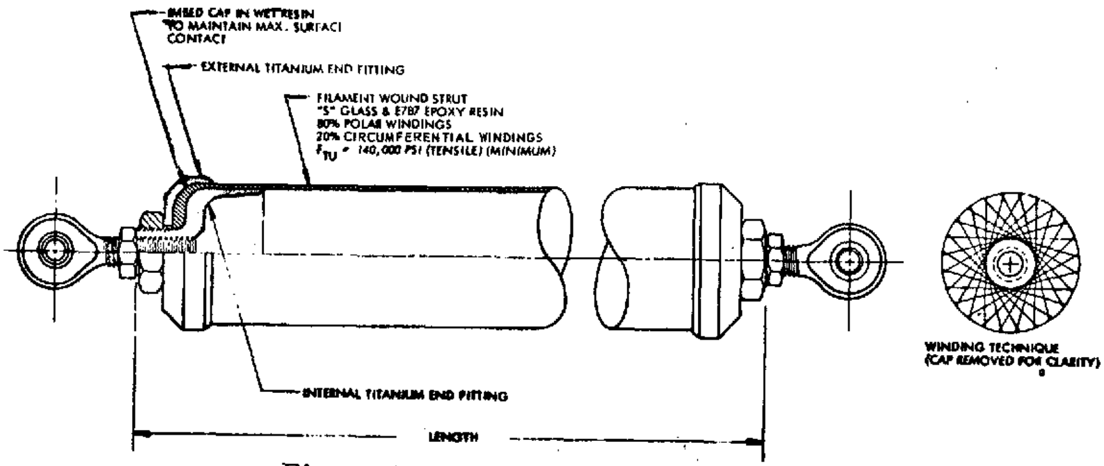


Figure 1. Filament Fiberglass Strut Concept

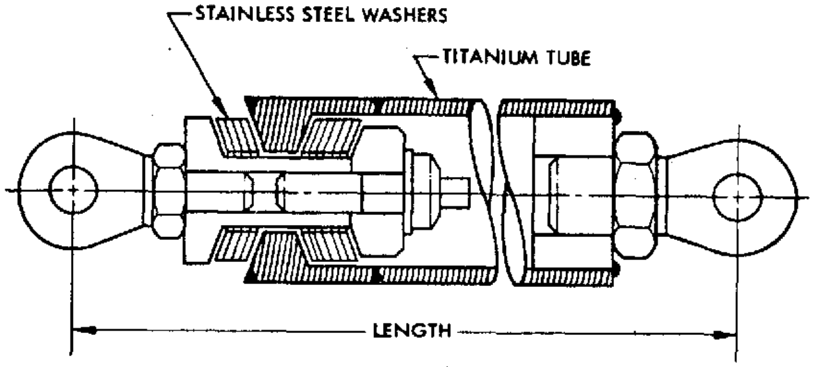


Figure 2. Stacked Washer Concept

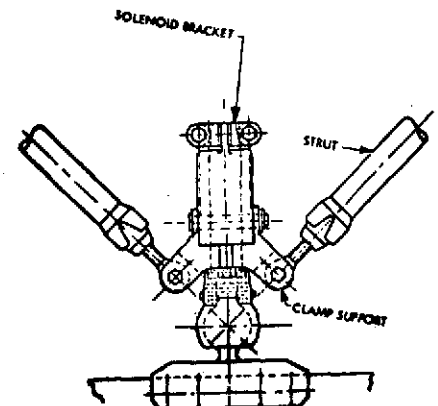


Figure 3. Ball and Clamp Strut Disconnect Concept

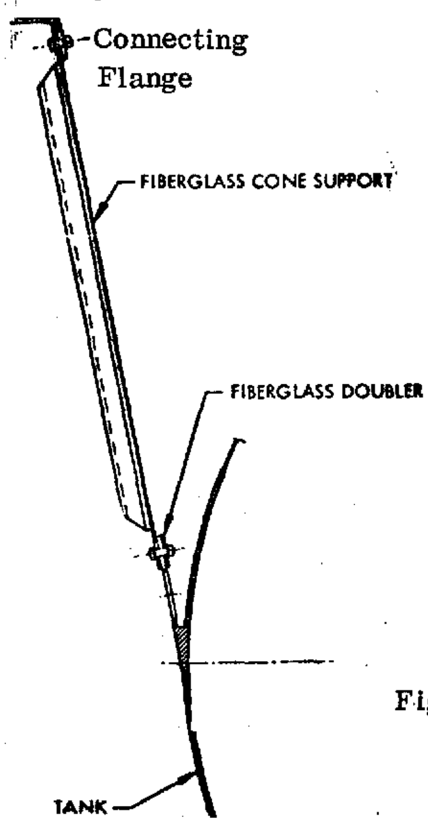


Figure 4. Internally Cooled Support Struts End Fittings

DEVELOPMENT OF ADVANCED MATERIALS FOR INTEGRATED TANK INSULATION SYSTEM FOR THE LONG TERM STORAGE OF CRYOGENS IN SPACE
Gille, J.P., MCR-69-405, NAS8-21330, September 1969.

OBJECTIVE. - To analytically and experimentally evaluate concepts for using vented hydrogen gas to reduce heat flux to LH_2 tanks during long term storage in space.

PERTINENT WORK PERFORMED. Using the Saturn S-IVB stage as a reference vehicle, analyses were made of the effect of using the hydrogen boiloff gas to intercept incoming heat to the tank through the three principle paths; tank support structure, connecting plumbing, and insulation system. Non-metallic materials were evaluated for use in the support structure, and thermal conductivity tests of candidate materials were performed. A four-foot diameter tank was insulated with 20 layers of double aluminized Mylar (DAM) nylon net multilayer insulation (MLI) and placed in a shroud insulated with 40 layers of DAM/net MLI (Figure 1). A tube/fin heat exchanger assembly was mounted between the two MLI systems. Space equilibrium tests were run both with and without boiloff gas in the heat exchanger.

MAJOR RESULTS. -

1. Based on analytical predictions, heat entering a cryogenic tank through the plumbing system can be reduced by up to 50% by using vent gas cooling.
2. Due to low heat flux and structural complexity, vent gas cooling of the tank support system is not warranted.
3. Composite materials can reduce structural support heat leaks by 60% or more compared with titanium.
4. A thermal test of a vent-cooled insulation system indicated a 67% reduction in the heat flow through the tank-mounted MLI system, but only a 19% reduction in total heat flow to the liquid hydrogen.

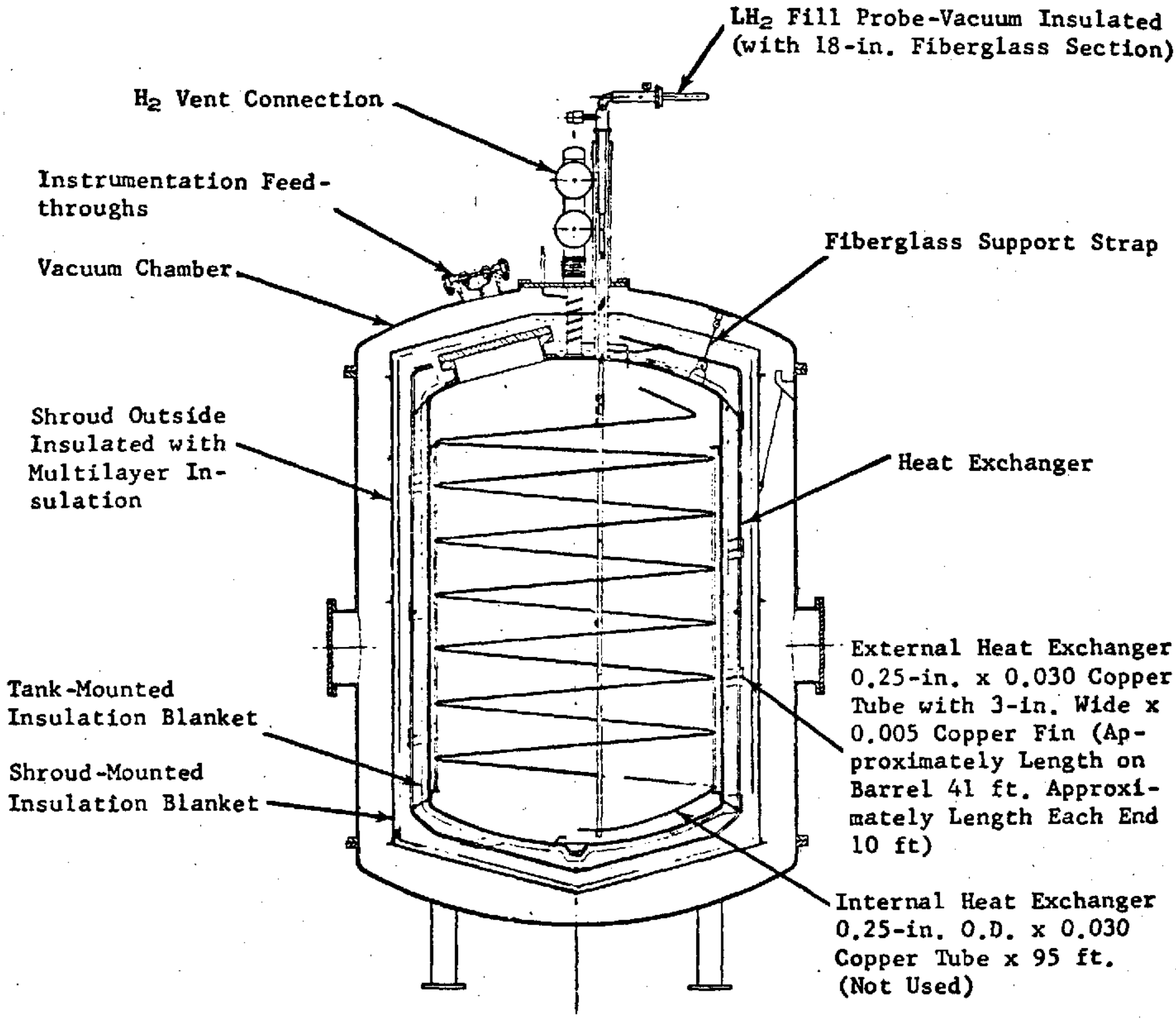


Figure 1. Integrated Tank Insulation System Test Installation

DESIGN OF A LOW CONDUCTIVE LIGHTWEIGHT SUPPORT STRUT FOR CRYOGENIC PROPELLANT TANKS
Bock, E. H., Aerospace Structure Design Conference, Seattle, Washington, August 1969

OBJECTIVE. - To develop a low conductive, lightweight support strut for cryogenic tanks.

PERTINENT WORK PERFORMED. Structural metals and composites which exhibit acceptable fracture toughness at LH_2 temperature were evaluated by the comparison of their ultimate tensile stress and thermal conductivity ratios. The support strut design was basically a tubular fiberglass member with titanium end-spools equipped with spherical ball rod fittings (Figure 1). To reduce internal radiation tunneling, the assembly was provided with a series of flocked aluminized mylar discs. The strut was manufactured by a lay-up of glass epoxy over a wash-away plaster mandrel. Both end-spools were wrapped with 13 wraps of one-inch bidirectional E-glass epoxy prepreg tape. A layer of unidirectional epoxy prepreg, 1448/MXB-7011 was then tightly wrapped around the entire mandrel length. The wrap was completed by a butt joint. A single wrap of one-inch wide bidirectional fabric was laid over the unidirec-wrap at the end spools. Another wrap of unidirectional fabric was laid up and the process was repeated until four wraps of unidirectional fabric were in place on the mandrel. Two final layers of bidirectional fabric were wrapped around each spool. The assembly was oven cured for two hours at 320°F. Two prototype struts were manufactured (Figure 2). One strut was subjected to thermal cycling, tension, compression and failure tests.

MAJOR RESULTS. -

1. Unidirectional fiberglass epoxy and boron epoxy exhibited values of ultimate tensile stress/thermal conductivity ratios of eleven times that of the nearest competitor, Titanium (Table 1).
2. Unidirectional, 1448 style E glass fabric impregnated with the MXB-7011 resin was selected for use in the support strut design.
3. The prototype strut failed under a tension load of 10,175 lb, more than double the ultimate design load.
4. The failure load obtained verified the allowable design stresses utilized.

Table 1. Room temperature structural/thermal material comparison.

MATERIAL	ULTIMATE TENSILE STRESS (psi)	THERMAL CONDUCTIVITY +70°F BTU/hr-ft°R	Φ_{st}*
Aluminum 2219-T81	60,000	74	810
Steel 347 Ann	75,000	8.6	8,720
Steel A286	140,000	7.5	18,700
Inconel X-750	155,000	7.2	21,500
Titanium 5 Al-2.5 Sn (ELI)	120,000	4.8	25,000
Unidirectional Glass Epoxy 1448/MXB-7011	130,000	0.47	277,000
Unidirectional Graphite Epoxy	94,300	35	2,700
Unidirectional Boron Epoxy	196,000	0.54	363,000

$$*\Phi_{st} = \frac{\text{Ultimate Tensile Stress}}{\text{Thermal Conductivity}}$$

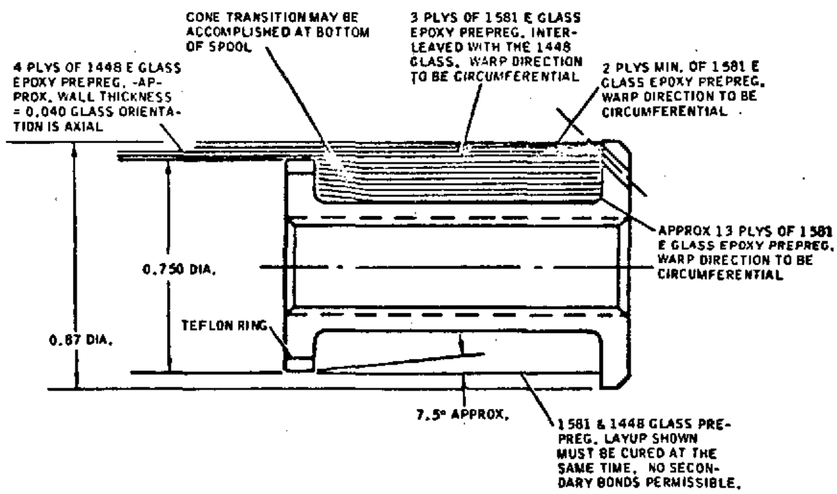


Figure 1. Strut layup showing spool fitting.

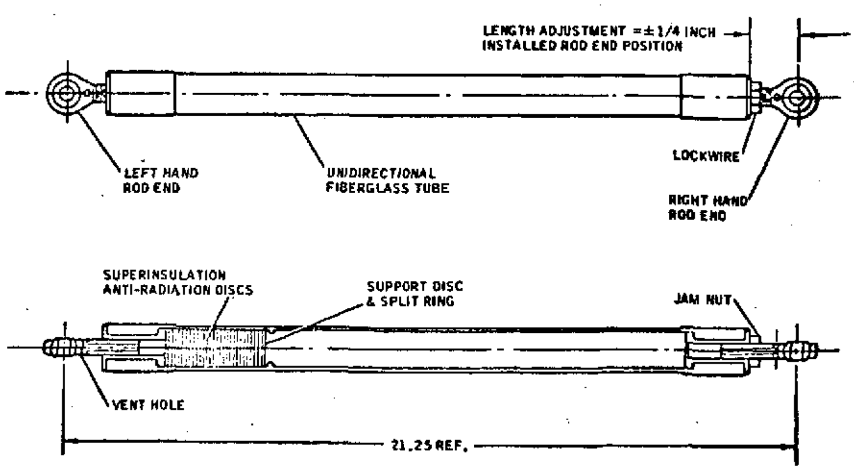


Figure 2. Support strut configuration.

ANALYTICAL INVESTIGATION OF THERMAL DEGRADATION OF HIGH-PERFORMANCE MULTILAYER INSULATION IN THE VICINITY OF A PENETRATION

Johnson, W. R., Sprague, E.L., NASA TN D-4778, September 1968

OBJECTIVE. - To determine analytically representative values for the direct lateral heat flow to a penetration, the net increase in heat flow to a tank, and the radius of the resulting thermally degraded area.

PERTINENT WORK PERFORMED. - A computer program was developed to analyze the effect of a penetration on multilayer insulation (MLI) performance. Separate models were developed for systems with and without buffer materials (Figure 1). Major assumptions of the analysis are that only radiation heat transfer is considered in the normal and only conduction in the lateral direction, the spacer does not contribute to lateral conduction, a radiation viewfactor of one exists between adjacent layers, and shield emittance is not a function of temperature. Thermal contact resistance (TCR) is input and is constant for all layers. The program adjusts shield edge temperatures, and calculates heat flow to the penetration, based on the given TCR.

The number of shields used varied from 5 to 160 for the system without the buffer and 5 to 80 for the system with buffer. When used, buffer height was set equal to insulation thickness, while width varied from near zero to twice the height. Average conductivities of buffer zone materials analyzed ranged from 0.004 to 0.0095 Btu/hr ft R.

MAJOR RESULTS. -

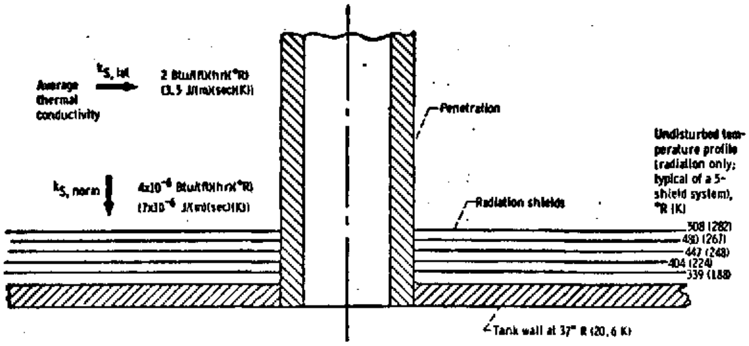
1. Lateral heat flow and net heat flow increase to the tank were found to be a strong function of the source temperature (Figure 2), comparatively less affected by penetration diameter and the number of shields (Figure 3), and only a weak function of shield emittance.

2. In general, to result in a net reduction in the heat flow to the tank, the buffer average conductivity must be less than 0.008 Btu/hr ft R.

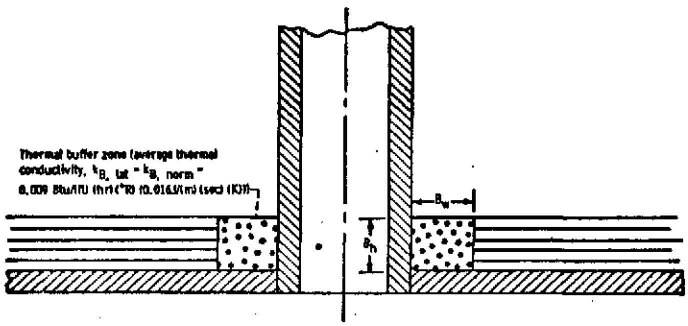
3. Optimum buffer configuration is a width approximately three-fourths that of the height.

COMMENTS. -

More information is necessary on contact resistances to make this analysis really useful.



(a) Shields butted to penetration.



(b) Use of thermal buffer zone.

Figure 1. - Penetration model.

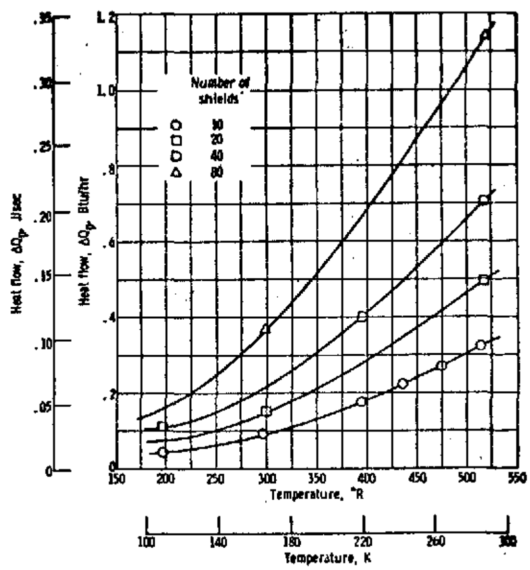


Figure 2. - Net increase in heat flow into tank for 2-inch- (5.1-cm-) diameter penetration as function of undisturbed top shield temperature. Shield thermal conductivity, k_S, experimental; shield emissivity, ϵ_S, 0.024.

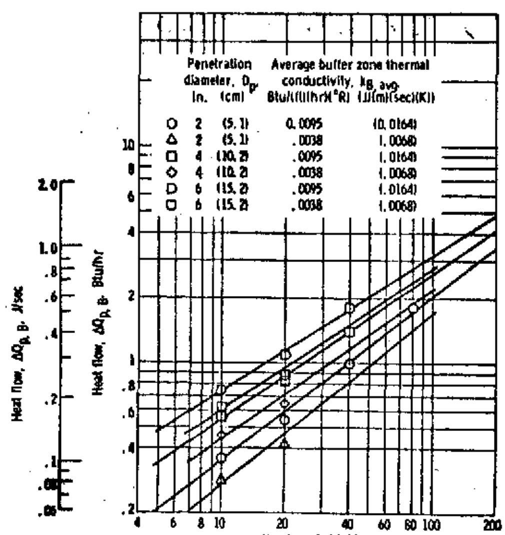


Figure 3. - Net increase in heat flow into the tank using a buffer zone around various diameter penetrations as function of number of shields. Radiating source temperature, T_{rs}, 520° R (289 K); shield thermal conductivity, k_S, experimental. shield emissivity, ϵ_S, 0.024.

DESIGN AND OPTIMIZATION OF SPACE THERMAL PROTECTION FOR CRYOGENS - ANALYTICAL TECHNIQUES AND RESULTS

Bonneville, J.M., ADL, NASA CR-54190, NAS3-4181, December 1964

OBJECTIVE. - To evaluate the effects of penetrations and to find methods for ascertaining their effect, and for decoupling them from the edges of foils.

PERTINENT WORK PERFORMED. - The analytical work was performed in 8 different studies: (1) basic effect of a penetration or a discontinuity, (2) radiative heat leaks through a gap, (3) gradation of thermal shorts, (4) limits to weak or linear shorts, (5) strong or non-linear shorts, (6) design of thermal shorts when a choice is possible, (7) decoupling of thermal shorts, and (8) penetration with temperature dependent thermal conductivities. Thermal resistance analytical models were developed for an understanding of the basic effects of penetrations. Resistance to heat flow along the following paths were considered in these models (1) from the environment to the outer foil, (2) through and along the foils, and (3) along the penetration. Graphical illustrations of the effect of penetrations were presented considering specific insulation types, a given number of foils and a varying thermal conductivity. The radiative heat leaks through various discontinuities such as gaps were graphically represented as a function of the ratio of gap width to insulation thickness for various values of the shielding factor, $n(2/\epsilon - 1)$, where n = number of shields and ϵ = emissivity. Methods for designing shorts for minimum heat leak were introduced. The important matter of decoupling from the edges of the foil is treated in detail. Figure 1 shows effective gap width.

MAJOR RESULTS. -

1. For continuous layers of multilayer insulation (MLI) the energy is forced to flow from layer to layer by radiation and conduction. In a gap between adjacent ends of foils there is a path of radiation which bypasses one or more layers, resulting in higher heat transfer to the tank wall.

2. Any penetration in the MLI leads to an increase in heat leak into the tank over that which would exist if the penetration and foils were thermally coupled.

3. Heat flow through MLI penetrations and gaps occurs in a complex pattern so that the representation in terms of the three resistances (1) from the environment to the outer foil, (2) through and along the foils and (3) along the penetration is not exact; however, the concept is useful for illustrating the various effects.

4. At low values of the conductances of the penetration, the heat leak varies directly as the conductance. At high values of the conductance (low values of the resistance) the resistance to parallel flow along the foil controls and the heat leak approaches an asymptotic value.

5. Decouplers (intermediary insulation) must be used when penetrations in thermal contact with the foil edges produce unacceptable heat leaks.

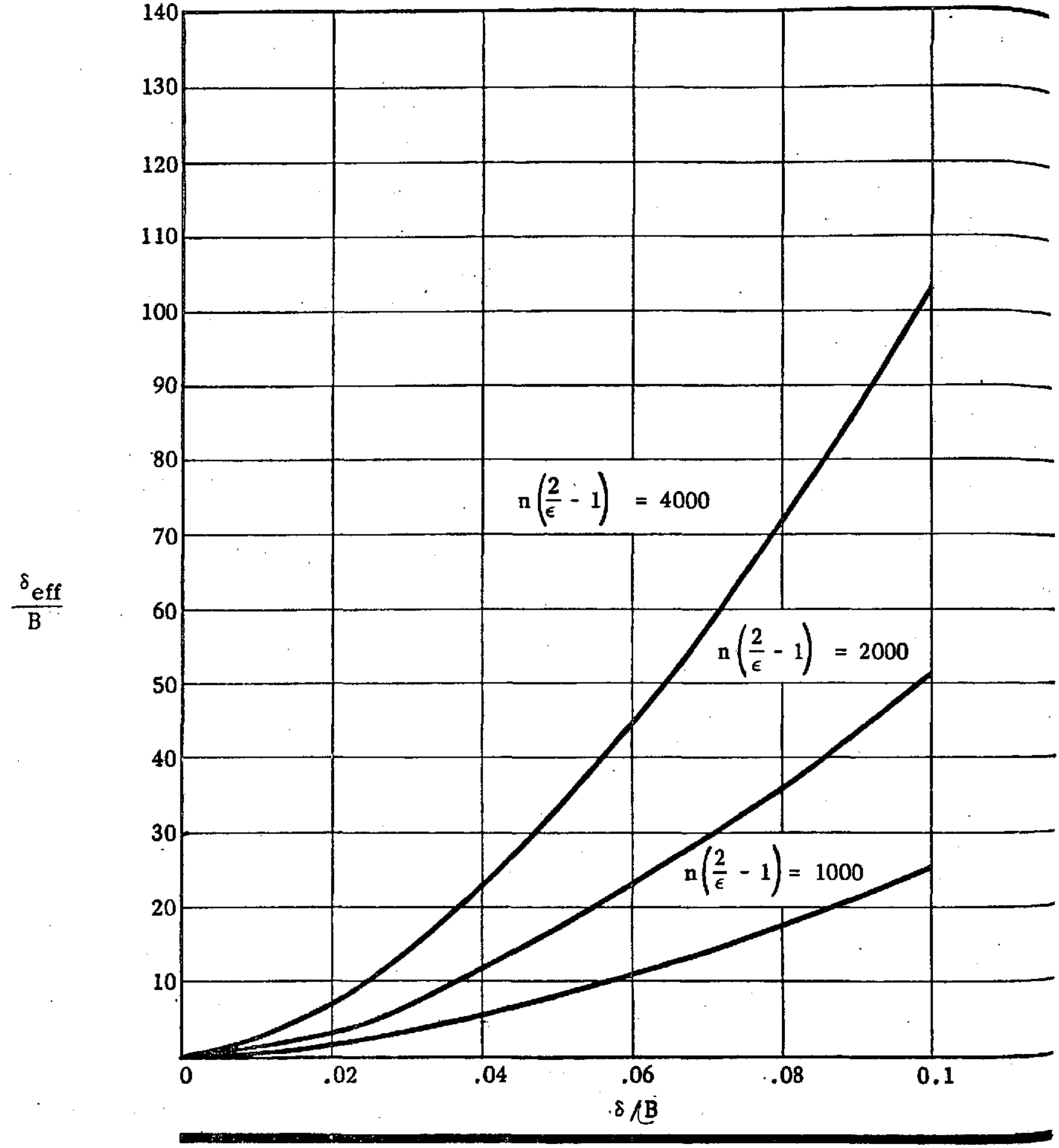


FIGURE 1 EFFECTIVE GAP δ IN UNITS OF THE INSULATION THICKNESS B, FOR VARIOUS VALUES OF THE SHIELDING FACTOR $n\left(\frac{2}{\epsilon} - 1\right)$.

APPENDIX A

AUTHOR INDEX OF SUMMARIZED REPORTS

Anon., "Design and Fabrication of Shadow Shield Systems for Thermal Protection of Cryogenic Propellants," November 1969, p. 3-14.

Anon., "Investigation Regarding Development of a High Performance Insulation System," July 1968, p. 2-44.

Anon., "Advanced Studies on Multilayer Insulation Systems," June 1966, p. 2-52.

Anon., "Advanced Studies on Multilayer Insulation Systems," January 1968, p. 2-48.

Barclay, D.L., et al, "Lightweight Evacuated Multilayer Insulation Systems for the Space Shuttle Vehicle," May 1973, p. 2-12.

Black, I.A., et al, "Basic Investigation of Multilayer Insulation Systems," October 1965, p. 2-54.

Bock, E.H., "Design of a Low Conductive Lightweight Support Strut for Cryogenic Propellant Tanks,"August 1969, p. 5-10.

Bonneville, J.M., "Design and Optimization of Space Thermal Protection for Cryogens Analytical Techniques and Results," December 1964, p. 5-14.

Bradshaw, R.D., et al, "Insulation Systems for Booster Main Cryogenic Tankage," June 1971, p. 3-12.

Bullard, B.R., "Cryogenic Tank Support Evaluation," December 1969, p. 5-6.

Burr, K.F., "Reusable Lightweight Modular Multi-Layer Insulation for Space Shuttle," July 1973, p. 2-10.

Chronic, W.L., "Oxygen Thermal Test Article (OTTA), August 1974, p. 2-4.

Cunnington, G.R., Tien, C.L., "Heat Transfer in Microsphere Cryogenic Insulation," 1972, p. 3-8.

DeWitt, R.L., Mellner, M.B., "Experimental Evaluation of a Purge Substrate Multilayer Insulation System for Liquid Hydrogen Tankage, May 1971, p. 2-30.

Doughty, R.O., "An Analytical and Experimental Development Program for Inflatable Solar Shields," May 1969, p. 3-18.

Fredrickson, G.O., "Investigation of High Performance Insulation Application Problems," August 1973, p. 2-8.

Gille, J.P., "Development of Advanced Materials for Integrated Tank Insulation System for the Long Term Storage of Cryogens in Space," September 1969. p. 3-16 and p. 5-8.

Gille, J.P., "Internal Insulation System Development," May 1973, p. 3-2.

Hacker, P.T., "Sealed-Foam, Constrictive-Wrapped, External Insulation System for Liquid-Hydrogen Tanks of Boost Vehicles," March 1965, p. 3-24.

Hale, D.V., "A Study of Thermal Conductivity Requirements," October 1967, p. 2-50.

Hall, C.A., et al, "Composite Propulsion Feedlines for Cryogenic Space Vehicles," August 1973, p. 4-6.

Johnson, W.R., Cowgill, G.R., "Thermal Analysis of Customized Multilayer Insulation of an Unshrouded Liquid Hydrogen Tank," March 1971, p. 2-36.

Johnson, W.R., "Analytical Investigation of Thermal Degradation of High-Performance Multilayer Insulation in the Vicinity of a Penetration," September 1968, p. 5-12.

Keller, C.W., "Fiberglass Supports for Cryogenic Tanks,"October 1972, p. 5-2.

Keller, C.W., "Thermal Performance of Multilayer Insulations," April 1971, p. 2-32.

Knoll, R.H., Bartoo, E.R., "Experimental Studies of Shadow Shields for Thermal Protection of Cryogenic Tanks in Space," November 1968, p. 3-20.

Kordsmeier, N.H., Jr., "Study of Attachment Methods for Advanced Spacecraft Thermal Control Materials," May 1968, p. 2-46.

Leonhard, K.E., "Vacuum-Jacketed Ducting Technology Investigation," June 1973, p. 4-8.

Leonhard, K.E., "Cryogenic Insulation Development," July 1972, p. 2-16.

Leonhard, K.E., "Cryogenic Insulation Development (Phase II)," December 1969, p. 2-40.

Leonhard, K.E., "Liquid Hydrogen Suction Line Insulation Research," July 1966, p. 4-10.

Leonhard, K.E., "Flightworthy High Performance Insulation Development," January through April 1971, p. 2-38.

Lofgren, C.L., Gieseking, D.E., "Multilayer Insulation Panels," April 1971, p. 2-34.

Lundeen, R., "Development of a Liquid Shroud Cryogenic Supercritical Pressure Storage System," May 1968, p. 3-22.

Nies, G.E., "Light Weight Modular Multilayer Insulation," June 1971, p. 2-28.

O'Neill, M.J., "Penetrations Through Multilayer Insulation Systems," March 1972, p. 5-4.

O'Neill, M.J., McDanal, A.J., "Study of Thermal Conductivity Requirements Volume I, II and III," June 1971, p. 2-26.

Parmley, R.T., et al, "Effect of Environment on Insulation Materials, February 1973, p. 2-14.

Perkins, P.J., Jr., "Experimental Study Under Ground-Hold Conditions of Several Insulation Systems for Liquid Hydrogen Fuel Tanks of Launch Vehicles, March 1965, p. 3-26.

Roodhouse, B.O., et al, "Space Shuttle Structural Test Program Cryogenic Tank Structure/Insulation Test, "March 1972, p. 3-6.

Schroeder, C.J., "Insulation Commonality Assessment (Phase I), February 1973, p. 3-4.

Schwartz, R., "Saturn S-II Advanced Technology Studies, Cryo Storage Thermal Improvement, February 1972, p. 2-18.

Schwartz, R., "Saturn-II Advanced Technology Studies, Improved Cryogenic Foam Insulation," December 1971, p. 3-10.

Shriver, C.R., et al, "Design Improvement, Qualification Testing, Purge and Vent Investigation, Fabrication and Documentation of A GAC-9 Insulation System," November 1971, p. 2-22.

Spond, D.E., et al, "Topical Report, Lightweight Thermally Efficient Composite Feedlines Preliminary Design and Evaluation," June 1974, p. 4-2.

Spond, D.E., "Vacuum Jacketed Composite Propulsion Feedlines for Cryogenic Launch and Space Vehicles, March 1974, p. 4-4.

Stochl, R.J., "Basic Performance of a Multilayer Insulation System Containing 20 to 160 Layers," April 1974, p. 2-6.

Sumner, I.E., Maloy, J.E., "Transient Thermal Performance of Multilayer Insulation Systems During Simulated Ascent Pressure Decay," July 1971, p. 2-24.

Tawil, M.N. Caloger, P., "The Use of Multilayer Insulation on the LM Vehicle, June 1969, p. 2-42.

Tien, C.L., et al, "Lateral Heat Transfer in Cryogenic Multilayer Insulation, 1972, p. 2-20.

Walburn, A.B., "Design and Development of Pressure and Repressurization Purge System for Reusable Space Shuttle Multilayer Insulation Systems, August 1974, p. 2-2.

APPENDIX B

REPORTS REVIEWED AND NOT SUMMARIZED

This section contains a listing of reports which were reviewed, but not summarized, including reasons for not summarizing. The listing is by category and author. The categories are the same as described for the detailed summaries, except that a general category has been added here to include reports covering more than one aspect of cryogenic thermal control or which do not fit into the basic categories. The page location of each category is presented below.

GENERAL

Cohen, A. D., GE, Stein, E. E., AFRPL, "Space Storability of Liquid Propellants," July 1965.

This is the same work as presented by Cohen, et al, 1964 in RPL-TDR-64-75 under Contract AF 04(611)-9078.

Cohen, A. D., et al, "Propellant Storability in Space," GE, RPL-TDR-64-75, Contract AF 04(611)-9078, June 1964.

The insulation systems, analyses and tests reported here have been superseded by later work.

Davis, G. L., "Thermal Protection System Optimization," Chrysler Corp., AIAA Paper No. 69-27, January 1969.

Tradeoffs are made between insulation, boiloff and propellant subcooling using existing data which does not add to the basic state-of-the-art.

Driscoll, D. G., "Cryogenic Tankage for Space Flight Applications," Linde, Advances in Cryogenic Engineering, Vol. 5, Paper No. B-3, 1959.

Represents only a general discussion of cryogenic tankage for space flight, mostly in the area of tank structure.

Gerth, B., Lundeen, R., "Development of Supercritical Pressure Cryogenic Storage and Supply Systems Incorporating the Radial Bumper-Discrete Shield Design," Bendix, NASA CR-92137, Contract No. NAS9-2978, April 1968.

Primarily deals with structural details of storage dewars with no insulation data significant to the current program.

Oliver, J. R., Dempster, W. E., "Orbital Storage of Liquid Hydrogen," NASA/MSFC, TND-559, August 1961.

Discussion is general and is based on other data.

Schroeder, C. J., et al, "Insulation Commonality Report Volume II Internal Insulation Ablators and Vacuum Jacketed Tanks Synopsis," NAR, SD73-SA-0083-2, Contract NAS7-200, September 1973.

This is a good compilation of work accomplished, however, pertinent information has been covered by individual summaries and/or reviews of the source material.

MULTILAYER INSULATION (MLI) SYSTEMS

Anon., "Application of High Performance Insulation to Large Conical Support Structures," Goodyear Aerospace, GER-14518 S/11, Contract No. NAS8-24884, October 1970.

The material and tasks presented in this report are similar to that contained in the summarized report "Investigation of High Performance Insulation Application Problems," by G.O. Frederickson.

Androulakis, J. G., "Effective Thermal Conductivity Parallel to the Laminations and Total Conductance for Combined Parallel and Normal Heat Flow in Multilayer Insulation," Grumman, AIAA Paper No. 68-765, June 1968.

The summarized article "Lateral Heat Transfer in Cryogenic Multilayer Insulation," by C. L. Tien, et al, reviews the results of this and other papers.

Androulakis, J. G., "Effective Thermal Conductivity Parallel to the Laminations of Multilayer Insulation," Grumman, AIAA Paper No. 70-846, July 1970.

The summarized article "Lateral Heat Transfer in Cryogenic Multilayer Insulation" by C. L. Tien, et al, reviews the results of this and other papers.

Babjak, S. J., et al, "Planetary Vehicle Thermal Insulation Systems," GE, DIN-68SD4266, JPL Contract No. 951537, June 1968.

The information presented in this report has been superseded by more recent documents such as the summarized report, "Cryogenic Insulation Development," by K. E. Leonhard.

Barber, J. R., et al, "Thermal Protection Systems for Cryogenic Fluids in Space," NASA/LeRC, Proceedings for Cryogenic Workshop, March 1972.

This paper discusses programs which are reviewed individually elsewhere.

Barclay, D. L., Strayer, J. W., "Lightweight Vacuum Jacket for Cryogenic Insulation," Boeing, Contract No. NAS3-15848, in progress.

This program is in progress.

Barry, D. G., "Parametric Study of Optimized Liquid Hydrogen Thermal Protection Systems for Nuclear Interplanetary Spacecraft," GD/FW, FZA-434-1, Contract No. NAS8-21080, August 1968.

This article is too specific and theoretical to add to the general state-of-the-art of cryogenic thermal control systems.

Bartlett, D. H., "Lightweight Hard Outer Shells for Evacuated MLI," Boeing, Proceedings for Cryogenic Workshop, March 1972.

The material presented is similar to that contained in "Lightweight Evacuated MLI for Space Shuttle," by D. L. Barclay, et al (1973), which is summarized.

Bartlett, D. H., Zimmerman, D. K., "Space Vehicle Integrated Thermal Protection/ Structural/Meteoroid Protection System," Boeing, NASA CR-121103, Contract No. NAS3-13316, April 1973.

This program primarily describes the structural integration of the thermal protection system with a meteroid protection system. The report does not present data significant to the current program.

Bell, J. E., "Hydrogen Thermal Test Article (HTTA)," Beech, Contract No. NAS9-12105, November 1971.

This is an interim report.

Bonneville, J. M., "Design and Optimization of Space Thermal Protection for Cryogens - Analytical Techniques and Results," ADL, NASA CR-54190, ADL 65958-02-01, Contract No. NAS3-4181, December 1964.

This report is a companion document to "Basic Investigation of Multilayer Insulation Systems," by Black, et al (1965) which is summarized.

Breuch, R., et al, "Handbook of Optical Properties for Thermal Control Surfaces, Vol. III," LMSC, June 1967.

This handbook presents a compilation of data published in the open literature. The significant data are presented in the MLI summaries.

Brogan, J. J., "Design of High-Performance Insulation Systems," LMSC, LMSC-A742593-1, Contract No. NAS8-11347, August 1965.

More complete and recent information is available in other reports, which are summarized.

Buckley, R. A., et al, "Development of Materials and Materials Application Concepts for Joint Use as Cryogenic Insulation and Micrometeoroid Bumpers," Goodyear, GER 11676 S/47, Contract No. NAS8-11747, June 1968.

The information in this report is obsolete. The GAC-4 type panelized insulation was replaced by the GAC-9 type insulation which is summarized in "Design Improvement, Qualification Testing, Purge and Vent Investigation, Fabrication and Documentation of a GAC-9 Insulation System," by Shriver, C. R., et al.

Bullock, R. E., et al, "Evaluation of Cryogenic Insulation Materials," GD/FW, NASA CR-2162, Contract No. NAS8-18024, December 1972.

This report describes the effects of radiation on organic materials and thermal insulation, supporting the development of a nuclear rocket vehicle, which is not signficant for the current low-g transfer program.

Cohen, A. D., GE, Stein, E. E., AFRPL, "Space Storability of Liquid Propellants," AIAA Paper No. 65-534, July 1965.

The essential information generated during this program has been obsoleted by recent developments in the MLI field.

Coston, R. M., "Handbook of Thermal Design Data for Multilayer Insulation Systems," Vol. II, LMSC, Contract No. NAS8-20353, June 1967.

This handbook presents a collection of data published in the open literature. The important data are presented in the MLI summaries.

Coston, R. M., et al, "Analytical and Experimental Studies of Gas Flow Through Multilayer Insulation," LMSC, LMSC-A742593-V, Contract No. NAS8-11347, August 1965.

The information given in this report has been superseded by the results of the summarized report "Design and Development of Pressure and Repressurization Purge Systems for Reusable Space Shuttle Multilayer Insulation Systems by A. B. Walburn.

Cunnington, G. R., Tien, C. L., "A Study of Heat Transfer Process in Multilayer Insulation," LMSC, AIAA Paper No. 69-607, June 1969.

The paper presents a theoretical investigation of heat transfer by simultaneous radiation and conduction in MLI, a subject which is adequately covered in other reports, which are summarized.

Emslie, A. G., "Gas Conduction Problem With Multilayered Radiation Shields," ADL, Report No. 63270-04-01, April 1961.

The material presented in this report is contained in "Liquid Propellant Losses During Space Flight," by R. B. Hinckley (1964).

Faddoul, J. R., "Lightweight Modular Multilayer Insulation," Linde, NASA CR-72856, Contract No. NAS3-12045, February 1971.

The evaluation of this work is included in the detailed summary of NASA CR-121166, by Burr (1973).

Fredrickson, G. O., Coes, M. C., "Fabrication of a Multilayer Insulation System for In-Space Storage of Cryogens," MACDAC, Proceedings for Cryogenic Workshop, March 1972.

The material presented in this paper is similar to that contained in the summarized report "Investigation of High-Performance Insulation Application Problems," by G. O. Frederickson (1973).

Getty, R. C., "Cryogenic Insulation Development (Phase I), GD/C, GDC-DDB67-007, Contract No. NAS8-18021, January 1968.

The information in this report is obsolete.

Glassford, A. P. M., "Outgassing Behavior of Multilayer Insulation Materials," LMSC, Contract No. NAS8-20758, no date.

This work is included in "Investigation Regarding Development of a High Performance Insulation System," Anon. (1968), which is summarized.

Glassford, A. P. M., "Prediction of Pressure During Evacuation of Multilayer Insulation, LMSC, Journal of Spacecraft and Rockets, Vol. 9, No. 5, May 1972.

The material presented in this paper is similar to that contained in "Investigations Regarding Development of a High-Performance Insulation System," Anon. (1968), which is summarized.

Goodwin, D. W., Brook, O. R., "Thermal Protection Systems for Cryogenic Propellants on Interplanetary Space Vehicles," GD/FW, FZA-416, Contract No. NAS8-11161, September 1966.

This work which is reported in four volumes is mainly theoretical and does not add significantly to the state-of-the-art of cryogenic thermal control systems.

Hinckley, R. B., "Liquid Propellant Losses During Space Flight," ADL, 63270-00-08, Contract No. NAS5-664, October 1962.

The material presented in this document is included in the final report on Contract NASw-615, "Liquid Propellant Losses During Space Flight (1964)," by R. B. Hinckley.

Hinckley, R. B., "Liquid Propellant Losses During Space Flight, ADL, 65008-00-04, Contract No. NASw-615, October 1964.

This is a comprehensive investigation covering a three year period. However, a later summarized report by Black, et al (1964) was essentially a continuation of and includes the significant developments of this work.

Hopkins, R. A., Chronic, W. L., "Long-Term Cryogenic Space Storage System," Beech, Advances in Cryogenic Engineering, Vol. 18, Contract No. NAS9-10348, August 1972.

For a summary of this program see Chronic (1974).

Hyde, E. H., "Practical Influences on Thermal Design of High Performance Insulation," NASA-MSFC, NASA TM X-53670, March 1967.

This article is a review of the status of multilayer insulation development in 1967. Essential elements of this material are reviewed and/or summarized elsewhere.

Hyde, E. H., "Performance and Reuse Potential of Multilayer Insulation (MLI)," NASA-MSFC, NASA/MSFC Quarterly Technology Review, August 1973.

This paper discusses programs which are reviewed elsewhere.

Kneisel, K. M., Bennett, F. O., "Prediction of Interstitial Gas Pressure in a Multilayer Insulation During Rapid Evacuation," GD/C, AIAA Paper No. 69-608, June 1968.

The material reported herein is similar to that contained in "Cryogenic Insulation Development," by K. E. Leonhard (1969), which is summarized.

Knopf, P. W., Murray, D. O., "Empirical Thermal Performance of Embossed/ Crinkled Aluminized Film Multilayer Insulation With Joints," LMSC, Proceedings of Symposium on Thermodynamics and Thermophysics of Space Flight, March 1970.

The results of this study are not reasonably adaptable to cryogenic temperatures.

Leonhard, K. E., et al, "Development of a Thick Superinsulation for Long-Term Cryogenic Storage," GD/C, Proceedings of Symposium on Thermodynamics and Thermophysics of Space Flight, March 1970.

The material reported herein is similar to that contained in "Cryogenic Insulation Development," by K. E. Leonhard (1969), which is summarized.

Lindquist, C. R., "Super Insulation Systems for Cryogenic Test Tank," Linde, NASA CR-102319, Contract Nos. NAS8-11740 and NAS8-24567, September 1969.

The work described herein is an early version of the Linde Self-Evacuating Multilayer Insulation (SEMI). A report by Burr (1973) is summarized.

Lindquist, C. R., Nies, G. E., "Lightweight Multilayer Insulation System," Linde, NASA CR-72363, Contract No. NAS3-7953, February 1968.

The summary of this report is included in the detailed summary of report NASA CR-121166, "Reusable Lightweight Modular Multi-Layer Insulation for Space Shuttle," Burr (1973).

Lofgren, C. L., Gieseking, D. E., "Demonstration of Manufacturing Techniques for Application of High Performance Cryogenic Insulation," Boeing, NASA CR-98459, Contract No. NAS8-21341, September 1968.

This material has been obsoleted by more recent work.

Nevins, C. D., "Designing for Cryogenic Insulation," NASA-MSFC, NASA TM X-53670, March 1967.

This article is a review of certain aspects of the status of multilayer insulation development in 1967. Essential elements of this material are reviewed and/or summarized elsewhere.

Niendorf, L. R., Nies, G. E., "Investigation of a Lightweight Self-Evacuating Prefabricated Multi-layer Insulation System for Cryogenic Space Propulsion Stages," Linde, NASA CR-72017, Contract No. NAS3-6289, July 1966.

The summary of this report is included in the detailed summary of report NASA CR-121166 by Burr (1973).

Paivanas, J. A., et al, "Multishielding - An Advanced Super-Insulation Technique," Linde, Advances in Cryogenic Engineering, Vol. 10, Paper E-1, August 1964.

The information presented in this paper is superseded by the work performed by Chronic, W. L., et al, Beech ER-15961, NAS9-10348, "Oxygen Thermal Test Article."

Parmley, R. T., Brogan, J. J., "Handbook of Thermal Design Data for Multilayer Insulation Systems," LMSC, LMSC-A742593-VI, Contract No. NAS8-11347, August 1965.

This report is a compilation of thermal and physical data that can be applied in the design of cryogenic thermal protection systems. Pertinent technology aspects are covered in summaries and/or reviews of the source material.

Perkins, P. J., et al, "Self-Evacuated Multilayer Insulation of Lightweight Prefabricated Panels for Cryogenic Space Propulsion Vehicles," NASA-LeRC, AIAA/ASME 8th Structures, Structural Dynamics and Materials Conference, March 1967.

This paper discusses the program by Burr (1973) which is summarized.

Pogson, J. T., MacGregor, R. K., "Effective Conductance Along Parallel Radiation Shields," Boeing, AIAA Paper No. 70-847, July 1970.

The summarized article "Lateral Heat Transfer in Cryogenic Multilayer Insulation," by C. L. Tien, et al, reviews this subject in detail.

Rhodes, J. E., "Large Scale Cryogenic Testing of High Performance Insulation (HPI) Systems," NASA-MSFC, Proceedings of Cryogenic Workshop, March 1972.

The facilities for large scale testing of multilayer insulation systems at NASA-MSFC are summarized. This article does not add to the state-of-the-art of cryogenic thermal control.

Schroeder, C. J., et al, "Insulation Commonality Report Volume 1, Multilayer Insulation Synopsis," NAR, SD73-SA-0083-1, NAS7-200, September 1973.

This is a good compilation of work accomplished, however pertinent information has been covered by individual summaries and/or reviews of the source material.

Shriver, C. B., et al, "Development of Materials and Materials Application Concepts for Joint Use as Cryogenic Insulation and Micrometeoroid Bumpers." Goodyear Aerospace, GER 14071 S/11, November 1969.

Essential work in this report was directed toward improving the thermal efficiency of GAC-4 type of multilayer panelized insulation concept. The improved concept is designated the GAC insulation system which is summarized in "Design Improvement, Qualification Testing, Purge and Vent Investigation, Fabrication and Documentation of GAC-9 Insulation System," by Shriver, et al.

Smith, D. D., et al, "Analysis of Insulation Optimization," LMSC, LMSC-A742593-VII, Contract No. NAS8-11347, August 1965.

The significant elements of this report are available in more current reports, which are summarized.

Sterbentz, W. H., Baxter, J. W., "Thermal Protection System for a Cryogenic Spacecraft Propulsion Module," Vol. II, LMSC, NASA CR-54879, LMSC-A794993, Contract No. NAS3-4199, November 1966.

A number of modifications were made to the system and additional tests were run by NASA-LeRC and reported by Dewitt and Mellner (1971) in NASA TND-6331, which is summarized.

Stimpson, L. E., Jaworski, W., "Effects of Overlaps, Stitches, and Patches on Multilayer Insulation," JPL, AIAA Paper No. 72-285, April 1972.

Analyses and tests of joints and fastening techniques have been conducted in more depth in other investigations which are summarized.

Stuckey, J. M., "Development of a Combined High Performance Multilayer Insulation and Micrometeoroid Protection System," NASA-MSFC, NASA TM X-53670, March 1967.

This article is a review of the status of combined multilayer insulation/meteoroid protection systems development in 1967. Essential elements of this material are reviewed and/or summarized elsewhere.

Vetrano, J. B., "Development of Techniques and Instrumentation for the Nondestructive Evaluation of Multilayer Insulation," Battelle Northwest, Contract No. NAS8-27479, November 1972.

This report presents an investigation leading to the development of techniques and instrumentation for the nondestructive evaluation of purged MLI prior to and after a shuttle orbiter flight. However, it is felt that the study is not complete enough to be used or to be summarized.

Walburn, A. B., "Development of a Reusable Flightweight Cryogenic Storage System," GD/C, AIAA Paper No. 74-726, July 1974.

This is the same work as presented by Walburn, et al, in CASD-NAS74-032, which is summarized.

Yates, I. C., Jr., "Cryogenic Insulation Manufacturing Technology," NASA-MSFC, NASA TMX-53670, March 1967.

This article is a review of the status of multilayer insulation manufacturing techniques and processes in 1967. Pertinent parts of this material are reviewed and/or summarized elsewhere.

Wingfield, K. A., Driscoll, R. J., "Evaluation of a Tank Mounted Insulation System Degradation," AFRPL, AFRPL-TR-70-22, June 1970.

Of the four storability tests completed, only one provided reliable data and the boiloff data of this test is questionable due to the inaccuracy of the tank pressure control system.

OTHER INSULATION SYSTEMS

Bronson, J. C., "Frost Formation on a Cylinder at Cryogenic Temperatures," Los Alamos Scientific Lab., LA-DC-10286, 1970.

This work is not pertinent to the low-g technology study.

Bullock, R. E., et al, "Evaluation of Cryogenic Insulation Materials and Composites for Use in Nuclear Radiation Environments," GD/FW, NASA CR-2162, Contract No. NAS8-18024, December 1972.

Insufficient data are presented to draw useful conclusions.

Chandler, W. A., Rice, R. R., "Cryogenic Storage System," NASA-JSC, U. S. Patent 3,304,729, February 1967.

The state-of-the-art in vapor-cooled shield systems has been extended by more recent work, such as that by Chronic, et al, (1974) which is summarized.

Fletcher, L. S., et al, "Thermal Contact Resistance of Selected Low Conductance Interstitial Materials," Arizona State Univ., AIAA Paper No. 68-31, January 1968.

The data presented are not in a form which would permit accurate calculation of contact resistances.

Doughty, R. O., et al, "Expandable Rigidizable Solar Shields for Protection of Cryogenic Propellants in Space," GD/FW, Journal of Spacecraft and Rockets, December 1970.

The work by Doughty (1969), which is summarized, includes that presented in this paper.

Gille, J. P., "Development of Advanced Material Composites for Use as Internal Insulation for LH_2 Tanks (Gas Layer Concept)," MMC, NASA CR-124222, July 1972.

The materials developed here were used to insulate a 6 ft diameter tank on Contract NAS3-14384, a study by Gille (1973) which is summarized.

Johnson, C. L., Hollweger, D. J., "Non-Evacuated Cryogenic Thermal Insulation Studies," Aerojet-General, ML-TDR-64-260, AF33(657)-11200, September 1964.

The objective of this program was to investigate the possibility of obtaining very low thermal conductivities in non-evacuated powders and is not pertinent to the current low-g technology study.

Jones, L. R., et al, "A Study of Lightweight Inflatable Shadow Shields for Cryogenic Space Vehicles," GD/FW, FZA-395, Contract No. NAS8-11317, January 1965.

This work was superseded by GD/FW Report, "An Analytical and Experimental Development Program for Inflatable Solar Shields," by Doughty, May 1969.

Knight, B. L., et al, "Analysis of Thermal Diffusivity Evaluation Under Transient Conditions for Powder Insulations," Marathon Oil Co., Advances in Cryogenic Engineering, Vol. 18, 1973.

The material in this paper is not presented in sufficient detail to be of use in the design of insulation systems for low-g transfer.

Maccalons, J. W., Thomas, D. A., "Development of External Protection Materials for Cryogenic Tanks, MMC, SAMPLE Vol. 19, 1974.

The paper presents a discussion on the application of cryogenic/ablative material systems to an aluminum substrate. This information is not significant to the current program.

Mark, F. E., Smith, M. E., "High Performance Spray Foam Insulation for Application on Saturn S-II Stage, NAR, Advances in Cryogenic Engineering, Vol. 16, Paper D-3, June 1970.

The paper presents the use of spray foam insulation on the external surface of the Saturn S-II stage and the information presented does not significantly advance the state-of-the-art.

McLaughlan, P. B., "Evaluation of an Externally Insulated Spacecraft Dewar," NASA-JSC, Advances in Cryogenic Engineering, Vol. 14, Paper F-2, August 1968.

This work is superseded by the information given in the summarized report "Oxygen Thermal Test Article," by Chronic, W. L., et al, NAS9-10348.

Parmley, R. T., "Mircospheres - A New High Performance Cryogenic Insulation," LMSC, Proceedings for Cryogenic Workshop, March 1972.

The material presented in this paper is similar to that by Cunnington and Tien (1972) which is summarized.

Parmley, R. T., Cunnington, G. R., "Microspheres - A New Super Insulation," LMSC, JANAF Combined Propulsion Conference, Las Vegas, Nevada, November 1971.

The material presented in this paper is similar to that contained in an article by Cunnington and Tien (1972) which is summarized.

Rhoton, R. L., "Cryogenic Storage and Expulsion Means," MACDAC, United States Patent No. 3,699,696, October 1972.

The information given under this patent is not sufficient and complete enough to be summarized.

Ryan, J. M., et al, "Lightweight Thermal Protection System Development," GD/C, AFML-TR-65-26, Vol. I, Contract No. AF33(657)-9444, January 1965.

This study does not add to the description of the current state-of-the-art of cryogenic thermal control systems.

Ryan, J. M., et al, "The Optimization of Thermal Composites," GD/C, AFML-TR-65-244, Contract No. AF33(615)-1672, December 1965.

An Attempt was made to locate new, high temperature fibrous insulation materials, which is not significant to the current subject.

Santoro, G. J., et al, "An Exploratory Study of the Microstructure of Mullite Fibers," NASA-LeRC, NASA TM X-2750, March 1973.

Characterization of mullite ($3Al_2O_3$-$2S_iO_2$) fibers for use as a high temperature heat shield for Space Shuttle is presented, which is not pertinent to the current program.

Sollami, B. J., et al, "Composite Insulation for Cryogenic Vessel," Bendix Corp., United State Patent No. 3,724,228, April 1973.

The information given is not sufficient and complete enough to advance the state-of-the-art of low-g fluid behavior, storage or transfer.

Stochl, R. J., Boyle, R. J., "An Analytical and Experimental Evaluation of Shadow Shields and Their Support Members," NASA-LeRC, NASA TM X-68099, Also Advances in Cryogenic Engineering, Vol. 18, 1972.

The material in this report is similar to that in the summarized study by Knoll and Bartoo (1968).

Williams, S. D., et al, "An Efficiency Study on Obtaining the Minimum Weight of a Thermal Protection System," NASA-JSC, NASA TM X-58126, January 1974.

This report describes a computer analysis technique for determining the minimum weights of Dynaflex insulation composites for use on the Space Shuttle thermal protection system (high temperature) and is not pertinent to the current subject.

FLUID LINES

Hall, C. A., et al, "Low Thermal Flux Glass-Fiber Tubing for Cryogenic Service," MMC, NASA CR-72797, Contract No. NAS3-12047, March 1971.

The results of this study are included in Hall, et al (1973) which is summarized.

Spond, D. E., et al, "Vacuum Jacketed Composite Propulsion Feedlines for Cryogenic Launch and Space Vehicles," MMC, NASA CR-134554, Vol. II, Contract No. NAS3-16762, March 1974.

This is Volume II of a summarized study by Spond, et al (1974).

TANK SUPPORTS AND PENETRATIONS

Bullard, B. R., "Cryogenic Tank Support Evaluation, Task I," LMSC, NASA CR-72538, Contract No. NAS3-7979, April 1969.

This is the first phase of a summarized study by Bullard (1969).

Hauser, R. L., "Thermal Analysis of Cryogenic Struts," Hauser Research and Engrg. Co., Report 5274-70-16, Contract No. NAS3-14627, November 1970.

This analysis is a straight forward heat transfer analysis. It does not add to the state-of-the-art of low-g technology.

Horton, T. R., "The Reduction of Heat Flux Into Cryogenic Storage Vessels by Use of Vapor-Cooled Support Tubes," Rocket Propulsion Establishment, Westcott, England, Technical Report 71/8 (AD 772474), September 1971.

The analytical technique is not accurate (author) and the numerical technique applies only to thin-walled tubes.

Izu, Y. D., Beasley, R. M., "Development of Composite Support Structures for Aerospace Cryogenic Applications," LMSC, AIChE-CSChE Meeting, Vancouver, British Columbia, September 1973.

This material is included in CR-72546 by Bullard (1969) which is summarized.

APPENDIX C

NASA - LITERATURE SEARCH - KEY WORDS

A retrospective literature search was conducted using the Convair IBM 370 and CDC Cyber 70 computers and the NASA Data Base. The portion of the Data Base searched was 30 September 1974 back through 1969.

A complete listing of the key words employed in the search is presented below. All documents containing words A thru C were cited plus those matching words D through I with words J through YY.

A. Weightless Fluids
B. Settling
C. Expulsion Bladders
D. Gravitation
E. Gravitational Effects
F. Reduced Gravity
G. Weightlessness
H. Gravitational Fields
I. Propellant Transfer
J. Fluids
K. Liquids
L. Liquefied Gases
M. Heat Transfer
N. Thermodynamics
O. Liquid-Liquid Interfaces
P. Liquid-Vapor
Q. Interface Stability
R. Liquid Surfaces
S. Hydrodynamics
T. Capillary Flow
U. Inlet Flow
V. Fluid Dynamics
W. Liquid Rocket Propellants
X. Fluid Mechanics
Y. Propellant Properties
Z. Venting
AA. Exhausting
BB. Interfacial Tension
CC. Wetting
DD. Interfaces
EE. Instruments
FF. Cryogenics
GG. Liquid Flow
HH. Water Flow
II. Fluid Flow
JJ. Vents
KK. Exhaust Systems
LL. Cryogenic Fluids
MM. Liquid Sloshing
NN. Ullage
OO. Rotating Fluids
PP. Rotating Liquids
QQ. Liquid-Vapor Equilibrium
RR. Free Boundaries
SS. Liquid Oxygen
TT. Liquid Hydrogen
UU. Refueling
VV. Fuel Control

WW. Acquisition

XX. Expulsion

YY. Flow

APPENDIX D

ABBREVIATIONS, DEFINITIONS AND NOMENCLATURE

D.1 INDUSTRY AND GOVERNMENT AGENCY ABBREVIATIONS

ADL	Arthur D. Little
AFAPL	Air Force Applied Physics Laboratory
AFFDL	Air Force Flight Dynamic Laboratory
AFRPL	Air Force Rocket Propulsion Laboratory
AMRL	Aerospace Medical Research Laboratory
ASME	American Society of Mechanical Engineers
CPIA	Chemical Propulsion Information Agency
GAC	Goodyear Aerospace Corporation
GD/C	General Dynamics Convair
GD/FW	General Dynamics Fort Worth
GE	General Electric
JPL	Jet Propulsion Laboratory
LMSC	Lockheed Missiles and Space Company
LTV	Ling Temco Vought
MACDAC	McDonnell Douglas Aircraft Company
MIT	Massachusetts Institute of Technology
MMC	Martin Marietta
NAR	North American Rockwell
NASA-GSFC	Goddard Space Flight Center
NASA-JSC	Johnson Space Center (Formerly MSC)
NASA-KSC	Kennedy Space Center
NASA-LeRC	Lewis Research Center
NASA-MSFC	Marshall Space Flight Center
NBS	National Bureau of Standards
NRC	National Research Corporation
STL	Space Technology Laboratory
SRI	Stanford Research Institute

D.1 INDUSTRY AND GOVERNMENT AGENCY ABBREVIATIONS (Cont'd)

SwRI	Southwest Research Institute
TRW	Thompson Ramo Woodridge
WPAFB	Wright Patterson Air Force Base

D.2 GLOSSARY OF TERMS

Al Aly	Aluminum Alloy
AM	Aluminized Mylar
CRES	Corrosion Resistant Steel
C-S-A-M	Crinkled Single Aluminized Mylar
DAM	Double Aluminized Mylar
DGK	Double Goldized Kapton
FEP	Teflon Polymer-Hexafluoropropylene
GHe	Gaseous Helium
GH_2	Gaseous Hydrogen
GM	Goldized Mylar
GN_2	Gaseous Nitrogen
GO_2	Gaseous Oxygen
He	Helium
H_2	Hydrogen
LH_e	Liquid Helium
LH_2	Liquid Hydrogen
LM	Lunar Module
LN_2	Liquid Nitrogen
LO_2	Liquid Oxygen
MLI	Multilayer Insulation
N_2	Nitrogen

D.2 GLOSSARY OF TERMS (Cont'd)

O_2	Oxygen
PPO	Polyphenylene Oxide
PV	Polyvinyl
SAM	SAM
Superfloc	Trade name for GD/C tufted insulation system
TPS	Thermal Protection System

D.3 NOMENCLATURE

C_p	specific heat at constant pressure
C_v	specific heat at constant volume
D	diameter
F_{tu}	ultimate tensile stress
g	gravitational constant
h	heat transfer coefficient
h_{fg}	latent heat of vaporization
k	thermal conductivity
L	length
$\dot{m}$	mass flow rate
P	absolute pressure
q, $\dot{Q}$	heat transfer rate
Q	volume flow rate
R	radius
t	time
T	absolute temperature
u	velocity
v	specific volume
V	volume

D.3 NOMENCLATURE (Cont'd)

α	thermal diffusivity
μ	dynamic viscosity
ϵ	emissivity
ν	kinematic viscosity (μ/ρ)
ρ	density
σ	surface tension, Stefan-Boltzmann constant

Subscripts

ℓ	liquid
v	vapor
g	gas

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