NASA Reference Publication 1002

Cryogenic Foam Insulation - Abstracted Publications

Frank R. Williamson

SEPTEMBER 1977

NASA

NASA Reference Publication 1002

Cryogenic Foam Insulation - Abstracted Publications

Frank R. Williamson

Cryogenics Division, Institute for Basic Standards
National Bureau of Standards, Boulder, Colorado

Prepared for
The Aerospace Safety Research and Data Institute,
NASA Lewis Research Center

NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Office

1977

PREFACE

This Reference Publication is part of a cryogenic fluids safety review performed by the NASA-Lewis Research Center. Major emphasis has been on oxygen safety. The objectives of the review include:

1. Recommendations to improve NASA cryogenic and oxygen handling practices by comparing NASA and contractor systems including the design, inspection, operation, maintenance, and emergency procedures.

2. Assessment of the vulnerability to failure of cryogenic and oxygen equipment from a variety of sources so that hazards may be defined and remedial measures formulated.

3. Formulation of criteria and standards on all aspects of handling, storage, and disposal of oxygen and cryogenic fluids.

This Reference Publication is composed of information from the available reports and publications on Cryogenic Foam Insulation. The documents abstracted and listed contain information on the properties of foam materials and on the use of foams as thermal insulation at cryogenic temperatures.

The properties include thermal properties, mechanical properties, and compatibility properties with oxygen and other cryogenic fluids. Uses of foams include applications as thermal insulation for spacecraft propellant tanks, and for liquefied natural gas storage tanks and pipelines.

CONTENTS

INTRODUCTION

This survey is composed of information from the reports and publications available in January, 1976, on Cryogenic Foam Insulation. One group of documents, listed alphabetically by first author, was chosen to include the most important or most informative papers on the properties and applications of foams. An abstract has been prepared for each document in this group, and the most important references are listed as found in the document.

Another group of documents, also listed alphabetically by author, generally includes less important papers than those in the first group. Some important papers are in the second group because information from them has been reviewed or repeated in documents included in the first group.

An author index and a subject index are provided. The indexes cover the authors and subjects of both groups of documents.

Paul M. Ordin of the NASA-Lewis Research Center was the Project Manager for NASA.

ABSTRACTED DOCUMENTS

PLASTIC AND ELASTOMERIC FOAM MATERIALS
Arden, B.
Northrop Corp., Calif., Nortronics Div., Rept. National Aeronautics and Space Administration Rept. No. NASA CR-100463, Contract NAS 7-430 (1966) 186 pp

The purpose of this report is to review contributions to the technology of plastic and elastomeric foam materials derived from NASA research and development programs. The emphasis is on actual or proposed use of foam materials in space vehicles. One chapter of the review is on foam systems for cryogenic insulation, mostly for liquid hydrogen tankage. It is noted that foams have much higher thermal conductivities than do evacuated multilayer insulations, but that advantages of weight, cost, producibility, and reliability have made foams the insulation of choice for short-term missions with liquid hydrogen.

Several foam insulations are described extensively. The first of these is the internal insulation developed for the S-IV-B third stage of the Saturn V. This was the "3-D foam," a polyurethane foam reinforced with glass threads oriented in three mutually-perpendicular directions, bonded to the inside of the tank with an epoxy adhesive, lined with a glass cloth reinforced polyurethane resin layer, and sealed with a coat of polyurethane resin. The second system is the external insulation developed for the S-II stage of the Saturn V vehicle. This was the polyurethane foam-filled phenolic honeycomb bonded to the outside of the tank, purged with helium to prevent condensation of air. A third insulation system is the external insulation developed for the Centaur vehicle. This was a polyurethane foam, sealed with an aluminized mylar vapor barrier, and held to the tank by a constrictive wrapping of glass filament. This final insulation was under development, and the development program is discussed quite extensively.

The report is an excellent review of the foam insulations developed for space vehicle liquid hydrogen tanks before 1966. It is limited by its age, and does not cover several later developments. Fifteen references are given for more comprehensive information on the foam insulations discussed.

Important references:

1. Perkins, P. J., Jr. and Esgar, J. B., AIAA Fifth Annual Structures and Materials Conf. (Palm Springs, Calif., Apr 1-3, 1964), NASA LERC Publication CP-8.

2. Sealed-Foam, Constrictive-Wrapped External Insulation System for Liquid Hydrogen Tanks of Boost Vehicles, NASA TN D-2685 (1965).

3. McGrew, J. L., Advances in Cryogenic Engineering 8, 387-392 (1963).

Important references (continued):

4. Dearing, D. L., Advances in Cryogenic Engineering 11, 89-97 (1966).

5. Shriver, C. B., Goodyear Aerospace Corp., Final Rept. GER-12249, NASA Contract NAS 3-5646 (Jun 25, 1965).

6. Burkley, R. A. and Shriver, C. B., Goodyear Aerospace Corp., Final Report GER-11193, NASA Contract NAS 3-3238 (Nov 1, 1963).

7. Knoll, R. H. and Oglebay, J. C., Lightweight Thermal Protection Systems for Space Vehicle Propellant Tanks, NASA, paper 746C, Presented International Automotive Eng. Congress (Detroit, Mich., Jan 11-15, 1965).

COMPRESSIVE PROPERTIES OF POLYURETHANE AND POLYSTYRENE FOAMS FROM 76 TO 300 K

Arvidson, J. M., Durcholz, R. L., and Reed, R. P. (National Bureau of Standards, Boulder, Colo. Cryogenics Div.)

Advances in Cryogenic Engineering 18, Proc. Cryogenic Engineering Conf. (Colorado Univ., Boulder, Aug 9-11, 1972), K. D. Timmerhaus, Editor. Plenum Press, New York, 194-201 (1973)

For many applications of foam insulation in cryogenic environments, compressive properties are more important than tensile properties. The ultimate strength (in the compressive mode) is not well defined for most foams, in that the foam does not reach an ultimate strength, but the rigid foam begins to crumble allowing higher and higher loads to be sustained as the cell structure collapses.

This paper complements another paper abstracted on page 89 giving tensile properties for foam insulation. The compressive properties, measured in transverse and longitudinal directions, were modulus of elasticity, proportional limit, yield strength, compressive strength and elongation. The materials were four densities of polyurethane (95.64 kg/m^3 to 31.72 kg/m^3) and two densities of polystyrene (99.48 kg/m^3 to 51.26 kg/m^3. Three of the polyurethane foams were rigid and one was flexible while both polystyrenes were rigid.

The paper gives tabular results for the compressive properties, but stress-strain curves are also presented. These results showed a strong dependence on density for compressive behavior. As with the tensile results reported in a previous paper the modulus of elasticity, yield strength and compressive strength increased with decreasing temperature while the elongation increased. An approximate linear dependence on density was found for the modulus and proportional limit. Longitudinal specimens were usually stronger than transverse specimens.

The results of the compression tests were compared to companion tensile results. Both the modulus of elasticity and yield strength were about twice as great in tension as in compression and this difference held for all temperatures. In ultimate strength the differences diminished at the lowest temperatures.

Important references:

1. Doherty, D. J., Hurd, R. and Lester, G. R., Chemistry and Industry (London) p. 1340 (Jul 1962).

2. Reed, R. P., Arvidson, J. M. and Durcholz, R. L., Advances in Cryogenic Engineering 18 (1972).

INTERNAL INSULATION SYSTEMS FOR LH_2 TANKS — GAS LAYER AND REINFORCED FOAM
Barker, H. H., Jr., McGrew, J. L., Buskirk, D. L., and Gille, J. P.
(McDonnell-Douglas Astronautics Co., Huntington Beach, Calif., and Martin Marietta Corp., Denver, Colo.)
Space Transportation Systems Propulsion Technology, Proc. Conf. (George C. Marshall Space Flight Center, Huntsville, Ala., Apr 6-7, 1971) - Vol 4 - Cryogens. National Aeronautics and Space Administration, Rept. No. NASA TM-X-67348, 1453-80 (Apr 1971)

Three forms of internal insulation for the liquid hydrogen tanks of the Space Shuttle were being developed: gas layer or capillary insulation, reinforced foam, and polyphenylene oxide foam. The polyphenylene oxide foam is described in the paper abstracted on page 108. This paper describes the other two concepts.

The reinforced foam, identified as 3-D foam insulation, was developed for use as internal insulation for the liquid hydrogen tanks of the Saturn-IV and S-IVB stages. It consisted of a polyurethane foam reinforced with glass threads in three mutually perpendicular directions. The foam was bonded to the tank wall with an epoxy adhesive, and sealed against hydrogen permeation with a layer of glass cloth impregnated with polyurethane resin. The insulation on each of two battleship vehicles survived over 100 cryogenic loadings, on an all-systems vehicle 300 loadings, and on each flight stage between 2 and 6 loadings. After initial modifications on the first battleship vehicle, no significant degradation was observed. Thermal conductivity of the foam approached that of helium gas. For the Space Shuttle, the maximum service temperature was increased to 450 K. The paper shows some results of weight-loss tests at high temperatures on various candidate materials, including a polyurethane foam which, after heat conditioning, was more stable than the previously-used foam, and seemed usable at 450 K. A total weight reduction by 20 or 25% seemed feasible.

The gas layer insulation consists of a honeycomb structure bonded to the tank wall and covered with a punctured membrane. Capillary forces at the membrane holes support a stable liquid/gas interface, separating liquid in the tank from the gaseous hydrogen within the honeycomb cells. This concept is similar to an open-cell foam with large cell size. The insulation appeared usable at temperatures up to 616 K to 644 K with available materials.

The authors conclude that both the reinforced foam and the gas layer insulation are feasible for use on the Space Shuttle.

A STRUCTURAL PLASTIC FOAM THERMAL INSULATION FOR CRYOGENIC SERVICE
Bennett, R. B. (Amspec, Inc., Columbus, Ohio)
Advances in Cryogenic Engineering 19, Proc. Cryogenic Engineering Conf. (Georgia Inst. of Tech., Atlanta, Aug 8-10, 1973), K. D. Timmerhaus, Editor. Plenum Press, New York, 393-9 (1974)

This paper describes a commercial rigid polystyrene foam developed as a load bearing insulation for the bases or bottoms of liquefied natural gas tanks. The material is a high density (52.8 kg/m^3) extruded foam.

Compressive stress-strain curves at 111 K and 296 K show that compressive strength increased gradually with decreasing temperature. Yield points at both temperatures were at about 4% strain. Long-term compressive creep was estimated at less than 2% after 20 years at maximum design load at 296 K, and was even lower at lower temperatures. Cyclic loading and freeze-thaw cycling had little effect on the foam. Thermal conductivity had an s-shaped curve with a maximum near 185 K and a minimum near 250 K. Measured thermal conductivities were 0.022 W/m•K at a mean temperature of 200 K and 0.030 W/m•K at 297 K. Complete replacement by diffusion of the freon blowing agent with methane would substantially increase the thermal conductivity, but over a period of 10 to several hundred years. Long term immersion tests in liquid methane, liquid ethane, liquid propane, and LNG showed complete compatibility. The foam contained a fire retardant. In actual applications to LNG tanks, the polystyrene foam performed well within design expectations.

ANALYSIS AND MEASUREMENT OF THE HEAT TRANSMISSION OF MULTI-COMPONENT INSULATION ON PANELS FOR THERMAL PROTECTION OF CRYOGENIC LIQUID STORAGE VESSELS

Bourne, J. G., and Tye, R. P. (Dynatech R/D Co., Cambridge, Mass.)
Heat Transmission Measurements in Thermal Insulations, Proc. Symp. Thermal and Cryogenic Insulating Materials (Philadelphia, Pa., Apr 16-7, 1973), American Soc. for Testing and Materials, Philadelphia, Pa., Special Tech. Publ. No. STP-544, 297-305 (Jun 1974)

The usual insulation for the liquefied natural gas tanks on ocean tanker vessels is external insulation, which provides structural load bearing as well as thermal insulation. Insulation systems combining foam insulation with balsa wood were developed, and this paper reports on thermal conductivity measurements of the insulation components and of scale models of the composite insulation systems. These measurements aided the development of an analytical model to predict the thermal performance of full-scale insulation systems.

The components tested were a commercial polyurethane foam, a commercial polystyrene foam, balsa wood with two grain orientations, and commercial foamed glass. A layer of the composite insulation consisted of alternating strips of balsa wood and foam insulation. Scaled samples consisted of three layers of the composite, with or without adhesive bonding, with or without plywood facings, and with varying angular displacement of strip orientation between layers. Thermal conductivities were measured between a cold face at 82 K and a hot face at 395 K. Results are tabulated for the five component materials and for six composite insulations. The analytical model used the properties of the components to predict the thermal conductivities of the composite insulations, with errors ranging from 0 to 7%. The authors conclude that the analytical approach is valid and useful.

Important references:

1. Tye, R. P., Proc. XIII International Congress of Refrigeration 1 (Washington, D.C.), Institute International de Froid, Paris (1971).

METHODS OF INSULATING PIPE WITH POLYURETHANE FOAMS
Brochhagen, F. K., and Schmidt, W. (Farbenfabriken Bayer A. A., Leverkusen, West Germany)
Plastics Inst. (London) Trans. J. 35, No. 117, 499-503 (1967)

Polyurethane foams have found increasing use in insulating pipelines. This paper reviews the methods of applying the foam to the pipe, and describes some of the limitations in using polyurethane foams as pipeline insulation. Service temperature limits are given as 73 K to 403 K for rigid foam and 233 K to 383 K for flexible foams.

The methods of application are foaming in place, installing prefabricated half-pipe sections, or pre-insulating the pipe in sections at the factory. In foaming in place, the reactive mixture is injected between the pipe and a sheet-metal jacket. This method is limited by temperature requirements for proper production of foam. Prefabricated half-pipe sections can be molded to shape or cut from rectangular shapes, and applied to the pipe as other solid insulations are. Flexible foams can be made as tubing to slip over the pipe, or as sheet to wrap around the pipe. Pre-insulated pipe is foamed in place under controlled conditions in the factory.

A problem with polyurethane foam insulation is its permeability to water vapor. This property makes it necessary to seal the foam in a vapor barrier for low-temperature applications.

PPO FOAM FOR CRYOGENIC APPLICATIONS
Burkinshaw, L. D. (General Electric Company, Bridgeport, Connecticut)
Proceedings of the International Conference on LNG 1st, Chicago, Ill. (Apr 7-12, 1968) (J. W. White and A. E. S. Neumann, Eds.) Institute of Gas Technology, Chicago, Ill. (1968) 12 pp

Polyphenylene oxide (PPO) foam was described in this paper as a potential component for cryogenic insulations. The foam is an anisotropic open cell foam produced in flat sheets. The open cells extend through the entire thickness of the sheet, all aligned in the same direction.

Foam densities ranged from 24 to 59 kg/m^3. Thermal conductivity of a foam of unspecified density was 0.025 W/m•K at 208 K and 0.058 W/m•K at 316 K. Compressive strength of the foam with load applied perpendicular to the plane of the sheet was greater than that of polyurethane foam of similar density over the temperature range from 220 K to 480 K. Compressive strength was strongly dependent on density and weakly dependent on temperature.

In a test as insulation, the PPO foam was sealed on one side and exposed directly to liquid nitrogen or liquid natural gas on the other side. The liquid cryogens penetrated less than 5 mm into the foam. Pressure increases caused only temporary increases in the penetration depth of the liquid. The reason for the limited penetration was not known, but it was suggested that liquid entering the pores boiled and produced a back pressure which prevented further penetration by the liquid. A proposed container would consist of a PPO foam liner within an outer metal housing.

DEVELOPMENT OF METHODS FOR APPLICATION OF POLYURETHANE SPRAY FOAM INSULATION SYSTEMS TO LIQUID HYDROGEN TANKS
Carter, J. M.
National Aeronautics and Space Administration, Huntsville, Ala., George C. Marshall Space Flight Center, Tech. Memo No. NASA TM-X-53897, 62 pp (Sep 1969)

Polyurethane foams had been used for insulating liquid hydrogen tanks for several years when, in 1967, two proposals were made to apply spray polyurethane foam as insulation for liquid hydrogen tanks on large flight type structures. These structures were the Nuclear Ground Test Module and the S-II vehicle. This report reviews the available spray foam application equipment, describes the modified commercial spray foam formulator developed for use, describes the methods of surface preparation, foam application, and surface finishing, and reports on the results of several test items insulated with the polyurethane spray foam.

The foam is sprayed onto a cleaned and etched aluminum tank exterior surface. Specific instructions are given for applying the spray. The exterior surface of the foam is sealed with a sprayed-on coating of polyurethane adhesive or with a fiberglass reinforced polyurethane adhesive coating. Spray foam insulation was applied to a 1.8 m diameter tank which was then subjected to a liquid hydrogen fill-drain cycle. Foam failures led to modification of the procedure. Spray foam was applied to a 76 cm rectangular dewar, which withstood liquid nitrogen and liquid hydrogen fill-drain cycles and exposure to radiation without visible damage. Some debonding was noted after further liquid hydrogen fill-drain cycles. Spray foam applied to a S-IC/S-II test container showed split and debonded areas after a cryogenic tanking procedure, but all defective areas were removed and repairs made.

The author concludes that a capability has been developed to satisfactorily apply polyurethane spray foam insulation to cryogenic propellant tanks, and that the foam insulation applied to test tanks satisfactorily withstood cryogenic cycling.

AN INVESTIGATION OF THE USE OF INTERNAL INSULATION FOR LIQUID HYDROGEN FUELED MISSILES

Coxe, E. R., Lowrey, R. O., Hunt, R. T., and Freeman, S. M.
(Lockheed-Georgia Co., Marietta)

Advances in Cryogenic Engineering 8, Proc. Cryogenic Engineering Conf. (Los Angeles, Calif., Aug 14-16, 1962), K. D. Timmerhaus, Editor. Plenum Press, New York, 404-10 (1963)

An experimental study was conducted to determine the suitability of several commercial plastic foams for use in composite internal insulation for liquid hydrogen tanks. The insulation considered was plastic foam adhesively bonded to the inside of the tank wall and covered by a vapor barrier bonded to the foam.

The first part of the program obtained the mechanical properties of three adhesives, six foams, and two vapor barriers. In the second part of the program, twelve composite insulation configurations were installed in 30-cm diameter tanks and tested by thermal cycling in liquid nitrogen and then in liquid hydrogen. In general, flexible foams resulted in the vapor barrier failing in tension under tank pressure, while the rigid foams failed under high thermal stresses. The best foams from these tests were a flexible polyurethane foam and a rigid epoxy foam. Composite insulations with these foams were subjected to pressure and vibration in liquid hydrogen. The polyurethane foam failed in compression and its vapor barrier failed in tension under pressure. The epoxy foam did not fail, but separated from the tank wall. The two systems were then applied to a 1 m diameter, 2.5 m long tank, and tested under pressure in liquid hydrogen. The polyurethane sample showed vapor barrier penetrations, and a thermal conductivity no better than that of hydrogen. The epoxy foam did not fail, and the vapor barrier did not rupture where it covered the epoxy foam, but there was considerable detachment of vapor barrier from foam and of foam from the tank wall.

The tests showed that the main problem with foam internal insulation is maintaining an intact vapor barrier. Local penetrations of the vapor barrier only resulted in contamination of the insulation with hydrogen gas, so that insulation performance is at least as good as that of gaseous hydrogen even with local failures of the vapor barrier.

LOW TEMPERATURE INSULATIONS-FOAMS AND COMPOSITES
Cryogenic Engineering News
Cryogenic Eng. News 4, No. 5, 20-5 (May 1969)

This review covers the subjects of foam insulation and composite insulation with the aid of data taken from a number of sources. The rather brief discussion of foams stresses the polyurethanes. Graphical data show the temperature dependence of thermal conductivity of freon-blown polyurethane foam, of polystyrene foams, and of teflon and a composite of teflon foam with teflon. Thermal conductivity versus pumping time is shown for polystyrene, epoxy, and isocyanate foams. Thermal conductivities are tabulated for polystyrene, epoxy, polyurethane, rubber, and silica foams. Thermal and mechanical properties of several densities of polyurethane foam are tabulated. Graphs and a table show the tensile, shear, and compressive strengths and the linear thermal expansions of polyester polyurethane, epoxy, polyurethane, and polyether foams. Composite insulations containing foams are very briefly discussed.

The review concludes with an extensive bibliography of 29 references, most of which deal with foam insulation. The primary application of this review would be as an introduction to the subject, with the bibliography providing sources of more detailed information.

Important references:

1. Development of Low-Density Rigid, Polyurethane Foam for Use on S-1C Flight Vehicle, Final Report, NASA CR-62110 (1964).
2. Barringer, C. M., Refrigerating Engineering New York 65, No. 4, 53-6 and 108-12 (1957).
3. Haskins, J. R. and Hertz, J., Advances in Cryogenic Engineering 7, Plenum Press, New York, 353-9 (1962).
4. Lewis Research Center Staff: Sealed-Foam, Constrictive-Wrapped, External Insulation System for Liquid-Hydrogen Tanks of Boost Vehicles, NASA TN D-2685 (1965).
5. McClintock, R. M., Advances in Cryogenic Engineering 4, 132 (1958).
6. Miller, R. N., Bailey, C. D., Beall, R. T. and Freeman, S. M., Advances in Cryogenic Engineering 8, Plenum Press, New York, Paper C-6 (1963).
7. Miller, R. N., Bailey, C. D., Beall, R. T., Freeman, S. M. and Coxe, E. F., Ind. Eng. Chem. 1, No. 4, 257-61 (Dec 1962).
8. Stoecker, L. R., Advances in Cryogenic Engineering 5, Plenum Press, New York, 273-81.

MATERIALS OF CONSTRUCTION FOR USE IN AN LNG PIPELINE

Dainora, J., Duffy, A. R., and Atterbury, T. J. (Battelle Memorial Inst., Columbus, Ohio)

American Gas Association, Arlington, Va., Rept. No. L40000, 127 pp (Apr 1968)

This report contains a 13-page section reviewing cellular insulation, including plastic foams, foam glass, cork, and balsa wood. The review is based on data taken from the literature. The major types of material discussed are urethane foams, polystyrene foams, epoxy foams, silicone foams, phenolic foams, syntactic foams, cellular glass, and cork and balsa wood. Nine data sources are cited in the discussion.

Much of the information included in this review is on properties at room temperature. Tables summarize the room temperature properties of the urethane, polystyrene, epoxy, silicone, syntactic, and glass foams. Mechanical properties and thermal conductivity of urethane foams, thermal conductivity of polystyrene foams, compressive strength of epoxy foams, and mechanical properties and thermal conductivity of phenolic foams are all presented graphically as functions of foam density at room temperature. Data of more direct interest for cryogenic insulation are graphs of thermal conductivities from 200 K to 400 K of cellular glass, cork, polystyrene foam, phenolic foam, and urethane foam; mechanical properties of urethane foams from 77 K to 297 K; thermal conductivities of polystyrene foams from 30 K to 310 K; mechanical properties of epoxy foam from 77 K to 310 K; and thermal conductivity of corkboard from 77 K to 300 K.

The review should serve as an introduction to and comparison between cellular insulation, rather than as a source of specific data.

Important references:

1. Gerstin, H., Product Engineering, 59-68 (Jun 1965).
2. Miller, R. N., et al., Advances in Cryogenic Engineering 8, Edited by K. D. Timmerhaus, Plenum Press, Inc., New York, 417-24 (1963).
3. Campbell, M. D., Haskins, J. R., Hertz, J., Jones, H., and Percy, J. L., MRG-312, Contract No. AF 33(616)-7984 (Compilation of Materials Research Data (Apr 1962)).
4. Haskins, J. F. and Hertz, J., Advances in Cryogenic Engineering 8, Edited by K. D. Timmerhaus, Plenum Press, Inc., New York, 353-9 (1963).
5. Fabian, R. J., Mater. Design Eng. (Mar 1958).
6. Gray, V. H., Gelder, T. F., Cochran, R. P., and Goodykoontz, J. H., NASA TN D476, Washington, DC (1960).

Important references (continued):

7. Jacobs, R. B., Technology and Uses of Liquid Hydrogen, Edited by R. B. Scott, W. H. Denton, and C. M. Nicholls, Macmillan Co., New York, 106-48 (1964).

EXPANDED POLYSTYRENE MOULDING TECHNIQUES APPLIED TO A LIQUID NITROGEN DEWAR

Dickson, E. M., and Sheffield, T. B. (Warwick Univ., Coventry, England)

J. Sci. Instrum. 3, No. 6, 466-8 (Jun 1970)

A method is described in detail for fabricating various shaped vessels by expanding polystyrene in a mold. The technique requires the construction of a mold in which pre-expanded polystyrene beads are expanded to form the vessel. The authors provide sufficiently detailed instructions so that either leak-proof (liquid) or non-leakproof vessels can be fabricated.

The authors have applied these molding techniques to the fabrication of a rather large (615 mm long and 230 mm in diameter) vessel intended as the liquid nitrogen shield surrounding a conventional glass finger Dewar holding liquid helium.

Included in the paper are detailed suggestions concerning such things as the styrofoam density needed for minimum thermal conductivity, the age of the polystyrene beads, etc.

Important references:

1. Dillon, J. F., Geschwind, S., Jaccarino, V., and Machalett, A., Rev. Sci. Instrum. 30, 559-61 (1959).

THE DEVELOPMENT OF INSULATION SYSTEMS FOR LARGE CAPACITY DOUBLE WALLED METALLIC LNG STORAGE TANKS
Dodd, P., and Todd, G. (Whessoe, Ltd., Darlington, England)
Proc. Fourth International Conf. Liquefied Natural Gas (Algiers, Algeria, Jun 24-7, 1974), Inst. Gas Technology, Chicago, Ill., Session-VI-Paper-8 (1974) 27 pp

This paper presents the design basis and results of development work on the insulation for a 50000 m^3 capacity liquefied natural gas storage tank. The design used foamed glass as the base insulation under the tank. Foamed glass had been used successfully as base insulation for smaller tanks, but the base insulation carries the weight of the tank and its contents, and a larger tank imposes larger loads. An experimental program of strength testing on foamed glass was carried out.

Compressive strength of foamed glass is highly dependent on the capping material, used on and between blocks of foamed glass to distribute the load and prevent stress concentrations. Initial ambient temperature tests were made with some 40 capping materials, including paper and cardboard, rubber, roofing materials, and fabric-reinforced asphalt materials. Ultimate compressive strengths varied widely, over a range of nearly 14 to 1, between capping materials. The four best capping materials were asphalts, two not reinforced, one reinforced with paper, and one with hessian. These materials were used in further tests, for ambient temperature creep, large-scale ambient compressive strength with eight layers of 100-mm thick blocks, and compressive strength of four layers of the blocks when one face was cooled to 77 K. The hessian-reinforced material was the only capping material that allowed the foamed glass to pass all of the tests.

The base insulation under the periphery of the tank is loaded with the weight of the tank shell and part of the sidewall insulation. For this area, a low density aerated concrete was substituted for the foamed glass. This concrete had a density of 600 kg/m^3, and a thermal conductivity of 0.09 W/m•K at a mean temperature of 200 K. Both the concrete and the foamed glass had additional advantages of being non-combustible and chemically inert in LNG.

An outline for design of a 100000 m^3 tank also considers foamed glass for the base insulation, but the authors conclude that the strength limits of foamed glass have been utilized and that future efforts will be directed toward other systems.

Important references:

1. Furber, B. N. and Davidson, J., The Thermal Performance of Porous Insulants in a High Pressure Gas Environment, 2nd Conf. Prestressed Concrete Reactor and their Thermal Insulation (Brussels, Nov 18-20, 1969).

INVESTIGATION OF THE VAPOR PERMEABILITY OF THERMAL INSULATION MATERIALS
Dudnik, D. M.
Foreign Technology Div., Wright-Patterson AFB, Ohio, Transl. No. FTD-HT-23-541-68, Oct 1969. Transl. of Kholod. Tekh. Tekhnol. No. 4, 45-9 (1967)

Water vapor permeabilities of several foamed plastics and thermal insulation materials are reported in this Russian paper. The measurements were intended as an aid to the refrigeration industry. Of the materials tested by one method, 12 are various polyurethane foams and 11 are identified by code designations only. A variation of this method was used with two polyurethanes, two polystyrene foams, foam glass, mineral wool, a foamed urea-formaldehyde resin, and some 13 unidentified materials. The tests measured loss of water through a sample over a period of 5 to 7 months. Temperature was held constant at 293 - 303 K. Results are in terms of water vapor penetrating a 1 m^2 area of sample in 1 h, through a 1 m thickness, under a pressure of 1 N/m^2, reported by the author in units of g•m/N•h.

The author concludes that all of the foam plastics investigated, with the exception of the foamed urea-formaldehyde and an elastic polyurethane foam, are good vapor insulators. In general, from the tabulated results, all of the polyurethane foams have higher permeabilities than the other plastic foams.

COOL-DOWN OF FOAM INSULATED CRYOGENIC TRANSFER LINES

Durga Prasad, K. A., Srinivasan, K. and Krishna Murthy, M. V. (Indian Inst. of Tech., Madras. Refrigeration and Airconditioning Lab.)

Cryogenics 14, No. 11, 615-7 (Nov 1974)

An experimental program was carried out to test the validity of an analytical method of estimating cooldown of foam-insulated transfer lines. The experiments were conducted with liquid nitrogen flowing into a copper tube insulated with polystyrene foam. The commercial foam was bonded to the copper with glue and sealed with a film of bitumen as moisture barrier. Temperatures at various locations were monitored during cooldown and compared to analytical predictions. The experimental and analytical results agreed well enough to validate the analytical method.

The authors report a "crashing" noise in the insulation near the end of cooldown. They attribute the noise to cell destruction caused by the differential thermal contraction of the foam and the metal tube. The authors recommend leaving sufficient gap between insulation and tube to accommodate the differential thermal contraction, and prevent degradation of the foam insulation.

Important references:

1. Srinivasan, K., Seshagiri Rao, V. and Krishna Murthy, M. V., Paper S-5. ICEC5 (Kyoto, 1974).

2. Durgaprasad, K. A., M Tech Dissertation, Indian Institute of Technology, Madras (1974).

RIGID OPEN CELL POLYURETHANE FOAM AS A CRYOGENIC MULTI-LAYER INSULATION COMPONENT

Faddoul, J. R., and Lindquist, C. R. (National Aeronautics and Space Administration, Cleveland, Ohio, and Union Carbide Corp., Tonawanda, N.Y.)

Annual Technical Conf. of the Society of the Plastics Industry, 12th (Washington, D. C., Oct 16-18, 1967), Paper. National Aeronautics and Space Administration, Cleveland, Ohio, Lewis Research Center, Tech. Memo. No. NASA TM-X-52332, 32 pp (1967). J. Cellular Plastics 4, No. 3, 1-10 (Mar 1968)

This paper describes the application of a rigid open cell urethane foam in a self-evacuating multilayer insulation panel concept. The insulation consists of aluminized mylar radiation shields separated by sheets of the foam, with the multilayer structure sealed inside a gas-tight vacuum jacket filled with carbon dioxide. In use, the insulation evacuates itself when the carbon dioxide condenses at the cold side of the insulation.

The open cell foam was first selected for development because it showed greater compressive strength than closed cell foam, it was easier to evacuate, and it had a better surface quality than closed cell foam when sliced to the 0.5 mm thickness of the foam spacers in the multilayer insulation. The paper shows compressive strengths of bulk samples of both open and closed cell foams at RT. Pressure-deflection curves of both types of foam at RT and 77 K show a permanent set after the first compressive cycle, but no further set in subsequent cycles. Offgassing tests show that the open cell foam has a much lower offgassing rate than the closed cell foam. A preliminary large scale thermal test used panels with 6 radiation shields and 7 foam spacers, applied to a calorimeter tank in a shingled configuration to give a total of 18 radiation shields. After filling the tank with liquid hydrogen, the net equilibrium heat flux was 2.5 W/m^2, better than the initial goal of 3.2 W/m^2. Several configurations of foam spacers, with punched holes or crisscrossed strips of foam used to reduce contact area, were tested for thermal performance. A small reduction in heat flux was achieved, along with a secondary advantage of improved gas conductance which allows more rapid self-evacuation of the insulation.

The authors conclude that the open cell foam shows promise, with further development to improve spacer configuration and cryopumping performance, of achieving the overall program goal of a net heat flux of 0.9 W/m^2 into a liquid hydrogen tank.

Important references:

1. Little (Arthur D.) Inc., Rept. No. ADL-67180-00-04, and NASA Rept. No. NASA CR-54929 (Jun 1966).

LOW-TEMPERATURE THERMAL AND MECHANICAL PROPERTIES OF POLYSTYRENE AND POLYETHYLENE FOAMS

Foley, R. J., and Jelinek, F. J. (Lawrence Livermore Lab., California Univ., Livermore, and Battelle Columbus Labs., Ohio)

International Cryogenic Engineering Conf., Proc. 5th (Kyoto, Japan, May 7-10, 1974), K. Mendelssohn, Editor. IPC Science and Technology Press, Sussex, England, 439-42 (1974)

An experimental program was conducted to determine the low temperature properties of several polystyrene and polyethylene foams of varying densities. These foams were candidate materials to improve insulation systems for storage of cryogenic materials.

Polystyrene foams were fabricated at densities of 50 and 100 kg/m^3. Thermal contractions and thermal conductivities were measured from 4 K to 300 K, and ultimate tensile and compressive strengths were measured at 20 K, 77 K, and 300 K. Thermal contractions were independent of density. Thermal conductivities showed a density dependence, with the denser material results 40% higher at 300 K and 80% higher at 4 K than the results on the less dense material. Strengths showed a density and temperature dependence, with higher densities and lower temperatures leading to greater tensile and compressive strengths.

Polyethylene foam was chilled and compressed to a density of 220 kg/m^3. The compression at low temperature ruptured previously-closed cells, resulting in an open-cell structure. It also resulted in anisotropic behavior. Thermal contractions and thermal conductivities were measured from 4 K to 300 K, with orientations parallel and perpendicular to the direction of compression. Both thermal contraction and thermal conductivity were considerably higher in the parallel orientation.

FOAM INSULATION FOR TANKS AND VESSELS
Foster, C. S. (Upjohn Co., Torrance, Calif.)
Chem. Eng. Progr. 70, No. 8, 55-6 (Aug 1974)

This rather short article describes the applications and advantages of a spray type polyurethane foam insulation material for application to large tanks and the like. Prior forms of polyurethane were blocks or blankets which resulted in high installation costs (\$38 to \$48/m^2). The use of mechanized, revolving scaffolds permits fast application and results in installed costs of \$11 to \$16/m^2. Examples are given of the use of spray type polyurethane for heated tanks as well as ammonia tanks and LNG tanks.

Included with the article is a comparison of the K-factor (thermal conductivity per unit thickness) of polyurethane with styrene foam, glass fiber, cork, asbestos fiber and glass foam. Comparative K-factors are given at four temperatures: 116 K, 239 K, 311 K and 367 K. At all temperatures polyurethane was a more efficient thermal insulation than the other materials.

RECENT EXPERIMENTAL DATA CONCERNING THE THERMAL CONDUCTIVITY OF FIBERGLASS AND POLYSTYRENE FOAM INSULANTS AT LOW TEMPERATURE

Fournier, D., and Klarsfeld, S. (Centre de Recherches Industrielles, St-Gobain Ind., Rantigny, France)

Some Thermophysical Properties of Refrigerants and Insulants, Proc. International Inst. of Refrigeration Commission B1 (Zurich, Switzerland, Sep 27-9, 1973), Bull. Inst. Int. Froid, Annexe 1973-4, 183-8 (1973)

Thermal conductivity measurements were made on several insulation materials, including polystyrene foams of three densities. The foam densities were 18.2, 21.3, and 33 kg/m^3, and measurements covered mean temperatures from 130 K to 300 K. At temperatures below about 230 K, the thermal conductivities were practically the same for all three densities. Above 230 K, a density effect appeared, with the higher density material having a lower thermal conductivity.

Thermal conductivity curves for polyurethane foam and polyvinyl chloride foam, taken from a paper by R. P. Tye, are shown for comparison with the polystyrene foams. At cryogenic temperatures, the polystyrene had the lowest and the polyurethane had the highest thermal conductivity.

Important references:

1. Tye, R. P., Proc. XIII International Congress on Refrigeration 1 (Washington, D.C.), 371-378 (1971).

NONMONOTONICITY IN SENSITIVITY TEST DATA
Gayle, J. B. (National Aeronautics and Space Administration, Huntsville, Ala., George C. Marshall Space Flight Center)
Mater. Res. Stand. 6, No. 3, 147-8 (Mar 1966)

This paper reports an apparently anomalous response in liquid oxygen impact sensitivity tests on an insulation system. The insulation consists of a mylar-aluminum-mylar laminate adhesively bonded to a polyester foam. The results of the tests show a rapid rise in the frequency of visible or audible reactions with liquid oxygen as the impact energy is increased, to a peak at an impact energy of 2 kg•m. As the impact energy is increased further, the reaction frequency drops to a minimum at 7 to 8 kg•m, then increases slowly.

Such anomalous behavior had been reported previously, but was often attributed to experimental error. Sufficient tests were made on the insulation material to confirm the existence of the irregular response, and further tests on the constituents of the insulation showed that the behavior was a characteristic of the polyester foam. Tests on other foams were planned.

The mechanism of the anomalous behavior was not known, but the fact that such behavior exists in a foam material emphasizes the need for caution in interpreting and extrapolating test results.

EVALUATION OF CRYOGENIC INSULATION MATERIALS AND COMPOSITES FOR USE IN NUCLEAR RADIATION ENVIRONMENTS
General Dynamics/Fort Worth
General Dynamics/Fort Worth, Tex., Rept. National Aeronautics and Space Administration, Rept. No. NASA CR-2162, Contract No. NAS 8-18024, 179 pp (Dec 1972)

The radiation effects tests described in this report are part of a long-term evaluation of materials subjected to high levels of nuclear radiation at cryogenic temperatures. The materials tests reported here include several composite structures, liquid level sensors, fission couples, valve-seal materials, explosives, bifuels and thermal insulation. The thermal insulation tests were conducted on a 20.4 m^3 tank insulated with polyurethane foam and complete with vapor barrier. In effect, this was a test of the complete assembly. The reactor facility was not adequate to irradiate the insulated tank so that the various materials were irradiated separately and the tank assembly was thermally cycled. The tank was subjected to five fill, drain and warmup cycles, using liquid nitrogen. Temperature, boiloff and strain measurements were used to aid in the evaluation.

Test results revealed considerable wrinkling and puckering of the outer glass cloth covering of the foam during filling, however, there was no evidence, visually or from temperature data that the insulation was damaged or that its effectiveness was impaired. The measured boiloff rate was 0.08 m^3/hr and the effective thermal conductivity was 0.00795 W/m•K. Data from strain gages mounted internally on the tank wall indicated that strains were within expectations during the pressure cycles (to 0.186 MPa). Data from the gages mounted on the outer surface of the insulation tended to have large variability, generally going from large positive values to large negative values during the cycles. This is probably a reflection of the considerable movement that obviously occurred due to the lowering of the pressure and partial condensation of the freon gas in the foam. After completion of the tests, the outer coating retained slight creases at the locations of the deeper wrinkles. However, there was no visual indication of insulation separation from the tank or other deterioration.

Important references:

1. General Dynamics/Fort Worth, Tex. Rept. No. FZK-348 (Jun 1968).
2. General Dynamics/Convair, Fort Worth, Tex. Rept. No. FZK-378 (Jun 1971).

FOAMGLAS INSULATION SYSTEMS FOR LOAD-BEARING APPLICATIONS IN THE STORAGE OF CRYOGENIC LIQUIDS

Gerrish, R. W. (Pittsburgh Corning Corp., Pittsburgh, Pa.)

Cryogenic Engineering Conference and International Cryogenic Materials Conference, Joint Meeting (Queens Univ., Kingston, Ontario, Canada, Jul 22-5, 1975) 10 pp

Blocks of foamed glass have been used as load-bearing thermal insulation in the base of cryogenic storage tanks for liquid natural gas, oxygen, nitrogen, and ethylene. Base insulations use capping or interleaving materials, such as asphalt, felts with asphalt, or asbestos paper, between layers of blocks to reduce stress concentrations. Some concern was expressed that differential thermal contraction could cause shear stresses at the interfaces, and reduce the compressive strength of the base insulation at low operating temperatures. This paper presents information on strength characteristics of foamed glass blocks at ambient and cryogenic temperatures, with standard and experimental capping or interleaving materials.

The foamed glass had a density of about 136 kg/m^3. The capping materials tested were a hot-melt asphalt, a hessian-reinforced asphalt, an asphalt-saturated roofing felt, asbestos paper, and a vermiculite aggregate. Compressive strengths were measured on a single layer with hot asphalt capping at ambient temperature as control, on a single layer with the test capping material at ambient temperature, on a two-layer stack at ambient temperature, and on a two-layer stack with one face at 77 K and the other face at ambient temperature. Compressive strengths were "yield" strengths for initial failure of some of the cells. Generally, ultimate compressive strengths were considerably higher.

The asphalt capping materials produced compressive strengths nearly twice as high as those with the felts and asbestos paper, apparently because the asphalts filled the top layer of cells and distributed the load better. Compressive strength with the asphalts dropped off slightly at cryogenic temperatures, as an effect of differential thermal contractions. With the vermiculite experimental capping, the average compressive strength was higher at cryogenic temperatures, showing that decreasing temperature increases the strength of the glass itself.

Important references:

1. Reyntjens, G. P., Univ. of Leuven Report, PV: R/I 3287/73, Leuven, Belgium (1973).

THERMAL INSULATION SYSTEMS, A SURVEY
Glaser, P. E., Black, I. A., Lindstrom, R. S., Ruccia, F. E., and Wechsler, A. E.
Little (Arthur D.), Inc., Cambridge, Mass., Rept. National Aeronautics and Space Administration, Washington, D. C., Office of Technology Utilization, Rept. No. NASA SP-5027, 154 pp (1967)

This review of thermal insulation includes a chapter on cryogenic insulation systems, which contains a section on foam insulation. After a discussion of the types, materials, and some advantages and disadvantages of foam insulation, some problems in application of foams to cryogenic tanks are described. Polyurethane foams on metal tanks cracked because of differential thermal expansion, until the problem was solved by using glass fibers as reinforcement. Cryopumping of air and oxygen enrichment of the condensed liquid presented the possibility of fire and explosion hazards. Extensive tests showed that catastrophic failure is possible but improbable with well-designed foam insulation. The specific foam insulation systems used with the Centaur and Saturn S-1C are described briefly.

The properties of foams are described with the aid of data taken from a paper by Miller, et al. (see abstract on page 73) These data include tensile and shear strengths of urethane, epoxy, polyurethane and polyether foams from 20 K to 394 K; load-compression strengths of the same foams at 20 K; and linear thermal expansions of six urethane and epoxy foams from 77 K to 300 K. Other data on thermal conductivity and on effects of radiation combined with cryogenic temperatures are in references mentioned in the review.

Another section of the same chapter, on composite insulations, describes the use of foams in honeycomb-foam insulations, such as the Saturn S-II insulation system, and in constrictive-wrap external insulation, such as a system designed for the Centaur. Exterior surface bonded foam insulation and an internally insulated fiberglass cryogenic storage tank using foam insulation are also described.

Important references:

1. Haskins, J. F., and Hertz, J., Advances in Cryogenic Engineering 7, 353-9 (1962).

2. Black, I. A., et al, NASA Rept. No. NASA CR-54191 (1964).

3. Heidelberg, L. J., NASA Tech. Note No. NASA TN-D-3068 (1965).

4. Key, C. F., and Gayle, J. B., NASA Tech. Memo. No. NASA TM-X-53144 (1964).

5. North American Aviation, Inc., Rept. NO. SID-63-600-2, NASA Contract No. NAS 7-200 (Jul 1964).

Important references (continued):

6. Islamoff, I., NASA-Marshall Flight Center, Huntsville, Ala., Rept. (1965).

7. NASA Rept. No. NASA CR-62110 (1964).

8. Isenberg, L., National SAMPE Symp. on Materials for Space Vehicle Use, 6th. Society of Aerospace Materials and Process Engineers (Nov 1962).

9. Kerlin, E. E., and Smith, E. T., NASA Rept. No. NASA CR-51140 (1962).

10. Lockheed Missiles and Space Co., Palo Alto, Calif., Rept. NASA Contract No. NAS 8-9500 (Oct 1964).

11. NASA Tech. Note No. NASA TN-D-2685 (1965).

EVALUATION OF URETHANE FOAM PANELS
Glemser, N. N.
General Dynamics/Astronautics, San Diego, Calif., Rept. No. GDA-AN62AMR4087 (Apr 1962) 15 pp

Rigid polyurethane foams, bonded to tanks as cryogenic external insulation, showed a tendency to grow or change dimension over a period of time. The growth caused cracking in the foam and failures in bonds to the tank, and loss of insulation effectiveness when atmospheric moisture and air could reach the metal tank surface. A test program was conducted to measure dimensional changes in foam samples subjected to various treatments.

Twelve freon-blown polyurethane foams were each treated to six test conditions, trimmed to standard size panels, and carefully measured in all three dimensions. The size measurements were repeated after storage at ambient conditions, every week for five to eight weeks. The test conditions included unstabilized foam, stabilized foam, stabilized foam formed at about 355 K, stabilized foam formed at about 380 K, stabilized foam vacuum-formed at about 380 K, and stabilized foam vacuum-formed at about 380 K and coated. All of the foams were dimensionally unstable and showed erratic but progressive growth with storage time. The growth was accelerated by heat and humidity. The foams with the lowest average growth rates were also least affected by the forming cycles. The author notes that polyurethane foams subjected to 100% humidity at 350 K can grow as much as 12% in 4 h.

The author recommends using foams with the highest heat distortion point and the lowest permeability and moisture absorption rate for best stability, coating or sealing cut surfaces of foam to retard moisture absorption, and investigating foams other than polyurethanes for use as insulation.

BONDED AND SEALED EXTERNAL INSULATIONS FOR LIQUID-HYDROGEN-FUELED ROCKET TANKS DURING ATMOSPHERIC FLIGHT
Gray, V. H., Gelder, T. F., Cochran, R. P., and Goodykoontz, J. H.
National Aeronautics and Space Administration, Cleveland, Ohio, Lewis Research Center, Tech. Note No. NASA TN-D-476, 51 pp (Oct 1960)

Several nonmetallic insulation materials capable of being bonded onto liquid-hydrogen tanks and sealed against air penetration into the insulation, were investigated for use on rockets and spacecraft. Emphasis was placed on the problems of insulating high-acceleration rocket vehicles which attain high velocities while in the atmosphere. Requirements for this application include resistance to aerodynamic loads and heat fluxes, and unreinforced plastic foams were excluded from the investigation because of their lack of strength at high velocity and temperature. However, one of the tested insulation systems used polyurethane foam as filler material in the cells of a phenolic honeycomb sandwich.

The insulation materials considered were two composition corkboards, foamed corkboard, balsa wood, a phenolic-glass cloth laminate, a waterglass laminate, an epoxy mastic with glass spheres and fibers, and phenolic honeycomb core with air, potassium titanate-epoxy mastic, dry potassium titanate, and two commercial low-density fillers, as well as the polyurethane foam filler. Several facing materials, seal materials, and bonding materials were also evaluated. Experimental data were taken on thermal conductivity, sealability, strength and high-temperature resistance. The overall temperature range was from 20 K to 730 K.

Thermal conductivity of the foam-filled honeycomb was greater than that of the foamed corkboard, balsa wood, composition corkboards, and the honeycomb filled with the lighter of the two commercial fillers, over the temperature range from 90 K to 200 K. The importance of sealing against air was shown, by measurements of boiloff from an insulated liquid-hydrogen container. The seal over the foam-filled honeycomb insulation developed leaks in an early test, and subsequent tests showed thermal conductivities rising to 230% of the original value as air condensed in the insulation. At high temperatures, composition corkboard failed gradually by charring between 600 K and 730 K, phenolic honeycomb failed at 600 K, but the polyurethane foam in the cells melted away at lower temperatures.

For the intended purpose, the composition corkboards were the best insulation. The balsa wood and foam-filled honeycomb might be suitable except for marginal strengths at the temperature extremes. Filling the cells of the honeycomb with low-density fillers, including polyurethane foam, was considered worthwhile, because the increase in weight was more than offset by the reduction in thermal conductivity.

Important references:

1. National Bureau of Standards Rept. No. 5A229 (Feb 1956).

2. Eppinger, C. E., and Love, W. J., Advances In Cryogenic Engineering 4, 123-31 (1959).

3. Wilkes, G. B., Refrig. Eng. 52, No. 1, 37-42 (Jul 1946).

4. Rowley, F. B., Jordan, R. C., and Lander, R. M., Refrig. Eng. 50, No. 6, 541-4 (Dec 1945).

AN ANALYTICAL MODEL FOR DETERMINING THE THERMAL CONDUCTIVITY OF CLOSED-CELL FOAM INSULATION

Hammond, M. B., Jr. (North American Rockwell, Downey, Calif. Space Div.)

Advances in Cryogenic Engineering 15, Proc. Cryogenic Engineering Conf. (California Univ., Los Angeles, Jun 16-18, 1969), K. D. Timmerhaus, Editor. Plenum Press, New York, 332-42 (1970)

An analytical model of a closed-cell polyurethane foam insulation is presented in this paper. The insulation was developed for spray-on application to the liquid hydrogen tanks of the Saturn V second stage (S-II). The model assumes parallel heat-flow contributions from solid conduction in the resin of the cell walls, gas conduction within the cells, and radiation from cell to cell. The cells are originally full of fluorotrichloromethane blowing agent, but air rapidly diffuses through the cell walls. The analytical model predicts the mole fraction of air in the cells.

In the insulation nearest the liquid hydrogen tank, in the cells below 50 K, the air is condensed and the dominant heat-flow is by solid conduction. Between 50 K and 250 K, gaseous air in the cells is dominant, while above 250 K the presence of freon mixed with the air reduces the conductivity. At higher temperatures, radiation becomes significant.

This model was one of several described in the paper abstracted on page 32.

Important references:

1. Hammond, M. B., Advances in Cryogenic Engineering 14 (1969).

2. Tye, R. P., Dynatech Report No. 798 (Ref. NASA-23) (22 Jul 1968).

ANALYTICAL MODELS FOR AIRBORNE-CRYOGENIC-INSULATION THERMAL PERFORMANCE
Hammond, M. B., Jr. (North American Rockwell Corp., Downey, Calif. Space Div.)
Advances in Cryogenic Engineering 14, Proc. Cryogenic Engineering Conf. (Cleveland, Ohio, Aug 19-21, 1968), K. D. Timmerhaus, Editor. Plenum Press, New York, 205-12 (1969)

In the process of designing thermal insulation systems for liquid hydrogen tanks of spacecraft, one requirement is to determine the thermal conductivity of the system and to establish the influences that might change the thermal conductivity in service. This paper summarizes three insulation designs, presents analytical predictions of thermal performance, and correlates the predictions with test results. Two of the three insulation designs involve foam insulation: a helium-purged foam-filled honeycomb external insulation, and a closed-cell foam external insulation.

The helium-purged foam-filled honeycomb used polyurethane foam pressed into a glass-phenolic honeycomb core, bonded to the outside of the liquid hydrogen tank wall and sealed with a vapor barrier film. The insulation was pressurized with helium to prevent air from penetrating into the insulation. The analysis showed that the helium purge gas was the predominant contributor to thermal conductivity of this system, which was the basic insulation designed for the Saturn-V second stage.

The helium-purged insulation was later replaced on the Saturn-V second stage with a closed-cell polyurethane foam sprayed on the tank. Analysis of this insulation showed that diffusion of air into the cells had great influence on the thermal conductivity. At temperatures below 255 K, the freon blowing agent was condensed and air in the cells was the primary contributor to heat conduction. At higher temperatures, the presence of freon mixed with the air tended to reduce gas conduction. This mechanism explains the S-shaped character of the thermal conductivity versus temperature curve of closed cell polyurethane foam.

Important references:

1. Hammond, M. B., Chem. Eng. Progr. Symp. Ser. 62, No. 61, 213 (1966).
2. Key, C. F. and Gayle, J. B., NASA TM S-43144 (1964).
3. Glaser, P. E., Black, I. A., Lindstrom, R. S., Ruccia, F. E. and Wechsler, A. E., NASA SP-5027, NASA Office of Technological Utilization, Washington, D.C. (1967).
4. Liquid-Hydrogen Tank Insulation Test Report, Space Div. of North American Rockwell Corp., SID 64-1157 (Jun 1964).
5. Hammond, M. B., Paper 68-766, AIAA Thermophysics Specialists Meeting (Jun 1968).

THERMAL CONDUCTIVITY OF PLASTIC FOAMS FROM -423 DEGREES TO 75 DEGREES F
Haskins, J. F., and Hertz, J. (General Dynamics/Astronautics, San Diego, Calif.)
Advances in Cryogenic Engineering 7, Proc. Cryogenic Engineering Conf. (Michigan Univ., Ann Arbor, Aug 15-17, 1961), K. D. Timmerhaus, Editor. Plenum Press, New York, 353-9 (1962)

This paper presents a method of measuring thermal conductivities of plastic foams from 20 K to room temperature, and gives results of measurements on polystyrene foam, polyurethane foam, a polyurethane foam-filled honeycomb composite, and a composite of polytetrafluoroethylene sheet and foam. A total of 13 foam materials was tested.

Of the two polystyrene foams tested, the fire-retardant material was the poorer insulator. Among the several polyurethane foams tested, thermal conductivities were about the same at 90 K and below, while the carbon dioxide-blown (high-temperature resistant) foams had thermal conductivities 50% higher than those of the freon-blown foams at 285 K. The foam-filled honeycomb was similar to the carbon dioxide-blown foam. Two fire-retardant polyurethane foams had nearly identical thermal conductivities at 90 K, but thermal conductivity of the molded formulation was 25% higher than that of the spray formulation at 285 K, with this result attributed to the finer cell structure usually obtained with spray foams.

The authors conclude that base resin and blowing agent have more effect on thermal conductivity at RT than at 90 K and below. At cryogenic temperatures, gases within the cells are condensed, and cell size and uniformity is the major factor contributing to good insulation properties.

Important references:

1. Stoecker, L. R., Advances in Cryogenic Engineering 5, 273 (1960).

2. Gray, V. H., and Gelder, T. F., Advances in Cryogenic Engineering 5, 131 (1960).

3. Waite, H. J., Advances in Cryogenic Engineering 5, 230 (1960).

CELLULAR PLASTICS FOR CRYOGENIC INSULATION
Hayes, R. G. (Upjohn Co., Torrance, Calif. CPR Div.)
Cryogen. Technol. 8, No. 4, 127-8 (Jul-Aug 1972)

This paper describes the application of polyurethane foam insulation to the piping of a major liquefied natural gas project. The Brunei project produces LNG for transport by ship to Japan. The project involves nearly 10 km of stainless steel pipe, factory preinsulated with a fire-retardant fluorocarbon-blown rigid polyurethane spray foam. Foam insulation was chosen rather than vacuum jacketing because of its ease of maintenance in the field.

The foam was applied in the factory to a length of pipe rotating at a controlled speed, from the spray equipment moving along the pipe length at a controlled speed. A 5-cm thickness of foam was applied and wrapped with glass fiber reinforced tape, a second 5-cm layer was applied and reinforced similarly, then a third foam layer was applied and wrapped with a glass reinforced epoxy vapor barrier 3 mm thick.

Polyurethane foam is seen by the author to be a potential insulation of choice for other LNG projects, including piping and LNG tankers, because of its insulating efficiency and its ease of maintenance in remote locations.

DEVELOPMENT OF URETHANE FOAMS FOR LNG INSULATION
Hayes, R. G. (Upjohn Co., Torrance, Calif. CPR Div.)
Advances in Cryogenic Engineering 20 (Presented at National Technical Meetings during 1973 and 1974), K. D. Timmerhaus, Editor. Plenum Press, New York, 338-42 (1975)

The purpose of the testing program was to find a polyurethane foam suitable for use as insulation for liquefied natural gas storage or transport containers. Eight polyurethane foam formulations were screened by measuring volume change and absorption after immersion in LNG. The four formulations least affected were used to make samples for mechanical strength testing at 296 K and 111 K. The two best formulations were selected for full-scale testing. Immersion in LNG for 1000 h caused no apparent loss in physical properties. Thermal conductivities were measured between surfaces at 111 K and ambient temperature, and thermal expansions between 77 K and 296 K were determined. In a test simulating service conditions as external insulation, the foams were attached to aluminum plate and cycled between 77 K and 289 K. One formulation warped, but the other remained nearly unchanged through 20 cycles.

The author concludes that the one best formulation of polyurethane foam will be a useful insulation for cryogenic systems down to 77 K, and is completely compatible with LNG.

EVALUATION OF A SUBSCALE INTERNALLY INSULATED FIBER-GLASS PROPELLANT TANK FOR LIQUID HYDROGEN

Heidelberg, L. J.

National Aeronautics and Space Administration, Cleveland, Ohio, Lewis Research Center, Tech. Note No. NASA TN-D-3068, 31 pp (Oct 1965)

The use of glass fiber reinforced plastics as structural materials for liquid hydrogen propellant tanks was investigated. The research program had the objective of designing, fabricating, and evaluating the thermal and structural performance of a subscale tank. The tank consisted of a structural shell of filament-wound fiber-glass, an internal insulation system of polyurethane foam enclosed in an aluminum-mylar-aluminum laminate vacuum jacket, and an impermeable liner of the same laminate. Thermal performance was evaluated by liquid hydrogen boiloff tests, and structural performance by pressure-cycling tests with liquid hydrogen in the tank.

Initial leak tests showed that the aluminum-mylar-aluminum laminate with adhesive-bonded seams produced leakproof vacuum jackets and liner. Thermal shocks with liquid nitrogen and liquid hydrogen did not cause leaks. The insulation performed satisfactorily. A large heat leak occurred where the laminated vacuum jackets were bonded together and provided an aluminum heat path through the insulation. Pressure cycling caused a liner failure at a pressure below the design goal. It was felt that changes in construction, to allow the liner to expand more, would bring the failure pressure closer to the ultimate strength of the filament-wound tank structure.

Important references:

1. Hanson, M. P., Richards, H. T., and Hickel, R. O., NASA Tech. Note No. NASA TN-D-2741 (1965).

2. Shriver, C. B., NASA Rept. No. NASA CR-127 (1964).

THE EFFECT OF HEAT FORMING ON THE THERMAL CONDUCTIVITY OF POLYURETHANE FOAMS
Hertz, J., and Haskins, J.
General Dynamics/Astronautics, San Diego, Calif., Quarterly Progress Rept. No. MRG-303, Contract No. AF33 616 7984, 8 pp (May 1963)

The insulation for the Centaur forward bulkhead was manufactured by heat-forming of polyurethane foam panels. This heat-forming process in vacuum at 372 K had the potential of removing the freon 11 blowing agent from the foam cells, and allowing air to replace it. This would result in an increased thermal conductivity and would introduce a source of error in determining heat transfer across the forward bulkhead. A test program was conducted to evaluate these possibilities.

Three polyurethane foams were supplied for test in the form of panels. The thermal conductivities were measured between 91 K and 296 K, the panels were subjected to the heat-forming process, and thermal conductivities were measured again. Thermal conductivities after heat-forming were 8% lower, 5% lower, and 5% higher than those before heat-forming for the three foams. Since experimental error could amount to 6%, and the expected changes were toward increases of thermal conductivity, it was concluded that the heat-forming caused no significant changes.

GETTING THE MOST FROM RIGID POLYURETHANE FOAMS
Hilado, C. J. (Union Carbide Chemical Co., South Charleston, W. Va.)
Chem. Eng. 74, No. 20, 190+192+194+196 (Sep 1967)

This article is a brief but thorough review of the application of rigid polyurethane foams as insulation over the entire temperature range from 5 K to 560 K. Graphs of generalized properties show thermal conductivity, tensile, compressive, flexural, and shear strength and modulus, and water vapor permeability, as functions of density at 297 K. Other graphs show generalized thermal conductivity and tensile and compressive strength as functions of temperature for isotropic closed-cell foams of 32 kg/m^3 density.

The total temperature range of application is divided into several parts. Below about 89 K, the thermal conductivity is very low, and the major problem is air condensation and liquid oxygen accumulation, with some danger of detonation on impact. Between 89 K and 211 K, the thermal conductivity is that of an air-filled foam, and moisture accumulation is the major problem. Between 211 K and 395 K, polyurethane foam is more effective than most other insulations, but suffers from dimensional changes and increased conductivity caused by air and water permeation. Low strength and thermal degradation are the major problems at temperatures above 395 K.

The review cites 23 references as sources of more detailed information.

Important references:

1. Hilado, C. J., J. Cell. Plast. 3, No. 4, 161-7 (Apr 1967).
2. Key, C. F., and Riehl, W. A., Repts No. MTP-P and VE-M-63-14 (Dec 1963).
3. Key, C. F., NASA Tech. Memo. No. NASA TM-X-53052 (May 1964).
4. Levy, M. M., J. Cell. Plast. 2 (Jan 1966).

A METHOD FOR DETERMINING THE EFFECTIVENESS OF THERMAL INSULATION SYSTEMS AT LOW TEMPERATURES

Hilado, C. J. (Union Carbide Corp., South Charleston, W. Va.)

J. Cell. Plast. 5, No. 2, 110-1 (Mar-Apr 1968)

A method of comparing piping thermal insulation systems is presented. The method is specifically designed to compare complete systems in an operational configuration rather than comparisons based on the thermal conductivity of the insulation alone. The configuration uses a one meter length of aluminum tube 7.6 cm in diameter, and closed at both ends. The insulation systems are installed complete with adhesive and vapor barrier. A test consisted of filling the tube, sealing the fill end and measuring, continuously, the weight loss from vaporization. This allowed the calculation of average heat transfer rates over a three hour period.

The paper presents results of a comparison of 2.5 cm thickness of cellular urethane and 10.1 and 15.2 cm thicknesses of cellular glass using both liquid nitrogen and solid carbon dioxide. In all cases the urethane performed much better than the cellular glass.

The heat transfer rates per unit length of pipe differed significantly from the values predicted on the basis of available thermal conductivity data for the insulation material. The actual values were lower than predicted for cellular polyurethane, and higher for cellular glass.

The total time required for a test is 1.5 hour which makes this a quick way to arrive at system comparisons.

Important references:

1. American Society for Testing and Materials, ASTM Std. 14, 172-9 (Nov 1967).

2. Haskins, J. F., ASTM Spec. Tech. Publ. No. 411, 3-12 (Feb 1966).

3. Karp, G. S., and Lankton, C. S., ASTM Spec. Tech. Publ. No. 411, 13-24 (Feb 1966).

4. Black, I. A., Wechsler, A. E., Glaser, P. E., and Fountain, J. A., ASTM Spec. Tech. Publ. No. 411, 74-94 (Feb 1966).

5. Black, I. A., Glaser, P. E., and Perkins, P., ASTM Spec. Tech. Publ. No. 411, 52-60 (Feb 1966).

6. Hollingsworth, M., ASTM Spec. Tech. Publ. No. 411, 43-51 (Feb 1966).

Important references (continued):

7. Kinzer, G. R., and Pelanne, C. M., ASTM Spec. Tech. Publ. No. 411, 110-8 (Feb 1966).

8. Gibbon, N. C., Matsch, L. C., and Wang, D. I. J., ASTM Spec. Tech. Publ. No. 411, 61-73 (Feb 1966).

A THERMAL PROTECTION SYSTEM FOR LIQUID HYDROGEN FUEL TANKAGE IN HYPERSONIC VEHICLES
Johnson, C. L. (Lockheed-California Co., Burbank)
AIAA Thermophysics Specialist Conf. (New Orleans, La., Apr 17-20, 1967), Paper No. AIAA-67-297 (1967)

A composite insulation system for the liquid hydrogen tanks of a hypersonic vehicle was designed and tested. In the design concept, the liquid hydrogen tank was the primary vehicle structure. A polyurethane foam was sprayed onto the outside of the tank and sealed with a glass cloth reinforced epoxy layer. Layers of silica fiber batting were wrapped over the foam and held in place with a stainless steel screen. Thin-walled inconel 718 tubing standoff posts were attached to the tank wall, and extended through the insulation to support inconel 718 heat shield shingles. The polyurethane foam provided cryogenic insulation, while the silica fiber insulation kept the high temperatures generated by aerodynamic heating from reaching the surface of the foam.

The insulation was applied to a calorimeter, and tested with liquid nitrogen or liquid hydrogen in the calorimeter and heat lamps at the outer surface. Heat flux values were satisfactory in the liquid nitrogen tests, but doubled with liquid hydrogen in the calorimeter. Calculations showed that the difference could be attributed to a relatively small amount of air condensing on the tank surface. Disassembly of the insulation revealed extensive thermal stress cracking of the polyurethane foam and its vapor barrier, which allowed air penetration and condensation.

Modifications to improve the insulation system included changing from spray-on foam to panels of the glass fiber reinforced polyurethane foam developed for the Saturn S-IV stage. The reinforcement was to strengthen the foam while application in panels left space for thermal stress relief. The vapor barrier was changed to a more flexible polyester cloth reinforced epoxy layer. The report states that the initial results demonstrated the practicability of the insulation system, and that the modifications should produce a system with acceptably low thermal conductivity.

INSULATION SYSTEMS FOR CRYOGENIC STAGES
Jonke, R. J.
Rev. Sci. Tech. CECLES/CERS 3, No. 1, 17-48 (1971)

This paper is a review of experimental work on thermal insulation systems for cryogenic propellant tanks, summarizing those systems which were candidates for the ELDO Europa III upper stage but were not finally selected for use. The systems covered are polyphenylene oxide (PPO) foam (described here as "polypropylene oxide foam"), polyvinyl chloride (PVC) foam, polyurethane foam, and polymethacrylimide foam. Another PVC foam was selected for the application, and is described elsewhere (see the paper abstracted on page 74).

The PPO foam is an anisotropic open-cell foam, with the cells oriented in a single direction. It was proposed as an external insulation, with the cells closed at one end by bonding to the tank wall, and at the other by a vapor barrier film and a protective glass cloth reinforced epoxy coating. Linear thermal expansion of the foam, both parallel and perpendicular to fiber orientation, is shown from 20 K to 300 K; tensile properties in both orientations are shown from 20 K to 400 K. Thermal conductivity is given as 0.024 W/m·K at a mean temperature of 166 K, and 0.009 W/m·K at 138 K. The foam was applied to a test tank, and during cooldown with liquid nitrogen, the vapor barrier delaminated from the foam. A prestressed constrictive wrap solved the problem, but a better bond might make prestressing unnecessary.

The polyurethane and PVC foams were studied in another program. Data are shown on thermal conductivities of the foams at temperatures from 20 K to 320 K. For the same density, the polyurethane shows slightly lower thermal conductivity than the PVC. The typical S-shaped curves of freon-blown foams are evident in the data. Thermal contractions, tensile strengths, and ultimate elongations of the foams are compared from 20 K or lower to 300 K or higher. A polyurethane foam reinforced with glass fibers was included in the comparisons. Small scale tests on tanks with liquid hydrogen also provided data. It was concluded that thermal performance of the foams was approximately equal, but higher elasticity at low temperature made the polyurethane a better choice than the PVC, and the fiber-reinforced polyurethane better than the plain foam.

In another program, a polymethacrylimide foam was evaluated, and thermoforming was investigated as a means of shaping this foam along with polyurethane and PVC foams. The polymethacrylimide required closely controlled high temperature for thermoforming, and was highly permeable to gas, making it unsuitable for insulation. Thermoforming was highly successful with PVC, while polyurethane foam tended to crack.

THERMAL INSULATION IN CRYOGENIC ENGINEERING
Kaganer, M. G.
Israel Program for Scientific Translations, Jerusalem, 1969. Transl. of Teplovaya Izolyatsiya v Tekhnike Nizkikh Temperatur, Izdatelstvo Mashinostroenie, Moscow, 226 pp (1966)

This Russian book on thermal insulation only briefly considers foam insulation. Evacuated powder, evacuated fiber, high-vacuum, and evacuated multilayer insulations receive much greater coverage.

The cellular materials considered are cork, expanded ebonite, a urea-formaldehyde foam, polystyrene foam, polyurethane foam, and foam glass. The properties of these materials are presented as general graphs or tabulations of thermal conductivity, specific heat, linear thermal expansion, and moisture permeability, in a general temperature range from 175 K to 300 or 325 K. The data are taken from the literature, and the literature should provide better sources of information on these properties.

Important references:

1. Dudnik, D. M., and Meltser, L. Z., Trudy OTIPKhP, 10, 75-86, Odessa (1961).
2. Cammerer, W. F., Kaeltetechnik 12, No. 4, 107-10 (1960).
3. Cooper, A., International Congress of Refrigeration, Proc. X, 1, 251-60 (1961).
4. Haskins, J. F., and Hertz, J., Advances in Cryogenic Engineering 7, 353-9 (1962).
5. Battle, B., and Laine, P., Suppl. Bull. Inst. Intern. du Froid, No. 4, 267-73, Annexe (1958).
6. Miller, R. N., Bailey, C. D., Beall, R. T., and Freeman, S. M., Advances in Cryogenic Engineering 8, 417-24 (1963).
7. Vahl, L., International Congress of Refrigeration, Proc. X, 1, 267-73 (1961).

MEASURED EFFECTS OF THE VARIOUS COMBINATIONS OF NUCLEAR RADIATION, VACUUM AND CRYOTEMPERATURES ON ENGINEERING MATERIALS
Kerlin, E. E., and Smith, E. T.
General Dynamics/Fort Worth, Tex., Nuclear Aerospace Research Facility,
Rept. No. FZK-290. National Aeronautics and Space Administration, Rept. No. NASA CR-77772, Contract No. NAS 8-2450, 520 pp (Jul 1966)

This report summarizes the work done during the last two years of a five year contract with NASA to measure the effects (singly and in combination) of nuclear radiation, vacuum and cryogenic temperatures on structural adhesives, structural laminates, potting compounds, electrical insulation, thermal insulation, dielectrics, thermal control coatings, seals, sealants and lubricants. The testing was done for the purpose of establishing guidelines in the selection of materials for the Space Nuclear Propulsion System (NERVA). Tests were conducted in air at ambient temperature, in liquid nitrogen, at 77 K and in liquid hydrogen at 20 K. The tests included mechanical and tensile properties (measured at test temperature and in test environment), lubricating properties, electrical properties and thermal conductivity for the foam insulation.

The foam thermal insulations tested are: polyurethane (polyether-polyester rigid foam), polyurethane (carbon dioxide blown rigid foam), urethane (polyester flexible foam), epoxy (rigid, spray foamed), polyurethane (polyether, rigid, halocarbon blown) and polystyrene. Measurements were made in the radiation environment in vacuum and air at ambient temperature and in liquid nitrogen and liquid hydrogen. The results indicate that radiation levels to 5 x 10^6 J/kg had no or insignificant effects on the thermal conductivity of all specimens tested. With regard to the compression test, not all of the foam materials have data reported because experimental difficulties resulted in a small number of reliable results. Because of these factors, the data presented are considered to be of marginal reliability. The authors did conclude, however, that for most foams the exposure to both vacuum and radiation reduced significantly the compressive strength.

Important references:

1. Kerlin, E. E., General Dynamics/Fort Worth, Tex. Rept. No. FZK-161-1 (Jan 1963).

2. Kerlin, E. E., and Smith, E. T., General Dynamics/Fort Worth, Tex. Rept. No. FZK-188-2 (May 1964).

COMPATIBILITY OF MATERIALS WITH LIQUID OXYGEN, III.

Key, C. F.

National Aeronautics and Space Administration, Huntsville, Ala., George C. Marshall Space Flight Center, Tech. Memo. No. TM-X-53533, 54 pp (Nov 1966)

This report summarizes in tabular form the results of the compatibility testing of a large number of materials with liquid oxygen. The classes of materials included are lubricants, sealants and threading compounds, thermal and electrical insulation, plastics, elastomers, adhesives, gaskets and packings, metals and alloys, solders, chemicals, solvents, paints and leak check compounds. The tests were conducted with the Army Ballistic Missile Agency (ABMA), LOX impact tester used according to MSFC-SPEC-106B. Two ratings are given, one for the individual sample or lot evaluated and the other for the material in general. The ratings are Satisfactory (S), Satisfactory, if each jar of sample is individually tested and found acceptable (J), Satisfactory if each batch is tested and found acceptable (BT), Insufficient test experience to rate sample adequately (I) and Unsatisfactory (U).

The foam insulation tested and the results are: H-Foam (batch rating - S, material rating - I), RL Foam (batch and material rating - (U), Styrofoam (batch and material rating - U). As would be expected foam insulations are not particularly compatible with liquid oxygen. No results are given for polyurethane foam.

Important references:

1. Lucas, W. R., and Riehl, W. A., ASTM Bulletin No. 244, 29-34 (Feb 1960).

2. Key, C. F., and Riehl, W. A., NASA Tech Memo. No. NASA TM-X-985 (Aug 1964).

3. Key, C. F., NASA Tech Memo. No. NASA TM-X-53052 (May 1964).

EFFECT OF LIQUID NITROGEN DILUTION ON LOX IMPACT SENSITIVITY

Key, C. F., and Gayle, J. B. (National Aeronautics and Space Administration, Huntsville, Ala., George C. Marshall Space Flight Center)

J. Spacecraft Rockets 3, No. 2, 274-6 (Feb 1966)

This paper summarizes an experimental investigation on the impact sensitivities of a number of materials in liquid nitrogen-oxygen mixtures. Earlier work had shown that organic materials were impact-sensitive in liquid oxygen, and that there was a chance of a catastrophic reaction if damaged insulation on a liquid hydrogen tank was impacted during ground hold, because air could condense in the insulation and become enriched in oxygen by fractionation processes. The liquid nitrogen-oxygen mixtures in this work represented liquid air and oxygen-enriched liquid air, ranging from 20% to 100% oxygen.

The materials tested included a polyurethane foam insulation, an epoxy foam, a foam of 132 kg/m^3 density identified by its commercial designation, and a foam-filled phenolic honeycomb. All of the foams were completely insensitive in 50% oxygen mixtures at impact energies up to 10 kg-m. Threshold impact energies dropped to 1 to 2 kg-m in 100% liquid oxygen. The foam-filled honeycomb was insensitive in 20% oxygen mixture (liquid air) up to 10 kg-m, but the threshold impact energy was only 3 kg-m in 30% oxygen mixture, and less than 1 kg-m in 100% liquid oxygen. While none of the materials reacted in liquid air, and the foams remained insensitive with considerable oxygen enrichment, the foam-filled honeycomb became impact sensitive in only slightly oxygen-enriched liquid air.

This paper summarizes the work reported in an earlier Technical Memorandum (below and in Secondary Documents). This summary contains the experimental results, but not all of the details on test methods.

Important references:

1. Key, C. F., and Gayle, J. B., NASA Tech. Memo. No. NASA TM-X-53144 (Oct 1964).

2. Key, C. F., and Gayle, J. B., NASA Tech. Memo. No. NASA TM-X-53208 (Feb 1965).

PRELIMINARY INVESTIGATION OF FIRE AND EXPLOSION HAZARDS ASSOCIATED WITH S-II INSULATION

Key, C. F., and Gayle, J. B.
National Aeronautics and Space Administration, Huntsville, Ala., George C. Marshall Space Flight Center, Tech. Memo. No. NASA TM-X-53144 (Oct 1974)

Insulation developed for the S-II vehicle was polyurethane foam bonded to the aluminum tank surface with an epoxy adhesive, reinforced with a phenolic-fiberglass honeycomb, and covered with an essentially impermeable vapor barrier. With the tank wall at liquid hydrogen temperature, any leakage in the vapor barrier was expected to allow air to condense inside the insulation. The condensate could contain appreciably more than 20% liquid oxygen, and could create a fire or explosion hazard in the event of an impact. A series of tests was conducted to evaluate this hazard.

Standard LOX impact tests on the composite insulation and its constituents showed a high sensitivity. Since condensate in the insulation would not be pure LOX, the tests were repeated in LOX/LN2 mixtures. Decreased oxygen concentration resulted in decreased sensitivity, down to zero sensitivity in 20% LOX mixture.

In a more realistic test configuration, the insulation was applied to flat aluminum plates and the vapor barrier was removed or punctured. Samples were immersed in LOX/LN2 mixtures for about 15 min, removed and allowed to stand for varying lengths of time, and impacted by about 125 0.013 g lead shot fired from a .22 calibre rifle. With the rifle located less than 1.3 m from the sample, reactions occurred consistently when LOX concentration in the mixture exceeded about 20%. Reaction frequency increased with increasing warm-up time after immersion in mixtures containing 20 to 30% LOX, consistent with the expectation that condensate becomes enriched with LOX during warm-up. Similar results were obtained with .177 calibre copper coated pellets fired from an air gun and with insulation applied to the curved surface of a test tank.

To achieve a more realistic simulation by eliminating direct immersion in LOX/LN2 mixtures, the insulation was applied to liquid hydrogen tanks and the vapor barrier was punctured to allow natural cryopumping. After maintaining the liquid hydrogen for 4 to 12 h, the hydrogen supply was cut off and the test tank impacted with bird shot fired from a 22 calibre rifle from a distance of 45 to 70 cm from the tank. Sustained burning occurred 10 min and 8 min after liquid hydrogen shutoff in two of the tests. The reaction after 10 min warm-up was more violent than that after 8 min warm-up, indicating either a larger quantity or more oxygen-richness of the condensate.

The authors conclude that there is a small but finite probability of catastrophic reaction if damaged S-II insulation is subjected to impact, shock, fire, or other stimuli during or after liquid hydrogen hold. The danger is greater during warm-up. This small hazard must be balanced against other factors to determine whether modification is required.

HEAT TRANSFER IN EXPANDED MATERIALS (UBER DEN WARMETRANSPORT IN SCHAUMSTOFFEN)

Koglin, B. (ERNO Raumfahrttechnik GmbH, Bremen, West Germany)

Kaltetechnik-Klimatisierung 21, No. 5, 122-5 (May 1969)

An experimental program was conducted to measure heat transmission in plastic foam insulation materials, and to establish the effects of variations in foam properties on the heat transfer mechanisms. A polyurethane foam of 40 kg/m^3 density and a polystyrene foam of 15 kg/m^3 density were the materials measured, and thermal conductivities were determined in the temperature range between 20 K and 350 K.

The polyurethane foam thermal conductivity showed characteristics typical of halocarbon-blown foams, with a maximum and a minimum in the curve between 230 K and 280 K, near the condensation temperature of the blowing agent, where variations in the vapor pressure cause the thermal conductivity to change. The thermal conductivity also showed an abrupt drop as the temperature decreased below about 50 K, a region where air in the cells of the foam has mostly condensed.

The polystyrene foam was made with air as the blowing agent. Its thermal conductivity showed a continuous increase with increasing temperature from 110 K to 330 K. Other measurements at a temperature of 308 K established the effects on thermal conductivity of air pressure in the cells, of temperature difference across the sample, of sample thickness, and of emissivity of the foam surface. These results along with simple models of heat transfer mechanisms were used to show the effects due to solid conduction, gas conduction, and radiation heat transfer. Convective heat transfer was negligible in the tests. The combined effects led to the conclusion that, for foam of a specific density, there is an optimum cell size for minimum thermal conductivity.

Important references:

1. DIN 52612, Beuth-Vertrieb, Berlin-Köln.
2. Koglin, B., Diss. TU Berlin (1967).
3. Haskins, J. F. and Hertz, J., Adv. Cryog. Eng. 7, 353 (1962).
4. Tariel, H. M., Boissin, J. C. and Segel, M. P., Adv. Cryog. Eng. 12, 274 (1967).
5. Zehendner, H., Kältetechn. 19, No. 1, 2 (1967).

MECHANICAL PROPERTIES OF FOAM MATERIALS IN THE TEMPERATURE RANGE OF 300°K TO 20°K (MECHANISCHE EIGENSCHAFTEN VON SCHAUMSTOFFEN IM TEMPERATURBEREICH VON 300°K BIS 20°K)

Kreft, H., and Wagner, D. (ERNO-Raumfahrttechnik GmbH, Bremen, West Germany)

Kaltetechnik-Klimatisierung 21, No. 9, 258-65 (Sep 1969)

An insulation consisting of foam bonded to the wall of a liquid hydrogen or liquid oxygen tank, and sealed with a vapor barrier bonded to the foam, was considered for upper rocket stages. Such insulation must withstand loads imposed by thermal contraction, external air pressure or vacuum, tank pressurization, and acceleration and air friction during launch. The mechanical properties of the materials must be known for design of the insulation system. Two foams, a polyurethane and a polyvinyl chloride, were tested along with four adhesives and an aluminized mylar vapor barrier.

Standard bar samples of both foams were tested for tensile strength at 20 K, 77 K, and 293 K, and for elongation and modulus at 77 K and 293 K. Flatwise tensile strengths of samples adhesively bonded between metal blocks were measured at 77 K and 293 K. Compressive strengths at 77 K and 293 K, tensile-shear strengths at 20 K, 77 K, and 293 K, and T-peel shear strengths at 77 K and 293 K were also measured for both foams. At all temperatures, the polyurethane foam had lower strengths and tensile modulus, and higher elongation, than the PVC foam. The PVC showed considerable sensitivity to temperature, with decreasing tensile and shear strengths and increasing compressive strength at lower temperatures. The polyurethane has the same general trends except that tensile strength of the bar samples increased at lower temperatures.

The authors conclude that the polyurethane has good mechanical properties at all temperatures being considered. The polyvinyl chloride foam has relatively high strength at room temperature and is brittle at lower temperatures.

Important references:

1. Kreft, H., Technischer Bericht RT/P-1/1/66, ERNO-Raumfahrttechnik GmbH, Bremen (Jan 1966).
2. Kreft, H., Abschlussbericht TB RT/Z/1/69, ERNO-Raumfahrttechnik GmbH, Bremen (Apr 1969).
3. Hollstein, W., Technischer Bericht 1204, Hamburger Flugzeugbau GmbH, Hamburg (Mar 1968).
4. Wagner, D., Technischer Bericht RT/S-86/68, ERNO-Raumfahrttechnik GmbH, Bremen (Jun 1968).
5. Wagner, D., Technischer Bericht RT/S-148/68, ERNO-Raumfahrttechnik GmbH, Bremen (Oct 1968).

CRYOGENIC PROPERTIES

Landrock, A. H. (Plastics Technical Evaluation Center, Picatinny Arsenal, Dover, N. J.)

Encyclopedia of Polymer Science and Technology Vol 4. John Wiley and Sons, Inc., New York, 415-49 (1966)

The article includes a summary of cryogenic foam insulation, reviewing some data from the literature. Data are taken from Miller, et al. (see the paper abstracted on page 73), on tensile, shear, and compressive strengths of rigid polyester-polyurethane, epoxy, semirigid polyurethane, and flexible polyether foams, between 20 K and 298 K. Other data from Bailey (included in the paper abstracted on page 73) show linear thermal expansions of six foams between 78 K and 295 K. Tabulations from Kropschot's papers (listed under Secondary Documents) demonstrate the high thermal conductivities of foams as compared with evacuated powder and multilayer insulations. The discussion on cryogenic foam insulation cites 14 references.

Important references:

1. General Dynamics/Astronautics, San Diego, Calif., Rept. No. MRG-162 (Jun 1960).
2. Hertz, J., and Haskins, J., General Dynamics/Astronautics, San Diego, Calif., Rept. No. MRG-202, 10 pp (Dec 1960).
3. Haskins, J. F., and Hertz, J., General Dynamics/Astronautics, San Diego, Calif., Rept. No. MRG-242, 21 pp (Jul 1961).
4. Hertz, J., and Haskins, J., General Dynamics/Astronautics, San Diego, Calif., Rept. No. MRG-303, 8 pp (Mar 1962).
5. Isenberg, L., and Johnson, C. L., Materials Compatibility and Contamination Control Process, Proc. National Symp., 4th (Hollywood, Calif., Nov 13-15, 1962). Soc. Aerospace Mater. Process Engrs. (SAMPE), 445-79 (1962).
6. Campbell, M. D., Haskins, J. F., Hertz, J., Jones, H., and Percy, J. L., General Dynamics/Astronautics, San Diego, Calif., Rept. No. MRG-312, 75 pp (Apr 1962).
7. Doherty, D. J., Hurd, R., and Lester, G. R., Chem. Ind. (London), 1340-53 (1962).
8. Griffin, J. D., and Skochdopole, R. E., Chapter 15 in Engineering Design for Plastics, E. Baer, Editor. Reinhold Publishing Corp., New York (1964).

POLYURETHANE FOAMS. TECHNOLOGY, PROPERTIES AND APPLICATIONS
Landrock, A. H.
Plastics Technical Evaluation Center, Dover, N. J., PLASTEC Rept. No. 37, 256 pp (Jan 1969)

This report discusses the state of the art of polyurethane foams as it existed in 1969. While much of the report is taken up with the chemistry and production of polyurethane foams, and with properties and applications outside the cryogenic temperature range, the chapter on Foam Properties includes sections on low-temperature effects, cryogenic effects, and liquid oxygen compatibility. The chapter on Military and Space Applications has a section on thermal insulation.

The low-temperature effects are mostly concerned with temperatures between room temperature and about 200 K. The section on cryogenic effects cites some 17 papers and reports from the literature. Specific data used in the discussion include a table of compressive strength, modulus, and deflection of three densities of foams, taken from Buxton, Hanson, and Fernandez (cited under Secondary Documents); graphs of tensile, shear, and compressive strengths of rigid, semi-rigid, and flexible foams, taken from Miller, Bailey, Beall, and Freeman (abstracted on page 73); and graphs of linear thermal expansions of two foams, taken from Bailey (cited under Secondary Documents) and from Miller, Bailey, Freeman, Beall, and Coxe (cited under Secondary Documents). A section on radiation effects on polyurethane foams also discusses combinations of radiation with exposure to vacuum and cryogenic temperatures. The section on liquid oxygen compatibility states that most polyurethanes are not LOX compatible, but that halogenated polyurethanes and those prepared from hexafluoropentanediol are compatible with LOX. The section on the application of polyurethane foams as insulation cites 8 references which deal specifically with cryogenic temperatures.

This report looks in depth at polyurethane foams and provides some comparisons with other foams as well. The bibliography of over 700 references from the literature aids in finding more detailed information.

Important references:

1. Haskins, J. F., and Hertz, J., General Dynamics/Astronautics, San Diego, Calif., Rept. No. MRG-242 (Jul 1961).
2. Dearing, D. L., Advances in Cryogenic Engineering 11, 89-97 (1966).
3. Johnson, P. M., Lewis, J. H., and Self, M. R., General Dynamics/Fort Worth, Rept. No. FZK-195 (Dec 1964).
4. Hauck, J. E., Mater. Des. Eng. 63, No. 5, 87-102 (May 1966).

Important references (continued):

5. Kropschot, R. H., Applied Cryogenic Engineering, Chapter 6, edited by R. W. Vance and W. M. Duke. Wiley, New York (1962).

6. Landrock, A. H., Encyclopedia of Polymer Science and Technology 4. Wiley-Interscience, New York, 415-99 (1966).

PROPERTIES OF PLASTICS AND RELATED MATERIALS AT CRYOGENIC TEMPERATURES
Landrock, A. H.
Plastics Technical Evaluation Center, Picatinny Arsenal, Dover, N. J.,
Plastec Rept. No. 20, 253 pp (Jul 1965)

This extensive compilation includes a section on foam cryogenic insulation, with a discussion summarizing data or conclusions from 22 references. The index lists over 64 references under the "foam" categories.

Graphical and tabulated data used in the discussion include data on the tensile, shear, and load-compression strengths of five foams at temperatures between 20 K and 395 K, taken from a paper by R. N. Miller, et al. (see abstract on page 73). Data on load-compression strengths of six foams at 20 K, 77 K, and 296 K were taken from another paper by R. N. Miller, et al. (cited under Secondary Documents). Linear thermal expansion of six foams between 78 K and 300 K were taken from a report by C. D. Bailey (cited under Secondary Documents). Thermal conductivities of polystyrene and polyurethane foams came from a 1961 report by J. F. Haskins and J. Hertz (cited under Secondary Documents). Other data on compressive strengths of polyurethane and polystyrene foams between 20 K and 300 K were taken from a report by M. D. Campbell, et al., and a journal article by D. J. Doherty, et al. (both cited under Secondary Documents). Tensile and shear moduli and anisotropy of the moduli, between 20 K and 300 K were taken from a book chapter by J. D. Griffin and R. E. Skochdopole (cited under Secondary Documents). Thermal conductivities of several foam materials at temperatures from 20 K to 300 K, and comparisons with vacuum powder and multilayer insulations, came from a chapter on Low-Temperature Insulation, by R. H. Kropschot, in the book Applied Cryogenic Engineering (cited under Secondary Documents).

This report on plastics at cryogenic temperatures is very comprehensive in the area of properties of materials. It represents the state of the art at the time of its publication, in 1965. Applications of materials were not covered in the report. Despite its age, the report remains a valuable source of information.

Important references:

1. Allen, R. J., and Van Paassen, H. L. L., Advances in Cryogenic Engineering 6, 548-54 (1961).

2. Hertz, J., and Haskins, J., General Dynamics/Astronautics, San Diego, Calif., Rept. No. MRG-303, Contract No. AF 33(616)-7984, 8 pp (Mar 1962).

3. Isenberg, L., and Johnson, C. L., Proc. National SAMPE Symp., 4th (Hollywood, Calif., Nov 13-15, 1962), 445-79 (1962).

Important references (continued):

4. Stoeker, L. R., Advances in Cryogenic Engineering 5, 273-81 (1960).

5. Vahl, L., Progress in Refrigeration Science and Technology, Vol 1, Proc. International Congress of Refrigeration, 10th (Copenhagen, Denmark, 1959). Pergamon Press, New York, 267-73 (1960).

6. Eyles, A. G., Advances in Cryogenic Engineering 10, 224-32 (1965).

DEVELOPMENT OF ADVANCED MATERIALS COMPOSITES FOR USE AS INSULATION FOR LH2 TANKS

Lemons, C. R., and Salmassy, O. K.
McDonnell-Douglas Astronautics Co., Huntington Beach, Calif., Research and Engineering Dept., Rept. No. MDC-G4492. National Aeronautics and Space Administration Rept. No. NASA CR-124388, Contract No. NAS 8-25973 (Apr 1973) 101 pp

This report is on a continuation of the work described in the report abstracted on page 58. The earlier work had developed and optimized an internal insulation system, consisting of 3D foam (a polyurethane foam reinforced with glass fibers oriented in three mutually perpendicular directions) bonded to the tank wall with epoxy adhesive and lined with a glass-cloth-reinforced epoxy layer. This system was applied to a one-meter dome and subjected to seven simulated mission cycles consisting of liquid hydrogen tanking, pressurization, and reentry heating to 450 K. The insulation withstood the simulated mission cycles with no apparent damage or degradation.

Another one-meter dome was insulated with a similar composite system, but using simpler butt joints between 3D foam panels. A syntactic foam material, epoxy resin filled with phenolic microballoons and glass fibers, was used as a gap filler in the butt joints. Only about half as much adhesive was used in bonding the foam to the dome. This modified insulation also withstood seven simulated mission cycles without significant damage or degradation, while reducing insulation weight and cost.

The authors conclude that the original structural and thermal objectives of the program were achieved, and that weight and cost reduction objectives were exceeded.

An appendix contains material and process specifications for the polyurethane foam, for the yarn-reinforced polyurethane foam, for the epoxy adhesive, and for installation of the internal insulation system.

Important references:

1. Salmassy, O., et al., MDAC Quarterly Summary Report MDC-G2525, Contract NAS 8-25973 (Sep 1971).

2. Lemons, C. R., Watts, C. R. and Salmassy, O. K., Summary Report Phase II MDC-G3677, Contract NAS 8-25973 (Jun 1972).

ADVANCES IN CRYOGENIC FOAM INSULATION
Lemons, C. R., Salmassy, O. K., and Watts, C. R.
McDonnell Douglas Astronautics Co., Huntington Beach, Calif., Paper No. MDAC WD 1756, Presented at Society of Aerospace Material and Process Engineers National Tech. Conf. on Space Shuttle Materials (Huntsville, Ala., Oct 5-7, 1971), Contract No. NAS 8-25973 (Sep 1971) 12 pp

An internal insulation was required for the liquid hydrogen tanks of both the booster and orbiter of the Space Shuttle. Prime considerations were reusability and heat resistance to survive reentry with wall temperatures up to 450 K. A thread-reinforced polyurethane foam internal insulation had proven reliable in the Saturn S-IV and S-IVB stages, and a program was conducted to modify this insulation to satisfy the requirements for the Space Shuttle.

The insulation was a polyurethane foam reinforced with glass fiber threads oriented in three mutually perpendicular directions. This 3D foam underwent expansion followed by shrinking when exposed to a temperature of 450 K. It could be stabilized by preheating to take care of the dimensional changes before applying the foam to the tank. A new formulation of polyurethane proved superior in having better stability after heating, lower density, and no cracking problem. Thermal conductivities of the new foam were measured in vacuum and helium environments at temperatures from 134 K to 325 K and found equivalent to the older foam. The insulation was applied to an aluminum dome by bonding with an epoxy adhesive, then sealed with a liner of glass-cloth reinforced polyurethane. The dome was subjected to simulated Space Shuttle service by cooling with liquid hydrogen, then heating to 450 K. The insulation survived testing with no apparent serious degradation. The authors concluded that the insulation system was shown to be ready for scale-up to large tank insulation.

DEVELOPMENT OF ADVANCED MATERIALS FOR USE AS INSULATIONS FOR LH2 TANKS

Lemons, C. R., Watts, C. R., and Salmassy, O. K.
McDonnell-Douglas Astronautics Co., Huntington Beach, Calif.,
Summary Rept. No. MDC-G3677, Jul 1971 - Apr 1972. National Aeronautics and Space Administration Rept. No. NASA CR-123928, Contract No. NAS 8-25973, 176 pp (Jun 1972)

The experimental program had the objective of developing reliable composite materials for a minimum weight internal insulation for the Space Shuttle liquid hydrogen tanks. The approach was to modify the reinforced foam insulation which had been developed for the Saturn S-IVB. This insulation, called 3D foam, consisted of a polyurethane foam reinforced with glass fibers oriented in three mutually perpendicular directions, bonded to the tank wall with epoxy adhesive and lined with a glass cloth reinforced epoxy coating.

A polyurethane foam formulated to withstand 450 K, as required for the Space Shuttle, was used, and foam fabrication was optimized to produce the lightest composite with the greatest strength possible. Some results of tensile, compressive, shear, and bond strengths at 77 K and 298 K are given. Adhesive bonding to the tank wall was optimized, vibration and acoustic fatigue tests were devised, various panel joints were evaluated, and methods of repairing the insulation were developed and tested.

The program succeeded in developing a satisfactory material and methods for manufacturing, applying, testing, and repairing the internal insulation. Detailed material and process specifications were to be prepared using the data from this experimental program.

Earlier work in this program was reported in the paper abstracted on page 57. A report of later work is abstracted on page 56.

Important references:

1. Salmassy, et al., MDAC Quarterly Summary Rept. No. MDC G2525 (Sep 1971).

2. MDC Rept. No. G2525 (Sep 1971).

3. MDC Rept. No. E0276 (Jun 1971).

4. MDAC Quarterly Rept. No. MDC G2740 (Jan 1972).

5. Dearing, D. L., MDAC Rept. No. SM-42545 (Nov 1962).

OPTIMIZATION ASPECTS AND TEST RESULTS OF A CRYOGENIC UPPER STAGE TANK INSULATION

Leupold, M., and Mueller, E.
Boelkow Entwicklungen GmbH, Munich, West Germany, Rept. No. U55-1, 35 pp (1967)

This paper describes a compound insulation for the upper stage of a space vehicle, combining foam insulation with superinsulation. The vehicle stage has both liquid hydrogen and liquid oxygen tanks to be insulated. The foam insulation is effective during ground hold and ascent while the superinsulation becomes most effective in space. The foam is bonded to the tank wall, superinsulation is applied over the foam, and the total insulation is enclosed in a vacuum bag and evacuated.

The insulation system was analytically optimized to balance propellant boiloff loss against insulation weight. This analysis assumed a constant 10 mm thickness of foam insulation, and varied the number of superinsulation layers according to mission length. Two foams were considered, a polyurethane foam and a polyvinyl chloride foam. In tests of tensile and shear strengths at 77 K and room temperature, the PVC foam was superior. Weight losses at elevated temperatures were measured because the insulation is exposed to aerodynamic heating. The PVC foam began to decompose at a temperature near 410 K, while the polyurethane remained stable at least up to 425 K.

A program was started to measure the effectiveness of compound insulation by measuring boiloff from insulated liquid nitrogen tanks. Only initial results are reported, and tests with liquid hydrogen tanks were planned.

SEALED-FOAM, CONSTRICTIVE-WRAPPED, EXTERNAL INSULATION SYSTEM FOR LIQUID-HYDROGEN TANKS OF BOOST VEHICLES
Lewis Research Center
National Aeronautics and Space Administration, Cleveland, Ohio, Lewis Research Center, Tech. Note No. NASA TN-D-2685, 157 pp (Mar 1965)

This report is a collection of nine chapters by various authors, describing the concept, design and testing of the external foam insulation system. The first chapter, by P. T. Hacker and J. B. Esgar, describes the insulation concept. The system consisted of 10 mm thick, 32 kg/m^3 density polyurethane foam panels, hermetically sealed within a mylar-aluminum-mylar laminate covering, protected from aerodynamic erosion by a thin fiberglass cloth layer, adhesively bonded to the tank wall to prevent air penetration, and held in place by a prestressed constrictive wrap of fiberglass roving. Chapter 2, by W. H. Roudebush, presents the calculated thermal conditions during a boost trajectory, which the insulation was designed to withstand.

Chapter 3, by L. J. Heidelberg, gives results of measurements of thermal conductivity of insulation panels. Panels were tested under compressive loads between surfaces at liquid hydrogen and ambient temperatures. The average thermal conductivity, 0.021 W/m·K at a mean temperature of 156 K, was considered a good indication of the thermal conductivity of the insulation held against a liquid hydrogen tank by constrictive wrapping. Changes in compressive load did not affect thermal conductivity, and addition of fiberglass separators produced small reduction of thermal conductivity while adding to weight and complexity of the insulation.

The insulation system was sealed to prevent cryopumping of air, but any leaks in the seal would allow air to condense in the insulation, and the collection of liquid air or liquid oxygen might create a hazardous condition in case of accidental impact. Chapter 4, by R. P. Dengler, describes tests of the impact sensitivity of the insulation and its component materials in the presence of liquid oxygen. In 40 tests, 10 produced some reaction and only 1 led to sustained combustion. These results, along with the effective hermetic sealing, the localized area of any leakage, the condensation of air rather than liquid oxygen, and the high impact magnitudes used in the test program, led to the conclusion that the probability of damage was very small.

Chapter 5, by P. J. Perkins, Jr., M. Colaluca, F. P. Behning, and F. Devos, reports on the fabrication and tests of insulated subscale tanks. Tests included equivalent thermal conductivity during ground hold, structural effect of rapid pressure drop during launch, and effect of surface heating during launch. Chapter 6, by R. P. Cochrane, V. O. Bazarko, and R. W. Cubbison, describes aerodynamic heating tests conducted in a jet engine exhaust and in a supersonic wind tunnel.

Chapter 7, by P. J. Perkins, Jr., C. B. Shriver, and R. A. Burkley, reports on application of the insulation to a full-scale centaur tank. Chapter 8, by H. F. Calvert, P. J. Perkins, Jr., W. C. Morgan, and M. A. Colaluca, describes ground-hold tests on the full-scale insulated tank. Chapter 9, by J. B. Esgar and P. T. Hacker, summarizes results of the program.

The subscale tests showed thermal conductivities about the same as those determined in the thermal conductivity tests. Full-scale tests showed even lower thermal conductivities, near 0.014 W/m·K, partially because of lower mean temperature of 110 K. The insulation, protected by the constrictive wrap and fiberglass cloth layer, withstood the simulated aerodynamic heating and pressure of launching. Leaks were observed in the tests, but were limited to relatively small areas, and had no apparent effect on thermal performance of the insulation. The insulation withstood all tests, and was considered suitable for use on hydrogen-fueled boost vehicles.

Important references:

1. McGrew, J. L., Advances in Cryogenic Engineering 8, 387-92 (1963).
2. Miller, R. N., Bailey, C. D., Beall, R. T., and Freeman, S. M., Advances in Cryogenic Engineering 8, 417-24 (1963).
3. Perkins, P. J., Jr., and Esgar, J. B., AIAA Annual Structures and Materials Conf., 5th (Palm Springs, Calif., Apr 1-3, 1964), Publ. CP-8, 361-71 (1964).
4. Gray, V. H., Gelder, T. F., Cochran, R. P., and Goodykoontz, J. H., NASA Tech. Note No. NASA TN-D-476 (1960).
5. Perkins, P. J., Jr., NASA Tech. Note No. NASA TN-D-2679 (1964).
6. Key, C. F., and Riehl, W. A., NASA Tech. Memo. No. NASA TM-X-54611 (1963).
7. Dengler, R. P., NASA Tech. Note No. NASA TN-D-1882 (1963).

MECHANICAL AND PHYSICAL PROPERTIES OF ORGANIC FOAMS
Lormis, F. E.
Bendix Corp., Kansas City, Mo., Final Rept. No. BDX-613-562-REV.
(Feb 1972) 60 pp

A test program was conducted to establish the cryogenic properties of organic structural foams. Four foams were investigated, including a rigid polystyrene foam, two rigid polyurethane foams, and a flexible polyurethane foam. The tests were for thermal conductivity, thermal expansion, and torsional shear modulus and shear strength between 77 K and 298 K.

In all of the shear tests, shear modulus and ultimate shear strength increased and ultimate angle of rotation decreased with decreasing temperature. Tests were run at 77 K, 195 K, and 298 K, except on the flexible polyurethane foam which was unable to support the test fixture at 298 K and only partially supported the fixture at 195 K. The author states that the polyurethanes showed orientation effects while the polystyrene did not. This statement is not confirmed by the data, which show little or no orientation effect for any of the foams. The author also states that the polystyrene was by far the most flexible at 77 K. While this is true of the rigid foams, the flexible polyurethane is shown by the data to be more flexible than the polystyrene at 77 K.

Thermal conductivity results are given for samples with a cold side between 75 K and 91 K and a hot side between 289 K and 303 K. Thermal expansion results are shown between 100 K and 298 K. In another test, tensile strengths of the polystyrene and a polyurethane were measured at room temperature using three different adhesive systems. It was concluded that there was little or no difference resulting from the type of adhesive. Conditioning times were determined in tests measuring the time required for the center of a polyurethane foam block to reach the testing temperature. The center of a cylindrical block 76 mm long by 29 mm diameter reached 77 K in 10 min after immersion in liquid nitrogen. The center reached the gas temperature in 45 min after being placed in gaseous nitrogen at 78 K. Conditioning times were assigned as 15 min in liquid and 60 min in gaseous coolants. The shear modulus and shear strength of a polyurethane foam were measured after long conditioning in gaseous nitrogen and after rapid cooling in liquid nitrogen. Strength and modulus were the same or higher in the liquid, showing that there was no degradation due to thermal shock.

Important references:

1. Miller, R. N., Bailey, C. D., et al., Advances in Cryogenic Engineering 8, 417-424 (1963).

Important references (continued):

2. Reed, R. P., Durcholz, R. L. and Arvidson, J. M., Advances in Cryogenic Engineering 16, 36-45 (1971).

3. Latter, G. I. and Prado, M. E., LRL Report, ENS 71-366, 1-12 (Feb 1971).

4. Lazarus, L. J., Bendix Report, EP 46411-00, 1-14 (Dec 1970).

5. Landrock, A. H., Plastec Report 20, Plastic Technical Evaluation Center, Picatinny Arsenal (Jul 1965).

6. Jelineck, F. J., Cryogenic Properties of Polystyrene and Polyethylene Foams, Progress Rept., Battelle Memorial Inst., Columbus, Ohio (Dec 1970).

THERMOPHYSICAL PROPERTIES OF THERMAL INSULATING MATERIALS
Loser, J. B., Moeller, C. E., and Thompson, M. B. (Midwest Research Inst., Kansas City, Mo.)
Air Force Materials Lab., Wright-Patterson AFB, Ohio, Rept. No. ML-TDR-64-5, Contract No. AF33(657)-10478 (Apr 1964) 362 pp

This report is a compilation of data on the thermophysical properties of insulating materials, resulting from a comprehensive literature survey and analysis of original test data published between 1940 and 1962. The data are presented graphically, and a reference table with each graph gives the sources of the data, the sample forms and test methods, and remarks on temperature ranges and accuracies.

The foam insulations included in the compilation are epoxy, glass, polystyrene, polyurethane, polyvinyl chloride, rubber, and silicon dioxide. The data for these forms are thermal conductivities as functions of temperature or pressure, and linear thermal expansions of the polyurethanes. The foam data came from 17 references.

The data pages are followed in the compilation by a section on experimental methods, which describes and evaluates the available methods of measuring thermal conductivity, thermal expansion, specific heat, total normal emittance, and thermal diffusivity. A glossary of synonyms and trade names, conversion factors, references, and an author index are part of the report. The report is an excellent and comprehensive summary of the available data on foam insulation, and the major limitation is the age of the compilation.

Important references:

1. Hickman, M. J. and Ratcliffe, E. H., Int. Inst. Refrign/IIF/Bul 35, No. 4 (presented 9th Int. Cong. Refrign. AG-S), 794 (1955).
2. Powers, R. W., Johnston, H. L., Hansen, R. H. and Ziegler, J. B., ASTIA AD 27-569, TR 264-16, 1-29 (May 1, 1963).
3. Verschoor, J. D., Refrig. Eng. 62, No. 9, 35-7, 98 (1954).
4. Kropschot, R. H., ASHRAE J. 1, No. 9, 48-54 (Sep 1959).
5. Corruccini, R. J., Chem. Engng. Progress 53, No. 6 (Jun 1957).
6. Haskins, J. F. and Hertz, J., Convair Astronautics Rept. MRG-242 (Jul 25, 1961).
7. Speil, S., Thermal Performance of Rigid Insulations at Cryogenic Temperatures, Presented AFOSR Conf. Aerodynamically Heated Structures (Arthur D. Little, Inc., Cambridge, Mass., Jul 1961).

STUDY OF THERMOPHYSICAL PROPERTIES OF CONSTRUCTIONAL MATERIALS IN A TEMPERATURE RANGE FROM 10 TO 400 K

Luikov, A. V., Shashkov, A. G., Vasiliev, L. L., Tanaeva, S. A., Bolshakov, Yu. P., and Domorod, L. S. (Heat and Mass Transfer Inst., Minsk, BSSR, USSR)

Heat Transmission Measurements in Thermal Insulations, Proc. Symp. Thermal and Cryogenic Insulating Materials (Philadelphia, Pa., Apr 16-7, 1973), American Soc. for Testing and Materials, Philadelphia, Pa., Special Tech. Publ. No. STP-544, 290-6 (Jun 1974)

The thermal conductivities, thermal diffusivities, and specific heats of several structural and insulating materials were measured. One of the materials was a polyurethane foam, identified by its Russian designation. The thermophysical properties are tabulated for the temperature range from 30 K to 300 K. The thermal conductivity of the material increased with increasing temperature over the entire temperature range. The authors note that these results differ from those reported by Tye. They attribute the difference to a denser foam, 49 kg/m^3 compared to the 32 kg/m^3 tested by Tye.

The Russian data do not show the s-shape characteristic of the thermal conductivity versus temperature curve reported by other investigators for polyurethane foam. This difference is attributed to the experimental conditions, with vacuum as the external medium, and the foam pores filled with helium during thermal treatment before the test. Such results emphasize the importance of matching test conditions to proposed operating conditions, and demonstrate the ways that different applications can affect insulation effectiveness.

Important references:

1. Tye, R. P., Proc. XIII International Congress of Refrigeration 1 (Washington, D.C.)(1971).

HIGH PERFORMANCE SPRAY FOAM INSULATION FOR APPLICATION ON SATURN S-II STAGE

Mack, F. E., and Smith, M. E. (North American Rockwell Corp., Downey, Calif.)

Advances in Cryogenic Engineering 16, Proc. Cryogenic Engineering Conf. (Colorado Univ., Boulder, Jun 17-19, 1970), K. D. Timmerhaus, Editor. Plenum Press, New York, 118-27 (1971)

This paper describes the overall program to develop a spray-on foam insulation for use as external insulation on the liquid hydrogen tanks of the Saturn S-II stage. Six spray foams were screened, and a flame retardant polyurethane foam with a density of 32 kg/m^3 was selected for further development. Evaluations were based on a "cryogenic strain compatibility" test, in which a thermal gradient and tensile strain were applied to a sample in the presence of liquid hydrogen. Samples were also subjected to simulated boost heating with altitude.

Process development included selection of proper spray equipment, selection of primers to insure adhesion of the foam to the aluminum tank wall, and evaluation of temperature and humidity effects during spraying to establish allowable processing conditions. A coating material was developed to protect the foam from weathering effects caused by exposure to ultraviolet in direct sunlight.

Small tank tests were used to verify spray-foam application feasibility, retention of insulating characteristics with extended environmental exposure, and structural integrity during vibration and heating. Smaller samples were subjected to environmental aging and wind tunnel tests. Foam panels were applied to surfaces of an X-15, and flights of the X-15 subjected the samples to combinations of heating, aeroshear, and altitude simulating the S-II flight profile. The resulting erosion of the foam led to another test program to develop erosion protection for the insulation. Finally, large-scale tank tests qualified the insulation for application to the S-II.

All of the screening, development, verification, and qualification tests were successful, and the spray foam material was shown to be an applicable insulation for large-scale liquid hydrogen boosters.

Important references:

1. Hammond, M. B., Advances in Cryogenic Engineering 15, 332-42 (1970).

2. North American Rockwell Rept. No. 69MA5502, Contract No. NAS 7-200 (Jun 1964).

3. Cioth, B. B., North American Rockwell Rept. No. SID 67-696 (Dec 1967) and SID 68-394 (Jul 1968).

INSULATION BY SYNTHETIC FOAMS IN CRYOGENICS

Mathes, H. (Messerschmitt-Boelkow-Blohm GmbH, Ottobrunn bei Munich, West Germany)

Kaeltetech.-Klim. 22, No. 2, 50-5 (Feb 1970)

This paper describes a foam insulation developed for use on the liquid oxygen and liquid hydrogen tanks of a rocket stage. The insulation consisted of foam panels, thermoformed and adhesively bonded to the tank surface. The experimental program involved the selection of the foam and adhesive, and the development of suitable fabrication methods for applying the foam to the tank.

Three types of foam were considered, a polyurethane foam, a cross-linked polyvinyl chloride foam, and a polymethacrylimide foam. In tests of thermoforming, the polyurethane had a tendency to crack and the polymethacrylimide required a rather precise high forming temperature. The PVC foam was chosen for the formed portion of the insulation. Panels were formed within a vacuum jacket in a heating chamber, over molds with the tank contours. A polyurethane adhesive was selected to bond the molded panels to the tank. Foamed-in-place polyurethane was applied around the flange portion of the tank. A polyvinylidene chloride film was used as a vapor barrier over the seams of the insulation, to prevent air leakage and condensation. The insulation as developed appeared to be satisfactory for its intended application.

Important references:

1. Zimni, W. F., and Meitzner, K., Kaeltetech.-Klim. 22, No. 2, 34-40 (Feb 1970).

2. Kreft, H., and Wagner, D., Kaeltetech.-Klim. 21, No. 9, 258-65 (1969).

3. Kreft, H., Schulz, J., and Hoffmann, H., ERNO Raumfahrttechnik GmbH, Bremen, Germany, Rept. (1967).

MECHANICAL PROPERTIES OF INSULATING PLASTIC FOAMS AT LOW TEMPERATURES

McClintock, R. M. (National Bureau of Standards, Boulder, Colo. Cryogenics Div.)

Advances in Cryogenic Engineering 4, Proc. Cryogenic Engineering Conf. (Massachusetts Inst. of Tech., Cambridge, Sep 3-5, 1958), K. D. Timmerhaus, Editor. Plenum Press, New York, 132-40 (1960)

The mechanical properties of a material must be known in order to evaluate its response to the thermal stresses imposed in low temperature applications. This is important in plastic foam insulations, which are often bonded to a more rigid structure, and sustain large temperature gradients across the material. This paper reports on the experimental determination of important mechanical properties of three expanded plastics.

The materials were polystyrene foam of two densities, 48 and 66 kg/m^3, and an epoxy foam of density 88 kg/m^3. The properties determined were elastic modulus in tension and tensile strength at temperatures from 76 K to 300 K, and a modulus of rigidity in rotational shear at temperatures from 20 K to 300 K. In every case, the elastic moduli showed a marked increase with decreasing temperature. Results are given in terms of the moduli divided by the densities, to take care of the density dependence of the elastic properties. The materials showed distinct anisotropy, with the properties being different in each of the three mutually perpendicular directions. However, the effect of temperature was the same in each direction. Microscopic examination confirmed the anisotropy of the foams, showing a preferred orientation of the cells in a sample. But the direction of the preferred orientation was not the same at all locations in a large sample. The best way to analyze the foams was judged to be to evaluate properties in the three mutually perpendicular directions, and use the average of the values to characterize each material.

Tensile strengths of the foams showed no particular trend of change with temperature. This was in contrast to bulk plastics, which showed an increase of tensile strength with decreasing temperature. The difference in behavior was attributed to the increased brittleness at low temperature leading to an increased notch sensitivity, and the inherently "notched" structure of a foam. The brittleness was confirmed by the decreases in ultimate elongation with decreasing temperature.

Important references:

1. Corruccini, R. J., Chem. Eng. Progr. Pt. 3, 53, 8 (Aug 1957).

POLYURETHANE FOAM INSULATION FOR CRYOGENIC LINES
McDonnell Aircraft Corp.
McDonnell Aircraft Corp., St. Louis, Mo., Final Rept. No. TR-052 068 44, 29 pp (Jul 1964)

An experimental program was conducted to determine some of the properties of a number of rigid polyurethane foams proposed for use as insulation on cryogenic lines in the Gemini spacecraft. Fourteen polyurethane foams were submitted for test, four as premolded specimens and the other ten as components to be mixed and molded in the laboratory. The premolded samples were tested for thermal embrittlement and water absorption. The other materials were molded around an aluminum tube, and tested for thermal embrittlement, water absorption, and thermal conductivity. Densities of the premolded samples were 29 to 37 kg/m^3, while the laboratory-molded samples ranged from 46 to 99 kg/m^3. The molding process in the laboratory used excess material to insure filling the mold, and was difficult to control.

The thermal embrittlement test was a very rough qualitative test, consisting of immersing a sample in liquid nitrogen for 15 s, removing the sample and hitting it against a table top, and examining it for apparent breaks or cracks. There was no evidence of thermal embrittlement as determined by this test. Water absorption testing consisted of measuring weight increase of a sample and penetration depth of water after 24 h immersion in dyed water. Water penetrated the foams to a depth of three to five cell diameters, thought to be the depth to the first undamaged layer of cells. Thermal conductivity measurements were made on the samples molded around an aluminum tube, by filling the tube with liquid nitrogen and recording the rate of boiloff. Thermal conductivities on ten samples ranged from 0.012 to 0.017 W/m•K, with an average of 0.015 W/m•K, at a mean temperature of 172 K.

EFFECTS OF NUCLEAR RADIATION AND CRYOGENIC TEMPERATURES ON NONMETALLIC ENGINEERING MATERIALS

McKannan, E. G., and Gause, R. L. (National Aeronautics and Space Administration, Huntsville, Ala. Marshall Space Flight Center)

J. Spacecraft Rockets 2, No. 4, 558-64 (Jul-Aug 1965)

The experimental program had the objective of evaluating materials for use in nuclear-powered spacecraft. The materials were tested by exposure to various combinations of nuclear radiation, cryogenic temperature, and vacuum environments. For the combination of nuclear radiation with cryogenic temperature, the materials evaluated were two structural adhesives, two structural laminates, two thermal insulations, and four electrical insulations. The thermal insulations were a polyurethane foam and a polystyrene foam. Compressive strength of the foam was used to evaluate the response to exposure, and the more pertinent property for insulation, the thermal conductivity, was left as the subject of some future evaluation.

Samples were irradiated to two dose levels and tested at 323 K in air, at 77 K immersed in liquid nitrogen, and at 20 K in liquid hydrogen. The two foams reacted similarly to exposure except that the polyurethane had higher compressive strengths than the polystyrene. Without radiation, compressive strength and modulus increased with decreasing temperature. Maximum compressive strength of unirradiated foam was observed at 20 K for polystyrene and at 77 K for polyurethane. Irradiation in air at 323 K badly degraded both foams. This result is attributed to reactions with residual blowing agents, which decompose and attack the foam. These reactions are inhibited at cryogenic temperatures, and radiation at low dose levels of about 0.5×10^6 J/kg increases the compressive strength and modulus of each foam at 77 K and 20 K, apparently by cross-linking. At higher dose levels of 1.2 to 1.3×10^6 J/kg, radiation-induced degradation competes with the cross-linking, and reduces strength and modulus at cryogenic temperatures.

Because of the severe degradation at room temperature, neither foam can be recommended for application in a nuclear radiation environment.

Important references:

1. Lucas, W. R., Symp. on Space Radiation Effects, ASTM Publ. No. 363 (1964).
2. Smith, E. T., 1963 Summer General Meeting of the Institute of Electrical and Electronics Engineers (Toronto, Canada) (1963).
3. Lockheed Missiles and Space Co., Palo Alto, Calif., Rept. No. NSP-63-35, Contract NAS 8-5600 (May 1963).
4. Aerojet-General Corp., Rept. No. 2339 (Jul 1962).
5. Smith, E. T., Radiation and Cryotemperature Tests, Annual Rept., Contract No. NASA 8-2450 (Nov 1961).

EVALUATION OF CRYOGENIC INSULATION MATERIALS AND COMPOSITES FOR USE IN NUCLEAR RADIATION ENVIRONMENTS. MATERIALS TESTS
McMillan, W. D., Bradbury, H. G., Carter, H. G., Lightfoot, R. P., and Kerlin, E. E.
General Dynamics/Fort Worth, Tex., Rept. No. FZK-347. National Aeronautics and Space Administration Rept. No. NASA CR-61920, Contract No. NAS 8-18024, 264 pp (May 1968)

The objective of this program was the evaluation of cryogenic insulation materials for application to a nuclear rocket vehicle, where the materials are exposed to cryogenic temperatures and nuclear radiation. The materials tested included foam and corkboard insulation, adhesives, and vapor barrier films. The mechanical property tests were tensile shear and compressive strengths for the insulation; shear and peel strength for the adhesives; and elongation and tensile strength for the films. Irradiation was performed at doses ranging from 9×10^5 to 2.5×10^6 J/kg. Two detonations occurred in the corkboard irradiation tests (caused by the reaction of hydrogen with trapped air in the corkboard cells). Tests were conducted in air, liquid nitrogen and liquid hydrogen. The insulation materials tested were four commercial urethane foams and one insulating cork.

The results showed that all of the foams maintained their compressive strength at low temperatures and under radiation. Radiation in air decreased the strength. Corkboard is significantly weaker than foam under all conditions. Under shear testing the foams performed well at all temperatures and radiation levels as did the corkboard except that the latter material showed degraded results after irradiation in air.

Tensile tests were also performed on composite insulation-adhesive-film insulation systems. In all cases failure occurred in the insulation, but the foams had higher strength than the corkboard.

Important references:

1. Kerlin, E. E., General Dynamics/Fort Worth, Tex., Division Rept. No. FZK-319 (Oct 1966).
2. Kerlin, E. E., and Lightfoot, R. P., General Dynamics/Fort Worth, Tex., Division Rept. No. FZK-328 (Jan 1967).
3. Kerlin, E. E., and Lightfoot, R. P., General Dynamics/Fort Worth, Tex., Division Rept. No. FZK-329 (Apr 1967).
4. McMillan, W. D., Carter, H. G., and Lightfoot, R. P., General Dynamics/Fort Worth, Tex., Division Rept. No. FZK-348 (Jun 1968).
5. Landrock, A. H., Technical Evaluation Center, Plastec Rept. 20, Picatinny Arsenal, Dover, N. J. (Jul 1965).

Important references (continued):

6. Kerlin, E. E., General Dynamics/Fort Worth, Tex., Rept. No. FZK-161-1 (Jan 1963).

7. Smith, E. T., General Dynamics/Fort Worth, Tex., Rept. No. FZK-161-2 (Jan 1963).

8. Kerlin, E. E., and Smith, E. T., General Dynamics/Fort Worth, Tex., Rept. No. FZK-188-1 (May 1964).

9. Kerlin, E. E., and Smith, E. T., General Dynamics/Fort Worth, Tex., Rept. No. FZK-188-2 (May 1964).

10. Kerlin, E. E., and Smith, E. T., General Dynamics/Fort Worth, Tex., Division Rept. No. FZK-290 (Jul 1966).

11. Eyles, A. G., Advances in Cryogenic Engineering 10, 224 (1965).

12. Miller, R. N., et al., Industrial and Engineering Chemistry, Product Research and Development 1, 257 (Dec 1962).

13. Miller, R. N., Bailey, C. D., Beall, R. T., and Freeman, S. M., Advances in Cryogenic Engineering 8, 417 (1963).

FOAMS AND PLASTIC FILMS FOR INSULATION SYSTEMS
Miller, R. N., Bailey, C. D., Beall, R. T., and Freeman, S. M.
(Lockheed-Georgia Co., Marietta)
Advances in Cryogenic Engineering 8, Proc. Cryogenic Engineering Conf.
(Los Angeles, Calif., Aug 14-16, 1962), K. D. Timmerhaus, Editor.
Plenum Press, New York, 417-24 (1963)

The use of liquid hydrogen as a rocket propellant created a demand for reliable and lightweight cryogenic insulation systems. To aid in the design of such systems, the properties of a number of materials were determined. This paper reports on the mechanical properties of three vapor barriers and four foams, and the thermal expansion of four adhesives, three vapor barriers, and seven foams.

The four foams tested for mechanical properties were a flexible polyether, a semirigid polyurethane, an epoxy, and a polyester polyurethane foam. Tensile and shear strength tests were conducted at 20 K, 77 K, 298 K, and 394 K. The semirigid polyurethane and the epoxy had the highest tensile strength at 20 K, at room temperature the polyester polyurethane was strongest, and tensile strengths of all the foams dropped off at high and low temperature extremes. The polyester polyurethane was strongest of the four at room temperature. Load-compression tests at 20 K, 77 K, and 298 K showed that the polyether, epoxy, and polyester polyurethane foams had good elastic recovery at room temperature, but the polyether embrittled and was crushed at 77 K, and the polyester polyurethane at 20 K, leaving only the epoxy foam retaining elasticity at liquid hydrogen temperatures.

The foams tested for thermal expansion were two epoxy, three polyurethane, a polystyrene, and a filled epoxy polyamide foam. Between 77 and 293 K, the polyurethanes and filled epoxy polyamide had the highest thermal expansion coefficients, and the epoxies had the lowest.

EXPERIMENTAL STUDY OF A NEW PVC FOAM INSULATION SYSTEM FOR LH_2-LO_2 SPACE VEHICLES

Muller, F. J. (Societe l'Air Liquide, Sassenage, France)

Advances in Cryogenic Engineering 16, Cryogenic Engineering Conf. (Boulder, Colo., Jun 17-19, 1970), K. D. Timmerhaus, Editor. Plenum Press, New York, 109-17 (1971)

This paper is an extension of an earlier paper, abstracted on page 101. The earlier paper described a polyvinyl chloride foam developed for use as an external insulation for spacecraft liquid hydrogen tanks. This paper describes an improved formulation of the PVC foam, its application as insulation for a launch vehicle, and evaluations of insulation system performance.

The original PVC foam was satisfactory for small scale test tanks, but had too little tensile elongation to withstand the combined effects of differential thermal contraction and tank pressurization of thin-walled tanks. The reformulated foam was reported to have nearly the same properties as the original foam, except for an improved ultimate elongation at 20 K.

The insulation system designed for the liquid hydrogen-liquid oxygen stage of the Europa III launch vehicle consisted of a layer of foam, 16 mm thick on the liquid hydrogen tank and 10 mm thick on the liquid oxygen tank, bonded to the aluminum tank wall with a fiberglass cloth reinforced epoxy adhesive, and a similar layer of epoxy-fiberglass applied over the foam to provide a base for a 0.5 mm coating of ablative material. Insulated test tanks were subjected to pressurization cycles while filled with liquid hydrogen, to expected dynamic pressures and temperatures in wind tunnel tests, and to vibration while filled with liquid hydrogen. No damage to the insulation was observed. A complete insulated tank assembly with liquid oxygen and liquid hydrogen in compartments separated by a common bulkhead was tested under ground hold conditions. The insulation proved satisfactory and remained undamaged. The author concludes that all tests have been fully successful, showing the suitability of the insulation for application to the launch vehicle as well as various other cryogenic equipment.

Important references:

1. Tariel, M., et al, Advances in Cryogenic Engineering 12, 274-85, Plenum Press (1967).

2. Muller, F., Thesis (1967).

THERMAL PERFORMANCE CHARACTERISTICS OF A COMBINED EXTERNAL INSULATION SYSTEM UNDER SIMULATED SPACE VEHICLE OPERATING CONDITIONS

Muller, F. J., and Klevatt, P. L. (L'Air Liquide, Sassenage, France and McDonnell Douglas Astronautics Co., Huntington Beach, Calif.)

Advances in Cryogenic Engineering 19, Proc. Cryogenic Engineering Conf. (Georgia Inst. of Tech., Atlanta, Aug 8-10, 1973), K. D. Timmerhaus, Editor. Plenum Press, New York, 482-9 (1974)

A combined foam-multilayer external insulation was designed for use on space vehicles such as the space shuttle orbiter or the Space Tug. This paper reports on tests of the long term thermal performance of the insulation system on a liquid hydrogen tank under simulated space vehicle operating conditions.

The insulation consisted of a 11-mm thick layer of polyvinyl chloride foam bonded to the tank, with a 10-shield multilayer aluminized mylar assembly attached over the foam, the entire system enclosed in a polyimide purge bag for purging with either helium or nitrogen. The insulation was applied to a liquid hydrogen tank 1.5 m long by 1.2 m diameter, the tank was filled with liquid hydrogen, and tests were run under simulated ground-hold steady state, ascent transient, space steady state, reentry transient, and post-mission ground-hold conditions. Transient and steady state heat fluxes were measured and agreed well with predicted values, except for the space flight condition where heat flux was twice that expected. The purge bag maintained its integrity throughout testing. The foam sublayer sustained some cracking, which apparently had no effect on performance and did not cause debonding.

The authors concluded that the insulation system proved feasible and a viable candidate for further consideration for use on space vehicles.

Important references:

1. Muller, F. J., and Flacon, B. G., CEC/SES/FM/BF/CM/CD/2I.860, McDonnell Douglas final Rept., L'Air Liquide (Jul 1972).

2. Muller, F. J., Advances in Cryogenic Engineering 16, Plenum Press, New York, 109 (1971).

A GUARDED HOT PLATE APPARATUS FOR THE MEASUREMENT OF THERMAL CONDUCTIVITY OF INSULATING MATERIALS AT LOW TEMPERATURES

Myncke, H., Van Paemel, O., and De Cnop, L. (Laboratorium voor Akoestiek en Warmtegeleiding K.U.L., Heverlee, Belgium)

Some Thermophysical Properties of Refrigerants and Insulants, Proc. International Inst. of Refrigeration Commission B1 (Zurich, Switzerland, Sep 27-9, 1973), Bull. Inst. Int. Froid, Annexe 1973-4, 157-61 (1973)

An apparatus was developed to measure thermal conductivities of insulation materials between 113 K and 273 K. This paper describes the apparatus and presents results of measurements of the thermal conductivity of glass foam. Two samples of the foam, having densities of 119 and 129 kg/m^3, were tested simultaneously at mean temperatures between 117 K and 274 K. The results are shown in tabulated and graphical forms, and are compared to the results obtained by W. F. Cammerer on a similar material in the temperature range between 117 K and 302 K. The curves of thermal conductivity versus temperature are similar but not identical, as would be expected from samples of similar but not identical materials. In both cases, the thermal conductivity decreases nearly linearly with decreasing temperature down to about 180 K, then decreases more slowly with further decrease of temperature.

POLYURETHANE FOAM INSULATION THERMAL AGING CHARACTERISTICS
Navickas, J., and Madsen, R. A. (McDonnell Douglas Astronautics Co., Huntington Beach, Calif.)
Cryogenic Engineering Conf. and International Cryogenic Materials Conf. Joint Meeting (Queens Univ., Kingston, Ontario, Canada, Jul 22-5, 1975) 12 pp

Thermal aging is the time-dependent thermal conductivity characteristic shown by closed cell polyurethane insulation. Freshly made foam has a relatively low thermal conductivity which gradually increases to a significantly higher value. This paper presents an analysis of the aging process for trichlorofluoromethane-blown foam aged in air at ambient temperature. The model starts with the closed cells of the foam filled with the blowing agent. Over a period of time air diffuses into the cells and mixes with the blowing agent. The thermal conductivity changes as the proportions of gases in the cells change. The blowing agent also diffuses out of the cells, but this is such a slow process that it is ignored in the analysis.

Thermal conductivity versus operating temperature curves were calculated for various aging times. With aging longer than about 100 h the curves show the s-shaped characteristic typical of polyurethane foams. After 500 h, the thermal conductivity at temperatures below 200 K remains constant, while the thermal conductivity at higher temperatures is still increasing slowly. Comparison of the calculations with experimental data shows reasonable agreement.

The authors conclude that the analytical model is valid, and can be used to extrapolate available thermal performance and thermal aging data to conditions where data are not available. Given diffusion characteristics, the model can be used with different blowing agents, exposure to different gases, and exposure at different pressures and temperatures. The authors note that, since aging effects are manifested much more rapidly at cryogenic operating temperatures, great care is required in interpreting thermal conductivity data taken at ambient operational temperatures. They feel that much of the inconsistency of data in the literature is due to differences in aging conditions.

Important references:

1. Stengard, R. A., New Information About Urethane Foam, duPont Bulletin (1962).
2. Guenther, F. O., Cellular Materials-Composition, Cell-Size, Thermal Conductivity, Society of Plastic Engineers Transactions (1962).
3. Skochdopole, R. E., Chemical Engineering Progress 57, 55 (1961).

Important references (continued):

4. Patten, G. A. and Skochdopole, R. E., Modern Plastics 39, 149 (1962).

5. Harding, R. H. and James, B. F., Modern Plastics 39, 133 (1962).

6. Hallinan, M. R., Himmler, W. A. and Kaplan, M., 19th Annual Conf. of the Society of Plastic Engineers (Pittsburgh, PA), Preprint Book 20-4, 2 (1962).

7. LeBras, L. R., Society of Plastic Engineers Journal 16, 420 (1960).

ON THE POTENTIALITIES OF POLYPHENYLENE OXIDE (PPO) AS A WET-INSULATION MATERIAL FOR CARGO TANKS OF LNG-CARRIERS

Opschoor, G.
Nederlands Scheeps-Studiecentrum TNO, Delft, Technische Afdeling,
Rept. No. 194-M (Jul 1974) 13 pp

Polyphenylene oxide foam was evaluated as an internal insulation for liquefied natural gas tanks. PPO foam consists of elongated open cells oriented in a single direction, so that they are open through the entire thickness of a layer of foam. When PPO foam is used as internal insulation, it is bonded to a tank wall so that one end of each open cell is sealed. The other end of each cell remains open to the liquid, the cell fills with gas, and gas pressure and capillary forces maintain a stable gas-liquid interface at the open end of the cell, making a vapor barrier unnecessary.

The linear expansion coefficients and the tensile, shear, and compressive strengths of PPO foam are given, at temperatures of 77 K and 293 K and with orientations parallel and perpendicular to cell orientation. The thermal conductivity with the cells filled with natural gas at 200 K is about 80% higher than that of polyurethane or polyvinyl chloride foam. Immersion of the foam in a mixture of LNG and higher hydrocarbons for 50 days resulted in greater flexibility and reduced thermal stresses. A urethane adhesive withstood the 50-day immersion without loss of strength.

For safety reasons, an internal insulation for LNG tankers must consist of two insulation layers separated by a vapor barrier. With this structure, a failure of either the primary insulation or the tank wall does not necessarily become a catastrophic failure. Several possible constructions are considered, using PPO as the primary internal insulation, bonded to an intermediate vapor barrier of plywood or metal. Cost of the PPO makes it unsuitable for the secondary insulation contained between the vapor barrier and the tank wall. Polyurethane foam, PVC foam, perlite, fiberglass, or balsa wood can be used. Calculations of insulation thickness were made for free-standing and membrane tanks using PPO as primary insulation, plywood as vapor barrier, and polyurethane or PVC foam as secondary insulation. The calculations show that polyurethane and PVC foams are nearly equivalent insulations, and both are better than PPO foam. The advantage of the PPO is in not requiring a vapor barrier. Calculations of thermal stresses show that the insulation systems are feasible. The authors recommend that research on PPO foam continue.

Important references:

1. Knobbout, J. A. and Colenbrander, C. B., Properties of PPO-Foam in Regard to its Application as Liquid Hydrogen Tank Insulation. C.T.I. Report No. 69-62195 (May 1969) (not published).

Important references (continued):

2. Opschoor, G. and van der Brugh, J., Investigation on the Resistance of PPO-Foam Against a Mixture of LNG with Heavier Hydrocarbons. C.T.I. Report No. 72-05358 (Oct 1972) (not published).

3. Een eerste Technische Evaluatie van de Toepasbaarheld van PPO-schulm als Isolatie in LNG-Tanks. C.T.I. Report No. 72-04515 (Oct 1972) (not published).

EFFECT OF ENVIRONMENT ON INSULATION MATERIALS
Parmley, R. T. (Lockheed Missiles and Space Co., Sunnyvale, Calif.)
Space Transportation System Propulsion Technology, Proc. Conf. (George C. Marshall Space Flight Center, Huntsville, Ala., Apr 6-7, 1971) - Vol 4 - Cryogens. National Aeronautics and Space Administration, Rept. No. NASA TM-X-67348, 1411-37 (Apr 1971)

The purpose of this program is to understand environmental effects on insulation by exposing 20 candidate insulation materials to 8 conditions representing operational environments. One of the 20 materials is a 32 kg/m^3 polyurethane foam, a candidate ground-hold insulation material.

The polyurethane foam was exposed to 40% relative humidity at 366 K, 95% relative humidity at 308 K, salt spray at 95% relative humidity and 308 K, water immersion at 294 K, gaseous oxygen at 294 K and 0.13 N/m^2, and prolonged exposure to vacuum at temperatures from 21 K to 365 K. The compressive strength of the foam was used as a measure of environmental effects. The compressive strength decreased after exposure to all of the environments. The greatest decrease was caused by exposure to vacuum and high temperature, and exposure to high temperature and 40% humidity had nearly as great an effect. The least effect was noted after the water immersion.

EXPERIMENTAL STUDY UNDER GROUND-HOLD CONDITIONS OF SEVERAL INSULATION SYSTEMS FOR LIQUID-HYDROGEN FUEL TANKS OF LAUNCH VEHICLES

Perkins, P. J.,Jr.
National Aeronautics and Space Administration, Cleveland, Ohio, Lewis Research Center, Tech. Note No. NASA TN-D-2679, 27 pp (Mar 1965)

Three proposed external insulation systems for liquid hydrogen fuel tanks of launch vehicles were applied to flight-weight tanks and tested under ground hold conditions. The three systems tested were corkboard insulation bonded to the tank and sealed with a phenolic varnish and a mylar film; polyurethane foam hermetically sealed in an aluminum-mylar-aluminum laminate vacuum bag, evacuated, and held in place with a nylon filament-wound constrictive wrap; and the sealed and constrictively wrapped polyurethane foam with a thin film of liquid nitrogen sprayed on the surface to reduce heat flow through the insulation. An uninsulated liquid hydrogen tank, with and without a natural accumulation of ice and frost, was also included in the investigation. Insulation effectiveness was measured by recording insulation surface temperature and rate of liquid hydrogen boiloff in the tank.

The corkboard insulation cracked during the cooldown with liquid hydrogen, particularly in areas of complicated geometry at the tank ends. The sealed and constrictively wrapped foam insulation performed satisfactorily although the outer surface showed wrinkling from thermal contraction. Total heat flow was about half that with the corkboard insulation. The liquid nitrogen spray provided a heat flow through the insulation only one-fifth of that without the liquid nitrogen spray. The uninsulated tank showed a very high heat influx, 50 times that with the polyurethane foam insulation, with considerable liquefaction of air on the walls of the tank. A natural accumulation of ice and frost prevented the formation of liquid air on the tank surface and cut the heat influx in half.

The sealed and constrictively wrapped polyurethane foam was the best of the insulation systems tested, in terms of insulation effectiveness and system weight.

Important references:

1. McGrew, J. L., Advances in Cryogenic Engineering 8, 387-92 (1963).

2. Gray, V. H., Gelder, T. F., Cochran, R. P., and Goodykoontz, J. H., NASA Tech. Note No. NASA TN-D-476 (1960).

3. Murphy, D. W., and Covington, D. T., Martin-Denver Co., Data Rept. No. 1317-61-4 (Aug 1961).

4. Haskins, J. F., and Hertz, J., Advances in Cryogenic Engineering 7, 353-9 (1962).

ANALYTICAL HEAT TRANSFER INVESTIGATION OF INSULATED LIQUID METHANE WING TANKS FOR SUPERSONIC CRUISE AIRCRAFT

Pleban, E. J.
National Aeronautics and Space Administration, Cleveland, Ohio, Lewis Research Center, Tech. Note No. NASA TN-D-5641, 37 pp (Jan 1970)

This report gives a detailed heat transfer analysis of foam insulated wing tanks for storing liquid methane fuel in a supersonic cruise aircraft. The analysis considered a range of insulation thickness from 1.27 to 5.08 cm, insulation density from 32 to 138 kg/m^3, internal tank pressures from ambient to 0.02 MPa, and both saturated and initially subcooled methane for typical SST missions with cruise Mach numbers of 2.7, 3.0 and 3.5. It was determined that the total vented boiloff losses could be kept to less than 1.5 percent of the initial fuel for Mach numbers up to 3.5 with wing tank insulation thickness of 2.54 cm under the following conditions:

1) The fuel stored in the wing tanks (assumed to be about 1/2 the total fuel load) is used during the early part of the flight.

2) Either the fuel is initially subcooled 14 K or the saturated liquid methane is subjected to a constant internal tank pressure of 0.01 MPa.

It was also determined that due to a higher fuel usage rate during the early part of the mission with high cruise Mach numbers, increasing the cruise Mach number from 2.7 to 3.5 did not result in increased boiloff.

Loading fuel for 20 minutes into tanks with an initial temperature of 294 K and followed by an additional 10 minute ground-hold resulted in a boiloff (recoverable) of less than 1.5% of the methane loaded into the tanks. The maximum boiloff rate would be less than 1/35 of the fill rate. It was verified, however, that regardless of the insulation thickness, the wing surface temperature depression during fill and ground hold can cause moisture to freeze under some weather conditions.

The insulation considered in the analysis was polyurethane foam. After the fuel is expended in the wing tanks, the wing and insulation temperatures rise rapidly, therefore, it does not appear feasible to use currently available polyurethane because of the excessive wing tank temperatures.

Important references:

1. Whitlow, J. B., Jr., Eisenberg, J. D., and Shovlin, M. D., NASA TN-D-3471 (1966).

Important references (continued):

2. Chambellan, R. E., Lubomski, J. F., and Bevevino, W. A., NASA TN-D-4295 (1967).

3. Eisenberg, J. D., and Chambellan, R. E., AIAA Paper 68-196 (Feb 1968).

4. Weber, R. J., NASA TM-X-1604 (1968).

5. Moeller, C. E., Loser, J. B., Snyder, W. E., and Hopkins, V., Midwest Research Inst. Rept. No. ASD-TDR-62-215 (Jul 1962).

THERMAL CONDUCTIVITY OF HEAT INSULATING MATERIALS
Powers, R. W., and Johnston, H. L.
Ohio State Univ. Research Foundation, Columbus, Cryogenic Lab., Rept. No. TR-264-16, Contract No. W33-038-AC-14794(16243), 59 pp (May 1953)

The insulating properties of a number of insulation materials were studied at liquid air and liquid hydrogen temperatures, with a view toward gaining information which could result in the development of better insulations, particularly for liquid hydrogen propellant tanks. Heat flows were measured with insulation materials placed between two concentric copper spheres. The space containing the insulation was evacuated or filled with hydrogen or nitrogen gas at various pressures.

The foam materials tested were two urea resin foams, of densities 14 and 24 kg/m^3, and a polystyrene foam of density 26 kg/m^3. Heat flows and thermal conductivities were measured on the low-density urea resin foam in vacuum at mean temperatures from 48 K to 188 K, in hydrogen at various pressures at mean temperatures from 49 K to 141 K, and in nitrogen at various pressures at mean temperatures from 110 K to 141 K. The higher density urea resin foam was measured in vacuum from 99 K to 188 K and in hydrogen at 99 K. The polystyrene foam was measured in vacuum from 102 K to 190 K and in hydrogen at 141 K. The authors note that, among the three foams tested, the low-density urea resin foam has the highest heat conductivity and the polystyrene foam has the lowest.

HEAT TRANSMISSION IN LOW CONDUCTIVITY MATERIALS
Pratt, A. W. (Aston Univ., Birmingham, England)
Thermal Conductivity 1, R. P. Tye, Editor. Academic Press, New York, 301-405 (1969)

This paper is principally directed toward the measurement of heat flow through thermal insulation materials. Before describing the methods of measuring heat flow, the paper discusses the mechanisms of heat transfer in thermal insulation. This discussion includes a brief summary of the typical properties of nine cellular plastics: two densities of expanded polystyrene, two densities of expanded polyvinyl chloride, foamed urea-formaldehyde, two densities of foamed phenol-formaldehyde, and two foamed polyurethanes, one blown with carbon dioxide and the other with fluorinated hydrocarbon. The properties given are approximate density, thermal conductivity at 283 K, maximum temperature recommended for continuous use, water absorption in seven days, and behavior in fire. Thus the information is not particularly valuable for cryogenic insulation. The more valuable part of the paper is the comprehensive discussion of measurement methods, the equipment used, and precautions necessary for accurate measurements. A reference section with more than 120 citations concludes the paper.

THERMAL CONDUCTIVITY OF WET-WALL LIQUID HYDROGEN STORAGE TANK INSULATIONS FOR SPACE APPLICATIONS

Rawuka, A. C., and Yundt, C. G. (Douglas Aircraft Co., Santa Monica, Calif.)

Cryogenic Engineering in the Aerospace Industry, Proc. Symp., National Meeting, 56th (San Francisco, Calif., May 16-19, 1965). Chemical Engineering Progress Symp. Series 62, No. 61, 1966. American Institute of Chemical Engineers, New York, 219-24 (1966)

Foamed plastic insulation systems have been used successfully as internal insulation in liquid hydrogen tanks. To predict performance of such systems, it was necessary to measure the thermal conductivity of the composite insulation under simulated design conditions. This paper describes the measurements, and reports changes in thermal conductivity of the insulation during exposure to liquid hydrogen.

The composite insulation consisted of foam bonded to the internal surface of the metal-walled liquid hydrogen tank, with a reinforced plastic liner laminated over the foam as a barrier to hydrogen diffusion. Two types of polyurethane foam were used, one reinforced with glass threads foamed in place at uniform spacings and oriented along the three principal directions. The foam was bonded to aluminum plate with epoxy adhesive. The barriers consisted of various weaves and weights of glass cloth, sometimes in combination with an aluminum-polyester-aluminum film sandwich, laminated to the foam and sealed with epoxy or polyurethane resin.

Tests consisted of measurements of thermal conductivity of insulation samples held between a 20 K cold side and a 300 K hot side. Samples were exposed directly to liquid hydrogen at various pressures for various times, to find the effects on the thermal conductivity. It was found that thermal conductivities increased with pressure and with time, indicating changes in the composition of the gaseous phase in the foam. Differences in foam density produced small differences in thermal conductivity, while variations in liner materials produced much larger differences. These effects are explained by hydrogen diffusion through the barrier layer into the foam. Air, which had originally diffused into the foam, migrates to the cold side and condenses leaving a partial vacuum into which the hydrogen diffuses. The thermal conductivity eventually approaches that for hydrogen gas. After long exposure to liquid hydrogen, analysis of the gas within the foam confirmed the presence of nearly pure hydrogen gas with traces of air.

The authors conclude that improvements in thermal conductivity of internal insulation can be achieved by controlling gaseous diffusion, and this depends on the choice of the least permeable liner material.

Important references:

1. Skochdopole, R. E., Chem. Eng. Progr. 57, No. 10, 55 (1961).

2. Lindsay, A. L., and Bromley, L. A., Ind. Eng. Chem. 42, 1508-11 (1950).

TENSILE PROPERTIES OF POLYURETHANE AND POLYSTYRENE FOAMS FROM 76 TO 300 K

Reed, R. P., Arvidson, J. M., and Durcholz, R. L. (National Bureau of Standards, Boulder, Colo. Cryogenics Div.)

Advances in Cryogenic Engineering 18, Proc. Cryogenic Engineering Conf. (Colorado Univ., Boulder, Aug 9-11, 1972), K. D. Timmerhaus, Editor. Plenum Press, New York, 184-93 (1973).

Polyurethane and polystyrene foams have low thermal conductivity and correspondingly low density and are thus useful for cryogenic insulation purposes. Their low cost, ease of molding and application are also positive factors. Increasingly, foam use in cryogenic applications requires load-carrying capacity. For efficient design in these cases, mechanical property information is needed. The literature, however, contains very little reliable and reproducible mechanical property data. This paper reports tensile data (transverse and longitudinal) at 76 K, 195 K and 300 K. The specific properties measured were modulus of elasticity, proportional limit, yield strength, tensile strength and percent elongation.

The foams tested in this work included 17 densities of polyurethane (124.64 kg/m^3 to 30.6 kg/m^3) and two densities of polystyrene (100.12 kg/m^3 to 52.23 kg/m^3). The results are given as averages, with each data value representing the average of about four tests. Variations for the various properties were $\pm$ 5 percent to $\pm$ 10 percent for tensile strength, with the variation due mainly to material inconsistency. The results showed that the modulus of elasticity, yield strength and tensile strength increased with decreasing temperature, while the elongation decreased. Strength and modulus were found to be approximately linearly dependent on density; however, at low temperatures the density dependence was greater. Specimens whose long axis was cut parallel to the cell rise direction were stronger than those whose long axis was cut normal to the cell rise direction. A companion paper abstracted on page 4 on compressive properties compares the tensile and compressive results.

Important references:

1. Reed, R. P., Durcholz, R. L., and Arvidson, J. M., Advances in Cryogenic Engineering 16, 37-45, Plenum Press (1971).

2. McClintock, R. M., SPE J. 14, 36 (1958).

3. Doherty, D. J., Hurd, R., and Lester, G. R., Chemistry and Industry (London), p. 1340 (Jul 1962).

4. Kreft, H., and Wagner, D., Kaltetechnik-Klimatisierung 9, 258 (1969).

5. Patel, M. R., and Finnie, I., UCRL Rept. No. 13193, Inst. Engr. Res., California Univ., Berkeley (1965).

LOW-TEMPERATURE TENSILE PROPERTIES OF POLYETHYLENE TEREPHTHALATE MULTIFIBER YARN AND POLYSTYRENE FOAM

Reed, R. P., Durcholz, R. L., and Arvidson, J. M. (National Bureau of Standards, Boulder, Colo. Cryogenics Div.)

Advances in Cryogenic Engineering 16, Proc. Cryogenic Engineering Conf. (Colorado Univ., Boulder, June 17-19, 1970). Plenum Press, New York, 37-45 (1971)

Polystyrene foam is used extensively as an insulating material in cryogenic applications. In many applications, knowledge of the temperature dependence of the tensile strength and modulus is beneficial. Foam properties are dependent on density, method of forming (mold or extrusion), and, very probably, on the conditions of forming. The foam data reported in this study were produced by a process using dry nitrogen gas and pre-expanded polystyrene beads. The tensile data indicate that polystyrene foam fabricated in this way is considerably stronger than any types tested previous to this study. Tensile strength, yield strength, percent elongation and modulus of elasticity data were taken on two densities of foam (0.094 and 0.051 g/cm^3) at temperatures of 20 K, 76 K, 195 K and 295 K. In both sample densities the tensile strength increased as the temperature was lowered. The denser foam had higher strength, the average strength at 295 K was 1.3 MPa and at 20 K it was 2.1 MPa. The lower density foam had a tensile strength average at 295 K of 0.74 MPa and at 20 K of 1.4 MPa. In both cases the load rate was 0.013 cm/min. The tensile strength of the foam samples was of the order of twice as great as that of previously reported tests. The paper also includes results for the tensile properties of polyethylene terephthalate yarn from 4 K to 295 K.

Important references:

1. Griffin, J. D. and Skochdopole, R. E., Engineering Design for Plastics (ed. E. Baer), Reinhold Publishing Co., N. Y. (1964) 995 p.
2. McClintock, R. M., SPE J., 14, 36 (1958).
3. Phillips, T. L. and Lannon, D. A., British Plastics 34, 236 (1961).
4. Brown, W. B., Plastics Progr. 1959, 149 (1960).
5. Cooper, A., Plastics Inst. Trans. (London) 26, 299 (1958).
6. Cooper, A., Plastics Inst. Trans. (London) 29, 39 (1961).

HEAT INSULATION IN THE SEA TRANSPORT OF LNG
Richard, L. (Gaz de France, Paris)
Rev. Prat. Froid 23, No. 284, 15-21 (Jan 1970)

This French paper discusses the types of insulation used in LNG tankers. The primary materials have been perlite and balsa wood, but polyvinyl chloride foams have received some use, and polyurethane foams have shown some promise.

The PVC foams for LNG tankers have had to satisfy specifications on density, compressive strength, heat transfer coefficient, and water absorption. In addition, because of the conditions on shipboard, a test of vibration resistance under load and high temperature gradient was devised. The foam must withstand the test conditions without cracking or deterioration of its physical properties. PVC foam was used on the "Jules Verne" to insulate the tank walls and the secondary barrier. It was also used to insulate the cryogenic piping, and a protective coating of glass cloth reinforced polyester resin proved to be satisfactory protection against weather and sea action. The paper lists one LNG tanker using PVC foam as supporting insulation and secondary barrier insulation, and four other tankers using PVC foam as the insulation of self-supporting tanks.

The polyurethane foams are described as having characteristics similar to the PVC foams, and as having the additional advantage of foaming in place. However, the polyurethanes are described as being susceptible to cracking in the vibration test, because their relatively high thermal contraction causes internal strains when the foam is subjected to high thermal gradients. Foaming in place is inexpensive, but it is difficult to obtain a homogeneous material with controlled properties.

The author notes that the final choice of insulation material for LNG tankers is decided by economic factors.

ENERGY-ABSORBING CHARACTERISTICS OF FOAMED POLYMERS

Rusch, K. C. (Ford Motor Co., Dearborn, Mich. Scientific Research Staff)

J. Appl. Polym. Sci. 14, No. 6, 1433-47 (Jun 1970)

This paper discusses a property of foams which is not generally considered in insulation systems. While impact energy absorption is not usually a critical property of insulation, it is related to the flexibility or brittleness of the material, which is a critical property for cryogenic insulation. Energy absorption characteristics also provide a measure of how fragile an insulation will be.

The energy absorption characteristics can be calculated from experimental compressive stress-strain data at slow compression rates. The calculated quantities are the energy-absorbing efficiency, the impact energy per unit volume, and the maximum decelerating force on an impacting body. An analytical scheme for determining these quantities is given, and calculations for two polyurethanes, at 77 K and 298 K, were carried out. The paper uses the results to illustrate the differences between flexible and brittle foams. A curve of efficiency versus impact energy has a higher peak for brittle than for flexible foam. A curve of maximum deceleration has a wider and flatter plateau for brittle than for flexible foam. Both of these effects are more pronounced for a higher density foam. In terms of impact-energy absorption, a brittle foam is superior to a flexible foam. Other factors in designing an energy-absorbing foam structure are also considered in the paper.

INVESTIGATION OF FABRICATION AND PROCESSING PARAMETERS ASSOCIATED WITH USE OF POLYURETHANE FOAMS IN SEALED CRYOGENIC INSULATION
Shriver, C. B.
Goodyear Aerospace Corp., Akron, Ohio, Rept. No. R-12249. National Aeronautics and Space Administration, Cleveland, Ohio, Lewis Research Center, Rept. No. NASA CR-72025, Contract No. NAS 3-5646, 85 pp (Jun 1965)

The sealed insulation consisted of a number of layers of aluminized mylar film separated by thin layers of polyurethane foam, with the composite structure enclosed in a vapor barrier. The insulation was self-evacuating when residual gases inside the vapor barrier were condensed at the cold wall. The experimental program was directed toward foam optimization by increasing the hole area in perforated foam, pretreating foam to reduce outgassing, developing a rigid open cell foam, and selecting foam with the best compression characteristics.

Foam separators with various open areas in various patterns of perforations were used to separate aluminized mylar films, and contact between films was monitored as a function of open area and applied pressure. Electrical contact between aluminized films was used as a conservative indication of thermal contact between films in the insulation. Separators with less than about 40% open area prevented contact between films at pressures of 100 kN/m^2. Multi-layer samples were made up using the most promising separator configurations, and sent out for thermal conductivity tests. Results of these tests are not given in this report.

Four polyurethane foams, three open cell and one closed cell, were tested for outgassing in vacuum and in vacuum at 422 K. Weight losses in vacuum alone ranged from 0.65% to 1.4%, and at 422 K were as high as 2.2%. The open cell foams lost weight faster than the closed cell foams. Attempts to rigidize flexible open cell foams by chemical treatment had limited success, but vendors supplied rigid open cell polyurethane foams. Compression test samples of one closed cell and three open cell rigid foams were made up of ten layers of foam alternating with nine layers of mylar film. Compression tests at room temperature and 77 K showed that all specimens showed elastic recovery at both temperatures after release of a 100 kN/m^2 load, and that compressive modulus increased with decreasing temperature. The closed cell foam was more rigid than the open cell foams. The best open cell foam showed a yield point at a load more than double the maximum pressure on self-evacuated insulation panels.

The report also gives permeability and outgassing test results on vapor barrier materials.

THE THERMAL CONDUCTIVITY OF FOAMED PLASTICS
Skochdopole, R. E. (Dow Chemical Co.)
Chem. Eng. Progr. 57, No. 10, 55-9 (Oct 1961)

The effects of the properties of foamed plastic insulations on the mechanisms of heat transfer are thoroughly analyzed. Results of the analyses are confirmed by comparison with literature data. Data were not available on the effects of foam cell size on convection heat transfer, so an experimental program was conducted on polystyrene foams with cell sizes varying from 0.6 to 6.0 mm. It was found that there was no convection effect with cell diameters less than about 4.0 mm.

The analysis shows the effects on thermal conductivity of changing foam density, cell size, polymer composition, and gas phase composition. While each of these factors can affect the thermal conductivity, the most important variable is the gas phase composition. The environmental effects of aging and temperature are shown to be mostly caused by changes in the composition of the gas phase. In aging, the gas phase changes by diffusion through cell walls. Temperature changes can change the composition of the gas phase by condensing or changing the vapor pressure of the foam blowing agent in the cells.

The aging model was verified by an experimental program, in which the thermal conductivity of a trichlorofluoromethane-blown polyurethane film was measured at intervals over a period of 206 days of aging in air at 333 K. After the aging period, the foam was mechanically compressed, then re-expanded by heating. After three such cycles, the foam cells were open and filled with air. The thermal conductivity was again measured, and the contributions of air and foam were calculated. A calculation based on the contribution of the foam and the thermal conductivity of the blowing agent agreed with the measured thermal conductivity of the foam before aging.

Important references:

1. Wilkes, G. B., Heat Insulation, Wiley, New York (1950).

2. Rowley, F. B., Jordan, R. C., and Lander, F. M., Refrig. Eng. 50, 541 (1954).

MEASUREMENT OF THE COMBINED EFFECTS OF NUCLEAR RADIATION AND CRYOTEMPERATURES ON NON-METALLIC SPACECRAFT MATERIALS

Smith, E. T. (General Dynamics/Fort Worth, Tex.)

AIEE Summer General Meeting (Toronto, Canada, Jun 17-21, 1963), Paper No. CP 63-1175, 36 pp (1963)

This paper presents the experimental results of a program to measure the combined effects of nuclear radiation and cryogenic temperatures on the mechanical (tensile and compressive) properties of nonmetallic structural materials for use in nuclear-powered spacecraft. The materials tested included two adhesives, two mechanical seal materials, two thermal insulations, two electrical insulation materials and a structural laminate. The materials were tested at ambient conditions, at 20 K, and at 77 K at zero radiation and up to 6 x 10^6 J/kg. The irradiation and subsequent testing were done without warming the sample, so that no chance was given for annealing out the radiation induced defects.

The two thermal insulations tested were a polyurethane foam and a polystyrene foam and both were tested with compressive loads only and compressive strength (unirradiated) increased with decreasing temperature although the polyurethane showed some degradation in going from 77 K to 20 K. Radiation levels decreased the compressive strength of both materials at ambient temperature but a threshold level between 5 x 10^5 J/kg and 0.2 x 10^6 J/kg was indicated at the lower temperatures. Radiation, up to this level, increased the compressive strength at 77 K and 20 K. Above these radiation dose levels, however, the strength dropped off severely. Any level of irradiation at ambient temperature served to reduce the compressive strength significantly. Both materials are recommended for use under relatively low radiation environments at cyrotemperatures. Most of the results of this paper are used by different authors in the paper abstracted on page 70.

Important references:

1. General Dynamics/Fort Worth, Tex. Rept. No. MR-N-254 (May 1961).
2. General Dynamics/Fort Worth, Tex. Rept. No. FZK-142 (Mar 1962).
3. General Dynamics/Fort Worth, Tex. Rept. No. FZK-147 (Jun 1962).
4. General Dynamics/Fort Worth, Tex. Rept. No. FZK-152 (Aug 1962).
5. General Dynamics/Fort Worth, Tex. Rept. No. FZK-161-2 (Jan 1963).

MEASURING THE THERMAL CONDUCTIVITY OF IRRADIATED FOAM-TYPE INSULATION MATERIALS

Smith, E. T., and Miller, R. E. (General Dynamics/Fort Worth, Tex.)
Advances in Cryogenic Engineering 12, Proc. Cryogenic Engineering Conf. (Boulder, Colo., Jun 13-15, 1966), K. D. Timmerhaus, Editor. Plenum Press, New York, 315-21 (1967)

This paper reports results of measurements made on four foam insulations at room, liquid nitrogen and liquid hydrogen temperatures. Control samples in unirradiated conditions were compared with irradiated samples subjected to gamma doses from 5×10^5 to 3×10^6 J/kg. The tests were performed as part of a program to select candidate materials for nuclear powered space vehicles. Organic materials are particularly vulnerable to radiation and deserve special attention. Insulating materials and insulation systems, because of the importance of their functions, were prime candidates for early assessment.

The four materials were polyurethane (polyether-polyester rigid foam, manufacturers designation CPR-200-2), polyurethane (polyether, rigid, halocarbon blown, manufacturers designation H-1502), epoxy (rigid, spray foamed, manufacturers designation EFS-175) and polyurethane (rigid foam, CO_2 blown, manufacturers designation CPR-1021-2). Tabular results for all four materials at room and liquid nitrogen temperatures are given for radiation levels of zero, 5×10^5, 1×10^6 and 3×10^6 J/kg. These results show that changes in the thermal conductivity of the four test materials as a result of the irradiation were slight to insignificant to the highest dose level achieved. The data obtained in the liquid hydrogen tests, both control and post irradiation, are questionable. The measured values of thermal conductivity are higher than expected and it was concluded that either the cell gases froze out completely, or a hydrogen leak occurred.

This paper contains a more detailed description of the thermal conductivity work reported in the paper abstracted on page 44.

COMPRESSIVE LOAD-DEFLECTION CHARACTERISTICS OF SEVERAL FOAM MATERIALS AT ROOM TEMPERATURE, 77 K AND 4.2 K

Stewart, W. F., Eash, D. T., and May, W. A. (Los Alamos Scientific Lab., N. Mex.)

Advances in Cryogenic Engineering 19, Proc. Cryogenic Engineering Conf. (Georgia Inst. of Tech., Atlanta, Aug 8-10, 1973), K. D. Timmerhaus, Editor. Plenum Press, New York, 385-92 (1974)

This report gives results of an experimental program to measure the compressive properties of candidate foam materials used as a rigid support for the primary coil of a 300 kJ superconducting energy storage coil. The coil is a model for a pulsed plasma thermonuclear fusion energy source. At the levels of current and voltage involved, large transient forces can be produced by misalignment of the primary and secondary coils. A foam pad (flexible at room temperature but rigid at 4.2 K) was considered to be a better means of adapting the coil supporting arms to the inner shell of the cryostat than springs or other mechanical or pneumatic (gaseous helium) damping systems.

The materials tested included various densities of gas-blown flexible polysiloxane foam, a polyether based flexible polyurethane, a proprietary flexible cellular silicone, and a low density rigid polystyrene foam. The results are presented as curves of load versus deflection at room temperature and 77 K with a few tests conducted at 4.2 K. Little difference was seen in the compressive tests at 77 K and 4.2 K. All of the candidate materials performed quite well and none of them were observed to crack or break during testing. One polysiloxane and a cellular silicone were compressively loaded to over 11.8×10^7 N/m^2 at 77 K and did not exhibit any sudden shifts in deflection. Following the 77 K test, the load-deflection data at room temperature were essentially the same as before the test. The report does not make a final recommendation as to the material to be used.

Important references:

1. Arvidson, M. J., Durcholz, R. L., and Reed, R. P., Advances in Cryogenic Engineering 18 (1972).

LOW-DENSITY FOAM FOR INSULATING LIQUID-HYDROGEN TANKS
Sumner, I. E.
National Aeronautics and Space Administration, Cleveland, Ohio, Lewis Research Center, Tech. Note No. NASA TN-D-5114, 52 pp (Mar 1969)

The objective of this investigation was to develop and test a lightweight polyurethane foam insulation for liquid hydrogen tanks of space vehicles that 1) could be foamed in place on the outside of the tank, 2) would not require any strengthening or reinforcing to prevent cracking and splitting when cooled to liquid hydrogen temperature, and 3) would have a thermal conductivity of approximately 0.015 J/m•K at a mean temperature of 135 K.

Three 0.56 m diameter aluminum spherical tanks having wall thicknesses of 0.056 cm were insulated with a 2.54 cm thick, rigid, freon-blown, polyurethane foam with a nominal density of 32 kg/m^3. Two tanks were insulated using a foaming-in-place process with each tank suspended in a cylindrical mold. The third tank was insulated with a slightly different polyurethane formulation and simplified foaming-in-place process where the foam constituents were poured directly on the tank wall and allowed to expand in a radial direction.

Testing of the insulated tank assemblies included 1) cooldown and boiloff tests to determine insulation temperature profiles, thermal conductivity and structural integrity under simulated ground-hold conditions, 2) vibratory compressive tests under simulated ground-hold and launch conditions, and 3) cooldown tests for simulated space-hold conditions where the entire foam thickness was cooled to temperatures near that of liquid hydrogen (21 K).

The initial (first two tanks) foaming-in-place process produced an unsatisfactory insulation, where the direction of foam rise relative to the tank wall varied from top to bottom, and which failed structurally under both ground-hold and space-hold conditions. The simplified process used on the third tank produced a satisfactory insulation in which the direction of foam rise was normal to the tank wall at all locations, which had uniform cell size and structure and which exhibited relatively uniform physical properties. The insulation fabricated with this process provided the desired thermal performance and remained structurally intact through all ground-hold, vibratory and space-hold tests.

Small samples of the insulation were used to measure the thermo-physical properties of the insulation material itself. Graphical results are presented for compressive yield strength, compressive modulus of elasticity, tensile yield strength, tensile modulus of elasticity, shear modulus of elasticity, thermal contraction and thermal conductivity.

Important references:

1. Dearing, D. L., Advances in Cryogenic Engineering 11, 89-97 (1968).

2. Hammond, M. B., Jr., Chem. Eng. Progr. Symp. Ser. 62, No. 61, 213-8 (1966).

3. Lewis Research Center Staff, NASA TN-D-2685 (1965).

4. Sterbentz, W. H., and Baxter, J. W., Lockheed Missiles and Space Co., Rept. No. LMSC-A7944993, Vol 2 and NASA CR-54879, Vol 2 (Nov 1966).

5. Haskins, J. F., and Hertz, J., Advances in Cryogenic Engineering 7, 353-9 (1962).

6. Sweet, H. S., and Steele, A. J., Lockheed Missiles and Space Co., Rept. No. LMSC-A709158 and NASA CR-59622 (1964).

THE APPLICATION OF RIGID CELLULAR P.V.C. AS AN INSULANT FOR VERY LOW TEMPERATURES
Tachdjian, N. (Ste Kleber Colombes Plastiques, France)
Bull. IIR Annexe 1965-6, Meeting of Comm. 8 (Sweden, Sep 13-17, 1965), 369-79 (1965)

This paper reviews polyvinyl chloride (PVC) rigid foam, its properties, and its application as thermal insulation. The problems of cracking and of creep are discussed at some length. Cracking results from differential thermal contraction between a foam insulation and facing or base materials attached to the foam. If the foam is not free to contract during cooling, it may crack. The best solution to the problem is described as application of the foam in such a way that it is left free to contract. Another solution is to increase the density of the foam in areas of potential cracking, to the point where the foam itself can sustain the loads imposed by thermal contraction. Tests for creep tendency are described as only partially complete. Creep characteristics are not necessarily constant with time, so that extrapolation from short-term tests can be disastrous. PVC foam is described as having very slow creep at temperatures below 278 K, and no detectable creep at temperatures below 238 K.

An appendix compares some of the properties of PVC foam with other foams. Approximate densities and thermal conductivities at a mean temperature of 273 K are tabulated. A nomogram gives the thermal conductivity of PVC foam as a function of hot face and cold face temperatures. Water vapor permeabilities and tensile and compressive strengths are tabulated. In most cases, PVC foam is shown as having superior properties.

KLEGECELL THERMAL INSULATION FOR LIQUID HYDROGEN TANK OF CRYOGENIC STAGE

Tariel, H. M., Boissin, J. C., Segel, M. P. (Societe L'Air Liquide, Centre d'Etudes Cryogeniques, Sassenage, France)

Advances in Cryogenic Engineering 12, Proc. Cryogenic Engineering Conf. (Boulder, Colo., Jun 13-15, 1966), K. D. Timmerhaus, Editor. Plenum Press, New York, 274-85 (1967)

Polyurethane foam insulation for liquid hydrogen tanks of spacecraft has the disadvantage that the cell walls are permeable, to air in the case of external insulation, and to hydrogen for internal insulation. Polyurethane foam also has relatively low mechanical strength. A rigid crosslinked polyvinyl chloride foam is proposed as a solution to these problems.

Two densities of PVC foam, 30 and 55 kg/m^3, were tested. The tests were tensile strength and modulus at 20 K, 77 K, and 300 K; compressive strength and modulus at 20 K, 77 K and 300 K; thermal contraction between 20 K and 373 K; permeability to air before and after exposure to liquid hydrogen; impact sensitivity in liquid oxygen; thermal conductivity between a surface at 20 K and a surface at 77 K to 345 K; and specific heat from 20 K to 300 K. The higher density material had higher tensile and compressive strengths. Tensile strengths decreased gradually with decreasing temperature. Compressive strengths decreased gradually with decreasing temperature to 77 K, then increased sharply at 20 K. Permeability to air was too small to measure. No reactions were observed with impact in liquid oxygen. Thermal conductivity increased non-linearly with increasing temperature from 0.007 W/m·K at 50 K to 0.027 W/m·K at 300 K. Specific heat followed an S-curve with a maximum near 50 K and a minimum near 150 K.

The proposed insulation system consists of the foam bonded to the outside of the tank wall with a polyurethane adhesive, and a constrictive fiberglass-polyurethane laminate wrapped over the foam as protection from vibration and external stresses, and a final external coating of ablative material as protection against atmospheric heating during launch. Sample small scale tanks insulated as proposed were reported to have withstood thermal cycling with liquid hydrogen, with no observable damage.

Important references:

1. Dearing, D. L., Advances in Cryogenic Engineering 11, 89-97 (1966).

2. Middleton, R. L., Advances in Cryogenic Engineering 10, 216-23 (1965).

3. NASA-Lewis Research Center, Tech. Note No. NASA-TN-D-2685.

INTERNAL INSULATION FOR LNG

Tatro, R. E., and Bennett, F. O., Jr. (General Dynamics, San Diego, Calif. Convair Div.)

Advances in Cryogenic Engineering 20 (Presented at National Technical Meetings during 1973 and 1974), K. D. Timmerhaus, Editor. Plenum Press, New York, 315-26 (1975)

This paper describes the gas-layer-insulation concept, the polyphenylene oxide (PPO) foam that accomplishes the concept, the properties of PPO as evaluated for aerospace applications, and the possibilities of using PPO as internal insulation for the tanks of liquefied natural gas tanker ships.

PPO foam is made up of parallel elongated open cells, oriented so that the cells are open through a layer of the foam. When the foam is bonded to a tank wall, so that the wall seals one end of the cells, and the tank is filled with a cryogenic liquid, the cells fill with vapors of the liquid, and gas pressure and surface tension prevent liquid from entering the cells. This forms an insulating stagnant layer of gas between the liquid and the tank wall. The properties of PPO foam discussed in the paper are the effects of thermal aging at 450 K and thermal cycling from 21 K to 450 K, density and uniformity of the foam, lateral permeability as a function of foam density and pressure drop, thermal conductivity as a function of density from 50 K to 190 K, compressive and tensile yield strengths in longitudinal and lateral directions as a function of foam density from 20 K to 400 K, and compatibility with liquid ethane and liquid methane.

Internal insulation in LNG tankers would have a number of advantages. Because the tank wall remains warm, structures and materials are less critical, heat leak due to structural supports is decreased, and less LNG is required for cooldown because the tank structure is not cooled. PPO foam, being open-celled, would not trap vapors and could be more easily purged than closed-cell foams, reducing the possibility of fires such as occurred in the Staten Island disaster. PPO foam is considered a promising candidate for internal insulation for LNG tankers.

Important references:

1. Yates, G. B., Advances in Cryogenic Engineering 20, 327 (1975).

2. General Dynamics, Convair Division Rept. No. GOCA 632-3-169, Contract NAS 8-27203 (Feb 15, 1973).

MEASUREMENTS OF HEAT TRANSMISSION IN THERMAL INSULATIONS AT CRYOGENIC TEMPERATURES USING THE GUARDED HOT PLATE METHOD
Tye, R. P. (Dynatech R/D Co., Cambridge, Mass.)
Progress in Refrigeration Science and Technology 1, Proc. International Conf., XIII (Washington, D. C., 1971). AVI Publishing Co., Inc., Westport, Conn., 371-8 (1973)

The thermal conductivities of five types of commercial insulating materials were measured. The materials tested were foamed glass, polyurethane foam (2 densities), polyvinyl chloride foam (4 densities and 2 blowing agents), vermiculite (3 grades), and a fiberglass blanket-type insulation. Thermal conductivities were measured in the temperature range from 120 K to 300 K, with some measurements on vermiculite near 90 K. A guarded hot plate apparatus was used and an accuracy of 3 percent is claimed for the results.

The two polyurethanes behaved identically over the temperature range, with an s-shaped curve having a maximum near 240 K and a minimum near 260 K. The PVC foams generally showed a steadily increasing thermal conductivity with increasing temperature. While the polyurethanes had lower thermal conductivities than the PVC foams at temperatures above 270 K, the inflected curve resulted in the PVC foams having conductivities 11% to 20% below the polyurethanes at temperatures below 230 K. The other materials had thermal conductivities substantially above the foams, increasing through the fiberglass blanket and the foamed glass to the three grades of vermiculite. Of the materials tested, the lowest thermal conductivity at cryogenic temperature is observed for the PVC foams.

Important references:

1. Thermal Insulation Systems, NASA SP-5027 (1967).
2. Dushman, S., Vacuum Technique, John Wiley & Sons, New York, 50 (1945).
3. Haskins, J. F., and Hertz, J., Advances in Cryogenic Engineering 7, 353 (1962).
4. Tariel, H. M., Boissin, J. C., and Segel, M. P., Advances in Cryogenic Engineering 12, 274 (1967).

SOME OBSERVATIONS ON THE COEFFICIENT OF THE THERMAL EXPANSION OF POLYSTYRENE FOAMS AT LOW TEMPERATURE

Vahl, L. (Technische Hogeschool, Delft, Netherlands)

Progress in Refrigeration Science and Technology, Proc. International Congress of Refrigeration, Xth (Copenhagen, Denmark, 1959) - Vol 1. Pergamon Press, 317-24 (1960)

Polystyrene foam panels used as insulation for low temperature equipment developed cracks after a period of operation. The cracks were thought to be caused by thermal stresses, but data on thermal contraction at low temperatures were not available. An experimental program was conducted to measure coefficients of thermal expansion.

Closed cell polystyrene foams of 12.4, 24.3, and 37.5 kg/m^3 densities were measured during cooling from 288 K to 123 K over a period of 3 h, hold at 123 K for 1 h, then rewarming to 288 K. The lowest-density foam had a relatively large thermal contraction, and contraction per degree of cooling was greater at lower temperatures. The contraction continued even during the period of hold at constant temperature. The sample exhibited a hysteresis effect, with the dimensional changes following different curves with respect to temperature during cooling and warming. The two higher-density foams behaved differently. The rates of thermal contraction were lower and remained constant over the temperature range, there was no dimensional change during hold at 123 K, and there was little or no hysteresis effect.

The author attributes the behavior of the lowest-density foam to differential thermal contraction of polystyrene in the cell walls and air contained in the cells. The greater contraction of the air apparently caused a breakdown of the cell walls. This breakdown continued as a sort of creep during hold at constant temperature. The destruction caused by thermal contraction makes foam of this density unsuitable for use as insulation at temperatures below about 230 K. Further examinations were recommended to determine whether the higher-density foams could be used below this temperature.

VESSELS FOR LIQUEFIED GASES FORMED FROM POLYSTYRENE FOAM PSB
Vedernikov, M. V., Filippov, V. A., and Krivets, L. I. (Academy of Sciences of the USSR, Leningrad. Inst. of Semiconductors)
Cryogenics 9, No. 5, 386-7 (Oct 1969)

This paper describes, in detail, a method for producing cryogenic containers from foamed polystyrene PSB (polystyrene beads). The method can be used in the laboratory with very little equipment and is particularly useful in forming vessels of large sizes or complex shapes where glass flasks are impractical. Experiments by the authors showed that the consumption of liquid nitrogen when using a foamed plastic vessel, even with comparatively little heat conduction in the casing of the submerged device, exceeds by only 35-50% its evaporation from a glass vessel of the same shape and volume. When more massive devices are cooled, this difference practically disappears.

The process of fabricating vessels of foam consists of three stages: 1) prefoaming the polystyrene beads in boiling water (they expand 10-30 times normal size), 2) curing of the prefoamed beads (in air at ambient temperatures), 3) molding, wherein the preformed beads are placed in the mold which is immersed in boiling water. This causes further expansion of the beads. The article is then removed from the mold and allowed to cool under ambient conditions.

OPEN CELL CRYOGENIC INSULATION
Yates, G. B. (General Dynamics, San Diego, Calif. Convair Div.)
Advances in Cryogenic Engineering 16, Proc. Cryogenic Engineering Conference (Boulder, Colo., Jun 17-19, 1970), K. D. Timmerhaus, Editor. Plenum Press, New York, 128-37 (1971)

The open-cell insulation concept was considered for use as internal insulation in the liquid hydrogen tanks of reusable space vehicles, such as the space shuttle. In this concept, narrow open cells are bonded to the tank wall at one end and open to the tanked liquid at the other. The cells are sized so that surface tension maintains a stable interface between liquid in the tank and gas in the cell. This paper describes an analysis and some preliminary tests of the concept.

The analysis showed that the open-cell concept has a lower thermal efficiency than previous closed-cell insulations, and about the same efficiency as a helium-purged system. The thermal conductivity of the insulation is essentially that of the gas filling the cells. Theoretical cell sizes to support stable interfaces with water, liquid hydrogen, liquid oxygen, and liquid nitrogen were calculated.

The three open-cell insulations tested were polyphenylene oxide (PPO) foam and two sizes of phenolic honeycomb. The larger cell-size honeycomb was faced with fine-mesh screen or filled with the PPO foam to maintain stable liquid/gas interface. Screening tests were run with insulation bonded to the bottom of an open beaker, which was then filled with liquid hydrogen. Larger scale tests used the insulation bonded to the inner surfaces of a rectangular 0.21 m^3 tank, filled with liquid hydrogen or liquid nitrogen. In all cases, the PPO foam was the lightest and most efficient of the insulations. Ability of the honeycomb to maintain a stable liquid/gas interface was marginal in some cases. Convection heat transfer was appreciable in the honeycombs but not in the PPO foam. The insulation kept the tank external surface at a temperature high enough to prevent condensation of air.

The author concludes that the feasibility of the concept was established.

Important references:

1. PPO Foam: A Unique High Temperature Insulation, Technical Data Sheet, General Electric Company, October 1967.

2. Kouffeld, R. W. J. and van Riesen, P. E., Ref. No. 67-02294, Centraal Technisch Instituut, T.N.O., Delft, 31 Jul 1967.

PPO FOAM. LIQUID HYDROGEN INSULATION

Yates, G. B. (General Dynamics, San Diego, Calif. Convair Div.)
Advances in Cryogenic Engineering 20 (Presented at National Technical Meetings during 1973 and 1974), K. D. Timmerhaus, Editor. Plenum Press, New York, 327-37 (1975)

An extensive fabrication and test program was carried out to demonstrate the use of polyphenylene oxide (PPO) foam as an internal insulation for liquid hydrogen tanks. Early results were reported in the paper abstracted on page 102, which described the concept and advantages of open-cell internal insulation. This paper describes application of the insulation to an aluminum test tank, and the test program simulating launch vehicle flight cycles.

The PPO foam was heat-formed to the necessary contours, trimmed into panels, and bonded to the tank walls with a urethane adhesive. The panels were made 2% oversize and compressed 2% during installation to form solid joints between panels without using adhesive, and to prevent joint gaps caused by thermal contraction. The test program consisted of 100 cycles of tanking and chilldown with liquid hydrogen, pressurization, rapid detanking, and heating of the tank surface. The cycles simulated service in a liquid-hydrogen-fueled reusable booster or reusable orbiter. Thermal performance of the insulation was determined by measuring boiloff rates and temperature gradients, which did not change significantly over the test program. Post-test examination showed no apparent deterioration of the PPO foam.

The authors conclude that PPO foam has been demonstrated to be a reliable and reusable internal insulation for liquid hydrogen. Its primary limitation is its relatively high thermal conductivity. Because the open cells of the foam are filled with gaseous hydrogen during service, the thermal conductivity must be equal to or greater than that of gaseous hydrogen.

Important references:

1. Yates, G. B., Advances in Cryogenic Engineering 16, 128 (1971).
2. Tatro, R. E. and Bennett, F. O., Jr., Advances in Cryogenic Engineering 20, 315 (1975).
3. Space Shuttle Structural Test Program Final Report, Convair Division of General Dynamics, Rept. No. 549-3-092 (Mar 1972).
4. Yates, G. B. and Tatro, R. E., Proceedings of the Space Transportation System Propulsion Technology Conference, Vol. IV, NASA, Marshall Space Flight Center, 1441 (Apr 1971).

PPO FOAM INTERNAL INSULATION

Yates, G. B., and Tatro, R. E. (General Dynamics/Convair, San Diego, Calif.)

Space Transportation System Propulsion Technology, Proc. Conf. (George C. Marshall Space Flight Center, Huntsville, Ala., Apr 6-7, 1971) - Vol 4 - Cryogens. National Aeronautics and Space Administration, Rept. No. NASA TM-X-67348, 1439-52 (Apr 1971)

The reusable mission of the Space Shuttle imposes new requirements on liquid hydrogen tank insulation systems. A candidate system is polyphenylene oxide (PPO) open cell foam used as internal insulation. Internal insulation is exposed only to a known and controlled environment, and the tank wall and insulation bond line are kept warm to minimize thermal stresses. The PPO foam is open celled and not subjected to cyclic pressure fatigue, and is a simple one-component insulation.

The PPO foam was made in thicknesses up to 8 cm, and densities from 30 to 180 kg/m^3. The open cells are elongated and extend through the thickness of the foam. Tests with helium showed the presence of some lateral gas movement between cells, but this had no apparent effect on thermal performance. At a temperature of 20 K, the foam exhibited 2% elongation and 2% elastic compression parallel to fiber direction. Face tensile, compression, core shear, and climbing drum peel tests were conducted between 20 K and 422 K. Tensile strengths decreased slightly with temperature increasing from 20 K to 300 K, then decreased more sharply with temperature increasing above 300 K. Compressive strengths gradually decreased with increasing temperature over the entire temperature range. Shear and peel strengths had more complicated temperature dependence, but were generally low at 20 K and high at 422 K. Samples bonded to aluminum were fatigue tested at 20 K, 294 K, and 394 K, and withstood 400 cycles at each temperature with no observable damage. Thermal conductivity at mean temperatures from 200 K to 350 K was from 1.10 to 1.25 times the thermal conductivity of gaseous parahydrogen at the same temperature. The foam could be hot-formed to various desired shapes.

The authors conclude that the feasibility of using PPO foam as internal liquid hydrogen tank insulation has been demonstrated.

HEAT CONDUCTIVITY MEASUREMENTS ON FOAM PLASTICS AT LOW TEMPERATURES

Zehendner, H. (Forschungsinstitut fuer Warmeschutz, Munich, Germany)

Kaeltetechnik.-Klim. 19, No. 1, 2-8 (Jan 1967)

This paper presents results of an extensive study of the cell structures and thermal conductivities of a number of commercially available foam insulations. The materials studied were two phenolic foams with densities 27 and 104 kg/m^3, a polyethylene foam with density 37 kg/m^3, four polystyrene foams with densities 12.7, 24, 37 and 62 kg/m^3, two polyurethane foams, one a cast foam with density 26 kg/m^3 and the other a spray foam with density 43 kg/m^3, two polyvinyl chloride foams with densities 43 and 70 kg/m^3, and a hard rubber foam with density 79 kg/m^3. Microphotographs of the cell structures of the foams are shown. Thermal conductivities of the foams were measured from 93 K to 323 K.

The thermal conductivities of the two phenolic foams show a nearly linear increase with increasing temperature, but with the high-density material having a thermal conductivity consistently higher than that of the low-density foam. This is attributed to the high-density foam having such small cells and such a high solid content that it acts more like solid than foam phenolic. Thermal conductivity of the polyethylene foam is higher than that of any of the other foams, and increases strongly with increasing temperature.

Thermal conductivities of the polystyrene foams were studied as a function of foam density. The curves of thermal conductivity versus temperature show a steady increase with increasing temperature, but differences between foams are difficult to see. A presentation of thermal conductivity versus foam density reveals that at any temperature level, there is a density having minimum thermal conductivity, and that this optimum density is higher at higher temperature.

The polyurethane foams have a complicated thermal conductivity curve, increasing with increasing temperature up to about 225 K, then decreasing until the temperature reaches about 272 K, then once more increasing with increasing temperature. The region between 225 and 323 K is further complicated by an age effect, in which older foams have a higher thermal conductivity than freshly-made samples. This aging effect is attributed to the gradual replacement of the fluorotrichloromethane blowing agent with atmospheric air by diffusion through the cell walls. This gradual increase in thermal conductivity was still continuing steadily at 30 months storage time.

The thermal conductivities of the polyvinyl chloride foams increased non-linearly with increasing temperature, with the low-density foam having lower thermal conductivity at temperatures below about 220 K, and the high-density foam superior above this temperature. The hard rubber foam showed a linear increase of thermal conductivity with increasing temperature.

Important references:

1. Cammerer, W. F., Kaeltetechnik 12, 107-10 (1960).
2. Achtziger, J., Kaeltetechnik 12, 372-5 (1960).
3. Schmidt, W., Kunststoffe 53, No. 7, 413-20 (1963).
4. Eiermann, K., Hellwege, K. H., and Knappe, W., Kolloid Z. 174, No. 2, 134-42 (1961).

INSULATION MATERIALS SELECTION CRITERIA FOR AN AERODYNAMIC PROTECTED CRYOGENIC STAGE (AUSWAHL UND EXPERIMENTELLE UNTERSUCHUNG EINES AERODYNAMISCHEN NICHT BELASTBAREN SCHAUMSTOFFISOLATIONS-SYSTEMS FUER KRYOGENE RAKETENSTUFEN)

Zimni, W. F., and Breves, E. O. (ERNO Raumfahrttechnik GmbH, Bremen, West Germany)

Luftfahrttechnik Raumfahrttechnik 16, No. 10, 251-7 (Oct 1970)

An experimental program was conducted to select an insulation system for use as external insulation on the liquid hydrogen and liquid oxygen tanks of a launch vehicle. The materials considered were polyurethane foam, the material used in the United States space program, and polyvinyl chloride foam, the material preferred in the French program. The test program included application of the foam to the surface of a liquid hydrogen tank and testing under simulated space flight conditions. Both foams were applied to tanks in two variations, the first with foam panels completely enclosed in mylar film vapor barrier, and the panels then bonded to the tank wall, the second with the foam bonded directly to the tank without any intervening film. Temperatures were measured during boiloff of liquid hydrogen in the tank, and heat leaks through the insulation into the tank were determined.

The test results led to the conclusion that the two materials were approximately equal in terms of thermal performance, while the polyurethane had some advantage in ease of application. The polyurethane foam has a high thermal expansion coefficient, which can be decreased by the addition of glass fiber reinforcement to the foam without degrading thermal performance. The tests qualified the materials for use as cryogenic tank insulation.

Important references:

1. Stumpf, O. and Zimni, W. F., Proc. of the XVIII Astronautical Congress, Vol III (Oct 1966).
2. Tariel, Boissin and Segel, Adv. Cryog. Eng. 12, 274 (1966).
3. Zimni, W. and Mertzner, K., Klimatisierung, No. 2 (1970).

THE THERMAL PROPERTIES OF FOAMS AND FOAMED HONEYCOMBS IN THE TEMPERATURE RANGE BETWEEN 20 AND 300 K

Zimni, W. F., and Meitzner, K. (ERNO-Raumfahrttechnik GmbH, Bremen, West Germany)

Kaeltetech.-Klim. 22, No. 2, 34-40 (Feb 1970)

This paper reviews measurements made over a period of several years, of the thermal properties of a number of foams and composite insulating materials. The polyurethanes, which were the most often used foams in the United States space program, and polyvinyl chloride foam, preferred by the French, were the primary materials investigated. The materials also included a phenolic foam, phenolic-fiberglass honeycombs filled with foam, and polyurethane foams with 5 to 10% glass fibers added. The properties measured were thermal conductivity, thermal expansion and specific heat.

Thermal conductivities were measured at mean temperatures between 20 K and 320 K. Comparisons of results show the effects of blowing agents, aging, densities, and sample thickness. Polyurethane and polyvinyl chloride foams of similar density, both blown with trichlorofluoromethane, had nearly identical thermal conductivities. An air-blown foam and a halocarbon-blown foam showed the same thermal conductivity up to about 250 K, but the air-blown foam lacked the S-curve characteristic typical of halocarbon-blown foams at higher temperatures. Thermal expansions were measured between 4 K and 380 K. Particularly striking was the very high thermal expansion of the polyurethane foam, and the great decrease of this expansion caused by the addition of glass fibers. Specific heats of foams were difficult to measure, but the specific heat of a very high density polyurethane foam is shown between 20 K and 350 K.

In general, the tests showed a superiority for halocarbon-blown foams over air-blown foams as insulation. Reinforcement of the polyurethane foam with glass fibers improved its thermal expansion coefficient and its elasticity.

Important references:

1. Kreft, H., and Wagner, D., Kaeltetech.-Klim. 21, No. 9, 258-65 (1969).
2. Koglin, B., and Zimni, W., ERNO Raumfahrttechnik GmbH, Bremen, Germany, Rept. (Oct 1967).
3. Stumpf, O., and Zimni, W., Proc. Astronautical Congress, XVII - Vol III (Oct 1966).
4. Koglin, B., Gesellschaft fuer Weltraumforschung mbH, Bonn-Bad Godesberg, Techn. Bericht (No Date).
5. Koglin, B., and Zimni, W., Techn. Rev. 2, No. 1, 3-28 (1967).

OTHER DOCUMENTS

OTHER DOCUMENTS

001
AGRAWAL,K.N. VERMA,V.V.
AN APPARATUS FOR THE STUDY OF HEAT AND MASS TRANSFER PROPERTIES OF INSULATING MATERIALS AT LOW MEAN TEMPERATURES. INDIAN J. TECHNOL. VOL 7, NO. 1, 4-8 (JAN 1969)

002
ALLEAUME,J.
THE TRANSPORT BY SEA OF NATURAL LIQUEFIED GAS AND OF ETHYLENE. (IN FRENCH) REV. GEN. FROID VOL 56, NO. 9, 1027-32 (SEP 1965)

003
ALLEN,R.J.
SURFACE INSULATION FOR CRYOGENIC FLUIDS. REV. SCI. INSTR. VOL 31, NO. 2, 203 (FEB 1960)

004
ALLEN,R.J. VAN PAASSEN,H.L.L.
FLOATING POLYSTYRENE BEADS AS INSULATION FOR CRYOGENIC FLUIDS. ADVANCES IN CRYOGENIC ENGINEERING VOL 6, 548-54 (PROCEEDINGS OF THE 1960 CRYOGENIC ENGINEERING CONFERENCE) PLENUM PRESS INC., NEW YORK (1961)

005
AMERICAN GAS ASSOCIATION
LNG INFORMATION BOOK - 1973. AMERICAN GAS ASSOC., ARLINGTON, VA., 100PP (1973)

006
ARNOLDY,C.
TECHNICAL ANALYSIS. PIPING. AN EXPANDING INTERFACE. CRYOGENICS AND ENERGY PERSONNEL. CRYOGEN. TECHNOL. VOL 7, NO. 6, 193-7 (NOV/DEC 1971)

007
ASAY,J.R. URZENDOWSKI,S.R.
GUENTHER,A.H.
ULTRASONIC AND THERMAL STUDIES OF SELECTED PLASTICS, LAMINATED MATERIALS AND METALS. ALBUQUERQUE UNIV., N. MEX., REPT. NO. AFWL TR-67-91 (JAN 1968) CONTR. NO. F29601-67-C-0042 262 PP

008
ASHIDA,K. OHTANI,M. ICHII,M.
KOBAYASHI,T.
CRYOGENIC THERMAL INSULATION. (IN GERMAN) GERMAN OFFEN. NO. 2,430,985 (JUN 1974)

009
ASHWORTH,T. SMITH,M.G.
A RADIAL HEAT-FLOW METHOD FOR POOR CONDUCTORS. THERMAL CONDUCTIVITY (PROCEEDINGS OF A CONFERENCE 9TH, IOWA STATE UNIV., AMES, OCT 6, 7 AND 8, 1969) H. R. SHANKS, ED., NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VA. (MAR 1970) CONF-691002 PP 524-9

OTHER DOCUMENTS
(CONT.)

010
ASKE,H.D. SPENCER,S.E.
INSULATED CRYOGENIC REFRIGERATOR COLD HEAD. U. S. PATENT 3,504,505 (APR 1970)

011
BACKHAUS,H.W. JANSSEN,R.
LNG INLAND TRANSPORTATION WITH RAILWAY TANK CARS AND RIVER-GOING TANKERS. INTERNATIONAL CONFERENCE ON LIQUEFIED NATURAL GAS, PROC. FOURTH. ALGIERS, ALGERIA, JUN 24-7, 1974. INSTITUTE OF GAS TECHNOLOGY, CHICAGO, ILL., SESSION-VI-PAPER-2, 16PP (1974)

012
BAEHR,F.
NEW THERMAL INSULATORS COMPARE FAVORABLY WITH PRESENT METHODS. CAN. PET. VOL 14, 34-6 (1973)

013
BAHRENBURG,H.H.
LN2--PIPE IT. HAUL IT. CRYOGENIC ENG. NEWS VOL 2, NO. 2, 22, 24-5 (FEB 1967)

014
BAHRENBURG,H.H.
URETHANE FOAM IS FLEXIBLE. CRYOGENICS IND. GASES VOL 4, NO. 7, 29-30 (JUL 1969)

015
BAILEY,A.B. CRUDDACE,R.G.
RICKETSON,B.W.A.
THE USE OF LIQUID HYDROGEN IN THE THIRD STAGE OF A SATELLITE VEHICLE. J. BRIT. INTERPLANET. SOC. VOL 18, NO. 5/6, 203-24 (SEP-DEC 1961)

016
BAILEY,B.M. BENEDICT,D.C. BYRNES,R.W.
CAMPBELL,C.R. FOWLE,A.A. MOORE,R.W.
PESTALOZZI,W.G. RICHTER,E.G.
RUCCIA,F.E. SCHULTE,C.A.
STORAGE, TRANSFER AND SERVICING EQUIPMENT FOR LIQUID HYDROGEN. LITTLE, ARTHUR D., INC., WADC TECH. REPT. 59-386 (JUL 1959) CONTR. AF 33(616)-5641, 772 PP

017
BAILEY,C.A.
HEAT TRANSFER AND THERMAL INSULATION. ADVANCED CRYOGENICS, 133-53. C.A. BAILEY, ED., PLENUM PRESS, NEW YORK (1971)

018
BAILEY,C.D.
LINEAR THERMAL EXPANSION OF ORGANIC MATERIALS AT CRYOGENIC TEMPERATURES. LOCKHEED AIRCRAFT CORP., MARIETTA, GA. REPT. NO. ER-5682 (MAY 1962) 39 PP

019
BANCROFT,G.H.
LIQUID PROPELLANT STORAGE TANK. U. S. PATENT NO. 3,695,050 (OCT 1972)

OTHER DOCUMENTS
(CONT.)

020
BARBER,J.R.
CRYOGENIC INSULATION TECHNOLOGY REVIEW FOR THE SPACE SHUTTLE. SPACE TRANSPORTATION SYSTEM TECHNOLOGY SYMPOSIUM, VOL 5, 146-66 (NASA LEWIS RESEARCH CENTER, CLEVELAND, OHIO, JUL 15-17, 1970) NATIONAL AERONAUTICS AND SPACE ADMINISTRATION TECH. MEMO. NO. X-52876

021
BARITO,R.W. EASTMAN,W.O.
PLASTIC AND ELASTOMERIC FOAMS. HANDBOOK OF PLASTICS AND ELASTOMERS, CHAPTER 7, 7-1 TO 7-79, C. A. HARPER, ED., MCGRAW-HILL, INC. (1975)

022
BARKER,H.H.,JR. LONG,R.L. ROSELLO,D. SOLDAT,G.J. SMITH,T.D.
CRYOGENIC CONTAINERS. U. S. PATENT 3,317,074 (MAY 1967)

023
BARTLETT,D.H. ZIMMERMAN,D.K.
SPACE VEHICLE INTEGRATED THERMAL PROTECTION STRUCTURAL - METEOROID PROTECTION SYSTEM, VOLUME 1. BOEING AEROSPACE CO., SEATTLE, WASH., REPT. NO. D180-15172-1. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION REPT. NO. NASA-CR-121103, CONTRACT NO. NAS3-13316, 397PP (APR 1973)

024
BEAUJEAN,J.M.
TANK FOR LIQUIFIED GASES. U. S. PATENT NO. 3,904,068 (SEP 1975)

025
BENFORD,A.E.
DESIGN CONSIDERATIONS WHEN USING POLYURETHANE FOAM IN REFRIGERATION APPLICATIONS. ASME DESIGN ENGINEERING CONFERENCE AND SHOW, CHICAGO, ILL. (APR 22-25, 1968) PAPER NO. ASME 68-DE-19, 7 PP

026
BERGER,DR.
NOVEL INGROUND STORAGE UNITS. (IN GERMAN) GAS WASSERFACH VOL 110, 1085-93 (SEP 1969)

027
BETTANINI,E. TRAPANESE,G.
EFFECT OF HUMIDITY ON THE THERMAL CONDUCTIVITY OF INSULATING MATERIALS. (IN ITALIAN) FREDDO VOL 20, NO. 6, 11-6 (1966)

028
BIAIS,M.
METHOD OF INSULATING TANKS FOR STORING OR TRANSPORTING LOW-TEMPERATURE LIQUIDS. U. S. PATENT 3,118,194 (JAN 1964)

029
BISIAUX,P.
HYDROGEN-OXYGEN PROPULSION IN FRANCE. (IN FRENCH) LASTRONAUTIQUE, NO. 1, 27-47 (1967)

030
BLACK,I.A. GLASER,P.E.
THERMAL CONDUCTIVITY TESTS OF CRYOGENIC INSULATION. PROC. OF THE SECOND CONF. ON THERMAL CONDUCTIVITY, OTTAWA, CANADA, OCT 10-12, 1962, 111-31. NATIONAL RESEARCH COUNCIL OF CANADA, DIV. OF APPLIED PHYSICS, OTTAWA.

031
BODLEY,R.W.
DESIGN CONSIDERATIONS FOR LNG STORAGE TANKS. CURRENT UNITED STATES PRACTICE. PROC. OF INTERNATIONAL CONFERENCE ON LIQUEFIED NATURAL GAS, LONDON, MAR 1969, 457-68

032
BOEING CO., SEATTLE, WASH.
DEMONSTRATION OF MANUFACTURING TECHNIQUES FOR APPLICATION OF HIGH PERFORMANCE CRYOGENIC INSULATION. FINAL REP. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, HUNTSVILLE, ALA. GEORGE C. MARSHALL SPACE FLIGHT CENTER, REP. NO. NASA-CR-98459, D2-139267-1 (SEP 1968) CONTR. NO. NAS8-21341 52 PP

033
BONALLACK,R.F. BILLS,H.
INSULATED BODIES FOR COMMERCIAL VEHICLES. U. S. PATENT NO. 3,481,642 (DEC 1969)

034
BORUP,H.H.
CRYOGENIC TANK. U. S. PATENT NO. 3,929,247 (DEC 1975)

035
BRANDT,N.B. SVISTOVA,E.A. SEMENOV,M.V.
A MINIATURE APPARATUS FOR OBTAINING INTERMEDIATE TEMPERATURES. CRYOGENICS VOL 11, NO. 1, 59-61 (FEB 1971)

036
BRISSAUD,J. DE FRONDEVILLE,B.
APPLICATION OF THE PYTHAGORE MEMBRANE TECHNIQUE TO LAND STORAGE OF LNG. (IN FRENCH) ENGINEERING, TRANSPORT AND OPERATIONS RESEARCH VOL 6, 307-14 (PROCEEDINGS OF THE WORLD PETROLEUM CONGRESS 7TH, 1967) ELSEVIER PUBLISHING CO., LTD. (1967)

037
BRITISH CHEMICAL ENGINEERING
ECONOMIC TRANSFER OF CRYOGENIC LIQUIDS. BRIT. CHEM. ENG., VOL 12, NO. 4, 579 (APR 1967)

OTHER DOCUMENTS
(CONT.)

038
BRITISH CHEMICAL ENGINEERING
PIPELINES FOR LOW TEMPERATURES. BRIT. CHEM. ENG. VOL 14, NO. 2, PPR 31-5 (FEB 1969)

039
BRITISH CRYOGENICS COUNCIL
CRYOGENICS SAFETY MANUAL. INSTITUTION OF CHEMICAL ENGINEERS, LONDON, ENGLAND (1970) 107 PP

040
BROCHHAGEN,F.K. SCHMIDT,W.
INSULATION OF PIPES WITH EXPANDED POLYURETHANE. (IN GERMAN) KUNSTSTOFFE VOL 57, NO. 4, 228-34 (1967)

041
BROGAN,J.J.
IMPACT OF PROPELLANT HEATING ON NUCLEAR SPACECRAFT INSULATION AND PRESSURIZATION SYSTEMS DESIGN. J. SPACECRAFT ROCKETS VOL 3, NO. 6, 932-4 (JUN 1966)

042
BUIST,J.M. DOHERTY,D.J. HURD,R.
URETHANE RIGID FOAMS, FACTORS AFFECTING THEIR BEHAVIOUR AS THERMAL INSULANTS. INTERN. CONGR. OF REFRIGERATION, 11TH, MUNICH (AUG 1963) PAPER II-22, 9 PP

043
BULLETIN TECH. BUREAU VERITAS
THE ANNA SCHULTE LIQUEFIED GAS CARRIER. (IN FRENCH) BULL. TECH. BUR. VERITAS VOL 56, NO. 2, 36-7 (FEB 1974)

044
BURGE,G.W.
CONCEPTUAL DESIGN OF AN INTEGRATED ON-DEMAND FLOW CRYOGEN FEED SYSTEM FOR IN-ORBIT APPLICATIONS. CRYOGENIC WORKSHOP, PROC., NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, HUNTSVILLE, ALA. GEORGE C. MARSHALL SPACE FLIGHT CENTER, 299-324 (MAR 19-20, 1972)

045
BUTTERWORTH,H.H.
THE INSULATION OF REFRIGERATED CONTAINERS AND ROAD VEHICLES. MOD. REFRIG. VOL 70, NO. 832, 50-3 (JUL 1967)

046
CAMPBELL,M.D. HASKINS,J.F. HERTZ,J. JONES,H. PERCY,J.L.
THIRTY DAY EVALUATION OF FOAMS AND HONEYCOMB FOR CENTAUR INTERMEDIATE BULKHEAD. GENERAL DYNAMICS/ASTRONAUTICS, SAN DIEGO, REPT. NO. MRG-312 (APR 1962) CONTR. NO. AF 33(616)-7984, 75 PP

047
CEINTREY,M.
HEAT-INSULATED CONDUIT OF UTILITY IN THE TRANSPORT OF FUELS OVER LONG DISTANCES. U. S. PATENT NO. 3,420,277 (JAN 1969)

OTHER DOCUMENTS
(CONT.)

048
CERQUETTINI,C.
SPRAYABLE POLYURETHANE FOAM INSULATION, SATURN S-II BOOSTER. SAMPE J. VOL 5, NO. 4, 28-9 (JUN-JUL 1969)

049
CHEMICAL PROCESS ENGINEERING
INSULATION WITH URETHANE FOAM. CHEM. PROCESS ENG. VOL 46, 659 AND 661 (DEC 1965)

050
CHEMICAL PROCESS ENGINEERING
PROTECTING CRYOGENIC LIQUIDS WITH BALL BLANKETS. CHEM. PROCESS ENG. VOL 52, NO. 2, 54 (FEB 1971)

051
CHEYNEY,D.R.
INSULATED TANK. U. S. PATENT NO. 3,931,908 (JAN 1976)

052
CLARK,J.A.
TRANSIENT CONDENSATION ON INSULATING SUBSTANCES FOR CRYOGENIC APPLICATION. ADVANCES IN CRYOGENIC ENGINEERING VOL 7, 360-6 (PROCEEDINGS OF THE 1961 CRYOGENIC ENGINEERING CONFERENCE) PLENUM PRESS INC., NEW YORK (1962)

053
CLARKE,J.S. KARCHER,G.G.
INSULATED CRYOGENIC TANK. U. S. PATENT 3,495,732 (FEB 1970)

054
CLARKE,R.C.
THERMALLY INSULATED CONTAINER. U. S. PATENT 3,250,416 (MAY 1966)

055
CLOSNER,J.J.
LNG STORAGE WITH PRESTRESSED CONCRETE. PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON LNG 1ST, CHICAGO, ILL. (APR 7-12, 1968) (J.W. WHITE AND A.E.S. NEUMANN EDS.) INSTITUTE OF GAS TECHNOLOGY, CHICAGO, ILL. (1968) PAPER 32 15 PP

056
CLOTFELTER,W.N. BANKSTON,B.F. DUREN,P.C.
THE NONDESTRUCTIVE EVALUATION OF LOW DENSITY FOAM-ALUMINUM COMPOSITE MATERIALS. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, HUNTSVILLE, ALA. MARSHALL SPACE FLIGHT CENTER, TECH. MEMO X-53940 (OCT 1969) 42 PP

057
COCHRAN,R.P. CUBBISON,R.W.
SUPERSONIC AERODYNAMIC HEATING TESTS ON A LIGHTWEIGHT EXTERNAL INSULATION SYSTEM FOR LIQUID-HYDROGEN TANKS OF BOOST VEHICLES. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, LEWIS RESEARCH CENTER, CLEVELAND, OHIO, TECH. NOTE NO. D-3300 (MAR 1966) 21 PP

058
CODEGONE,C. FERRO,V.
A SQUARE PLATE APPARATUS FOR MEASURING THE THERMAL CONDUCTIVITY OF INSULATING MATERIALS AT LOW TEMPERATURES. BULL. IIR ANNEXE 1964-2, 15-22 (PRESENTED AT MEETING OF COMM. 2, TURIN, ITALY, SEP 9-11, 1964)

059
CODEGONE,C. FERRO,V. SACCHI,A.
THERMAL OSCILLATIONS THROUGH WALLS. PROGR. REFRIG. SCI. TECHNOL. VOL 2, 61-9 (PROC. INT. CONGR. REFRIG., 12TH, MADRID, SPAIN, AUG 30-SEP 6, 1967) INST. INT. FROID, PARIS (1969)

060
CODLIN,E.M.
CRYOGENICS AND REFRIGERATION. A BIBLIOGRAPHICAL GUIDE. IFI/PLENUM DATA CORP, NEW YORK (1968) 311 PP, AND VOL 2 (1970) 283 PP

061
COLDING,L.
INSULATION WITH POLYSTYRENE. (IN DANISH) KULDE (COPENHAGEN) VOL 20, NO. 6, 81-8 (DEC 1966)

062
COOK,H.C.
METHOD OF MANUFACTURING PIPE SECTIONS FOR THE TRANSPORTATION OF CRYOGENIC LIQUIDS. U. S. PATENT 3,453,716 (JUL 1969)

063
COOPER,A.
EXPANDED EBONITE FOR THERMAL INSULATION OF LIQUEFIED GASES. MOD. REFRIG. VOL 68, NO. 805, 339-42, 359 (APR 1965)

064
COOPER,H.C.
STORAGE RESERVOIR FOR LIQUEFIED GASES. U. S. PATENT 2,512,308 (JUN 1950)

065
COSTON,R.M. ZIERMAN,C.A.
CRYOGENIC THERMAL-CONDUCTIVITY MEASUREMENTS OF INSULATING MATERIALS. AMER. SOC. TESTING MATER. SPEC. TECH. PUBL. NO. 411 (1967) PP 25-42

OTHER DOCUMENTS
(CONT.)

066
COULTER,D.M.
DESIGN CONSIDERATIONS FOR A LIQUEFIED NATURAL GAS PIPELINE. ADVANCES IN CRYOGENIC ENGINEERING VOL 15, 28-35 (PROC. OF CRYOGENIC ENGINEERING CONFERENCE, LOS ANGELES, CALIF., JUN 16-18, 1969) K.D. TIMMERHAUS ED., PLENUM PRESS, NEW YORK (1970)

067
COULTER,D.M. NORRIS,D.H. WALKER,G.W.
PIPE LINE DESIGNS FOR THE FAR NORTH. PIPE LINE IND. VOL 31, 41-5 (DEC 1969)

068
CRAWFORD,D.B. BERGMAN,R.A.
INNOVATIONS WILL MARK LNG-RECEIVING TERMINAL. OIL GAS J. VOL 72, NO. 31, 57-61 (AUG 1974)

069
CREASER,L.F.
FLEXIBLE INSULANTS FOR CONTAINERS AND CONDUITS. U. S. PATENT NO. 3,682,824 (AUG 1972)

070
CROCKETT,L.K. WITZELL,W.E.
MATERIALS PROPERTIES AND ALLOWABLES FOR THE SPACE SHUTTLE. SPACE TRANSPORTATION SYSTEMS TECHNOLOGY, PROC. SYMP. (CLEVELAND, OHIO, JUL 15-17, 1970) VOL 3. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, WASHINGTON, D. C., REPT. NO. NASA-TM-X-52876, 273-87 (JUL 1970)

071
CROUCH,G.D.
POLYSTYRENE FOAM. LNG TANK INSULATION. CRYOGENICS IND. GASES VOL 6, NO. 5, 39 (SEP/OCT 1971)

072
CROWL,R.E.
AN LNG SHIP-LOADING PIPELINE. LNG/CRYOGEN. VOL 1, NO. 2, 6-11 (APR/MAY 1973)

073
CRYOGENIC TECHNOLOGY
A SHIFT TOWARD LNG. TECHNICAL ANALYSIS. PIPING AND PIPING SPECIALTIES. CRYOGENIC TECHNOL. VOL 6, NO. 6, 212-6 (NOV-DEC 1970)

074
CRYOGENIC TECHNOLOGY
TECHNICAL PRODUCT ANALYSIS. MATERIALS AND INSULATION. CRYOGENICS IMPROVEMENTS, NOW. CRYOGENIC TECHNOL. VOL 6, NO. 1, 22-4 (JAN-FEB 1970)

075
CRYOGENICS AND INDUSTRIAL GASES
LNG IMPORT TERMINAL. DESIGN CONSIDERATIONS. CRYOGEN. IND. GASES VOL 7, NO. 5, 41-8 (SEP-OCT 1972)

OTHER DOCUMENTS
(CONT.)

076
CRYOGENICS AND INDUSTRIAL GASES
SINGLE LAYER APPLICATION FOR LNG PIPE INSULATION. CRYOGEN. IND. GASES VOL 8, NO. 5, 21-2 (SEP-OCT 1973)

077
CRYOGENICS AND INDUSTRIAL GASES
URETHANE FOAM INSULATES BRUNEI PIPELINES. CRYOGEN. IND. GASES VOL 7, NO. 4, 27-9 (JUL-AUG 1972)

078
CURRY,J.E.
CRYOGENIC INSULATION. SPACE TRANSPORTATION SYSTEMS TECHNOLOGY, PROC. SYMP. (CLEVELAND, OHIO, JUL 15-17, 1970) VOL 3. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, WASHINGTON, D. C., REPT. NO. NASA-TM-X-52876, 297-308 (JUL 1970)

079
DAVIES,C.B.
LNG TRANSPORTATION-ITS GROWTH AND DEVELOPMENT. PETROL. REV. VOL 24, NO. 284, 251-8 (AUG 1970)

080
DAVIS,B.K. CARTER,J.M. SIMPSON,W.G.
DEVELOPMENT OF POLYURETHANE SPRAY FOAM INSULATION. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, MARSHALL SPACE FLIGHT CENTER, HUNTSVILLE, ALA., MANUFACTURING DEVELOPMENT MEMO. NO. MDM-15-67, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION TECH. MEMO. NO. X-60658 (AUG 1967) 29 PP

081
DE WINTON,C.
THE ACHIEVEMENTS AT GLENMAVIS. GAS WORLD VOL 176, NO. 4604, 415-21 (NOV 1972)

082
DE WIT,J. WARDALE,J.K.S. DICKIE,D. DENHAM,J.B.
LAND STORAGE TANKS FOR REFRIGERATED LIQUID PRODUCTS. METAL CONSTR. BRIT. WELD. J. VOL 6, NO. 3, 96-100 (MAR 1974)

083
DEAN,F.E.
THE INTERCONTINENTAL TRANSPORT OF LIQUEFIED NATURAL GAS. CRYOGENICS VOL 6, NO. 2, 65-76 (APR 1966)

084
DEARING,D.L.
DEVELOPMENT OF THE SATURN S-IV AND S-IVB LIQUID HYDROGEN TANK INTERNAL INSULATION. ADVANCES IN CRYOGENIC ENGINEERING VOL. 11, 89-97 (PROCEEDINGS OF THE 1965 CRYOGENIC ENGINEERING CONFERENCE) PLENUM PRESS, INC., NEW YORK (1966)

085
DEASON,C.
SIX-MILE CRYOGENIC SYSTEM SERVES OFFSHORE BRUNEI LOADING PLATFORM. PIPE LINE IND. VOL 38, NO. 3, 55-7 (MAR 1973)

086
DELAND,R.E. HAROLDSEN,O.O. HELLEY,L.R. PORTER,R.N.
TASK 6 STORABLE PROPELLANT MODULE ENVIRONMENTAL CONTROL TECHNOLOGY. SUMMARY REPORT. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, REP. NO. NASA-CR-111082, TRW-14051-6007-T0-00 (JUL 1970) CONTR. NO. NAS7-750 73 PP

087
DELAND,R.E. HAROLDSEN,O.O. PORTER,R.N.
SPACE STORABLE PROPELLANT MODULE THERMAL CONTROL TECHNOLOGY. TRW SYSTEMS GROUP, REDONDO BEACH, CALIF., SUMMARY REPT. NO. TRW-14051-6009-R0-00-VOL 2. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION REPT. NO. NASA-CR-117959, CONTRACT NO. NAS7-750, 129PP (MAR 1971)

088
DELAND,R.E. HAROLDSEN,O.O. PORTER,R.N.
SPACE STORABLE PROPELLANT MODULE THERMAL CONTROL TECHNOLOGY - SUMMARY REPORT, VOL I - OF(2)/B(2) H(6) PROPULSION MODULE. TRW SYSTEMS GROUP, REDONDO BEACH, CALIF., REPT. NO. TRW-14051- 6009-R3-33-VOL 1, PREPARED FOR JET PROPULSION LAB., PASADENA, CALIF. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION REPT. NO. NASA-CR-117900, CONTRACT NO. NAS7-750, 215PP (MAR 1971)

089
DELAND,R.E. HAROLDSEN,O.O. PORTER,R.N.
TASK 3 SPACE STORABLE PROPELLANT MODULE ENVIRONMENTAL CONTROL TECHNOLOGY. SUMMARY REPORT. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, REP. NO. NASA-CR-110941, TRW-14051-6004-T0-00 (JUN 1970) CONTR. NO. NAS7-750 74 PP

090
DESAI,R.R. DOHN,G.D.
STRUCTURAL LIGHT-WEIGHT PANEL FOR CRYOGENIC AND ELEVATED TEMPERATURE APPLICATIONS. U. S. PATENT NO. 3,669,815 (JUN 1972)

091
DESAI,R.R. DOHN,G.D.
STRUCTURAL LIGHT-WEIGHT PANEL OF HIGH STRENGTH, HAVING THERMAL INSULATION PROPERTIES AND ENCLOSURES FORMED THEREBY. U. S. PATENT NO. 3,773,604 (NOV 1973)

092
DI MATTEO,G.A. KREISLER,R.I. WOODS,J.A.
THERMAL CONDUCTIVITY OF INSULATING MATERIALS BY THE GUARDED HOT PLATE METHOD. GENERAL DYNAMICS/ASTRONAUTICS, SAN DIEGO, CALIF., REPT. NO. GDA-7-D-476 (OCT 1958) 30 PP

093
DIMENTBERG,M.
THE DESIGN AND OPERATION OF AN LNG PIPELINE FROM THE ARCTIC. INTERNATIONAL CONFERENCE AND EXHIBITION ON LIQUEFIED NATURAL GAS, 3RD, WASHINGTON, D.C., SEP 24-28, 1972, INSTITUTE OF GAS TECHNOLOGY, CHICAGO, ILL., SESSION-VII/PAPER-7, 19 PP (1972)

094
DIMENTBERG,M.
DEVELOPMENT OF LNG PIPELINE TECHNOLOGY. CRYOGENICS IND. GASES VOL 6, NO. 5, 29-36 (SEP/OCT 1971)

095
DIMENTBERG,M.
LNG VIA PIPELINE. CRYOGENIC ENG. NEWS VOL 3, NO. 3, 34-44 (MAR 1968)

096
DINAPOLI,R.N.
DESIGN NEEDS FOR BASE-LOAD LNG STORAGE, REGASIFICATION. OIL GAS J. VOL 71, NO. 43, 67-70 (OCT 1973)

097
DINAPOLI,R.N.
DESIGN NEEDS FOR BASE-LOAD LNG. PETROL. INT. VOL 14, NO. 3, 58-62 (MAR 1974)

098
DOHERTY,D.J. HURD,R. LESTER,G.R.
THE PHYSICAL PROPERTIES OF RIGID POLYURETHANE FOAMS. CHEM. IND. (LONDON), 1340-56 (JUL 1962)

099
DOUGHTY,R.O. JONES,L.R. CLIFTON,J.V.,JR.
EXPANDABLE RIGIDIZABLE SOLAR SHIELDS FOR PROTECTION OF CRYOGENIC PROPELLANTS IN SPACE. J. SPACECRAFT ROCKETS VOL 7, NO. 12, 1419-24 (DEC 1970)

100
DOYLE,W.E.
HOW TO EVALUATE INSULATION FOR CRYOGENIC PIPING. HEATING, PIPING, AIR CONDITIONING VOL 37, NO. 12, 93-9 (DEC 1965)

101
DRYDEN,H.L.
METHOD OF MAKING A FILAMENT-WOUND CONTAINER. U. S. PATENT 3,535,179 (OCT 1970)

102
DUDNIK,D.M. STEPANENKO,A.N.
THERMAL CONDUCTIVITY AND DIFFUSIVITY OF INSULATING MATERIALS. (IN RUSSIAN) KHOLOD. TEKH. VOL 45, NO. 1, 27-9 (1968)

103
DUFFY,A.R. DAINORA,J.
CONSIDERATIONS FOR LNG PIPE MATERIAL SELECTION. PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON LNG 1ST, CHICAGO, ILL. (APR 7-12, 1968) (J.W. WHITE AND A.E.S. NEUMANN EDS.) INSTITUTE OF GAS TECHNOLOGY, CHICAGO, ILL. (1968) PAPER 42 19 PP

104
DUFFY,A.R. SHOUP,A.J.
LNG TANK IS INTERNALLY INSULATED, FLEXIBLY LINED. OIL GAS J. VOL 64, NO. 32, 52-5 (AUG 1966)

105
DUFFY,A.R. SHOUP,A.J.
600,000-BBL LNG TANK TO USE INTERNAL INSULATION, FLEXIBLE LINER. OIL GAS J. VOL 64, NO. 31, 114-8 (AUG 1966)

106
DUMONT,A.
PRESENT POSSIBLE USE OF RIGID POLYURETHANES FOR INSULATION. COMMUN. CENTRE ET. SCI. TECH. FROID, BELG., NO. 2, 11-23 (JUN 1962)

107
DUPUY,R.
INDUSTRIAL INSULATING AND HEAT-PROOF MATERIALS. (IN FRENCH) MEM. SOC. INGRS. CIVILS FRANCE, NO. 4, 23-30 (APR 1964)

108
DURR,C.A.
PROCESS TECHNIQUES AND HARDWARE USES OUTLINED FOR LNG REGASIFICATION. OIL GAS J. VOL 72, NO. 19, 56-66 (MAY 1974)

109
EAKIN,B.E. KHAN,A.R. ANDERSON,P.J.
HONEYCOMB INSULATION PANEL FOR CRYOGENIC TEMPERATURES. U. S. PATENT 3,556,917 (JAN 1971)

110
EDESKUTY,F.J. WILLIAMSON,K.D.,JR.
STORAGE AND HANDLING OF CRYOGENS. PAPER PRESENTED AT AMERICAN INST. OF CHEMICAL ENGINEERS AND INST. MEXICANO DE INGENIEROS QUIMICOS JOINT MEETING, 3RD, DENVER, COLO., AUG 30-SEP 2, 1970. ALSO PUBLISHED IN ADVANCES IN CRYOGENIC ENGINEERING VOL 17. PLENUM PRESS, NEW YORK, 56-68 (1972)

111
EGAN,F.C. TOOLEY,M.R.
GLENMAVIS CRYOGENIC PLANT COMMISSIONED. GAS WORLD VOL 176, NO. 4644, 133-7 (AUG 1973)

OTHER DOCUMENTS
(CONT.)

112
ELROD,C.W.
A COMPARISON OF SUBCOOLED VERSUS LIQUID HYDROGEN REQUIREMENTS. AIR FORCE AERO PROPULSION LAB., WRIGHT-PATTERSON AFB, OHIO, REPT. NO. AFAPL-TR-66-15 (APR 1966) 29 PP

113
ESCHER,W.J.D.
LIQUID HYDROGEN - FUTURE AIRCRAFT FUEL. BACKGROUND, PAYOFF, AND CRYOGENIC ENGINEERING CHALLENGE. ADVANCES IN CRYOGENIC ENGINEERING, VOL 20 (A COLLECTION OF INVITED PAPERS AND CONTRIBUTED PAPERS PRESENTED AT NATIONAL TECHNICAL MEETINGS DURING 1973 AND 1974), K. D. TIMMERHAUS, EDITOR. PLENUM PRESS, NEW YORK, 70-81 (1975)

114
EVENSON,J.H.
LIQUID HYDROGEN TANK INSULATION TESTS. GENERAL DYNAMICS/ASTRONAUTICS, SAN DIEGO, CALIF., REPT. NO. GDA-10E-1483 (MAR 1962) 36 PP

115
EWING,G.H. SMITH,F.L.
DESIGN, CONSTRUCTION, AND OPERATION OF AN LNG PEAKSHAVING PLANT. LIQUEFIED NATURAL GAS (PROCEEDINGS OF THE INTERNATIONAL CONFERENCE AND EXHIBITION 2ND, PARIS, FRANCE, OCT 19-23, 1970) VOL 2 13 PP

116
EYLES,A.G.
THERMAL AND PRESSURE-INDUCED STRAINS IN INTERNAL CRYOGENIC INSULATIONS. ADVANCES IN CRYOGENIC ENGINEERING VOL 10, 224-32 (PROC. OF CRYOGENIC ENGINEERING CONFERENCE, PHILADELPHIA, PA., AUG 18-21, 1964) PLENUM PRESS, NEW YORK (1965)

117
FALCK-PEDERSEN,G.
INSULATION IN GAS TANKERS. (IN NORWEGIAN) KULDE (COPENHAGEN) VOL 19, NO. 4, 116-9 (AUG 1965)

118
FEIND,K.
THERMAL CONDUCTIVITY OF INSULATION. (IN GERMAN) KALTETECHNIK VOL 18, NO. 6, DKV ARBEITSBLATT 2-41A (JUN 1966)

119
FERRO,V. SACCHI,A.
THERMAL CONDUCTIVITY MEASUREMENTS OF INSULATING MATERIALS DOWN TO ABOUT -200 DEGREES. RIC. SCI., REND., SEZ. A VOL 8, NO. 6, 1667-79 (1965)

120
FFOOKS,R.C.
MARINE TRANSPORT OF L.N.G. ENGINEERING, TRANSPORT AND OPERATIONS RESEARCH VOL 6, 285-94 (PROCEEDINGS OF THE WORLD PETROLEUM CONGRESS 7TH, 1967) ELSEVIER PUBLISHING CO., LTD. (1967)

121
FILIPE,A. LAINE,P.
ANISOTROPY OF THE THERMAL CONDUCTIVITY OF POLYURETHANE RIGID FOAMS EXPANDED IN SITU. (IN FRENCH) BULL. INST. INTERN. FROID ANNEXE 1961-3, 165-71 (PRESENTED AT MEETING OF COMM. 2, 3, 6B, + 8, CAMBRIDGE, SEP 20-22, 1961)

122
FILSTEAD,C.G.,JR.
THE DESIGN AND OPERATION OF LNG SHIPS WITH REGARD TO SAFETY. SHIPPING WORLD SHIPBUILDER VOL 165, NO. 3866, 259-62 (FEB 1972)

123
FONER,S.
SINGLE WALLED, SPACE SAVING, LIQUID NITROGEN DEWARS. REV. SCI. INSTRUM. VOL 40, NO. 10, 1362-3 (OCT 1969)

124
FORBES,F.W. MARTEL,C.R.
EXPANDABLE CRYOGENIC PIPE. ADVANCES IN CRYOGENIC ENG. VOL 8, 411-6 (PROC. CRYOGENIC ENGINEERING CONFERENCE, LOS ANGELES, CALIF., AUG 14-16, 1962) PLENUM PRESS INC., NEW YORK (1963)

125
FOURNIER,D. LEROY,J.P. DEGENNE,M.
A NEW INSTRUMENT FOR MEASURING THE CONTRACTION OF CELLULAR INSULANTS AT LOW TEMPERATURE. EARLY EXPERIMENTAL RESULTS OBTAINED. (IN FRENCH) SOME THERMOPHYSICAL PROPERTIES OF REFRIGERANTS AND INSULANTS. (PROC. INTERNATIONAL INSTITUTE OF REFRIGERATION COMMISSION 31, ZURICH, SWITZERLAND, SEP 27-29, 1973) BULL. INST. INT. FROID, ANNEXE 1973-4, 163-72 (1973)

126
FRADKOV,A.B.
ON THE QUESTION OF NEW METHODS OF HEAT INSULATION FOR APPARATUS OF INTENSE COLD. AKAD. NAUK S.S.S.R. DOKLADY VOL 81, NO. 4, 549-51 (1951) (TRANS. BY MORRIS D. FRIEDMAN, INC., NEEDHAM HEIGHTS, MASS. NO. F-116)

127
FREEMAN,S.M.
PROPERTIES OF VAPOR BARRIERS, ADHESIVES AND FOAMS AT CRYOGENIC AND ELEVATED TEMPERATURES. LOCKHEED AIRCRAFT CORP., GEORGIA DIV., MARIETTA, GA., REPT. NO. ER-5687 (APR 1962) 53 PP

OTHER DOCUMENTS
(CONT.)

128
FUJIHASHI,Y. NAGOYA,Y. SHIBATA,K.
CHARACTERISTICS OF THIN WALL REFRIGERATORS USING RIGID POLYURETHANE FOAM. HITACHI REV. VOL 14, NO. 9, 14-8 (1965)

129
FULMER,O.
MODEL 55 INSULATION INVESTIGATION, WS 107A. GENERAL DYNAMICS/ASTRONAUTICS, SAN DIEGO, CALIF., REPT. NO. GDA-55B-2307-1 (NOV 1959) 39 PP

130
GAS WORLD
CRYOGENIC LOSSES REDUCED BY BALLS. GAS WORLD VOL 173, NO. 4521, 291 (APR 1971)

131
GAUSE,R.L.
NUCLEAR GROUND TEST MODULE INSULATION DEVELOPMENT. RESEARCH ACHIEVEMENTS REVIEW VOLUME 2, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, HUNTSVILLE ALA. GEORGE C. MARSHALL SPACE FLIGHT CENTER, TECH. MEMO. 53670 (1967) PP 69-79

132
GENERAL DYNAMICS/CONVAIR
CHARACTERISTICS OF A GELLED LIQUID HYDROGEN POLYPHENYLENE OXIDE (PPO) FOAM OPEN-CELL INSULATION SYSTEM, PHASE 1. GENERAL DYNAMICS/CONVAIR, SAN DIEGO, CALIF., AEROSPACE DIV., REPT. NO. GDCA-632-3-169. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, HUNTSVILLE, ALA., GEORGE C. MARSHALL SPACE FLIGHT CENTER, REPT. NO. NASA-CR-124114, CONTRACT NO. NAS8-27203, 93PP (FEB 1973)

133
GENERAL DYNAMICS/CONVAIR
DESIGN AND DEVELOPMENT OF POLYPHENYLENE OXIDE FOAM AS A REUSABLE INTERNAL INSULATION FOR LH2 TANKS. PHASE 1. GENERAL DYNAMICS/CONVAIR, SAN DIEGO, CALIF., AEROSPACE DIV., REPT. NO. GDCA-632-1-89. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION REPT. NO. NASA-CR-123798, CONTRACT NO. NAS8-27566, 80PP (JUN 1972)

134
GENERAL DYNAMICS/CONVAIR
DESIGN AND DEVELOPMENT OF POLYPHENYLENE OXIDE FOAM AS A REUSABLE INTERNAL INSULATION FOR LH2 TANKS, PHASE 2. GENERAL DYNAMICS/CONVAIR, SAN DIEGO, CALIF., PROGRESS REPT. NO. GDCA-632-3-140, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION REPT. NO. NASA-CR-123955, CONTRACT NO. NAS8-27566 (SEP 1972) 67 PP

OTHER DOCUMENTS
(CONT.)

135
GENERAL DYNAMICS/CONVAIR
DESIGN AND DEVELOPMENT OF PRESSURE AND REPRESSURIZATION PURGE SYSTEM FOR REUSABLE SPACE SHUTTLE MULTILAYER INSULATION SYSTEM. GENERAL DYNAMICS/CONVAIR, SAN DIEGO, CALIF., QUARTERLY PROGRESS REPT., NO. REPT-584-4-708-QR-1, JUL-SEP 1971. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION REPT. NO. NASA-CR-121073, CONTRACT NO. NAS8-27419, 173PP (DEC 1971)

136
GENERAL DYNAMICS/CONVAIR
FIXED INSULATION DEVELOPMENT PROGRAM. GENERAL DYNAMICS/CONVAIR, SAN DIEGO, CALIF., FINAL REPT. NO. GDC-BTD68-058, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION REPT. NO. NASA-CR-105599, CONTRACT NO. NAS3-3248 (MAY 1969) 271 PP

137
GENERAL ELECTRIC CO.
TESTING OF DIELECTRIC MATERIALS AND APPLICATION TECHNIQUES IN ELECTRONIC PACKAGING. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, HUNTSVILLE, ALA. GEORGE C. MARSHALL SPACE FLIGHT CENTER, FINAL REPT. NO. NASA-CR-102454, DOC-69SD-4371 (DEC 1969) CONTR. NO. NAS8-21333 128 PP

138
GERSTIN,HARRY
HOW TO EVALUATE THE RIGID PLASTIC FOAMS. PROD. ENG. VOL 36, NO. 13, 59-68 (JUN 1965)

139
GIBSON,G.H. WALTERS,W.J.
CONSIDER SAFETY, RELIABILITY, COST IN SELECTING TYPE OF LNG STORAGE. OIL GAS J. VOL 69, NO. 6, 65-9 (FEB 1971)

140
GIBSON,G.H. WALTERS,W.J.
SOME ASPECTS OF L.N.G. STORAGE. LIQUEFIED NATURAL GAS (PROCEEDINGS OF THE INTERNATIONAL CONFERENCE AND EXHIBITION 2ND, PARIS, FRANCE, OCT 19-23, 1970) VOL 1 13 PP

141
GIERYGA,J.M. JOB,C. LANDLER,Y.
EVOLUTION OF THE THERMAL CONDUCTIVITY OF CELLULAR PLASTIC MATERIALS. (IN FRENCH) PROGR. REFRIG. SCI. TECHNOL. VOL 2, 195-207 (PROC. INT. CONGR. REFRIG. 12TH, MADRID, SPAIN, AUG 30-SEP 6, 1967) INST. INT. FROID, PARIS (1969)

142
GLASER,P.E.
CRYOGENIC INSULATIONS. MACHINE DESIGN VOL 39, NO. 19, 146-52 (AUG 1967)

OTHER DOCUMENTS
(CONT.)

143
GLASER,P.E.
THE DEVELOPMENT OF THERMAL INSULATIONS AND TECHNIQUES FOR USE AT VERY LOW TEMPERATURE. PROGR. REFRIG. SCI. TECHNOL. VOL 2, 3-27 (PROC. INT. CONGR. REFRIG. 12TH, MADRID, SPAIN, AUG 30-SEP 6, 1967) INST. INT. FROID, PARIS (1969)

144
GLASER,P.E.
EFFECTIVE THERMAL INSULATION. MULTI-LAYER SYSTEMS. CRYOGENIC ENG. NEWS VOL 4, NO. 4, 16-24 (APR 1969)

145
GLASER,P.E.
THERMAL PROTECTION SYSTEMS FOR LIQUID HYDROGEN TANKS. LITTLE, A. D., INC., CAMBRIDGE, MASS., REPT. NO. NASA-CR-62859 (NOV 1962) CONTR. NO. NAS5-664, 64 PP

146
GLASER,P.E. BLACK,I.A.
CRYOGENIC INSULATION SYSTEMS. BULL. INST. INTERN. FROID ANNEXE 1960-2, 79-90 (1960)

147
GOFMAN-ZAKHAROV,P.M.
COVERINGS FOR LIQUEFIED-GAS STORAGE CONTAINERS. NIZKOTEMPERATURNOYE KHRANENIYE SZHIZHENNYKH TEKHNICHESKIKH GAZOV, IZDATELSTVO TEKHNIKA, KIEV, UKRAINIAN SSR (1966) PP 141-5 TRANSL. BY JOINT PUBLICATIONS RESEARCH SERVICE, WASHINGTON, D. C., NO. JPRS-42287, TT-67-32916, 10-4 (AUG 1967)

148
GORMAN,P.T.
EXTERNALLY INSULATED HULL STRUCTURE. U. S. PATENT 3,283,734 (NOV 1966)

149
GRAY,V.H. GELDER,T.F.
EXTERNALLY BONDED AND SEALED INSULATION FOR LIQUID-HYDROGEN-FUELED ROCKET TANKS. ADVANCES IN CRYOGENIC ENGINEERING VOL 5, 131-8 (PROCEEDINGS OF THE 1959 CRYOGENIC ENGINEERING CONFERENCE) PLENUM PRESS, INC., NEW YORK (1960)

150
GREENBERG,S.
METHANE FUEL SYSTEMS FOR HIGH MACH NUMBER AIRCRAFT. NATIONAL AERONAUTIC AND SPACE ENGINEERING AND MANUFACTURING MEETING, LOS ANGELES, CALIF., OCT. 6-10, 1969. SOCIETY OF AUTOMOTIVE ENGINEERS PAPER 690668 16 PP

151
GRIFFIN,J.D. SKOCHDOPOLE,R.E.
PLASTIC FOAMS. ENGINEERING DESIGN FOR PLASTICS, CHAPTER 15, REINHOLD PUBLISHING CORP., NEW YORK (1964) PP 995-1071

OTHER DOCUMENTS
(CONT.)

152
GUTZMER,H.A.
THERMAL CONDUCTIVITY OF HELIUM-PERMEATED STYROFOAM. GENERAL DYNAMICS/ASTRONAUTICS, SAN DIEGO, CALIF., REPT. NO. GDA-7D2399 (AUG 1959) 14 PP

153
HALE,D.
LNG ECONOMICS AND TECHNOLOGY - 2ND EDITION. ENERGY COMMUNICATIONS, INC., DALLAS, TEX., 238PP (1974)

154
HALE,D.
LNG TANKER DEVELOPMENTS. PIPELINE GAS J. VOL 199, NO. 11, 52-3 (SEP 1972)

155
HALE,D.V.
STUDY OF THERMAL CONDUCTIVITY REQUIREMENTS. VOLUME 1. HIGH PERFORMANCE INSULATION THERMAL CONDUCTIVITY TEST PROGRAM. LOCKHEED MISSILES AND SPACE CO., HUNTSVILLE, ALA., REPT. NO. NASA-CR-61279, LMSC/HREC-D148611-1 (1969) CONTR. NO. NAS8-21347 109 PP

156
HALE,D.V. ONEILL,M.J.
STUDY OF THERMAL CONDUCTIVITY REQUIREMENTS HIGH PERFORMANCE INSULATION. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, HUNTSVILLE, ALA. GEORGE C. MARSHALL SPACE FLIGHT CENTER, FINAL REPT. NO. NASA-CR-102600, LMSC/HREC D162128 (FEB 1970) CONTR. NO. NAS8-21347 79 PP

157
HALE,D.V. RENY,G.D. HYDE,E.H.
A GUARDED ELECTRICAL CYLINDRICAL CALORIMETER FOR MEASURING THERMAL CONDUCTIVITY OF MULTILAYER INSULATION. ADVANCES IN CRYOGENICS ENGINEERING VOL 15, 324-31 (PROC. CRYOGENIC ENGINEERING CONFERENCE, LOS ANGELES, CALIF., JUN 16-18, 1969) K.D. TIMMERHAUS ED., PLENUM PRESS, NEW YORK (1970)

158
HAMMOND,M.B.,JR.
AN ANALYTICAL MODEL FOR DETERMINING THE THERMAL CONDUCTIVITY OF CLOSED-CELL FOAM INSULATION. AIAA THERMOPHYSICS CONF. 3RD, LOS ANGELES, CALIF. (JUN 24-26, 1968) PAPER NO. AIAA 68-766 10 PP

159
HAMMOND,M.B.,JR.
LIQUID HYDROGEN TANK INSULATION FOR THE S-II BOOSTER. CHEM. ENG. PROGR. SYMP. SER. VOL 62, NO. 61, 213-8 (1966)

OTHER DOCUMENTS
(CONT.)

160
HAMPTON,H.A. HURD,R.
RECENT DEVELOPMENTS IN THE USES OF POLYURETHANE RIGID FOAMS AS HEAT INSULATING MATERIALS. PROGRESS IN REFRIGERATION SCIENCE AND TECHNOLOGY VOL 1, 317-24 (PROC. OF XTH INTERN. CONGR. OF REFRIG., COPENHAGEN, 1959) PERGAMON PRESS (1960)

161
HARDING,R.H.
HEAT TRANSFER THROUGH LOW-DENSITY CELLULAR MATERIALS. IND. ENG. CHEM. PROCESS DESIGN DEVELOP. VOL. 3, NO. 2, 117-25 (APR 1964)

162
HARDING,R.H.
PREDICTING THE PERFORMANCE OF FOAM-INSULATED CONTAINERS. J. CELLULAR PLASTICS VOL 2, NO. 4, 206-13 (JUL 1966)

163
HASKINS,J.F.
MEASURED VALUES FOR THE COEFFICIENTS OF LINEAR EXPANSION OF FOLYCEL 420 AND CONOLON 506 AT LOW TEMPERATURES. GEN. DYNAMICS CORP., CONVAIR ASTRONAUTICS DIV., REPT. MRG-154 (MAY 1960) 10 PP

164
HAUCK,J.E.
PLASTIC FOAMS. MATER. DESIGN ENG. VOL 63, NO. 5, 87-102 (MAY 1966)

165
HAWKER SIDDELEY DYNAMICS, LTD.
EUROPEAN SPACE TUG. PRE-PHASE A STUDY. APPENDIX 3 - PROPELLANT CONTROL AND PROPULSION. HAWKER SIDDELEY DYNAMICS, LTD., HATFIELD, ENGLAND, REPT. NO. HSD-TP-7227-APP-3, EUROPEAN LAUNCHER DEVELOPMENT ORGANISATION CONTRACT NO. ELDO-CTR-17/7/44, 103PP (JAN 1971)

166
HAWKER SIDDELEY DYNAMICS, LTD.
EUROPEAN SPACE TUG. PRE-PHASE A STUDY, PART 2, VOLUME 3. PROPELLANT AND PROPULSION. HAWKER SIDDELEY DYNAMICS, LTD., HATFIELD, ENGLAND, REPT. NO. HSD-TP-7264-VOL 3, EUROPEAN LAUNCHER DEVELOPMENT ORGANISATION CONTRACT NO. ELDO-CTR-17/7/44, 89PP (AUG 1971)

167
HAYAKAWA,S. IIJIMA,T. ITO,K. MATSUMOTO,T. ONO,T. UYAMA,K. NISHIMURA,T.
A BALLOON-BORNE INFRARED TELESCOPE COOLED BY LIQUID NITROGEN. JPN. J. APPL. PHYS. VOL 14, NO. 7, 1041-7 (JUL 1975)

OTHER DOCUMENTS
(CONT.)

168
HAYNES,J. HARALSON,H.S.
DEVELOPMENT OF NONDESTRUCTIVE TEST DEVICE FOR EVALUATION OF 3/4 INCH THICK POLYURETHANE SPRAY-ON FOAM INSULATION (SOFI) ON THE SATURN S-II STAGE. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, MARSHALL SPACE FLIGHT CENTER, HUNTSVILLE, ALA., TECH. MEMO. NO. X-53852 (MAY 1969) 40 PP

169
HEDBERG,C.R.
CRYOGENIC INSULATION DEFLAGRATION/DETONATION SENSITIVITY TEST REPORT. GRUMMAN AEROSPACE CORP., BETHPAGE, N.Y., REPT. NO. SUBST 381-100R-03, GIDEP-501.78.19.00-K4-01 (OCT 1970) 13 PP

170
HEFFNER,G.R.
REEFER TRENDS. J. CELLULAR PLASTICS VOL 2, NO. 6, 310-6 (NOV 1966)

171
HELDENFELS,R.R.
STRUCTURAL PROSPECTS FOR HYPERSONIC AIR VEHICLES. AEROSPACE PROCEEDINGS 1966 (ROYAL AERONAUTICAL SOC. CENTENARY CONGR. AND INTERNATIONAL COUNCIL OF THE AERONAUTICAL SCIENCES CONGRESS 5TH, LONDON, ENGLAND, SEP 12-16, 1966) J. BRADBROOKE ET AL EDS, SPARTAN BOOKS, NEW YORK (1967) VOL 1 PP 561-83

172
HERTZ,J.
CAST FOAM INSULATION EVALUATION. GEN. DYNAMICS/ASTRONAUTICS, SAN DIEGO, REPT. NO. MRG-275 (DEC 1962) CONTR. NO. AF 33(616)7984, 25 PP

173
HERTZ,J. KNOWLES,D.
SURVEY OF THERMAL PROPERTIES OF SELECTED MATERIALS. GENERAL DYNAMICS/CONVAIR, SAN DIEGO, CALIF., REPT. NO. ZZL-65-008 (FEB 1965) CONTR. NO. AR-504-1-553, 172 PP

174
HIGGINS,R.G. MCCONARTY,W.A. ANTHONY,F.M.
DESIGN AND ANALYSIS OF LIGHTWEIGHT THERMAL PROTECTION SYSTEMS. BELL AEROSYSTEMS CO., BUFFALO, N. Y., REPT. NO. AFML-TR-67-377 (DEC 1967) CONTR. NO. F 33(615)-67-C-1091 174 PP

175
HILADO,C.J. PROOPS,W.R.
THERMAL CONDUCTIVITY OF RIGID URETHANE FOAM INSULATION IN LOW TEMPERATURE SERVICE. J. CELLULAR PLASTICS VOL 5, NO. 5, 299-303 (SEP-OCT 1969)

176
HILDENBRAND,C.V.
URETHANE FOAM INSULATION HAZARDS. SAFETY IN AMMONIA PLANTS AND RELATED FACILITIES, 109-10 (PROC. 17TH ANNUAL SYMPOSIUM, AICHE NATIONAL MEETING, SALT LAKE CITY, UTAH, AUG 19-21 1974) AICHE (AMMONIA PLANT SAFETY), NEW YORK (1975)

177
HILL,W.E.
MATERIALS FOR FOAM TYPE INSULATION. CRYOGENIC RESEARCH AT MSFC. RESEARCH ACHIEVEMENTS REVIEW VOL 4, NO. 2, 178-84 (NOV 1971). NATIONAL AERONAUTICS AND SPACE ADMINISTRATION TECH. MEMO. NO. X-64561

178
HILLBERG,E.T. ISENBERG,L.
INSULATED TANK BASE AND INSULATED BLOCK. U. S. PATENT NO. 3,818,664 (JUN 1974)

179
HOCKING,C.S.
GAS FILLED THERMAL INSULATION. HIGH MOLECULAR WEIGHT GASES AND CELLULAR POLYURETHANE. KYLTEKN. TIDSKR. VOL 19, NO. 2, 21-3 (APR 1960)

180
HOLCOMBE,A.H.
STORAGE AND DISTRIBUTION OF CRYOGENIC LIQUIDS. CRYOGENICS IND. GASES VOL 4, NO. 6, 67-70 (JUN 1969)

181
HOLLAND,W.D.
THE MEASUREMENT OF THERMAL CONDUCTIVITY OF A PLASTIC FOAM AT CRYOGENIC TEMPERATURES. LOCKHEED-GEORGIA CO., MARIETTA, GA. REPT. NO. ER-5683 (JUL 1962) 9 PP

182
HOOVER,T.E.
LNG PIPE LINES ARE FEASIBLE. PIPE LINE IND. VOL 35, NO. 6, 21-4 (DEC 1971)

183
HOOVER,T.E.
TECHNICAL FEASIBILITY AND COST OF LNG PIPELINES. LIQUEFIED NATURAL GAS (PROCEEDINGS OF THE INTERNATIONAL CONFERENCE AND EXHIBITION 2ND, PARIS, FRANCE, OCT 19-23, 1970) VOL 1 10 PP

184
HORD,J. PARRISH,W.R. VOTH,R.O. HUST,J.G. FLYNN,T.M. SINDT,C.F. OLIEN,N.A.
SELECTED TOPICS ON HYDROGEN FUEL. NATIONAL BUREAU OF STANDARDS, BOULDER, COLO., CRYOGENICS DIV., REPT. NO. NBSIR 75-803 (JAN 1975) 207 PP

OTHER DOCUMENTS
(CONT.)

185
HUDGENS,H.R.,JR.
CELLULAR PLASTICS IN RAILROAD REFRIGERATOR CARS AND PIGGYBACK TRAILERS. J. CELLULAR PLASTICS VOL 2, NO. 6, 316-7 (NOV 1966)

186
HUGGETT,C.
FIRE HAZARDS IN SPACECRAFT ATMOSPHERES. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, HUNTSVILLE, ALA. MARSHALL SPACE FLIGHT CENTER, ANNUAL MEETING 5TH WORKING GROUP ON EXTRATERRESTRIAL RESOURCES, TECH. MEMO. X-63870 (MAR 1967) PP 191-8

187
HUGGETT,C. VON ELBE,G. HAGGERTY,W. GROSSMAN,J.
THE EFFECTS OF 100 PERCENT OXYGEN AT REDUCED PRESSURE ON THE IGNITIBILITY AND COMBUSTIBILITY OF MATERIALS. ATLANTIC RESEARCH CORP., ALEXANDRIA, VA., ADVANCED TECHNOLOGY DIV., FINAL REPT. NO. SAM TR-65-78 (DEC 1965) CONTR. NO. AF41 (609)-2478 35 PP

188
HUGHES,T.A.
LIQUID HYDROGEN INSULATION MATERIALS. AEROJET GENERAL CORP., AZUSA, CALIF., REPT. NO. 62-60, MN 442 A (1962) 9 PP

189
HURST,S.C.
THERMAL INSULATION OF CRYOGENIC PLANT. CHEM. PROCESS ENG. VOL 52, NO. 2, 43 AND 46 (FEB 1971)

190
ICHINOSE,Y.
A NEW CONTAINMENT SYSTEM FOR LNG CARRIERS. APPLICATIONS OF CRYOGENIC TECHNOLOGY, VOL 6, PROC. CRYO/73 CONF., 6TH, LOS ANGELES, CALIF., OCT 2-4, 1973, S. H. BOOTH AND R. W. VANCE, EDITORS. SCHOLIUM INTERNATIONAL INC., FLUSHING, N. Y., 35-46 (1974)

191
ISENBERG,L.
THERMAL CHARACTERISTICS OF CRYOGENIC INSULATION. NO. AM. AVIATION, INC., DOWNEY, CALIF., REPT. (NOV 1963) IDEP 347.15.00.00-F1-02, 33 PP

192
ISENBERG,L. HILLBERG,E.T.
THERMALLY INSULATED CONTAINER. U. S. PATENT NO. 3,757,982 (SEP 1973)

193
ISENBERG,L. JOHNSON,C.L.
STRUCTURAL CRYOGENIC INSULATION FOR LIQUID-FUEL ROCKETS. AEROJET-GENERAL CORP., AZUSA, CALIF., SPEC. REPT. NO. 2676 (AUG 1963) 31 PP

OTHER DOCUMENTS
(CONT.)

194
JACKSON,R.G.
CONTAINERS FOR LIQUEFIED GASES. U. S. PATENT NO. 3,595,424 (JUL 1971)

195
JACKSON,R.G.
IMPROVEMENTS IN STORAGE CONTAINERS FOR COLD LIQUEFIED GASES. BRITISH PATENT 1,203,496 (AUG 1970)

196
JACKSON,R.G.
THERMAL INSULATION STRUCTURES. U. S. PATENT 3,525,661 (AUG 1970)

197
JOHNSTON,H.L.
LIQUID HYDROGEN PROPELLANT FOR AIRCRAFT AND ROCKETS. OHIO STATE UNIV. RESEARCH FOUNDATION, COLUMBUS, PROGR. REPT. NO. 22 (MAR 1949) CONTR. NO. W33-038-AC-14794(16243) 79 PP

198
JOURNAL OF REFRIGERATION (LONDON)
INSULATION OF SHIPBOARD ETHYLENE TANKS. J. REFRIG. (LONDON) VOL 9, NO. 8, 203 (AUG 1966)

199
KAHLENBERG,F.
THE INFLUENCE OF GAS-FILLED CELLS ON THE THERMAL CONDUCTIVITY OF RIGID POLYURETHANE FOAM. INTERN. CONGR. OF REFRIGERATION, 11TH, MUNICH (AUG 1963) PAPER II-19, 3 PP

200
KAO SOAP CO., LTD., JAPAN
POLYURETHANE FOAM LAYERS FOR TEMPERATURE MAINTENANCE IN LOW-TEMPERATURE RESERVOIRS. (IN FRENCH) FRENCH DEMANDE NO. 2,158,382 (OCT 1972)

201
KATSUTA,K.
LOW TEMPERATURE LIQUID STORAGE TANK OF THE INTERNAL HEAT INSULATING TYPE HAVING CRACK DETECTING MEANS. U. S. PATENT NO. 3,921,438 (NOV 1975)

202
KATSUTA,K.
LOW TEMPERATURE LIQUID STORAGE TANK OF THE INTERNAL HEAT INSULATING TYPE HAVING LEAKAGE DETECTING MEANS. U. S. PATENT NO. 3,913,341 (OCT 1975)

203
KELLER,E.E.
SAFETY OF MATERIALS IN CONTACT WITH LIQUID OXYGEN. GENERAL DYNAMICS/CONVAIR, SAN DIEGO, CALIF., REPT. NO. GDC-8614 (FEB 1957) 26 PP

OTHER DOCUMENTS
(CONT.)

204
KELLER,J.P.
INSULATED UNDERGROUND CONDUIT. U. S. PATENT 3,484,509 (DEC 1969)

205
KERLIN,E.E. SMITH,E.T.
MEASURED EFFECTS OF THE VARIOUS COMBINATIONS OF NUCLEAR RADIATION, VACUUM, AND CRYOTEMPERATURES ON ENGINEERING MATERIALS. VOLUME I. RADIATION-VACUUM AND RADIATION-VACUUM-CRYOTEMPERATURE TESTS. GENERAL DYNAMICS/FORT WORTH, TEX., ANN. REPT. NO. FZK-188-1 (MAY 1964) CONTR. NO. NAS8-2450, 509 PP

206
KERLIN,E.E. SMITH,E.T.
MEASURED EFFECTS OF THE VARIOUS COMBINATIONS OF NUCLEAR RADIATION, VACUUM, AND CRYOTEMPERATURES ON ENGINEERING MATERIALS. VOLUME II. RADIATION-CRYOTEMPERATURE TESTS. GENERAL DYNAMICS/FORT WORTH, TEX., ANN. REPT. NO. FZK-188-2 (MAY 1964) CONTR. NO. NAS8-2450, 286 PP

207
KEY,C.F. GAYLE,J.B.
EFFECT OF LIQUID NITROGEN DILUTION ON LOX IMPACT SENSITIVITY. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION TECH. MEMO. NO. X-53208 (FEB 1965) 31 PP

208
KHAN,A.R. ANDERSON,P.J. EAKIN,B.E.
CAVERN STORAGE OF LIQUEFIED NATURAL GAS. ENGINEERING, TRANSPORT AND OPERATIONS RESEARCH VOL 6, 323-32 (PROC. WORLD PETROLEUM CONGRESS 7TH, 1967) ELSEVIER PUBLISHING CO., LTD. (1967)

209
KHAN,A.R. EAKIN,B.E. ANDERSON,P.J.
INSULATING MEANS FOR UNDERGROUND STORAGE SYSTEM. U. S. PATENT 3,418,812 (DEC 31, 1968)

210
KILPERT,R. WINSOR,E.J. BAUER,R.H.
SPRAYED INTERNALLY INSULATED PIPE. U.S. PATENT 3,425,455 (FEB 1969)

211
KLEMENS,P.G. GREENBERG,I.N.
RADIATIVE HEAT TRANSFER THROUGH COMPOSITE MATERIALS. J. APPL. PHYS. VOL 44, NO. 7, 2992-5 (JUL 1973)

212
KNOBBOUT,J.A. COLENBRANDER,C.B.
PROPERTIES OF PPO IN REGARD TO ITS APPLICATION IN LH TANK INSULATION. CENTRAL TECHNICAL INSTITUTE T.N.O., DELFT, NETHERLANDS, REPT. NO. 69-02195 (MAY 1969) 104 PP

OTHER DOCUMENTS
(CONT.)

213
KNOBBOUT,J.A. VAN BEZOOYEN,N.
THERMAL SHOCK INVESTIGATIONS. CENTRAL TECHNICAL INST., TNO, THE HAGUE, NETHERLANDS, REPT. NO. 69-03952, 11PP (OCT 1969)

214
KNOX,P.M.,JR. MCGREW,J.L.
LIQUEFIED GAS CONTAINER INSULATION. U. S. PATENT 3,224,623 (DEC 1965)

215
KNOX,R.E.
INSULATION PROPERTIES OF FLUOROCARBON EXPANDED RIGID URETHANE FOAM. AM. SOC. HEATING, REFRIG., AIR CONDITIONING ENGRS. SEMI-ANNUAL MEETING (NEW YORK, FEB 11-14, 1963) PAPER, 8PP

216
KOGLIN,B. ZIMNI,W.F.
DETERMINATION OF THE THERMAL CONDUCTIVITY, THE SPECIFIC HEAT AND THE WEIGHT BY VOLUME (GROSS DENSITY) OF INSULATIONS FOR ROCKET TANKS FILLED WITH LIQUID HYDROGEN. PART I. DESCRIPTION OF MEASUREMENT PROCEDURE. ELDO/CECLES REV. TECH. VOL 2, 3-28 (1967) TRANSL. BY TECHTRAN CORP., GLEN BURNIE, MD., NO. NASA-TT-F-11146 (JAN 1968) CONTR. NO. NASW-1695 27 PP

217
KOLFF,A.R. VAN GELSDORP,B.A.
PROPERTIES AND MANUFACTURE OF HARD EXPANDED POLYURETHANE ADAPTED TO REFRIGERATING INSULATIONS. (IN DUTCH) NED. VER. KOELTECHN. MEDED. VOL 54, NO. 5, 160-6 (SEP-OCT 1961)

218
KRAUS,S.
EROSION OF POLYURETHANE INSULATION. J. SPACECR. ROCKETS VOL 12, NO. 4, 209-12 (APR 1975)

219
KROPSCHOT,R.H.
ADVANCES IN THERMAL INSULATION. ADVANCES IN CRYOGENIC ENGINEERING, VOL 16, 104-8 (PROCEEDINGS OF THE CRYOGENIC ENGINEERING CONFERENCE, COLORADO UNIV., BOULDER, JUNE 17-19, 1970). PLENUM PRESS, N. Y. (1971)

220
KROPSCHOT,R.H.
CRYOGENIC INSULATION (MATERIALS AND TECHNIQUES). AM. SOC. HEATING, REFRIG. AIR CONDITIONING ENGRS. J. VOL 1, 48-54 (SEP 1959) PRESENTED AT ASHRAE ANNUAL MEETING (LAKE PLACID, N.Y., JUN 22-24, 1959)

OTHER DOCUMENTS
(CCNT.)

221
KROPSCHOT,R.H.
LOW TEMPERATURE INSULATION. APPLIED CRYOGENIC ENGINEERING FOR BALLISTIC MISSILES AND SPACE VEHICLES, 152-69 JOHN WILEY AND SONS, INC., NEW YORK (1962)

222
KURYLA,W.C. CHILDERS,J.W.,JR.
COLD CRACK-FREE RIGID URETHANE FOAMS. U. S. PATENT 3,472,800 (OCT 1969)

223
KVAMSDAL,R.
EXPERIENCE FROM DESIGN CONSTRUCTION AND INITIAL COMMISSIONING OF THE FIRST MOSS ROSENBERG LNG CARRIERS. NEW DEVELOPMENTS. LNG 73, PROC. SECOND LNG TRANSPORTATION CONF. (LONDON, ENGLAND, OCT 23, 1973). IPC INDUSTRIAL PRESS, LTD., LONDON, ENGLAND, 58-72 (1974)

224
KVAMSDAL,R. RAMSTAD,H. BOGNAES,R. FRANK,H.J.
THE DESIGN OF AN 88 000 M(3) LNG CARRIER WITH SPHERICAL CARGO TANKS AND NO SECONDARY BARRIER. LIQUEFIED NATURAL GAS (PROCEEDINGS OF THE INTERNATIONAL CONFERENCE AND EXHIBITION 2ND, PARIS, FRANCE, OCT 19-23, 1970) VOL 1 30 PP

225
LACAZE,A.
NEUTRON MODERATION AT VERY LOW TEMPERATURES. (IN FRENCH) COMMISSARIAT A L ENERGIE ATOMIQUE, GRENOBLE, FRANCE, CENTRE D ETUDES NUCLEAIRES, REPT. NO. CEA 2012, 99 PP (1962)

226
LAING,G.
PRE-INSULATED PIPELINES. NATURAL GAS VOL 1, NO. 5, 31-3 (AUG 1968)

227
LAING,G.
PRE-INSULATED PIPELINES. PIPES PIPELINES INTERN. VOL 13, NO. 8, 36-8, 41 (AUG 1968)

228
LANGTON,R.G.
LIQUID HYDROGEN TANK THERMAL CALCULATIONS FOR A SYNCHRONOUS ORBIT MISSION. ROYAL AIRCRAFT ESTABLISHMENT, FARNBOROUGH, ENGLAND, TECH. REPT. NO. 65064 (APR 1965) 98 PP

229
LASHMET,P.K. MEIER,R.N. SIEGRIST,G.W.
A STUDY ON CLOSED-LOOP CRYOGENIC SYSTEMS FOR TELEMETRY MASER AMPLIFIERS. AIR PRODUCTS AND CHEMICALS, INC., ALLENTOWN, PA., REPT. NO. ASD-TR-61-311 (AUG 1961) CONTR. NO. AF 33(616)-7231 98 PP

230
LAVERMAN,R.J.
APPARATUS FOR MEASURING THE THERMAL CONDUCTIVITY OF INSULATING MATERIAL. U. S. PATENT 3,592,060 (JUL 1971)

231
LEACH,L.L.
INSULATIONS FOR CRYOGENIC VESSELS. PETROL. REFINER VOL 41, NO. 11, 241-4 (NOV 1962)

232
LEMONS,C.R.
CRYOGENIC STORAGE VESSEL. U. S. PATENT NO. 3,814,275 (JUN 1974)

233
LIGI,J.J.
PROCESSING WITH CRYOGENICS. PART 1. HYDROCARBON PROCESS. VOL 48, NO. 4, 93-6 (APR 1969)

234
LIGI,J.J.
PROCESSING WITH CRYOGENICS. PART 2. HYDROCARBON PROCESS. VOL 48, NO. 5, 137-40 (MAY 1969)

235
LITTLE (ARTHUR D.), INC.
BASIC INVESTIGATION OF MULTI-LAYER INSULATION SYSTEMS. LITTLE (ARTHUR D.), INC., CAMBRIDGE, MASS. FINAL REPT. ADL-65958-00-04, NASA CR-54191 (OCT 1964) CONTR. NO. NAS3-4181 298 PP

236
LITTLE (ARTHUR D.), INC.
DESIGN OF THERMAL PROTECTION SYSTEMS FOR LIQUID HYDROGEN TANKS. LITTLE, ARTHUR D., INC., CAMBRIDGE, MASS., REPT. NO. NASA CR 55252 (APR 1963) CONTR. NO. NAS 5-664 AND NASW-615, 79 PP

237
LITTLE (ARTHUR D.), INC.
REFRIGERATED TRANSMISSION LINE STUDY. VOLUME II. TECHNIQUES AND REFRIGERATION SYSTEMS FOR COOLING COMPONENTS OF MICROWAVE RECEIVING SYSTEMS TO 80-100 DEGREES K. LITTLE (ARTHUR D.), INC., CAMBRIDGE, MASS., REPT. NO. NASA-CR-88120, C-68600, VOL II (MAR 1967) CONTR. NO. NAS7-100 AND JPL-951638 166 PP

238
LOCK,J.
THERMAL INSULATION FOR PROCESS PLANT. PROCESSING VOL 21, NO. 4, 31-5,8 (APR 1975)

OTHER DOCUMENTS
(CONT.)

239
LOCKHEED MISSILES AND SPACE CO.
SHUTTLE CRYOGENIC SUPPLY SYSTEM OPTIMIZATION STUDY VOLUME 6 - APPENDIXES. LOCKHEED MISSILES AND SPACE CO., SUNNYVALE, CALIF., FINAL REPT. NO. LMSC-A991396-VOL-6. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION REPT. NO. NASA-CR-133959, CONTRACT NO. NAS9-11330, 282PP (JUN 1973)

240
LOFGREN,C.L. GIESEKING,D.E.
DEVELOPMENT OF MANUFACTURING TECHNIQUES FOR APPLICATION OF HIGH PERFORMANCE CRYOGENIC INSULATION. BOEING CO., SEATTLE, WASH. MISSILE AND INFORMATION SYSTEMS DIV., REPT. NO. NASA-CR-61557, D2-109005-1 (OCT 1967) CONTR. NO. NAS8-21172 58 PP

241
LOM,W.L.
LIQUEFIED NATURAL GAS. JOHN WILEY AND SONS, INC., NEW YORK, 185PP (1974)

242
LORENTZEN,H.L.
INTERNAL INSULATION OF CONTAINERS FOR LIQUIDS HAVING LOWER BOILING POINT THAN ATMOSPHERIC TEMPERATURE. U. S. PATENT NO. 2,958,442 (NOV 1960)

243
LOVE,C.C.,JR.
LIQUID HYDROGEN STORAGE PARAMETERS FOR A LUNAR VOYAGE. GENERAL DYNAMICS/ASTRONAUTICS, SAN DIEGO, CALIF., REPT. NO. GDA- AE600848 (AUG 1960) 36 PP

244
LUDTKE,P.R.
DEVELOPMENT OF INSULATION TRANSFER-STANDARDS USING A FLAT PLATE CALORIMETER. NAT. BUR. STAND. (U.S.), INTERNAL REPT. NO. 73-301, 46PP (MAR 1973)

245
LUSK,D.T. DORNEY,D.C.
LNG STORAGE TANK SYSTEMS. INTERNATIONAL CONFERENCE AND EXHIBITION ON LIQUEFIED NATURAL GAS, 3RD, WASHINGTON, D.C., SEP 24-28, 1972, INSTITUTE OF GAS TECHNOLOGY, CHICAGO, ILL., SESSION-V/PAPER-5, 12 PP (1972)

246
LUSK,D.T. DORNEY,D.C.
LNG STORAGE-TANK SYSTEMS ARE SAFE AND VERSATILE. OIL GAS J. VOL 70, NO. 41, 91-5 (OCT 1972)

247
LYONS,R.H.
LABORATORY TESTS LIQUID HYDROGEN INSULATION MATERIAL. AEROJET-GENERAL CORP., SACRAMENTO, CALIF., REPT. NO. MN 538 (NOV 1962) IDEP REPT. NO. 501.78.50.00-A6-06, 1 PP

248
MACCALOUS,J.W. THOMAS,D.A.
DEVELOPMENT OF EXTERNAL PROTECTION MATERIALS FOR CRYOGENIC TANKS. NEW INDUSTRIES AND APPLICATIONS FOR ADVANCED MATERIALS TECHNOLOGY, 534-41 (PROC. NATIONAL SAMPE SYMPOSIUM AND EXHIBITION 19TH, BUENA PARK, CALIF., APR 23-25, 1974) SOCIETY FOR THE ADVANCEMENT OF MATERIAL AND PROCESS ENGINEERING, AZUSA, CALIF. (1974)

249
MARINE ENGINEERING/LOG
A BIG MARKET FOR EXOTIC, EXPENSIVE MATERIALS. MARINE ENG./LOG VOL 77, NO. 10, 48-9 (SEP 1972)

250
MARINE ENGINEERING/LOG
MANY CARGO CONTAINMENT SYSTEMS ARE AVAILABLE. MARINE ENG./LOG VOL 77, NO. 10, 40-3 (SEP 1972)

251
MARINE ENGINEERING/LOG
MOSS VERFT DELIVERS ITS FIRST SPHERICAL ALUMINUM-TANK LNG CARRIER. MARINE ENG./LOG VOL 79, NO. 3, 50-2 (MAR 1974)

252
MARKS,J.B. HOLTON,K.D.
PROTECTION OF THERMAL INSULATION. CHEM. ENG. PROGR. VOL 70, NO. 8, 46-9 (AUG 1974)

253
MARSHALL,J.E.
AN INFLATABLE THERMAL RADIATION SHIELD FOR SPACE APPLICATIONS. PROCEEDINGS OF THE AEROSPACE EXPANDABLE STRUCTURES CONF. 2ND, MINNEAPOLIS, MINN. (MAY 25-27, 1965) PP 305-38

254
MARTIN,R.
NEW LNG TANKER IS STEP TOWARD ECONOMIC WORLDWIDE GAS MARKET. AM. GAS J. VOL 193, 41-3 (JUN 1966)

255
MATESANZ,A.
INSULATING FOR CRYOGENICS. CHEM. PROCESSING VOL. 24, 28-30, 37 (JUL 1961)

OTHER DOCUMENTS
(CONT.)

256
MATTAROLO,F.
NEW INSULANTS AND MODERN INSULATING TECHNIQUES. (IN FRENCH) PROGR. REFRIG. SCI. TECHNOL. VOL 2, 29-57 (PROC. INT. CONGR. REFRIG. 12TH, MADRID, SPAIN, AUG 30-SEP 6, 1967) INST. INT. FRCID, PARIS (1969)

257
MAYO,F.
THE STORAGE OF LIQUEFIED HYDROCARBON GASES. INST. PETROL. REV. VOL 19, 233-42 (JUL 1965)

258
MCCANDLESS,T.D.
PHYSICAL PROPERTY STUDY OF POLYSTYRENE FOAM (210-050). ACF INDUSTRIES, INC., ALBUQUERQUE, N. MEX., REPT. NO. ACF-10 (JUN 1965) CONT. NO. AT(29-1)-1352, 32 PP

259
MCCLINTOCK,R.M.
LOW TEMPERATURE PROPERTIES OF PLASTICS FOAMS. SOC. PLASTICS ENGRS. J. VOL 14, NO. 11, 36-8 (NOV 1958)

260
MCGREW,J.L.
A COMPARATIVE STUDY OF AIRBORNE LIQUID HYDROGEN TANK INSULATION. ADVANCES IN CRYOGENIC ENG. VOL 8, 387-92 (PROC. OF CRYOGENIC ENGINEERING CONFERENCE, LOS ANGELES, CALIF., AUG 14-16, 1962) PLENUM PRESS INC., NEW YORK (1963)

261
MCINTIRE,O.R. KENNEDY,R.N.
STYROFOAM FOR LOW-TEMPERATURE INSULATION. CHEM. ENG. PROGR. VOL 44, NO. 9, 727-33 (SEP 1948)

262
MCMILLAN,W.D. CARTER,H.G. LIGHTFOOT,R.P.
EVALUATION OF CRYOGENIC INSULATION MATERIALS AND COMPOSITES FOR USE IN NUCLEAR RADIATION ENVIRONMENTS. INSULATION SYSTEM TEST. GENERAL DYNAMICS/FORT WORTH, TEX., REPT. NO. FZK-348 (JUN 1968) CONTR. NAS8-18024 137 PP

263
MEARNS,W.,III PEET,J.R. STRACKE,F.H. TOBYE,I.T.
VESSEL FOR TRANSPORTING LOW TEMPERATURE LIQUIDS. U. S. PATENT 3,101,861 (AUG 1963)

264
MEESEN,H.
TANKER FOR LIQUID GAS. U. S. PATENT 3,122,259 (FEB 1964)

265
MENARD,J. SEGEL,M.
CRYOGENIC ASPECTS OF THE DEVELOPMENT OF A HYDROGEN-OXYGEN STAGE STRUCTURE. CRYOGENIC ENGINEERING - PRESENT STATUS AND FUTURE DEVELOPMENT (PROC. OF THE INTERNATIONAL CRYOGENIC ENGINEERING CONF. 1ST, TOKYO AND KYOTO, JAPAN, APR 9-13, 1967) HEYWOOD TEMPLE INDUSTRIAL PUBLICATIONS, LTD., LONDON, ENGLAND (1968) PP 52-7

266
MENARD,J. SEGEL,M.
INTEGRAL TANKS OF CRYOGENIC STAGE H3.5. (IN FRENCH) ELDO TECH. REV. VOL 2, 137-57 (1967)

267
MEYERS,N. DANNENMUELLER,J. HUGHES,I.G.
A NEW CRYOGENIC STORAGE SYSTEM FOR SPACECRAFT. ASTRONAUT. AERON. VOL 7, NO. 9, 62-7 (SEP 1969)

268
MILLER,R.N. BAILEY,C.D. FREEMAN,S.M. BEALL,R.T. COXE,E.F.
PROPERTIES OF FOAMS, ADHESIVES, AND PLASTIC FILMS AT CRYOGENIC TEMPERATURES. IND. ENG. CHEM. PRODUCT RES. DEVELOP. VOL 1, NO. 4, 257-61 (DEC 1962)

269
MILLER,R.T.
CRYOGENICS IN STORAGE OF NATURAL GAS. J. METALS VOL 23, NO. 10, 34-9 (OCT 1971)

270
MINGES,M.L.
THERMAL INSULATIONS FOR AEROSPACE APPLICATIONS. MINUS 423 DEGREES TO PLUS 3000 DEGREES F. AERONAUTICAL SYSTEMS DIV., AF SYSTEMS COMMAND, WRIGHT-PATTERSON AFB, OHIO, REPT. NO. ASD-TDR-63-699 (DEC 1963) 23 PP

271
MINGES,M.L. MEISELMAN,J.M. BROADUS,J.G.
A SYSTEM FOR MEASUREMENT OF CRYOGENIC THERMAL CONDUCTIVITY OF SOLIDS TO LIQUID NITROGEN TEMPERATURES (-320 DEGREES F). AIR FORCE SYSTEMS COMMAND, WRIGHT-PATTERSON AFB, OHIO, REPT. NO. ASD-TDR-63-756 (OCT 1963) 35 PP

272
MODERN PLASTICS
URETHANE FOAM INSULATES LARGEST LNG SHIP-LOADING SYSTEM. MOD. PLASTICS VOL 49, NO. 2, 32-4 (FEB 1972)

273
MODERN REFRIGERATION AND AIR CONDITIONING
REFRIGERATED GAS TANKERS - THEIR DESIGN AND FUTURE. MOD. REFRIG. AIR COND. VOL 72, NO. 850, 67-70 (JAN 1969)

274
MOELLER,C.E.
SPACECRAFT DEMANDS BRING NEW THERMAL INSULATIONS. PROD. ENG. VOL 37, NO. 4, 91-5 (FEB 1966)

275
MOELLER,C.E. LOSER,J.B. SNYDER,W.E. HOPKINS,V.
THERMOPHYSICAL PROPERTIES OF THERMAL INSULATING MATERIALS. MIDWEST RES. INST., KANSAS CITY, MO. TECH. DOCUMENTARY REPT. NO. ASD-TDR-62-215 (JUL 1962) CONTR. NO. AF 33(616)-7875, PROJ. NO. 7381, TASK NO. 735103, 328 PP

276
MOLNAR,W.
INSULATION. CRYOGENIC FUNDAMENTALS, G. G. HASELDEN ED, ACADEMIC PRESS, NEW YORK (1971) PP 199-235

277
MORGAN,R.
HOW TO SELECT CRYOGENIC INSULATION. PETRO/CHEM ENGR. VOL 40, NO. 7/8, 56-8 (JUL 1968)

278
MORRISON,W.L.
INSULATED CONTAINER. U. S. PATENT NO. 3,106,307 (OCT 1963)

279
MOTOR SHIP
FIRST SULZER RNMD TYPE DUAL-FUEL DIESEL ENGINE ENTERS SERVICE IN LNG SHIP VENATOR. MOTOR SHIP VOL 54, NO. 641, 423-3 (DEC 1973)

280
MUELLER,K.
A NEW LNG STORAGE TANK DESIGN. (IN GERMAN) GAS WASSERFACH VOL 113, 294-5 (JUN 1972)

281
MULLER,F.
A THERMAL INSULATION SYSTEM FOR HIGH ENERGY HYDROGEN-OXYGEN LAUNCH VEHICLES. ELDO-CECLES/ESRO-CERS SCI. TECH. REV. VOL 3, 49-64. (PRESENTED AT ELDO SYMPOSIUM ON CRYOGENIC STAGE EXPERIMENTAL WORK, APR 22-23, 1970)

282
MURACA,R.F.
POLYMERS FOR SPACECRAFT HARDWARE. MATERIALS CHARACTERIZATION, PART I. STANFORD RESEARCH INST., MENLO PARK, CALIF., REPT. NO. NASA-CR-81377, IR-3, PT. 1 (DEC 1966) CONTR. NO. NAS7-100, JPL-950745 144 PP

OTHER DOCUMENTS
(CONT.)

283
MYNCKE,H. VAN ITTERBEEK,A.
METHOD FOR THE SIMULTANEOUS MEASUREMENTS OF THE THERMAL CONDUCTIVITY OF INSULATING MATERIALS AT DIFFERENT MEAN TEMPERATURES. BULL. IIR ANNEXE 1966-2, 15-22 (MEETING OF COMMISSION 2, TRONDHEIM, NORWAY, JUN 22-24, 1966)

284
NAGANO,H. FUKASAWA,M. KUMA,S. SUGIYAMA,K.
FIELD TEST OF LIQUID NITROGEN COOLED CRYOGENIC POWER CABLE. CRYOGENICS VOL 13, NO. 4, 219-23 (APR 1973)

285
NAGAOKA,J.
HEAT INSULATOR FOR RAPIDLY COOLED LOW TEMPERATURE CHAMBERS. PROGRESS IN REFRIGERATION SCIENCE AND TECHNOLOGY VOL 1, 260-7 (PROC. OF XTH INTERN. CONGR. OF REFRIG., COPENHAGEN, 1959) PERGAMON PRESS (1960)

286
NAVAL AIR SYSTEMS COMMAND
TECHNICAL MANUAL OF OXYGEN/NITROGEN CRYOGENIC SYSTEMS. NAVAL AIR SYSTEMS COMMAND, WASHINGTON, D. C., REPT. NO. NAVAIR 06-30-501 (MAR 1971) 425 PP

287
NICHOLSON,J.D.
THERMAL INSULATION MATERIALS. CHEM. PROCESS. VOL 17, NO. 3, 41-50 (MAR 1971)

288
NIENDORF,L.R. NIES,G.E.
INVESTIGATION OF A LIGHTWEIGHT SELF-EVACUATING PREFABRICATED MULTI-LAYER INSULATION SYSTEM FOR CRYOGENIC SPACE PROPULSION STAGES. LINDE DIV., UNION CARBIDE CORP., TONAWANDA, N. Y., FINAL REPT. NASA-CR-72012 (JUL 1966) CONTR. NO. NAS3-6289 293 PP

289
NIES,G.E.
LIGHTWEIGHT MODULAR MULTILAYER INSULATION. UNION CARBIDE CORP., TONAWANDA, N.Y., FINAL REPT., NATIONAL AERONAUTICS AND SPACE ADMINISTRATION REPT. NO. NASA-CR-72856, CONTRACT NO. NAS3-12045 (FEB 1971) 257 PP

290
NISHIMAKI,K. KURIHARA,T.
METHOD AND STRUCTURE FOR THERMALLY INSULATING LOW TEMPERATURE LIQUID STORAGE TANKS. U. S. PATENT NO. 3,895,146 (JUL 1975)

291
NISHIMAKI,K. YOSHIKAWA,I.
STORAGE TANKS FOR ULTRA LOW TEMPERATURE LIQUIDS. U. S. PATENT NO. 3,670,917 (JUN 1972)

OTHER DOCUMENTS
(CONT.)

292
NOMA,T.
THERMAL INSULATION FOR CRYOGENIC CONTAINERS. U. S. PATENT NO. 3,802,948 (APR 1974)

293
NORED,D.L. HENNINGS,G. SINCLAIR,D.H. SMITH,G.T. SMOLAK,G.R. STOFAN,A.J.
STORAGE AND HANDLING OF CRYOGENIC FLUIDS. PROC. CONFERENCE ON SELECTED TECHNOLOGY FOR THE PETROLEUM INDUSTRY, LEWIS RESEARCH CENTER, CLEVELAND, OHIO (DEC 8-9, 1965). NASA SPEC. PUBL. SP-5053 (1966) PP 125-53

294
NORRIE,D.H. WALKER,G.
LNG PIPELINES - A STATUS SURVEY. PROC. ANN. CONV. NAT. GAS PROCESSORS ASSOC. 47TH, TECH. PAPERS (1968) PP 65-70

295
NORTH AMERICAN ROCKWELL CORP.
IN-SPACE PROPELLANT LOGISTICS. VOLUME 3, TRADE STUDIES. NORTH AMERICAN ROCKWELL CORP., DOWNEY, CALIF., SPACE DIV. REPT. NO. SD072-SA-0053-3-VOL-3. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION REPT. NO. NASA-CR-123749, CONTRACT NO. NAS8-27692, 240PP (JUN 1972)

296
ODONNELL,J.P.
GAS COUNCIL USING LIQUEFIED NATURAL GAS FOR PEAK SHAVING. OIL GAS J. VOL 69, NO. 40 (OCT 1971)

297
OIL AND GAS JOURNAL
INSULATION METHOD SAID TO CUT HEAT LOSSES. OIL GAS J. VOL 73, NO. 35, 129-31 (SEP 1975)

298
OIL AND GAS JOURNAL
URETHANE FOAM TO INSULATE OFFSHORE LNG LINE. OIL GAS J. VOL 70, NO. 16, 82-4 (APR 1972)

299
OREFICE,J.D.
THE EXPANDING INSULATION IN CONSTRUCTION. AIR CONDITIONING, HEATING, VENTILATING VOL 66, 45-8 (JUN 1969)

300
PARTINGTON,L.G.
SOME ASPECTS OF RIGID URETHANE FOAM TECHNOLOGY IN REFRIGERATION. (2). MOD. REF. VOL 68, NO. 812, 1073-5 (NOV 1965)

301
PASTUHOV,A. GONDOUIN,M.
STATUS REPORT ON LNG TANKER DESIGNS. ADVANCES IN CRYOGENIC ENGINEERING VOL 19, 282-91 (PROC. CRYOGENIC ENGINEERING CONFERENCE, ATLANTA, GA., AUG 1973) PLENUM PRESS, NEW YORK (1974)

OTHER DOCUMENTS
(CONT.)

302
PAUL,E. WITTENBERG,M. FREYSCHMIDT,E.
LOW TEMPERATURE TECHNOLOGY. FACILITIES AND CONSTRUCTION MATERIALS FOR CONDUCTION, TRANSPORT AND STORAGE OF LIQUID HYDROGEN. LOW-TEMPERATURE PROPERTIES OF METALS, ALLOYS, AND NON-METALLIC MATERIALS - A BIBLIOGRAPHY. KERNFORSCHUNGSANLAGE, JUELICH, WEST GERMANY, ZENTRALBIBLIOTHEK, REPT. NO. JUL-BIBL-4 (SEP 1964) 64 PP

303
PEARS,C.D.
THE THERMOPHYSICAL PROPERTIES OF PLASTIC MATERIALS FROM -50F TO OVER 700F. SOUTHERN RESEARCH INST., BIRMINGHAM, ALA., FINAL REPT. (APR 1965) CONTR. NO. AF33 657 8594, 87 PP.

304
PEARSON,H.R.
EVALUATION OF COMPOSITE INSULATIONS FOR CENTAUR F-2 LIQUID HYDROGEN TANK. GEN DYNAMICS/ASTRONAUTICS, SAN DIEGO, QUART. PROGR. REPT. NO. 2, PHASE 1 (DEC 1962) CONTR. NO. AF 33(616)-7984, AR-592-1-333, 11 PP

305
PENNOCK,A.P.
ANOMALIES IN FOAM CONDUCTIVITY. LOCKHEED-GEORGIA CO., MARIETTA, REPT. NO. ER-6366, 36PP (AUG 1963)

306
PERKINS,P.J.,JR.
INSULATION SYSTEM. U. S. PATENT 3,392,864 (JUL 1968)

307
PERKINS,P.J. DENGLER,R.P. NIENDORF,L.R. NIES,G.E.
SELF-EVACUATED MULTILAYER INSULATION OF LIGHTWEIGHT PREFABRICATED PANELS FOR CRYOGENIC SPACE PROPULSION VEHICLES. LEWIS RESEARCH CENTER, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, CLEVELAND, OHIO, TECH. MEMO. NO. X-52266 (1967) 16 PP PRESENTED AT AIAA/ASME STRUCTURES, STRUCTURAL DYNAMICS AND MATERIALS CONF. 8TH, PALM SPRINGS, CALIF. (MAR 29-31, 1967), NATIONAL AERONAUTICS AND SPACE ADMINISTRATION TECH. NOTE NO. D-4375 (1968) 25 PP

308
PERKINS,W.E.
REFRIGERATION REQUIREMENTS FOR PERISHABLE PROTECTIVE VEHICLES. J. CELLULAR PLASTICS VOL 2, NO. 6, 318-21 (NOV 1966)

309
PETROLEUM INTERNATIONAL
LNG TECHNOLOGY PACES GROWTH IN WORLD GAS TRADE. PETROL. INT. VOL 15, NO. 1, 28-30 (JAN 1975)

OTHER DOCUMENTS
(CONT.)

310
PIPELINE AND GAS JOURNAL
DOUBLE BARRIER KELLGAZ TANK USES CONCRETE, FLEXIBLE MEMBRANE. PIPELINE GAS J. VOL 199, NO. 11, 69-72 (SEP 1972)

311
PITTMAN,C.M. BROWN,R.D.
SURFACE RECESSION CHARACTERISTICS OF A CRYOGENIC INSULATION SUBJECTED TO ARC-TUNNEL HEATING. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION TECH. MEMO. NO. X-3291 (NOV 1975) 29 PP

312
POOLE,R.R.
INTER-WALL FOAMED THERMAL INSULATION. U. S. PATENT 3,446,881 (MAY 1969)

313
POTTIER,M.B.A. ROUX,C.B.
TANKS FOR THE STORAGE AND TRANSPORT OF CRYOGENIC FLUIDS. U. S. PATENT 3,400,849 (SEP 1968)

314
PRATER,P.G.
DESIGN CONSIDERATIONS OF AN LNG PEAK SHAVING FACILITY. CRYOGENICS IND. GASES VOL 5, NO. 5, 15-9 (MAY 1970)

315
PROBERT,S.D.
THERMAL INSULATION. CHEM. PROCESS ENG. HEAT TRANSFER SURVEY, 175-80 (1968)

316
PROBERT,S.D.
THERMAL INSULATION IN RELATION TO CRYOGENICS. UNIVERSITY COLL. OF SWANSEA, WALES, REPT. NO. TRG 1455 (R/X) (1967) 105 PP

317
RAWUKA,A.C.
SIGNIFICANCE OF THERMOPHYSICAL PROPERTY TESTING AT CRYOGENIC TEMPERATURES. DOUGLAS AIRCRAFT CO., INC., SANTA MONICA, CALIF. MATERIALS RESEARCH AND PRODUCTION METHODS, PAPER NO. 3953 (1966) 29 PP PRESENTED TO SOCIETY OF PLASTIC ENGINEERS REGIONAL MEETING, ANAHEIM, CALIF. (JUN 27-28, 1966)

318
RAWUKA,A.C. YUNDT,C.G.
THERMAL CONDUCTIVITY OF WET WALL LIQUID HYDROGEN STORAGE TANK INSULATIONS FOR SPACE APPLICATIONS. AICHE 56TH NATL. MEETING, SAN FRANCISCO (MAY 16-19, 1965) PREPRINT NO. 22D

319
REVUE GENERALE DU FROID
THE TERMINAL METHANE PORT AT HAVRE. (IN FRENCH) REV. GEN. FROID VOL 59, NO. 9, 993-9 (SEP 1968)

OTHER DOCUMENTS
(CONT.)

320
REYNOLDS,T.W.
AIRCRAFT-FUEL-TANK DESIGN FOR LIQUID HYDROGEN. NATL. ADVISORY COMM. AERONAUT. RESEARCH MEMO. NO. RM E55F22 (AUG 1955) 27 PP

321
RHODES,J.E.
LARGE SCALE CRYOGENIC TESTING OF HIGH PERFORMANCE INSULATION (HPI) SYSTEMS. CRYOGENIC WORKSHOP, PROC., NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, HUNTSVILLE, ALA. GEORGE C. MARSHALL SPACE FLIGHT CENTER, 243-60 (MAR 19-20, 1972)

322
RITTENHOUSE,J.B. SINGLETARY,J.B.
MATERIALS FOR SPACE STATIONS. METAL PROGR. VOL. 89, NO. 2, 57-63 (FEB 1966)

323
ROBBINS,M.D. KELLEY,J.A. ELLIOTT,L.
MISSION ORIENTED R AND D AND THE ADVANCEMENT OF TECHNOLOGY, THE IMPACT OF NASA CONTRIBUTIONS, VOLUME 2. DENVER RESEARCH INST., COLO., INDUSTRIAL ECONOMICS DIV. FINAL REPT., NATIONAL AERONAUTICS AND SPACE ADMINISTRATION REPT. NO. NASA-CR-126562, CONTRACT NO. NSR-06-004-063, 358 PP (MAY 1972)

324
ROBERTS,W.M. DOHN,G.D.
CRYOGENIC INSULATING PANEL SYSTEM. U. S. PATENT NO. 3,894,372 (JUL 1975)

325
ROOKE,D.E. FILSTEAD,C.G.,JR.
SIX YEARS OPERATIONAL EXPERIENCE WITH THE METHANE PRINCESS AND METHANE PROGRESS. LIQUEFIED NATURAL GAS (PROCEEDINGS OF THE INTERNATIONAL CONFERENCE AND EXHIBITION 2ND, PARIS, FRANCE, OCT 19-23, 1970) VOL 2 14 PP

326
ROSENWASSER,S.N. WATANABE,S.F.
DEVELOPMENT OF PULSED LASER INTERFEROMETRIC HOLOGRAPHY FOR INSPECTION OF FOAM INSULATION ON LARGE METALLIC STRUCTURES. MCDONNELL DOUGLAS ASTRONAUTICS CO., HUNTINGTON BEACH, CALIF., REPT. NO. MDC-G3578 (SEP 1973). ASM, SME, AND ASNT, WESTERN METAL AND TOOL EXPOSITION AND CONFERENCE, LOS ANGELES, CALIF., MAR 11-15, 1974, PAPER, 70 PP

327
RUSCIGNO,H.
STITCHED FOAM THERMAL INSULATION PROTECTION SYSTEM FOR THE LH(2) TANK WALL OF THE CENTAUR FLIGHT VEHICLE. GENERAL DYNAMICS/CONVAIR, SAN DIEGO, CALIF., PROGR. REPT. NO. GD/C-BTD-64-078, NASA-CR-54418 (APR 1965) CONTR. NO. NAS3-3232 77 PP

OTHER DOCUMENTS
(CONT.)

328
SAUERBRUNN,I.
COMPLAINTS ABOUT REFRIGERATING INSULATIONS AND THEIR REMEDIES. (IN GERMAN) KALTE (HAMBURG) VOL 20, NO. 9, 443-9 (SEP 1967)

329
SAUERBRUNN,I.
PLASTIC FOAMS IN REFRIGERATION TECHNIQUES. (IN GERMAN) HEIZUNG-LUFTUNG-HAUSTECH. VOL 18, NO. 9, 346-51 (SEP 1967)

330
SCHLUMBERGER,E.M. PLOUM,A.J.W.
MEMBRANE TANKS. U. S. PATENT 3,150,794 (SEP 1964)

331
SHIBATA,F. GONDOUIN,M.
THE STORAGE OF LNG. THE TECHNIGAZ TECHNIQUE. HIRATSUKA EXPERIENCE AND REALISATION. INTERNATIONAL CONFERENCE AND EXHIBITION ON LIQUEFIED NATURAL GAS, 3RD, WASHINGTON, D.C., SEP 24-28, 1972, INSTITUTE OF GAS TECHNOLOGY, CHICAGO, ILL., SESSION-V/PAPER-4, 14 PP (1972)

332
SHIPPING WORLD SHIPBUILDER
GERMAN DESIGNED STANDARD SHIPS - A BULK CARRIER AND AN LNG CARRIER. SHIPPING WORLD SHIPBUILDER VOL 166, NO. 3877, 142-3 (JAN 1973)

333
SHRIVER,C.B.
DESIGN AND FABRICATION OF AN INTERNALLY INSULATED FILAMENT WOUND LIQUID HYDROGEN PROPELLANT TANK. GOODYEAR AEROSPACE CORP., AKRON, OHIO, REPT. NO. NASA CR-127 (NOV 1964) CONTR. NO. NAS 3-2291, 62 PP

334
SHRIVER,C.B.
FILAMENT-WOUND CONTAINER. U.S. PATENT 3,392,865 (JUL 1968)

335
SIEDERS,R. TAAL,L.
TANK FOR STORAGE AND TRANSPORTATION OF LOW BOILING LIQUEFIED GAS. U. S. PATENT NO. 3,484,277 (DEC 1969)

336
SIGMUND,F.
THERMALLY INSULATED PIPE. U. S. PATENT NO. 3,685,546 (AUG 1972)

337
SINDT,C.F.
INSULATION OF LIQUID OXYGEN DEWARS. NAT. BUR. STAND. (U.S.), INTERNAL REPT. NO. 73-308, 45PP (APR 1973)

OTHER DOCUMENTS
(CONT.)

338
SISLER,C.W.
PROCEDURE EVOLVED FOR THERMAL INSULATION STANDARD. PLANT ENG., 160-1, 164 (OCT 1965)

339
SMALL,A.B. GORMAN,P.T. MCGARRY,F.J.
CRYOGENIC INSULATION SYSTEM. U. S. PATENT NO. 3,607,531 (SEP 1971)

340
SMITH,E.T.
INVESTIGATION OF COMBINED EFFECTS OF RADIATION AND VACUUM AND OF RADIATION AND CRYOTEMPERATURES ON ENGINEERING MATERIALS. VOLUME II, RADIATION-CRYOTEMPERATURE TESTS. GEN. DYNAMICS/FORT WORTH, TEXAS, ANNUAL REPT. NASA CR 51140 (NOV 1962) CONTR. NO. NAS8-2450, 253 PP

341
SMITH,H.S.,JR.
CRYOGENIC CONSTRUCTION AND ARTICLE THEREFOR. U. S. PATENT NO. 3,924,039 (DEC 1975)

342
SMITH,J.C. KUMMINS,J.S.
PROTECTIVE COATINGS FOR FOAM INSULATION. CHEM. ENG. PROGR. VOL 70, NO. 8, 57-9 (AUG 1974)

343
SMITH,J.C. KUMMINS,J.S.
PROTECTIVE COATINGS FOR POLYURETHANE FOAM TANK INSULATION. AMERICAN INSTITUTE OF CHEMICAL ENGINEERS NATIONAL MEETING, 76TH, TULSA, OKLA., MAR 10-13, PAPER (1974) 9 PP

344
SMITH,J.K.
A STUDY OF THE DEVELOPMENT OF A NEW LOW COST INSULATION SYSTEM FOR USE ON SATURN V S-II STAGE. BOEING CO., HUNTSVILLE, ALA. LAUNCH SYSTEMS BRANCH, REPT. NO. D5-13496 (FEB 1969) 37 PP

345
SMYLY,E.D. SWOGER,W.F. PEARS,C.D.
PROPERTIES OF ABLATION AND INSULATION MATERIALS. VOLUME 3. THERMAL AND MECHANICAL PROPERTIES OF LOW-DENSITY PHENOLIC-NYLON AND SILICONE-PHENOLIC ABLATORS. SOUTHERN RESEARCH INST., BIRMINGHAM, ALA., REPT. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION REPT. NO. NASA-CR-111909, CONTRACT NO. NAS1-7732-1, 321PP (JUN 1971)

346
SOLLAMI,B.J. LUNDEEN,H.R. GERTH,B.F.
COMPOSITE INSULATION FOR CRYOGENIC VESSEL. U. S. PATENT NO. 3,724,228 (APR 1973)

OTHER DOCUMENTS
(CONT.)

347
SPIETH,C.W.
ESTABLISHING PROVEN DESIGN CRITERIA FOR CRYOGENIC BOOST TANKS. BEECHCRAFT RES. AND DEVELOP. INC., BOULDER, COLO. ENG. REPT. NO. 7074 (SEP 1959) CONTR. NO. AF 33(616)-5154, SUPPL. S3(59-207) PROJ. NO. 3084, TASK NO. 30304, FTRDI MR59-1, 246 PP

348
SPIETH,C.W.
ESTABLISHING PROVEN DESIGN CRITERIA FOR CRYOGENIC BOOST TANKS. BEECHCRAFT RES. AND DEVELOP. INC., BOULDER, COLO. ENG. REPT. NO. 7602 (MAR 1960) CONTR. NO. AF 33(616)-5154, SUPPL. S3(59-207) PROJ. NO. 3084, TASK NO. 30304, FTRDI MR 60-1, 222 PP

349
SPIETH,C.W.
STUDY OF INTEGRATED CRYOGENIC FUELED POWER GENERATING AND ENVIRONMENTAL CONTROL SYSTEMS. VOLUME II. CRYOGENIC TANKAGE INVESTIGATION. BEECHCRAFT RESEARCH AND DEVELOPMENT, INC., BOULDER, COLO., REPT. NO. ASD-TR-61-327, V.2 (NOV 1961) CONTR. NO. AF 33(616)-7508 388 PP

350
SPIETH,C.W. BELL,J.E. CONNELLY,J.G. CORBETT,R.J. COVINGTON,G.D. STOECKER,L.R. SUTTON,H.E.
ROCKET VEHICLE TANKAGE RESEARCH FOR A CRYOGENIC PROPELLANT. BEECH AIRCRAFT CORP., BOULDER, COLO., REPT. NO. WADC TR 58-530 (SEP 1958) CONTR. NO. AF 33(616)-5178, 152 PP

351
SRINIVASAN,K. SESHAGIRI RAO,V. KRISHNA MURTHY,M.V.
OPTIMUM INSULATION THICKNESS FOR CRYOGENIC TRANSFER LINES. INTERNATIONAL CRYOGENIC ENGINEERING CONF., PROC. 5TH (KYOTO, JAPAN, MAY 7-10, 1974), K. MENDELSSOHN, EDITOR. IPC SCIENCE AND TECHNOLOGY PRESS, SUSSEX, ENGLAND, 570-3 (1974)

352
SRINIVASAN,K. SESHAGIRI RAO,V. KRISHNA MURTHY,M.V.
SELECTION OF INSULATION FOR CRYOGENIC TRANSFER LINES. CRYOGENICS VOL 15, NO. 4, 230-1 (APR 1975)

353
STASTNY,E.
APPLICATION OF PLASTIC FOAMS, ESPECIALLY OF STYROPOR, AS INSULATING MATERIALS IN THE REFRIGERATION INDUSTRY. (IN GERMAN) KALTETECHNIK. VOL 12, NO. 3, 75-80 (MAR 1960)

354
STASTNY,F.
PLASTICS FOR REFRIGERATING INSULATION.
KALTE (HAMBURG) VOL 14, NO. 5, 249-54
(MAY 1961)

355
STILES,R.E.
TEXAS EASTERN PIONEERS LNG STORAGE
TECHNOLOGY. PIPE LINE IND. VOL 33, NO.
6, 30-2 (DEC 1970)

356
STOECKER,L.R.
ON THE EVACUATION OF PLASTIC FOAMS TO
REDUCE THEIR THERMAL CONDUCTIVITY.
ADVANCES IN CRYOGENIC ENGINEERING VOL 5,
273-81 (PROCEEDINGS OF THE 1959 CRYOGENIC
ENGINEERING CONFERENCE) PLENUM PRESS,
INC., NEW YORK (1960)

357
STUCKEY,J.M.
DEVELOPMENT OF A COMBINED HIGH
PERFORMANCE MULTILAYER INSULATION AND
MICROMETEOROID PROTECTION SYSTEM.
RESEARCH ACHIEVEMENTS REVIEW VOLUME 2,
NATIONAL AERONAUTICS AND SPACE
ADMINISTRATION, HUNTSVILLE ALA. GEORGE C.
MARSHALL SPACE FLIGHT CENTER, TECH. MEMO.
53670 (1967) PP 55-68

358
STUMPF,O. ZIMNI,W.F.
THE THERMODYNAMIC DESIGN OF CRYOGENIC
HIGH-ENERGY H(2)-O(2) UPPER STAGES AND
SPACE PROBES FOR LONG DURATION MISSIONS
WITH SPECIAL CONSIDERATION OF THE ELDO-B
LAUNCHERS. PROBLEMS OF PROPULSION AND
RE-ENTRY (PROC. INTERN. ASTRONAUTICAL
CONGRESS 17TH, MADRID, SPAIN, OCT 9-15,
1966) M. LUNC ET AL EDS., GORDON AND
BREACH, INC., NEW YORK (1967) VOL 3, PP
39-50

359
SURDI,V.L. ROMAINE,D.
LOW TEMPERATURE PIPING DESIGN. PETRO.
REFINER VOL 43, NO. 6, 116-24 (JUN 1964)

360
TARIEL,H.
THERMALLY INSULATED RECEPTACLE FOR A
CRYOGENIC FLUID. U. S. PATENT 3,578,541
(MAY 1971)

361
TARIEL,H. GUYON,R. GAGNEUX,Y.
MULLER,F. LOUIS,Y.
THERMAL INSULATION OF RECEPTACLES FOR
CRYOGENIC FLUIDS. U. S. PATENT NO.
3,769,118 (OCT 1973)

362
TAYLOR,B.N. MACK,E.E.
EFFECT OF CONVECTION IN HELIUM-CHARGED,
PARTIAL-FOAM INSULATIONS FOR LIQUID
HYDROGEN PROPELLANT TANKS. ADVANCES IN
CRYOGENIC ENGINEERING VOL. 11, 65-76
(PROCEEDINGS OF THE 1965 CRYOGENIC
ENGINEERING CONFERENCE) PLENUM PRESS,
INC., NEW YORK (1966)

363
TEMPLE,R.W.
THE WORLDS LONGEST PROCESS PLANT.
LIQUEFIED NATURAL GAS (PROCEEDINGS OF THE
INTERNATIONAL CONFERENCE AND EXHIBITION
2ND, PARIS, FRANCE, OCT 19-23, 1970) VOL
1 22 PP

364
TIEN,C.L. CUNNINGTON,G.R.
CRYOGENIC INSULATION HEAT TRANSFER.
ADVAN. HEAT TRANSFER VOL 9, 349-417
(1973)

365
TORNAY,E.G.
LIQUEFIED GAS TANKER CONSTRUCTION USING
STIFFENER MEMBERS. U. S. PATENT NO.
3,922,987 (DEC 1975)

366
TRENNER,L.
RECEPTACLES FOR THE STORAGE OF LIQUEFIED
GASES AT CRYOGENIC TEMPERATURES. U. S.
PATENT NO. 3,655,086 (APR 1972)

367
TURNER,W.C.
CRITERIA FOR INSTALLING INSULATION
SYSTEMS IN PETROCHEMICAL PLANTS. CHEM.
ENG. PROGR. VOL 70, NO. 8, 41-5 (AUG
1974)

368
TYE,R.P.
THE THERMAL CONDUCTIVITY OF TWO THERMAL
INSULATING MATERIALS. DYNATECH CORP.,
CAMBRIDGE, MASS., REPT. 798,
NASA-CR-61915 (JUL 1968) CONTR.
NAS8-21262 10 PP

369
VAHL,L.
CHARACTERISTICS OF EXPANDED POLYSTYRENE
PLATES. (IN DUTCH) NED. VER. KOELTECHN.
MEDEJ. VOL 34, NO. 5, 151-9 (SEP-OCT
1961)

370
VAN BUSKIRK,E.C. SURLAND,C.C.
SANDERS,V.
LOW-TEMPERATURE INSULATION. CHEM. ENG.
PROGR. VOL 44, NO. 10, 803-6 (OCT 1948)

OTHER DOCUMENTS
(CONT.)

371
VEERLING,C.W.N.
A SUBMARINE OFFSHORE LOADING LINE FOR LNG. INTERNATIONAL CONFERENCE AND EXHIBITION ON LIQUEFIED NATURAL GAS, 3RD, WASHINGTON, D.C., SEP 24-28, 1972, INSTITUTE OF GAS TECHNOLOGY, CHICAGO, ILL., SESSION-II/PAPER-8, 17 PP (1972)

372
VERSCHOOR,J.D.
THERMAL CONDUCTIVITY OF COMMERCIAL INSULATION AT LOW TEMPERATURE. REFRIG. ENG. VOL 62, 35-7 (SEP 1954)

373
VRANCKEN,P.L.L.
CURRENT L.N.G. TANKER DESIGNS. GAS J. VOL 349, NO. 5651, 173-7 (MAR 1972)

374
WAITE,H.J.
STYROFOAM (EXPANDED POLYSTYRENE) INSULATION AT LOW TEMPERATURE. ADVANCES IN CRYOGENIC ENGINEERING VOL 1, 230-4 (PROCEEDINGS OF THE 1954 CRYOGENIC ENGINEERING CONFERENCE) PLENUM PRESS INC., NEW YORK (1960)

375
WALKER,G. COULTER,D. SOOD,N.
LIQUEFIED NATURAL GAS PIPELINES FOR ARTIC GAS RECOVERY. PROC. OF INTERNATIONAL CONFERENCE ON LIQUEFIED NATURAL GAS, LONDON, MAR 1969, 503-23

376
WALTERS,W.J. GIBSON,G.H.
LAND-BASED L.N.G. STORAGE TANKS. GAS J. VOL 349, NO. 5651, 179-84 (MAR 1972)

377
PIPELINE AND GAS JOURNAL
SPRAY-ON FOAM INSULATES TANKS. PIPELINE GAS J. VOL 201, NO. 8, 76 (JUL 1974)

378
WATSON,J.F.
PROPERTIES OF ENGINEERING MATERIALS AT EXTREME SUBZERO TEMPERATURES WITH SUPPLEMENTARY INFORMATION ON LIQUID HYDROGEN. GENERAL DYNAMICS/ASTRONAUTICS, SAN DIEGO, REPT. NO. EMG-44 (DEC 1958) 136 PP

379
WATSON,J.F.
PROPERTIES OF ORGANIC MATERIALS AT LOW TEMPERATURE INCLUDING COMPATIBILITY WITH LIQUID OXYGEN. GENERAL DYNAMICS/ASTRONAUTICS, SAN DIEGO, CALIF., REPT. NO. GDA-MRG-80 (JUN 1959) 77PP

380
WATSON,J.M. SEVCIK,V. PEIFER,J.
FOAM-INSULATED LIQUID HYDROGEN TARGET FOR STREAMER CHAMBERS. NUCL. INSTRUM. METHODS VOL 105, NO. 1, 33-6 (1972)

OTHER DOCUMENTS
(CONT.)

381
WEISHAUPT,J. SELLMAIER,A.
INSULATION FOR LARGE TECHNICAL LOW TEMPERATURE PLANT. (IN GERMAN) LINDE-BER. TECHNIK WISS., 3-13 (NOV 1961)

382
WEN,SHU-LIN
PROGRESS ON THERMAL INSULATION MATERIALS. (IN CHINESE) HUA HSUEH TUNG PAO NO. 3, 58-64 (1974)

383
WENT,A.R. IVERS,A.P.
DESIGN AND OPERATION CONSIDERATIONS - INSULATED AND REFRIGERATED TRANSPORT. J. REFRIG. VOL 11, NO. 5, 125-36 (MAY 1968)

384
WESTERN PLASTICS
RIGID URETHANE FOAM IN THE WEST. WESTERN PLASTICS VOL 15, NO. 3, 15-21 (MAR 1968)

385
WHITE,G.W. PENN,W.H.
TECHNICAL PROBLEMS WITH INGROUND STORAGE. AMERICAN GAS ASSOCIATION OPERATING SECTION CONFERENCES, PHILADELPHIA, PA. (MAY 12-15, 1969) PAPER 10 PP

386
WHITELOCKE,A.J.B.
RIGID POLYURETHANE FOAM PIPE SECTIONS. PIPES PIPELINES INT. VOL 16, 17-9 (1971)

387
WIJNBERG,J.G.
RELIQUEFACTION PLANT OF THE LPG-TANKER ANTILLA CAPE. BULL. INST. INT. FROID ANNEXE VOL 1969-5, 103-8 (1969)

388
WILSON,D.J. HALE,D.V. WHITACRE,W.E.
ORBITAL PROPELLANT DEPOT SYSTEM. ADVANCES IN CRYOGENIC ENGINEERING VOL 17, 160-5 (PRESENTED AT CRYOGENIC ENGINEERING CONFERENCE, BOULDER, COLO., JUN 17-19, 1970) PLENUM PRESS, INC., NEW YORK (1972)

389
WILSON,G.C. BALLINGER,J.C.
THERMAL DESIGN CRITERIA FOR CENTAUR PROPELLANT TANKS. GENERAL DYNAMICS/ASTRONAUTICS, SAN DIEGO, CALIF., REPT. NO. GDA-AE60-0072 (JAN 1960) CONTR. AF 18(600)-1775 19 PP

390
WILSON,J.J.
AN INTRODUCTION TO THE MARINE TRANSPORTATION OF BULK LNG AND THE DESIGN OF LNG CARRIERS. CRYOGENICS VOL 14, NO. 3, 115-20 (MAR 1974)

OTHER DOCUMENTS
(CONT.)

391
WITHERS,D.D.
CRYOGENIC TANK DESIGN AND METHOD OF MANUFACTURE. U. S. PATENT NO. 3,765,558 (OCT 1973)

392
WOOD,C.C. PAUL,H.G.
CRYOGENIC TECHNOLOGY ASPECTS OF SPACE FLIGHT. CRYOGENIC ENGINEERING - PRESENT STATUS AND FUTURE DEVELOPMENT (PROC. OF THE INTERNATIONAL CRYOGENIC ENGINEERING CONF. 1ST, TOKYO AND KYOTO, JAPAN, APR 9-13, 1967) HEYWOOD TEMPLE INDUSTRIAL PUBLICATIONS, LTD., LONDON, ENGLAND (1968) PP 13-9

393
WOOD,G.
TEMPERATURE LIMITATIONS OF POLYMERIC MATERIALS. PART I - GENERAL REVIEW. ROYAL AIRCRAFT ESTABLISHMENT, FARNBOROUGH, ENGLAND, REPT. NO. RAE-TN-CPM-34 (OCT 1963) 22 PP

394
WOOD,M.
MANUFACTURERS OPTIMISTIC ABOUT U.S. AND FOREIGN LNG MARKETS. LNG/CRYOGEN. VOL 1, NO. 2, 17-22 (APR/MAY 1973)

395
WORBOYS,R.V. ESTEBANEZ,J.
THERMALLY INSULATED CONTAINER FOR TRANSPORTING LOW TEMPERATURE LIQUIDS. U. S. PATENT 3,502,239 (MAR 1970)

396
WYCKAERT,L.
THE BRUNEI LNG SHIP LOADING SYSTEM. PAPER PRESENTED AT THE AMERICAN INSTITUTE OF CHEMICAL ENGINEERS 71ST NATIONAL MEETING, HELD AT THE STATLER HILTON HOTEL, DALLAS, TEXAS, FEB. 20-23, PAPER-10B (1972) PAPER PREPARED FOR CRYOGENIC SOCIETY OF AMERICA INC. 6TH CRYOTECHNOLOGY EXPOSITION AND CONF., WASHINGTON, D.C., AUG 30, 1971

397
YAMAMOTO,K.
STORAGE TANK OF COLD LIQUEFIED GAS. U. S. PATENT 3,581,931 (JUN 1971)

398
YASUI,G.
RIFT RADIATION EFFECTS PROGRAM IRRADIATIONS NO. 1 AND 2. CRYOGENIC INSULATION MATERIALS. LOCKHEED AIRCRAFT CORP., MISSILES AND SPACE DIV., SUNNYVALE, CALIF., REPT. NO. NSP-63-35 (MAY 1963) CONTR. NO. NAS8-5600, 67 PP

399
YOSHIMURA,K.
CRYOGENIC INSULATING MATERIAL. U. S. PATENT NO. 3,895,159 (JUL 1975)

OTHER DOCUMENTS
(CONT.)

400
YOSHIMURA,K.
LOW TEMPERATURE INSULATING MATERIAL. (IN FRENCH) FRENCH DEMANDE NO. 2,206,292 (NOV 1973)

401
ZINNIGER,T.C. BURKE,P.J.
CRYOGENIC LIQUID CONTAINMENT SYSTEM. U. S. PATENT NO. 3,927,788 (DEC 1975)

AUTHOR INDEX

SUBJECT INDEX

	Abstract page numbers	Other document numbers
Polystyrene foam	4, 6, 7, 12, 13, 15, 17, 18, 20, 21, 22, 33, 43, 44, 45, 49, 51, 54, 62, 64, 68, 70, 73, 85, 86, 89, 90, 94, 95, 97, 104, 105, 109	003, 004, 009, 016, 021, 026-028, 037, 046, 049, 052-054, 058, 059, 061, 071, 088, 091, 094, 095, 102, 107, 112, 118, 125, 128, 138, 146, 147, 151, 152, 164, 170, 173, 174, 176, 188, 193, 196, 197, 201, 216, 220, 221, 225, 229, 231, 233, 238, 241, 243, 244, 251, 252, 256, 258, 259, 261, 264, 270, 271, 275-279, 283, 285-287, 290, 293, 299, 300, 305, 308, 315, 316, 320, 324, 328, 329, 339-342, 349, 350, 353, 354, 356, 369, 372, 374, 378, 379, 381, 383, 393, 397
Polyurethane foam	2, 4, 5, 7, 8, 10, 11, 12, 13, 17, 19, 21, 24, 26, 28, 29, 31, 32, 33, 34, 35, 36, 37, 38, 39, 41, 42, 43, 44, 46, 47, 49, 50, 51, 52, 54, 56, 57, 58, 59, 60, 62, 64, 65, 66, 67, 69, 70, 71, 73, 77, 81, 82, 83, 86, 87, 89, 91, 92, 93, 94, 95, 96, 97, 98, 103, 109, 111, 112	001, 005, 006, 008, 010, 011, 013, 014, 016-027, 030, 032-034, 036-040, 042, 043, 045-049, 051, 053, 055-057, 062, 066-068, 070, 072-078, 080, 083-085, 087-099, 101-106, 108-110, 112, 114, 115, 121, 123-125, 127-129, 131, 135-138, 142-145, 148, 149, 151, 153-160, 162-164, 167-170, 172-183, 185, 188-190, 192-196, 198-202, 204-210, 214-218, 221-224, 226-229, 232, 233, 236-241, 244, 248-250, 252, 253, 255-257, 260, 262, 263, 267-270, 272, 273, 275-278, 282, 284, 286-295, 297-301, 304-309, 311-319, 322-324, 326-330, 333, 334, 336-338, 340-344, 347-357, 362, 363, 365, 366, 368, 371, 373, 375, 377-379, 381, 383-387, 390-396, 398-401

1. Report No. NASA RP-1002	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle CRYOGENIC FOAM INSULATION - ABSTRACTED PUBLICATIONS		5. Report Date September 1977
		6. Performing Organization Code
7. Author(s) Frank R. Williamson		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address National Bureau of Standards Cryogenics Division Boulder, Colorado 80302		11. Contract or Grant No.
		13. Type of Report and Period Covered Reference Publication
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This survey is composed of information from the reports and publications available in January 1976 on cryogenic foam insulation. One group of documents was chosen to include the most important or most informative papers on the properties and applications of foams. An abstract has been prepared for each document in this group, and the most important references are listed as found in the document. Another group of documents generally includes less important papers than those in the first group. Some important papers are in the second group because information from them has been reviewed or repeated in documents included in the first group.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Insulation Foams Cryogenic equipment Cryogenics	Unclassified - unlimited STAR Category 27

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	164	A08

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1977

National Aeronautics and
Space Administration

Washington, D.C.
20546

Official Business
Penalty for Private Use, $300

THIRD-CLASS BULK RATE

Postage and Fees Paid
National Aeronautics and
Space Administration
NASA-451

U.S.MAIL

10 1 1U,C,SPGEN,110777 S00903DS 740731
DEPT OF THE AIR FORCE
AF WEAPONS LABORATORY
ATTN: TECHNICAL LIBRARY (SUL)
KIRTLAND AFB NM 87117

NASA

POSTMASTER: If Undeliverable (Section 158
Postal Manual) Do Not Return