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External Insulation Systems

for

Cryogenic Storage Systems

Contract NAS 9-10583

BIBLIOGRAPHY/SYNOPSIS AND CATEGORY REPORT
(TYPE II DATA)

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ABSTRACT

Cryogenic storage systems for the extended space missions of the future will require more fluid capacity than current systems, and thus new design and development techniques will need to be evaluated.

This report describes the results of the first phase of a program to investigate high performance external insulation systems for use on flight weight cryogenic gas storage systems. "External insulation" here means anything added to a cryogenic storage system for the purpose of thermally protecting it from its environment. This definition excludes the vacuum annulus of a dewar. The fluids stored are hydrogen and oxygen.

This report covers the period March 2, 1970, to July 2, 1970. The purpose of the work performed during this period was to: (a) perform a literature search on all of the available material concerning external insulation studies and/or evaluation; (b) provide a complete bibliography of the material researched in (a), above; (c) furnish a synopsis for each of the most useful references contained in the bibliography, and (d) categorize the results of this work to facilitate evaluation and assessment.

1.0 INTRODUCTION

External insulation systems have been studied quite extensively in the past few years. However, there is no single source which evaluates these various studies and assesses the relative merits and/or deficiencies of each concept. This study is meant to bring together all of the available information in a single source manual and provide the basis for determining the areas in which future development should be undertaken.

This present report describes the first phase of a complete program designed to accomplish the above objectives. This report describes the literature search and presents the bibliography and synopses of each relevant study. It concludes by categorizing the studies into patterns according to the principal materials and concepts involved.

2.0 CRYOGENIC INSULATION SYSTEMS

Insulations used in spacecraft must withstand a variety of environmental conditions, ranging from those during ground hold through launch to space flight. To meet these conditions several insulation-placement techniques have been developed. These general types of insulation are discussed now in order to give perspective to the particular examples that appear later in the synopses.

2.1 External Insulation

External insulation has been used for the liquid-hydrogen storage tanks tanks of large boosters such as the Saturn S-II and S-IV and for many smaller cryogenic-fluid storage vessels developed for the Apollo program. External insulation is the most widely used because -

- Complex tank shapes can be insulated
- Insulation thickness can be built up in successive layers or in individual sections.
- Insulation can be integrated with supports and pipes.
- Sections of insulation can be more easily repaired.

External insulation often requires that either an outer shell or a vapor-tight

barrier be placed over it. After this process has been completed, however, the tank is quite fragile and must be handled with care to prevent damage to the insulation.

2.2 Internal Insulation

In this technique, which is applicable primarily to large tanks, the insulation is placed inside the tank shell. The major advantages of such placement are -

- The insulation does not need to withstand aerodynamic heating and pressures during vehicle launch.
- Mechanical handling of the complete cryogenic tank is simpler than that of a tank with a fragile external insulation.
- The insulation is not penetrated by external lines and projections.

The disadvantages of internal insulation are -

- The insulation must be attached securely to the inner wall and the cryogenic liquid must be prevented (by a vapor barrier) from leaking into the insulation. If such leakage occurs, the liquid will vaporize at, or near, the warm wall and drastically reduce the insulation's effectiveness.
- Defective portions of the insulation are hard to locate and repairs are difficult to make.
- Any separation of the insulation from the wall caused by thermal

contraction, vibration, or sloshing will result in an increased heat leak; loose sections of the insulation can plug the liquid supply lines.

2.3 Jettisonable Insulation

An alternative, applicable to large space-vehicle cryogenic-fluid storage tanks, is to jettison the insulation after launch. In this case, the insulation is effective only during ground hold and for that time period during launch when high external pressures (dynamic) and temperatures are experienced. Jettisoning the insulation prevents heat absorbed by the insulation during launch from being transferred to the tank. The insulation is held in place mechanically and is not bonded to the tank wall with adhesive. To prevent air condensation, the space between the insulation and the tank wall must be purged with helium.

3.0 MATERIALS FOR INSULATION SYSTEMS

Insulations can be categorized according to the form of the materials, such as: loose fill (e.g., bubbles, fibres, flakes, granules, and powders), flexible (e.g., batting, blanket, felt, and multilayer), rigid (e.g., block, board, brick, honeycomb, and molded, foamed, or sprayed-in-place materials). In addition to design criteria and economic consideration, the choice of insulation materials is usually dictated by the operating temperature range.

The weight of insulation materials that are to be used in space-flight applications must also be optimized. For these applications, flexible materials are typically employed. Loose-fill materials, either evacuated or at atmospheric pressure, are employed for storage, transportation, or transfer of cryogenic fluids. Rigid insulation materials are used for both space-flight and terrestrial applications requiring mechanical strength.

3.1 Multilayer Insulations

A multilayer insulation usually consists of many layers of alternate radiation-reflecting shields separated by low-conductivity spacers. This assembly is placed perpendicular to the flow of heat. Each layer contains a thin

low-emissivity radiation shield enabling the layer to reflect a large percentage of the radiation it receives from a warmer surface. The radiation shields are separated from each other to reduce the heat transferred from shield to shield by solid conduction. The gas in the space between the shields is removed to decrease the conduction by gas molecules. Each component of the insulation is designed specifically to perform a particular function:

- o Radiation shields - to attenuate radiation
- o Spacers - to decrease solid conduction
- o Evacuation - to decrease gas conduction

When the designer selects materials for multilayer insulation, he endeavours to reduce each of the three possible heat-transfer modes. Technological advances resulting in more effective radiation-shield materials, low-conductivity spacers, and improved gas-removal methods show promise for multilayer insulations. The above discussion makes no allowance for the existence of non-separated multilayer insulations, such as crinkled aluminized mylar.

3.2 Foams

Organic and inorganic foams are commonly used as insulating materials in industrial and construction applications. Because such foams have many advantages for cryogenic and space-vehicle applications, efforts have been made to develop suitable foam formulations; establish the physical,

chemical, and structural properties of foams; and integrate foams with thermal insulation systems. Having a cellular structure of discrete or interconnected voids, the foams provide effective insulation.

Inorganic foams are difficult to produce in densities of 1 to 5 lb/ft^3 (0.016 to 0.08 g/cm^3) and generally have inferior physical properties at these low densities. Organic foams can be readily made in this low-density range and exhibit good physical properties. For many insulation applications, low-density organic foams offer certain advantages, which include:

- o Ease of fabrication
- o Relatively low cost
- o Self-supporting structure

Foams can be used either as a single insulation or combined with other materials to form a thermal insulation system. Like plastics, organic polymer foams can be divided into two basic classifications, thermoplastic foams and thermosetting foams.

3.2.1 Thermoplastic foams

Thermoplastic foams soften at temperatures of 150° to 250°F (65° to 120° C), and, in most cases, tend to become brittle at cryogenic temperatures. Thermoplastic foams can be made from such polymers as

cellulose acetate, polystyrene, styrene-acrylonitrile copolymer, polyvinyl chloride, polyethylene, and polypropylene. Of these foams, polystyrene and polyvinyl chloride are by far the most common.

Polystyrene foams can be subdivided into two basic types: molded expandable beads and extruded foam. Limited use has been made of polystyrene foams in cryogenic insulation applications; their utility is limited by low-temperature embrittlement and inability to withstand extreme thermal cycling. Until recently, most polyvinyl chloride foams were flexible formulations, which also suffer from severe low-temperature embrittlement. Recently, rigid polyvinyl chloride foams of high density have become commercially available, and they are used for insulation and structural support of tanks for transporting liquefied petroleum gas.

3.2.2 Thermosetting foams

Among the thermosetting polymers, foams are commonly made with phenolic, urea-formaldehyde, epoxy, and polyurethane resins. Urea-formaldehyde foams are brittle and do not have good structural properties at low densities. At low densities the phenolic resin foams tend to be brittle and friably at room temperature and are difficult to fabricate because the formation of the foam requires the use of a strong acid

catalyst and highly volatile, flammable blowing agents. Epoxy foams have had only limited use because of the difficulties in satisfactorily controlling the foaming. They also exhibit only fair physical properties and are relatively expensive.

Among the thermosetting foams, polyurethanes are by far the most widely used in industrial and building applications and in cryogenic insulation.

3.3 Powders and Fibers

The desirable properties of an evacuated powder or fiber insulation are:

- Low thermal conductivity
- Low density
- Particle size small enough to obtain the pressure-dependent region of gas conduction in a moderate vacuum
- Distribution of particles by size to minimize effects of shock and vibration
- Low vapor pressure at the operating temperature

The vapor pressure of the material should be as low as is consistent with the desired moderately low operating pressure. Furthermore, transfer of material in the vapor phase from the warmer to the cooler portion of an

insulation and subsequent condensation is undesirable because a build-up of deposits between individual particles could increase the areas of contact.

3.3.1. Powder Insulations

Although mica, diatomaceous earth, carbon, calcium silicate, titanium dioxide, iron oxide, and plastic microspheres have been investigated as potential powder insulations; perlite (a silica powder), colloidal silica, and silica aerogel have been investigated more extensively.

Expanded perlite is produced from a volcanic glassy rock that occurs in widely distributed deposits. This rock is ground to a fine powder and then expanded by heating to above 1500° F (800°C). Microscopic voids forming in the expanding, heat-softened glass cause a porous structure and account for the expanded perlite's low density. Perlite is available in various grades containing particles ranging in size from 100 to 1600 microns (4×10^{-3} to 6×10^{-3} in.).

Colloidal silica is a white, fluffy, submicroscopic particulate silica prepared in a hot gaseous environment (2000°F (1100°C)) by the vapor phase hydrolysis of silicon tetrachloride. The average size of primary particles of colloidal silica ranges between 150 and 200 Å.

Silica aerogel is prepared from a gel in which water is replaced with an alcohol. The alcohol is subsequently removed, leaving a skeleton submicroscopic structure which is retained as the solid is ground to powder. These materials have been mixed with fine metallic powders or flakes (such as copper and aluminum) and carbon.

Preheating permits the efficient removal of absorbed gases and particularly moisture. After preheating, fine powders are effective absorbers of reduced residual gases; therefore, their exposure to the atmosphere should be minimized prior to use.

The choice of particle size to obtain a desired density and to prevent compaction under a load, particularly when evacuated powders may be subjected to atmospheric-pressure loading, must be carefully considered. In double-walled pressure vessels, the powder has to be vibrated to settle particles to a density sufficiently high to prevent formation of voids in the insulated space during operation. Filters with extended surfaces, such as perforated tubes wrapped with several layers of fine glass fiber, are required to prevent small particles from clogging evacuation ports or entering the vacuum pumps.

3.3.2 Fiber insulation

In most thermal insulation applications where vibration and shock are

expected, fibers have distinct advantages. For cryogenic applications, submicron-diameter glass fibers have been widely used. Very similar considerations govern the use of both powder and fiber insulations. When fibers are used as spacers for multilayer insulations, to reduce the possibility of outgassing, they are prepared without any binders or lubricants. Fibers with low-vapor-pressure binders have been used as supports to space an inner vessel from an outer shell. To insure that multilayer insulations interposed between them are not subjected to compressive loads, such supports have been designed to take acceleration loads.

3.4 Composite Insulations

The optimum insulation system should combine maximum insulation effectiveness, minimum weight, and ease of fabrication. It would be desirably to use only one insulation material, but since no single insulation material has all the desirable physical and strength characteristics required in many applications, composite insulations have been developed. These composite insulations represent a compromise between thermal effectiveness, handling properties, and adequate service life. For cryogenic applications, composite insulations consist of a polyurethane foam: reinforcement for the foam to provide adequate compressive strength; adhesives for sealing and securing the foam to a tank; enclosures to prevent damage to the foam from mechanical contact, vibration, and aerodynamic heating; and vapor barriers to maintain a separation between the foam and atmospheric gases.

3.4.1 Honeycomb-foam insulation

Several external insulation systems use honeycomb structures. Phenolic resin-reinforced fiber-glass-cloth honeycomb is most commonly used. The honeycomb is bonded to the tank with a suitable seal, and a vapor barrier is applied to the exterior of the honeycomb. In such a system, the cells in the honeycomb can be interconnected and evacuated through external pumping, interconnected and purged with helium, or sealed and allowed to reach a low pressure within the sealed cells when the tank is filled with a cryogenic liquid.

The effectiveness of a honeycomb insulation can be considerably improved if its cells are filled with a low-density polyurethane foam. Several techniques have been used for preparing foam-filled honeycomb. For example, the liquid components can be foamed in place to fill the honeycomb cells. This system has not proved effective, however, because of large waste, nonuniform cell structure in the foam, and nonuniform filling of the honeycomb cells. The most common method of preparing foam-filled honeycomb is to press the rigid, phenolic resin-reinforced fiber-glass honeycomb into a preformed sheet of low-density foam. The thin honeycomb walls cleanly cut through the foam so that it fills each cell. However, the foam is not sealed or bonded into the cells; it simply lies within them. This lack of bonding has certain disadvantages because atmospheric gases or helium can diffuse through the insulation. In this,

as in other honeycomb insulations, the honeycomb provides compressive strength and allows the insulation to absorb stresses created by differential expansion between the insulating materials and the tank during chilldown. A helium-purged, externally sealed honeycomb system was developed for the Saturn S-II insulation system.

3.4.2 Sealed evacuated honeycomb insulations

One concept considered for a cryogenic insulation was a sealed honeycomb in which the residual air in the individual cells was condensed to provide a vacuum in each cell. A removable bag of lightweight polyester film was to be placed around the exterior of the insulation to permit a helium purge and to prevent diffusion of air into the insulation in the event of any leaks in the outer seal. This outer bag was to fall away just prior to vehicle liftoff. This concept was not tried because an outer bag was not found that was sufficiently reliable to withstand wind, mechanical loading and other ground hazards and capable of being removed rapidly from the vehicle.

3.4.3 Self-sealing

Meteoroid particles impacting cryogenic propellant tanks will not only penetrate the tank wall but may also generate forces that could cause catastrophic failure of the tank. External thermal shielding and insulating

systems for the tanks can be designed to incorporate an exterior meteoroid bumper together with a low-density energy-absorbing material between the bumper and the tank wall to provide meteoroid protection. Attention has been given to using structures similar to sealed exterior insulations as self-sealing shields for micrometeorite protection. If a cryogenic propellant tank is penetrated by a micrometeorite, the cryogenic propellant will solidify when it encounters the vacuum of space. If there is a porous medium around the penetration, the solidifying propellant will cling to this medium and plug the hole. Tests were made by filling a honeycomb with porous media, such as fiberglass and an open-cell polyester foam.

The most favorable self-sealing results were obtained with the open-cell polyester foam, which produced sealing of punctures as large as 0.050 inch in diameter.

3.5 Other Materials

A large number of other materials have been screened as possible candidates. Those which have proved useful are corkboard and balsa wood. Although balsa wood is a good nonporous insulator, it is brittle and difficult to fabricate into thin sections. Corkboard is readily available and relatively nonporous, Also, it has a low thermal conductivity but a high density which limits its use for space vehicles. Corkboard tends to separate and crack near the tank walls during cooldown. Like balsa, it is difficult to fabricate in curved sections.

4.0 APPROACH USED IN THIS STUDY

Several National Documentation Centers which hold the raw material for technical bibliographies in computer searchable forms were used in this study. They were chosen to insure currenteness, completeness, and timeliness.

Such searches are current, as these centers insert acquisitions on a daily basis rather than periodically (e.g., such as the Chemical Abstracts do).

They are also complete, as they cover every entry source, as opposed to, for instance, only the acquisitions of a given library, or only a limited field of literature (e.g., the chemical literature of the Chemical Abstracts).

Such searches are normally quick, thus insuring timeliness. Some conventional library searches may never catch up with the rate the literature is being produced. Computer searches are much faster (2-3 days in some instances for a complete search) than human search and are therefore quickly accessible.

In addition to the national documentation centers, private libraries of the principal investigators were used, chiefly as a check upon how

well the Centers were covering the field. Also, a very useful bibliography and set of reprints were supplied by the Technical Contract Monitor, Mr. M. L. Davis, of the Power Generation Branch at the NASA Manned Spacecraft Center, Houston, Texas. This bibliography is in Section 10.0

The Centers used for this study, their characteristics and capabilities essential to this program are described in the following sections.

4.1 National Documentation Centers

A complete literature search was requested of each of the Centers described below. The specific request was:

> Please perform a literature search on the topic of:
>
> EXTERNAL INSULATION SYSTEMS FOR CRYOGENIC STORAGE SYSTEMS
>
> Cryogenic storage systems for the extended space missions of the future will require more fluid capacity than current systems, and thus new design and developmental techniques will need to be evaluated. We wish to investigate high performance external insulation systems for use on flight weight cryogenic gas storage systems. By "external insulation" we mean anything added to a

cryogenic storage system for the purpose of thermally protecting it from its environment. This definition excludes the vacuum annulus of a dewar. The fluids stored are hydrogen and oxygen.

This statement was deliberately designed to include all possible relevant key words to insure a complete, valid computer search, and was made of each of the Centers.

4.1.1 The National Bureau of Standards Cryogenic Data Center

This center, at Boulder, Colorado:

(a) Enters approximately 8000 papers per year,

(b) Conducts approximately 120 major searches per year, and

(c) Provides a Current Awareness Service to 700 paid subscribers and another on Superconducting Devices to 150 paid subscribers per year.

Annually, it searches 200 journals cover-to-cover, 3 title announcement periodicals, and 20 abstract journals. By this means, it covers about 300,000 titles.

Other activities of this Center include:

Literature Searching. An awareness of publications and reports of

cryogenic interest is maintained by the regular review of nearly two hundred periodicals cover to cover, by a weekly review of the "Current Contents" service, by reviewing some fifteen abstract journals, and by noting references in cryogenic documents. 150 to 200 items are noted weekly.

Literature Procurement. Published literature is obtained from local, national, and foreign libraries. A sizable portion is obtained on microfiche from the Technical Library at Delft, Holland. (The service from Delft is economical, fast, and quite comprehensive.) Report literature is procured mostly from the large national centers (NASA, DDC, and the Clearinghouse for Federal, Scientific and Technical Information. Many new reports are obtained directly from corporate sources as a part of the Data Center's program of information exchange.

Cataloging, Coding, and Machine Processing. In addition to standard library cataloging of pertinent literature selected for the system, it is coded into nine main subject categories such as properties of solids and of fluids, cryogenic processes and equipment, instrumentation and laboratory apparatus, cryogenic techniques, etc. Further characteristic coding is then assigned as to the type of document, temperature range, type and range of data, etc. This is followed by comprehensive subject coding

based on the Data Center's thesaurus or dictionary of terms.

Bibliographic Storage and Retrieval. All cataloging and coding is converted to machine readable form for automated processing on the Boulder Laboratories' Control Data Corporation 3600 computer. The principal programs used are for searching, dictionary term identification, and for catalog tape output. Smaller programs are also in use for additional indexing, tape updating, corrections, etc. Custom bibliographies are prepared for specific subjects or for broad subject areas.

Current Awareness Service. Weekly lists of new literature of cryogenic interest are prepared and distributed to subscribers.

Custom Bibliographies. Over 60,000 accessions of cryogenic literature have been entered into the Data Center's system. Approximately 30,000 of these on properties of materials (for both fluids and solids) have been processed for machine searching. Detailed and/or extensive bibliographies can be prepared with computer facilities. Likewise, some 4,000 patents, 10,000 articles on processes and equipment, and 5,000 articles on instrumentation have now been processed for machine retrieval.

Local Use of the Data Center. Visitors are invited to use the Center's library, world literature file, catalog and abstract

files, microfilm facilities, etc., whenever it is convenient for them to do so. The staff of both the Data Compilation and the Documentation units are happy to help with answers to questions, to aid with hard-to-find type of literature, or to offer advice as to best sources of information.

This description is perhaps laborious, but is meant to indicate how important and unique this Center is to the current program. It did in fact provide the fastest, most complete and most relevant bibliography, see Section 6.0. In fairness to the other centers, it should be mentioned that NBS was queried first, and duplications in other bibliographies were removed, thus shortening them.

4.1.2 The Science Information Exchange of the Smithsonian Institution

The Science Information Exchange (SIE) is the only National Documentation Center of research in progress. It is therefore THE source of current research, as opposed to completed (published) research.

The SIE registers research proposals and projects by receiving more than 100,000 unpublished summaries each year, reporting who is planning what research, where, and how supported. These summaries are provided on a voluntary basis by Federal departments and agencies, also hundreds of state, university, private granting and commercial organizations.

Inquiries are answered regarding information about research planned or in progress. SIE's approach allows it to serve both the specific needs of individual projects and the broad requirements of research program reviews. This role applies to all echelons of management responsibilities, from the bench level scientist managing a single project, to the scientist-administrator responsible for multimillion dollar programs covering thousands of projects.

The capability of the SIE system to select and retrieve any combination of information elements has led to a wide variety of information products and services. Fifty-five thousand requests for information were answered last year. They ranged from very simple ones to large computer listings, compilations and tabulations of thousands of selected information elements and printed catalogs covering all current research in broad subject fields.

SIE bridges the gap between the start of projects and their subsequent publication one to several years later, thus complementing the work of libraries and documentation centers that deal with the published results of research. Through it, program strengths, weaknesses and overlap or duplication can be spotted before rather than after the fact and coordination of concurrent efforts can be achieved.

The keynote of the SIE system is flexibility for meeting new demands combined with efficient production capability conditioned by over 20 years of actual demand and service to the national research management community. Last year, approximately one million reports on research currently underway were selected and distributed to meet the specific information needs of thousands of users.

The SIE is thus the means of finding literature on research still in progress from all sources.

The results of the SIE search are in Section 7.0

4.1.3 The Defense Documentation Center

The Defense Documentation Center (DDC) is the central facility within the Department of Defense for processing the supplying scientific and technical reports of Defense-sponsored research, development, test, and evaluation (RDT&E) efforts.

It collects, organizes, and announces new additions to the Defense technical report universe.

The DDC maintains more than 800,000 technical reports which cover Defense RDT &E efforts in all subject areas, and an automated data

processing system to retrieve reports of special interest to user organizations.

It supplies full-text copies of these reports, on demand, either in standard-size or in microimage formats.

The DDC supplies bibliographies of technical reports having special topical relevance or other unique interest and value.

It also announces the availability of new additions to the technical report collection through the Center's Technical Abstract Bulletin, which describes the classified and limited distribution documents... and through the Commerce Department's U.S. Government Research and Development Reports, which contains announcements of unclassified technical reports of the Defense Department and other Federal agencies. Both announcement publications are distributed twice each month with companion volume indexes which provide comprehensive search tools.

The DDC is essentially a clearinghouse of information concerning current Defense-sponsored research and exploratory development activities.

The Defense Documentation Center provides a bibliography service. Users may request "report bibliographies." Upon receipt of request

DDC will make a computer search of the collection to locate those technical reports most pertinent to the user's research problem or project. Requesting organization specifies how far back to search, e.g., six months, one year, three years, or any time span desired.

The user describes his research problem, project or other subject interest in his own words. DDC converts description to its computer language for processing. The resultant bibliography is sent to user in the form of a bound document. Each page contains a description of a single document to enable the user to determine its pertinence to his current efforts. Average DDC processing time (excluding postal transmission) for bibliography requests is three workdays.

The DDC bibliography used in this Program is in section 8.0.

4.1.4 The NASA Scientific and Technical Information System

NASA's scientific and technical information system assembles the results of worldwide aerospace research and development activities. It summarizes, indexes, and stores this knowledge. It helps individual persons find and benefit from the particular parts of this great mass of technical literature that are most likely to help them solve their problems.

The NASA information bank now contains more than half a million documents.

Thousands more are added to it every month.

These government, industry, research institute, and university reports, journal articles, and reviews contain the details of findings of NASA personnel, contractors, subcontractors, and grant-holders. Along with these items, the information bank regularly receives new technical literature and specialized reports such as project records, patents, etc., from other U.S. Government agencies, laboratories and institutions supported by private industry, and other major sources of aerospace knowledge throughout the world.

The NASA Scientific and Technical Information Facility in College Park, Md., receives hundreds of documents daily. These are checked to avoid duplication, examined for relevance, and cataloged descriptively. Each document accepted as a potentially valuable addition to this information bank is then given an accession number and, if appropriate, is recorded on microfiche. The accession number serves as a unique identification tag for the document thenceforth, and both compact and full-size copies of every page can be made from the microfilm for storage and distribution as needed.

Indexers examine each item when it is deposited in the system, document the bibliographic data that accompanies it, and select terms under which it is listed in subject and other indexes.

Abstractors read the abstracts submitted with documents, sometimes edit and condense these summaries, and write abstracts of documents which have been received without them. Then, after further reviewing, complete bibliographic records are placed in the memory of a high-speed electronic computer. From then on, the machine provides ready access to the citations of all documents for all users.

From the day a document is acquired, it can be located quickly by its accession number. This number can be ascertained from other bibliographic information in the computer. A searcher need only know the corporate source, or the authorship, or the subject, or the number assigned to the document in another U.S. Government agency's information system, or the number of a contract under which the work was performed, to be directed to a report he needs.

The references selected from the NASA search are found in Section 9.0.

4.2 Categories

Major categories were determined based on the information found in the bibliography and in the synopses. Typically, these were based on concepts, materials, and techniques.

Ironically, the categories were themselves categorized. In the course of the study, approximately 440 leads were found in the literature and 220 of these were deemed of sufficient interest to warrent acquiring hard copies and studying. One hundred ninety-two synopses were prepared and this number will grow somewhat more. Because the technological base was indeed so broad, it was decided to prepare two types of categories: one dealing with Materials and Concepts; the other dealing with specific properties necessary to assess the utility of the insulation. These two categories are described below.

4.2.1 Material/Concepts Categories

The categories selected here are eleven in number and are:

1. Publication Categories - indicated by EI, TB, RV, AT, PR, and PA in Column 1 (explanation below)
2. Materials Categories - indicated by SI, MC, CK, FM, HC, CA and IN in Column 2 (explanation below)
3. Shroud Mount
4. Vapor Cooled or Refrigerated
5. Continuous Wrap
6. Blankets, Panels, or Shingles
7. Pumped, Evacuated, or Cryopumped
8. Purged or Gas Filled

9. Perforations, Pump Channels

10. Installation - includes bonding, sealing, taping, penetrations, and supports

11. Mission Studies, Economic Studies

In order to convey as much information as possible, the PUBLICATION CATEGORIES were in turn broken down, and given a two letter code. The code which appears inColumn 1 of the tables of Section 12.0 is:

(1.) EI: External Insulation Technology

External Insulation as defined in this program, actual tankage data

(2.) TB: Technological Base, includes:

- o Closely Related Insulation Techniques

  Techniques closely related to the category 1, (EI), originally intended for another purpose but applicable in concept to this program.

- o Related Empiricism and Tests

  Empirical studies and tests contributing to the technological base of this program

- o Long-Term Storage

  Not necessarily touching upon external insulation explicitly, but still contributing to the technological base

(3.) RV: Reviews

General review articles, some part or all of which touch upon this technology

(4.) AT: Analytical Techniques

(5.) PR: Properties of Materials, Relevant Tests, and Techniques

(6.) PA: Patent

Likewise, the MATERIAL CATEGORIES were coded in column 2 of the tables of Section 12.0, and the code is:

(1.) SI: Super Insulation, non-conducting layers separated by reflecting shields, or reflecting shields alone

(2.) MC: Multilayer Composites, layers of non-conducting material not separated by shields

(3.) CK: Cork

(4.) FM: Foam

(5.) HC: Honeycomb (nearly all are foam filled)

(6.) CA: Composites - aggregates

Conglomerate materials not necessarily in layers

(7.) IN: Internal

The next group of categories refer to specific TECHNIQUES or APPLICATIONS. An (x) appears in the appropriate column of the tables of Section 12. They include:

(1) Shroud Mount

(2) Vapor Cooled or Refrigerated

(3) Continuous Wrap

(4) Blankets, Panels, Shingles

(5) Pumped, Evacuated, or Cryopumped

(6) Purged or Gas filled

(7) Perforations, Pump Channels

The final two categories of the tables of Section 12, marked with an (x) if appropriate are:

INSTALLATION

Includes bonding, sealing, taping, penetrations, supports and:

MISSION STUDIES, ECONOMIC STUDIES

4.2.2 Assessment Categories

Given all of the above information, it is now productive to pull it together for the purpose of assessing the information, enabling pattern recognition, and providing a systematic basis for choosing one scheme over another. Accordingly, fifteen Assessment Categories were selected. They are:

1. Density
2. Effective thermal conductivity
3. Porosity
4. Absorptivity, including any sealing requirements
5. Radiant heat transfer properties

6. Environmental compatibility, including fluid compatibility and susceptibility to ground-hold, boost, and spaceflight environments.
7. Mechanical properties, including any support requirements.
8. Useful life
9. Bonding methods, including any problems associated with bonding
10. Forming methods, including any problems associated with forming
11. Reusability
12. Ground hold requirements
13. Approximate cost
14. Availability, e.g. major manufacturers
15. Notes: any other property or information considered necessary and/or helpful in assessing possible uses of an external insulation scheme.

The data of the Synopses (Section 11) and of the Material/Concepts Categories (Section 12) are then lumped into general types and displayed in the assessment Categories, Section 13.

5.0 HOW TO USE THE BIBLIOGRAPHIES

The Bibliography format is:

Accession Number	TITLE Author Literature Citation Affiliation Synopses Number	Availability

The body of a listing is the: (a) title, in all caps, (b) author(s), (c) customary literature citation, and (d) affiliation of the authors. This was made as conventional as possible and warrants no further explanation.

The ACCESSION NUMBER is simply a serial number assigned to each entry as it was received in this study. It is nothing more than a locator, peculiar to this report. They are:

NBS-1 thru NBS-n, to indicate an entry in the NBS Bibliography, Section 6.0.

SIE-1 thru SIE-n, for the SIE Bibliography, Section 7.0.

DDC-1 thru DDC-n, for the DDC Bibliography, Section 8.0.

NASA-1 thru NASA-n, for the NASA Bibliography, Section 9.0.

and TCM-1 thru TCM-n, for the Technical Contract Monitor Bibliography, Section 10.0.

All are left open-ended to provide for future additions.

The SYNOPSES NUMBER is also simply a serial number assigned to each synopses as it was made. It is a locator for the Synopses in Section 11.0, and are indicated S-1 through S-n. They, too, are deliberately open-ended.

The AVAILABILITY is the source from which each document may be obtained. Often a document is available from more than one source. In these cases, the preferred (quicker, cheaper) source is listed first.

The availability codes and sources are:

CFSTI

Clearinghouse for Federal Scientific
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The CFSTI is the preferred source in almost all cases. When ordering, give the complete citation as it appears in the bibliography and any other identifying numbers that appear with the availability such as the AD number, NASA number, etc.

While these codes identify other availability sources, they also aid the CFSTI in acquiring the documents rapidly.

NBS

The NBS number is NOT to be used for ordering documents, as the NBS Cryogenic Data Center does not supply copies of documents. This number is the NBS Accession Number. It is used by them in preparing custom bibliographies, and is given here to facilitate comparison against any future bibliographies that may be prepared. It is useful for this purpose only, and should NOT be referenced when ordering documents from other sources.

NASA

This is a unique identifying number assigned to each document that is acquired, by NASA or AIAA, for processing and storage in the NASA Information System. The letter "N" identifies the reference as a technical report, and the number "69" tells the user that it was abstracted and announced in STAR in 1969.

STAR is one of the most widely used guides to the NASA scientific and technical information system's and stands for: Scientific and Technical Aerospace Reports (STAR).

The STAR reports, indicated by NASA N--number, are conveniently obtained from the CFSTI.

A word of caution about the NASA bibliography is appropriate. The NASA system alphabetizes the authors. Thus the first author (the conventional way of citing a report) is often not listed first, which hinders searching this bibliography by author. Therefore, we have underlined the actual first author wherever possible.

All other bibliographies list the authors in the conventional way.

AIAA

The letter "A" denotes a published literature reference, and the number "69" tells the user that the reference was abstracted and announced in IAA in 1969.

IAA is a NASA publication similar to STAR and stands for International Aerospace Abstracts.

Such reports are most conveniently obtained from:

American Institute of Aeronautics and Astronautics, Inc.

Technical Information Service

750 - 3rd Avenue

New York, New York 10017

The unit prices established by the IAA are:

$0.25 per page hard copy, minimum order $3.00, and

$0.50 for microfiche.

AD

This stands for Accession Document Number and is the accession number

assigned by the Defense Documentation Center (see Section 4.1.3). AD reports are most conveniently obtained from the CFSTI, and will be obtained more rapidly if the AD number is given in the order.

In summary, there are two principal sources of copies of the reports listed in the bibliography.

If CFSTI appears, order from the Clearinghouse for Federal Scientific and Technical Information (address above).

If AIAA appears, order from the American Institute of Aeronautics and Astronautics (address above).

In addition, anyone wishing to consult NASA publications and sponsored documents may do so at a large number of public, university, and other libraries. The most nearly complete collections, however, are available at the public libraries (usually the central ones) in the following cities:

CALIFORNIA: Los Angeles, San Diego
COLORADO: Denver
CONNECTICUT: Hartford
DELAWARE: Wilmington Institute Free Library
MARYLAND: Enoch Pratt Free Library Baltimore
NEW JERSEY: Trenton
NEW YORK: New York, Brooklyn, Buffalo, Rochester
OHIO: Cleveland, Cincinati, Dayton Toledo, Akron
OKLAHOMA: Oklahoma City
TENNESSEE: Memphis
TEXAS: Forth Worth, Dallas

MASSACHUSETTS: Boston
MICHIGAN: Detroit
MINNESOTA: St. Paul, Minneapolis
MISSOURI: Kansas City, St. Louis
WASHINGTON: Seattle
WISCONSIN: Milwaukee

Also, NASA's technical documents and bibliographic tools are deposited in 11 special libraries. Each library listed below is prepared to furnish to the general public services of personal reference, interlibrary loans, photocopies, and help in obtaining personal copies of NASA documents by microfiche if requested. These special libraries are located as follows:

CALIFORNIA: Univ. of California Library, Berkeley
COLORADO: Univ. of Colorado Libraries, Boulder
DISTRICT OF COLUMBIA: Library of Congress
GEORGIA: Georgia Institute of Technology, Atlanta
ILLINOIS: The John Crerar Library, Chicago
MASSACHUSETTS: Mass. Instit. of Technology, Cambridge
MISSOURI: Linda Hall Library Kansas City
NEW YORK: Columbia Univ., New York
PENNSYLVANIA: Carnegie Library of Pittsburgh
TEXAS: Southern Methodist Univ., Dallas
WASHINGTON: Univ. of Washington Library, Seattle

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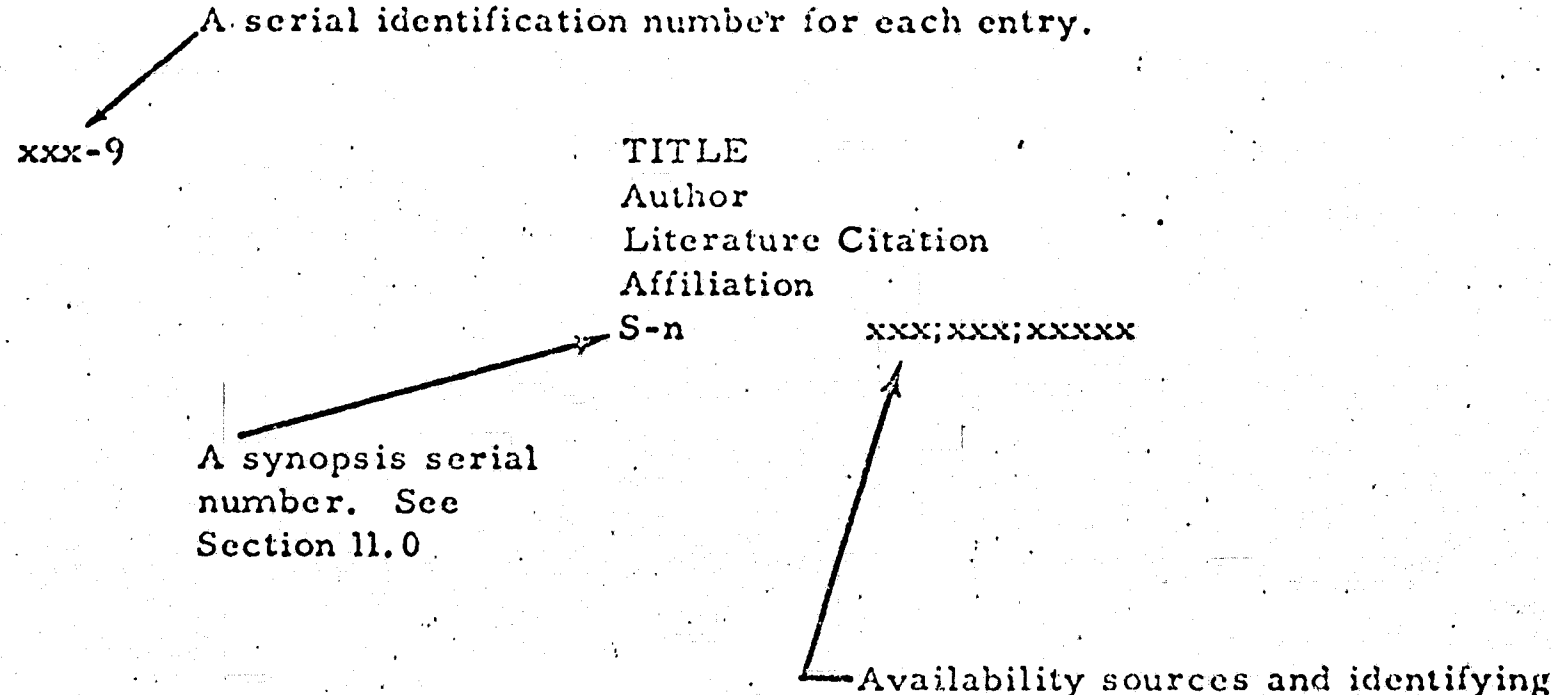
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CFSTI:	Clearinghouse for Federal Scientific and Technical Information.
NBS:	An identification number unique to the NBS Cryogenic Data Center. Do NOT order from NBS. DO NOT use for identification outside of NBS.
STAR N, or NASA N:	Abstracted in the International Aerospace Abstracts. Order from the American Institute of Aeronautics and Astronautics.
AD, or DDC AD:	Accession Document number of the Defense Documentation Center. Order from CFSTI.

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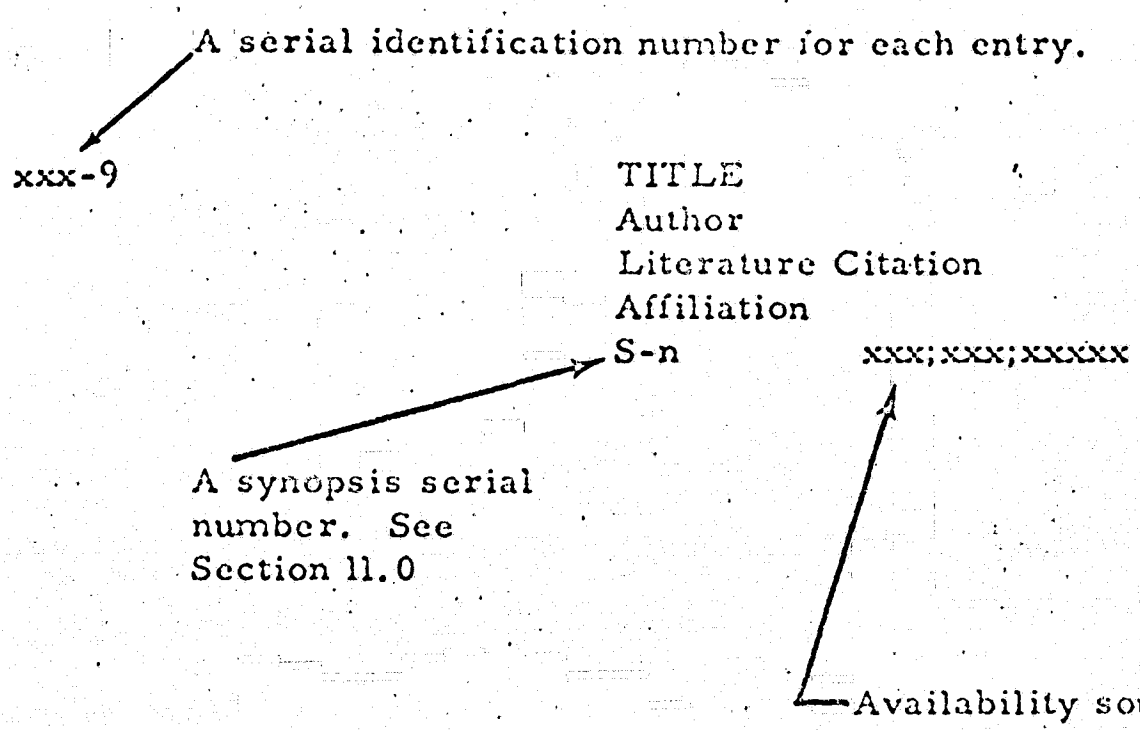
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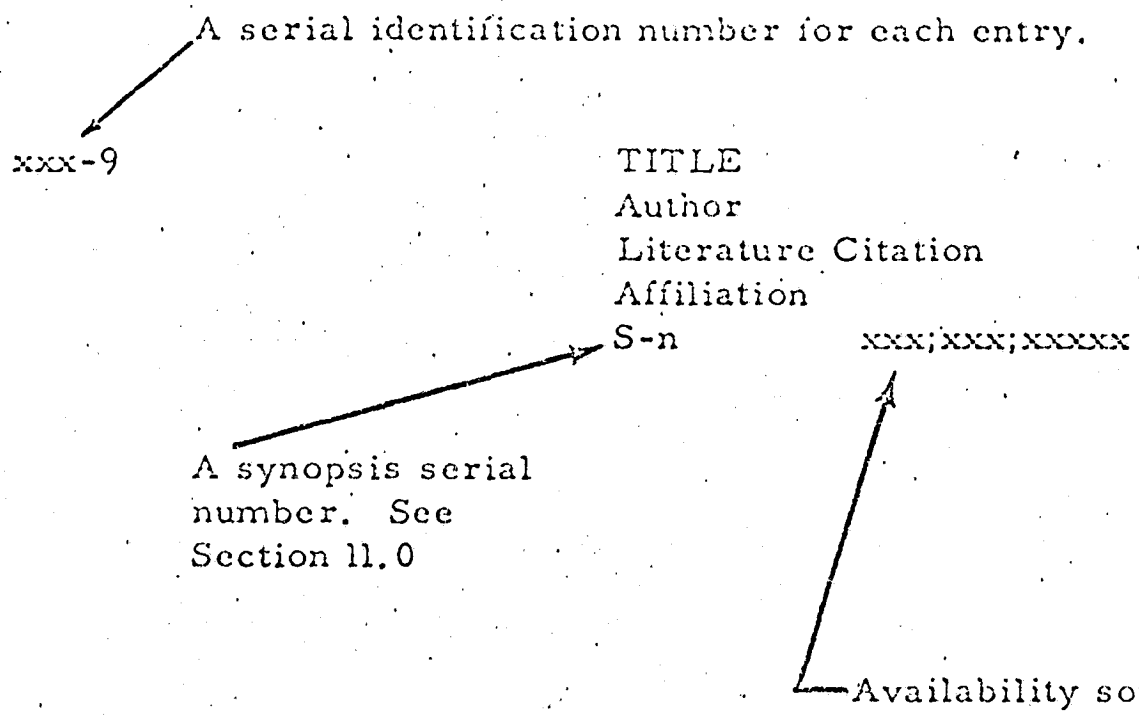
Mr. M. L. Davis

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NBS:	An identification number unique to the NBS Cryogenic Data Center. Do NOT order from NBS. DO NOT use for identification outside of NBS.
STAR N, or NASA N:	Abstracted in the International Aerospace Abstracts. Order from the American Institute of Aeronautics and Astronautics.
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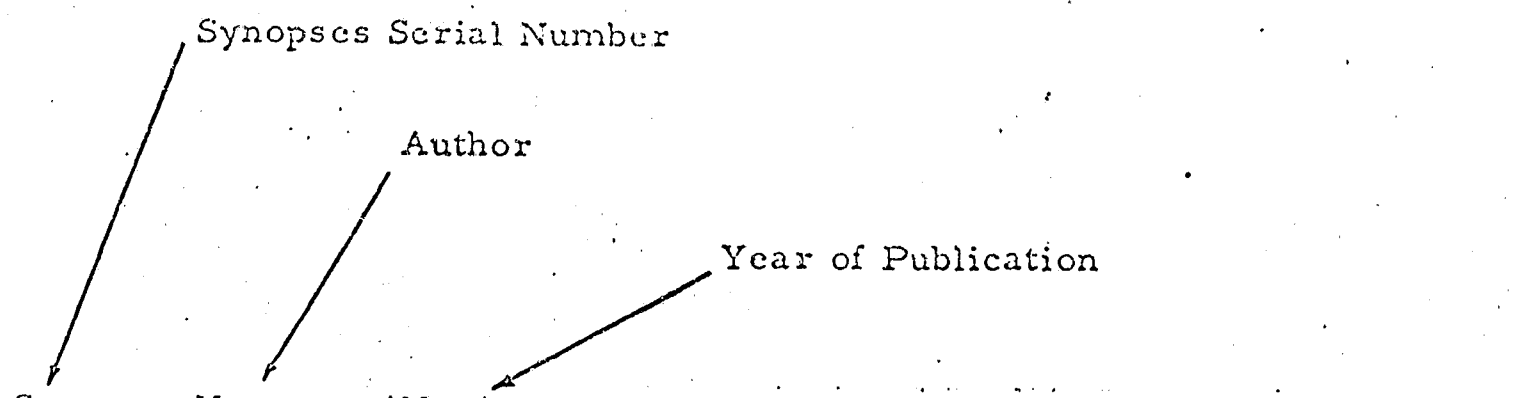
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S-127 In Progress

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SYNOPSES

11.0 SYNOPSES
FORMAT



NBS:	Section 6.0
SIE:	Section 7.0
DDC:	Section 8.0
NASA:	Section 9.0
TCM:	Section 10.0

S-1 Caren (1967) presented a theoretical discussion of multilayer insulation. Equations for radiation and conduction were developed which include the radiation absorption and/or scattering of the spacer material. A discussion of scattering theory is presented to indicate that a particular particle size is required to optimize scattering.

This insulation model was used to study the effect of penetrations. A two dimensional numerical conduction with one dimensional radiation analysis was performed for various size penetrations with prescribed temperature distributions and various assumed thermal shorts to the insulation.

In general, this calculation showed that filler may be used up to the penetration, but high conductivity material must be separated from it. An optimum balance between lateral conduction and increased radiation was found for all cases. They also mentioned the advantage of cooling insulation layers with the boil-off gas. (NBS-65)

S-2 Johnson (1968) presented an analytical study of the thermal degradation of an evacuated aluminized Mylar external insulation near a penetration. Spacers were used between the Mylar layers. Two models were analyzed for use in preliminary design; the results are presented both graphically and in terms of curve fits of the analytic data.

Details of the model and its numerical solution were given. The first model studied was a multilayer butted against a penetration with lateral conduction and radiation perpendicular to the layers. The second model interposed a non-radiating block of insulation

between the open-ended multilayer and the penetration. Effects of contact resistance were discussed.

It was noted that lateral conductivity in thin films may be an order of magnitude lower at low temperatures than bulk materials due to mean free path effects.

Curve fits of the numerical results indicated the insulation degradation is proportional to temperature squared. The buffer insulation proved effective for conductivities less than 0.008 BTU/hr. ft. ^{o}R and width to height ratios of 0.75. No experimental verification was presented. (NBS-119)

S-3 McMordie (1967) presented a short description of a method which can be used to compute the degradation of radiation shields due to perforations. A typical case is solved using the network approach to radiation transfer. The net transfer is a function of emittance, perforation area, number of shields and type of boundary conditions. No experimental data was given. Graphs of the numerical results were presented. (NBS-74)

S-4 Ruccia (1967) presented an experimental investigation which measured thermal conductivity of 14 external vacuum-type multilayer insulations mounted on a 48-by 27-inch tank. Mylar with various thicknesses of aluminum, gold, and silver were used with nylon, silk, fiberglass, and urethane foam spacers.

The heat flux was sensitive to the surface coating, with performance improving with thickness of coating and with application of coatings to both sides. A minimum heat flux of .31 BTU/hr. ft.^{2} for room temperature to LN_2 was found for 5 silver shields and silk spacers. Approximately one-half of this resulted from conduction. Note, the gold and silver coatings reduced the flux to about 65% of the aluminum values.

An analysis of the effect of a helium leak in the insulation was made and compared favorably with two calibrated leak tests. (NBS-66)

S-5 Perkins (1968) has patented (for the government) an external cryopumped foam insulation. Relatively large panels of Freon blown polyurethane foam are sealed with a Mylar-aluminum-Mylar sandwich bonded to the exposed faces using a polyester adhesive. The sealed panels are bonded to the tank, and all joints are taped closed. A thin layer of glass cloth is wrapped over the panels to protect them thermally, and a fiberglass or nylon filament is applied to support the insulation against launch loads. A filament winding machine may be used for the application. Under ground hold conditions, the insulation conductivity is 0.10 B-in/hr. ft^2R. (NBS-110)

S-6 Perkins (1968) presented an experimental evaluation of externally mounted self-pumped shingle-type multilayer insulation. Shingles were made of impermeable laminates of aluminized Mylar sealing alternate layers of open polyurethane foam (.02" thick) and aluminized Mylar shields. Air was pumped out and CO_2 was introduced to minimize chances of air entering and to take advantage of its low vapor pressure, 10^{-8} torr at 77°K. Thus, the insulation cryopumps during loading.

All vacuum and installation joints were Mylar bonds using Narmco 7343/7139 polyerethane-type adhesive. Permeability and out-gassing tests were reported for a number of Mylar-type films. Load deflection and conductivity tests were made. Cryopumping and thermal conductivity tests were made in both a flat plate and 30-inch diameter cylindrical calorimeter.

Typical panels of 18 radiation shields weighing .3416 lb/ft^2 cryopumped to 5×10^{-3} torr in 3 hours. Typical heat fluxes from

room temperature to LH_2 were 23 B/hr. ft.^{2} for ground hold, (1/4 that of helium purged insulation) and 5.1 B/hr. ft.^{2} in the unloaded space condition. Mechanical vacuum pumping provided .86 B/hr. ft.^{2} compared to .36 B/hr. ft.^{2} for pumped multilayer insulation. (NBS-85)

S-7 Folkman (1968) presents theoretical and experimental studies of vacuum type multilayer insulation. Aluminized Mylar was used in the crinkled state with one side metalized, and metalized on both sides with Dexiglass paper, nylon net, and dimpled separators. The nylon net provided the best conductivity-density product.

Considerable theoretical study was reported to determine the effects on heat transfer of providing gaps between insulation blankets or perforations in the layers to enhance evacuation. The analysis was compared with four test data points to indicate some degree of correlation in magnitude and trend.

A simple calculation of heat transfer to a tank through shroud-mounted (as opposed to tank-mounted) insulation was made. The shroud mount eliminates direct conduction, but increases the radiative area. The calculation indicates that the shroud area can be only 20 to 40% greater than the tank wall to realize any benefit over tank-mounted insulation. It should be noted that perforations and penetrations were not considered in the shroud-tank mounted insulation comparison. (NBS-100)

S-8 McLaughlan (1968) presents heat leak measurements for an NRC externally mounted vacuum type insulation. The insulation was mounted on a flight-type 29-inch diameter oxygen tank which had an integral vacuum insulation with two radiation shields.

Five, 25, 50, and 100 layers of insulation were used in conjunction with a boil off vapor cooling line attached to the shell and a low conductivity (teflon and steel wire) tank mounting system. The insulation was laid over the tank and cut and taped to accommodate curves and penetrations.

Test data were recorded for environmental temperatures of 0, 70, and 140F. Approximately, heat leak dropped 30, 40, and 50% for 5, 25, 50, and 100 insulation layers, respectively. Vapor cooling was removed in one test with 25 layers of insulation resulting in an overall heat leak of 70% of uninsulated as compared to 60% with cooling.

Considerable time was required to stabilize the insulated and cooled system. (NBS-106)

9 Burkely (1966) evaluated a self-evacuating sealed cell system. It consists of a "sealed cell sublayer and a helium purged heat-resistant outer layer. The sublayer was a Mylar honeycomb panel having a density of 2.1 lbs/ft^3 and each cell hermetically sealed within coverings of Mylar film and thin aluminum foil." "Under ambient conditions, thermal conductivity values as low as 0.10 to 0.15 BTU-in/ft^2 hr ^{o}F were realized." No significant degradation was observed after repeated cycling between ambient and liquid hydrogen temperature.

The report describes in detail the fabrication process and suggests a possible improvement in density by bonding the Mylar honeycomb directly to the hydrogen tank side walls. Some cracking of Mylar bonds was noted. (NBS-59)

10 Glaser (1969) describes primarily multilayer insulation (MLI) systems (alternate layers of reflecting materials and materials of low thermal conductivity), although other systems are discussed and comparisons of performance are given. This system has the best insulation performance yet attained with thermal conductivity (K value) at least an order of magnitude better than the next-best system (opacified powders). K values of 2×10^{-4} BTU-in/hr-ft^2 ^{o}F and better are reported.

MLI are particularly sensitive to the presence of residual gas, however. Glaser states "The effectiveness of MLI is 100 times greater than that of an evacuated powder, but requires a gas pressure 100 times lower to reach it." "MLI must be maintained at pressures below about 10^{-4} torr to provide the desired insulation effectiveness." MLI under one atmosphere pressure have K values 0.1-0.6 BTU-in/hr ft^2 ^{o}F. MLI without modification appears unsuitable for unshrouded tanks of cryogenic fluids in the atmosphere. (NBS-125)

S-11 Rawuka (1966) investigated insulation of the inside surface of cryogenic tanks. Foam was bonded with Lefkoweld 109/LM52 adhesive to the inside metal surface with a reinforced plastic liner laminated over the foam. The plastic film is polyester (Scheldahl Co. GT15) sandwiched between two layers of aluminum foil. Glass cloth impregnated with epoxy was used to reinforce the plastic hydrogen barrier. Various foams and lay-up methods were tested.

The performance over long time periods (32 hours) was found to be highly dependent on the type of foam and barriers used. Changes in thermal conductance resulted from partial cryopumping of hydrogen into the cells of the foam. Increase of the hydrogen tank pressure caused increase in thermal conductance. The primary reason for the increase is the nearly ninefold increase in thermal conductivity of hydrogen over that of air which hydrogen replaces.

"The Narmco 7343/7139 polyurethane resin used in combination with type 116 glass cloth was the most satisfactory liner in keeping the 3-D foam insulation thermal conductivity to a low value (0.025 BTU/hr ft ^{o}F after 32 hours). (NBS-44)

S-12 Glaser (1967) has compiled a textbook-like publication which begins with a discussion of applications of insulation and principles of thermal insulation systems. He then covers the more specific topics of "cryogenic insulation systems," "structural and noninsulating components," and "high temperature thermal protection systems."

The relative merits of external and internal placement of insulation are first discussed under "cryogenic systems." The reasons given for the greater popularity of external placement are that complex shapes can be insulated, insulation thickness can be built up as desired, insulation can be integrated with pipes and supports,

repair is easier. Advantages of internal placement are freedom from problems of aerodynamic heating and pressure, less likelihood of mechanical damage, less penetrations by pipes and projections.

Regarding weight effectiveness, Glaser shows for various systems the weight per unit area required to give a specified heat transfer rate. For example, to limit the heat transfer rate to liquid hydrogen to 50 BTU/hr ft^2 would require about 0.6 lb /ft^2 of vacuum jacketed multilayer insulation, 0.8 lb /ft^2 of composite foam and multilayer or 3.0 lb /ft^2 of helium purged multilayer. Results of thermal and structural tests are given for spacer materials, radiation shields, and vapor barriers. Twenty-two different configurations of multilayer systems are covered, as well as four foams, powders, and fibers, and foam-filled honeycomb systems. Shingle-type blankets, application methods, and bonding materials are treated in detail, as are purging requirements, effects of external pressure, and constrictions.

This is a very extensive work. (NBS-84)

S-13 Bonneville (1964) concentrates on multilayer insulation primarily in a space environment. The author discounts the practicality of shrouded blankets which would be able to maintain the necessary insulation vacuum of 10^{-4} torr or better in the ground-hold condition. He cites problems of added weight and the possibility of leakage of air into the vacuum space causing later build-up of pressure.

Most of the effort is devoted to very detailed analyses of heat-flux and effects of penetrations, thermal shorts, speed of pumping in the space environment, shield perforations, close spacing of shields (radiation tunneling), etc. (NBS-19)

S-14 Perkins (1967) describes flexible, vacuum tight casings of aluminized Mylar enclosing layers of polyurethane foam and aluminized Mylar radiation shields that were applied to the cryogenic tanks shingle-fashion by adhesives. The casings were prefilled with CO_2 which cryopumped down to at least 5×10^{-3} torr on contact with the cryogen. Heat flux of 23 BTU/hr ft^2 for an outside temperature of $70^{\circ}F$ was reported. This is stated to be about 1/4 that of helium purged multilayer systems. Under simulated space conditions (not self-evacuated) in a vacuum chamber at 10^{-5} torr, a heat flux of 0.86 BTU/hr ft^2 was obtained.

The effects of compression of the insulation by mechanical constraints or by the atmospheric pressure were studied. This led to the use of the polyurethane separators as the heat flux was much less affected by compression. The best cryopumping vacuum was sometimes not achieved for several hours. (NBS-73)

S-15 Dixon (1968), in Part I of a two-part article, suggests the following advantages of placing the insulation inside the cryogenic tank: (1) avoids a possible cryopumping problem (of air), (2) eliminates possible damage to insulation during handling, (3) permits bonding to relatively warm surface. The system consists of polyurethane foam tiles epoxy bonded to the tank wall, a fiber glass liner impregnated with polyurethane resin, and finally a sealer of polyurethane resin. No performance figures are given. See Part II, below. (NBS-127)

S-16 Dixon (1968), in Part II of a two-part article, included a section on thermal control systems. Several insulation systems were evaluated: (1) helium purged with deformed Mylar paper or mesh

separators, (2) nitrogen purged with a foam or cork substrate, (3) evacuated bag with paper spacer and aluminized Mylar radiation shields. The tests indicated that helium purged systems are the most attractive for longer missions. The time for the insulation to become evacuated after launch is 2 to 12 hours. Effective thermal conductivities are not given, but insulation efficiency = weight of insulation plus boil-off ÷ weight of propellant (the lower the figure, the greater the effectiveness) was used for evaluation. As an example, for a 30-day mission system (1) attained an efficiency of 0.07; (2) 0.08; and (3), about 0.13. See Part I, above. (NBS-109)

S-17 Burge (FY 69) led a program whose objectives were to determine the design effects of various potential heat sources and losses on cryogenic propellant storability during vehicle stop-start operation in a space environment. Various potential heat sources and losses include pressurization system, insulation support systems, P. U. system, feed system, venting losses, and thermal coatings.

He is to determine analytically the effects of the above items on propellant storability and vehicle performance for an LH_2/LF_2 system. Optimum designs will be selected for each item and incorporated, where practical, into a test apparatus for evaluation in a 1-G space simulation chamber at the AFRPL. Test results will be used to correlate and appropriately modify the analytical models for the purpose of reoptimizing the vehicle design parameters. (SIE-1)

S-18 McKellar (FY 69) was to develop techniques for the attachment of advanced, composite, thermal control materials to operate in the temperature range of 200 to 800 degrees K. Second surface mirror materials used in conjunction with multiple layer insulation systems have application for thermal protection of near-solar mission spacecraft, areas adjacent to orientation or propulsion rockets and for cryogenic storage tanks. The use of particular thermal control and insulation materials is dependent upon attachment methods compatible with thermal conductivity, surface geometry, temperature, substrate material, removal ease, shock, vibration and dynamic structure requirements, peculiar to the spacecraft. This work will result in the selection and evaluation of one or more.

The results of a literature search, hardware experience, and an engineering analysis will be used in a parametric study to select potential attachment methods. Experimental evaluation of the selected methods will be performed to insure compatibility with general spacecraft requirements. (SIE-2)

S-19 DeWitt (FY 69) worked to improve the basic understanding of full-scale multi-layer insulation systems and provide information for applying insulation technology to future vehicle designs.

Wide differences between theoretical performance of multi-layer insulation systems and measured data are caused by complex interactions not sufficiently understood. In this task the performance of a full-scale insulation system will be measured as the number of insulation layers is increased. The work will be done using an existing 7 foot diameter tank which has been insulated with up to 60 layers. The number of layers will be increased in steps up to a total of 200 which would be required for long duration missions, e.g., transit times to Mars. The systematic full-scale program will provide better design information by eliminating the inconsistencies resulting from correlations of random test data. Testing is done in a 25-foot diameter vacuum chamber with an LH_2 cryopanel. (SIE-3)

S-20 Loukota (FY 69) was supported by NASA to determine the ability of fragile multilayer insulations for cryogenic tankage to withstand a rocket launch dynamic environment. The application is to spacecraft cryogenic propellant tankage contained within an aerodynamic shroud. The problem is that multilayer insulation and their attachment methods pose a serious design problem due to the high vibration, acoustic, and longitudinal acceleration environments.

A full-scale, 105-inch diameter cryogenic tank will be insulated, placed in a shrouded rocket sled, pre-chilled with liquid nitrogen, and accelerated to the maximum expected level of a Saturn V launch. Vibration and acoustic levels from the rocket sled will also be present.

At the reporting date of February, 1968, no adverse effects of the combined environments were detectable on the insulation system,

composed of aluminized Mylar and Dexiglas spacers. A second insulation system of aluminized Mylar and polyurethane foam spacers was to be tried. (SIE-4)

S-21 Wood (FY 68) worked to continue development of flightworthy high performance insulation systems including all insulation penetration such as structural supports, piping penetration, electrical connectors and manhole covers for cryogenic and non-cryogenic vessels with storage and stay times up to 60 days.

The use of high performance insulation has been studied and found to be a requirement on most cryogenic vehicles in orbit for more than about six hours. Additionally, high performance insulation has been considered desirable for application to such vehicles as the Multiple Docking Adapter, the Apollo Telescope Mount, and some of the Apollo Application Program Flight Experiments. Studies involving reliquefaction, and slush necessitate development of superinsulation. Ultimate application will be on future manned vehicles.

Wood was to continue development of light weight-low thermal conductivity helium purged insulation systems. The next objective was to modify an existing tank system with more typical flight type hardware and structural supports and up-grade system design. Analytical studies will be performed and verified with component and scale tests. (SIE-5)

S-22 Zimmerman (FY 68) was to develop the analytical simulations necessary to properly describe the performance of various thermal protection systems and then to evaluate several complete systems in order to determine their relative performance characteristics.

The application of cryogenic propellants to missions involving long propellant storage times will, in general, require the use of a combination of thermal protection techniques (multilayer insulation,

low conductivity or vapor cooled supports, shadow shields, zero g venting devices, etc.). The cryogenic propellant requirements for several unmanned missions involving long propellant storage times will be determined. Then several complete thermal protection systems involving combinations of the above-mentioned protection techniques will be postulated. The resulting performance characteristics and potential problem areas will be evaluated. (SIE-6).

S-23 Nevins (FY 67) was to investigate, design, and determine the structural and thermal performance of insulation concepts for cryogenic tankage. Emphasis was placed on non-integral liquid hydrogen tankage requiring storage time in space for 30 days.

This program included the development of basic cryogenic tankage, insulation systems, and associated hardware necessary for the satisfactory performance of liquid hydrogen tankage. Both pre-evacuated and purged insulation schemes were to be pursued through concept definition, component test design, full-scale insulation system design, fabrication assistance, and test surveillance. Promising systems were to undergo detailed investigation of problem areas and necessary re-design to improve performance. Associated hardware development, dissimilar metal joining, propellant line gaskets, low conductivity structural supports, flexible vacuum jackets, etc., were also to be pursued.

A helium purged NRC-2 system was given thermal tests on a 105-inch diameter tank. A vacuum jacketed Linde-SI-62 system was applied to a second 105-inch diameter tank and evaluated in preparation for simulated ground hold and space thermal tests. A system utilizing a Mylar Honeycomb for a substrate and a superimposed nitrogen purged NRC-2 was discontinued due to difficulties in the Mylar Honeycomb. (SIE-7)

S-24 Achhammer (FY 68) worked to gain an understanding of the relationships between the mechanical properties of polyethylene terephthalate and other polymers and their physical state as determined by their method of preparation; and to determine the optimum physical state of these polymers in respect to their acceptability as liner and bladder materials for use at cryogenic temperatures. (SIE-8)

S-25 Hinckley (FY 68) was to evaluate the interaction of radiant and conductive heat transfer in multilayer insulation, since such interactions currently make the interpretation of heat transfer data difficult. His approach was to evaluate multilayer insulations to determine the relationship between total number of layers, boundary temperatures, shield emissivities, layer spacing, and total heat flow. (SIE-9)

S-26 Brogan (FY 69) conducted a program to develop a complete insulation system design for storing cryogenics in large-size tankage, such as the S-IIB-S-IVC and modular nuclear vehicle, with a boil-off loss not to exceed 5%/year. He was to develop low heat leak - light weight structural supports, analytical expressions for the thermal conductivity of insulation materials as a function of boundary temperatures and insulation assemblies including the meteoroid shield and the purge gas system. The program was to provide complete documentation for application of insulation system to an LH_2 test tank that can be scaled considering both thermal and structural considerations.

The approach was to perform flat plate calorimeter tests to determine thermally the best candidate insulation material. The selected materials were to be extensively studied for outgassing and

venting characteristics, adaptability to different tank configurations and attachment techniques, handling qualities and thermal performance with fasteners and tank attachment installed. Strut designs, such as the ball and clamp, vapor cooled, and conical supports were to be studied and the lowest heat leak - lightest weight design to be fabricated and thermally tested. The optimum insulation assembly, selected strut design, purge gas system, and meteoroid shield were to be integrated into a complete insulation system and tested on a scaled LH_2 tank.

Methods of attaching the insulation to the tank wall, such as buttons and threads, Velcro fasteners, etc., were studied. Strut designs were conceived and evaluated. Purge lines, meteoroid shields, structural supports, etc., were integrated into a complete system design. (SIE-10)

S-27 Burkley (FY 69) led a program to investigate, design, fabricate, test and evaluate an advanced liquid hydrogen insulation meteoroid protection system for large tankage, approximately 33 feet in diameter, to be used in deep space missions. Problems relative to insulation thickness, insulation of structural supports, bulkheads and propellant lines, manufacturing techniques, purge and venting were investigated. The study was meant to be used to establish design criteria (structural and thermal), evaluate materials application and manufacturing methods. (SIE-11)

S-28 Phillips (FY 70) was to obtain preliminary design information on the structural integrity and thermal performance of plastic honeycomb insulation applied internally to liquid hydrogen tanks. This effort will be used to determine the reliability of this lightweight insulation under

repeated pressure cycles at liquid hydrogen temperature. The data obtained will aid in the evaluation of utilizing liquid hydrogen in conventional aircraft for specialized missions.

At the reporting date of August, 1969, cryotherm testing of plastic honeycomb had been completed. Radiant heat testing of non-metallic, reusable, heat shield material was in progress. (SIE-12)

-29 Leonard (FY 69) conducted a program to investigate integral and non-integral fuselage-tank structures with nitrogen purged fibrous insulation systems for hydrogen fueled hypersonic airplane. In-house analytical studies were to be made to define an advanced fuselage-LH_2-tank structure concept for hypersonic airplanes making use of N_2 purged fibrous insulation. On the basis of these studies, models were to be designed, fabricated and subjected to static loading and heating investigations in the laboratory and to dynamic test conditions in a hypersonic wind tunnel that simulates correct dynamic loading and aerodynamic heating. (SIE-13)

S-30 Yates (FY 69) was the principal investigator on a program to develop manufacturing techniques and processes to apply high performance multilayer insulation for long duration storage of cryogenic fluids in space vehicles. Manufacturing techniques developed will be applicable to advanced cryogenic space vehicles for orbital, lunar, and planetary flight, and non-cryogenic space vehicles and payloads requiring high performance insulation. This work unit is designed to support design activities and to advance manufacturing technology.

Manufacturing techniques were to be developed to evaluate preliminary design concepts applied to calorimeters, test tanks, and test fixtures for thermal and structural testing. Results expected include design data, fabrication methods, inspection techniques, tooling and equipment information, cost information, and production techniques.

In this program a high performance insulation system (aluminized Mylar and Dexiglass) was applied to a 105 inches diameter tank and successfully tested on a rocket sled which subjected the insulation structural support system to Saturn V acceleration, vibration, and acoustic loads. Several small test tanks were insulated for thermal tests. (SIE-14)

S-31 Lindquist (FY 68) worked to develop a lightweight, self-evacuating multi-layer insulation system for liquid hydrogen tankage. The system thermal performance is meant to be equivalent to purged systems on an 8-day mission and must be capable of being handled in modular packages. The approach was to optimize an insulation system consisting of radiation shields and spacers enclosed within a CO_2-filled impermeable case. Exposure of the case to LH_2 temperature condenses the CO_2 and produces a self-evacuated multi-layer insulation (SEMI) system. Optimization of the system requires development of better spacer configurations and better casing materials. Techniques for application of the system to varying geometry tankage will be developed.

At the reporting date, March 1967, a system having a demonstrated Q/A of 22 BTU/sq. ft.-hr. in ground hold and .8 BTU/sq. ft.-hr. under space conditions had been developed for cylindrical tankage. Ultimate vacuums achieved within the individual panels were in the range of 10-20 microns. (SIE-15)

S-32 Lindquist (FY 69) conducted a program to develop a lightweight, self-evacuating multi-layer insulation system for liquid hydrogen tankage. The system thermal performance was to be superior to that of purged systems for mission times up to 8 days. The system was meant to be contained in easily handled modular panels.

The approach was to investigate the effectiveness of an open space separator for increasing cryopumping gas transport within the panel. An 82-inch diameter spherical tank was to be insulated with a 30-shield system to determine the thermal performance history during an eight-day mission profile. The effectiveness of the total system was to be demonstrated by subjecting it to a 30-day pre-launch environment and repeating the eight-day mission profile test.

By the reporting date, March 1968, cylindrical application of the system had been demonstrated. A ground hold heat flux of 12 BTU/square feet-hr and a space heat flux of .7 BTU/square feet-hr was obtained with no degradation of the system after being exposed to the atmosphere for 33 days. (SIE-16)

S-33 Burge (FY 68) was to obtain a test device to experimentally assess a thermal performance comparison of shroud-mounted superinsulation with tank mounted superinsulation utilizing the cryogenic propellant LH_2.

He was to modify an available 8-foot diameter spherical tank utilizing essential thermodynamic characteristics, instrumentation positioning, and penetrations as the basic test article delivered under contract AF 04/611/-10750. The primary difference in the two test articles was to be that the basic test article had shroud mounted insulation and the 8-ft. tank had insulation mounted directly to the tank wall. Both articles were to be tested under the same simulated space environmental conditions at the AFRPL. (SIE-17)

S-34 Gray (1960) investigated several nonvacuum insulations for external application to booster stages. Cork and various phenolic laminate foam filled honeycombs were examined. Thermal conductivity, tensile and shear strength, bonding techniques to aluminum and resistance to aerodynamic heating were experimentally determined from room to liquid hydrogen temperature.

Polyurethane foam filled honeycomb showed the best overall performance of the 6 fillers tested. Cork, in general, performed better than the honeycombs. A mean conductivity of .0167 $B/ft.^2$ hrF was found for cork; it resisted temperatures to 850F in sonic air flow and had a tensile strength of 60 psi at room temperature. The honeycomb had about twice the conductivity and three times the strength but its resin flowed under heating.

1 mil Mylar film was used to seal the surface to minimize condensation. Epon 820 epoxy was adequate for bonding the insulation to "air blasted" aluminum surfaces. The reduction in thermal conductivity of epoxy by addition of glass spheres was shown; this material is suggested as a filler insulation for fittings and penetrations. (NBS-1)

S-35 Love (1960) presented a parametric theoretical study of heat transfer to an external multilayer insulated hydrogen rocket tank in the space environment. Curves of sun originated heat absorption as a function of distance and surface radiative properties were presented. Heat load to the hydrogen was calculated for various radiation parameters, insulation conductivities and thicknesses typical of evacuated Lindy SI 12 and SI 4 superinsulations. Effects

of typical fiberglass tank supports and insulation between the oxygen and hydrogen tanks were shown parametrically.

A typical space mission was examined to determine hydrogen storage lifetimes. The results were presented as a function of insulation conductivity. The effect of permitting pressure rise from atmospheric to 35 psi extended the mission greatly. One year storage of hydrogen was predicted for very large volumes with pressure rise and 14 percent venting using the optimum multilayer insulation scheme. (NBS -2)

S-36 Olivier (1961) considered various design parameters for long term storage of liquid hydrogen in space. Analytic comparisons were made between vented and nonvented superinsulated storage modes. It was pointed out that venting not only reduces delivered payload but it suffers from the complication of venting under zero gravity conditions.

Typical calculations for a 18 ft. diameter cylindrical tank with external insulation showed storage times up to two years for nonvented subcooled hydrogen. Curves and equations were presented to show effects of heat transfer, coefficients, surface coatings, tank geometries, radiation geometries and the transient effects of cyclic heating in addition to vented vs. nonvented performance curves.

The chief disadvantage to nonvented storage is that the equilibrium pressure is determined by the highest local temperature while vented storage pressure generally depends on the bulk temperature. Thus, a random orientation is required for nonvented storage to minimize direct radiation to one side of the tank, and local heat leaks may be troublesome. They

noted that albedo and earth infrared supply 54% of the solar radiation flux in a 300 n-mi orbit. This "two sided" radiation eliminated shadow shields from consideration. (NBS-4)

S-37 Clark (1962) presented an analytic study of transient condensation of warm pressurization gases on internal tank surfaces. The analysis showed that adding internal insulation which has low density and specific heat can reduce the amount of pressurant required to pressurize the system.

The low conductivity combined with low thermal inertia permits rapid warm up of the ullage volume walls and thus reduces the amount of condensation as compared to metal walls. A sealed foam is the recommended insulation material. The detailed equations are presented. (NBS-5)

S-38 Frainier (1961) presented a theoretical study of externally mounted blankets of SI-4 superinsulation and fiberglass layup for use in hydrogen space storage. His results were plotted in terms of weight penalty, i.e. insulation plus boil off, as a function of time from filling.

One minute of atmospheric pressure operation was assumed for the calculations on a 6000 lb. cylindrical tank. It is shown that fiberglass is the most efficient for less than 82 hours of storage with the superinsulation significantly better for longer missions.

Using the sum of the insulation weight and boil off expressed in terms of insulation parameters, an optimum insulation thickness was determined for any mission time by mathematically minimizing the weight penalty. The superiority of fiberglass for short missions was attributed to an over-insulated condition for the multilayer due to minimum thickness required for application.

A concept for liquid nitrogen shielding of oxygen tanks during ground hold is also discussed. (NBS-6)

S-39 Merrill (1963) studied unevacuated external insulation for large liquid hydrogen cylindrical tanks. A multilayer of eight layers of fiberglass and aluminum foil with helium gas purging to eliminate air condensation was tested. Its thermal performance was adequately predicted by equating pure conduction in the insulation and purge gas with natural air convection heat transfer to the surface.

The second insulation consisted of a cork substrate sealed with Mylar and several layers of unpurged fiberglass. The sealed substrate provided insulation for the open layers to prevent air condensation.

Mechanical tests showed that a fiberglass mat between the cork and the aluminum tank was required to bond the material with Shell Epon #820 epoxy. These test results also verified the conduction free convection predictions. No test data is presented. (NBS-8)

40 Lindquist (1963) studied the effects of bearing pressure on flexible Mylar sealed superinsulation consisting of 75 layers of fiberglass paper and aluminum foil. An 18 inch diameter cylindrical hydrogen tank was used to evaluate the insulation. A surrounding shell permitted tests at reduced pressures. An atmospheric load conductivity of 4.7×10^{-4} B/hr.ft.R was measured. Conductivity measurements at other pressures were not reported.

Curves showing layers of insulation per inch of thickness as a function of pressure were reported and show little scatter over five pressure cycles or

extended pressurization periods. Insulation wrapped at 110 layers/in., sealed, evacuated and loaded to 1 atmosphere returned to 72% of installed height after pressure cycling. The insulation expanded uniformly with decreasing pressure load until a pressure below 100 microns was reached where no further change was noted. Evacuation times were long so no estimate was made for the expansion-time behavior with rapidly changing pressure load. (NBS-9)

S-41 Spieth (1958) reported plans for testing the effects of aerodynamic heating on a typical missile tank. The report concentrates on the structural design and plans to investigate insulations. (NBS-10)

S-42 Hnilicka (1963) presented a brief discussion of the relative merits of NRC type superinsulation. A comparison was made with a typical foam type insulation to demonstrate the weight and performance benefits of superinsulation.

A general discussion of lay up techniques was given and the importance of penetrations and insulation joints was pointed out. A number of typical thermal conductivities for foams and fiberglass in both unevacuated and evacuated configurations was presented for comparison. (NBS-11)

S-43 Perkins (1964) performed thermal conductivity tests on a 48 inch cylindrical tank with ASME heads and 70 layers of Linde SI-62 evacuated super insulation applied externally. The insulation was jacketed by a laminate of 1-mil aluminum sandwiched between 1/2-mil Mylar films.

The insulation lay up method is described in some detail. Plain cellophane tape was used to fasten the various layers.

Overall thermal conductivity and insulation thickness were measured for external pressures from 4×10^{-3} ATM to 1 ATM. Conductivity values varied from 90×10^{-5} B/hr.ft.R to 8×10^{-5} B/hr.ft.R as external pressure was decreased. Internal pressure was less than .5 micron Hg.

The conductivity ranged from 50 to 100% greater than flat plate calorimeter data. This effect was attributed to pressure exerted by the vacuum jacket, possible gaseous conduction and lay up techniques. (NBS-13)

S-44 Johnson (1963) performed a literature search for theoretical means of calculating thermal conductivity of nonevacuated powder insulation. Reviews of theoretic gaseous conduction in the continuum to free molecular regimes were presented and discussed. Effects of solid-gas parallel conduction were described and interparticle contact resistance was discussed. It is noted that interparticle resistance is poorly understood but generally quite high; therefore it is not a significant parameter in the total heat transferred.

The difficulties in calculating radiative transfer in the packed bed were noted. They point out that the nonevacuated powder conductivities show a definite pressure dependence to very low pressures so it was concluded that radiation is not large for most conditions studied.

They pointed out that beds filled with small particles are subject to agglomeration resulting in conductivity properties normally associated with

larger particles.

Calculations were presented for several bed models indicating that conductivities as low as 1.25×10^{-3} B/hr.ft.R may be achieved with atmospheric pressure and noncondensing gases. (NBS-15)

S-45 Haskins (1962) measured thermal conductivity of three glass fiber reinforced phenolic honeycombs with helium purge gas and internal evacuation. The cores were 1, 2.2 and 5.5 lb/ft^3 with 2 lb/ft^3 polyurethane foam filling the lightest honeycomb. For mean temperatures near LH_2, the evacuated conductivities were 0.010, 0.013 and 0.017B/ft.hrF respectively. Adding one atmosphere of helium increased the conductivity an order of magnitude for 3/8 in core, 3 in thick honeycomb. (NBS-16)

S-46 Swalley (1965) performed an experimental study of the heat transfer through an evacuated multilayer insulation with a flexible Mylar-aluminum-Mylar jacket. The system was mounted on a simulated flight design tank which included pipe and support penetrations as well as a removable manhole port.

The insulation lay up scheme is discussed with particular reference to the penetration. It was found that plumbing heat leak could be reduced about 50% if wall mounted valves were placed inside the tank to permit easier insulation lay up. The fiberglass tank support structure was wrapped with insulation which interleaved with the wall insulation. The supports represented about 50% of the total heat leak.

The flexible vacuum jacket was suseptable to pinhole formation at three-corner folds and showed some permanent set after evacuation and pressur-

ization cycling. Flight size tankage required several pump-out ports to achieve good vacuum in reasonable time and also were required to perform meaningful leak checks. (NBS-17)

S-47 Van Vliet (1965) presented an iterative technique for calculating heat flux through composite multilayer insulations where conduction and radiation act in series. The technique uses radiative heat balances in series with conductive balances where the total heat flux is constant for each layer.

A flux is prescribed and various surface temperatures are determined from both a conductive and a radiative equation. The two temperatures for a surface are appropriately averaged and a new heat flux is calculated from the radiation balance, this flux is averaged with the previous interaction and new temperatures are calculated. No estimates of convergance requirements are given.

The solution technique points out that solid insulation materials are most effective near the hot wall where small temperature differences result in large radiative heat fluxes. In this location, relatively thin conduction insulation can provide more temperature drop for the same heat flow; thus a number of radiative shields can be replaced by a thin solid insulator. (NBS 27)

S-48 Taylor (1966) presented an experimental and analytical study of heat transfer through a polyurethane and helium filled phenolic glass honeycomb, external insulation. A summary of free convection correlations was presented

and their applicability to various geometries is discussed. The correlations were used to predict heat transfer in gas filled honeycomb; the values compare favorably with test results. The correlations were then used to predict performance with partial filling of polyurethane.

Experiments conducted on the helium foam system indicated a two fold reduction in conductivity by filling 50% of the voids with foam. This conductivity was essentially as low as the 100% filled honeycomb but a considerable weight saving was realized. The optimum foam placement is midway between hot and cold surfaces. (NBS-30)

S-49 Cohen (1965) presented the results of LN_2 boil off tests conducted in a space simulator using Linde and NRC evacuated external insulations. The simulator was equiped with vacuum capability and sun and earth radiant heat sources. Active (retractable in zero gravity) tank supports were simulated by cooling the one-G supports with LN_2 and installing a low gravity secondary wire support system.

210 layers of Linde SI-62 and 200 layers of NRC-2 (crinkled aluminized Mylar) were used. Vent and support lines were wrapped concentrically with insulation; no special treatment of the penetrations was described. SI-62 was used on a 3' x 6' cylinder, 4' sphere, 8' sphere and 2' shperes; NRC was tested on the 8' sphere. Thermocouple and boil off measurements are reported.

The NRC and SI-62 had comparable performance but the NRC weighed approximately 30% of the SI-62. Supports and penetrations provide a large percent of the heat leak.

He concluded that long term storage (less than 10% boil off per year) of LH_2 becomes practical for tank diameters in excess of fifteen feet. (NBS-31)

S-50 Parmley (1966) presented experimental data and analysis for evacuated externally mounted shingle type multilayer insulation. Aluminized (one side) Mylar was bonded to 26 inch diameter aluminum test tanks in a shingle pattern. Penetrations were insulated with concentric fiberglass battings.

Both analysis and tests indicated a performance degradation of approximately 40% for 28 inch long shingles compared to parallel layer insulation due to radiation tunneling between layers and conduction along the surfaces. Various shingle lengths were tested.

The principle advantages of the insulation are ease in application, ready venting of trapped or leakage gas, and positive support against flight loads. Also, leakage gas is vented locally, minimizing the insulation area affected.

Flight simulation tests including thermal shock, rapid pumpdown, vibration, acceleration and acoustic loading did not degrade performance. (NBS-32)

S-51 McIntire (1948) presented a general review and discussion of the conductivity of styrofoam. A typical conductivity at room temperature of 0.023B/ft.hr.R was given. The effects of cell size and density were discussed.

A fifteen to twenty percent reduction in conductivity was achieved by adding small amounts of powdered aluminum to reduce radiative transfer. (NBS-33)

S-52 Dawson (1965) has patented an internal insulation of the shingle type. The principle is to trap boil off vapors in sealed passages formed by bonding U shaped overlaping shingles together and at their uppermost edge.

The shingles are formed from thin metalic foils to provide a long vertical slit when assembled against the tank walls or to lower substrate. The slit is open to the cryogen at the bottom. During tank cool down, boil off vapors enter the slit and become the mode of transfer perpendicular to the wall. Very long shingles are used to minimize axial conduction and the shingles may be 3 or more deep due to their length.

The pressurized (due to liquid head) vapor provides mechanical stability for the thin wall shingles for resistance to forces produced by acceleration or liquid sloshing. (NBS-34)

S-53 Getty (1966) performed thermal conductivity measurements in a small calorimeter on eleven types of evacuated external multilayer insulations. All insulations were layers of aluminized Mylar with some provision for separating the layers.

Both NRC and Linde superinsulations were tested. Other configurations of spacers included nylon springs, nylon flocking, glass cloth and mat and one where spacing was maintained by application of tension.

All results compared favorably with published information, where available. With some experimental background, reasonable predictions can be made. The Mylar in tension provides a pure radiation bench mark for comparison. Compared on a heat flux vs insulation weight basis, the NRC type Mylar without separate spacers had about 60% lower flux for a given weight than spacer type insulation.

The emissivity of aluminized Mylar was found to be .04 to .05. (NBS-35)

S-54 Nast (1966) studied the purging characteristics of three externally mounted multilayer insulation systems on a 26 by 37 inch cylindrical tank. Aluminized Mylar with spacers, crinkled Mylar layers with fiberglass substrate and aluminum foil with spacers were tested.

Purge bags were made of heat-sealed Aclar film. Purge inlets were located at the top of the tank and exited at the bottom to take advantage of helium's bouyance effect as compared to air.

Exit gas was analysed to determine the air content and in several instances a hypodermic needle was used to sample the residual gas within the insulation. These samples did not differ appreciably from the exit gas.

In all cases, approximately 5 system volumes of helium were required to obtain a steady minimum air concentration. This equilibrium level was a strong function of purge bag leakage. (NBS-36)

S-55 Hertz (1966) performed thermal conductivity, ultimate strength, and elastic modulus tests for 12 "structural" plastics which may be used for tank support. Data was taken in a helium environment from room temperature to -423°F. Various filled epoxys or resins were used.

Typical fillers tested were: glass cloth, cotton fabric, cellulose, acrylic fiber and polyester fibre. In addition Kel-F, nylon and polystyrene were investigated. Samples were 1x1x1/2 in. thick.

Polystyrene and Nylon were subject to thermal shock failure. All materials tested showed decreases in conductivity and increases in tensile strength as the temperature decreased.

Based on the ratios of density and conductivity to strength, the glass-reinforced epoxies were the most efficient materials, Kel-F produced the lowest conductivity.

Curves of thermal expansion were also presented for each material. (NBS-37)

56 A. D. Little Inc. (1962) published a quarterly report on a study of storing cryogenic propellants in space. Their insulation schemes were based on external evacuated multilayer types.

A simplified trade off analysis of weight penalties of insulated vs refrigerated storage was presented. Their analysis resulted in a parameter which describes the region in which refrigeration becomes attractive. The analysis assume refrigerator weight proportional to its capacity. Typical calculations show a savings using refrigeration for a 8 ft. radius tank if storage exceeds 4000 hrs; a 4 ft. radius requires 2000 hours of storage.

A two dimensional heat transfer analysis of thermal degradation of multilayer insulation penetrations was completed. The insulation was assumed to be thermally shorted to the penetration. An included temperature differential variation across the insulation of 10% or greater was considered to be the criteria for serious degradation. Based on this criteria and the assumption of large insulated areas, typical maximum allowable penetration wall thicknesses were calculated, (assuming large D/t for the penetrations). Typical allowable wall thickness for one inch of superinsulation (aluminized Mylar) are 2.2×10^{-3}, 3.9×10^{-5} and 2.2×10^{-6} inches for Teflon, stainless steel, and aluminum respectively. Doubling the insulation thickness in-

creased the allowable penetration thickness by about 2.5 times.

A number of thermal conductivity tests were run on two evacuated insulations. Fiberglass matting and 10 layers of aluminum foil with fiberglass spacers had conductivities of 4.8×10^{-4} and 1.7×10^{-5} B/hr. ft. F respectively, at a mean temperature of -140F, (Room to liquid nitrogen).

A discussion of the meteoroid shield design problem is given. It is pointed out that fibergalss may be as effective as metal for this purpose because of its energy absorbing capability and low weight. (NBS-39)

S-57 Nast (1966) presented a semiemperical study of the flow of gases through a multilayer insulation in the direction parallel to the layers. Both continuum and free molecular flow regimes were considered.

Multilayer insulation composed of aluminized Mylar and fiberglass spacers was studied. Equations for flow parallel to the layers were developed for continuum and molecular flow regimes. The material permeability and free molecular flow diffusion coefficients were experimentally determined parameters for the analysis. Numerical techniques were used to calculate the pressure in the insulation as a function of layer density, path length to a vent and a Saturn type external pressure history. Both nitrogen and helium were considered in the insulation.

Experiments showed that the premeability decreased by two orders of magnitude when the layer density was doubled. Path length also was a stron effect with time to reach 10^{-5} torr from atmospheric increasing from 6 to 18 to 50 minutes for 2, 5 and 10 ft. lengths using a 6 minute external decay time.

Nitrogen required twice as long as helium but due to its lower conductivity the nitrogen system resulted in less boil off. (NBS-41)

S-58 Allen (1963) has patented the use of externally mounted Styrofoam, filled with helium, for surrounding and filling voids in clusters of cryogenic tanks.

The insulation is enclosed in a mylar bag with stainless steel retention straps. The insulation is jettisonable by destroying the straps and mylar bag using a "ripcord" cable. (NBS-45)

S-59 Hnilicka (1966) has patented what appears to be the basic NRC external multilayer insulation. It uses crinkled layers of vacuum deposited aluminum on a Mylar substrate.

The aluminum should be less than one microinch thick and the Mylar about .25 mil thick. A packing density of 30 layers to the inch is recommended. It operates in a vacuum. Heat flow can be regulated upward from the minimum by providing a device to compress the insulation. No installation means or vacuum barrier is discussed. (NBS-47)

S-60 Tariel (1967) performed comprehensive material behavior tests at cryogenic temperature for an externally mounted polyvinyl chloride foam (Klegecell G - 300). The foam is filled with CO_2, air and Freon 11 at 3 atmospheres without significant leakage. Tensile and compressive modules and strength were measured.

Tensile strength is of the order of 60 psi and compressive strength is

about 90 psi. Thermal contraction and specific heat were given. A mean thermal conductivity of 1.8×10^{-4} w/cm^2 ^oK was found for hydrogen temperatures. Its density varies from 30 to 55 Kg/m^3.

The foam is applied in formed panels with polyurethane adhesive and a fiberglass cloth external coating to support the material under launch loads. (NBS-48)

S-61 Nast (1967) investigated the effects on thermal conductivity of leakage into both shingle type and multilayer insulation. Aluminized Mylar shingles were taped to a substrate of purged fiberglass or sealed polyurethane foam. Multilayer insulation was composed of aluminum foil with Dexiglas spacers and double aluminized Mylar with Dexiglas spacers.

Controlled leaks of hydrogen and helium were introduced and boil off from a 26 by 36 inch tank was measured. The shingle type insulation showed almost no degradation due to leakage in the shingle area. This was attributed to the rapid out-gassing and localized venting through individual shingles. Leaks introduced into the shingle substrate or the multilayer showed large degradation due to gas trapping. The degradation increased linearly with increasing leak rate.

Hydrogen leakage resulted in twice the degradation caused by a helium leak of the same flow rate. (NBS-50)

S-62 Thomas (1967) discussed installation of vacuum type multilayer insulation on a shroud surrounding the tanks rather than on the tanks themselves. 3 insulations were considered; Aluminized Mylar and paper, dimpled Mylar with coatings on both sides and NRC.

The concept takes advantage of the low radiative transfer through multilayer insulation. If mounted on the outer wall, no direct conduction occurs and the radiation dominates. Thus both the low radiative transfer property of the material and the non-linear radiation effects (low surface temperature surrounding the tanks) are exploited.

Other advantages include ease of installation and handling, minimization of losses due to penetrations and ease of leak detection. Also, long runs for tank supports and plumbing may be utilized since their radiative environment is not as severe with the shroud mounted insulation. Disadvantages include an increased area to insulate, increase in ground hold heat leak, and the insulation is subjected to aerodynamic heating.

A theoretical study of a typical mission showed no weight or heat leak differences between the concepts for vacuum service. Thus trade off must depend on installation, maintenance etc. (NBS-51)

S-63 Smith (1967) reported the results of experiments designed to determine if nuclear radiation causes thermal conductivity degradation in foam insulations. A radiation environment would be present for cryogenic insulation on a nuclear rocket.

Four types of foam were tested at room temperature and LN_2 temperature both before and after typical gamma irradiation. Essentially no change in the conductivity was noted for doses up to 3×10^{10} ergs/gm(C). (NBS-52)

S-64 Cohen (1966) is a summary of earlier work reported in Cohen (1965). See S-19, NBS-31. (NBS-53)

S-65 Nelson (1966) has presented a discussion of the effects of mechanical environmental conditions on external vacuum type multilayer insulation. Both NRC and Linde type insulations were applied to a 26 inch diameter hydrogen tank. These tanks were subjected to acceleration, vibration, acoustic loading and the pressure decay associated with a Saturn launch.

Heat leak measurements were made before and after the environmental exposures. No detrimental conductivity effects were noticed. It was noted that the outermost layer of aluminum foil was degraded by acoustic loading but aluminized Mylar did not degrade.

An analysis of thermal stress in a sphere of foam insulation was given. An integral equation was developed and solved by the method of successive approximations.

No data is given. (TCM-12), (See also S-66, NBS-54)

S-66 Nelson (1966) tested four types of external multilayer vacuum type insulations to see if they could withstand typical launch mechanical loads. Tests included a base point thermal performance, then acceleration, vibration, acoustics and rapid pump down. Finally another thermal performance test was made. None of the insulations showed significant thermal or mechanical degradation. The four systems included aluminized Mylar and Dexiglas spacer, aluminum foil and Dexiglas spacer, fiberglass substrate with an overlay of Dacron and NRC shingles and sealed foam substrate with NRC shingles. The layered material was fastened with plastic rods and buttons. No details of lay up or bonding to the tank were given.

This paper refers to the same study report in TCM-12 but gives a different discussion. (NBS-54). (See also S-65, TCM-12)

S-67 Parmley (1966) has patented a shingle type external insulation which vents to space. A film of Mylar is bonded to the tank wall. Shingles made of Mylar with strips of vacuum deposited aluminum running laterally on the shingle are bonded to the substrate. The aluminum strips provide small gaps in the lengthwise conduction path. Successive shingles are arranged so the gaps do not overlap, ensuring radiation protection. An open weave fabric material forms an outer boundary to support and locate the shingles. (NBS-60)

S-68 Crawford (1966) presented a study of the evacuation problems associated with gas purged NRC external insulation. Tests were conducted on large specimens to simulate the conductance paths expected on full scale tankage.

Plain superinsulation could not be pumped below 10^{-3} torr in 20 hours. Analysis of the trapped gases indicated that air was being desorbed. Thus, tests with nitrogen purging only compounded the effect. Conduction tests showed heat leaks of 60 times the predicted radiative rate.

Insulation blankets with 5 percent of its area perforated to improve the pumpdown rate were tested. 10^{-3} torr was achieved in 4 hours and 10^{-4} in 12 hours with no purge preconditioning. However, the heat leak was approximately 8 times the theoretical unperforated insulation. The heat flux in this case indicated an increase in radiation but also significant gas conduction was apparent.

The combination of hot (250°F) Helium purging and .5 percent perforations resulted in the best performance in the study. A one hour purge and subsequent pump down resulted in 10^{-4} torr in 2 hours and 2.8×10^{-5} at the blanket midpoint after 4 hours. The heat flux was reduced to approximately 4 times the predicted radiative flux. Solid conduction was responsible for the excess over radiation.

Thus, the result of purging and perforations effectively eliminated gaseous conduction. Some data was presented on the effect of arrangement and size of perforations on the pump down time. (NBS-61)

S-69 Glaser (1967) presented a brief review of the various types of insulation in use in 1967. Powders, Fibers, Foams, Honeycomb and Multilayer insulations were included. Representative data showing the effects of boundary temperatures, interstitial gas pressure, emissivities and external applied pressure were presented.

The discussion described the important modes of heat transfer, installation means, weight, and space requirements of the various insulation types. Seven multilayer combinations were included in the conductivity vs. external pressure information. (NBS-76)

S-70 Murray (1968) measured the thermal degradation associated with a penetration in 50 layers of double aluminized Mylar separated by Dexiglas. The heat leak down the penetration itself was determined by measuring temperature differences in a brass element of known conductivity and area installed in series with the penetration. A constant boil off rate was maintained by an auxilary heater to minimize changes in heat leak in vent and concentric fill lines.

Heat leak in the insulation and radial temperature profiles were measured for direct shorting and with 1 and 2 inch annular intermediary insulations. The penetration was one inch in diameter while to total insulated area was 17 ft^2.

An optimum thickness of intermediary insulation was felt to lie between the 1 and 2 inch sizes tested. The shorted insulation showed an increase of 5% in total heat leak. There was essentially no degradation in performance with the 1 inch annulus and up to 7% for 2 inches when tested with LN_2. Data for LH_2 showed a 20% degradation in the shorted configuration. Intermediaries were not tested with LH_2. (NBS-77)

S-71 Crawford (1967) this appears to be a re-hash of the data and analysis presented by Crawford (1966).

See S-68, NBS-61 (NBS-81)

S-72 Schalla (1967) presented a theoretical optimization study of several external insulations for large cryogen tanks. Typical Saturn and post-Saturn missions were considered. Comparisons were made on a weight penalty basis which included effects of payload reduction caused by boil off at various phases of the mission.

Multilayer systems with vacuum, helium and nitrogen purges were investigated. Vacuum systems were considered to be less reliable than purged systems.

Shadow shielding was mentioned but discarded for reliability, orientation and imprecise thermal control reasons. Refrigeration systems were considered too heavy. A chart of advantages and disadvantages of these systems

Comparison of helium and nitrogen purged systems resulted in the choice of helium to save the added weight of the sealed insulation substrate required to prevent nitrogen liquification. A set of general weight penalty equations were used to calculate optimum helium purged insulation schemes considering ground hold, ascent, storage and subsequent restarts.

It was found that thicker insulation on the ullage portion of the tank reduced weight penalties by minimizing stratification caused pressure rise during boost. This idea resulted in a 4% savings over applying insulation uniformly. Graphical results present the weight loss index for various missions and vent modes. (NBS-82)

S-73 Middleton (1968) has patented (for the Govt.) an externally mounted cryopumped honeycomb insulation. An open cell fiberglass reinforced phenolic honeycomb is bonded to the tank wall with a vacuum sealer of polyester and aluminum foil bonded over the cells.

On filling the tank, the residual air and gases will be cryopumped to provide vacuum. An external layer of sealed helium filled honeycomb is bonded over the vacuum cells to increase the insulation quality. This layer insures against forming excessive solid air resulting from atmospheric leaks. Punctures would only allow helium leakage to the tank.

Thermal performance is about four times as good as a typical helium purged foam filled insulation. At a mean temperature of -200F the conductivity is 0.017B-/hr.ft.F for insulation weighing .5 lb/ft^2 and about .6 in. thick. Some aerodynamic loads might be supported by such a scheme. (NBS-96)

S-74 Faddoul (1968) presents another discussion of the cryopumped external shingle experiments reported in Perkins (1968). This paper discusses some alternate spacer configurations and shows that their final performance was not changed greatly from the original Perkins (1968) (NBS-85, S-6) data and analysis. (NBS-98)

S-75 Leupold (1967) presented a theoretical optimization study of a composite NRC-2 external insulation mounted on a polyurethane substrate. Polyvinyl chloride was investigated but it showed excessive weight losses in a vacuum. A two component polyurethane adhesive was used to bond the foam.

Permeability tests lead to selection of a 13 micron aluminum, 25 micron Mylar and 13 micron aluminum laminate for vacuum control on both the substrate and the superinsulation. This material withstood 200C in a vacuum without degradation. Weight penalties based upon insulation weight boil off and stratification pressure rise were computed for typical 4, 20 and 200 day missions.

A 10 mm foam layer was adequate to maximize ground hold performance. 60 layers of NR C with the foam resulted in a weight penalty of 40 Kg for a 200 hour mission for a 15.24 m^3 tank. A limited amount of LN_2 boil off data was presented but excessive spurious heat leaks minimize the usefulness of the data. (NBS-99)

S-76 Heathman (1968) presented an experimental study of liquid hydrogen fuel tankage for a typical hypersonic cruise vehicle. The report includes the structural and fluid management designs as well as an external helium filled insulation system. Environmental temperature for the outer surface of

insulation was about 1200F.

A permeable all-quartz fiber (Micro-quartz) was selected for insulation because of its high temperature properties, reliability and fabricability. The insulation was formed into removable blankets, contained in a wire cloth envelope secured by means of wire lacing between studs on the tank and blanket. The blanket was built up to 4 inches by sandwiching quartz "felts" compressed to 4.0 lb/ft^3 between layers of wire cloth using wire tufting on 4 inch centers. A convection barrier of stainless steel foil was included to break the helium natural convection path.

The handling, formability and installation ease proved to be excellent. Blankets were butted together under compression to take up effects of thermal shrinkage. No thermal conductivity was reported but boil off data in the 1200 F environment indicated a conductivity of the order of about 0.0082B/hrftF. It was felt that considerable moisture was absorbed in the insulation. (NBS-103)

S-77 Hammond (1968) presented an analytic study of the thermal conductivity for a freon expanded foam filled and sealed honeycomb external insulation. Limited conductivity tests verified the theoretical prediction of .001B-/hr ftF. for room to liquid hydrogen temperatures.

The model includes radiative transfer through the foam, conduction in the honeycomb, gaseous freon conduction in the foam, diffusion of air into the foam and its contribution to gaseous conduction. Limited diffusion tests indicate that the mole fraction of freon in the foam is reduced to 50% after 10,000 hour shelf life.

It was assumed solid conduction and radiation in the foam act in parallel.

Foam conduction was assumed negligible and its radiative properties were estimated from limited absorptivity measurements. Gaseous freon and air conduction was assumed in the insulation region which remained above their respective condensation temperatures. Similarly, air conduction was computed using diffusion data to find partial pressures in the insulation region above the air condensation temperature. (NBS-104)

S-78 Hammond (1969) reported on an analytic calculation of effective conductivities for three externally mounted honeycomb-freon expanded foam insulations. The analysis in all cases was the same as noted for Hammond (1968). The results compare favorably with the limited test data reported.

Freon expanded foam in a sealed honeycomb showed conductivities typical of helium alone. Cryopumped sealed Mylar honeycomb was found to be mechanically unsuitable for thermal cycling but installation of an overlayer of helium purged foam eliminated the problem. Analysis of this insulation resulted in conductivities of 0.017B-/hr-ft F but helium diffusion was found to degrade performance rapidly. Since Mylar is less permeable to helium at low temperatures, it was recommended that purging should not be initiated until cool down had started. The insulation analysed in Hammond (1968) (NBS-104, S-77) was also reviewed in this paper. (NBS-107)

S-79 Schweikle (1969) discussed the need for zero gravity experiments to determine the operating characteristics of cryogenic tanks. A discussion of differences to be expected between space flight and ground tests was presented.

Areas of interest include insulations, stratification, venting and transfer.

It was pointed out that multilayer insulations often differ from predictions by 100% when installed on a typical tankage system. Also, no multilayer insulation had been flown at that time.

As built experimentation was highly recommended for insulations using vacuum chambers with particular attention paid to local thicknesses and separation of all sources of heat leak. Typical experimental programs were suggested for the stratification, venting and transfer problems in zero gravity. (NBS-111)

S-80 Wilson (1960) reported on a theoretical investigation of the thermal performance of the Centaur vehicle on a typical synchronous orbit mission. The tankage was insulated on its external surface using 4 jettisonable panels. The panels were made of one inch thick freon blown polyurethane foam (2 lb/ft^3 and conductivity equal to .01 B/hr ft F) sandwiched between .10 mil layers of resin impregnated fiberglass sheets. A helium purge space of .1 inch was maintained between the panels and tankage by fiberglass spacers. The panels were held in place by 2 stainless steel straps.

The bulkhead between the LO_2 and LH_2 was insulated with non-impregnated fiberglass which cryopumps on loading. This material had a conductivity of 0.0005 B/hr.ft F. Typical heat transfer calculations were made for this insulation using unreported ground, boost and orbital environment parameters. (NBS-121)

81 Tawill (1969) presented an extensive experimental study of NRC vacuum insulation degradation caused by practical application problems. Typical considerations include means of supporting panels for handling and

and attaching, effective and repeatable seams, pumpdown, and installation repeatability.

The measurements were made in a calorimeter to simulate a thermal control system for a manned spacecraft. All results were referenced to the unmodified blanket effective emissivity defined as: $\epsilon_{eff} = \frac{Q_{total}}{A\,(T_i^4 - T_u^4)}$. Joints were specified as $\Delta\epsilon$ per foot of joint per ft^2 insulation. Other factors were treated similarly.

No difference was noted for .15 and .25 mil mylar substrates and an insulation blanket shelf life of one year showed no degradation. Metalizing both sides of the Mylar produced no significant thermal improvement. Kapton substrates provided the same thermal performance as Mylar but a weight penalty resulted from the unavailability of very thin films. Pressures of 5×10^{-5} Torr were required to achieve maximum performance.

A number of "layer retainers" were tested for ease in handling and to provide installation means. A seam joint which provides a snap type fastener to ensure the joint repeatability was tested. The final joint provides seam coverage of 4 blanket layers resulting in a degradation of about 30% for each foot of joint per ft^2 of panel.

It was noted that Mylar will burn freely when ignited so all blankets were sandwiched in non flamable Kapton.

The result of these tests were applied to the final, as assembled, LM insulation system showing a thermal performance twice the flat blanket value. Flight data showed a further degradation of about 80% which was probably due to local thining or pinching effects in the assembled unit. (NBS-126)

S-82 Sumner (1969) reported tests of polyurethane insulation foamed in place on 22 inch diameter spherical liquid hydrogen tanks. Two methods of foaming were tried. The first method made use of a cylindrical form around the sphere into which the foam constituents were poured. This method gave rise to problems of structural integrity when the samples were cooled down. Cracks and eventually severe structural and thermal degradation were attributed to distortions in the growth of the foam caused by the constraints of the cylindrical form.

A simplified technique in which the foaming agents were poured directly onto the sphere without a form allowed a radial expansion and gave superior results. The foam produced in this manner remained sound throughout the simulated ground hold, vibration, and space hold tests. Foam density of 2.14 lb/ft^3 and an effective thermal conductivity of 0.079 BTU/(hr $ft\ ^oF$) were reported. (NBS-123)

S-83 Oberding (1964) analyzed the thermal problems associated with an orbital mission to mars. Solar and planetary radiation heat loads were calculated and heat transfer through insulation, fill and vent lines, etc. Optimum insulation thickness was calculated. Superinsulation was assumed (radiation shields separated by an insulating medium) of the Linde company designated SI-44. The optimum thickness for one year storage turned out to be 3.1 inches. Heat transfer in the vicinity of Mars would be 2.12 BTU/hr for a five foot spherical tank containing hydrogen at the boiling point. (NBS-78)

S-84 Glemser (1962) evaluated twelve urethane foams with the primary concern of determining dimensional stability with time, temperature and humidity conditions. The foams were all of 3 lb/ft^3 density and 8 x 8 x 1 inch

All of the foams ...ed an erratic but progressive increase in the width measurem... but the thickness sometimes increased, sometimes decreased. Dim...ion changes were attributed primarily to humidity conditions. Foa...ost resistant to moisture were the most stable. The brand design...as "E" exhibited the lowest growth rate of 0.00048 in/in/week. The ...nd names corresponding to the code letter may be obtained from the ...ors on a need-to-know basis. (NBS-122)

S-85 Sterbentz (19...escribes tests of multilayer blanket insulation for application in an ...day lunar mission. Of concern were the ability of these blankets ...their attachments to withstand boost loads, provide ground hold, boos...d orbital insulation. Also, optimization of tank support systems was inve...ted. The blankets consisted of helium purged fiber-glass substrate su...nded by an Aclar purge bag, alternate layers of double aluminized Mylar ...Dexiglas spacers (36 each). These were attached by buttons and ve...fasteners. The tanks with insulation installed were given vibration an...oustical tests, space environment tests in a vacuum chamber, and acce...ation tests in a centrifuge.

Some minor lo...degradations were observed including mylar film puncture by the bu..., and loosening of velcro fasteners. The heat flux was 1.25×10^{-4} BT...c ft^2 compared to 0.83×10^{-4} as predicted. This was attributed to poor ...rol of the thickness (1 in to 2 1/8 in variation) of the blankets. See NBS...(S-180) for details of this study. (NBS-64)

S-86 Rittenhouse (19...gave a talk on adhesively bonded cryogenic insulation systems for the co...nce on Structural Adhesive Bonding (Marshall Space

Flight Center). The specific type of insulation discussed was a multilayer blanket system applied over a helium purged fiberglass substrate.

Lefkoweld 109/LM52 epoxy was used for attachment of fiberglass reinforced members, Velcro fasteners, and thermocouples, strain gauges and other devices. Six adhesives passed the screening for bonding the velcro fasteners and Aclar purge bag: Pittsburg Plate Glass K-218-34, Narmco 7343/7193, Dupont 46971, Dupont 46971/RC805, Lefkoweld 109/LM52, Dupont rubber base tape on Mylar. Tensile or peel strength numbers were not given. (NBS-62)

S-87 Apisa (1966) first reviewed ground hold liquid hydrogen insulation systems. These were categorized in Table 1 as (1) helium gas purged (2) sealed-cell, cryopumped, and (3) vacuum jacketed, cryopound. The requirements for prelaunch conditions are best satisfied by a sealed construction. This type of system has at least four times the thermal efficiency of helium gas purged systems. Since a small puncture could degrade a large area of insulation if large continuous vacuum jackets were employed. Goodyear investigated shingled multilayer blankets. The best thermal conductivity was listed as 0.04 BTU - in/ft^2-hr-^oF.

This report is concerned with micrometeorite protection in space. With the objective of developing a lightweight micrometeorite bumper a test program was undertaken. From hypervelocity impact tests two composite insulation systems were developed. The first consisted of a bumper of 0.015 in fiberglass cloth impregnated with polyurethane resin overlaying a 37 layer, gas purged aluminized Mylar - foam blanket. The

eleven layer layer aluminized Mylar-foam blanket in contact with the tank. The second type substituted a 3/8 in cell Mylar honeycomb in contact with the tank. Some permeation of the sealed CO_2 cryopumped honeycomb was evident causing degradation of the insulation to about 0.171BTU in/hr $ft^{2o}F$. (NBS-67)

S-88 NASA TECH BRIEF 66-10024 (1966) describes the invention of Aluminized fiberglass sheets which may be stacked in layers with spacers of permeable material. This arrangement allows rapid evacuation in the space environment. Address for further inquiries is given. (NBS-71)

S-89 Anderson (1966) gives some of the same material as Sterbentz (S-85). An additional description of a shingle system of multilayer blankets was described. A graph (Fig. 7) shows that thermal conductivity data decreasing from 32×10^{-5} to 8×10^{-5} BTU/hr $ft^{o}R$ as the shingle length increased from 8 to 28 inches. This is due to the longer heat path in the longer shingle. Also shown clearly are changes due to multilayer density and residual gas pressure.

In regard to acoustic tests it was interesting to note that aluminum foil radiation shields suffered failure in a acoustic field of 150 db. There are problems with both aluminum foil and aluminized Mylar. The high thermal conductivity of the former is liable to cause thermal shorting and its low strength makes it susceptible to tears; while aluminized Mylar can be more transparent and is subject to poor adhesion of aluminum to the Mylar. (NBS-12)

S-90 Anderson (1965) made a more complete summary of the mechanical degradation tests on external multilayer insulations reported by Nelson (1966) (See NBS-54, Synopsis No. 66). (NBS-38)

S-91 Key (1964) reported the results of tests made to determine the explosion hazard associated with the Saturn S-II insulation. They conclude that the probability of an explosion caused by oxygen enrichment of cryopumped air is not great but should be considered.

The insulation system was composed of polyurethane foam bonded to a tank with epoxy adhesive. Phenolic fiberglass honeycomb was pressed into the foam to reinforce it and an unspecified vapor barrier was applied over the composite.

Permeation was found to be 10^{-10} SPU (cc gas through 1 cm^3 of material in 1 sec. under 1 cm Hg differential pressure) which was considered negligible. Various samples were purposely damaged and exposed to mixtures of LN_2 and LO_2 and air. The panels were subjected to impacts; explosions resulted for oxygen concentrations greater than 20 percent. In the natural cryopumped air cases, the reaction was a function of the tank wall temperature indicating oxygen fractionization as the tank warms up creating higher oxygen concentrations. (NBS-28)

S-92 Faddoul (1968) reported on an experimental investigation of foam spaced aluminized Mylar shingle insulation. Heat flux, compressive strength, outgassing, load deflection, and pump-out were investigated. The shingles offer improved cryopumping performance as compared to continuous super-insulation.

Large blanket-type shingles were fabricated from .02-in. sheets of open cell urethane foam and alternate layers of double aluminized Mylar. The multilayer was sealed in a 4-ply laminate of aluminized Mylar bonded with Narmco 7343/7139 adhesive (urethane). Polyester,

nadic methyl anhydride and epoxy adhesives were investigated also, but each was subject to leakage after flexing at low temperature.

Panels were bonded to a tank using the urethane adhesive, and all joints were sealed with strips of 4-ply aluminized Mylar. The shingles are laid up to provide 3 layers of shingles at all points providing a net of 18 shields. Average emissivities for the aluminum were found to be 0.03. The interstitial gas, CO_2, cryopumps by diffusing through the shingle to the tank.

The vacuum jacket permeability was 10^{-6} cc He/S/ft^2 which should be adequate for 30-day storage in air. Both continuous spacers and spacers with holes were tested. A heat flux of about 6.5 B/hr. ft.^{2} was found for both types of spacers when tested between room and LH_2 temperatures. The open spacers did provide significant pump-down improvements. The heat flux was a strong function of external loading, but the spacer area did not affect this result significantly. The overall weight of the insulation was 2lb/ft^3 and had allowable compressive loading of 22 psi. (NBS-120)

S-93 Dunning (1968) presented an analytical study of the feasibility of using existing refrigerators to improve the performance of a 39-inch diameter advanced Apollo tank. The available refrigerators were reviewed. Typical calculations were made to show increased performances, but no specific weight trade-offs were made. He concludes that a Stirring cycle refrigerator operating at 260 to 350R at 10 watts and weighing about 1 pound per watt would be acceptable. North American Philips and Hughes Aircraft were developing such systems with coefficient of performance of about .02; a COP of .1 would be required. (TCM-1)

94 Forge (1968) has suggested the application of a substrate of fiberglass when installing polyurethane external insulation. The foam is subject to cracking loose from a tank wall when exposed to thermal cycling.

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Effects of launch date, vehicle orientation and uncertainties in conductivity or specific heat were studied and found to be relatively insignificant. (TCM-4)

S-97 Dearing (1966) elaborated some additional test data for the Saturn S-IV internal reinforced foam insulation discussed in TCM-3 and TCM-4. As noted in the other reports, the conductivity degraded with time due to diffusion of hydrogen gas into the foam. Conductivity vs. time data were reported here showing a 50% degradation in 50 hours (.025 to .037 B/hr. ft. F). Scale model tests resulted in essentially the same conductivities as the calorimeter.

Mechanical tests at LH_2 temperature showed compressive and tensile strengths of 220 and 160 psi respectively for the reinforced foam. No thermal stress cracking was noted. (TCM-5)

S-98 Cryogenic Engineering News (1969) presented a summary of thermal conductivity data for 21 powders and fiber insulations. Apparent thermal conductivities were shown for various mean temperatures.

Effects of internal gas pressure and density on Perlite's thermal conductivity were given. Six other material thermal conductivities were shown as a function of density.

The conductivity of Perlite and Silica Aerogel were shown as a function of amount of aluminum powder opacifier added. (TCM-6)

S-99 McLaughlan (1967) reported on an experimental determination of heat leak reduction due to adding vacuum type NRC-2 external insulation to a Bendix "Phase B" oxygen tank. The tank has a vacuum annulus with vapor cooled shields and a 25-inch diameter pressure vessel.

The vent line was wrapped on 6-inch centers on the outer shell and 25 layers of NRC-2 were applied over the line and shell. A teflon insulated ring served to attach 4, 1/16-inch stainless steel mounting wires about 3 1/2-feet long. The supports were required to limit thermal shorting of the cooling and insulation scheme. An identically mounted, unmodified tank was tested simultaneously in a vacuum chamber. The insulation and cooling reduced the heat leak (boil off) by about 30% over the entire supercritical density range used in Apollo applications. (TCM-9)

S-102 Roberson (1969) reported on the thermal performance (equilibrium constant pressure vent rate) tests on a 39-inch diameter single wall supercritical externally insulated tank. The vent gas was expanded through a Joule-Thompson valve and routed around the pressure vessel outer wall. A 2-inch layer of polyurethane foam was used to accommodate ground hold requirements. One hundred layers of NRC-2 were applied over the foam to provide vacuum performance. Fiberglass rods supported the vessel in a vacuum chamber. The J-T valve regenerative cooling reduced the heat leak by about 30%. An as-installed conductivity of 4×10^{-5} B/hr.ft.^{o}R was measured for the 100 layers of NRC installed at 50 layers/inch. (TCM-10)

S-103 Cryogenic Engineering News (Jan. 1969) presented a brief introduction to cryogenic insulation and some representative thermal conductivity and density values. Several powders, fibers, multi-layers, opacified powders and fiberglass were included. Typical conductivity vs. interstitial gas pressure curves were presented for four materials, (Fiberglass, Perlite, Santocel and SI-62). (TCM-11)

S-104 Coston (1966) has presented additional data on the spaced aluminized Mylar and NRC external insulation pumpdown characteristics reported in Nast (1966), (NBS-41, S-57). Permeabilities across

the layers for 50 to 60 layers of either insulation were about 2.0×10^{-7} ft^2 while 136 layers of spaced material produced a permeability of 9.72×10^{-10} ft^2.

Diffusion coefficients parallel to the layers were also measured. Spaced Mylar material resulted in diffusivity of about .3 ft^2/sec while spaced aluminum foil gave 1.38 ft^2/sec. The crinkled Mylar (NRC) gave the highest values, (3.73 ft^2/sec.). The density of layers did not have an effect on the parallel diffusivities. (DDC-7)

S-105 Jackson (1966) presented a study of CO_2 filled external fibrous insulation for application to hypersonic airplanes. The environment requires exclusion of air at 1500F for long periods of time. Under these conditions no adequate reliable sealing system was found for use with foams or multilayers. Helium purge was ruled out by the excessive volumes required.

The CO_2 system would eliminate the sealing requirements by utilizing a transpiration effect. Fibrous insulation would be applied directly to the tank. A mixture of He and CO_2 would be introduced during ground hold; the CO_2 forms a frost layer near the tank. Experiments showed the CO_2 frost density was proportional to its partial pressure in the He atmosphere. Twenty-five lb./ft.^{3} was found to be optimum when considering both flight loads and heat leak. CO_2 sublimes during flight, absorbing heat; secondly, its vapors intercept heat in the insulation by transpiration and minimizes counter diffusion of air to the tank.

Presence of insulation didn't affect the frost density, but did promote uniformity due to the ease of lateral mixing compared to radial diffusion. This system appears to be lighter and more reliable than an on-board helium purge system. Analytic equations for optimizing the CO_2 deposit were given. (NASA-7).

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S-106 Middleton (1964) presented an experimental investigation of an externally mounted cryopumped honeycomb insulation. Mylar honeycomb was sealed by bonding 2 mil Mylar to the tank side with polyurethane adhesives. At the outer side, a 3 mil aluminum film was bonded on with epoxy phenolic. The sandwich was bonded to the tank with polyurethane adhesive.

This system, operating in a vacuum, had a conductivity of .01B/hr. ft. R at a mean temperature of 290R and a density of 4. 5lb/ft^3. A second insulation scheme utilized the same honeycomb with a helium purged perforated phenolic honeycomb bonded over it. Aluminum film bonded with epoxy phenolic adhesive provided the outer seal. This material had a conductivity of 0, 016 B/hr. ft. R, and a density of 10 lb/ft^3. The outer aluminum foil was selected to withstand aerodynamic forces. Calorimeter and 70-inch diameter tank tests showed good agreement.

Typical tensile and compressive strengths were given for the various joints at temperatures for 325 to -423F. (NASA-12).

S-107 Ishaghoff (1963) described a method of field installation of quilted multilayer insulation blankets. The blankets were designed for ease of manufacture and handling.

SI-12 insulation was handsewn loosely to plastic sheets on each side of a 26-layer lay-up. The web-type glass fiber filler permitted folding of the blanket without damage. At the edges, the aluminum foil was cut evenly with the spacer extending beyond the foil to eliminate shorting. The plastic material extended beyond the filler.

Metallic clamps hold the end of each blanket to provide a mechanical attachment point. The blankets were butted together during installation and the joints sewn. Glass-cloth tapes were tied circumferentially and longitudinally to further support the blanket system. No data on performance was given. (NASA-16, NBS-12).

S-108 Nakagawa (1968) reports on experiments with multilayered aluminized Mylar-glass cloth insulation. Of particular interest was the reduction in thermal conductivity by at least a factor of three brought about by crumpling the aluminized Mylar. As an example, at a pressure of 5×10^{-5} torr, a 40-layer crumpled shield material showed a thermal conductivity of 8×10^{-5} K cal/m. hr. ^{o}C where a non-crumpled specimen of the same number of layers gave 7×10^{-4} K cal/m. hr. ^{o}C (apparently a factor of 8.7 higher). The effect of residual pressure was surprisingly small. In the range 10^{-5} to 1.8×10^{-3} torr a 20-layer specimen increased from 1.45×10^{-4} to 2.59×10^{-4} K cal/m. hr. ^{o}C. (NBS-89)

S-109 Caren (1968) analyzed mathematically the heat transfer due to anisotropies in multilayer insulation due to penetration. Techniques for arranging the multilayer geometry around penetrations to minimize the degradation of heat flow are given. It is stated that in actual applications the thermal conduction through multilayer systems is at least twice the conduction in idealized latoratory apparatus. These latter thermal conductivities may be as low as 1.73×10^{-7} w/cm ^{o}K. (NBS-112)

S-110 Burkinshaw (1968) reports on the properties and suggests uses of PPO (polyphenylene oxide) foam. This material is less brittle (4% elongation at -324 ^{o}F) than polyurethane foam. The PPO foam has an open cell structure so that air or water can pass through it. Tests with liquid nitrogen, however, showed that when the cells on the warm side were sealed off with glass reinforced polyurethane resin and a metal sheet, the liquid penetrated only a short distance (0.5 cm out of 6 cm). Thus, the author suggests using the foam as an internal insulation bonded to the tank wall. Penetration of liquid hydrogen has not been tested.

An effective thermal conductivity of the foam is not given, but the value for the resin material itself is given at -85.6°F as 0.174 BTN-in/ft^{2}F. (NBS-87)

S-111 Crawford (1967) evaluated the space evacuation of a multilayer insulation NRC-2 (National Research Corp.). This insulation consists of crinkled 1/4 mil Mylar film with about 400 Å of aluminum deposited on one side. Blankets of this material are purged with helium gas to prevent condensation of air while in the earth's atmosphere. A problem exists in the evacuation of this material in the space environment. Tests showed residual gas pressure of 10^{-3} torr and greater persists after several hours in the space environment when pumping is from the edges of the blanket. Perforations amounting to 5% of the surface provided sufficient evacuation speed, but caused excessive radiation heat transfer.

A development program gave rise to a preconditioning technique which apparently solved the outgassing problem. This consisted of purging the blankets with hot helium gas. Hot helium removed the absorbed gas where hot nitrogen did not. This purging was coupled with a small amount of perforation to facilitate pumping. (NBS-90)

S-112 Clay (1965) reported the work of General Dynamics/Convair on superinsulation research. Residual gaseous conduction did not comply with textbook equations. Predictions by usual rarefied gas conduction equations gave values 5.4% low for LN_2 and 25% high for LH_2 in special tests. A computer program is presented which optimizes the insulation systems for conditions of ground, boost, and space. A complete development program was carried out which resulted in self- evacuated multilayered insulation panels.

An interesting innovation was the fusion welding of seals between Mylar-metal laminates. These joints proved to have 5000 psi shear strength at room temperature. Another innovation was flocked

aluminized Mylar which was tested and found to be a good insulator resilient and outgassed quickly. The effective thermal conductivities of these materials were on the order of 10^{-5} BTU/hr ft ^{o}R. Vapor cooling of shields was also analyzed. (NBS-101)

S-113 Niendorf (1966) presents a very extensive report on self-evacuating multilayer insulation. Property data surveys and experimental tests led to the selection of the various components. Aluminized Mylar was selected on the basis of permeability tests for the vacuum casing material. This was bonded with Narmco 7343/7139 adhesive. The multilayer materials were double aluminized Mylar separated by 0.02 in. thick sheets of open cell polyurethane foam. The open cell foam was determined to be a good holding agent for the frozen CO_2 cryopumping material.

Cryopumping tests under vibration were made to evaluate the holding ability of the spacer material and the ultimate cryopumping pressure. This was about 4.7 microns when the insulation blankets were surrounded by atmospheric pressure. The heat leak for the total system under simulated space environment conditions was 0.86 BTU/hr ft^2. Test failures prevented the determination of the atmospheric condition thermal performance. (NBS-58)

S-114 Wood (1967) describes research on the Centaur insulation which is outside the hydrogen tank, the S-IV and S-IV B inside the tank, and the S-II stage insulation is again outside.

Centaur insulation can be jettisoned. "An insulation which is not jettisoned would have to have an insulation performance index between 0.05 and 0.12 to be as efficient as the Centaur insulation."

The S-IV and IV B have fiber glass reinforced polyurethane foam bonded inside the tank with an epoxy resin coated fiberglass barrier.

This performance is about 1/2 that of Centaur. The fiberglass honeycomb filled with polyurethane foam performs the same as the S-IV B. An improved system for S-II will consist of a fiberglass honeycomb outer layer which serves as a purge channel for the Mylar honeycomb inner layer. This has a performance index of 0.18 which is said to be better than any known insulation exclusive of superinsulation. (NBS-79)

S-115 Norcd (1966) presented a general review of cryogenic technology. A general di scussion of foams, powders, fibers and multilayer insulation was given.

Typical curves of thermal conductivity as a function of internal gas pressure were shown. Silver coating was reported to reduce the thermal conductivity of multilayer systems to 60% of the aluminized version.

Velcro fasteners (mats of stiff plastic hooks pressed into mats of nylon loops) were described for installing removable blankets of superinsulation. (NBS-57)

S-116 Burge (1968) reported on the thermal performance of full sized LH_2 and LN_2 flight simulation tanks using NRC type shroud mounted insulation. The tankage was mounted within a shroud and installed in a vacuum chamber which was capable of simulating space environment pressures, temperatures and radiation.

The tanks were mounted on fiberglass rods. The insulation consisted of 11 layers of doubly aluminized 1/2 mil Mylar alternated with 10 layers of dimpled (Dimplar) sheets. Eight blankets were fabricated and attached to the shroud using twenty 1/4 by 1 1/4 in long teflon studs. Joints were interwoven and taped with 6 in. wide strips.

Thermocouples were used on the supports and other penetrations to compute their contribution to the measured boil off. Original tests verified the theoretical performance predictions. But, after the

system had been opened for various modifications, considerable insulation degradation resulted. The measured heat leak increased 7 fold. Apparently, workmen had damaged the insulation and moisture had penetrated it causing a 20% loss of the aluminum coating. Thus, the primary advantage to shroud mounting was not proven, i.e. maintainability was not necessarily improved. (DDC-2)

S-117 Connelly (1962) presented a progress report on environmental testing of a 7,000 gallon flight type liquid hydrogen tank. The report summarized the structural design and mentioned its insulation system.

Formed segments of fiberglass were bonded to the titanium tank using Sta-Bond 511-A adhesive. The fiberglass was chosen to withstand aerodynamic loads and heating. Poured foam insulation was used in the regions of complicated geometry. No test data was given. (DDC-5)

S-118 Dahlin (1966) presented the results of flat plate tests to evaluate bonding and sealing techniques for cork insulation (Sheller TB955). In all cases the cork was bonded to aluminum.

A mounting system of 13 studs for each 4 square feet of specimen was tried but excessive cracking resulted after thermal cycling. Vac-Seal 1912 adhesive proved to be the most successful cork to aluminum bonding agent.

Mylar and Aluminized Mylar seal bags showed some leakage as indicated by the amount of cryopumping. A Zero Perm laminated

bag which was bonded with Vac-Seal and taped proved to be the best sealer material when applied over a sprayed urethane coating. Cracks which appeared in the cork apparently were the result of cryopumping; thus, the outer seal design controls the effectiveness of cork insulation. Insulation applied internally showed extensive degredation.

A LH_2 to room temperature conductively of .017 B/HrftR was found for 3, 3/4 inch , layers of sealed cork. (DDC-8).

S-119 Isenberg (1963) presented a general review of the heat transfer mechanisms and their associated mathematical models for various insulations. Evacuated and gas filled multilayer, foam and powder insulations were discussed.

The mathematical models presented were composed of linear combinations of simple one dimensional, radiative, solid conductive, and gas conductance expressions.

One interesting point was made regarding the minimum spacing for radiative shields. The shields should be separated by distances greater than the radiation mean free path to avoid quantum heat transfer effects. This criteria sets the shield spacing at greater than 20 and 150 microns for room and liquid hydrogen temperatures respectively. (DDC-14).

S-120 Isenberg (1963) presented a general review of insulation systems for external application. Superinsulation, evacuated powder, gas filled powder, foam, and honeycomb reinforced foams were discussed.

The requirements for vacuum maintenance, purging and air tight seals were outlined for each system. The combination of environment and mission requirements suggests the importance of low heat capacity and good re-radiative properties to permit rapid cooldown of the insulation for filling and to dissipate launch heating. A typical outer skin temperature of 650F was reported for the launch phase.

A foam type insulation with reinforcing of phenolic glass fiber honeycomb was selected for further study. Adding the honeycomb raised the basic foam conductivity by 24% as measured in a calorimeter.

The insulation system was installed by bonding the honeycomb core panels to thin formed metal shells to take advantage of high temperature curing which were subsequently welded to the tank. Extra panels of insulation were then bonded over the weld joints.

Total hemispheric emissivities were reported for various radiation shield materials at room temperature including aluminum, stainless steel, copper, nickel, gold, and silver. Typical densities and conductivities were reported for various foams, corks and super-insulation under atmospheric external pressure and a mean temperature of -250F. (DDC-15).

S-121 McGregor (1967) reported on a detailed analytical and experimental investigation of the effects of frost formation on the heat transfer to a cryogenic container. A set of integral boundary layer equations were solved to determine the heat transfer in turbulent free convection

S-122 Yuhas (1965) studied the bonding properties of mylar and the formability of mylar honeycomb. No data or materials information was given but he concludes that liquid type adhesives are stronger and more flexible than tape type bonds.

He notes that Mylar honeycomb can be compressed to 50% of its room temperature height with essentially 100% dimensional recovery. Blankets were formed to mild contours using vacuum pressure in molds at 400F. (DDC-23)

S-123 Hertz (1962) reported on tests made to evaluate bonding systems for external foam and honeycomb-foam insulations. A 5 ft. long by 1 ft. in diameter aluminum cylinder was used for the thermal and pressure cycling tests.

Polyurethane foam panels (? lb/ft^3 Reichold 8625-8605) were bonded to the aluminum using: Epon 828/Versamid 125 in fiberglass cloth, Coast Pro Seal 777, Hexcel 1252, Hexcel 1219 and Silastic 140. Twenty thermal cycles to LH_2 temperature were made for each agent. Only the Epon/Versamid and Coast Pro Seal survived these tests without major failure.

The urethane filled honeycomb was machined and bonded to the same apparatus using AF-41 (epoxy-nylon unsupported tape) adhesive. The exterior was covered with 4 plys of Epon 828-951 hardener impregnated 181 fiberglass. The cylinder was pressurized to 1020 psig with liquid nitrogen. The honeycomb and bonding were not damaged but the fiberglass seal failed due to stress cracking.

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The honeycomb system was also applied to the inside wall and pressurized to 35 psi. This system showed excessive thermal cracking both in the seal and the foam. (DDC-12)

S-124 Marion (1967) presented a comprehensive cost analysis technique and applied it to six typical external insulation systems on a comparative basis. Absolute magnitude costs were not considered but estimates of the differences between systems formed the basis for comparison.

A figure of merit was used to evaluate the cost per pound of payload for each system. Typically, development cost was the largest contributor with manufacturing cost an order of magnitude less.

Each insulation was designed to provide the same space performance to provide a means of comparison without optimizing cryogen thermodynamics etc. Costs considered include, payload weight loss, development, capital equipment required, manufacturing, launch cost, reliability and material costs. The basis for estimating these was given including actual material costs.

The six systems studied included continuous, shingled and shroud mounted superinsulations both with and without purging. The important design parameters were discussed. It was noted that water vapor will destroy aluminum reflective films in 12 to 24 hours. Typical performance curves were shown for ground and space environments for each system.

Complete results were given as a function of desired system thermal performance. Calculations were made to show the sensitivity of the analysis to initial assumptions; these results show that the relative cost ranking of the materials did not change as various components of the cost estimate were changed systematically. (i.e. if one cost was assumed to be a much different percentage of the total system cost.) In all cases the system with the lowest thermal conductivity, a cryopumped substrate with 50 layers of NRC, always was the cheapest system in terms of payload in orbit regardless of insulation cost. (NBS-80).

S-125 Higgins (1967) presented a comprehensive study of liquid hydrogen insulation systems for hypersonic cruise and reentry vehicles. Surface termperatures up to 2000F are expected so ceramic foam and various cooling systems were selected and described. Superinsulation was selected for the low temperature portion of the insulation system.

Extensive data was presented for a number of superinsulations. Several spacer materials were examined for use with aluminized Mylar radiation shields, (foam, glass paper, crinkled polyester film, glass fabric, silk netting, nylon netting, and vinyl coated fiber glass screen.) Thermal conductivity as a function of spacer material, external pressure, cold and hot wall temperatures and internal pressure, were reported. The cold wall temperature had little effect

while the conductivity was proportional to the third power of the hot wall temperature.

The effects of pump-down perforations was discussed. 10% opening decreased the side wall pumpout time by 3 orders of magnitude but increased the effective conductivity by 5 fold. About 2% openings appeared to be a good compromise with larger individual holes minimizing the thermal degradation, (1/16 inch holes produced a conductivity 60% higher than the same area in 1/4 inch holes.) Crinkled insulations had less degradation due to perforations than flat layered insulations.

Load compression strength, coefficient of linear expansion, conductivity vs. mean temperature and density were reported for 14 thermoplastic, thermosetting and Teflon foams. Freon blown polyurethane foam had the lowest conductivity. (NBS-86)

-126 Heathman (1968) has reported an analysis of a high temperature-cryogenic insulation systems of ceramic foam for hypersonic cruise vehicles. This is a more comprehensive treatment of the work reported in NBS-103(S-76) and includes considerable structural design information.

3.5 lb/ft^3 microquartz was used in a helium environment. Blankets

were made up by enclosing the felt like material in a quartz cloth using quartz thread. The blankets were laced to mounting studs using quartz or wire thread. Conductivity was measured between LH_2 and 800R giving values of 0.04 and 0.085 B/hr ft R for helium atmospheres of 8 and 760 mm Hg. respectively.

A number of mission performance studies were presented. Some properties of slush hydrogen were given. (NBS-114)

S-127 Cryogenic storage systems for the extended space missions of the future will require more fluid capacity than current systems, and thus new design and development techniques will need to be evaluated.

This work investigates high performance external insulation systems for use on flight weight cryogenic gas storage systems. "External insulation" in this study means anything added to a cryogenic storage system for the purpose of thermally protecting it from its environment. This definition excludes the vacuum annulus of a dewar. The fluids stored are hydrogen and oxygen.

The purpose of this work is to: (a) perform a literature search on all of the available material concerning external insulation studies and/or evaluation; (b) provide a complete bibliography of the material researched in (a) above; (c) furnish a synopsis for each of the most useful references contained in the bibliography; (d) categorize the results of this work to

facilitate evaluation and assessment; (e) assess which concepts have the best thermal characteristics, applicability maintainability, and reliability; (f) select five concepts as being the most promising; (g) evaluate these five concepts and choose three for extensive study; and perform a parametric study of the three remaining.

External insulation systems have been studied quite extensively in the past few years. However, there is no single source which evaluates these various studies and assesses the relative merits and/or deficiencies of each concept. This study is meant to bring together all of the available information in a single source manual and provide the basis for determining the areas in which future development should be undertaken.

This work is being performed during the period March 2, 1970 to March 1, 1971. The Technical Contract Monitor is Mr. M. L. Davis, Power Generation Branch. (TCM-13)

S-128 Coston (1967) presented an analytic and experimental study of a multilayer insulation system. A purged fiberglass sublayer was mounted on a cylindrical tank for performance testing. Dexiglass spaced double-aluminized Mylar was attached to the purge bag with Velcro fasteners. Installed conductivities of 5.2×10^{-5} to 8.6×10^{-5} B/hr.ft.R were measured; this compares to 3.6×10^{-5} B/hr ft R measured in a flat plate calorimeter.

The investigation included an empirical study of penetration effects. It was concluded that insulating spacers should be used to minimize parent insulation temperature profile disturbances. Conductivities of spaced insulation and NRC (unspaced) were measured for heat flow parallel to the layers as a function of mean temperature giving .02 and .025B/hr.ft.R respectively. The latter material apparently exhibited some radiation tunneling. The thin deposits of aluminum had a conductivity with a linear temperature dependence.

Both outgassing data and diffusion coefficients were measured. The data was reported in raw form but could be useful. (NBS-115)

S-129 Barry (1967) presented a brief discussion of a manned Mars mission. The various trajectory and orbit parameters and vehicle requirements were outlined. Adiabatic vehicle surface temperatures were calculated for Earth orbit, Mars transfer and Mars orbit. These values are 370R, 242R and 100 to 300R respectively. The Mars orbit temperatures decrease with increasing altitude and solar orientation of the spacecraft. (NBS-113)

S-130 Allesina (1968) presented the conceptual rationale for making economic comparisons of various space systems and components. Insulations were discussed in a rather general way illustrating their position in the overall concept. (NBS-102)

S-131 Vance (1967) presented a very general review of cryogenic technology in the aerospace field including superinsulation, refrigeration and cryo-evacuation. (NBS-97)

S-132 Price (1967) presented a detail discussion of NRC-2 insulation lay up techniques for an 8 foot tank. A tank was actually insulated for a future test sequence; the detail procedure for installation was described, step-by-step.

The lay up scheme consists of a top cap, bottom cap and 6 "orange peel" segments for the vertical runs. Complete thicknesses were bench assembled and taped together for handling purposes. Vertical sections were hung from three nylon studs which contributed an equivalent heat leak of one square foot of insulation. From the equator of the tank downward, Dacron thread was laced through the insulation and buttons were tied in place to minimize compressive loading. The bottom cover was held by a Dacron net. All joints were interleaved and taped where necessary. Penetrations were wrapped with insulation and interleaved with special insulation washer material at the tank wall. (DDC-22)

S-133 Babjack (1967) presented an extensive study of multilayer insulation systems for Mars mission spacecraft thermal control. Approximately 25 candidate radiation barrier materials were considered. Tests were performed to evaluate absorptivity, emissivity, weight loss and thermal conductivity. Materials were subjected to typical decontamination proceedures. Insulation blankets were fabricated and the effects of rapid depressurization were evaluated.

Decontamination precedures require heat cycling and exposure to wet ethylene oxide. Each candidate material was exposed to this environment and the resultant effects on thermal and bonding properties were measured. ALUMINIZED MATERIALS DID NOT SURVIVE THESE TESTS. Gold coating appears to be much more suitable.

Extensive thermal conductivity, absorptivity, and emissivity data was reported for room to LN_2 temperatures. Effects of space environmental radiation on the optical properties of shield materials was reported; no greatly significant effects were noted. Decompression tests were reported for several size pannels supported by nylon studs and stitching. The effects of layer density, seams, joints and constrictions were noted.

The final design, assembly and installation philosophy was presented. (NBS-83)

S-134 Berdelman (1965) presented an analytical technique for determining thermal stresses in composite wall tankage. The problem of thermal expansion

stresses in a foam insulation bonded to a metal hydrogen tank for use in a hypersonic cruise vehicle was treated.

The technique for computing both hoop and axial stresses involved successive interations using a virtual displacement technique. Each member is allowed to expand freely to an equilibrium size at the new temperature; a new system geometry is assumed and loads are calculated to deform the system to the new geometry. Since there are no net external forces on the composite, the calculated loads must cancel when the proper final geometry has been assumed. The iteration continues by adjusting the geometry until the forces cancel overall; then the internal stresses can be computed. Variable properties were easily included in the calculation. (NASA-15)

S-135 Hammond (1966) presented an early progress report on the Saturn S-II helium purged polyurethane filled honeycomb insulation. This work was reported in more detail and summarized in NBS-96 and NBS-107. (NBS-43)

S-136 Orr (1961) presented a simple theoretical method for optimizing insulation thicknesses. The propellant fraction is maximized at constant deliverable cryogen to find a relationship between boil off and insulation parameters for various space storage times. The resultant equation is an algebraic quadratic which must be solved numerically. (NBS-3)

S-137 Rogers (1969) reported on an extensive theoretical and experimental study of external insulation usage for synchronous orbit and Mars missions. Simulated space tankage was insulated using normal shop techniques and tested in a space simulator. Installed insulation performed to within a factor of two of the calorimeter values, (2×10^{-5} B/hr. ft F).

Seven types of insulation were investigated to determine repeatability in performance as affected by shop type installation. NRC-2 unspaced insulation was chosen for its low K-ρ product and the ability to control density mechanically. Spaced insulations would wrinkle during normal handling, causing a variance in layer density of as much as 100%. Foam spacer materials were more repeatable but adequate radiation layer densities could not be achieved.

Pump down tests showed that two 4 foot wide interleaved pannels of 50 layers of NRC-2 would not evacuate below 10^{-2} mmHg in 12 hours at room temperature. This could be improved significantly by a 24 hour vacuum bake-out at 225F. When the pannels were exposed to LN_2 temperatures at one wall, 10^{-4} mmHg was reached in 3 hours without excessive ballooning during rapid pump down; but bake-out was not considered to be manditory.

Blankets were installed on the tank in 50 inch square pannels of 40 layers of NRC. Nylon monofilament threads on 12 inch centers were sewn through the insulation and looped through adhesive patches on the outer layer. The

thread was attached to "Velcro loop pile" patches which were bonded to the tank using Narmco 7343 adhesive. Blankets were jointed by interleaving 10 layer groups with corresponding layers of adjacent panels. The insulation was removed and reinstalled several times without apparent damage.

Fiberglass composite rods were selected to support the tank because of a low conductivity to strength ratio. Tests indicated that radiation shielding was required for the support rods.

Space chamber tests indicated that one "g" loading on the insulation, when the cylindrical tank was mounted horizontally resulted in a 2 fold degradation of performance compared to zero "g" results, (i.e. a long vertical tank where the "g" force did not compress the insulation). (NASA-31)

S-138 Wilkins (1961) presented a general review of hydrogen storage technology and the effects of orth-para hydrogen conversion in the liquid. Evacuated powder and multilayer insulations were considered for a double walled storage vessel. Nitrogen shielding and vapor cooling were also considered.

Calculation procedures for boil off with the various thermal protection systems including the effects of ortho-para concentrations for the two forms of hydrogen were given. (NBS-7)

S-139 Barry (1966) presented a theoretical study of shadow shielding for lunar

and Mars missions. Shielding with external insulation was compared to foam or superinsulation alone. Calculations showed no significant savings over superinsulation alone for the lunar mission because of the albedo effects on the non-solar side of the vehicle. The Mars mission study showed a significant improvement when superinsulation was shielded and the vehicle sun oriented.

Shadow shields would be made in the form of a collapsable bag which would be inflated by gas pressure. G. T. Schjeldahl Co's 0.00075 inch thick Mylar aluminized on both sides would be used. A cold stiffening elastomer such as a vinyl-base lacquer coating would be applied to provide rigidity for low-g loading. The shield would be jettisoned before high thrust maneuvers and another deployed. A solar absorptance of 0.11 and a total emittance of 0.025 were reported for the aluminized Mylar. (NASA-10)

S-140 Boensch (1968) discussed the structural design of hypersonic cruise vehicles. The recommended insulation of removable Microquartz blankets sandwiched between layers of wire cloth was mentioned. (NASA-1)

S-141 Cody (1966) presented a theoretical and experimental study of shingle type multilayer insulation. Emphasis was placed on the helium purging, evacuation, leakage and outgassing characteristics. Predictions of the interstitial gas pressures were made using estimated diffusion, outgassing

and sublimation coefficients. Details of the calculations and results were given. Very small outgassing rates prohibited a vacuum of less than 10^{-3} mmHg. These results were compared to 105 inch diameter tank tests.

Insulation was made up of the battens of 48 layers of NRC-2 which were attached to the tank at their innermost end with a metallic pin. A purge bag was installed over the system with purge inlets located at the existing penetrations. Vent lines were provided for space evacuation lines were valved off for ground hold.

The tankage tests showed that gas pressures may vary by two orders of magnitude along the insulation for the ninety hour vacuum test. Thermal performance was about 3 times that predicted. This was attributed to the variation of installed insulation thickness combining with outgassing to permit considerable gaseous conduction.

Small scale evacuation tests of the purged insulation indicated that considerable water vapor was evolved at 10^{-3} mm Hg even though purge gases contained only 50 parts per million at room temperature. A 250°F helium purge test resulted in a significant decrease in water outgassing and attendant increase in evacuation rates. (NBS-68)

S-142 Collom (1968) presented a description of localized separaters for super-

insulations, (Patent applied for). Dacron flocking was bonded to single aluminized Mylar using Narmco 7343 adhesive to provide radiation shield separation. The "dots" were spaced in a triangular pattern and were about 0.040 inches high to facilitate evacuation.

Small scale tests indicated a thickness recovery of 80 to 90% after a 6 "g" acceleration load was applied. Tests to determine effective emissivity as a function of "flock" spacing showed a 30% increase for 3/4 inch spacing and a 100% increase over no flocking for 1/4 inch spacing of the supports. Thermal conductivities of the order of 3×10^{-5} B/hr. ft. R were measured.

The spacer was applied in tufts by covering the entire surface with adhesive and using substrate vibration to orient the fibers to assure the proper spacing and orientation. (NASA-2)

S-143 Cochran (1966) presented an experimental investigation of aerodynamic loading on an external sealed foam insulation. The sealed foam withstood a typical Centaur vehicle launch environment of Mach 1 to 3.5 with surface temperatures up to 650°F for periods up to two hours. Unsealed foam of the same composition suffered considerable degredation.

The sealed insulation was made up of panels of 2 lb./ft.^{3} freon-blown

polyurethane foam. Layers of 0.4 inch thick foam were encapsulated in a covering of Mylar-aluminum-Mylar laminate, (each layer was 0.0005 inch thick). Panels were adhesively bonded to the model tank with an 8 inch square glue line grid pattern. Joints were filled with strips of foam and covering material. The entire panel system was covered with glass cloth and wrapped with pretensioned fiberglass filaments for insulation support and environmental protection. (NBS-49)

S-144 Christensen (1959) presented a theoretical model for heat transfer through radiation shields with a solar radiation source. Heat flux was presented parametrically to show the effects of outer surface absorptivity and emissivity, number of shields, shield emissivity, and solar radiant intensity.

The best commercially avalable outer coating (at that time) was white enamel paint which has an absorptivity - emmisivity ratio of .25. It was suggested that shields be spaced on cylindrical tanks by mounting in tension between rings at either end of the tanks. (DDC-4)

S-145 Lindquist (1968) presented the results of an extensive experimental and theoretical study of foam spaced, shingle type, purged, multilayer insulation. Out-gassing, gas transmittance, purge gas, and cryopumping were studied as a function of spacers and external seals.

Several foam and nylon spacer geometries were investigated. A composite

spacer of solid polyurethane foam (.02 inch thick, 2lb./ft.^{3}) sandwiched between two additional layers of foam with 1-1/4 inch square holes on 2 inch centers was selected to maximize gas transmittance and minimize conductivity. (The system proved to give the same performance at less cost than foam strips.) A laminate of Mylar-aluminum - aluminum-Mylar was selected to seal the surface exposed to the atmosphere while aluminized Mylar sealed the internal surfaces.

The panels were attached to themselves and the tank with an application of Goodyear G-207 contact adhesive primer coat and Narmco 7343/7139 adhesive. Johns Manville Co. BFF three inch wide pressure sensitive tape was used to ensure vacuum tight external joints.

Compressive strength of the shingles was greater than 20 psi. Outgassing tests indicated a need for a hydrogen getter to maintain low internal pressures; 0.5 grams of Union Carbide palladium oxide was selected. The outer seal has a permeability of less than 4×10^{-8} atmcche/sec.ft.^{2} atm and the inner seal showed 5×10^{-6}, both at room temperature. Several purge gases were investigated; CO_2 was selected because of its low vapor pressure.

Approximately 40 hours were required to reach acceptable vacuums. Preliminary tests have shown that a single layer of perforated honeycomb

can decrease the pump down time 15 fold without degrading the other insulation properties. An evacuated conductivity of 1.49×10^{-4} B/hr. ft. R was measured; nonevacuated performance was degraded 15 fold. A purged storage life of 30 days without significant thermal degradation was achieved. Preconditioning the insulation at 200°F for 24 hours was very helpful in reducing pump down time.

External purge bags were investigated and discarded because of reliability, weight and cost .

Extensive data and detail theoretical techniques were presented for conductivity with internal and external pressures, transient outgassing and pump down, basic gas transmittance and actual tank insulation schemes. Data was derived from both flat and tank installed samples. (NBS-118)

S-146 Reed (1965) reported on a theoretical method of optimizing the number of layers of NRC-2 shingles required to minimize weight penalties. Both normal and lateral heat conduction were considered. Insulation weight, cool down requirements and steady state boil off were considered. 54 layers of insulation provided the optimum performance for a 30 day storage period for a 105 inch diameter tank.

Methods of rupturing the purge bag to provide evacuation were considered. It was concluded that Mylar purge bag peel type joints, joined with 1/2 mil

Schjeldahl GT-100 Tape would provide a predictable release due to differential pressures. A second pneumatic type "opener" with spring loading to ensure maintenance of the opening was also described. (NBS-10)

S-147 Romero (1967) presented a semi-active insulation system for use on the moon or other long cyclic heat flux environments.

The lunar night temperatures reach 200R which is below liquid oxygen temperatures; therefore, the scheme permits boil off gas or auxilary gas in the insulation during the night to cool and/or subcool the oxygen. The insulation is vented to space before the daytime radiation impinges. Several hours are required to complete the evacuation. If pressure rise in the tank is permitted during the day, calculations showed that this storage mode could operate subcritically indefinitely. (NASA-4)

S-148 Carstens (1965) presented a theoretical comparison of the storability and weight-performance factors associated with four candidate rocket fuel combinations for earth orbit and lunar storage missions. Hydrogen/oxygen, hydrazine/fluorine, hydrazine/nitrogen tetroxide, and diborane/oxygen difloride were considered. Vented, non-vented, and refrigerated storage modes were considered for the cryogens. Superinsulation, foam, and powder insulations were studied.

The analysis includes an optimization of insulation thickness, based on

weight penalty, for each storage mode. The fuels themselves were compared on a weight required for a specified mission, after storage, using ISP for the basis.

For the cryogens, non-vented storage was optimum for short missions with refrigeration superior for the longer missions. Superinsulation was required to be competitive with the storable fuels.

The H_2/F_2 system proved to be the most effective for storage times up to 2 weeks. For longer missions, B_2H_6/OF_2 showed a slight advantage.

Details of the insulation optimization scheme, space environment, and calculation of surface temperatures considering all sources of radiation were given. (NASA-11)

S-149 Coston (1967) presented an experimental determination of the effective conductivity of a multilayer insulation in the direction parallel to the layers The insulation consisted of 6.35×10^{-6} meter Mylar with two layers of approximately 400 Å aluminum on each surface. 7.11×10^{-5} meter Dexiglass spacers were used.

The material was packed to 3230 layers/meter in a calorimeter and conductivity measurements were made for mean temperatures varying from 50 to 225K. The mean effective conductivity vs arithmetic mean temperature was curve fit to the data: $K=11.48 \times 10^{-3}+10.02 \times 10^{-5}T$(watt/MK).

Considering the electron mean free path, the film thickness and room temperature bulk material conductivities, the aluminum layers must be the overriding conductor in the system. Normally, aluminum's conductivity peaks at low temperature due to mean free path effects. Since the film thickness is of the order of the room temperature mean free path (which increases with decreasing temperature), the mean free path effects do not produce a temperature dependence. (NASA-3)

S-150 Minges (1963) presented a general review of insulation systems and heat transfer characteristics which may be applicable to lifting body re-entry systems. Consideration was given to the high temperature and low temperature requirements as separate classes.

Thermal conductivities were shown for 13 high temperature powders and fibers as a function of mean temperature. Similar data were presented for several foams and superinsulations for cryogenic temperature applications.

A summary table lists conductivity and densities for 5 representative insulations used in each regime; this shows superinsulation and multilayer microquartz felt with nickel shields to be most effective for low and high temperatures respectively.

An interesting parametric representation of heat flux for multilayer superinsulations was developed to show the optimum number of insulation layers for different environmental temperatures. This analysis was based

upon the assumption that solid conduction increases linearly with packing density; i.e. total insulation thickness was held constant while the number of radiation shields was increased. (NBS-14)

S-151 Isakson (1955) presented a study of externally mounted liquid hydrogen tanks for aircraft application. A general review of the properties of 10 foams was given. Materials include cellulose acetate, epon resin, polystyrene, phenolic resin, and isocyanate resin.

Densities varied from 2 to 20 lb./ft.^{3} with compressive strengths varying from 7 to 190 psi, increasing with density. Thermal expansion coefficients of approximately 2 x 10^{-5}/F were reported. Room temperature conductivities range from 0.016 to .025 B/hr.ft.R, increasing with density. (DDC-13)

S-152 Johnson (1964) presented an extensive review of theoretical heat transfer models for gas filled powders. The theories were discussed and compared to experimental data for carbon black-silica powder mixtures filled with helium, neon and nitrogen at atmospheric pressures.

Particle sizes were chosen to limit gaseous conduction in the transition region between continuum and free molecular flow regimes.

A model was developed for the heat flow. Gas conductivity, gas-solid interactions, and conductivity in absorbed gas layers were assumed to act in parallel.

For a mean temperature of -200F, conductivities of 0.0005, 0.01, 0.012 and 0.025 B/hr.ft.F were measured for evacuated, nitrogen, neon and helium fills, respectively. Comparison of the data and the models, using experimentally determined adsorbed phase transfer properties, resulted in good correlation for the mean temperatures investigated (-100 to -200F) and powder bed densities from 6 to 22 lb./ft.^{3}.

Analysis of the correlations indicate that gaseous conduction is the predominant effect and transfer from gas to solid to gas was relatively unimportant. The adsorbed gas phase may contribute up to 50% of the total transfer and solid conduction and contact resistance contributions were overshadowed by the adsorbed phase.

The effects of particle aggregation were also discussed. It was noted that the responsible Van der Waals forces become more significant as particle size is decreased. (DDC-17)

S-153 Carr (1967) presented the results of an environmental simulation and a lifetime in orbit test for a crinkled gold coated Kapton insulation.

The insulation, mounted on a 14 inch long cylindrical tank, was subjected to 10^{-8} torr vacuum at a mean temperature of -120°F for 60 days. Then it was subjected to a typical liquid rocket vibration environment.

The thermal performance, 0.35 watts/ft.^{2} for 19 layers of insulation, was not affected by the environmental vibration simulation.

The Kapton layers were perforated with 9, 1/8 inch diameter, holes per square foot. The blankets were attached to the tank using nylon studs (Tinger Fasteners made by General Electric Co.) and split nylon washers. The fasteners were attached to the tank using Velcro nylon hook and pile tape, (Velcro Corp.) and the blanket joints were taped with adhesive backed Kapton tape, (Technical Flourocarbons Eng., Inc.). The gold coated Kapton was provided by National Metalizing. (NASA-21)

S-154 Gosch (1965) presented mission studies for a hypersonic hydrogen fueled aircraft. The performance calculations assumed a micro-quartz helium purged external insulation. Its thermal conductivity was reported to be 0.02B/hr.ft.R at 100R and .03 at 500R. (DDC-25)

S-155 Hacker (1965) described an external sealed foam type insulation. Freon blown polyurethane foam with an apparent conductivity of 0.011 B/hr.ft.R, 2 lb./ft.^{3} density, and 0.3B/lb.R specific heat, was the basic insulation.

0.0005 inch aluminum foil sandwiched between 0.005 inch layers of Mylar was bonded to either side of the foam with polyester adhesive to seal the material. This sealant layer has no measurable permeability and adds to the panel rigidity for handling.

Panel edges were covered with vacuum formed Mylar channel sections and the butt joints sealed with a tape form of the sealing material. The

panels were bonded to the tank to prevent gas trapping and leakage.

A 0.003 inch thick style 106 fiberglass cloth impregnated with Dow Corning Silicone A-4000 adhesive was wrapped over the panels to provide protection from the launch environment. The entire insulation system was wrapped with fiberglass roving applied by a filament winding machine. The wrap is designed to compress the insulation to a load of 2 lb./in^2. This material provides the basic structural support.

NBS reports 20 through 25 present a detail discussion of this insulation. (NBS-26)

S-156 Heidelberg (1965) presented the results of flat plate calorimeter thermal conductivity measurements for the foam insulation described in NBS-26

A mean overall conductivity of 0.012B/hr.ft.R was measured at the mean temperature of 282R. No difference in conductivity was noted when the panel was evacuated by cryopumping instead of mechanically. An increase in compressive loading from 2 (design point) to 15 pounds per square inch did not affect the conductivity measurements. A test to determine panel joint efficiency was not conclusive. (NBS-20)

S-157 Dengler (1965) studied oxygen impact sensitivity of the foam insulation described in NBS -26.

The basic foam showed essentially no reaction in the presence of liquid oxygen. The composite of foam with a Mylar-aluminum-Mylar seal attached with Vitel PE207 (Goodyear Tire and Rubber Co.) adhesive showed some mild reaction in 1/4 of the tests. The occurance of reaction could not be corretated with any of the test parameters.

Foam permeability tests were made to evaluate the possibility of air saturation over a large area when a localized seal failure occurs. The permeability was found to be 0.36 cc air/cc foam/hr./ATM at room temperature. This value is so small that cryopumping will be localized in the immediate vicinity of a seal leak. Therefore, the probability of an accident is minimized. (NBS-21)

S-158 Perkins (1965) presented the results of subscale tankage tests performed on the foam insulation described in NBS-26.

Thermal conductivity measurements showed a degradation of about 10% a compared to flat plate calorimeter values, (NBS-20). The conductivity was insensitive to panel bonding, edge seals and protuberances.

Panel bonding by use of full adhesive coverage or edge plus grid pattern

bonding were equally effective in prevention of cryopumping.

Launch pressure decay and heating tests were conducted. The insulation was able to withstand these environments without thermal performance degredation. The environment included temperatures to 615F with dynamic pressures to 952 lb/ft^2 and velocities to Mach 2. (NBS-22)

S-159 Perkins (1965) presented the detail design, fabrication and installation procedures for the foam insulation described in NBS-26.

Narmco 7343/7139 resin mixture was used to bond the various components together and the entire blanket to the aluminum tank. The aluminum was prepared for bonding by cleaning with toluene and scrubbing with methylethyl ketone. A prime coat of Vitel PE 207 resin was used on the aluminum.

Holes were cut in the panels to accomodate protrusions. Vacuum formed Mylar-aluminum-Mylar sealing material was used to seal the blankets around the holes. The holes were then filled by foaming polyurethane in place. Where-ever possible, the entire protuberance was sealed by a patch of the sealing material.

The outer wrap was made of eight-strand epoxy-preimpregnated S/HTS fiberglass roving. A room temperature curing, temperature-resistant silocone resin was used to bond the windings to the insulation and itself. Pretension was selected to assure the insulation integrity after accounting for thermal shrinkage and the compressive loading on the foam. (NBS-23)

S-160 Calvert (1965) presented a detailed description of two ground hold tests performed on a full size Centaur tank insulated with the foam described in NBS-26

Two ground hold boil off tests were conducted 34 days apart. The first test lasted 25 hours and the second 11 hours. The tank ends were not insulated with the foam panels so the conductivity data (with end leaks subtracted out) represents the cylindrical portion including various protrusions.

A conductivity of 0.008 B/hr. ft. R was measured for a mean temperature of 200°R. This value is 30 to 40 percent lower than values measured in subscale tests. The difference was attributed to fewer panel joints per unit area in the large tank layup.

Conductivities measured in the second test were only 4 percent higher than the original values. A number of blisters and cracked foam areas developed in the insulation during warm up after each test. Generally these areas were localized and near a protuberance. They apparently did not affect performance significantly as shown by the agreement between the two tests. A detail description of the damaged areas was given. (NBS-24)

S-161 Esgar (1965) presented a concise summary of the foam insulation development work and testing which was described in detail in NBS-20, 21, 22, 23, 24 and NBS 26. (NBS-25)

S-162 Evenson (1962) presented the results of an experimental study of adhesives for bonding polyurethane filled phenolic honeycomb to aluminum tanks. Nine adhesive materials were applied and subjected to twenty thermal cycles from room to liquid hydrogen temperatures. The vessel was cycled to 900 psi twenty times to stress the bonds at hydrogen temperature.

Epon 828-Versamid 125 (Shell Chem. Co. - General Mills) impregnated fiberglass mat, Lefkoweld 109 (Leffingwell Chem Co.), FM1000 (Bloomingdale Rubber Co.), AF-41 (Minnesota Minning and Manufacturing Co.) and Proseal 777 (Coast Pro-Seal and Manufacturing Co.) adhesives successfully survived the testing. The first two were recommended because the latter three require long and/or high temperature curing cycles.

Hexcel 1219 and 1252, Epon 828 - Hardner 951, and Silastic 140 (Dow Corning Chemical CO.) all failed in the bond line during thermal cycling. (DDC-9)

S-163 NASA (1967) Contains reports NBS-92, 93, 94, 95 and NASA-23, 24. This composite report presents the results of the MSFC insulation studies up through 1967. (NBS-91)

S-164 Gilstad (1967) reviewed the general requirements for insulations which will be used in manned missions in the 70's. The requirements for developing a reliable superinsulation capable of storing cryogens in space for 12 months were described.

Gilstad notes that full scale testing and/or flight testing will be required to fully demonstrate the performance of superinsulations. He notes that McGill University is/was studying the meteoroid protection problem. (NBS-92)

S-165 Hyde (1967) presented a review of the theoretical and experimental studies of a multilayer (NRC-2) shingle insulated 105 inch diameter tank. All the information presented here has been published elsewhere (See NBS-118) and summaries are includedin this report. He does point out that scale-up of subscale and calorimeter data can result in 60 percent errors. This report is included in NBS-91. (NBS-93)

S-166 Nevins (1967) discussed a number of mechanical superinsulation attachment schemes. Various samples were subjected to dynamic mechanical loading to simulate flight environments. 5 schemes were investigated.

One type incorporated a loose fitting rope to which the insulation battens were clipped using a spring type clamp; this attachment required very careful design to survive. Tension bands over the blanket or interwoven with the layers were successful in purged insulation applications. Pins holding shingled battens were adequate for a purged condition. Button and string lacing was tested successfully for a purged configuration.

An extensive series of permeability tests were made on 30 metal-plastic

laminates to evaluate their applicability for vacuum sealing. A four layer laminate of 0.5 mil Mylar, 2-0.35 mil aluminums and 0.5 mil Mylar proved to have the lowest permeability. A sublayer of "two-way stretch nylon" provided resistance to creasing and consequent leakage. Actual tank tests indicated that seams are quite unreliable and that small leaks are very difficult to find. Therefore, evacuated insulation was not considered to be as promising as purged insulation where leakage is not so critical. (NASA-24)

S-167 Yates (1967) described the manufacturing and installation of both a purged shingle type insulation and a continuous wrap evacuated insulation. The shingle type insulation proved to be easier to handle and install; also, the purge bag was much more reliable than a vacuum bag.

The shingle insulation was made up of 6 battens of 8 layers of NRC-2 aluminized Mylar. The battens were cut to various lengths to produce a shingle effect. All the sheets were bonded together at one end with thermoplastic adhesive on 19 inch intervals. Small holes were punched through the bonded area for installation on aluminum pins bonded to the tank with NARMCO 7343 adhesive. An "E-ring" retainer was used. Excess material on curved surfaces was tucked, folded and taped. Battens were taped to lower shingles at their outer extremities. The purge jacket was made of 5 mil Mylar. Curved sections were vacuum formed and joined with contact adhesive. Precut battens were installed around penetrations and interleaved with penetration insulation. Preformed vacuum jacket transition pieces were bonded to the main jacket and to purge manifolds at the penetration. This installation was straight forward and posed no particular handling problems. Satisfactory performance was achieved but it was considerably less than expected.

Linde SI-62 (aluminum foil and glass fiberpaper) was selected for a continuous vacuum insulation lay up. Aluminum foil tension bands were bonded to the tank wall cylindrical sections. Insulation was wrapped simultaneously with the tension bands to provide layer support. Holes for penetrations had to be cut on

each revolution, this caused considerable delay. The tension band was bonded to the last insulation layer at its outer extremity. The tank ends were insulated with interleaved and taped discs of SI-62. Penetrations were insulated with helically wrapped material and interleaved with the tank insulation. The vacuum bag was made of 1 mil Mylar - .8 mil lead - 1 mil Mylar laminate sheet. Curved parts were vacuum formed. Joints were made with a portable heat sealer. This material was quite sensitive to handling damage. 0.5 torr was achieved in the vacuum bag. No performance tests had been made for this insulation. (NASA-23)

S-168 Stuckey (1967) summarized the performance of two foam spaced superinsulations with a micrometeroid bumper layer. 30 mil thick polyurethane foam was used for the spacers; it was spot bonded to each reflective layer using quick drying adhesive. For tanks less than 120 inches in diameter, 1/2 inch wide aluminized Mylar ribbon filament was wound over the spacer for each reflective layer. On larger tanks, the same materials were made into panels from flat sheets and bonded to the tank. Both systems weigh about 2 lb./ft.^{3}. 30 inch diameter Calorimeter conductivity measurements showed conductivities of 4×10^{-5} and 6×10^{-5} B/hr. ft. R. Helium purge ground hold tests gave conductivities of about .045B/hr. ft. R.

The micrometeoroid protection system uses the energy absorption capabilities of the insulation in conjunction with an outer layer of 1 mil 181 fiberglass cloth

impregnated with polyurethane resin. For 10^{-1} to 10^{-5} g particles impacting at a velocity of 30,000 ft/sec, an optimum insulation thickness of 2 inches was required to absorb the energy. The preconstructed bumper layer was installed in two pieces using pressure sensitive tape.

Aerodynamic heating tests (up to 450°) resulted in degradation of the outermost 2 or 3 Mylar layers. It was recommended that aluminized Kapton be used in the outer layers because of its greater thermal capability. (NBS-94)

S-169 Wood (1967) reviewed, briefly, the MSFC plans for continuing insulation development studies for long term space storage. This will require better thermal performance at lower densities. This needs to be demonstrated by tankage tests as opposed to calorimeter data. (NBS-95)

S-170 Colaluca (1963) reported the thermal conductivity of 70 layers of evacuated SI-62 insulation on a cylindrical tank. The insulation was wrapped continuously on the cylinder. Individual interleaved gores were used on the tank heads. These were secured with cellophane tape. A vacuum bag of 1 mil aluminum sandwiched between 2-1/2 mil Mylar sheets was applied in the same pattern and sealed with contact adhesive.

Conductivity as a function of external pressure was measured. Values varied from about 10^{-3} B/hr. ft. R for 1 atmosphere loading to 9×10^{-5} B/hr. ft. R at about 10^{-3} atmospheres external load. The lower value was about 4 times

that expected for an idealized insulation. This difference was attributed to gas conduction in the insulation where the pressure was 0.5 micron Hg. (NASA-17)

S-171 Leonhard (1967) presented a description of an extensive insulation development program. The insulation utilizes layers of double aluminized Mylar separated by .040 inch thick tufts of dacron fibers. The tufts were bonded to the mylar with Narmco 7343 adhesive. The tufts were positioned and aligned by use of a vibration technique. The insulation was purged.

The insulation was installed in blankets with their joints sealed with tape. Fiberglass retainer pins are used at both ends of the cylindrical section. Both the end gores and side wall blankets were attached to the pins. Fiberglass washers and dacron thread were used to retain the layup. The outer surface is treated with a dacron layer to provide a purging barrier. Dacron is used throughout because of its low outgassing coefficient.

15 layers of "superflock" had a heat transfer coefficient of 0.2 to 0.32 B/hr.ft.^{2} which is superior to NRC-2, (approximately 20% on a weight basis.) Depressurization tests showed that 10^3 microns of internal pressure could be reached in 140 seconds. At that pressure level gaseous conduction was eliminated and free molecular transfer existed.

The study included extensive evacuation tests and analysis. Outgassing coefficients and diffusion parameters were discussed extensively. Computer programs for calculating pressure decay were developed and are documented in

the report.

Extensive theoretical and experimental thermal data were presented to show the effects of emissivity, spacer properties, number of shields, gas pressures and temperature. The report includes extensive data on shield reflectivity as a function of radiation wave length, shield temperature, and type and size of the spacing tufts. (DDC-19)

S-172 Lindquist (1969) presented a comprehensive review of a superinsulation development program including basic and tankage data, installation procedures, and design drawings. Evacuated aluminum foil - 106 Dexiglas paper laminate was used in the insulation design. Outgassing, permeability, and conductivity data were presented for 21 films, laminates and adhesives for use in design trade-off studies.

Insulation was applied to cylindrical tank sections in a continuous wrap with aluminum bands used to support the material and control its density. Circular discs were used on the tank heads; these were interleaved and taped to their respective cylindrical layers. Layers had to be cut individually to accomodate penetrations.

A flexible vacuum jacket was made from a laminate of 1 mil Mylar - 0.8 mil lead - 1 mil Mylar. This material has permeability of 5×10^{-10} ft.^{3}/ft^2 ATM which was repeatable after various flex tests. Curved parts were made by vacuum forming. Joints were made with Schjeldahl GT-200 adhesive and heat sealed.

DuPont Adiprene L-100 adhesive was used for joining to aluminum. Armstrong A-12 adhesive was used to repair minute vacuum leaks. Penetrations were covered with rigid metal jackets joined to the flexible jacket by o-ring seals.

Extensive data on outgassing and vacuum conductance were reviewed and presented to evaluate pump-down characteristics and procedures. It was recommended that all materials be pre-processed at 300°F for 30 hours and that the entire system be maintained at 200°F during evacuation. Both theory and test demonstrated a 50 hour pumping duration to achieve 100 microns Hg on a 105 inch diameter tank. A molecular sieve getter was employed also. Perforations in the shield near the pump-out ports were required to achieve this performance.

Thermal tests simulating the space environment resulted in effective conductivities of 7.3×10^{-5} B/hr.ft.R as compared to predicted values based on calorimeter data of 3.5×10^{-5}. Ground hold tests showed a conductivity of 70×10^{-5} B/hr.ft.R or about one and one half times the predicted value.

They note that aluminized plastic shields would reduce system weight. Also, preevacuated systems are limited to usage on small tanks because of the complexity of sealing they require. (NASA-36)

S-173 Bullard (1969) presented an interim report on cryogenic tank support studies. The final report covering this work is presented in NASA-37. The report summarized an analytic study of 12 support concepts and includes data for multiple interface structures (stacked washers). Various mission studies were presented.

S-174 Bullard (1969) presented the results of a theoretical (see NASA-34) and experimental investigation of 6 cryogenic tank support concepts.

1. Fiberglass tube support,
2. Titanium strut with stacked washers in series,
3. Ball and socket titanium support which can be partially disconnected (the socket expanded to minimize contact) for low "G" loading periods,
4. A vent gas cooled titanium tube support,
5. continuous thin wall fiberglass cone,
6. continuous fiberglass honeycomb cone.

The supports were designed for a 5,500 lb tank with 5.7 g acceleration and 6 g vibration.

Detail temperature profile and conductance data were given for LH_2 and LN_2 cold temperatures. These data compared favorably to the predictions. Conductivities were reported as a function of temperature.

The ball-socket joint proved to be 50% less efficient than predicted due to uncertainties in contact areas. The washer system using stainless steel components proved to be very sensitive to mean temperature; the thermal resistance dropped an order of magnitude at room temperature compared to LN_2 temperature.

Overall, the filament-wound fiberglass tube strut offers the most potential

from considerations of weight, thermal performance, simplicity, and versatility. At a temperature of 250R its conductivity was 0.2B/hr.ft.R. (NASA-37)

S-175 Boeing (1967) presented the results of an experimental study of pump down rates for purged multilayer insulations. Nylon tulle (net), Fortrel scrim (a polyester) and .045 inch thick mylar honeycomb spacers were tested with inch diameter perforations on 0.03 inch centers in the mylar will optimize pump down time.

Six material preconditions were tried:

1. room temperature nitrogen purge,
2. room temperature helium purge,
3. 200°F nitrogen purge,
4. 200°F helium purge,
5. 250°F vacuum and nitrogen backfill,
6. 250°F vacuum and helium backfill.

In all cases helium purging was preferable to nitrogen. The Fortrel scrim and honeycomb materials could be pumped to 10^{-4} torr in one hour with room temperature purging and in 7 minutes after the hot purge. Pressure differentials across these insulations were insignificant. The Nylon produced very long evacuation times for room temperature preconditioning because of its affinity for water vapor. Pressure time curves were given for each test. (DDC-24)

-176 Laser (1964) presented a compilation of thermophysical property data of insu lating materials for both low and high temperature application. Data is presented as a function of temperature. The data includes: thermal conductivity, diffusivity, compressive strength, density, melting point, continuous service temperature, typical available form and modulus of elasticity. It also includes a summary of test methods used to measure these properties. (DDC-20)

S-177 Heathman (1966) presented a preliminary report on the design and testing of insulation for a hypersonic cruise vehicle. Preliminary design of tankage and a Microquartz high temperature insulation system was described. Various mission studies were presented. The final phases of this investigation were reported in NBS-103 and NBS-114. (DDC-11)

S-178 Sterbentz (1966) presented a complete documentation of the technical studies, data, and design incorporated into the superinsulation system summarized in NBS-64.

Complete compilations of gas flow, temperature profiles, permeabilities, diffusion coefficients, and thermal conductivities are presented as a function of design parameters, (shingle thickness and length, blanket density, support methods, joint design, operating temperatures, etc.). Prediction methods were described and compared to test data. Detail installation techniques and

drawings were included. (NBS-63) (See S-190 also).

S-179 Bell (1962) provided a general review of foam and fiberglass insulation systems and technology which existed in 1962. Some data on conductivity, pump down time, and thermal contraction were given. (DDC-1)

S-180 Crawford (1966) presented the results of external insulation system tests performed on 5 types of superinsulation. Each insulation was mounted on a cylindrical tank and subjected to ground hold simulation, combined mechanical and acoustical excitation, acceleration, boost pressure-time history, and space simulation.

NRC-2 type insulation was easy to install in blankets which can be folded and reinstalled without damage. Tears were easily repaired with clear Mylar adhesive tape. Blankets were installed with overlapping edges and secured by clamping (plastic) to a Dacron rope. The standard material survived the ground hold and mechanical tests. Its space performance was unacceptable due to excessive outgassing and high gaseous flow impedance.

NRC-2 perforated by drilling with thin wall stainless steel tubing (at 550 rpm, 90 layers can be cut at once) was mounted over a sealed honeycomb substrate. The substrate cracked and lost its seal due to differential thermal contraction. Space performance was hindered by the large area of perforations.

0.5% perforated, 250° helium purged NRC without substrate proved to be the most efficient insulation tested. It was easy to handle but the installed layer density was hard to control. It could be pumped to 10^{-4} torr in 4 to 5 hours. Its apparent conductivity to hydrogen temperature in the space environment was about an order of magnitude better than the others tested, (4.7×10^{-5} B/hr. ft. R).

A pre-evacuated Linde SI-62 system was attached in the same fashion as the NRC-2, The material was much more susceptible to handling damage. Dobeckmun Metalam PZ 5526 (Mylar - aluminum/aluminum - Mylar) laminate proved to be the best vacuum jacket. A substrate of two-way stretch nylon cloth bonded to the jacket improved resistance to flexure damage. Joints were bonded and doubled with Goodyear G-207 adhesive and Dobeckmun 32899 tape. Two to three hours of pumping were required to achieve 150 microns without preconditioning. Also, after external pressure removal, 2 -1/2 hours were required for 80% recovery of insulation height. A leak tight seal never was achieved so the measured thermal performance was very poor.

The last insulation studied was a purged, dimpled, aluminum coated, phenolic impregnated, fiberglass cloth, (5 mils thick). The insulation was mounted on nylon studs screwed onto aluminum studs which were bonded to the tank. This scheme greatly enhanced evacuation but suffered from excessive conduction. Its conductivity was an order of magnitude greater than the NRC-2. It was felt that further development of the concept could greatly improve its performance. (NBS-108)

S-181 Kerlin (1966) presented a test plan for evaluating nuclear radiation effects on typical superinsulation materials including tapes, adhesives, radiation barriers and spacing materials. This report discusses the test plan and the selection of materials for the tests based upon their known non-radiation insulation properties. (NBS-75)

S-182 Bush (1965) presented a study of Linde and NRC type insulations. The report includes a decision making scheme for comparing insulations. Typical idealized design criteron were formulated to provide a design base.

The general properties of Linde and NRC insulations were described including NRC data on joint heat leaks for interleaved and a rolled type joint. Typical heat leak for a rolled joint is 0.0225 B/hr./foot of length. The general properties of Marshield insulation (aluminum coated, dimpled, 5 mil fiberglass) was also described, it weighs 2 to 5 $lb./ft.^3$. A theoretical analysis of the Marshield insulation was given, it indicates that performance improvements over Linde and NRC may be achieved as a result of greater installed height and improved penetration treatment. Various sealed substrate for prevention of cryopumping were described also.

A method of calculating an optimum insulation design for a given mission in terms of weight penalty was presented in detail.

Typical installation and theoretical performance information was given for

spherical and cylindrical tanks with NRC-2 over a sealed honeycomb substrate, He purged NRC-2, He purged Marshield, pre-evacuated NRC-2 and Linde SI. Generally purged NRCinsulation was installed with nylon rope to which the blankets were attached. The edges were interleaved in groups of ten layers. Evacuated NRC was considered in several individually sealed blankets which were bonded to a substrate. The joints were made by rolling the halves together and taping. A spaced, evacuated, NRC was also considered (fiberglass cloth spacers used in the lower 1/3 of the layers) to improve ground hold characteristics. This approximately doubled the space heat leak and halved the ground hold heat leak. This material as well as the Linde would be supported by the rope-clamp system. The Marshield would be mounted in panels on bonded pins.

A rather complete insulation rating system was devised to include not only the thermophysical data but also reliability, manufacturing problems, service, and development required. Based upon a point rating system, the sealed honeycomb substrate and passive NRC was judged to be the best insulation studied due to "recent success" in bonding honeycomb and the inherent reliability and simplicity of the system. Second and third rated were NRC-2 and Marshield purged insulations. These were selected over the vacuum types because of th unreliability associated with vacuum bags.

Detail heat transfer calculation procedures were reported for optimizing insulation and supports. Also, the internal radiation in pipes was treated.

(NASA-30)

S-183 Carr (1964) presented the results of a space simulation test made on a spherical tank. Solar radiation, albedo and earth reflected radiation were simulated in a vacuum chamber.

The insulation was made up of 210 layers of NRC-2; installation procedures were not described. The test results show a degredation from calorimeter based predictions of 50% when installed on a four foot diameter sphere. This discrepency was blamed upon the insulation mounting studs and degredation at the penetrations.

It was concluded that the insulation system would be adequate for one year oxygen mission (10-20% boil off in 4 foot sphere) but would be unacceptable for long term hydrogen storage. (NBS-18)

S-184 Knoll (1968) presented a general discussion and analysis of shadow shield performance. Experiments were performed to verify the analysis and determind the shield-structural support interaction effects.

Effects of emissivity, shield spacing, radiation source temperature, and shield support properties were presented parametrically. The importance of obtaining low emissivity surfaces for the supports was noted. Also, thermal shorting of the supports to the shield can enhance the performance by trading linear conductive transfer for the non-linear radiative flux.

The tests indicated good correlation with analytic prediction methods. (NASA-18)

S-185 Allgeier (1968) presented a description of the fuel cell, metabolic oxygen, and dilutent gas requirements for 6 to 24 month space missions. Storage tanks similar to those used in Gemini, Apollo and Advanced Apollo systems were considered.

It was concluded that these double wall design concepts can not perform adequately without lowering the environmental temperatures.

Design curves were presented to show the fluid and heat leak requirements, and tank sizes for various mission lengths and/or number of men participating. Curves of tank area and weight were given for various tank L/D and pressures.

It was recommended that refrigeration be studied for the longer mission.

(NASA-19)

S-186 Cerquettini (1969) described the procedure for applying the polyurethane foam Saturn S-II insulation.

An epoxy-phenolic primer coating (M602 primer from Pittsburg Plate Glass Co.) is baked on at 290°F. Then an air drying primer (primer M of the Furane Plastic Co.) is painted over the first coat. B-250A urethane foam (NOPCO Chemical Co.) is sprayed directly over the primer. The foam dries in a few minutes. If the foaming operation is stopped, the edge is coated with NARMCO 7343 adhesive to seal it and to provide a new starting point. A Chem-Seal Corp. polyurethane resin is applied over the foam to provide a fungus and moisture barrier. This material can be machined at low speeds.

(NASA-32)

-187 Knobbout (1969) presented some basic material properties for polyphenylene oxide film and foam. Mechanical properties, thermal expansion, diffusion coefficient and bonding agents were reported.

Sheet material had a yield stress of about 800 Kg/cm^2 at room temperature; it increased to 1100 at 20K. The foam had a yield stress of about $2Kg/cm^2$. Both the film and foam had thermal expansion coefficients of about $4.7 \times 10^{-5}/K$.

The water diffusion coefficient was an order of magnitude greater than Mylar ($7.3\ g/m^2$ 24hr. cm Hg). The oxygen diffusion coefficient was 3 orders of magnitude greater than Mylar ($250 \times 10^{-10} cm^3/cm^2$ secc cmHg).

No satisfactory adhesive had been found for the temperature range of 20K to 400K.

This material is of interest because it can withstand higher temperatures than most polymers such as polyesters. (NASA-35)

S-188 NASA (1966) presented a description of a double layered, sealed, honeycomb insulation. The inner sealed core is made of Mylar and sealed with Mylar film and polyurethane adhesive at the cold wall. Its outer seal is an aluminum film bonded with a modified epoxy adhesive. This layer cryopumps.

An outer sealed and perforated phenolic honeycomb is bonded on with epoxy phenolic adhesive. This layer's outer seal is an epoxy phenolic bonded aluminum film. Helium purge gas is introduced to eliminate air diffusion to the lower insulation and the cold wall. (NBS-70)

S-189 Rotter (1965) presented an economic study of insulation for 370,000 and 575,000 gallon liquid hydrogen earth storage dewar. The tanks were double walled. Perlite powder and superinsulation were compared.

The basis for comparison included direct material and installation cost, daily LH_2 loss, cooldown loss, maintenance, facility time loss for warmup and cooldown, and any safety derived from insulation protecting the pressure vessel from external forces.

In a five year life time, superinsulation proved to be more cost effective. Linde type insulation with a flat plate conductivity of 2×10^{-5} B/hr ft R was considered. Its installed conductivity was assumed to be 10^{-4} B/hr ft R. Installed cost for the 370,000 gal tank was reported to be $16,000 per inch of thickness. The 575,000 gal tank insulation was $22,000 per inch of thickness. (NASA-29)

S-190 Lockheed (1964) presented the results of an extensive superinsulation development and evaluation program. Conductivities, diffusion coefficients pump out data, and flight load simulation were studied. Five insulation configuarations were considered. Those can be summarized as blankets of Linde type spaced materials and unspaced NRC-2 type materials installed on a sealed foam substrate. Both types were purged. Blankets were

held together by a 4 to 8 inch spaced nylon thread weave with plastic buttons. Shingles were taped to the substrate which was attached to the tank with Velcro fasteners. A 2 mil Aclar bag was used to contain the helium purge gas.

Flat plate tests of the system (including joints etc.) gave evacuated conductivities of 3×10^{-5} B/hr ft R for the Linde blanket mock up and 7×10^{-5} B/hr ft R for 28 inch long NRC type shingles at a mean temperature of 330R. Installed conductivities were approximately 10×10^{-5} and 12×10^{-5} B/hr ft R respectively. These values were not appreciably degraded by acoustic, virbration and "g" loading simulations. Conductivities parallel to the layers was also given.

Gas flow parallel to the insulation layers was measured. 70 layers per inch of spaced insulation had a permeability of 10^{-7} ft^2 and a free molecular diffusion coefficient of .36 ft^2/sec. Pump down tests on this insulation installed on a 36 inch tank indicated that 2 hours were required to reach a stable pressure.

Purge tests indicated that about 6 purge space volumes of helium were required to reduce the air fraction to 0.001.

Light aluminum foil was degraded with exposure directly to a 150 'db acoustic' field. (NBS-56)

S-191 Love (1960) presented a review of the heat load environment for a lunar mission. Several insulations were reviewed. Typical conductivity values were used to compute parametric mission capabilities. Various thermodynamic operating modes were discussed and related to performance effects. (NBS-105)

S-192 Gorham (1966) presented a discussion of the manufacturing and installation methods for "super floc" superinsulation. The instulation is made of 1/4 mil doubly aluminized Mylar spaced with tufts of dacron thread bonded to its surface. The tufts are positioned on the uncured epoxy coated mylar using a vibration technique.

Perforations were made in the mylar to facilitate pump out. A 1000°F punch was used.

This insulation concept is described in much greater depth in DDC-19 (S-171) (NBS-117)

Note: All additional references ordered for the preparation of synopses have proved unobtainable from any source.

12.0

MATERIALS/CONCEPTS CATEGORIES

MATERIALS/CONCEPTS CATEGORIES

For a complete description of these categories, see Section 4.2.1, page 28.

Briefly, the code is:

PUBLICATION CATEGORIES

EI: External Insulation Technology

TB: Technological Base

RV: Reviews

AT: Analytical Techniques

PR: Properties of Materials, Relevant Tests, and Techniques

PA: Patent

MATERIAL CATEGORIES

SI: Super Insulation

MC: Multilayer Composites

CK: Cork

FM: Foam

HC: Honeycomb (nearly all are foam-filled)

CA: Composites - aggregates

IN: Internal

TECHNIQUES OR APPLICATIONS An (x) appears in the appropriate Column. They are:

Shroud Mount

Vapor Cooled or Refrigerated

Continuous Wrap

Blankets, Panels, Shingles

Pumped, Evacuated, or Cryopumped

Purged or Gas-filled

Perforations, Pump Channels

PUBLICATION	MATERIALS	TECHNIQUES/APPLICATIONS: Shroud Mount	Vapor Cooled, Refrigerated	Continuous Wrap	Blankets, Panels, Shingles	Pumped, Evacuated, Cryopumped	Purged, Gas Filled	Perforations, Pump Channels	INSTALLATION	MISSION & ECONOMIC STUDI
Gray (1960) NBS-1 S-34	TB	HC				X				X	X
Love (1960) NBS-2 S-35	AT	SI					X			X	X
Olivier (1961) NBS-4 S-36	AT	SI					X				X
Clark (1962) NBS-5 S-37	AT	MC			X						
Franier (1961) NBS-6 S-38	AT	SI			X		X				X
Merrill (1962) NBS-8 S-39	AT	MC			X			X			
Lindquist (1962) NBS-9 S-40	EI	SI			X		X				
Spieth (1958) NBS-10 S-41	RV	N/A									
Hnilicka (1963) NBS-11 S-42	RV	SI								X	
Perkins (1964) NBS-13 S-43	ET	SI			X		X			X	
Johnson (1963) NBS-15 S-44	AT	CA						X			
Haskins (1962) NBS-16 S-45	TB	FM					X	X	X		

PUBLICATION	MATERIALS	Shroud Mount	Vapor Cooled, Refrigerated	TECHNIQUES/APPLICATIONS: Continuous Wrap	Blankets, Panels, Shingles	Pumped, Evacuated, Cryopumped	Purged, Gas Filled	Perforations, Pump Channels	INSTALLATION	MISSION & ECONOMIC STUDIES
Swalley (1964) NBS-17 S-46	EI	SI			X		X			X	
Van Vliet (1965) NBS-27 S-47	AT	MC			X					X	
Key (1964) NBS-28 S-91	TB	HC					X			X	
Taylor (1966) NBS-30 S-48	TB	HC						X			
Cohen (1965) NBS-31 S-49	EI	SI			X		X			X	
Parmley (1966) NBS-32 S-50	TB	SI				X	X			X	
McIntire (1948) NBS-33 S-51	RV	FM								X	
Dawson (1965) NBS-34 S-52	PA	IN				X					
Getty (1966) NBS-35 S-53	TB	SI					X				
Nast (1966) NBS-36 S-54	TB	SI						X	X		
Hertz (1966) NBS-37 S-55	TB	CA								X	
Anderson (1965) NBS-38 S-90	AT	SI			X		X		X		

PUBLICATION	MATERIALS	TECHNIQUES/APPLICATIONS: Shroud Mount	Vapor Cooled, Refrigerated	Continuous Wrap	Blankets, Panels, Shingles	Pumped, Evacuated, Cryopumped	Purged, Gas Filled	Perforations, Pump Channels	INSTALLATION	MISSION & ECONOMIC STUDIE
Little (1962) NBS-39 S-56	TB	SI		X			X			X	
Nast (1966) NBS-41 S-57	AT	SI			X			X	X		
Allen (1963) NBS-45 S-58	PA	FM						X		X	
Hnlicka (1966) NBS-47 S-59	PA	SI					X				
Tariel (1966) NBS-48 S-60	TB	FM				X	X	X			
Nast (1967) NBS-50 S-61	EI	SI			X	X		X			
Thomas (1967) NBS-51 S-62	PR	SI	X		X		X			X	
Smith (1967) NBS-52 S-63	TB	FM					X				
Cohen (1966) NBS-53 S-64	EI	SI			X		X			X	
Nelson (1966) NBS-54 S-66	TB	SI			X		X		X		
Faddoul (1968) NBS-98 S-74	TB	SI				X	X				
Parmley (1966) NBS-60 S-67	PA	SI				X	X				

PUBLICATION	MATERIALS	TECHNIQUES/APPLICATIONS: Shroud Mount	Vapor Cooled, Refrigerated	Continuous Wrap	Blankets, Panels, Shingles	Pumped, Evacuated, Cryopumped	Purged, Gas Filled	Perforations, Pump Channels	INSTALLATION	MISSION & ECONOMIC STUDI
Folkman (1968) NBS-100 S-7	AT	SI	X		X		X		X	X	
Hammond (1968) NBS-104 S-77	AT	HC			X						
McLaughlan(1968) NBS-106 S-8	EI	SI		X	X		X			X	
Hammond (1968) NBS-107 S-78	AT	HC			X		X				
Perkins (1968) NBS-110 S-5	PA	FM				X	X			X	
Schweikle (1969) NBS-111 S-79	RV	SI					X			X	
Johnson (1968) NBS-119 S-2	AT	SI								X	
Faddoul (1967) NBS-120 S-92	EI	SI				X	X		X	X	
Wilson (1960) NBS-121 S-80	AT	FM				X		X			
Tawil (1969) NBS-126 S-81	EI	SI			X		X		X	X	
Dunning (1968) TCM-1 S-93	AT	N/A		X							X
Forge (1968) TCM-2 S-94	PR	FM								X	

PUBLICATION	MATERIALS	Shroud Mount	Vapor Cooled, Refrigerated	Continuous Wrap	Blankets, Panels, Shingles	Pumped, Evacuated, Cryopumped	Purged, Gas Filled	Perforations, Pump Channels	INSTALLATION	MISSION & ECONOMIC STUDIES
				TECHNIQUES/APPLICATIONS						
Dearing (1965) TCM-3 S-95	TB	IN			X						
Dearing (1965) TCM-4 S-96	RV	IN									X
Dearing (1966) TCM-5 S-97	RV	IN									X
(1969) TCM-6 S-98	TB	CA						X			
McLaughlan(1967) TCM-7 S-99	EI	SI		X	X		X			X	
Saucier (1969) TCM-8 S-100	AT	N/A		X							
Saucier (1967) TCM-9 S-101	EI	SI		X	X					X	
Roberson (1969) TCM-10 S-102	EI	SI		X	X					X	
(1969) TCM-11 S-103	PR	CA						X			
Coston (1966) DDC-7 S-104	TB	SI			X		X		X		
Jackson (1966) NAS-7 S-105	AT	MC		X		X	X				
Middleton (1964) NAS-12 S-106	TB	HC				X	X				

PUBLICATION	MATERIALS	Shroud Mount	Vapor Cooled, Refrigerated	Continuous Wrap	Blankets, Panels, Shingles	Pumped, Evacuated, Cryopumped	Purged, Gas Filled	Perforations, Pump Channels	INSTALLATION	MISSION & ECONOMIC STUDIES
				TECHNIQUES/APPLICATIONS						
Ishaghoff (1964) NAS-16 S-107	TB	SI				X	X			X	
Burge (1969) SIE-1 S-17	AT	N/A						X	X		X
McKellar (1969) SIE-2 S-18	TB	CA								X	
DeWitt (1969) SIE-3 S-19	EI	SI			X					X	
Loukota (1969) SIE-4 S-20	EI	SI	X							X	
Wood (1968) SIE-5 S-21	TB	SI						X	X		X
Zimmerman ('68) SIE-6 S-22	AT	SI		X					X		
Nevins (1967) SIE-7 S-23	EI	SI					X	X			
Achhammer ('68) SIE-8 S-24	PR	CA								X	
Hinckley (1968) SIE-9 S-25	AT	SI			X	X		X	X		
Brogan (1969) SIE-10 S-26	AT	SI							X	X	
Burkley (1969) SIE-11 S-27	TB	MC							X	X	

PUBLICATION	MATERIALS	TECHNIQUES/APPLICATIONS: Shroud Mount	Vapor Cooled, Refrigerated	Continuous Wrap	Blankets, Panels, Shingles	Pumped, Evacuated, Cryopumped	Purged, Gas Filled	Perforations, Pump Channels	INSTALLATION	MISSION & ECONOMIC STUDI
Phillips (1970) SIE-12 S-28	TB	HC						X			
Leonard (1969) SIE-13 S-29	AT	CA						X		X	
Yates (1969) SIE-14 S-30	EI	SI								X	X
Lindquist (1968) SIE-15 S-31	TB	SI					X			X	
Lindquist (1969) SIE-16 S-32	EI	SI					X		X	X	
Burge (1968) SIE-17 S-33	EI	SI	X						X	X	
Burkely (1966) NBS-59 S-9	EI	HC				X	X	X	X	X	
Glaser (1969) NBS-125 S-10	EI	SI			X		X			X	
Rawuka (1966) NBS-44 S-11	IN	FM			X		X			X	
Glaser (1967) NBS-84 S-12	RV	All	X	X	X	X	X	X	X	X	X
Bonneville ('64) NBS-19 S-13	AT	SI	X		X		X		X		
Perkins (1969) NBS-73 S-14	EI	SI	X			X	X			X	

PUBLICATION	MATERIALS	TECHNIQUES/APPLICATIONS: Shroud Mount	Vapor Cooled, Refrigerated	Continuous Wrap	Blankets, Panels, Shingles	Pumped, Evacuated, Cryopumped	Purged, Gas Filled	Perforations, Pump Channels	INSTALLATION	MISSION & ECONOMIC STUDI
Dixon (1968) Part I NBS-127 S-15	IN	FM				X				X	
Dixon (1968) Part II NBS-109 S-16	EI	SI			X			X			
Sumner (1969) NBS-123 S-82	EI	FM			X					X	
Oberding (1964) NBS-78 S-83	AT	SI			X		X				X
Sterbentz (1966) NBS-64 S-85	EI	SI	X			X		X			X
Rittenhouse ('65) NBS-62 S-86	TB	SI				X		X		X	
Apisa (1966) NBS-67 S-87	EI	SI				X	X				
Anderson (1966) NBS-42 S-89	EI	SI	X			X	X		X	X	
Glemser (1962) NBS-122 S-84	PR	FM				X		X			
Burkinshaw (1968) NBS-87 S-110	PR	FM				X		X			
NASA Tech. Brief NBS-71 (1966) S-88	PA	CA				X				X	
Caren (1968) NBS-112 S-109	AT	SI		X	X	X					

PUBLICATION	MATERIALS	TECHNIQUES/APPLICATIONS: Shroud Mount	Vapor Cooled, Refrigerated	Continuous Wrap	Blankets, Panels, Shingles	Pumped, Evacuated, Cryopumped	Purged, Gas Filled	Perforations, Pump Channels	INSTALLATION	MISSION & ECONOMIC STUDIES
Nakagawa (1968) NBS-89 S-108	EI	SI			X					
Niendorf (1966) NBS-58 S-113	EI	SI	X			X	X		X		
Clay (1965) NBS-101 S-112	EI	SI		X		X	X			X	
Crawford (1967) NBS-90 S-111	EI	SI				X		X			
Wood (1967) NBS-79 S-114	RV	FM			X			X	X		X
Houd (1966) NBS-57 S-115	RV	FM								X	

PUBLICATION		MATERIALS	TECHNIQUES/APPLICATIONS: Shroud Mount	Vapor Cooled, Refrigerated	Continuous Wrap	Blankets, Panels, Shingles	Pumped, Evacuated, Cryopumped	Purged, Gas Filled	Perforations, Pump Channels	INSTALLATION	MISSION & ECONOMIC STUDIES
Burge (1968) DDC-2 S-116	EI	SI	X			X	X			X	
Connelly (1962) DDC-5 S-117	RV	CA								X	
Dahlin (1961) DDC-8 S-118	TB	CK								X	
Isenberg (1963) DDC-14 S-119	RV	SI					X				
Isenberg (1963) DDC-15 S-120	PR	SI					X	X		X	
McGregor (1967) DDC-21 S-121	AT	N/A					X				
Yuhas (1965) DDC-23 S-122	TB	HC								X	
Hertz (1962) DDC-12 S-123	TB	HC								X	
Marion (1967) NBS-80 S-124	AT	SI			X	X	X	X			X
Higgins (1967) NBS-86 S-125	PR	SI					X	X	X		
Heathman (1968) NBS-114 S-126	TB	FM				X		X		X	
Flynn (1970) TCM-13 S-127	RV	ALL	X	X	X	X	X	X	X	X	X

PUBLICATION	MATERIALS	TECHNIQUES/APPLICATIONS: Shroud Mount	Vapor Cooled, Refrigerated	Continuous Wrap	Blankets, Panels, Shingles	Pumped, Evacuated, Cryopumped	Purged, Gas Filled	Perforations, Pump Channels	INSTALLATION	MISSION & ECONOMIC STUDIES
Coston(1967) NBS-115 S-128	EI	SI				X		X		X	X
Barry (1967) NBS-113 S-129	TB	N/A									X
Allesina (1968) NBS-102 S-130	TB	N/A									X
Vance (1967) NBS 97 S-131	RV	SI		X			X				
Price (1967 DDC 22 S-132	EI	N/A				X	X			X	
Babjack (1967) NBS 83 S-133	PR	SI				X	X	X			X
Berdelman (1965) NASA 15 S-134	AT	FM				X					
Hammond (1966) NBS 43 S-135	TB	HC				X		X			
Orr (1961) NBS 3 S-136	AT	N/A									X
Rogers (1969) NASA 31 S-137	EI	SI				X		X		X	X
Wilkins (1961) NBS 7 S-138	RV	MC		X							
Barry (1966) NASA 10 S-139	TB	SI	X								

PUBLICATION	MATERIALS	TECHNIQUES/APPLICATIONS: Shroud Mount	Vapor Cooled, Refrigerated	Continuous Wrap	Blankets, Panels, Shingles	Pumped, Evacuated, Cryopumped	Purged, Gas Filled	Perforations, Pump Channels	INSTALLATION	MISSION & ECONOMIC STUDIES
Boensch (1968) NASA 1 S-140	PR	CA				X		X			
Cody (1966) NBS 68 S-141	EI	SI				X		X		X	
Collom (1968) NASA 2 S-142	TB	SI				X		X	X	X	
Cochran (1966) NBS 49 S-143	TB	FM				X	X				
Christensen (1959) DDC 4 S-144	AT	SI			X						
Lindquist (1968) NBS 118 S-145	EI	SI				X		X	X	X	
Reed (1965) NBS 40 S-146	AT	SI				X		X			
Romero (1967) NASA 4 S-147	TB	SI			X			X			X
Carstens (1965) NASA 11 S-148	AT	SI		X							X
Coston (1967) NASA 3 S-149	TB	SI				X					
Minges (1963) NBS 14 S-150	RV	MC						X			
Isakson (195) DDC -13 S-1 1	PR	FM									

PUBLICATION	MATERIALS	TECHNIQUES/APPLICATIONS: Shroud Mount	Vapor Cooled, Refrigerated	Continuous Wrap	Blankets, Panels, Shingles	Pumped, Evacuated, Cryopumped	Purged, Gas Filled	Perforations, Pump Channels	INSTALLATION	MISSION & ECONOMIC STUDIE
Johnson (1964) DDC-17 S-152	AT CA						X			
Carr (1967) NASA-21 S-153	EI SI						X	X	X	X
Gosch DDC-25 S-154	TB MC						X			
Hacker (96) NBS-26 S-155	EI FM				X	X				
Heidelberg (1965) NBS-20 S-156	TB FM				X	X				
Dengler (1965) NBS-21 S-157	TB FM				X	X			X	
Perkins (1965) NBS-22 S-158	TB FM				X	X			X	
Perkins (1965) NBS-23 S-159	EI FM				X	X			X	
Calvert (1965) NBS -24 S-160	EI FM				X	X			X	
Esgar (1965) NBS -25 S-161	TB FM				X	X			X	
Evenson (1962) DDC-9 S-162	PR HC				X				X	
NASA (1967) NBS -91 S-163	RV SI									

PUBLICATION	MATERIALS	Shroud Mount	Vapor Cooled, Refrigerated	Continuous Wrap	Blankets, Panels, Shingles	Pumped, Evacuated, Cryopumped	Purged, Gas Filled	Perforations, Pump Channels	INSTALLATION	MISSION & ECONOMIC STUDIES
				TECHNIQUES/APPLICATIONS						
Gilstad (1967) NBS-92 S-164	RV	SI								X
Hyde (1967) NBS-93 S-165	EI	SI				X		X			
Nevins (1967) NASA-24 S-166	EI	SI			X	X	X	X		X	
Yates (1967) NASA-23 S-167	EI	SI			X			X		X	
Stuckey (1967) NBS-94 S-168	EI	SI			X			X		X	
Wood (1967) NBS-95 S-169	RV	SI									
Colaluca NASA-17 S-170	EI	SI			X		X			X	
Leonhard (1967) DDC-19 S-171	EI	SI				X		X	X	X	
Lindquist (1969) NASA-36 S-172	EI	SI			X		X		X	X	
Bullard (1969) NASA-34 S-173	AT	MC								X	
Bullard (1969) NASA-37 S-174	TB	MC								X	
Boeing (1967) DDC-24 S-175	TB	SI			X			X	X		

PUBLICATION	MATERIALS	TECHNIQUES/APPLICATIONS: Shroud Mount	Vapor Cooled, Refrigerated	Continuous Wrap	Blankets, Panels, Shingles	Pumped, Evacuated, Cryopumped	Purged, Gas Filled	Perforations, Pump Channels	INSTALLATION	MISSION & ECONOMIC STUDI
Laser (1964) DDC-20 S-176	PR	SI										
Heathman (1966) DDC-11 S-177	PR	MC				X		X				
Sterbentz (1966) NBS-63 S-178	EI	SI				X		X	X	X		
Bell (1962) DDC-1 S-179	RV	FM										
Crawford (1966) NBS-108 S-180	EI	SI			X	X	X	X	X	X		
Kerlin (1966) NBS-75 S-181	RV	SI										
Bush (1965) NASA-30 S-182	TB	SI			X	X	X	X	X		X	
Carr (1964) NBS-18 S-183	EI	SI				X	X					
Knoll (1968) NASA-18 S-184	TB	SI				X						
Allgeier (1968) NASA-19 S-185	RV	SI										X
Cerquettini (1969) NASA-32 S-186	TB	FM									X	
Knobbout (1969) NASA-35 S-187	PR	FM										

PUBLICATION	MATERIALS	TECHNIQUES/APPLICATIONS: Shroud Mount	Vapor-Cooled, Refrigerated	Continuous Wrap	Blankets, Panels, Shingles	Pumped, Evacuated, Cryopumped	Purged, Gas Filled	Perforations, Pump Channels	INSTALLATION	MISSION & ECONOMIC STUDY
Rotter (1965) NASA-29 S-189	AT	SI					X			X
Lockhead (1964) NBS-56 S-190	EI	SI				X		X	X	X		
Love (1960) NBS-105 S-191	RV	NA										X
Gorham NBS-117 S-192	TB	SI				X		X	X	X		
NASA (1966) NBS-70 S-188	TB	HC										

13.0

ASSESSMENT CATEGORY

13.0 ASSESSMENT CATEGORIES

In the conduct of this program, approximately 440 leads were found in the literature. About 220 of these were of sufficient interest and relevance to warrant acquiring reprints or hard copies. After examining the actual reports themselves, about 192 synopses were prepared. After cataloging was accomplished, it became cost-effective to catalog and abstract the technologies themselves that were apparent from the search and synopses. The result of this condensation is the Assessment Categories that follow.

The effect is to provide an index and abstract of the technological base deemed pertinent and applicable to the intent and scope of this program, in addition to an index and abstract of the literature itself.

13.1 INSULATION TECHNOLOGY CATEGORIES

The first step was to identify the major insulation schemes that had been found in the literature search. After this is done, one then groups all of the articles and reports under that particular technology and prepares a synopsis of that technology as a whole from all of the articles that contribute to it. The insulation technologies identified (Assessment Categories), and treated in this way, are:

1. Cork Insulation, Exterior
2. Honeycomb External Insulation, Evacuated, Purged and Foam Filled.
3. Foam External Insulation-Polyurethane, Styrofoam, Polyvinyl Chloride

4. Continuous Wrapped, Spaced, Evacuated Multiple Reflective Shield External Insulation

5. Multiple Reflective Layer, External Insulation in Discrete Panels or Blankets, Purged or Evacuated

6. Multiple Reflective Layer, Spaced External Insulation Panels on a Purged Fiberglass Substrate

7. Cryopumped Multiple Polyurethane Foam Spaced Reflective Shields in a Shingle Configuration Mounted Externally

8. Purged Multiple Reflective Shields in a Shingle Configuration Mounted Externally

9. Purged Multiple Reflective Shields in Shingle Configuration Mounted on a Purged Fiberglass Substrate External to the Tank

10. Purged External Reflective Layer Insulation in Panels with Special High Flow Spacers

11. Internally Mounted Polyurethane Foam Insulation

12. Helium Purged Micro-Quartz High Temperature Cryogenic Insulation

13. Shroud Mounted Insulation

Within each Assessment Category, fifteen different characteristics or properties were described wherever possible.

They are:

1. Density

2. Effective thermal conductivity

3. Porosity

4. Absorptivity, including any sealing requirements

5. Radiant heat transfer properties

6. Environmental compatibility, including fluid compatibility and susceptibility to ground-hold, boost, and spaceflight environments.

7. Mechanical properties, including any support requirements.

8. Useful life

9. Bonding methods, including any problems associated with bonding

10. Forming methods, including any problems associated with forming.

11. Reusability

12. Ground hold requirements

13. Approximate cost

14. Availability, e.g. major manufacturers

15. Notes: any other property or information considered necessary and/or helpful in assessing possible uses of an external insulation scheme.

The purpose of this Section is to pull together all of the information available in the Synopses for the purposes of assessing the information, enabling pattern recognition, and providing a systematic basis for choosing one scheme over another.

ASSESSMENT CATEGORY

CORK INSULATION, EXTERIOR

REFERENCES

TCM-6 S-98	TCM-11 S-103	NBS-1 S-34	NBS-8 S-39
NBS-33 S-51	NBS-76 S-69	DDC-8 S-118	

DENSITY:

6 to 20 lbs/ft^3

Cork can be made to any density in this range by compression in manufacture. 6lb/ft^3 is usually used.

K EFF

Density of 6 lbs/ft^3

T, $^\circ$F	K, B/hr ft$^\circ$R
100	0.0121
-100	0.107
-300	0.0125

POROSITY:

No data available

SEALING AND ABSORPTIVITY:

Spray surface with Adiperene L315 polyurethane 5 to 10 mil. thick. Bond "Zero-Perm" laminated bag to cork using Dupont 46971 to attach. Tape joints with pressure sensitive tape.

RADIANT PROPERTIES:

Optically thick.

ENVIRONMENTAL COMPATIBILITY

Resists ablation; can withstand 850°F if varnish coated.

MECH. PROPS. AND SUPPORT REQUIREMENTS:

Tensile strength

Armstrong: 16 psi at room temperature.

	Sheller TB 955: 30 psi.
	Strength increases approximately 6x at hydrogen temperatures.
LIFE:	Absorbs 10% of its weight in water in 4 days at 150° F and 100% humidity.
BONDING:	Cork to cork, Narmco 7344
	Cork to "Zero-Perm" film, Vac Seal Type 1912
	Cork to aluminum, Epon 820 impregnated with 181 fiberglass layer.
	Mylar to Mylar for seal, use DuPont 46971
FORMING:	Pliable and can be hot molded.
REUSABILITY:	May withstand re-entry but would need refurbishing if not protected.
GROUND HOLD REQUIREMENTS:	May need purge equipment to keep water vapor out of the material and to limit air cryopumping.
APPROX. COST:	Probably the least expensive insulating material and easiest to install.
AVAILABILITY & MANUFACTURER:	Armstrong and Sheller manufacture cork. See AC-40 for a listing of manufacturers and addresses where they are available.

ASSESSMENT CATEGORY

HONEYCOMB EXTERNAL INSULATION, EVACUATED, PURGED, AND FOAM FILLED

REFERENCES:

NBS-1 S-34	NBS-16 S-45	NBS-28 S-91	NBS-30 S-48
NBS-76 S-69	NBS-96 S-73	NBS-104 S-77	NBS-107 S-78
NBS-70 S-188	NBS-59 S-9		

DENSITY: Core, 2.2 lbs/ft^3; foam 2 to 4 lbs/ft^3; overall, about 2 to 3lbs/ft^3.

K EFF:

Fill	B/hr ft^oR	T, ^oF
Freon	0.013	-200
Air	0.0375	-200
Vacuum	0.0092	-280
Vacuum alone	0.01	-250
Helium	K of Helium	--
1/2 Vacuum and 1/2 foam	0.0092	-180

POROSITY: 10^{-10} cc He/cc material/CmHg pres./Sec for typical barriers. For typical sealants, air penetrates closed foam urethane.

SEALING AND ABSORPTIVITY: 1 mil Mylar, Saran, Nylon Phenolic-Tedlar laminate, aluminum foil, use Mylar at cold wall only. Vacuum breaks in a few hours when helium present at room temperature for all materials.

RADIANT PROPERTIES: Foam is optically "thick"; radiation conductivity at T -100 F is:

$$K = \frac{4\sigma\ Tm^3\delta}{\phi} = 0.0015\ B/hr\ ft^{\circ}R$$

ENVIRONMENTAL CAPABILITY: 0.0015-inch aluminum foil outer surface will protect for launch loads. 3-ply glass cloth cured in epoxy resin core or outer layer degrades at about 850°F.

MECH. PROPS. AND SUPPORT REQUIREMENTS: Polyurethane foam loses strength at low temperatures. Phenolic fiberglass core has a tensile strength of 940 psi at room temperature and 600 psi at hydrogen temperatures. Shear strength is about 80% of the tensile strength. Thermal expansion coefficient is about 5 x that of aluminum.

LIFE: Foam-filled degrades 4% in 50 hours due to hydrogen permeability, if exposed to hydrogen gas.

BONDING: Epon 820 filled with glass cloth to match thermal expansion of aluminum; or Bloomingdale Rubber Co. HT-424 for bonding core. Epon 820, aluminum to aluminum bond tensile strength is 6,200 psi for air blasted surfaces.

FORMING: Foam filled after honeycomb applied.

REUSABILITY: May develop leaks upon thermal cycling. Must be covered by other material for re-entry.

GROUND HOLD REQUIREMENTS: Vacuum or purging required. Needs ground equipment to maintain vacuum or He gas purge supply. Ports of manifolds will have to be disconnected and sealed before launch. Some honeycombs are permanently sealed with either vacuum or gas in them; these are very susceptable to damage. Air and moisture must be omitted.

APPROX. COST: Somewhat more expensive than cork or foam.

AVAILABILITY & MANUFACTURER: Hexcel Corporation manufactures honeycon'b. See AC-40 for a listing of manufacturers and addresses where they are available.
May use vacuum foam filled layer near tank and Helium filled foam over-layer to insure no cryopumping of air. Very sensitive system with respect to air cryopumping and explosion hazards.

ASSESSMENT CATEGORY

FOAM EXTERNAL INSULATION

POLYURETHANE, STYROFOAM, POLYVINYL CHLORIDE

REFERENCES:

NBS-11 S-142	NBS-14 S-150	NBS-20 S-156	NBS-21 S-157
NBS-22 S-158	NBS-23 S-159	NBS-24 S-160	NBS-25 S-161
NBS-26 S-155	NBS-28 S-91	NBS-33 S-51	NBS-43 S-135
NBS-45 S-58	NBS-48 S-60	NBS-49 S-143	NBS-52 S-63
NBS-76 S-69	NBS-86 S-125	NBS-99 S-75	NBS-104 S-77
NBS-110 S-5	NBS-121 S-80	NBS-15 S-134	NBS-32 S-186
NASA-35 S-187	DDC-5 S-117	DDC-9 S-162	DDC-12 S-123
DDC-13 S-151	DDC-14 S-119	DDC-15 S-120	TCM-2 S-94
TCM-3 S-95	TCM-4 S-96	TCM-5 S-97	

DENSITY: Minimum foam density of 2 lb/ft^3 gives the best properties. It may be made heavier. All data below is for 2 lb/ft^3.

K EFF: Freon filled foams, values in BTU/ft.hr.R for room temperature to liquid hydrogen temperatures.

Polyurethane: 0.008 to 0.012 for compressive pressures from 0 to 15 psig, calorimeter values degrade 10% in tank mounting.

Styrofoam: 0.023, addition of aluminum powder reduces K by 15%

Polyvinyl Chloride: 0.015

POROSITY: All foams: permeability 0.36 cc Air/cc hr ATM

SEALING AND ABSORPTIVITY: All foams:

Air or warm sealing: sandwich of 0.0005 inch Mylar -0.0005 aluminum foil -0.0005 Mylar has no measurable permeability.
Cold seal for LN_2 or LH_2 temperature: type 181 fiberglass cloth impregnated with 70% by weigh epoxy resin and coated with 6 coats of polyurethane resin.
Room temperature moisture and fungus barrier: Chemseal Corp. polyurethane resin.
For sprayed on polyurethane, locations where the operation is stopped and restarted must be coated with Narmco 7343 adhesive.
Polyvinyl Chloride outgasses excessively.

RADIATION PROPERTIES: Foam is optically "thick"; radiation conductivity at T = -100 is:

$$K = \frac{4\sigma T^3 m \delta}{\Phi} = 0.0015 \text{ B/hr ft R}$$

ENVIRONMENTAL CAPABILITY: All foams:—
The Mylar-aluminum-Mylar sealing layer will survive 392F in a vacuum. For launch environment: A covering of style 106 fiberglass impregnated with Dow Corning Silicone A-4000 and wound with epoxy impregnated S/HTS fiberglass roving withstand 615F at Mach 2 and a dynamic pressure of 952 lb/ft^2.

MECH. PROPS. AND SUPPORT REQUIREMENTS: Supported as described in bonding and environmental capability.

Thermal contraction for all foams from room to liquid hydrogen temperature:

7.7×10^{-3} in/in.

Polyurethane at liquid hydrogen temperature
ultimate tensile strength 160 lb/in^2
ultimate compressive strength 160 lb/in^2

Polyvinyl Chloride at room temperature:
ultimate tensile strength 60lb/in^2
ultimate compressive strength 90 lb/in^2

LIFE:

All Foams:
For raw foam, air displaces 50% of the freon filling in 10,000 hours of shelf life. Raw foam degrades in performance 50% in 50 hours, when exposed to cold hydrogen gas. Foam with sealing layers has shown no thermal degradation in ground hold tests run 3-4 days appart.

BONDING:

Polyurethane:
Foam to aluminum:
Use either full area bonding or a grid of bond lines. Clean aluminum with toluene followed by methylethyl ketone.
Use Vitel PE207 primer, (Goodyear tire and Rubber).

EPON 828 - Versamid 125 in fiberglass mat (Shell Chemical Co. - General Mills) with room temperature cure.

Lefkoweld 109 (Leflingwell Chemical Co.) with room temperature cure.

FM-1000 (Bloomingdale Rubber Co.) with high temperature cure (250F)

Bond mylar -aluminum - mylar sealing jacket to foam with Vitel PE207 primer.

For spraying on aluminum use
Pittsburg Plate Glass Co. M602
epoxy-phenolic primer cured at 290F,

then apply air drying Furane Plastic's primer M

Polyvinyl Chloride:
Bond to aluminum with polyurethane adhesives

FORMING:

No information is available for styrofoam.
May be blown with freon 11 or $C0_2$.
Some low speed machining is possible.
May be molded during its manufacture.
Can be sprayed on.
The mylar-aluminum-mylar seal layer is vacuum formed to compound curve shapes.

REUSABILITY:

Only polyurethane foam data is available.
The foam bonded by the above methods and sealed with mylar-aluminum-mylar and an external fiberglass support survived 20 cooldowns to LH_2 temperature and 20 tank pressurizations to 90.0 lb/in^2. In ground hold tests 34 days appart, some cracking was noted but no significant thermal degradation occurred. Sprayed foam has been flown on the Saturn V.

It is doubtfull that this material can survive re-entry without additional protection.

GROUND HOLD REQUIREMENTS:

There appears to be no special requirements except that it is susceptable to mechanical damage.

COST:

Relatively inexpensive compared to superinsulation but more expensive than cork.

AVAILABILITY & MANUFACTURE:

Polyvinyl Chloride: Klegcell-G-300
Polyurethane: Reichold 8625-8605
(Reichold Chemical Co.)
NOPCO Chemical Co. B-250A
Manufactures addresses are given on AC-40 where available.

NOTES:

Damage to polyurethane sealing surfaces may create an explosion hazard due to air cryopumping and oxygen fractionization. This hazard has been studied and is classified as moderate, (i.e. about 1/4 of the samples tested resulted in a reaction but this takes the combined presence of a large leak and a rather strong impact.)
Gamma irradiation of 3×10^{10} ergs/gm(c) does not thermally degrade polyurethane foam.

ASSESSMENT CATEGORY

CONTINUOUS WRAPPED, SPACED, EVACUATED, MULTIPLE REFLECTIVE SHIELD EXTERNAL INSULATION

REFERENCES:

NBS-6 S-38	NBS-9 S-40	NBS-13 S-43	NBS-17 S-46
NBS-31 S-49	NBS-38 S-90	NBS-41 S-57	NBS-50 S-61
NBS-53 S-64	NBS-54 S-66	NBS-65 S-1	NBS-66 S-4
NBS-74 S-3	NBS-77 S-70	NBS-80 S-124	NBS-89 S-108
NBS-94 S-168	NBS-99 S-75	NBS-100 S-7	NBS-119 S-2
NBS-126 S-81	NASA-17 S-170	NASA-23 S-167	NASA-24 S-166
NASA-30 S-182	NASA-36 S-172	DDC-7 S-104	

DENSITY: Dexiglass spaced Linde SI-62 weighs 4.21 lb/ft^3 (Aluminum foil shields)

KEFF: Linde SI-62: cylinder wrapped and interleaved with discs covering heads and evacuated:

K = 7 to 10 X 10^{-4} B/hr ft° R with external atmospheric pressure

K = 4 to 9 X 10^{-5} B/hr ft° R with 10^{-3} or less ATM external pressure

POROSITY: Vacuum jacket permeability:

1 mil Mylar-0.8 mil lead-1 mil Mylar - 5 X 10^{-10} ft^3/ft^2 ATM

Mylar - aluminum foil - aluminum foil - Mylar (1 mil each) - 10×10^{-9} ft^3/ft^2 ATM

50 layers of Aluminized Mylar - 2.0×10^{-7} ft^3/ft^2 ATM
136 layers of Aluminized Mylar - 9.72×10^{-10} ft^3/ft^2 ATM

Diffusion coefficient parallel to layers, layer density had no effect.

dexiglass spaced aluminized Mylar - 0.3 ft^2/sec
dexiglass spaced aluminum foil - 1.38 ft^2/sec
unspaced crinkled aluminized Mylar - 3.73 ft^2/sec

Approximately 50 hour pump down after 200°F. helium preconditioning

SEALING AND ABSORPTIVITY:

Two types of vacuum seal have been used successfully.

Dobeckman Metalam PZ 5526 0.5 mil Mylar - 0.35 mil aluminum foil - 0.35 mil aluminum foil - 0.5 mil Mylar supported by two-way stretch nylon net. This material can withstand 200°C. in a vacuum without appreciable degradation.

1 mil Mylar - 0.8 mil lead - 1 mil Mylar vacuum formed with Schjeldahl GT-200 adhesive sealed joints.

Linde SI-62 needs several pump out ports and a 300°F., 30 hour preconditioning and a 200°F. pump down bake. Molecular sieve getter is also recommended.

RADIANT PROPERTIES:

Aluminum foil emissivity - 0.025
Dexiglass paper assumed transparent.

ENVIRONMENTAL CAPABILITY:

Tension band and wrapped insulation scheme can survive launch mechanical loads.

Aluminum foil degrades when subjected to direct sound field of 150 db.

Micrometerite shield of polyurethane adhesive impregnated 15 mil 181 fiberglass overlayer with 2 inches of insulation

can stop average particles. This material can withstand 450°F.

MECH. PROPS. AND SUPPORT REQUIREMENTS: Use aluminum foil tension bands bonded to the tank, wrapped within the layered insulation, and bonded to the insulation outer surface provides layer density control and support for inertial launch loads.

110 layer per inch insulation returns to 72% of its installed height after being exposed to 1 atmospheric external load and then exposed to a vacuum.

LIFE: Must be instalied permanently and must be evacuated because it can not be exposed to excessive air and moisture. No other information is available.

BONDING: For Mylar-Lead-Mylar vacuum seal; use Schjeldahl GT-200 adhesive and heat sealing for joints. Small vacuum leaks can be repaired with Armstrong A-12 adhesive. Mylar-Aluminum foil-Aluminum foil-Mylar bags can be sealed with Goodyear G-207 adhesive and Dobeckman 32899 tape. No other details available.

FORMING: Continuously wrapped (both spacer and shields) on cylindrical sections along with the aluminum foil tension strap supports. Tank heads are insulated with interleaved and taped discs. Penetration cut-outs must be made on each revolution. Vacuum barrier is vacuum formed and bonded together. Rigid metal transitions from penetrations to the vacuum jacket are bonded on using Dupont Adiprene L-100 adhesive, (for Mylar-lead-Mylar). Perforations in the Mylar are required to achieve reasonable pump down time. Penetrations should be insulated from the insulation by material with a conductivity less than 0.008 B/hrft°R.

REUSABILITY: Should be capable of a number of cool down cycles if the vacuum bag is not damaged. It probably can not withstand direct aerodynamic heating and loads for either launch or reentry.

GROUND HOLD REQUIREMENTS: Generally needs 200°F. helium purge after installed to permit pump down. It requires 50 hours of pumping to reach 100 microns internal pressure. Unless leaks can be entirely eliminated, continuous pumping will be required.

COST: One of the most expensive systems covered in this report. Vacuum maintainence and protuberance installation difficulties make this more expensive than the continuous wrap concept would suggest.

AVAILABILITY & MANUFACTURER: LINDE (UNION CARBIDE), see AC-40 for a listing of manufacturers addresses were available.

NOTES: Mylar burns freely but Kapton does not; therefore Kapton (heaver) might replace the outer Mylar layers. Also aluminized Mylar degrades when sterilized with wet ethylene oxide (1967). Gold coating was not affected by sterilization.

Pre-evacuated systems are not recommended for tanks with diameters greater than 105 inches because of leakage and handling problems.

The aluminum foil used here suffers mechanical damage when exposed directly to 150 db. acoustic noise.

A number of other spacer materials have been investigated in the laboratory.

ASSESSMENT CATEGORY

MULTIPLE REFLECTIVE LAYER, ENTERNAL INSULATION IN DISCRETE PANELS OR BLANKETS, PURGED OR EVACUATED

REFERENCES:

NBS-12 S-107	NBS-42 S-89	NBS-50 S-61	NBS-56 S-190
NBS-57 S-115	NBS-63 S-178	NBS-67 S-87	NBS-80 S-124
NBS-83 S-133	NBS-84 S-12	NBS-90 S-111	NBS-94 S-168
NBS-101 S-112	NBS-112 S-109	NASA-16 S-107	NASA-24 S-166
NASA-30 S-182	NASA-31 S-137	DDC-2 S-116	DDC-22 S-132
SIE-9 S-25			

DENSITY:

SI-62 Linde dexiglass spaced aluminum foil - 4.2 lb/ft^3
30 mil polyurethane foam spaced aluminized Mylar 2 lb/ft^3
NRC (National Research Co.) 1/4 mil aluminized (400Å)
Mylar weighs 30% of same vacuum performance Linde insulation

KEFF:

Tape joined foam spaced aluminized Mylar He purged ground hold .045 B/hr ft°R
evacuated - 6 X 10^{-5} B/hr ft°R

Linde SI-62 interleaved blankets with thread and button supports and evacuated with no external load - 9 X 10^{-5} B/hr ft°R, 10^{-3} B/hr ft°R for ground hold. Nylon net spacers provide slightly lower conductivity.

NRC-2, 40 layer interleaved blankets, evacuated (5 X 10^{-5} torr) -4 X 10^{-5} B/hr ft°R
Ground hold, He purged - He conductivity (about .045 B/hr ft°R)
Ideal conductivity - 2 X 10^{-5} B/hr ft°R
rolled and taped joints 0.0225 B/hr ft°R length
rolled and snaped joint degrades 30% of a square foot heat leak per foot of length
nylon stud supports contribute [illegible] ft^2

POROSITY: See continuous wrapped multiple shield assessment table.

SEALING AND ABSORPTIVITY: NRC requires 0.5% perforations to pump to 10^{-4} torr in 4 hours due to outgassing. 24 hour 225°F. helium purge is recommended. Vacuum formed 5 mil Mylar, Alcar and impregnated fiberglass have been used for a purge bag successfully for NRC or the foam spaced aluminized Mylar.

See continuous multiple shield assessment table for spaced insulation vacuum jacket requirements

Aluminum laminates have been fusion welded into vacuum tight joints

RADIANT PROPERTIES: Emissivities:

Aluminum foil - 0.025
Aluminumized Mylar - 0.025 to 0.047
Silver Mylar - 0.011 to 0.017
Gold Mylar - 0.017

ENVIRONMENTAL CAPABILITY: Button and thread sewn blankets and bonded foam blankets attached with Velcro fastiners and stud mounted NRC both withstand inertial launch loads. All the blanket designs will probably need aerodynamic protection for launch and reentry environments. Micrometeorite protection is probably required.

MECH. PROPS. AND SUPPORT REQUIREMENTS: Evacuated, dexiglass spaced (Linde) insulation takes 2 hours to recover 80% of its installed height after removing the external atmospheric load.

NRC insulation may be mounted on nylon studs in an adhesive reinforced "spot" at an upper point of the tank. The lower parts of the blankets are held in a nylon net attachted to studs.

Also, Velcro fasteners sewn to the insulation and bonded to the tank with NARMC07343 adhesive are used with each of the insulations.

The NRC and Linde also have been clamped to a nylon rope netting to support it.

One sheme encloses the material in a plastic bag which has a metalic clamp at the top which is used as a hanger.

LIFE: Readily removable for repair. Purge bags for NRC and foam spaced are not as easily damaged as a vacuum jacket. In a dry atmosphere there is no degradation with time. NRC has successfully endured a 1 year shelf life without special precautions.

BONDING: Velcro fasteners and nylon studs bonded to aluminum with NARCO7343 adhesive. For vacuum bag joints, see continuous multiple shield assessment table. No details were given for purge bags.

FORMING: Generally, panels are filled, cut, and interleaved in bunches of 10 insulation layers. Individual layer interleaving is possible but requires more installation effort without appreciable performance gains.

NRC type insulation, which can be folded easily, has been joined by rolling two blankets together and securing with tape or snaps.

Penetrations can be precut. Vacuum insulations use bonded preformed metal seals at penetrations. Purged insulations use vacuum formed bonded Mylar at penetrations.

Penetrations should be insulated from the multilayer insulation by material with a conductivity less than 0.008 B/hr ft^{o}R.

Perforations in 90 layers of NRC aluminized Mylar may be made with a sharpened stainless steel tube rotated at 550 rpm.

REUSABILITY: Should be capable of a number of cool down cycles provided the vacuum bag or purge bag is not damaged. Purge bags are much more reliable than vacuum bags. Some additional aerodynamic environmental protection will be required for launch and reentry.

GROUND HOLD REQUIREMENTS: Generally a 250° F. helium purge is required after installation to limit outgassing. Approximately 10 system volumes of helium are required to reduce air and moisture to an acceptable level. After the initial purge, either vacuum (Linde) or room temperature purge (NRC and Foam spaced) must be maintained until launch to provide ground hold performance and minimize air and water adsorption.

APPROXIMATE COST: The blanket system should be cheaper than the continous wrap superinsulation. Blankets and shingles should be competitive pricewise but more expensive than fiberglass, foam, and honeycomb.

AVAILABILITY & MANUFACTURERS: LINDE (UNION CARBIDE CO.) makes the dexiglas spaced material. National Research Co. make the unspaced NRC material. See AC-40 for the manufacturer's addresses, where available.

NOTES: Blankets provide a ready means for demounting insulation for tank and/or insulation repair. See also, the notes given in the continuous wrapped multiple shield assessment table.

Crinkling the Mylar on the spaced configurations may reduce the conductivity by a factor of three.

Aluminized Mylar burns and is suseptable to degradation when exposed to water and/or decontamination procedures.

ASSESSMENT CATEGORY

MULTIPLE REFLECTIVE LAYER, SPACED, EXTERNAL INSULATION PANELS ON A PURGED FIBERGLASS SUBSTRATE

Note: (Linde dexiglass spaced aluminum foil is the basic space insulation, its detail blanket properties may be found in the blanket assessment table.)

REFERENCES:	NBS-36 S-54	NBS-56, S-190	NBS-62 S-86	NBS-63 S-178
	NBS-64 S-85	NBS-84 S-12	NBS-99 S-75	NBS-115 S-128

DENSITY: Not available: 0.4 inch fiberglass (about 0.5 lb/ft^3) plus 36 layers of dexiglass spaced aluminum foil.

KEFF: 5.2×10^{-5} B/hr ft$^\circ$R (1.5 times predicted) in evacuated state. Less than helium conductivity (.045 B/hr ft$^\circ$R) for ground hold.

POROSITY: Not available

SEALING AND ABSORPTIVITY: Use a heat sealed Alcor purge bag on the fiberglass substrate. Approximately 5 volumes of helium purge are required to achieve an equilibrium (low) air concentration. No purge or vacuum is used on the multilayer insulation.

RADIANT PROPERTIES: See multiple layer blanket assessment table.

ENVIRONMENTAL CAPABILITY: See multiple layer blanket assessment table.

MECH. PROPS. AND SUPPORT REQUIREMENT: Bond fiberglass to tank Fasten superinsulation blankets to substrate purge bag with Velcro fasteners.

LIFE:	The superinsulation is not protected by a bag so it is susceptable to mechanical damage. On the other hand, the purge bag is protected by replaceable multilayer blankets. Shelf life does not appear limited.
BONDING:	Bond fiberglass to tank using Lefkoweld 109/LM152 epoxy. Bond Velcro fasteners to Alcor purge bag and insulation with NARMCO7343/7193.
FORMING:	Preassemble insulation blankets by quilting with nylon thread with button retainers. Bond to Velcro fasteners under heavily stitched areas.
REUSABILITY:	Should survive numberous cool downs but will require aerodynamic environmental protection for launch and reentry.
GROUND HOLD REQUIREMENTS:	The sublayer of fiberglasss must be purged. This system not as prone to damage as the other superinsulations since no outer purge or vacuum bag is required. It must be protected from excessive amounts of moisture due to adsorption characteristics.
APPROXIMATE COST:	About the same as the plain purged multilayer blankets. Greater than foam, cork and honeycomb.
AVAILABILITY & MANUFACTURER:	LINDE (UNION CARBIDE) make this superinsulation. See AC-40for manufacturer's addresses where available.
NOTES:	This insulation provides a compromise between ground hold insulations (cork, foam, etc.) and the purged or evacuated superinsulations.

ASSESSMENT CATEGORY

CRYOPUMPED MULTIPLE POLYURETHANE FOAM SPACED

REFLECTIVE SHIELDS IN A SHINGLE CONFIGURATION MOUNTED ENTERNALLY

REFERENCES:

NBS-32 S-50	NBS-41 S-57	NBS-58 S-113	NBS-60 S-67
NBS-73 S-14	NBS-84 S-12	NBS-85 S-6	NBS-93 S-165
NBS-98 S-74	NBS-112 S-109	NBS-118 S-145	NBS-120 S-92
NASA-23 S-167			

DENSITY: CO_2 filled foam spacer is 0.02 inches in thickness and weighs 2 lb/ft^3. 18 layers of double aluminized Mylar and spacer with jacket and mounts weighs 0.34 lb/ft^2.

KEFF: Evacuated shingle conductivity; (calorimeter data)

Length, inches	K B/hr ft^oR
8	32×10^{-5}
12	12×10^{-5}
20	10×10^{-5}
28	7.5×10^{-5}

28 inch long installed shingles in a vacuum - 1.49×10^{-4} B/hr ft^oR.

28 inch long installed shingles under atmospheric load 2.24×10^{-3} B/hr ft^oR

28 inch long installed shingles with mechanical evacuation instead of cryopumping with no load - 2.51×10^{-5} B/hr ft^oR

May improve conductivity by providing small lateral gaps in the aluminized surface to minimize conduction along the shingle (patent).

POROSITY:

Permeability of sealing materials at room temperature under 1 atmosphere load, cc He/sec ft^2

Mylar-Aluminum foil - Aluminum foil-Mylar laminate (1 mil each) - 4×10^{-8}

Mylar-Lead foil-Mylar laminate - 2×10^{-9}

Aluminized Mylar - 5×10^{-6}

SEALING AND ABSORPTIVITY:

Seal with 4 ply aluminized Mylar bonded with NARMCO7343/7139 adhesive or Mylar-Aluminum foil-Aluminum foil-Mylar bonded with Johns Manville Co. BFF pressure sensitive tape. Also, may use Mylar-Lead-Mylar. For low temperature side aluminized Mylar is sufficient.

Recommend Mylar be preconditioned at 200°F. for 24 hours to decrease outgassing.

Outgassing rates in vacuum at room temperature, (H_2O, N_2, CO), microliter/sec ft^2

Polyurethane open foam 0.1

Aluminized Mylar 2.5

Water vapor comes off at 10^{-3} mm Hg.

Recommend 0.5 grams of Union Carbide palladium oxide getter in each shingle.

Vacuum seal may be on individual shingles for ease in installation and handling or an overall bag may be used. Individual bags are sealed with pressure sensitive tape between shingles.

RADIANT PROPERTIES:

Emissivity:

Double aluminized Mylar - 0.03 at room temperature
0.018 at LN_2 temperature

Thin foam appears to be transparent.

ENVIRONMENTAL CAPABILITIES:

Positive support for launch acceleration loads but probably

needs protective cover for other launch environmental conditions, (heat, air loads). Thermal shock, rapid depressurization, vibration, acceleration and accoustic loads do not damage the system. Aluminum foil degrades when directly exposed to 150 db. noise levels. It must maintain an air tight seal for ground hold. It probably requires micrometeorite protection for long missions.

MECH. PROPS. AND SUPPORT REQUIREMENTS: Bond complete shingles to aluminum tank at one end. Or attach with studs at one end using an adhesive reinforced patch.

Compressive strength of the shingle is 22 lb/ft^2

LIFE: Four layers of aluminized Mylar bonded sealer permits 30 day storage without thermal degradation.

Local tank leaks result in localized degradation only. Moisture delaminates aluminum from the Mylar so it must be kept dry.

BONDING: Bond various aluminized Mylar and aluminum foil-Mylar laminates together using NARMCO7343/7139 adhesive.

For bonding to aluminum, air blast the surface and apply Goodyear G-207 primer followed by NARMCO7343/7139 adhesive.

FORMING: For compound corners: cut, fold and tape the shingles. Vacuum forming is used on the vacuum seal. May be prebuilt and penetration accommodations made before time of installation.

REUSABILITY: Should be capable of many cool down cycles as long as outer vacuum jacket is not damaged. This insulation will require thermal and mechanical protection for reentry and maybe for launch.

GROUND HOLD REQUIREMENTS: Must ensure that no vacuum leaks are made by damaging. Requires 3 hours of cryopumping to achieve 5×10^{-3} torr. 40 hours are required to reach maximum vacuum performance. This requires a long tankage precooling period. One layer of perforated honeycomb in each shingle can reduce the cryopumping time to about 3 hours.

APPROXIMATE COST:

Prefabrication and easy installation provide a cost advantage over the butt joint panels or continuous wrap super-insulations especially were penetrations are required. Maintainence of the vacuum barrier may be expensive. Definitely more expensive than foams, honeycombs and cork.

AVAILABILITY & MANUFACTURER:

Insulation material manufacturer not given. Other material manufacturer's addresses are given on AC-40 where available.

NOTES:

Vacuum bag is hard to maintain. Individual shingle bags proved to be easier to work with than an overall bag. Creases tend to produce vacuum leaks.

CO_2 fill has a vapor pressure of 10^{-8} torr at liquid nitrogen temperatures.

NOTE: Typical decontamination procedures (1967) result in the loss of aluminum from the Mylar film. Gold is not so susceptable.

Water vapor also delaminates the aluminum from Mylar.

Shingles provide relatively unrestricted pumpout or cryopumping paths.

Mylar burns freely.

ASSESSMENT CATEGORY

PURGED MULTIPLE REFLECTIVE SHIELDS IN A

SHINGLE CONFIGURATION MOUNTED EXTERNALLY

REFERENCES: (see Cryopumped shingles) plus:

NBS-56	NBS-68	NBS-93	NBS-118
S-190	S-141	S-165	S-145

DENSITY: 48 layers of aluminized Mylar weigh 0.168 lb/ft^2

KEFF: Conductivity to LN_2 temperature is a function of the He purge gas pressure inside. It varies from approximate helium conductivity (.045 B/hr ft^oR) to 3.5×10^{-5} B/hr ft^oR in a vacuum.

POROSITY: See purged continuous blanket assessment category.

SEALING & ABSORPTIVITY: Use an open weave fabric for the purge jacket. 5 mil vacuum formed purge jacket is also satisfactory.

54 inch long layups require 60 sec to pumpdown without a purge bag cover. Actual tank installation requires 5 hours to pump to 10^{-5} torr through pump out ports which must be opened to space. A pressure difference of 2 orders of magnitude may exist in the shingle during evacuation. See the cryopumped shingles assessment table for outgassing information. Diffusion coefficient for free molecular flow pumpout is 4.43 ft^o/sec.

A 24 hour 250°F. helium purge should be used to reduce outgassing.

RADIANT PROPERTIES: Emissivity.

Single aluminized Mylar, aluminum side - 0.03 at room temperature.

0.018 at LN_2 temperature

No information available for Mylar side.

ENVIRONMENTAL CAPABILITIES:	See cryopumped shingle assessment table except that helium purging during ground hold eliminates the air leakage problem.
MECH. PROPS. AND SUPPORT REQUIREMENTS:	Bond the 48 layers of each shingle together at one end on 19 inch centers with thermoplastic adhesive. Punch small holes in the bonded areas for aluminum mounting pins and secure with plastic retaining washers. Bond aluminum pins to an aluminum tank using NARMCO7343 adhesive.
LIFE:	Local tank leaks only degrade the material locally. Must be kept dry as moisture delaminates aluminum from the Mylar.
BONDING:	See cryopumped shingle assessment table.
FORMING:	See cryopumped shingle assessment table.
REUSABILITY:	See cryopumped shingle assessment table.
GROUND HOLD REQUIREMENTS:	A 24 hour 250°F. helium purge is required after installtion to minimize absorbed gases which would outgas in space. A continuous helium purge is required to minimize air and water absorption. At launch, the purge ports must be sealed. After a vacuum environment is achieved, the pump out ports must be opened.
APPROXIMATE COST:	This should be cheaper than cryopumped shingles because the purge bag is not nearly as susceptable to significant damage as the vacuum barrier. Leakage should be easier to detect with a purge bag also. Its installation is easier than continuous or blanket superinsulations because protrusions can be accommodated before installation. It will be more expensive to manufacture than foam, honeycomb or cork.
AVAILABILITY & MANUFACTURER:	National Research Corp. makes the aluminized Mylar. See AC-40 for the addresses of the various manufacturers.

NOTES:

The vacuum bag has a considerable reliability and handling advantage over vacuum bags but requires an active vent port for space evacuation.

As in the cryopumped case, the aluminized Mylar degrades when subjected to sterlizing procedures (1967) and/or water vapor.

Shingles provide relatively unrestricted pumpout or cryopumping passages.

Mylar burns freely.

ASSESSMENT CATEGORY

PURGED MULTIPLE REFLECTIVE SHIELDS IN SHINGLE CONFIGURATION MOUNTED ON A PURGED FIBERGLASS SUBSTRATE EXTERNAL TO THE TANK

REFERENCES: (See cryopumped shingles) plus:

NBS-50 NBS-63 NBS-64
S-61 S-178 S-85

DENSITY: Fiberglass substrate 1.5 inches thick weighs 0.5 lb/ft^3 and the single aluminized Mylar shingles weigh 1.1 lb/ft^3 for 40 layers/inch.

KEFF: For liquid hydrogen temperatures and vacuum surroundings:

Shingles - 12×10^{-5} (1.4×10^{-5} theoretically)

Substrate - 32×10^{-5}

In the ground hold condition N_2 and He gas conductivities apply, respectively.

POROSITY: Not given

SEALING & ABSORPTIVITY: Inner fiberglass insulation is purged with helium and sealed with Mylar or a Mylar-Dacron-Mylar laminate. The outer nitrogen purged multilayer is sealed with an Aclar bag.

The diffusion coefficient parallel to the aluminized Mylar layers was 4.43 ft^2/sec for free molecular flow pumpout conditions.

RADIANT PROPERTIES: See purged multilayer shingle assessment table.

ENVIRONMENTAL CAPABILITIES: See cryopumped shingle assessment table except both the

	insulation regions are purged for ground hold, eliminating the air leakage problem.
MECH. PROPS. AND SUPPORT REQUIREMENTS:	Bond aluminized Mylar shingles to substrate purge bag. Stitch purge bag and fiberglass substrate to Velcro fasteners which mate with others bonded to the tank. No mechanical properties were given.
LIFE:	No information available but should be reasonably long since absorbed gases can be purged before launch.
BONDING:	No information given but see cryopumped single assessment table for general methods. Fiberglass may be bonded to aluminum with Lefkoweld 109/LM52 epoxy.
FORMING:	Interleave and overlap gore shaped shingles at tank poles.
REUSABILITY:	Probably can not withstand reentry loads and may need launch thermal and pressure protection. Can withstand vibration, acceleration, pumpdown and acoustics. Purge bags are less likely to be damaged than vacuum bags.
GROUND HOLD REQUIREMENTS:	Needs a helium purge for the fiberglass substrate and nitrogen purge for the multilayer shingles. The helium eliminates nitrogen condensation while the nitrogen eliminates oxygen and water penetration.
APPROXIMATE COST:	Shares advantages of other shingle insulations except two purge bags must be used and maintained. Probably costs a little more than the purged shingle insulation and about the same as the cryopumped shingles.
AVAILABILITY & MANUFACTURER:	National Research Corp. makes the alaminized Mylar. See AC-40 for the addresses of the various manufacturers.
NOTES:	As with the other aluminized Mylar insulations, this will degrade under typical sterilization methods and exposure to moisure.

Maintainence of two purge bags might be eliminated if a coating could be applied to protect the aluminum from moisture. This would simplify the system considerably.

Mylar burns freely.

ASSESSMENT CATEGORY

PURGED EXTERNAL MULTIPLE REFLECTIVE LAYER INSULATION IN PANELS WITH SPECIAL HIGH FLOW SPACERS

(Note: These materials are under development; all their properties are not known yet.)

REFERENCES: NBS-108, S-180; NASA-2, S-142; NASA-30, S-182; DDC-19, S-171

DENSITY: Marshield: dimpled phenolic impregnated fiberglass 5 mil spacers and aluminized Mylar - 2 to 5 lb/ft^3

Superflock: Aluminized Mylar spaced by 0.04 inch high tufts of Dacron thread:

Aluminized Mylar sheets - 1.8×10^{-3} lb/ft^2

KEFF: Marshield: Values of about 1×10^{-4} B/hr ft° R have been measured but it is expected to achieve about 2×10^{-5} B/hr ft° R with more development.

Superflock: 3×10^{-5} B/hr ft° R (calorimeter data) for vacuum conditions. It is believed to have, potentially, 20% greater effectiveness than NRC-2 (2×10^{-5} under laboratory conditions)

POROSITY: No data available but should be similar to other aluminized Mylar purged type insulations.

SEALING & ABSORPTIVITY: No data available for Marshield. Superflock uses Dacron purge bag and tufts because of low outgassing characteristics. This material will pump to 10^3 microns Hg in 140 seconds.

RADIANT PROPERTIES: No specific data is available for Marshield. Superflock: Dacron spacers on 3/4 inch centers increase the shield emissivity by 30%.

ENVIRONMENTAL CAPABILITY: No specific information given but they probably require protection from aerodynamic loads and heating and a micrometeorite shield probably is required.

MECH. PROPS AND SUPPORT REQUIREMENTS:	Marshield: Blankets attached with bonded nylon studs and retainers. Superflock: Blankets attached with bonded fiberglass studs and retainers. This material recovers 80 to 90% of uncompressed height after loading.
LIFE:	No data is available.
BONDING:	Studs bonded to aluminum with NARMCO7343 adhesive. Dacron tufts bonded to reflective layers with NARMCO7343 adhesive
FORMING:	Blankets are pliable. Blankets may be prefabricated with appropriate plan shapes and interleaved on installation. Joints are taped. Dacron tufts are positioned on a fresh coated reflective film by a vibration technique.
REUSABILITY:	No information was given but these systems will probably require launch and reentry protection. Cooldowns should not effect these insulations.
GROUND HOLD REQUIREMENT:	Both insulations require purging until launch to minimize air cryopumping. Positive spacing may improve the ground hold performance.
COST:	These materials will cost somewhat more than conventional blanket materials because of special manufacturing operations required for the spacing.
AVAILABILITY & MANUFACTURER:	General Dynamics is developing Superflock. Marshall Space Fligh Center is developing Marshield. See AC-40 for manufacturer's addresses where available.
NOTES:	These insulations permit much more rapid pump down than the conventional superinsulations. Aluminized Mylar burns and is subject to degradation when exposed to moisture and/or decontamination procedures.

ASSESSMENT CATEGORY

INTERNALLY MOUNTED POLYURETHANE FOAM INSULATION

REFERENCES:	NBS-5 S-37, NBS-34 S-52, TCM-3 S-95, TCM-4 S-96, TCM-5 S-97
DENSITY:	Fiberglass thread reinforce polyurethane foam one inch thick - 5.2 lb/ft^3
KEFF:	0.025 B/hr ft° R
POROSITY:	Permeability = 0.36 cc Air/cc hr ATM
SEALING AND ABSORPTIVITY:	Seal with layer of 181 fiberglass impregnated with epoxy 70% by weight. This has no measureable liquid hydrogen permeability but gas at atmospheric pressure permeation degrades the thermal performace 50% in 50 hours.
RADIANT PROPERTIES:	Foam is optically thick.
ENVIRONMENTAL CAPABILITES:	Being internal, it is protected from aerodynamic loads and ground hold damage. This material has been flown successfully on the Saturn S-V.
MECH. PROPS. AND SUPPORT REQUIREMENTS:	Ultimate compressive strength = 220 lb/in^2 Ultimate tensile strength = 160 lb/in^2 Bonded to tank.
LIFE:	Storage life is indefinite. When in contact with gaseous hydrogen, at atmospheric pressure its thermal performance degrades 50% in 50 hours.
BONDING:	Epoxy resin used
FORMING:	Information was not given but foam is usually molded during panel manufacture

REUSABILITY: This insulation has been used successfully in Saturn - V applications. No stress cracking on cooldown has been noted. The material would have to be protected thermally for reentry.

GROUND HOLD REQUIREMENTS: None except that the hydrogen should not be loaded too long before launch since its vapor degrades the insulation.

COST: This is one of the least expensive insulations to purchase and apply. It is protected from mechanical damage but would be expensive to repair due to access difficulties.

AVAILABILITY & MANUFACTURER: Reichold Chemical Co.
NOPCO Chemical Co.

See AC-40 for manufacturer's addresses where available.

NOTES: This insulation is not affected by penetrations. Internal insulation can reduce pressurant gas requirements by minimizing cold wall condensation in the ullage space. This material would present an explosion hazard if used with oxygen.

ASSESSMENT CATEGORY

HELIUM PURGED MICRO-QUARTZ HIGH TEMPERATURE CRYOGENIC INSULATION

REFERENCES:	NBS-103 S-76	NBS-114 S-126	NASA-1 S-140	NASA-7 S-105
	DDC-11 S-177	DDC-25 S-154		

DENSITY: 4 lb/ft^3

KEFF: 0.02 B/hr ft°R at 100R
0.03 B/hr ft°R at 500R

It uses a stainless steel convection barrier in the insulation.

POROSITY: No information available

SEALING AND ABSORPTIVITY: Some means must be provided to contain the purge gas. Apparently the vehicle structure provides this function.
It absorbs water vapor to some unreported degree.

RADIANT PROPERTIES: No information available.

ENVIRONMENTAL CAPABILITY: Can withstand continuous 1,200°F.

MECH. PROPS. AND SUPPORT REQUIREMENTS: Mounted on studs with wire lacing. No mechanical property data was reported.

LIFE: It is designed for indefinite usage.

FORMING: Micro-quartz "felts" are sandwiched between two wire cloths and quilted on .4 inch centers with wire lacing. A stainless steel foil is included to break up convective patterns. The blankets are butted together under compression to accommodate thermal shrinkage. The blankets are attached to studs with wire lacing.

REUSABILITY: This insulation was designed for use in hypersonic aircraft. With an outer protective skin, it can be reused indefinitely.

GROUND HOLD REQUIREMENTS: Helium purging is required to avoid air cryopumping.

COST: Unknown.

AVAILABILITY AND MANUFACTURER: Unknown.

ASSESSMENT CATEGORY

SHROUD MOUNTED INSULATION

Any insulation can be mounted on a separate shroud rather than on the tank. No special materials or installation procedures are required.

Four basic advantages over tank mounting are accrued:

No direct conduction from hot surface to tank.

Insulation is not as susceptable to degradation at penetrations for normally tank mounted hardware.

Bonds are made to a warm surface.

The tank is readily accessible.

There are four major disadvantages:

Insulation is subject to aerodynamic heating since it is usually bonded to the outermost wall.

For typical superinsulations, the shroud wall must not have more than 20 to 40% greater area than the tank to achieve comparable performance.

Insulated area and thus weight is greater.

Additional ground hold insulation is required.

REFERENCES:

NBS-51	NBS-100	SIE-4	SIE-17
S-62	S-7	S-20	S-33

MANUFACTURERS' ADDRESSES

Armstrong Cork Company
1010 Concord Street
Lancaster, Pennsylvania 17604
717-397-0611

Chemiseal Company
9236 Faust
Detroit, Michigan 48228
313-272-0566

Coast Pro-Seal
P.O. Box 54748 Terminal Annex
Los Angeles, California 90054

Dow Corning Chemical Company
Plastics Division
1000 Main Street
Midland, Michigan 48640
517-636-1000

Diamond Shamrock Corporation
Napco Chemical Company Division
60 Park Place
Newark, New Jersey 07101

Furane Plastic, Inc.
5121 San Ferondo Road
West Los Angeles, California 90039
213-245-1151

General Dynamics Corporation
1 Rockefeller Plaza
New York, New York 10020

General Mills, Inc.
Chemical Division
Kankakee, Illinois 60901
815-932-6751

Goodyear Tire and Rubber
1144 East Market Street
Akron, Ohio 44305

Hexcel Products, Inc.
2332 Fourth at Channing
Berkeley, California 94710

Johns Manville, Perlite Corporation
Non-Metallic Minerals and Industrial Insulation
504-T Railroad
Joliet, Illinois 60436
815-727-4571

Leffingwell Chemical Company
117 South Berry
Brea, California 92621

Norton Company Metal Division
NRC Metal Division
45 Industrial Place
Newton, Massachusetts 02164
617-969-7690

Pittsburg Plate Glass Company
One Galiway Center
Pittsburg, Pennsylvania 15222

Reichhold Chemicals, Inc.
523 North Broadway
White Plains, New York 10602

Shell Chemical Corporation
50 West 50th Street
New York, New York 10020

Sheller-Globe Corporation
Mitchell and Smith Division
8900 Hampton Boulevard
Norfolk, Virginia 23505

Standard Packaging Corporation
200 East 42nd
New York, New York 10017

Union Carbide Corporation
Chemical and Plastic
270 Park Avenue
New York, New York 10017
212-551-2345

Whittaker Corporation
Narmco Materials Division
600 Victoria Street
Costa Mesa, California 92627
714-548-1144

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