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SUMMARY REPORT

MATERIALS TECHNOLOGY ADVANCEMENT PROGRAM
FOR
EXPANDABLE MANNED SPACE STRUCTURES

By Kenneth L. Cordier and William B. Cross

Goodyear Aerospace Corporation
Akron, Ohio

for

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Akron, Ohio

for Langley Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

This report was prepared by Goodyear Aerospace Corporation (GAC), Akron, Ohio, under NASA-LRC Contract NAS 1-9112. The contractor's number for this report is GER-14779.

The work was administered under the direction of the NASA-LRC Space Systems Research Division. Mr. Charles I. Tynan, Jr. of the Life Support Branch, Habitable Structures Unit, was the program director for NASA-LRC.

This effort was started in May 1969 and concluded in February 1970. The program was directed by the Space Systems and Analytics Division, managed by Mr. S. J. Pipitone of GAC.

This program was a group effort headed by Mr. L. Jurich, program manager of the Astronautics Programs Department, assisted by K. L. Cordier, project engineer; W. B. Cross and S. Blate, materials technology; Dr. C. E. Welling, staff materials consultant; D. S. Kimes, composite materials laboratory; J. J. Meola, thermal control analysis; M. L. Lahr, quality assurance analysis; D. A. Neman, contract administration; and R. L. Hall, engineering administration.

The authors wish to acknowledge the assistance of Dr. Matthew I. Radnofsky, Head of the Supporting Development Branch, NASA-MSC Crew Systems Division for help early in the program by providing detailed information on MSC rationale for testing non-metallic materials used in manned space structures and for suggestions of candidate nonflammable type materials. We also wish to acknowledge the assistance of Mr. Harry F. Kline and Mr. David L. Pippen of NASA-MSC for their assistance in scheduling the White Sands Test Facility for flammability and gas analysis work, and Mr. Burton G. Cour-Palais of NASA-MSC for experimental work with micrometeoroid barrier test samples.

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By Kenneth L. Cordier and William B. Cross
Goodyear Aerospace Corporation

SUMMARY

Existing materials technology for expandable structures has been applied to full-scale models of airlocks, space station modules, and lunar shelters. These models, which successfully demonstrated design requirements for packaging, leak rates, and structural integrity, did not utilize nonflammable materials and hence were not compatible with an oxygen pressurized internal environment. This report documents the results of an extensive materials screening effort and selection process, fabrication of composite materials, qualification testing and a definition of construction techniques required for "flight quality" mission hardware. As a result of the development program, promising designs of fire-resistant composite wall structures were evolved for expandable manned space structures.

INTRODUCTION

The materials approach used up to this time in the design of expandable structures for manned space structure applications is based on a four-layer composite material. This composite consists of an unstressed inner layer functioning as a pressure bladder (XPB) for gas retention, a structural layer (XSL) which carries the transmitted pressure loads, a micrometeoroid barrier (XMB) which prevents penetration of the pressure bladder by high velocity particles, and an outer cover (XOC) which encapsulates the total material composite (XTC) and provides a smooth surface for the application of thermal control coatings.

The existing technology (Figure 1) for expandable structure materials is represented by the combined technologies of the Air Force D-21 Expandable Airlock Experiment (Contract F33615-67-C-1380) and the NASA-LRC Lunar Shelter (Contract NAS1-4277) and Moby Dick (Contract NAS1-6673) structures, developed by Goodyear Aerospace. Figure 2 depicts this development, showing a diagram of the four-layer elastic recovery materials concept. Compatibility with an O_2 pressurized environment, and hence non-flammability of the materials under orbital environment conditions, was not provided in these structures, but as a result of the newly developed nonflammable materials techniques in this program, would be provided on future manned space structures.

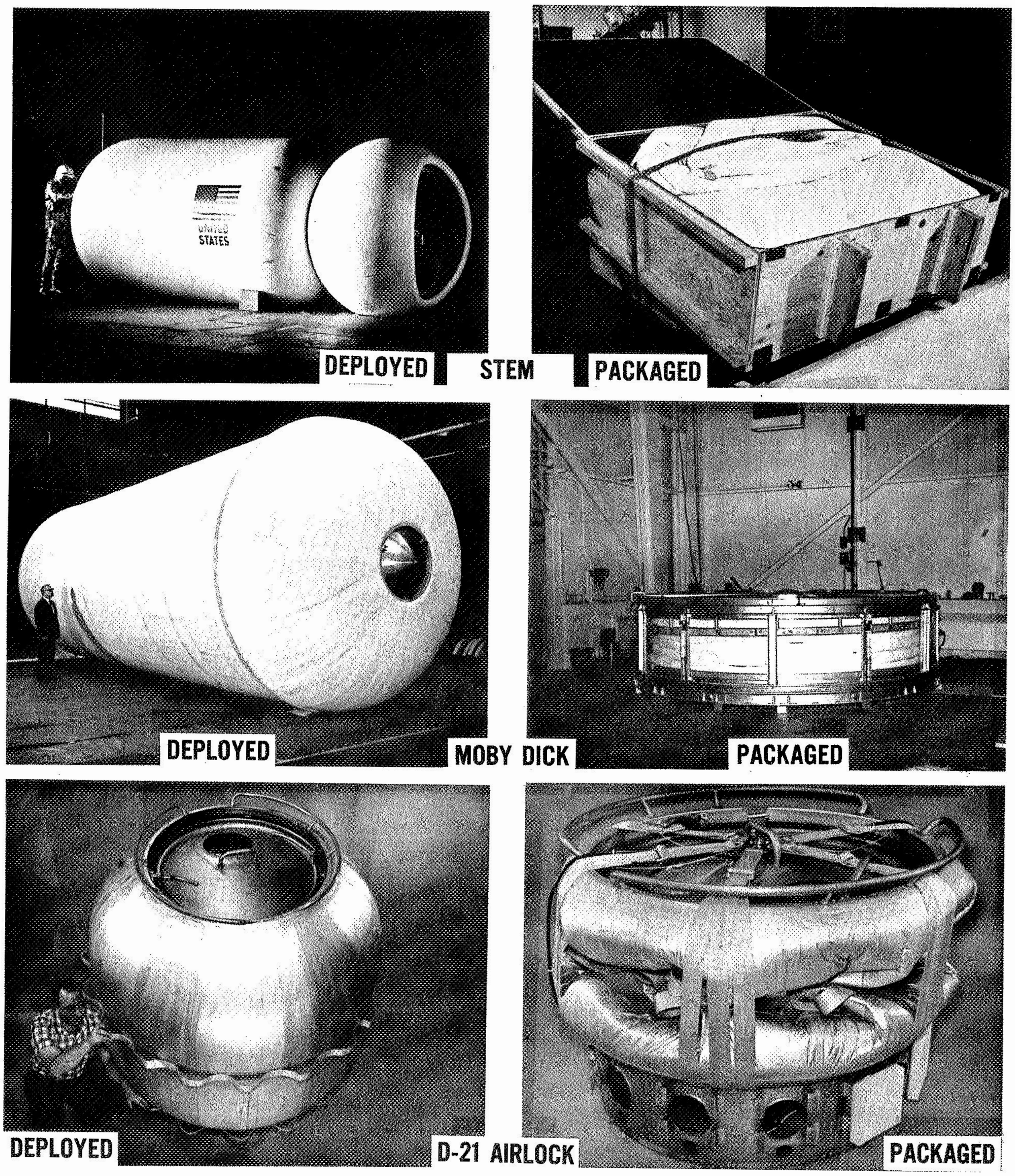


Figure 1. Existing Technology

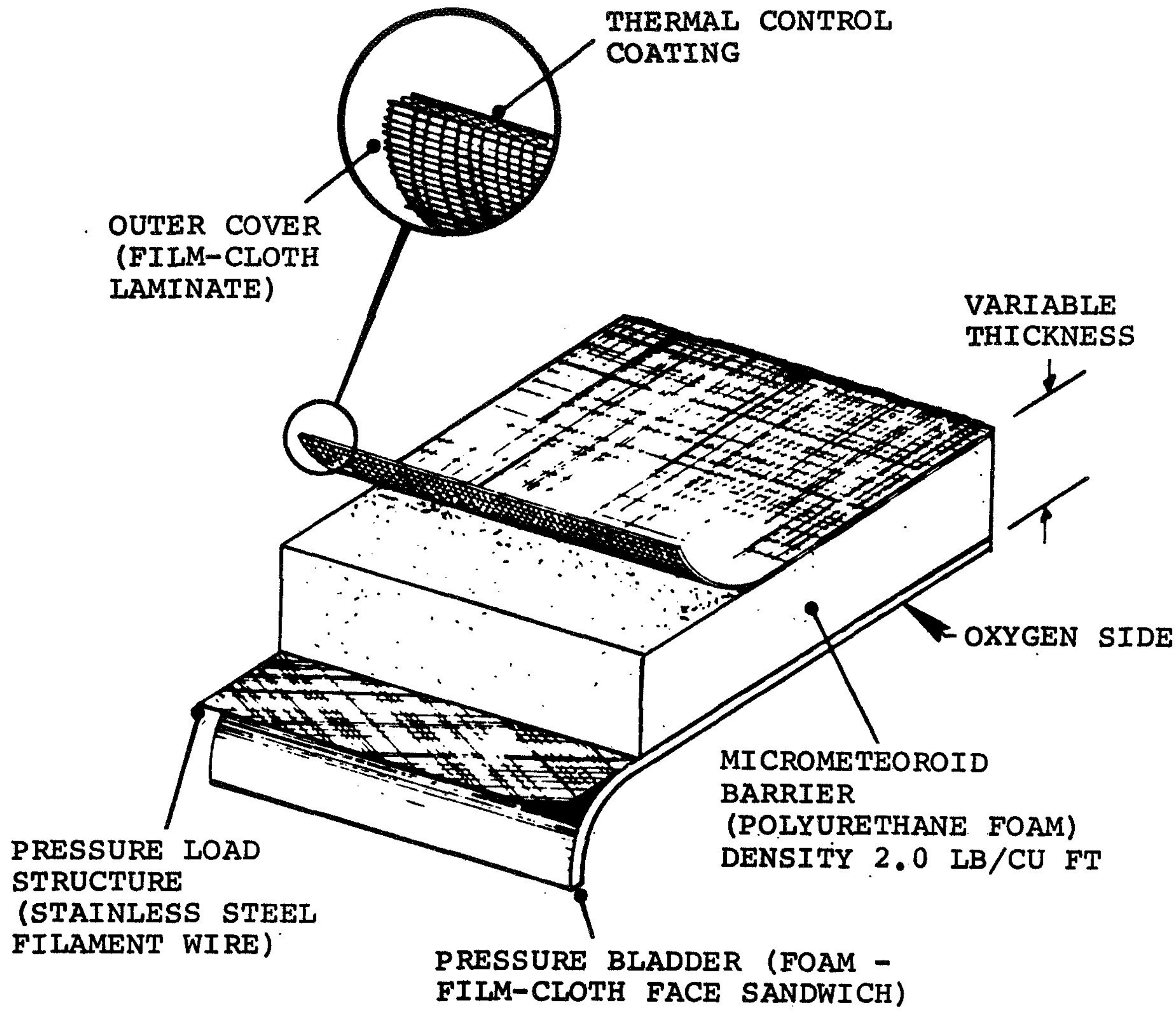


Figure 2. Elastic Recovery Materials Technique

This program was initiated to meet new and current requirements that expandable type manned space structures be compatible with an oxygen pressurized environment.

The objective of this program was to upgrade the development of expandable structures materials to a level where the technology could be applied to the fabrication of "Flight Quality" hardware, specifically a habitable type lunar personnel shelter. This objective was approached within the concept of a four-layer materials composite (pressure bladder, structural layer, micrometeoroid barrier, and outer cover) previously developed in the existing technology (Figure 1). Specifically, the effort was achieved in two ways, primarily by upgrading the development of the four-layer materials composite relative to the flammability hazard, and secondly, by establishing practical fabrication techniques logic for translating the materials technology into a space-qualified structure.

The general approach to the investigation was based on the use of experimentally obtained information and NASA technical guidelines and specifications for the evaluation of manned spacecraft materials. The program was conducted in the following phases:

Task I - Conduct candidate materials selection and screening.

Task II - Conduct composite materials fabrication and qualification testing.

Task III - Define fabrication techniques, thermal control system design, and quality assurance requirements.

This report is a summary of the detailed technical discussion of the program presented in a separate report (Reference 1).

TECHNICAL DISCUSSION

Candidate Materials Selection

General. - A screening study for the selection of candidate individual materials with potential low burning rates in a 100 percent oxygen atmosphere was conducted in the Task I Phase. NASA guidelines and recommendations were used as the basis for candidate materials selection criteria. The program started with an extensive search for non-flammable type materials through an industry survey and literature review. Quantities of candidate materials were subsequently obtained for screening tests which lead to a final selection of composite elements for a 4-element composite wall structure.

Candidate Materials Selection Criteria. - The order of significance of the evaluation factors as related to the candidate materials selection was applied in the following manner.

(1) Crew Safety (in accordance with Reference 2)
Flammability
Toxic Hazards

(2) Mission Success
  (a) Ground Environment (in accordance with Reference 3)
    Humidity effects
    Effects of temperature extremes
    Fungus resistance
  (b) Space Environment (in accordance with Reference 4)
    Mechanical properties
    Thermal conductivity
    Gas tightness
    Micrometeoroid impact protection
    Packageability

(3) Mass Properties Efficiency

Candidate Materials Search. -

Industry Survey: An extensive industry wide search was initiated early in the program seeking new or improved materials potentially non-flammable in a 6.2 psia, 100 percent oxygen atmosphere. The most promising materials to come out of the survey at that time as possible candidates for elements in a composite materials construction are:

Films - Aclar 33C
- Kapton

Fabrics - Beta Glass
- Refrasil (Silica)

Foams - Fluorel (#1062-C)
- Asbestos (K20)

Elastomers - Fluorel (L-3203-6)

Adhesives - Fluorel (#1066)

Fibers - Chromel R
- Stainless Steel
- Rene 41

Foils - Aluminum

Many of the candidate Category "A" usage materials, investigated mainly on the basis of the results published in the COMAT* list (Reference 5) were found to be flammable when tested in the GAC screening test program. Category A defines materials toxicity and flammability characteristics required for major exposed materials usage in a crew bay atmosphere (Reference 2). It was found that the results of flammability tests on individual materials can often differ with a slight change in processing, thickness, post cure, etc., although they may be acceptable when used in a composite construction.

Polymer Materials Review. - A literature review of the newer types of polymers, particularly those having known or predicted high temperature stability, was carried out.

Relatively little information has been published regarding the behavior of new polymers in tests for flammability in an oxygen atmosphere.

*Characteristics of Materials

Information on availability, fabrication procedures, and cost has been developed for some of the materials considered. In most cases one or more of these latter factors are highly unfavorable in the context of the present program. Only Item 1 (PBI) and Item 8 (PI) of the following group appear to be of definite interest, for possible rigid structure applications, such as terminal end rings or hatches. The following list of polymers were investigated during the review:

(1) Polybenzimidazole (PBI)

(2) Poly(bisbenzimidazobenzophenanthroline) (BBB)

(3) Perfluoroalkylene Triazine Polymers

(4) Polyquinoxalines

(5) Polybenzothiazole

(6) Fluorinated Polyurethanes

(7) Polyhydrazides-Polyoxadiazoles

(8) Polyimide Resins and Foams (PI)

(9) Ladder Polymers

(10) Silazane Polymers

(11) Cordelan Fiber

(12) Phosphonitrilic Fluorelastomer

(13) Thermally Treated Polymers

(14) Miscellaneous flame retardants

Candidate Materials Screening Tests and Composites Development

Individual Materials Screening Tests. - During the materials screening phase candidate films, foils, foams, elastomers and adhesives were purchased and evaluated to establish their suitability for use in a lunar shelter. Testing was performed to establish:

(1) Flammability characteristics in 100 percent oxygen at 6.2 psia

(2) Weight loss in vacuum

(3) DTA* and TGA* performance

(4) Odor characteristics

(5) CO and organic compound offgassing characteristics.

(6) Mechanical properties; such as, stress-strain, low temperature behavior, adhesion, etc.

(7) Oxygen permeability

*DTA - Differential Thermal Analysis
*TGA - Thermogravimetric Analysis

The results of these tests were then analyzed to establish if candidate materials met or exceeded NASA Category A requirements (Reference 2), and other baseline contractual requirements supplied by NASA-LRC. The normal sequence for screening the candidate materials is contained in Figure 3. After obtaining a quantity of a candidate material a sample was subjected to an upward propagation flammability test in 100 percent oxygen at 6.2 psia in GAC's laboratory facility. Material found to be non-burning or self-extinguishing within 0.5 inch or less after extinguishing the ignitor (Category A Requirements) was then further evaluated as outlined in Figure 4.

In some cases materials which exhibited slow burn characteristics or those thought to be the best available in a particular class (e.g., film, foam, etc.) were conditionally accepted for additional screening efforts. This conditional acceptance was justified on the basis that these materials would be incorporated into a composite having protective non-burning outer layers and that the composite would be required to pass the upward propagation flammability test. These composites were of the flame/gas barrier type and their development is covered in the section of this report entitled "Development of Flame/Gas Barrier Composite".

Upward Propagation Flammability Tests: To accelerate candidate selection to gain a better understanding of the variables which control material flammability, GAC assembled laboratory equipment to evaluate the upward burning characteristics of candidate materials in a 6.2 psia 100 percent oxygen environment.

Table I summarizes the type of material, source, thickness tested, sample size and mounting, ignitor type, and results of the test.

The results of the GAC study indicate that with the exception of certain fiberglass, asbestos, and metal cloth, no single layer material was found which, when used in approximate thicknesses required, would be capable of passing the NASA-Category A requirements for flammability.

Vacuum Weight Loss Behavior: The results of weight loss tests conducted on the candidate materials were very low and within the 0.5 percent acceptable limit.

Stress-Strain vs Temperature: The stress-strain properties of each candidate material were determined over a broad temperature range.

Temperature Effects Study: To obtain a better knowledge and clearly illustrate the effect of temperature on strength characteristics of single layer candidate materials, previous stress-strain data obtained at various temperatures (-100° F to 250° F) were analyzed. From these data, plots of tensile load at a pre-selected strain level as a function of sample temperature,

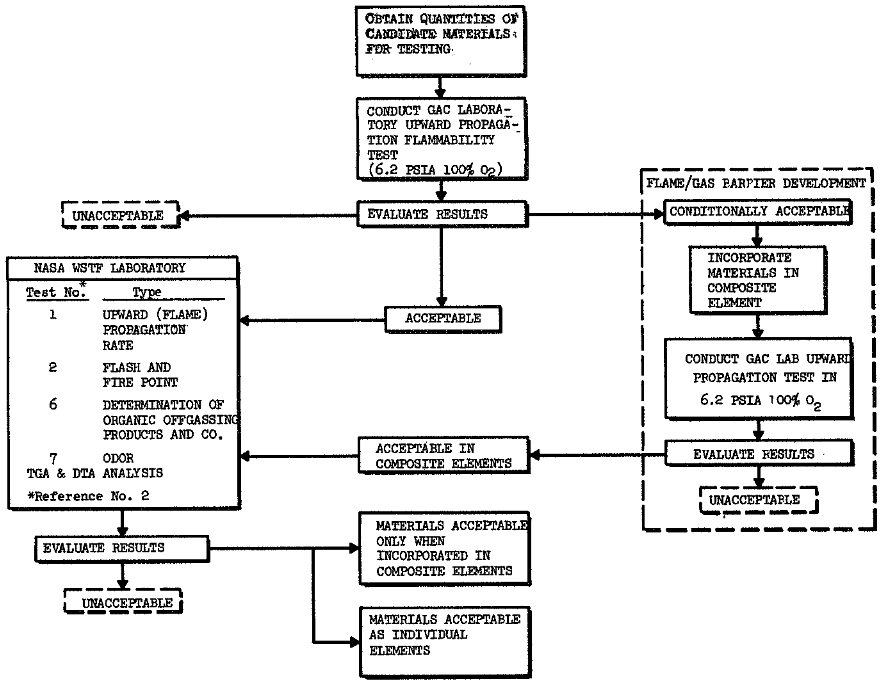


Figure 3. Work Flow Chart for Primary Screening Tests

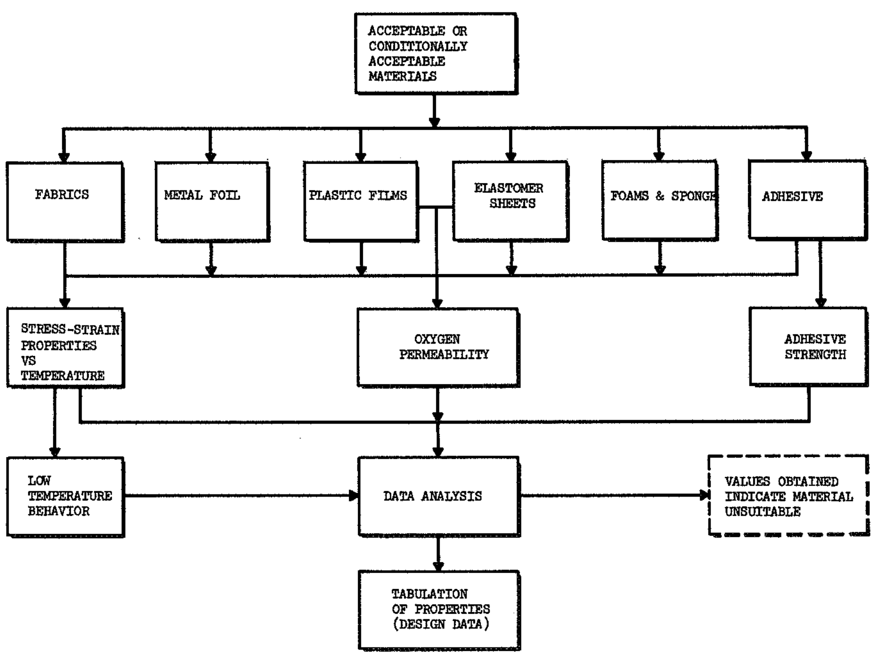


Figure 4. Work Flow Chart for Characterization and Screening Tests

TABLE I. RESULTS OF GAC UPWARD PROPAGATION FLAMMABILITY TESTS IN 6.2 PSIA 100% OXYGEN ON CANDIDATE SINGLE LAYER MATERIALS

Material	Manufacturer or Source	Approx. Thickness In.	Test Variables: Sample Size, In.	Test Variables: Ignitor Type*	Test Variables: Sample Mounting**	Observations
Films						
Aclar 33c Film	Allied Chem. Corp.	0.001	2 1/2 x 5	TP	EC	Very fast burn
Kapton Film	E.I. dupont de Nemours and Co.	0.001	2 1/2 x 5			Very fast burn
Mylar Film		0.001	2 1/2 x 5			Very fast burn
Mylar Film (Aluminized)		0.001	2 1/2 x 5			Very fast burn
Saran Film		0.001	2 1/2 x 5			Very fast burn
Teflon, FEP Film		0.003	2 1/2 x 5			Fast burn
XRP Film		0.0025	2 1/2 x 5			Slow burn
XRP Film	E.I. dupont de Nemours and Co.	0.005	2 1/2 x 5		EC	Very slow burn
Coated and Uncoated Fabric						
Fluorel (L-3203-6) Coated on X410 cloth	Raybestos-Manhattan, Inc.	0.011	3/4 x 3 1/2		TC	Very fast burn
x400 Cloth with 3310-46-6/ FRGL-8 Coating	Chemstrand Research Ctr	0.016	2 1/2 x 5		EC	Fast burn
Fluorel (No.1076 Elastomer) on Beta Glass	NASA-MSC	0.025	3/4 x 3 1/2		TC	Fast burn
Viton 238-26-1 coated Beta Glass	E. I. dupont de Nemours and Co.	0.005	3/4 x 3 1/2			Fast burn
Fluorel Coated Beta Glass No. RL-3520	Raybestos-Manhattan, Inc.	0.005	3/4 x 3 1/2			Slow burn
Fluorel Coated on Stainless Steel Cloth	Raybestos-Manhattan, Inc.	0.012	3/4 x 3 1/2			Slow burn
Fluorel (L-3203-6) Coated on asbestos Cloth	Raybestos-Manhattan, Inc.	0.017	3/4 x 3 1/2			Self-Extinguishing in about 1-1/2 inches
Fluorel (RL-3489-1 RE-FSET) Coated Beta Glass	Raybestos-Manhattan, Inc.	0.008	3/4 x 3 1/2		TC	Self-Entinguishing in about 1-1/2 inches
Fiberglass Cloth 116/ Volan A	J. P. Stevens and Company	0.003	2 1/2 x 5		EC	No ignition
Beta Cloth X4484 (Teflon coated yarn)	Owens/Corning	0.007	2 1/2 x 5			Melted in ignition area but did not ignite
Asbestos Cloth (L-69-54 Novatex)	Raybestos-Manhattan, Inc.	0.021	2 1/2 x 5	TP		No ignition
Rene' 41 Cloth (0.0016 1 strand 200 x 200) cleaned in MEK	Unique Wire Co.	0.003	2 1/2 x 5	SE		No ignition
Durette Cloth	Chemstrand Research Ctr	0.016	2 1/2 x 5	TP	EC	Fast burn
Foams (Sponge)						
Diammonium Phosphate Impregnated Scott Foam	GAC	0.500	2 1/2 x 5		TC	Very fast burn
Fluorel Sponge RL-2060	Raybestos-Manhattan, Inc.	0.100	3/4 x 3 1/2			Very fast burn
Fluorel Sponge RL-2060	Raybestos-Manhattan, Inc.	0.050	3/4 x 3 1/2			Very fast burn
Fluorel Sponge RL-2060	Raybestos, Manhattan, Inc.	0.150	3/4 x 3 1/2			Fast burn
Fluorel Sponge L-3622-3	Raybestos-Manhattan, Inc.	0.150	3/4 x 3 1/2			Fast burn
Fluorel Sponge # 1062-C	Mosites Rubber Co.	0.050	3/4 x 3 1/2			Fast burn
Fluorel Sponge # 1062-C	Mosites Rubber Co.	0.050	2 1/2 x 5	TP		Fast burn
Impregnated Cellulose Sponge (49% wt Diammonium Phosphate)	GAC	0.500	2 1/2 x 5	SE		Slow burn
Fluorel Sponge L-3622-2	Raybestos-Manhattan, Inc.	0.150	3/4 x 3 1/2	TP		Slow burn
LITOFLEX Asbestos Foam KG-25	Rex Asbestwerke (Germany)	0.800	3/4 x 3 1/2	TP		Very slow burn Red glow combustion
Cellulose Sponge (treat)	NASA-MSC	0.500	2 1/2 x 5	SE		Very slow burn
Cellulose Sponge (untreated)	NASA-MSC	0.500	2 1/2 x 5		TC	Very slow burn
Compressed Cellulose Sponge (untreated)	NASA-MSC	0.500	2 1/2 x 5		EC	Very very slow burn
Compressed Cellulose Sponge (treated)	NASA-MSC	0.500	2 1/2 x 5		EC	Extremely slow burn
Impregnated Cellulose Sponge (74 wt % Diammonium Phosphate)	GAC	0.500	2 1/2 x 5		TC	Self-extinguishing in about 1.7 inches
Impregnated Cellulose Sponge (59 wt % Diammonium Phosphate)	GAC	0.500	2 1/2 x 5			Self-extinguishing in about 2.7 inches
LITOFLEX Asbestos Foam K20	Rex Asbestwerke (Germany)	0.900	3/4 x 3 1/2	SE		No ignition
Fluorel Sponge # 1062-C	Mosites Rubber Co.	0.250	3/4 x 3 1/2	TP	TC	No ignition
Elastomers						
Fluorel Elastomer L-3203-6 (Uncured)	Raybestos-Manhattan, Inc.	0.021	3/4 x 3 1/2		TC	Slow burn
Fluorel Elastomer L-3203-6 (Cured)	Raybestos-Manhattan, Inc.	0.014	3/4 x 3 1/2			Slow burn
Fluorel Elastomer L-3203-6 (Cured)	Raybestos-Manhattan, Inc.	0.075	3/4 x 3 1/2			No ignition
Fluorel Elastomer # 1059	Mosites Rubber Co.	0.070	3/4 x 3 1/2		TC	No ignition
Adhesives						
Fluorel Adhesive # 1066 (coated on 1 mil Al Foil)	Mosites Rubber Co.	0.003	2 1/2 x 5		EC	Self extinguishing
Fluorel Adhesive RL-3788 (coated on 1 mil Al Foil)	Raybestos-Manhattan, Inc.	0.003	2 1/2 x 5	TP	EC	No ignition

* TP indicates 1 x 2 inch tissue paper ignitor
SE indicates 0.22 in. dia. x 1.25 in. silicone elastomer ignitor

** EC indicates sample was mounted by clamping two side edges
TC indicates sample was mounted by clamping top edge

were constructed. A typical temperature vs stress curve is shown for the Mosites #1062-C Fluorel Sponge (Figure 5). The curve shows a characteristic gradual increase to a point where further reduction in temperature brings about a very sharp increase in strength due to a change in modulus of the material. This change results from a sudden (second order) transition which is referred to as the "glass transition" (T_g); since it describes a point below which molecular motion necessary for rubber elasticity ceases and the material begins to take on properties normally associated with glass. To determine approximate "glass transition" (T_g) temperature of the Fluorel material tested, the slope of the strength vs temperature curve in the change region were extended to an intercept point as shown in Figure 5. This intercept point is taken as the T_g temperature point.

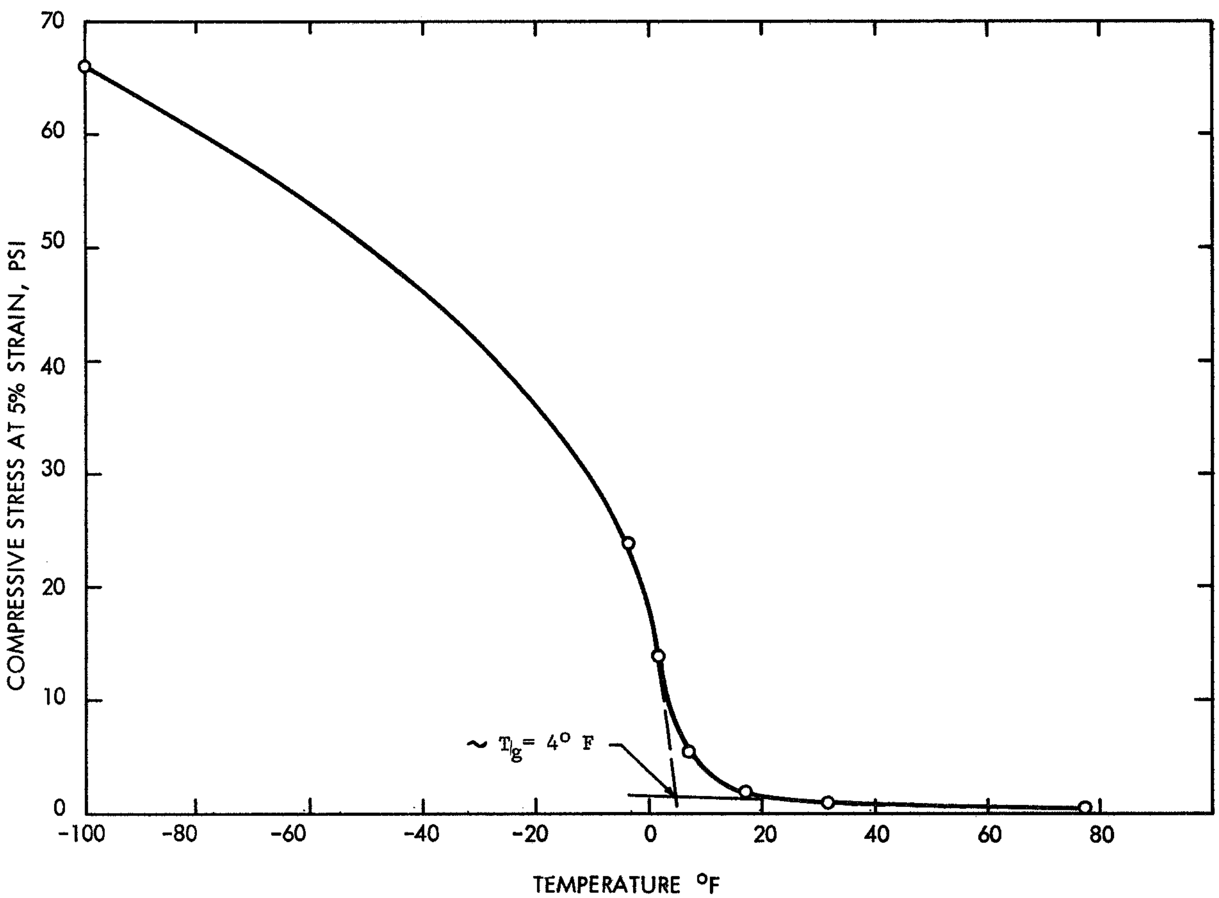


Figure 5. Effect of Temperature on Strength of 12.8 lbs/ft^3 Mosites #1062-C Fluorel Sponge

Oxygen Permeability: Oxygen permeability of various gas barrier materials was measured at approximately 74° F on Dow gas transmission cells in accordance with ASTM D-1434-66 procedures. The thickness of each material was taken as the average of 10 measurements made over the surface of the disc. Figure 6 presents a summary of the results obtained.

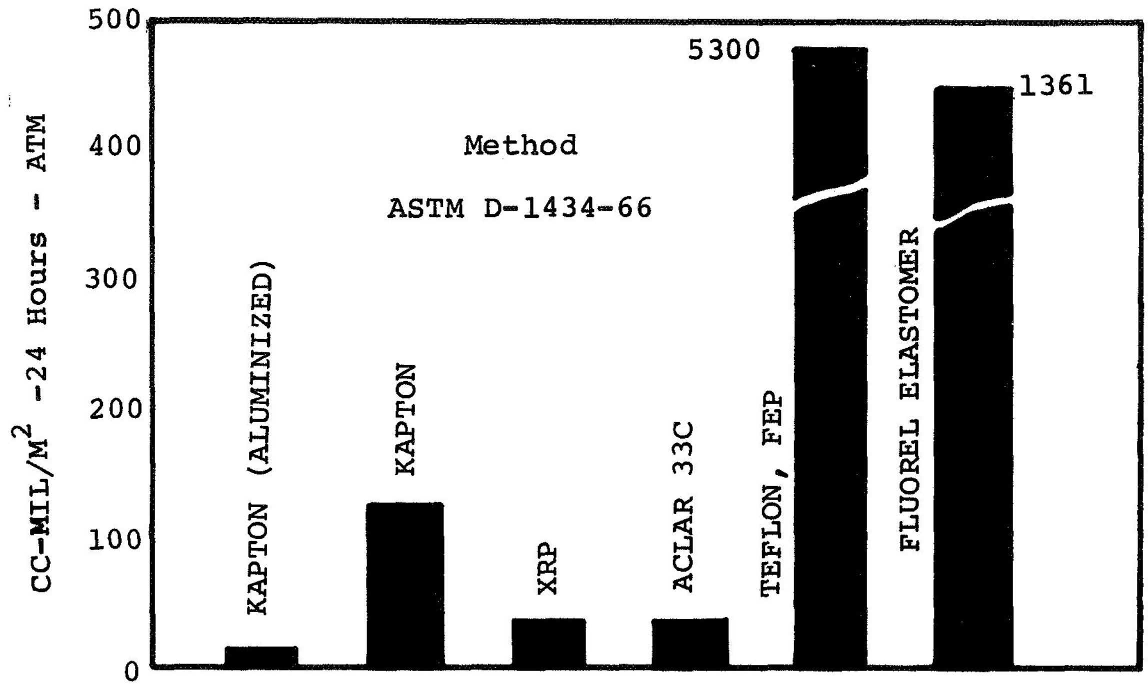


Figure 6. Comparison of Oxygen Permeability

Development of a Flame/Gas Barrier Subcomposite. -

General: After considerable investigation during the materials screening phase, it became increasingly apparent that presently available thin layer adhesives, plastic films, elastomeric sheets, and sponge materials would not pass the NASA Category A flammability requirements. In an attempt to utilize available low burning rate materials and still provide a satisfactory, safe, and packageable lunar shelter, a suggestion was made to NASA that a flame resistant facer sheet material be applied to the oxygen side of the gas barrier subcomposite. This suggestion was accepted and work was initiated on development of a flame/gas barrier subcomposite.

During the course of the work, 22 candidate flame/gas barrier subcomposites were fabricated and tested.

Subcomposite flame/gas barrier systems were evaluated on the basis of:

(1) Upward flame propagation in 100% oxygen at 6.2 psia test results.

(2) Special diaphragm flammability in 100% oxygen at 6.2 psia test results.

Details of these tests are covered in the following paragraphs.

Upward Propagation Flammability Tests: The upward propagation flammability testing was conducted in a manner similar to that described previously for the single layer materials.

A summary of the test results obtained on all candidates is provided in Table II. Examination of the results indicates that with the exception of XPB-2, XPB-3, XPB-5, and XPB-6, all subcomposites met the acceptance requirements of Category A since all were found to be highly self-extinguishing. It was found that with the addition of a single layer of foil, XPB-2 and XPB-3 would also pass the self-extinguishing requirement.

As experimental studies continued it was soon realized that, by applying the protective flame resistant facer sheet materials to materials having low burn rate characteristics, a pressure bladder subcomposite could be developed that would pass the upward flame propagation rate requirements.

While passage of this requirement is mandatory, it provided little insight into what might happen should a sizable fire develop next to the surface of the flame/gas barrier. The need for more information in this area prompted the development of the special diaphragm flammability test.

Pressurized Diaphragm Flammability Tests: To perform the pressurized diaphragm flammability test, a 6.5-inch diameter specimen of a candidate flame/gas barrier subcomposite material, backed up with a structural layer, is clamped in the double bell jar apparatus as shown in Figure 7. A standard NASA silicone rubber ignitor is then installed in the center of the specimen, 1/16-inch from the surface of the material.

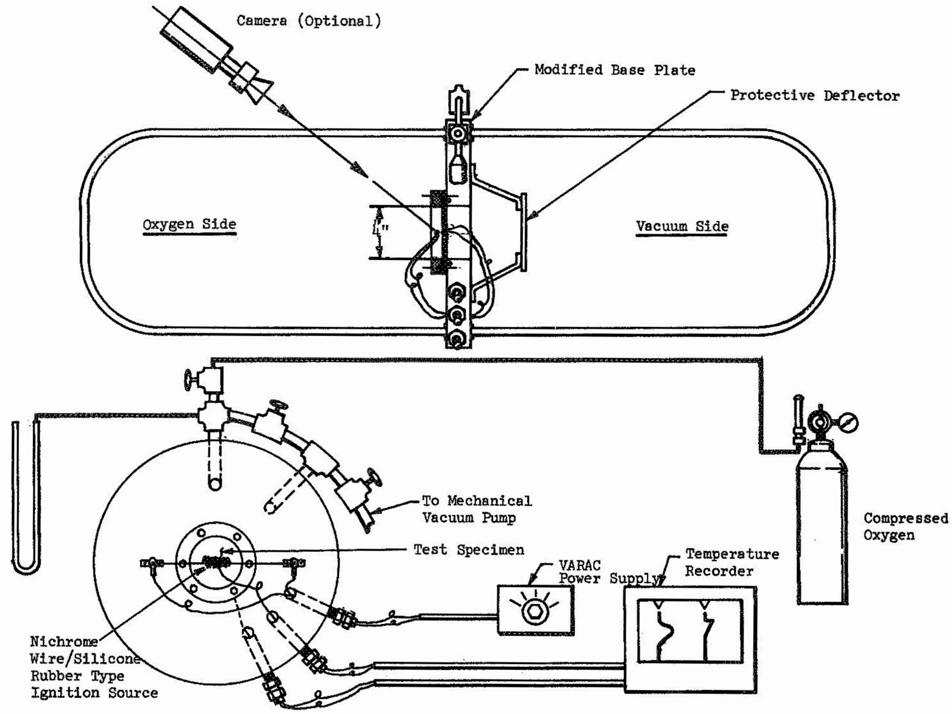
Thermocouples are installed to monitor flame temperature and temperature of the backside of the structural layer, and then the pressure in both chambers is lowered to 1000 microns Hg. The two chambers are then isolated from each other and the chamber containing the ignitor is back-filled with gaseous oxygen to a pressure of 6.2 psia.

Actual testing of the specimen is initiated by passing sufficient current through the Nichrome wire ignitor holder to ignite the silicone rubber insert, and recording flame and structural layer temperatures. Failure of the gas barrier is indicated by a fast increase in pressure in the vacuum-side chamber.

TABLE II. RESULTS OF GAC UPWARD PROPAGATION FLAMMABILITY TESTS IN 6.2 PSIG 100% OXYGEN ON CANDIDATE FLAME/GAS BARRIER SUBCOMPOSITES

Material	Approx. Thickness In.	Test Variables			Results	
		Sample Size, In.	Ignitor Type*	Sample Mounting**	Observations	Max. Height of Thermal Damage Inch ****
XPB-2	0.075	3/4x3-1/2	TP	TC	Fast Burn	
XPB-2 on 1-mil Al Foil	0.076	2-1/2x5	TP	EC	***	0.3
XPB-3	0.050	3/4x3-1/2	TP	TC	Slow burn	
XPB-3	0.050	2-1/2x5	TP	EC	Fast burn	
XPB-3 on 1-mil Al Foil	0.051	3/4x3-1/2	TP	TC	Slow burn	
XPB-3 on 1-mil Al Foil	0.051	3/4x3-1/2	TP	EC	***	0.1
XPB-3 on 1-mil Al Foil	0.051	2-1/2x5	TP	EC		0.1
XPB-3 on 20-mil Al Sheet	0.070	3/4x3-1/2	TP	EC		0.1
XPB-4 (Run 1)	0.075	2-1/2x5	TP	EC		0.2
XPB-4 (Run 2)	0.060	2-1/2x5	SE		***	0.5
XPB-5	0.065		TP		Fast burn	
XPB-6	0.065		TP		Burned inner core	
XPB-7	0.075		SE		***	0.8
XPB-8 (Run 1)	0.065					1.7
XPB-8 (Run 2)	0.065					1.7
XPB-8 (Run 3)	0.065					1.7
XPB-8 (Run 4)	0.065					1.7
XPB-9	0.050					0.6
XPB-10 (Run 1)	0.065					0.7
XPB-10 (Run 2)	0.065					0.7
XPB-10 (Run 3)	0.075					0.6
XPB-10 (Run 4)	0.075					0.6
XPB-10 (Run 5)	0.065					0.7
XPB-10 (Run 6)	0.070					0.6
XPB-11	0.090					0.5
XPB-12 (Run 1)	0.080					0.5
XPB-12 (Run 2)	0.075					0.4
XPB-13	0.080					0.5
XPB-14 (Run 1)	0.075					0.8
XPB-14 (Run 2)	0.075					0.8
XPB-14 (Run 3)	0.075					0.8
XPB-14 (Run 4)	0.075	2-1/2x5	SE	EC	***	0.8

*TP indicates 1 x 2 inch tissue paper ignitor
SE indicates 0.22 in. dia. x 1.25 in. silicone elastomer ignitor
** TC indicates sample was mounted by clamping top edge
EC indicates sample was mounted by clamping two side edges
*** Ignited but self-extinguished after burning 0.5 inches or less after extinguishment of ignitor
**** Values indicated include thermal damage caused by ignitor burn along with any self-sustained combustion after ignitor extinguishment



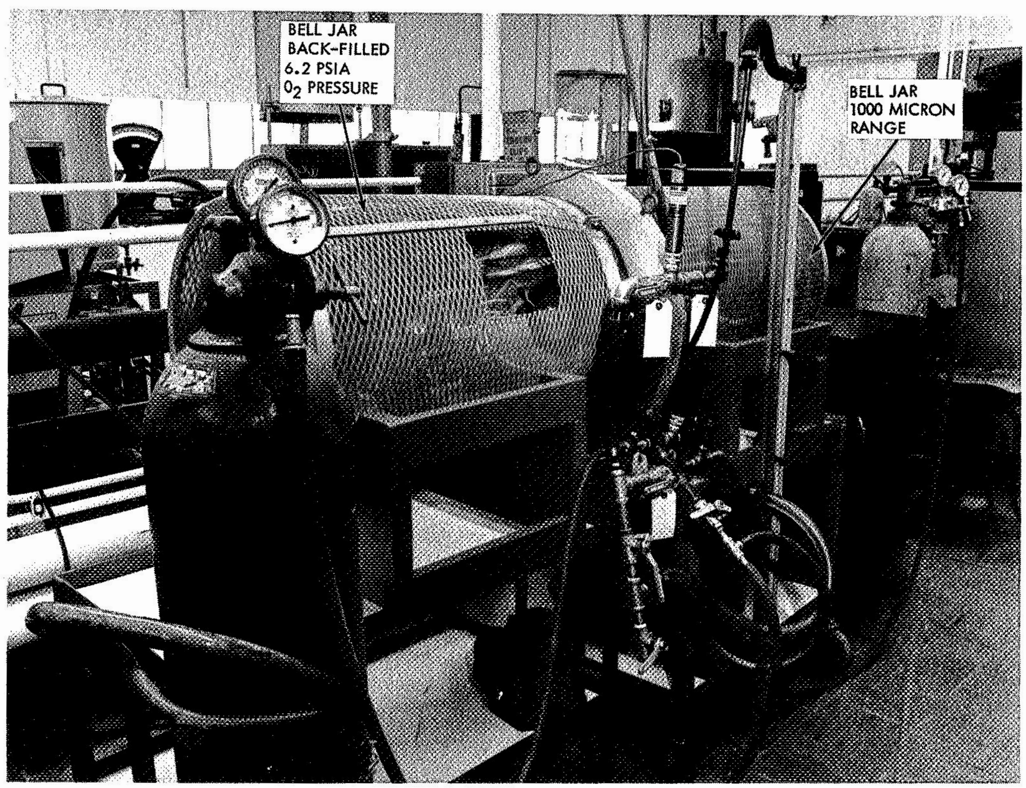


Figure 7. Diaphragm Flammability Test Apparatus

Following the test, specimens are removed and carefully inspected to determine the extent of the flame damage. The temperature time profiles obtained during the test are inspected to ensure that the ignitor temperature was reached during the test, and to document the maximum temperature seen by the structural layer during the test. During the XPB-14 diaphragm flammability tests, the maximum temperature seen by the structural layer was approximately 250° F after 1.5 minutes silicone ignitor burning time. Flame temperature for silicone ignitors varied between 1500° F and 2000° F.

A complete tabulation of the diaphragm test results obtained on various experimental flame/gas barrier composites are presented in Table III.

Analysis of the data obtained shows that subcomposites XPB-7, XPB-8, XPB-10, XPB-12, XPB-13, XPB-17, XPB-18, XPB-19, XPB-20 and XPB-21 experienced extensive damage. However, XPB-7, XPB-8, XPB-10 and XPB-13 did continue to maintain a gas seal because the back foil layer was not destroyed. Those displaying the best flame damage resistance were XPB-11, XPB-14, XPB-16 and XPB-22.

Of those considered acceptable XPB-14A (Figure 8) was selected as the best overall candidate. This material was retested using two silicone ignitors and, although considerable more heat energy was applied, it still maintained good integrity with damage extending only through the second aluminum foil layer.

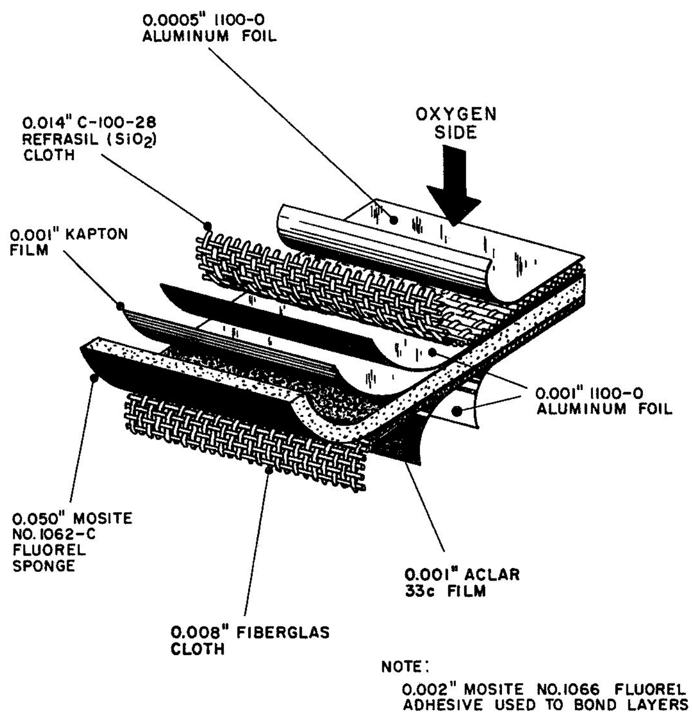


Figure 8. Recommended Flame/Pressure Bladder Subcomposite (XPB-14A)

TABLE III. RESULTS OF DIAPHRAGM FLAMMABILITY TESTS IN 6.2 PSIA 100% OXYGEN ON CANDIDATE FLAME/GAS BARRIER SUBCOMPOSITES

Material	Manufacturer or Source	Approx. Thickness, Inch	Ignitor Type	Approx. Surface Burn Area, Sq. In.	Burn Depth
XPB-7	GAC	0.075	SE*	2.2	Through all but backside 1-mil foil layer
XPB-8		0.065		2.7	Through all but backside 1-mil foil layer
XPB-10		0.065		1.5	Through all but backside 1-mil foil layer
XPB-10		0.065		0.7	Through all but backside 1-mil foil layer
XPB-10		0.075		2.5	Through all but backside 1-mil foil layer
XPB-10		0.075		2.1	Through all but backside 1-mil foil layer
XPB-10		0.070		2.5	Through all but backside 1-mil foil layer
XPB-11		0.090		1.0	Through outside foil layer only
XPB-12		0.080		1.5	Through 2nd foil layer
XPB-12		0.075		1.3	Through 2nd foil layer
XPB-12		0.075		1.5	Through 2nd plastic film layer
XPB-12		0.075		1.5	Through 2nd foil layer
XPB-13		0.080		2.4	Through all but backside 1-mil foil layer
XPB-14		0.075		1.2	Through outside foil layer only
XPB-14		0.075		1.2	Through outside foil layer only
XPB-14		0.075		1.2	Through outside foil layer only
XPD-14		0.075	SE*	1.2	Through outside foil layer only
XPB-14		0.075	SE**	2.7	Very small hole thru 2nd foil layer
XPB-16		0.034	SE*	1.6	Through outside foil layer only
XPB-16	GAC	0.034	SE	1.4	Through outside foil layer only
XPB-17	NASA-LRC	0.032		***	Burned through all layers
XPB-18	NASA-LRC	0.150		***	Burned through all layers
XPB-19	NASA-LRC	0.020		***	Burned through all layers
XPB-20	NASA-LRC	0.017		***	Burned through all layers
XPB-21	NASA-LRC	0.166		***	Burned through all layers
XPB-22	NASA-MSC	0.061		-	Outside Beta Glass Melted Slightly
XPB-22	NASA-MSC	0.061	SE*	-	Outside Beta Glass Melted Slightly

* SE indicates 0.22 in. dia. x 1.25 in. silicone elastomer ignitor

** Two silicone ignitors used

*** Specimen was extinguished with Nitrogen because of excessive burning

NASA-WSTF Laboratory Tests. - Selected single layer materials and flame/gas barrier composites were supplied to NASA-WSTF Laboratory for comprehensive evaluation results of the testing are tabulated in Table IV, and substantiate the selection of the recommended materials.

Composite Materials Qualification Tests (4-Element)

The two selected total wall composites, XTC-4 and XTC-6, were subjected to a series of tests selected for qualifying them for flight unit applications. A summary of the tests performed as part of this qualification phase is presented in Table V.

Fabrication Techniques Development

As the materials screening phase of the program was completed, it became obvious that the fabrication technique processes would be completely interdependent with the materials selection in translating the final upgraded materials into "flight quality" hardware. Therefore, based on the results of the Task I materials screening phase, candidate individual materials were selected for application in a total composite wall construction incorporating the flame/gas barrier subcomposite (XPB-14A) structural layer, micrometeoroid barrier, and outer cover with thermal control coating. Six variations of a total composite wall design were fabricated at the end of the Task I phase and submitted for NASA-LRC consideration. As shown in Figure 9, these were XTC-1, XTC-2, XTC-3, XTC-4, XTC-5, and XTC-6.

After evaluation of the six advanced total composite wall constructions, XTC-4 and XTC-6 were mutually selected by NASA-LRC and GAC as the candidate total composites for evaluation in the Task II Qualification Test Program, and application to a lunar shelter structure. The process development for the two selected total composites proceeded in an orderly step-by-step program during this phase, resulting in definition of a specific fabrication process defined in enough detail to produce an expandable structure of "flight hardware" quality (Reference 1).

Thermal Control System Analysis

As the method of achieving heat transfer is completely interdependent with the fabrication technique task of the program, the thermal control analysis

TABLE IV. SUMMARY OF TEST RESULTS OBTAINED ON MATERIALS SUPPLIED TO NASA-WSTF FOR EVALUATION

Material	Thickness, In	Manufacturer or Source	Upward Flame Propagation Rate In 100% Oxygen at 6.2 psia [a]: Propagation Rate, in/sec	Observations	Odor Test [a] Max. Allow. Score<2.5: (A)	(B)	(C)
Mosites #1066 Fluorel Adhesive	(b) 0.002	Mosites Rubber Company, Inc.	3.68	Burned with orange flame	0.2	0.1	0.9
RL-3788 Fluorel Adhesive	(b) 0.002	Raybestos Manhattan Inc.	0.88	Burned with orange flame	0.2	0.3	1.3
81677 Beta Fabric	0.007	J. P. Stevens & Co., Inc.	0.00	Melting in immediate area of Igniter	0.2	0.4	1.0
Aclar 33c Film	0.001	Allied Chemical Co.	3.32	Burned with orange flame	0.3	0.4	0.8
Mosites #1062-C Fluorel Sponge	0.050	Mosites Rubber Company, Inc.	0.390	Burned with orange flame	0.0	0.4	1.6
XPB-10 Composite	0.065	Goodyear Aerospace Corp.	0.00	Failed to support combustion	0.1	0.5	1.6
Kapton Film	0.0005	E.I. duPont de Nemours & Co., Inc.	3.59	Burned with orange flame	0.1	0.0	0.4
Lito Flex K20 Asbestos Foam	0.75	Rex Asbestwerke Schabisch Hall, West Germany	0.00	Failed to support combustion	0.2	0.3	1.2
C-100-28 Refrasil	0.014	Hitco	0.00	Failed to support combustion	0.1	0.0	0.4
XPB-14A Composite	0.070	Goodyear Aerospace Corp.	0.00	Failed to sustain combustion	0.2	0.4	1.3
Al-4 White Se Polyester Foam	1.00	Merryweather Foam Latex Co.	50.00	Burned with orange flame	0.2	0.4	1.4
AD 917 Vitel Adhesive	(c) 0.002	Goodyear Tire & Rubber Co.	2.73	Burned with orange flame	0.2	0.1	0.5
XPB-14A-1(d) Composite	0.070	Goodyear Aerospace Corp.					

Material	Carbon Monoxide, [a] μgm/gm Max. Allow. 25.0	Total Organics, [a] μgm/gm Max. Allow. 100.0	Flash and Fire Point Temperature [a] Min. Allow. 450°F	DTA Temp of Max. Exotherm, °C	TGA: Temp of Max Endotherm, °C	TGA: Temp of Initial Wt Loss, °C	TGA: Wt, Change, %	MSC Test Report Number
Mosites #1066 Fluorel Adhesive	2.5	1.6	None to 315°C No visible change	290	None	255	0.6	2300
RL-3788 Fluorel Adhesive	0.9	1.7			None			2301
81677 Beta Fabric	1.3	0.4	None to 315°C	> 315	None	260	0.7	2302
Aclar 33c Film	1.3	13.0	None to 315°C	> 315	210	> 315	0.1	2303
Mosites #1062-C Fluorel Sponge	0.8	13.0	None to 315°C No visible change	> 315	None	300	1.1	2304
XPB-10 Composite	4.6	571.0	None to 315°C No visible change	> 315	None	245	1.2	2305
Kapton Film	2.5	5.8	None to 315°C No visible change	> 315	None	80	0.6	2349
Lito Flex K20 Asbestos Foam	4.5	15.0	None to 315°C No visible change	> 315	None	75	3.8	2350
C-100-28 Refrasil	0.8	0.5	None to 315°C No visible change	> 315	90	<25	4.6	2351
XPB-14A Composite	0.9	102.0	None to 315°C No visible change	> 315	None	160	1.1	2352
Al-4 White Se Polyester Foam	0.8	1.5	Flash Point, 271°C No fire point to 315°C	280	80	90	15.4	2353
AD 917 Vitel Adhesive	1.4	1,867.0	Flash point, 294°C No fire point to 315°C	> 315	None	90	5.8	2354
XPB-14A-1(d) Composite	1.3	15.0						2382

(a) Tested in accordance with MSC-D-NA-0002
(b) Applied to one side of 0.001" thick aluminum foil
(c) Applied to two sides of 0.001" thick aluminum foil
(d) XPB-14A-1 Same as XPB-14A except processed for minimum adhesive solvent entrapment

(A) 1-part sample atmos. to 29-parts 0_2
(B) 1-part sample atmos. to 9-parts 0_2
(C) No dilution

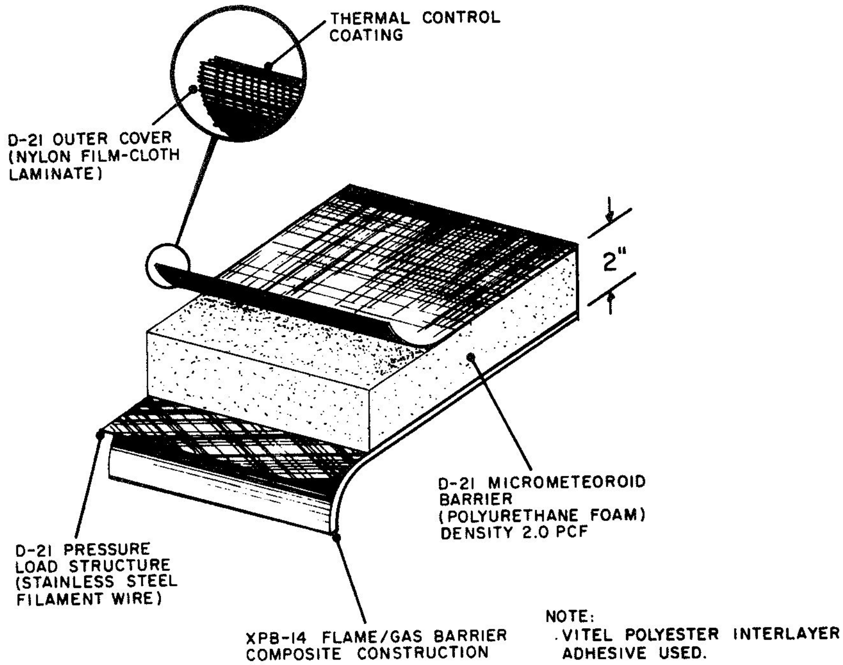
TABLE V. SUMMARY OF QUALIFICATION TESTS PERFORMED ON SUBCOMPOSITE AND TOTAL COMPOSITE FINAL CANDIDATES

Component / Test	Flame/Gas Barrier, XPB-14A	Structural Layer, XSL-3	Micrometeoroid Barrier, XMB-4	Outer Cover, XOC-2	Total Wall Composite,		Super-Insulation Blanket
					XTC-4	XTC-6	
1. Flammability 100% Oxygen at 6.2 psia							
a. Upward flame Propagation Test	X						(1)
b. GAC Diaphragm Flammability Test	X					X	
2. Packageability							(2)
a. Elastic Recovery; 75% compression for 30 days at 160°F			X				
b. Effect of Temperature on deployment force; -100°F to 75°F					X	X	
c. Single fold test; ability to unfold after 7 days at 160°F					X	X	
d. Effect of repeated creasing on gas impermeability						X	
3. Micrometeoroid Impact NASA-MSC-LRC Test					X (20 6"x6" specimens supplied to NASA)	X (20 6"x6" specimens supplied to NASA)	X (206 "x6" specimens supplied to NASA)
4. Thermal/Vacuum Exposure; 5×10^{-6} mm Hg, 48 hours at 160°F	X						
5. Effluent Gas Analysis							
a. Odor	X						
b. CO	X						
c. Total Organics	X						
6. Ply Adhesion	X					X	
7. Effect of Thermal Shock; -320° F to 250° F					X	X	
8. Stress-Strain Properties -100°F to 250°F	X	X single strand @ 75°F	X				X
9. Taber Abrasion	X			X			
10. Tear Resistance	X						X
11. Puncture Resistance	X	X combined with flame gas/barrier				X	
12. Humidity Resistance					X	X	
13. Fungus Resistance					X	X(3)	
14. Blocking Resistance				X			
15. Solar Absorptance and Infrared Emittance Properties				X			
16. Thermal Conductivity					X	X	X

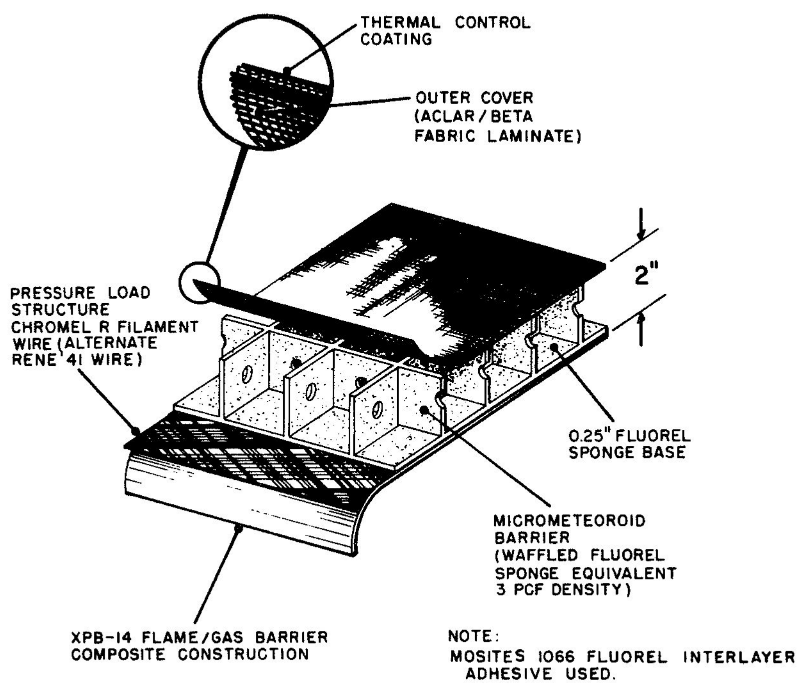
(1) Super-insulation blanket burns in 100% Oxygen at 6.2 psia - not required to pass Category A Test

(2) Super-insulation considered very packageable - no problems anticipated in this area

(3) Same material as used in XTC-6 evaluated

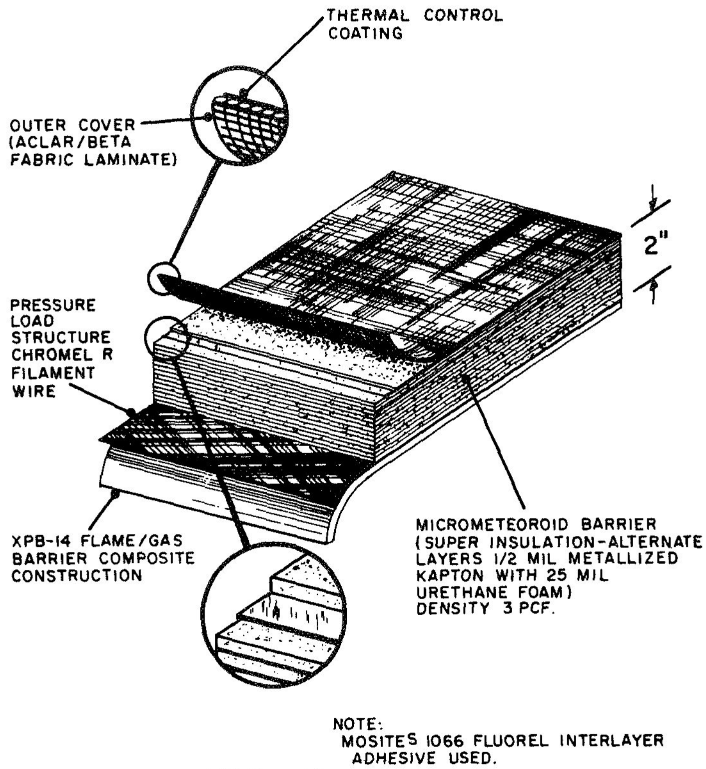


XTC-1

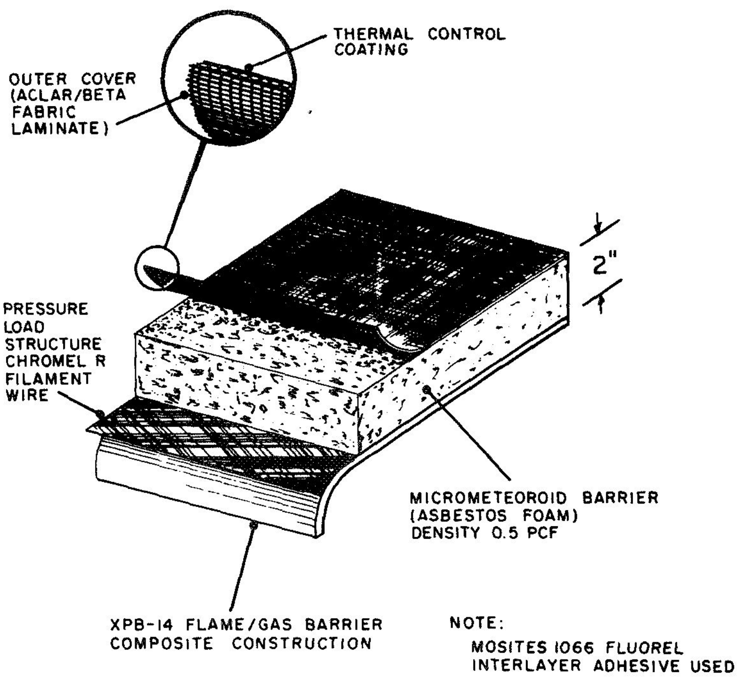


XTC-2

Figure 9. Advanced Composite Wall Constructions (Sheet 1)

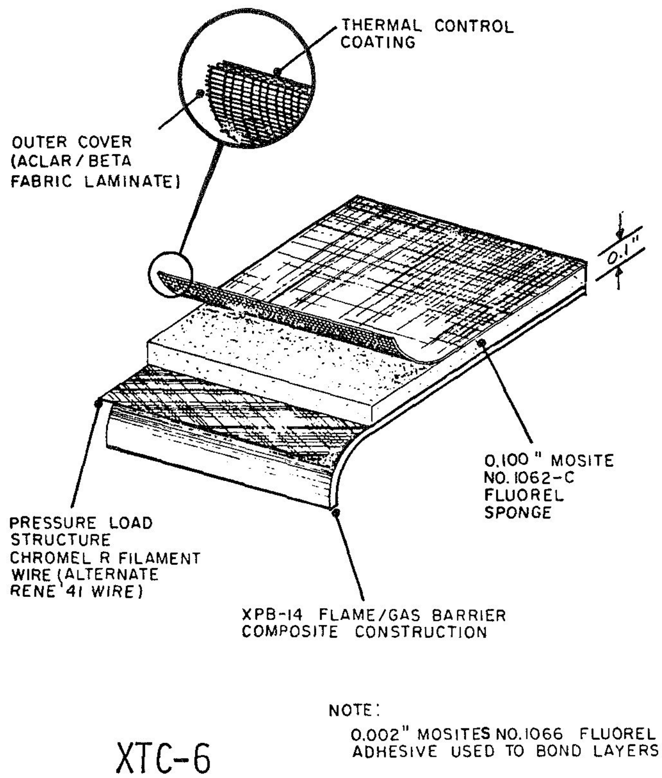


XTC -3



XTC-4

Figure 9. Advanced Composite Wall Constructions (Sheet 2)



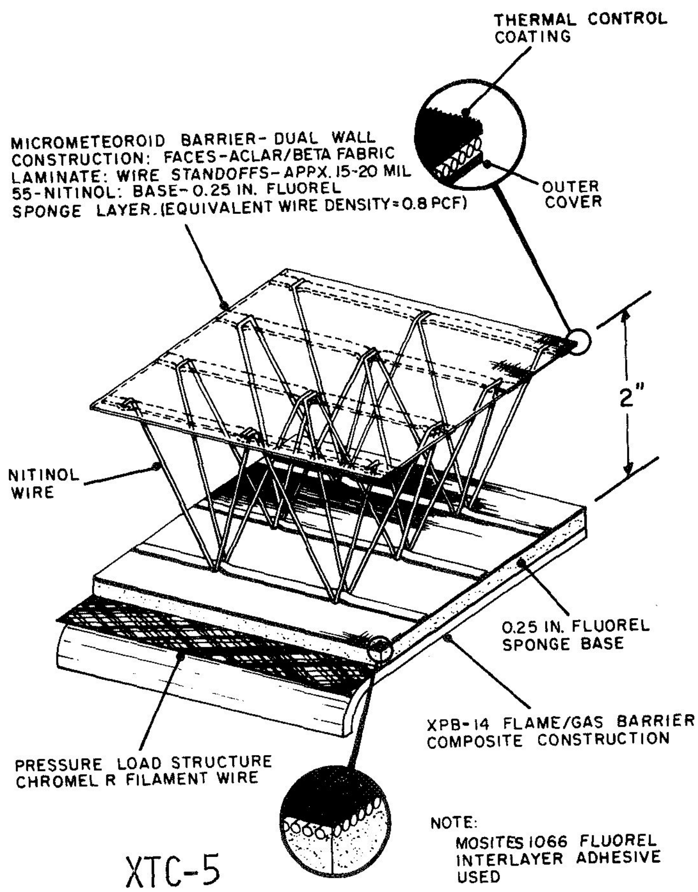


Figure 9. Advanced Composite Wall Constructions (Sheet 3)

effort deals primarily with determining heat transfer rates as related to total composites XTC-4 and XTC-6 mutually selected by NASA-LRC and GAC as the most promising candidate structures. Requirements for heat transfer between the inner and outer surface of the composite wall structure are related to the magnitude of external and internal heat loads. Studies directed towards the definition of thermal control for lunar shelter missions have indicated the requirements for heat transfer range from low values for low temperature environments, and low internal heat loads to high values for high temperature environments and high internal heat loads. Consequently, two different thermal control system concepts were analyzed for the program, defined as quasi-passive and active.

Quasi-passive. - This system will use the shelter as a space radiator for rejecting the internal generated heat loads, and is related to the XTC-6 total composite concept for heat transfer requirements.

Active. - This system will require some type of external heat exchanger where the internal heat energy as well as the penetrated energy through the shelter walls must be dissipated. This thermal control system is related to the XTC-4 total composite concept for heat transfer requirements.

The magnitude of maximum and minimum limits of heat transfer attainable with each of the XTC-4 and XTC-6 total composites is expected to provide most ranges of heat transfer anticipated for future space mission structural design requirements. Experimental test procedures and results for thermal conductivity are detailed in Reference 1.

Inspection and Quality Assurance Analysis

A program plan for methods of inspection and quality assurance is defined in sufficient detail in the Reference 5 final report for implementation with the fabrication process instructions, for production of "flight hardware" quality space structures.

CONCLUSIONS AND RECOMMENDATIONS

As a result of the logically phased development program of candidate materials selection and screening tests and qualification testing of total composites, very promising conceptual designs for composite wall structures were evolved applicable to expandable space structures. Two concepts of total composite wall construction are recommended, identified as XTC-4 and XTC-6 (Figure 9). In composite XTC-4, the micrometeoroid barrier is provided as a built-in "layer" of the total composite, and in composite XTC-6, the primary micrometeoroid barrier is provided exterior to the expandable structure, such as a "pup tent" overlay.

Although the primary objective in the program was to upgrade expandable type materials relative to the flammability hazard as applied to the fabrication of composite wall structures, many of the materials that were found acceptable for the total composites could also serve as candidates for other space structure material categories; e.g., curtains and bunks or other flexible type material furnishings. Also, other candidate materials evaluated in the survey such as the PBI polymer could provide a non-flammable rigid type resin-fabric laminate where required for terminal end rings, hatches or other rigid structural applications.

On the basis of the results of the candidate materials selection and screening test effort, it is concluded that presently there are no available plastic films, flexible adhesives, or thin gage elastomers that will satisfactorily meet the Category A Upward (Flame) Propagation Rate Test requirements.

Extensive development and test efforts conducted during the program have shown that it is feasible to construct the major subcomposite of the wall system, such as the flame/gas barrier, from a combination of nonflammable materials and materials with slow, in oxygen, burn rates in such a manner that the component will pass an upward flame propagation test. It has also been shown that considerable improvement in resistance to fire and heat damage is obtained through the use of a 3-layer "flame barrier" element. This element, consisting of bonded aluminum foil/Refrasil cloth/aluminum foil proved to be the best of the several investigated. Due to the high melting point of the Refrasil cloth and the heat sink characteristics of the aluminum foil the system affords excellent shielding for only a small additional weight.

In view of the excellent performance of the "flame barrier", it is possible that this concept might be applied to other design areas such as, aircraft, diving chambers, test chambers, etc.

While a large number of standard NASA tests were applied during the evaluation, it was felt that due to the unique characteristic of expandable shelters, a special test should be conducted to simulate what would happen if a sizable fire developed next to the surface of the shelter wall. This test, referred to as a Pressurized Diaphragm Flammability Test, proved highly informative and greatly assisted in the development of finally selected XPB-14A flame/gas barrier design. It is recommended that this system, or one similar, be adopted by NASA to evaluate future expandable structure wall materials.

The low temperature deployment is now considered to be the most critical requirement for any expandable type space structure. The cold temperature behavior of the selected total composites XTC-4 and XTC-6 was investigated during the qualification test phase of the program. A special fold test conducted on total composite specimens XTC-4 and XTC-6, indicated they would have a satisfactory low temperature deployment capability to -5°F and with possible deployment capability extending to a maximum of -43° F. It is recommended that further investigation of low temperature deployment capability of the XTC-4 or XTC-6 total composites be investigated in the form of a three-dimensional expandable structure, so as to narrow down the critical deployment temperature range.

Compatibility of the selected XTC-4 and XTC-6 total composite materials was also resolved with the other interdependent areas of fabrication processes, thermal control heat transfer, and quality assurance implementation. A step-by-step specific fabrication process is defined in enough detail to produce an expandable structure of "flight hardware" quality. The magnitude of maximum and minimum limits of heat transfer attainable with each of the XTC-4 and XTC-6 total composites is expected to provide most ranges of heat transfer anticipated for future space mission structural design requirements. A method of inspection and quality assurance program is defined in detail for implementation with the fabrication process for production of a "flight hardware" quality space structure.

As a result of program achievements, an updated expandable structure technology is now available for manned space mission applications such as auxiliary space station structures, airlocks, lunar shelters, or other space structure applications that require expansion in one piece from a small package into a larger dimension. Furthermore, while the strength-to-weight ratio comparison of expandable vs conventional hard structures are nearly equal, significant weight savings can be made with the expandable structure design. This is due to the expandable structures low packaging volume resulting in smaller drag area exposed during the launch phase with correspondingly smaller shroud area and structural loads.

This program herein was initially Phase I of a proposed two-phase effort of development. Phase II was proposed as practical application of the Phase I effort, to be demonstrated by the fabrication and test of a "second generation" space structure of "flight hardware" quality. As the Phase I materials technology and advancement has been successfully completed in this program effort, it is strongly recommended that the Phase II "flight quality" hardware program for a representative type expandable structure be implemented at the earliest possible date, so as to provide a solid technology for the development of mission-oriented space hardware.

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