Alternative Foam Treatments For The Space Shuttle's External Tank

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ALTERNATIVE FOAM TREATMENTS
FOR THE SPACE SHUTTLE'S
EXTERNAL TANK

by

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ABSTRACT

The Space Shuttle Columbia accident and the recent excitement surrounding Discovery's return to space brought excessive media attention to the foam products used on the External Tank (ET). In both cases, videos showed chunks of foam or ablative material falling away from the ET during lift off. This led to several years of investigation and research into the exact cause of the accident and potential solutions to avoid the problem in the future. Several design changes were made prior to the return to flight this year, but the ET still shed foam during lift off.

Since the Columbia accident, the loss of foam on ETs has been a significant area of interest for NASA, United Space Alliance, and Lockheed Martin. The Columbia Accident Investigation Board did not evaluate alternative materials but certainly highlighted the need for change. The majority of the research previously concentrated on improving the design and/or the application process of the current materials. Within recent years, some research and testing has been done to determine if a glass microsphere composite foam would be an acceptable alternative, but this work was overcome by the need for immediate change to return the shuttle to flight in time to deliver supplies to the International Space Station.

Through a better understanding of the foam products currently used on the ET, other products can be evaluated for future space shuttle flights and potential applications on new space vehicles. The material properties and the required functionality of alternative materials can be compared to the current materials to determine if suitable replacement products exist. This research also lends itself to the development of future space flight and unmanned launch vehicles.

In this paper, the feasibility of alternative material for the space shuttle's external tank will be investigated. Research on what products are used on the ET and a set of functional requirements driving the selection of those materials will be presented. The material properties of the current ET foam products will be collected and an evaluation of how those materials' properties meet the functional requirements will be accomplished. Then significant research on polymeric foams and ablative materials will be completed to learn how these various products can be applied in this industry. With this research and analysis, the knowledge gained will be used to select and evaluate the effectiveness of an alternate product and to determine feasibility of a product change with the current ET and the importance of maintaining the shuttle launch schedule. This research will also be used to evaluate the potential application of the alternative product on future platforms.

There are several possible outcomes to this research. This research could result in a recommended change to the ET foam material or a perfectly acceptable alternative material that could result in a cost or schedule impact if implemented. It is also possible that there exists no suitable alternative material given the existing functional requirements. In any case, the alternative material could have future applications on new space vehicles. A set of results from the research and analysis will be provided along with a recommendation on a future material for use on space vehicles.

Dedicated to the STS-107 space shuttle Columbia crew and their families.

Rick D. Husband, Commander

William C. McCool, Pilot

Michael P. Anderson, Payload Commander

David M. Brown, Mission Specialist

Kalpana Chawla, Mission Specialist

Laurel Blair Salton Clark, Mission Specialist

Ilan Ramon, Payload Specialist

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LIST OF ACRONYMS/ABBREVIATIONS

C	Celsius
CEV	Crew Exploration Vehicle
CFC	Chlorofluoromethane
ET	External Tank
F	Fahrenheit
GWP	Global Warming Potential
ISS	International Space Station
LWT	Light Weight Tank
NASA	National Aeronautics and Space Administration
NCFI	North Carolina Foam Insulation
ODP	Ozone Depletion Potential
SLA	Super Lightweight Ablator
SLWT	Super Light Weight Tank
SWT	Standard Weight Tank
USA	United Space Alliance

1 INTRODUCTION

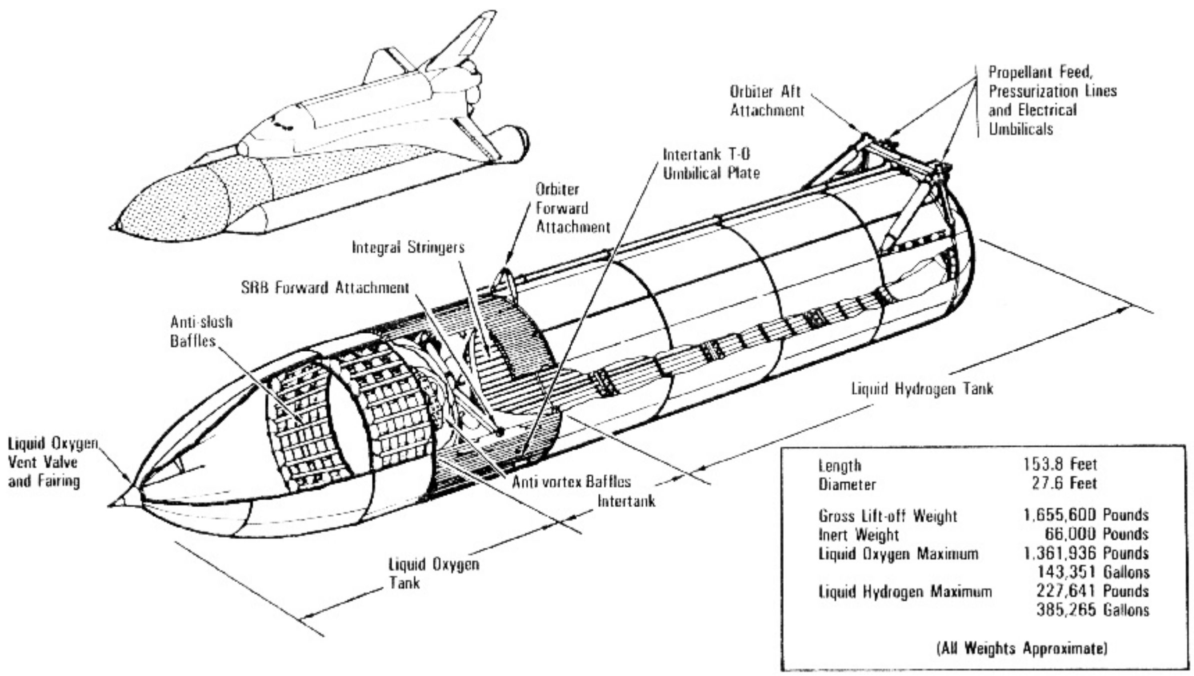
When space shuttle Columbia was destroyed during reentry on Feb 1, 2003, the nation once again mourned the loss of seven astronauts. People who followed the space program from the beginning knew that this loss would be felt for a very long time. It took about two years for the shuttle program to recover from this tragedy just as it did after the 1986 Challenger accident. Eighty-five successful shuttle flights took place between these shuttle disasters. Were those flights just lucky?

Since the Columbia accident, the loss of foam on the External Tank (ET) has been a significant area of interest for NASA, United Space Alliance, and Lockheed Martin. The Columbia Accident Investigation Board did not evaluate alternative materials but highlighted the need for change. The majority of the research previously concentrated on improving the design and/or the application process of the current materials. Within recent years, some research and testing has been done to determine if a glass microsphere composite foam would be an acceptable alternative, but this work was overcome by the need to return the shuttle to flight in time to deliver supplies to the International Space Station.

Through a better understanding of the foam products currently used on the ET, other products can be evaluated for future space shuttle flights and potential applications on new space vehicles. The material properties and the required functionality of alternative materials can be compared to the current materials to determine if suitable replacement products exist. This research also lends itself to the development of future space flight and unmanned launch vehicles.

1.1 Background

The space shuttle's external tank stores and supplies the fuel for the orbiter's three main engines during lift-off and ascent. There are three major sections to the ET, the liquid oxygen tank, the intertank, and the liquid hydrogen tank, shown in Figure 1, for a total height of 153.8 feet and a diameter of 27.6-feet.



Lightweight External Tank

Source: http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/et.html

Figure 1 External Tank Diagram

The liquid oxygen tank holds approximately 143,000 gallons (1,361,936 lbs) in a 19,563 ft^3 tank and supplies oxygen to the space shuttle's main engines at a rate of approximately 2,787 pounds per second. Similarly, the liquid hydrogen tank has a volume of 53,518 ft^3 containing about 385,000 gallons (227,641 lbs) and fuels the main engines at a rate of 465 pounds per second to the main engines. The intertank separates the oxygen and hydrogen tanks, houses the ET instrumentation, and provides an interface for ground operations. It is 270 inches long and weighs 12,100 pounds.

The ET has seen several changes since the beginning for the shuttle program in order to reduce its weight. For every pound of weight removed from the ET, the shuttle's payload capacity is increased by almost one pound. After STS88, the first mission to the International Space Station (ISS), the weight became critical as the shuttle was required to carry heavier payloads to the ISS. The changes to the ET are summarized in Table 1.

Table 1. External Tank Evolution

Tank Type	Missions	Inert Weight	Construction Materials
SWT (white) Standard Weight Tank	STS1 - 2	75,500	Aluminum, Steel Alloy & Titanium
SWT (orange) Standard Weight Tank	STS3-5, 7	75,000	Aluminum, Steel Alloy & Titanium
LWT Light Weight Tank	STS6, 8-90	65,500	Aluminum, Steel Alloy & Titanium
SLWT Super Light Weight Tank	STS90 - on	58,000	Aluminum Lithium Alloy

In addition to the changes to reduce the ET weight, changes to the foam blowing agents were required in order to comply with new EPA regulations on the use of FREON. HCFH-142b was selected as the replacement for FREON. In 1997, this blowing agent change was implemented for STS87, just prior to the introduction of the SLWT for STS90.

The ET thermal protection system serves two purposes. It provides insulation for the fuel, which in turn protects the tank from the formation of ice during fueling on the launch pad, and it protects the tank from the heat generated by aerodynamic forces during ascent. The thermal protection system is made up of spray-on foam insulation and molded ablative materials with a total weight of 4,823 pounds, 8% of the total inert tank weight.

1.2 Columbia Accident

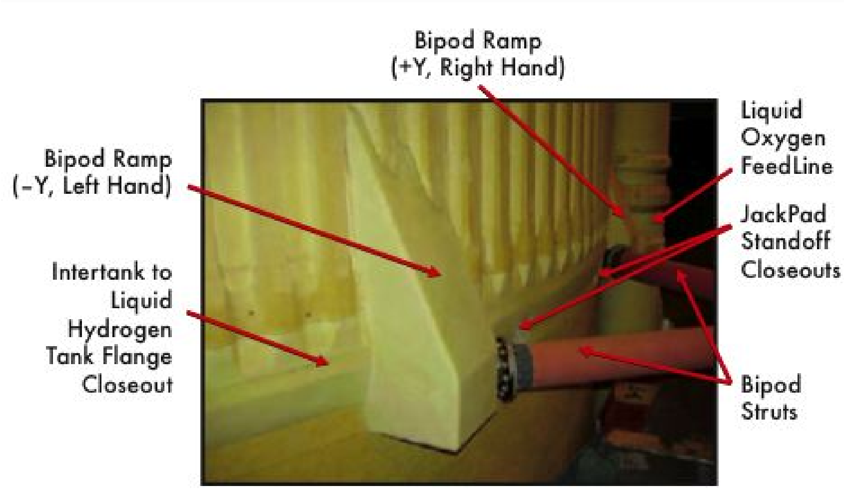
The ET thermal protection system gained public visibility after the Columbia accident. The Columbia Accident Investigation Board's (CAIB) final report details the damage sustained by the orbiter during lift-off. The following passage from the report summarizes the issue at hand.

> *"The physical cause of the loss of Columbia and its crew was a breach in the Thermal Protection System on the leading edge of the left wing. The breach was initiated by a piece of insulating foam that separated from the left bipod ramp of the External Tank and struck the wing in the vicinity of the lower half of Reinforced Carbon-Carbon panel 8 at 81.9 seconds after launch. During re-entry, this breach in the Thermal Protection System allowed superheated air to penetrate the leading-edge insulation and progressively melt the aluminum structure of the left wing, resulting in a weakening of the structure until increasing aerodynamic forces caused loss of control, failure of the wing, and breakup of the Orbiter."*

The left bipod ramp, as seen in Figure 2, is identified by the upper red circle and the impact location on the shuttle's wing is identified by the lower red circle. Figure 3 provides a closer look at the left bipod which is used to lower aerodynamic drag and thus prevent aerodynamic heating of the structural fittings connecting the ET to the shuttle. In the cutaway drawing of the bipod ramp, Figure 4, the various materials used to build up the ramp are identified and the basic ramp size id defined.

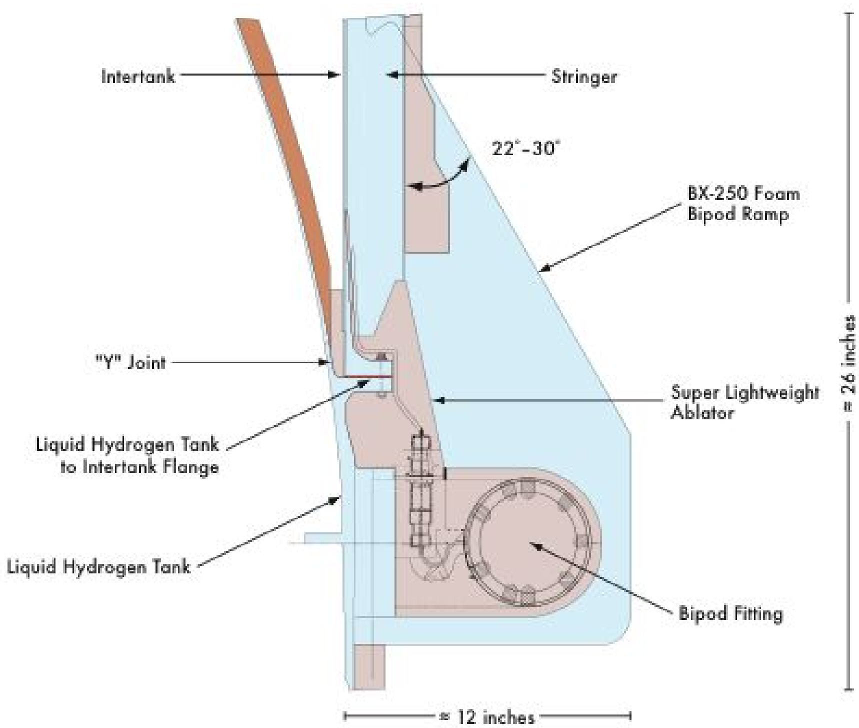
Source: CAIB Report

Figure 2 Columbia at the Launch Pad



Source: CAIB Report

Figure 3 Left Bipod Attachment Area



Source: CAIB Report

Figure 4 Bipod Ramp Cutaway Drawing

The bipod ramp is created from a super lightweight ablator (SLA-561) and insulating foam (BX-250). After both materials are applied and allowed to cure, the area is shaved to form the more aerodynamic ramp shape. The finished product is visually inspected but no nondestructive testing is preformed. These materials will be discussed in greater detail in Section 2.

1.3 Discovery's Return to Space

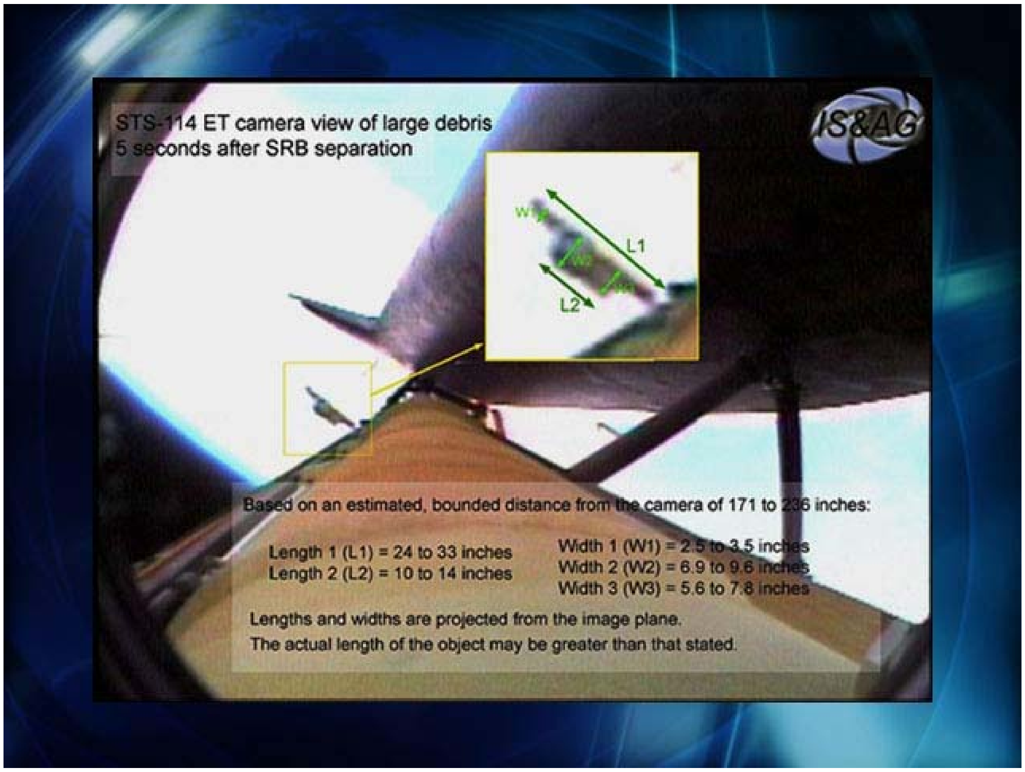
The recommendations from the CAIB resulted in several changes to the ET prior to Discovery's return to space. The Marshall STAR Special Edition, July 14, 2005 provided the following summary of the ET enhancements.

> *"First, the large insulating foam ramps that flew on STS-107 have been removed from the forward bipod fittings — part of the tank-to-Orbiter attachment structure — and replaced with rod-like heaters to help prevent ice from forming on the fittings. In the original design, the ramps helped to prevent ice buildup on the fittings — a potential debris source. The fittings themselves — each tank has two — are the same basic design as before. Secondly, a small, flashlight-size camera has been placed in the tank's liquid oxygen fuel line fairing to record any possible debris that might be shed during ascent. The Thermal Protection System on the tank's bellows — joints that allow the tank's fuel line to flex — also has been reshaped to a squared "drip-lip" that allows moisture to run off instead of building. Plus a copper-nickel alloy strip heater, similar to heaters used on the Solid Rocket Motor joints, will keep the bellows area slightly warmer than freezing, about 40*

degrees Fahrenheit. And lastly, the bolts on the tank's liquid hydrogen flange — a bracket that permits one object to attach to another — are being reversed, a sealant is now being applied to the bolt threads, and the final foam spray on the flange area now includes a new process that incorporates a mold to form the foam."

In addition to the physical modifications, the application process was revisited. Employees were retrained and certified for the spraying procedure. During the foam application, an additional employee is present to verify proper spray technique. Upon completion, non-destructive testing is done to check for voids under the foam surface. These tests include backscatter radiography for thin foam or near surface investigation and tetrahertz imaging for areas of thicker foam. Both testing procedures are similar to conventional X-rays except the image is produced from backscatter instead of emitting through the subject. Flaws in the foam ranging from .25 inches to 2 inches have been detected and were found to be sources of de-lamination requiring repair. These procedural changes may seem insignificant but the foam blowing agent and consistency of the application will determine the mechanical properties of the final product. Properties, such as strength and density, can easily be adversely affected by an inconsistent spraying technique or voids in the material.

Even with all these enhancements, video revealed that the ET still lost foam during Discovery's lift-off, as seen in Figure 5. This triggered NASA to suspend all future missions until the problem could be solved.



Source: www.space.com/missionlaunches/050727_rtf_sts114_shuttle_grounded.html

Figure 5 Video from Discovery's Lift-off

The post flight inspection of the shuttle thermal protection tiles revealed a drastic reduction in the number of damaged tiles compared to previous flights. Under any other circumstances, this would be considered a success but when human life is at risk, close isn't good enough.

1.4 Materials

1.4.1 Ablative Material

Ablative material is required to protect structural members that would be exposed to high temperatures created by aerodynamic forces. Although this protective layer is referred to as a material, it's actually a complex composite, which reacts to heat through thermal ablation. The widely accepted definition of thermal ablation is a self-controlled uniform process of heat absorption, utilizing the entire heat content of a material to include vaporization or even disassociation and utilizing air flow for continuous removal of the resulting products.

1.4.2 Polymeric Foam

Polymeric foams encompass a wide variety of materials with applications across a multitude of fields. Foams can be classified as flexible, semi-flexible, or rigid depending on the degree of hardness required for the application. They can be further classified by how the foam is formed. Thermoplastic polymers are solids that contain a blowing agent, which are melted to take to desired shape and cooled back to a solid stable foam. Thermosetting foams are partially reacted fluid, which is foamed by adding a blowing agent and then cured to form a stable solid foam. In order to limit the scope of the material investigation, polymeric foam research will be limited to rigid thermosetting foam products.

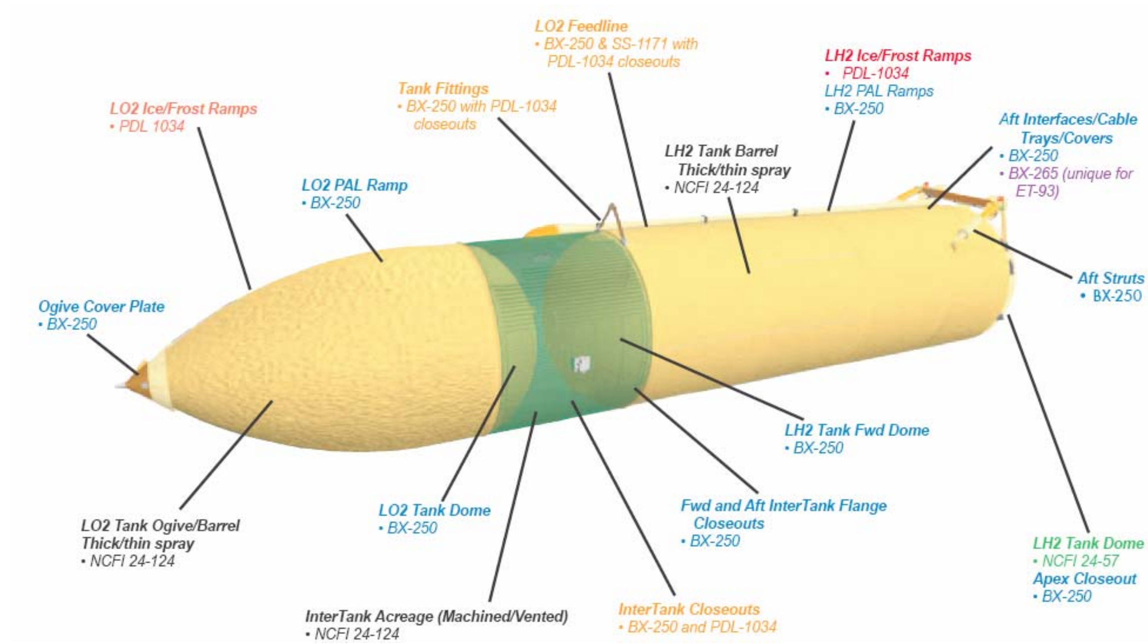
2 CURRENT PRODUCTS IN USE

2.1 Products

The CAIB report provided an excellent summary of most of the foam products used in the ET thermal protection system. The following excerpt and Figure 6 are taken directly from the CAIB report. Figure 7 offers further details on where the ablative materials are applied.

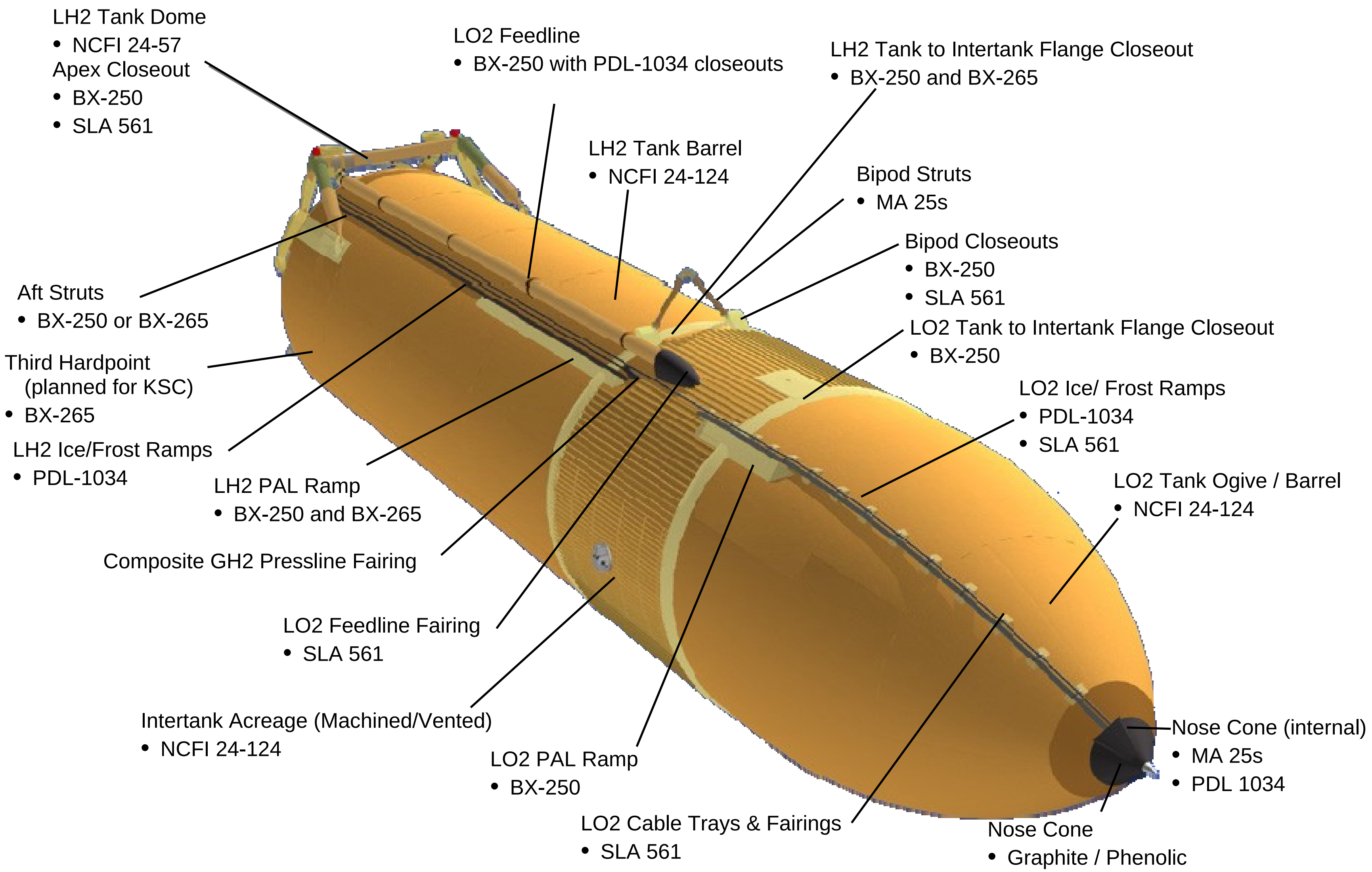
> *"Most of the External Tank is insulated with three types of spray-on foam. NCFI 24-124, a polyisocyanurate foam applied with blowing agent HCFC 141b hydrochlorofluorocarbon, is used on most areas of the liquid oxygen and liquid hydrogen tanks. NCFI 24-57, another polyisocyanurate foam applied with blowing agent HCFC 141b hydrochlorofluorocarbon, is used on the lower liquid hydrogen tank dome. BX-250, a polyurethane foam applied with CFC-11 chlorofluorocarbon, was used on domes, ramps, and areas where the foam is applied by hand. The foam types changed on External Tanks built after External Tank 93, which was used on STS-107, but these changes are beyond the scope of this section.*
>
> *Metallic sections of the External Tank that will be insulated with foam are first coated with an epoxy primer. In some areas, such as on the bipod hand-sculpted regions, foam is applied directly over ablator materials. Where foam is applied over cured or dried foam, a bonding enhancer called Conathane is first applied to aid the adhesion between the two foam coats.*

After foam is applied in the intertank region, the larger areas of foam coverage are machined down to a thickness of about an inch. Since controlling weight is a major concern for the External Tank, this machining serves to reduce foam thickness while still maintaining sufficient insulation."



Source: CAIB Report

Figure 6 ET-93 Foam Systems and Locations



Source: Muratone, slide 5

Figure 7 Ablative and Foam Products on the ET

The products identified in Figures 6 and 7 are collected in Table 2 with their function and manner of application.

Table 2. Existing Products in Use

Material Number	Foam Type	Function	Blowing Agent
NCFI 24-124	Polyisocyanurate	Insulation	HCFH 141b
NCFI 24-57	Polyisocyanurate	Insulation	HCFH 141b
BX-250	Polyurethane	Insulation	CFC-11
BX-265	Polyurethane	Insulation	HCFH 141b
MA-25	Elastomeric silicone	Ablator	N/A
SLA-561	Cork filled elastomeric silicone	Ablator	N/A
PDL-1034	Urethane	Repairs	N/A

2.2 Material Properties

The material properties for the previously listed products are shown in Table 3.

Table 3. Properties of Existing Products

Material Number	Typical Tensile Strength @ -423	Typical Tensile Strength @ +300	Min Compression Strength	Max Thermal Conductivity
NCFI 24-124	34	32	25	0.025
NCFI 24-57	49	36	35	0.0225
PDL-1034	50	71	30	0.016
BX-250	62	35	24	0.015
BX-265	62	35	24	0.015
SLA-561	60	60	72	0.038
MA-25	40	40	-	0.06

Source: Paul Sierpinski, USA – ET Mechanical Engineer

3 FUNCTIONAL REQUIREMENTS FOR ET THERMAL PROTECTION PRODUCTS

3.1 Ablative Material Requirements

The general requirements for ablative materials are well defined in Chapter 4 of MATERIALS FOR MISSILES & SPACECRAFT by Parker. According to Parker, the utilization of all heat-absorbing properties can only take place if the material can be retained at the surface long enough to vaporize. This requires a framework of material of higher refractoriness in which the ablative materials are embedded and held in place until vaporization. The ablation process must be confined to a minuscule surface layer for uniform surface removal and function continuously during the heating process. A material of low conductivity will provide a steep thermal gradient. When ablative materials of high conductivity are required, a matrix material of low conductivity in continuous phase is needed to reduce the overall conductivity of the composite. Uniformity can further be ensured by a heterogeneous material structure where any change of state is confined in the thickness direction. All these requirements make a heterogeneous (composite) material imperative for ablative materials. The following primary requirements must be met in the development or selection of ablative materials.

- High heat content
- Low overall thermal conductivity
- Heterogeneous or composite structure

3.2 Foam Insulation Requirements

The foam insulation must maintain an interior temperature that keeps its contents, oxygen and hydrogen, at a liquid state while preventing ice and/or frost from forming on the exterior parts and surfaces of the ET. It's important to note that liquid oxygen is stored at –297 ^{o}F (-183 ^{o}C) and liquid hydrogen is stored at –423 ^{o}F (-253 ^{o}C).

3.3 Derived Functional Requirements

As previously mentioned in Section 1.1, the total weight of the foam and ablative materials on the ET is 4,823 pounds and for every pound of weight removed from the ET, the shuttle's payload capacity is increased by almost one pound. This provides a derived requirement for the weight of any material change. The new foam or ablative materials shall have a minimal impact on the ET weight. This can be interpreted to mean the alternative product must have a low density.

Another derived requirement comes from the evolving environmental laws related to the blowing agents used to apply various foam products. Environmental concerns about the ozone layer and the greenhouse effect led to laws restricting the use of Freon and/or CFC blowing agents. In order to give industrial users a chance to react to the laws, the restrictions are being gradually implemented for users of existing products. However, the laws do not give any latitude for the use of new products or replacement products. Blowing agents are rated by their global warming potential (GWP) and ozone depletion potential (ODP). This leads to the derived requirement that any alternative product selected for the ET shall use a blowing agent with low GWP and ODP values.

4 EXISTING PRODUCTS VS THE FUNCTIONAL REQUIREMENTS

4.1 Ablative Materials

In Section 2.1, SLA-561 and MA-25 are listed as ablative products currently in use on the ET. They are both described as elastomeric silicone composites, which meets the composite structure requirement. Table 4 identifies the ingredients that make up the SLA-561 composite. The low thermal conductivity requirement is met by the values shown in Section 2.2 (both values are less than 0.1). Section 2.2 also lists tensile strength values at 300 ^{o}F, which mean the materials are still structurally sound with high heat content.

Table 4. Composition of SLA-561

Ingredient Material	**Ingredient Density** (g/cm^3)	**% by mass**	**% by Volume**	**Volumetric Parts**
Elastomer	0.995	24.57	5.55	100
Silica Fibers	2.2	2.92	0.3	5.4
Carbon Fibers	1.85	2.34	0.3	5.4
Silica Microspheres	0.18	35.1	43.9	790.99
Phenolic Microspheres	0.092	5.85	14.35	258.55
Cork	0.186	29.22	35.6	641.51
Total		100	100	1801.85

Source: Donskoi, Page 143

4.2 Foam Insulation

Section 2.1 identified NCFI 24-124, NCFI 24-57, BX-250, and BX-265 as insulation products used on the ET. Table 3 in Section 2.2 shows that all these insulation products still have tensile strength at –423 ^{o}F, therefore meeting the temperature requirements. However, it is not obvious from the Properties of Existing Products table, Table 3, that these products also have relatively low densities. In general, the physical properties of rigid urethane foams depend on density. The relationship between density and tensile strength is linear; therefore the low strength values shown in the table are also an indication of low density.

4.3 Blowing Agents

Table 2 in Section 2.1 lists the blowing agents used for each foam product used on the ET. Most of the ET foam products use HCFC-142b with an ODP value of 0.06 and a GWP value of 1,800. Table 5 compares the properties of those blowing agents with other CFC and HCFC blowing agents. Table 6 summarizes a few of the new blowing agents either under development or on the market. HCFC-142b has lower ODP and GWP values than some of the other blowing agents, which meets the requirement, but there is room for improvement.

Table 5. Properties of CFC & HCFC Blowing Agents for Cellular Polymers

Compound	Molecular Weight	Boiling Point ^oC	Thermal Conductivity W/(mK)	ODP Relative to CFC-11	GWP Relative to CO_2
Trichlorofluoromethane (CFC-11)	137.4	23.8	0.0084	1	3400
Dichlorodifluoromethane (CFC-12)	120.9	-29.8	0.0098	1	7100
Chlorodifluoromethane (HCFC-22)	86.5	-40.8	0.0106	0.5	1600
Chloro-1,1-difluroethane (HCFC-142b)	100.5	-9.2	0.0107	0.06	1800
1,1-Difluoroethane (HFC-152a)	66.1	-24.7	0.0137	0	150
Dichlorodifluoroethane (HCFC-141b)	117	32	0.067	0.1	610
1,1,1,2-Tetrafluoroethane (HFC-134a)	102	-26.5	0.0126	0	1200
Pentafluoropropane (R-245fa)	134.1	15.2	0.097	0	820
Pentafluorobutane (R-365mfc)	148	40	0.073	0	830

Source: Klempner, Page 194

Table 6. Properties of CFC Free Blowing Agents for Cellular Polymers

Compound	Molecular Weight	Boiling Point ^oC	Thermal Conductivity W/(mK)	ODP Relative to CFC-11	GWP Relative to CO_2
Methyl Chloride	50.5	-24.2	0.0105	0.018	-
Ethyl Chloride	64.5	12.3	0.0095	0.003	-
n-Pentane	72.2	36.1	0.095	0	11
I-Pentane	72.2	27.9	0.092	0	11
n-Butane	58.1	-0.5	-	0	-
I-Butane	58.1	-11.7	0.0161	0	-
Carbon Dioxide	44	-88.2	0.0168	0	1

Source: Klempner, Page 194

5 POLYMERIC FOAM ALTERNATIVES

Section 5 introduces several polymeric foam product alternatives and provides the associated mechanical properties for those products. A comparison of their properties is presented in Section 7 along with the feasibility of utilizing these products on the ET.

5.1 Thermoplastic Structural Foam

The term “Structural Foam” originally referred to cellular thermoplastic parts with integrated solid skins. Now, the term covers any high-density rigid cellular plastics strong enough for structural applications. Table 7 summarizes the properties for a variety of thermoplastic materials.

Table 7. Physical Properties of Thermoplastic Structural Foam

(at .250 Wall With 20% Density Reduction)										
Property	**Unit**	**Method of Testing**	**High Density Polyethylene**	**ABS**	**Modified Polyphenylene Oxide**	**Polycarbonate**	**Thermoplastic Polyester**	**Polyproylene**	**High Impact Polyproylene**	**High Impact Polystyrene w/FR**
Specific Gravity	lbs./ft.^{3}	ASTM-D-792	0.60	0.86	0.85	0.90	1.20	0.67	0.70	0.85
Deflection temperature under load	^{o}F at 66 psi ^{o}F at 264 psi	ASTM-D-792	129.6 93.5	187 172	205 180	280 260	405 340	167 112	189 176	194 187
Coefficient of thermal expansion	in. / in. / ^{o}F X 10^{-5}	ASTM-D-696	12	4.9	3.8	2	4.5	5.2	9	4.5
Tensile Strength	psi	ASTM-D-638	1,310	3,900	3,400	6,100	9,910	1,900	1,800	2,300
Tensile modulus	psi	ASTM-D-638		2,500,000	235,000	300,000	1,028,000	79,000	141,160	245,000
Flexural modulus	psi	ASTM-D-790	120,000	2,800,000	261,000	357,000	1,000,000	80,400	200,321	275,000
Compression strength (10% deformation)	psi	ASTM-D-695	1,840	4,400	5,200	5,200	11,300	2,800	3,447	-
Combustibility rating	psi	UL Standard 94^o	-	V-0	V-0/5V	V-0/5V	V-0	HB	HB	V-0

Source: Landrock, Page 224

5.2 Phenolic Foam

Phenolic foams are classified as follows:

Type A - High closed-cell content
Low thermal conductivity
High fire resistance

Type B - High closed-cell content
Low thermal conductivity
Low fire resistance

Type C - Open cell
High strength

Type D - Open cell
Low strength

These general properties are summarized in Table 8.

Table 8. General Properties of Typical Phenolic Foams

Material	Phenolic Foam				(cf) PIR Foam
Items	**Closed Cell, Type A**	**Closed Cell, Type B**	**Open Cell, Type C**	**Open Cell, Type D**	
Density (kg/m^3)	40	40	50	25	35
Thermal Conductivity (kcal/mh ^oC)	0.020	0.020	0.035	0.035	0.020
Closed-Cell Content (%)	90	90	0	0	90
Water Absorption (g/100 cm^3)	4	4	12	12	3
Limited Oxygen Index (%)	50	33	33	33	26
Surface Fire Test					
C_A	5	25	10	5	50
T θ (min, ^oC)	50	170	50	70	80
After-glowing Time (sec)	0	0	0	0	0
Popping	None	Exiting	None	None	None
Criteria	OK	No Good	OK	No Good	OK

Source: Landrock, Page 207

5.3 Resol-Type Foam

Resol-Type foam is formed as a result of a reaction between phenol and aldehyde in the presence of a catalyst. Its properties vary depending on the ratio of the reactants and the manufacturing process. The block foaming process results in bulk production of foam blocks that can then be cut to the desired shape. Table 9 shows the range of properties that can be obtained during the block foaming process.

Table 9. General Properties of Resol-Type Foam Prepared by the Block Foaming Process

Properties	Value Ranges	
Density (kg/m^3)	60	35
Compression Strength (kg/cm^2)	2	1.6
Flexural Strength (kg/cm^2)	8	5.5
Tensile Strength (kg/cm^2)	1.1	1.1
Thermal Conductivity (kcal/mh ^oC)	0.029	0.025
Thermal Expansion ($l/^oC$)	$3 X 10^{-5}$	$3 X 10^{-5}$
Water Absorption ($g/100cm^2$)	2	2
Limiting Oxygen Index	>40	>40
Specific Heat (cal/g ^oC)	0.48	0.48

Source: Landrock, Page 208

Resol-Type foam can also be produced through a spray process but it requires a temperature of 10 – 20 ^oC for the foam to fully form. The general properties of the sprayed foam are summarized in Table 10.

Table 10. General Properties of Resol-Type Foam Prepared by the Spray Process

Properties	Values
Density (kg/m^3)	35 - 45
Compression Strength (kg/cm^2)	Less than 10
Water Absorption ($g/100cm^2$)	3 to 4
Water Absorption (kg/cm^2)	More than 1.0
Thermal Conductivity (kcal/mh ^oC)	Less than 0.03

Source: Landrock, Page 208

5.4 Novolac Type Foams

Similar to Resol-Type foam, Novolac-Type foam production uses phenols and aldehydes as reactants. Novolac-Type foam differs in that it requires the presence of an acidic catalyst. It can be formed in a mold or hot press with negligible variation in the final properties. The general properties of Novolac-Type foam are collected in Table 11.

Table 11. General Properties of Novolac Type Foam

Properties	Values
Density (kg/m^3)	40
Compression Strength (kg/cm^2)	1.8
Flexural Strength (kg/cm^2)	5.9
Water Absorption ($g/100cm^2$)	0.5
Thermal Conductivity (kcal/mh ^oC)	0.024
Specific Heat (cal/g ^oC)	0.3

Source: Landrock, Page 209

5.5 PVC Foams

PVC foam is used as the core for sandwich panels in structural and non-structural applications. In the aerospace industry, it is commonly used externally for radomes and internally for floors. Tables 12 and 13 provide the properties of PVC foams at various densities for linear and cross-linked PVC.

Table 12. Linear PVC Foams

	Density (kg/m^3)		
	60	**90**	**140**
Compression Strength (MPa)	0.38	0.9	1.6
Compression Modulus (GPa)	0.03	0.056	0.135
Tensile Strength (MPa)	0.9	1.4	2.4
Tensile Modulus (GPa)	0.03	0.05	0.09
Thermal Conductivity (W/m C)	0.034	0.037	0.039

Source: Biron, Page 391

Table 13. Crosslinked PVC Foams

	Density (kg/m^3)		
	30	**100**	**400**
Max Service Temp (degrees C)	80	80	80
Min Service Temp (degrees C)	-200	-200	-200
Compression Strength (MPa)	0.22	1.7	11.24
Compression Modulus (GPa)	0.012	0.125	0.5
Tensile Strength (MPa)	0.51	3.1	12.4
Tensile Modulus (GPa)	0.02	0.105	0.469
Thermal Conductivity (W/m C)	0.03	0.04	0.06

Source: Biron, Page 391

5.6 Polyethylene, Polypropylene, and Polyetherimide

Polyethylene, Polypropylene and Polyetherimide are grouped together because of their similar properties as shown in Table 14. Like PVC, these foams are used in sandwich panel technology. Although these products have similar properties, they have very different applications. Polyethylene and Polypropylene are limited to non-structural applications such as helmets and the damping core of car bumpers. This limitation is caused by a very low compressive strength value. As seen in Table 14, Polyetherimide has a higher compressive strength value and therefore it is suitable for structural applications. It is commonly used in the automotive industry and in the aerospace industry for radomes. It is also frequently used in cryogenic applications.

Table 14.   Foam Properties

	Polyethylene	**Polypropylene**	**Polyetherimide**
Density (kg/m^3)	25 to 185	23 to 70	80
10% Compression Stress (MPa)	0.012 to 0.160	0.02 to 0.07	0.95
50% Compression Stress (MPa)	0.080 to 0.33	0.11 to 0.56	-
Tensile Strength (MPa)	0.14 to 3.9	0.20 to 1.2	1.8
% Elongation @ Break	80 to 425	15 to 400	-
Thermal Conductivity (W/m K)	0.034 to 0.067	0.034 to 0.042	0.025
Service Temperatures (degrees C)	-80 to +100	-80 to +120	-194 to +180

Source: Biron, Page 394

6 ABLATIVE MATERIAL ALTERNATIVES

Section 6 introduces several ablative material alternatives and provides the associated mechanical propertied for those products. A comparison of their properties is presented in Section 7 along with the feasibility of utilizing these products on the ET.

6.1 Concept of Ablation

According to Chapter 13 of MATERIALS BACKGROUND TO SPACE TECHNOLOGY, successful ablative materials require that the absorption of a quantity of heat (q) result in a small loss of material (m). Meaning, the heat of ablation (Q) should be large. The following relationships will not be discussed in any detail but will be referenced in future property tables.

$$Q = \frac{\dot{q}}{\dot{m}} \qquad (1)$$

$$\dot{q} = h(T_e - T_w) \qquad (2)$$

$$Q = Q_A + \eta(h_e - h_w) \qquad (3)$$

Where:

$\dot{q}$ = rate of heat absorption

$\dot{m}$ = rate of material loss

T_e = temperature @ edge

T_w = temperature @ wall

h = specific enthalpy (subscript for wall or edge)

η = transpiration factor

Q_A = sum of heat required to raise the material to sublimation temperature

These equations are applicable for ablative materials which undergo sublimation. Sublimation is the change of material state from solid to gas without going through the liquid phase. In other types of ablative materials, the gas (or liquid) can be trapped under a charred surface that is rapidly formed during initial heating. This trapped gas (or liquid) will then absorb the heat and protect the structure underneath. The protection provided by ablative materials is directly related to the thermal history imposed on them. The effectiveness may degrade if the severity of the conditions is reduced.

Chapter 4 of MATERIALS FOR MISSILES AND SPACECRAFT provides the following example of an ablative material and the changes that occur to make it effective. Phenolic resin-fiber glass is not a high heat resistant matrix but at high heat flux rates it is charred instantly. This forms a highly heat resistant carbon skeleton where the glass fibers are held in place while melting. The glass also changes state during the heating process. The flux constituents boil away leaving almost pure silica at the surface. This acts as a highly viscous shield that maintains a uniform surface while slowly moving downstream.

6.2 Materials

6.2.1 Teflon

During ablation, Teflon undergoes sublimation resulting in a radio-transparent material. This is a valuable characteristic when the object being protected houses an antenna. Table 15 summarizes the experimental results of testing to determine the intrinsic heat capacity, molecular weight ratio, and the transpiration factors. This information can be used to determine the heat of ablation (Q) and mass losses as described in equations 1, 2, and 3. It compares Teflon with other materials such as polyethylene which melts and vaporizes rather than subliming.

Table 15. Teflon Material Comparisons

Test Material	**Intrinsic Heat Capacity** (BTU lb $^{-1}$)	**Molecular Weight Ratio** (μ)	**Transpiration Factors** (from Equations 1, 2, & 3)		
			η_L	η_{Tsub}	η_{Tsup}
Ceramic Teflon	550	0.043	0.27	0.09	0.07
Teflon	750	0.175	0.40	0.21	0.11
Ethyl Cellulose	1000	0.428	0.50	0.36	0.15
Polycarbonate	1250	0.428	0.50	0.36	0.15
Polyethylene	2000	0.428	0.50	0.36	0.15

Source: Kennedy, Page 162

To determine the heat of ablation (Q), the transpiration factor is multiplied by the change in specific enthalpy across the material thickness and then added to the intrinsic heat capacity.

6.2.2 Syntactic Foam

Syntactic foams are defined as composites consisting of hollow microspheres and a thermosetting resinous matrix. Thermosetting matrix resins consist of two component liquid systems, which can be blended with hollow microspheres at room temperature. Thermosetting resins include epoxy, phenolic, unsaturated vinyl ester, silicone, polyurethane, and polyisocyanuate resins. Syntactic foam has the following advantages:

- Isotropic properties
- Very low water absorption
- Very high strength (compressive) to weight ratio

The properties of an example syntactic product, XP-241 from Scotchply, are shown in Table 16.

Table 16. Properties of Scotchply XP-241 Syntactic Foam

Property	42 lb/cu. Ft.	40 lb/cu. Ft.	38 lb/cu. Ft.	36 lb/cu. Ft.
Net Bouyancy (nominal, in sea water), lb/cu. ft.	22	24	26	28
Compression strength, uniaxial, ultimate, p.s.i.	13,400	11,000	10,200	9,600
Compression yield, 0.2% effect, uniaxial, p.s.i.	10,400	9,000	8,500	8,100
Compression modulus, uniaxial, p.s.i.	480,000	458,000	383,000	373,000
Hydrostatic crush point, p.s.i.	17,000	14,000	13,400	12,600
Tensile strength, p.s.i.	4,600	3,600	-	3,300
Flexural strength, p.s.i.	6,000	6,100	-	3,800
Shear strength, p.s.i.	4,400	4,100	-	3,800
Bulk modulus, p.s.i.	582,000	538,000	353,000	308,000

Source: Landrock, Page 159

Similar to SLA 561, a super lightweight ablator currently used on the ET, the composition of SLA-741 and SLA-220 can be found in the following tables (Tables 17 and 18). The material properties of these products will be included in Section 6.2.5, Tables 24 and 25.

Table 17. Composition of SLA-741

Ingredient Material	**Ingredient Density** (g/cm^3)	**% by mass**	**% by Volume**	**Volumetric Parts**
Elastomer	0.995	24.57	5.3	100
Silica Fibers	2.2	2.92	0.28	5.28
Carbon Fibers	1.85	2.34	0.28	5.28
Silica Microspheres	0.18	23.4	27.9	580
Phenolic Microspheres	0.092	5.85	13.64	257.35
Cork	0.186	40.92	47.2	840.56
Porosity		-	5.4	101.88
Total		100	100	1890.35

Source: Donskoi, Page 143

Table 18. Composition of SLA-220

Ingredient Material	**Ingredient Density** (g/cm^3)	**% by mass**	**% by Volume**	**Volumetric Parts**
Elastomer	0.995	31	7.8	100
Silica Fibers	2.2	4.7	0.5	6.41
Silica Microspheres	0.18	64.3	91.7	1175.64
Total		100	100	1282.05

Source: Donskoi, Page 143

6.2.3 Rubber Products

Organosilicon rubber materials have been successfully used for heat shielding at low and moderate heat flows. General Electric has developed a variety of rubber heat shielding products that have been used on programs such as Saturn and Polaris. Some of these products and their properties are summarized in Table 19.

Table 19. Properties of Vulcanized HSM General Electric Company

Material	**Density** (kg/m^3)	**Strength Limit @ Stretching** (kGs/cm^2)	**% Elongation @ break**	**Hardness** (Scale A)	**Resistance to Cold** (degree C)	**% Shrinkage**	**Heat Conductivity** (W/m grad)
RTV-77	1330	35	220	50	-67.8	0.3	-
RTV-88	1470	53	110	65	-67.8	0.3	-
RTV-90	1470	53	190	60	-67.8	0.2	-
RTV-511	1180	24.6	180	45	< -100	-	0.26
RTV-560	1420	56	160	60	< -100	-	0.31
RTV-577	1350	33.6	180	50	< -100	-	0.31
RTV-580	1490	56	110	60	< -100	-	0.31

Source: Donskoi, Page 116

Upon further testing at the RTV-500 series products at General Electric, the actual ablation characteristics have been established. Table 20 shows both the linear and weight ablation rates for RTV-511, RTV-560, RTV-577, and RTV-580 based on an exposure temperature of 2,705 ^{o}C and an unspecified thickness.

Table 20. Heat Shielding Properties of General Electric Rubbers

Material	Back Side Temp (degree C)	Linear Ablation Rate (mm/s)	Weight Ablation Rate (g/cm^2s)
RTV-511	28	0.0195	2.34x10-3
RTV-560	50	0.016	2.24x10-3
RTV-577	26	0.0172	2.34x10-3
RTV-580	50	0.0122	1.80x10-3

Source: Donskoi, Page 118

Dow Corning has also developed several organosilicon rubber products. The properties of a few of those products are listed in Table 21.

Table 21. Physical & Mechanical Properties of Dow Corning Company Rubber

Material	**Density** (kg/m^{3})	**Resistance Limit @ Stretch** (kGs/cm^2)	% **Elongation @ Break**	**Hardiness by Shore** (Scale A)
Q-90-006	1480	38.6	150	50
Silastic S-2048	1210	70	400	50
Silastic S-6511	1320	39.5	300	60

Source: Donskoi, Page 120

These products and other Dow products have been used on the minuteman Missile and the Titan and Saturn programs. Table 22 shows the heat shielding properties and effectiveness of Q-90-006, S-2048, and S-6511.

Table 22. Heat Shielding Properties of Dow Corning Company Rubber

Material	Surface Density of Heat Flow (kJ/m^2s)	Heat Penetration Rate (mm/s)	Effectiveness Coefficient
Q-90-006	450	0.03	49
	2960	0.05	33
	11320	-	-
Silastic S-2048	450	0.03	63
	2960	0.048	43
	11320	1.2	1.7
Silastic S-6511	450	0.04	47
	2960	0.045	42
	11320	0.4	5.4

Source: Donskoi, Page 120

Also developed and tested by Dow Corning, heat shielding spray coatings that vulcanize at room temperature have been utilized by the Titan program and the X-15 plane. A few of these products and their mechanical properties are shown in Table 23.

Table 23. Spray Coating Material Properties

Material	Density (kg/m^3)	Strength Limit @ Stretching (kGs/cm^2)	% Elongation @ Break	Specific Heat Capacity (kJ/kg grad)
92-009	1090	42	600	1.465
92-007	1540	21	250	1.465
92-027	870	35	50	1.34

Source: Donskoi, Page 121

6.2.4 Low-Density Products

The ablative materials currently in use on the ET fall into the category of a low-density product and will show up in many of the tables shown in this section. Low-density heat shielding products can be developed in 1 of 2 ways.

1. Foams with chemically induced pores.
2. The addition of lightweight fillers in the foam. (Note: if the filler material is microsphere then it is syntactic foam).

Lockheed Martin Company, formerly Martin Marietta, has tested many of the products in the market. Table 24 summarizes the results of some of the Lockheed Martin testing.

Table 24. Properties of Low Density Heat Shielding Materials (as Tested)

Material	**Density** (kg/m^2)	**Heat Conductivity Coefficient** (W/m grad)	**Specific Heat Capacity** (kJ/kg grad)	**Sample thickness** (mm)	**Back Side Temp** (degree C)
SLA-561	197	0.052	1.255	12.2	104
SLA-741	182	0.052	1.338	15	53
Phenol-nylon-based	520	0.108	1.586	13	24
Cork: Armstrong-514	303	0.055	2.09	7.9	90
Material 2755	520	0.072	2.09	13	11

Source: Donskoi, Page 136

Table 25 lists several other products and their properties that have been considered and/or used by Lockheed Martin for various projects.

Table 25. Properties of Low Density Heat Shielding Materials (Vendor Data)

Material	**Density** (g/cm^3)	**Heat Conductivity Coefficient** (W/m grad)	**Specific Heat Capacity** (kJ/kg grad)
Phenol-nylon	0.52	0.86 - 1.31	1.59
ESA-3560F	0.51	1.01	1.22
NASA-602	0.58	1.27	1.68
DC-325	0.87	1.51	1.34
ESM-1004	0.62	1.78	1.38
AVCO 5026	0.5	0.88	1.81
Cork: Armstrong 2755	0.53	0.58 - 0.86	2.10 - 2.52
Cork: Armstrong 514	0.3	0.55	2.1
SLA-561	0.225	0.52	1.26
SLA-741	0.215	0.52	1.34
SLA-220	0.25	0.79	0.97
Teflon	2.15	2.45	1.05
Porous Teflon	0.51 - 0.71	0.60 - 0.68	1.05
Melted Quartz	2.21	19.3	0.71
Boric Nitride	2.27	328.3	0.8

Source: Donskoi, Page 140

7 EVALUATE EFFECTIVENESS & FEASIBILITY OF ALTERNATE PRODUCTS

7.1 Polymeric Insulating Foam Products

Table 26 combines the data from various tables in Section 5 of this paper. It offers a convenient way to compare the properties of the insulating foam alternatives.

Table 26. Properties of Insulating Foam

	Material	**Density** (kg/m^3)	**Compression Strength** (MPa)	**Tensile Strength** (MPa)	**Thermal Conductivity** (W/m C)	**Original Reference**
PVC Foam	Linear PVC Foams	60	0.38	0.9	0.034	Table 12
	Linear PVC Foams	90	0.9	1.4	0.037	Table 12
	Linear PVC Foams	140	1.6	2.4	0.039	Table 12
	Crosslinked PVC Foams	30	0.22	0.51	0.03	Table 13
	Crosslinked PVC Foams	100	1.7	3.1	0.04	Table 13
	Crosslinked PVC Foams	400	11.24	12.4	0.06	Table 13
Sandwich	Polyethylene	25 to 185	0.080 to 0.33	0.14 to 3.9	0.034 to 0.067	Table 14
	Polypropylene	23 to 70	0.11 to 0.56	0.20 to 1.2	0.034 to 0.042	Table 14
	Polyetherimide	80	not available	1.8	0.025	Table 14
Molded Foam	Novolac Type	40	0.17	not available	0.024	Table 11
	Resol-Type (Spray)	35 - 45	0.98	not available	0.03	Table 10
	Resol-Type (block)	35 - 60	.15 - .19	not available	.025 - .029	Table 9
	Phenolic Foams	25 - 50		not available	.020 - .035	Table 8
Structural Foam	High Density Polyethylene	600	12.6	9	not available	Table 7
	ABS	860	30.3	26.8	not available	Table 7
	Mod. Polyphenylene Oxide	850	35.8	23.4	not available	Table 7
	Polycarbonate	900	35.8	42.1	not available	Table 7
	Thermoplastic Polyester	1200	77.9	68.3	not available	Table 7
	High Impact Polyproylene	700	23.7	12.4	not available	Table 7
	High Impact Polystyrene w/FR	850	not available	15.9	not available	Table 7

Unfortunately, this table doesn't tell the entire story. The manufacturing process for several of these foam products limits the feasibility of using them on the ET in the existing design configuration. PVC, Polyethylene, Polypropylene, and Polyetherimide foams can easily be eliminated from the selection process because their application requires a sandwich panel configuration. The use of sandwich panel technology on the ET would drive a redesign of the external skins of the tank. This redesign effort would be a considerable cost and schedule impact. The manufacturing process for Novolac-type and Resol-type foams also eliminates them as alternative coatings for the ET. Both of these products would require custom molded foam sections that would then need an adhesive to be installed on the ET. A revised manufacturing process would also result in a cost and schedule impact. The structural foams summarized in Section 5.1 are high in density by design, which precludes them from being applied as insulating foam for the ET. Of the polymeric insulating foams covered in this paper and summarized in Table 26, there appears to be no suitable alternate product for the ET in the current design configuration.

On the other hand, if the ET were to undergo a redesign, then a sandwich panel insulation could be implemented. In this configuration, the existing skins on the ET would be replaced with a polyetherimide foam core panel and the internal support structure could see a weight reduction due to the increase strength of the panel skins. Since the polyetherimide foam has the same thermal conductivity value as the existing products in use, no additional spray foam would be required on the exterior surfaces of the ET. In essence, the ET would be a huge thermos for the shuttle fuel and the only additional material application would be the ablative material necessary to protect heat sensitive areas during liftoff. While shuttle missions are suspended and the program is already seeing a schedule impact, the time being spent to solve the spray foam problems could be used for this redesign effort.

Section 4.3 introduced alternative blowing agents for use with insulating foam products. The most feasible change would be to keep the existing insulation materials and change the blowing agent used to apply the material. There are several blowing agents with similar properties to HCFH-141b currently in use. For example, R-245fa is a non-flammable propellant now in use in some insulation applications.

7.2 Ablative Materials

Table 27 is an accumulation of the data from various tables in Section 6. It offers an easy comparison of the mechanical and thermal properties of the different ablative materials.

Table 27. Properties of Alternative Ablative Materials

	Material	Density (kg/m^3)	Strength Limit @ Stretching (kGs/cm^2)	% Elongation @ break	Heat Conductivity (W/m grad)	Specific Heat Capacity (kJ/kg grad)	Original Reference
Rubber Products	RTV-77	1330	35	220	not available	not available	Table 19
	RTV-88	1470	53	110	not available	not available	Table 19
	RTV-90	1470	53	190	not available	not available	Table 19
	RTV-511	1180	24.6	180	0.26	not available	Table 19
	RTV-560	1420	56	160	0.31	not available	Table 19
	RTV-577	1350	33.6	180	0.31	not available	Table 19
	RTV-580	1490	56	110	0.31	not available	Table 19
	Q-90-006	1480	38.6	150	not available	not available	Table 21
	Silastic S-2048	1210	70	400	not available	not available	Table 21
	Silastic S-6511	1320	39.5	300	not available	not available	Table 21
	92-009	1090	42	600	not available	1.465	Table 23
	92-007	1540	21	250	not available	1.465	Table 23
	92-027	870	35	50	not available	1.34	Table 23
Low Density	Phenol-nylon	520	not available	not available	0.86 - 1.31	1.59	Table 25
	ESA-3560F	510	not available	not available	1.01	1.22	Table 25
	NASA-602	580	not available	not available	1.27	1.68	Table 25
	DC-325	870	not available	not available	1.51	1.34	Table 25
	ESM-1004	620	not available	not available	1.78	1.38	Table 25
	AVCO 5026	500	not available	not available	0.88	1.81	Table 25
	Armstrong Cork 2755	530	not available	not available	0.58 - 0.86	2.10 - 2.52	Table 25
	Armstrong Cork 514	300	not available	not available	0.55	2.1	Table 25
Syntactic	SLA-561	225	not available	not available	0.52	1.26	Table 25
	SLA-741	215	not available	not available	0.52	1.34	Table 25
	SLA-220	250	not available	not available	0.79	0.97	Table 25
Miscellaneous	Teflon	2150	not available	not available	2.45	1.05	Table 25
	Porous Teflon	510-710	not available	not available	0.60 - 0.68	1.05	Table 25
	Melted Quartz	2210	not available	not available	19.3	0.71	Table 25
	Boric Nitride	2270	not available	not available	328.3	0.8	Table 25

Of the ablative products covered in Section 6 and summarized in Table 27, there appears to be a couple alternatives to the materials currently being used as heat protection on the ET. The rubber and Teflon products all have high strength values, which equates to high density, and therfore eliminates them as contenders. The low-density heat shielding products, many of which are syntactic materials, offer a couple alternatives. The syntactic materials SLA-741 and SLA-220 have density values very close to that of SLA-561. Table 28 offers a combined look at the ingredients for those products.

Table 28. Ingredient Comparison for SLA Products

Ingredient Material	SLA-741	SLA-561	SLA-220
	% by Volume	**% by Volume**	**% by Volume**
Elastomer	5.3	5.55	7.8
Silica Fibers	0.28	0.3	0.5
Carbon Fibers	0.28	0.3	0
Silica Microspheres	27.9	43.9	91.7
Phenolic Microspheres	13.64	14.35	0
Cork	47.2	35.6	0
Porosity	5.4	0	0
Total	100	100	100

Upon closer investigation of the SLA-741 ingredients, Table 28 shows that it has a much higher cork content then SLA-561. This higher cork content has two major impacts on the end product. First, it gives SLA-741 a lower density (0.215 g/cm^3) and second, the cork makes it much more brittle and hence lower strength. While a lower density is a good thing, a more brittle product would increase the amount of potential foam lost during launch, which eliminates SLA-741 as an alternative. On the other hand, SLA-220 has no cork, which should drastically reduce the foam lost during lift-off. The lack of cork also impacts the material properties of the end product, specifically density and specific heat capacity. To get a better understanding of how a material change to a product of higher density would impact the weight, Table 29 provides an estimate of the weight associated with the ablative materials. The weight is based on the area and thickness of SLA-561 in various locations on the ET. The locations were selected from Figure 7 and the area and thickness are approximations.

Table 29. Weight Estimate & Comparison

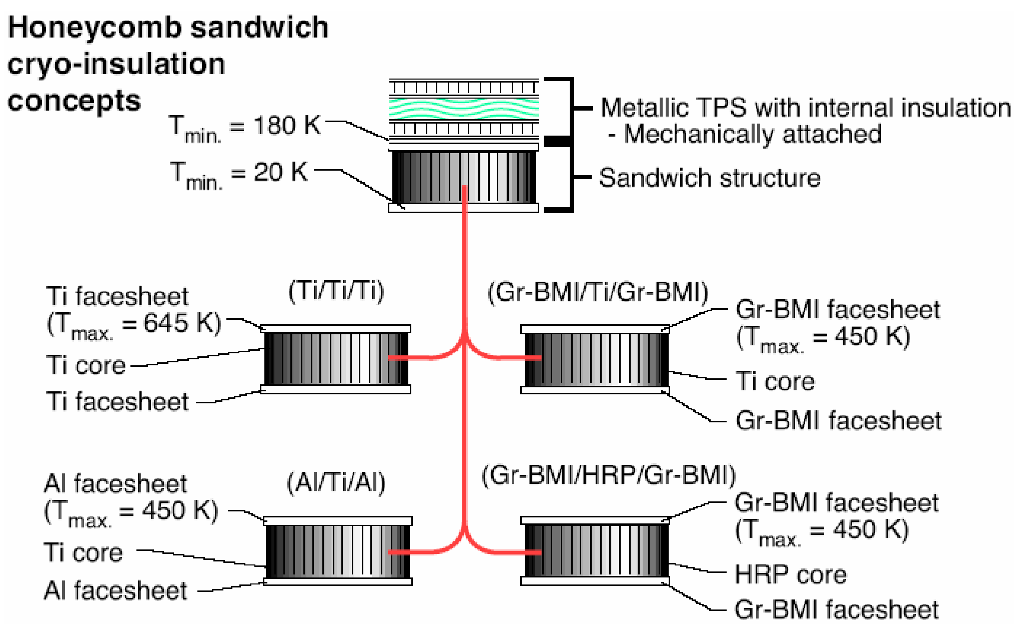
Location	**Area** (in^2)	**Thickness** (in)	**Volume** (in^3)	**SLA-561 Density** (lb/in^3)	**SLA-220 Density** (lb/in^3)	**SLA-561 Weight** (lb)	**SLA-220 Weight** (lb)
Bipods	1152	2	2304	0.008	0.009	18.432	20.736
Cable Tray	7200	2	14400	0.008	0.009	115.2	129.6
Frost Ramps	2016	2	4032	0.008	0.009	32.256	36.288
Apex Closeout	5760	2	11520	0.008	0.009	92.16	103.68
Feedline Fairing	3600	2	7200	0.008	0.009	57.6	64.8
					Totals	315	355

Table 29 results in a total weight of 315 pounds for SLA-561 and 355 pounds for SLA-220, a difference of only 40 pounds. An 11% increase in the total weight of the thermal protection system is an insignificant loss in payload capability relative to the peace of mind associated with making the crew safer during liftoff. While the lower specific heat capacity will require testing to determine the impact, these property differences are not significant enough to eliminate SLA-220 as an alternative ablator for the ET.

8 POTENTIAL FUTURE APPLICATIONS

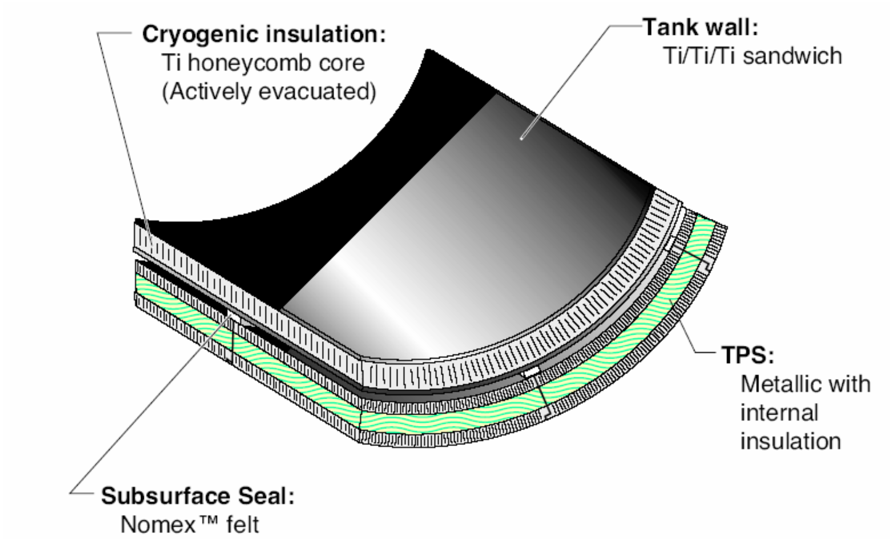
8.1 Polymeric Foam Products

Although none of the insulating materials covered in this paper were suitable for the ET, they should not be precluded from consideration for application on future spacecraft. If the selection of any one of these products was made during the design phase of a new program, it could easily be applied. For example, the Langley Research Center describes the use of sandwich panel technology in the THERMAL STRUCTURES TECHNOLOGY DEVELOPMENT FOR REUSABLE LAUNCH VEHICLE CRYOGENIC PROPELLANT TANKS report. Figures 8 and 9 depict the concepts detailed in the report.



Source: Langley Research Center

Figure 8 Sandwich Panel Insulation Concept



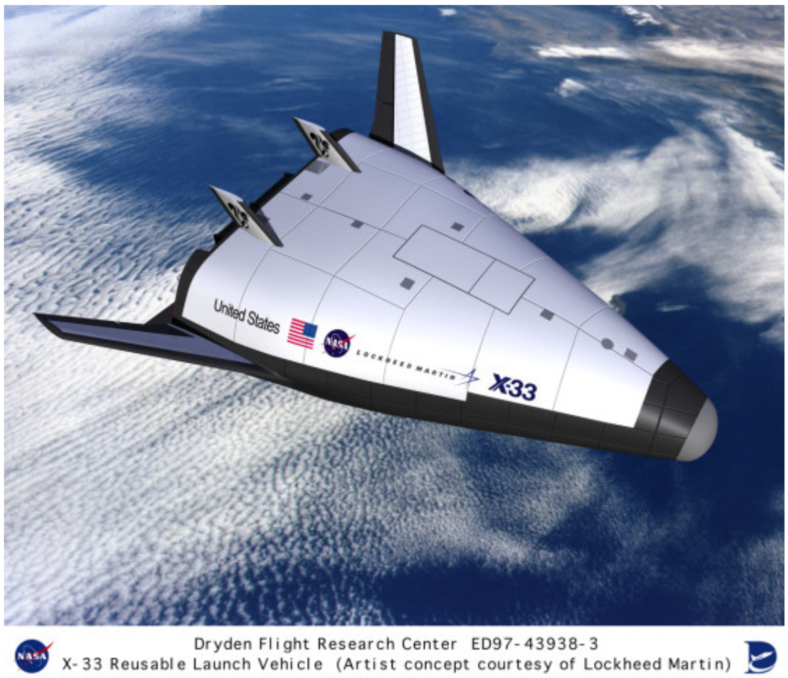
Source: Langley Research Center

Figure 9 Contoured Sandwich Panel Application

In these figures, the tank structure, cryogenic insulation, and the thermal protection are considered a single system. Figure 8 shows a few of the options for the inner sandwich panel materials. Figure 9 depicts the titanium sandwich panel acting as a pressure vessel, primary structure, insulation, and the thermal protection support structure. Only the internal titanium sandwich panel face sheet needs to be impermeable to liquid oxygen. The outer face sheet can be penetrated to attach the thermal protection sandwich panel.

8.2 Ablative Materials

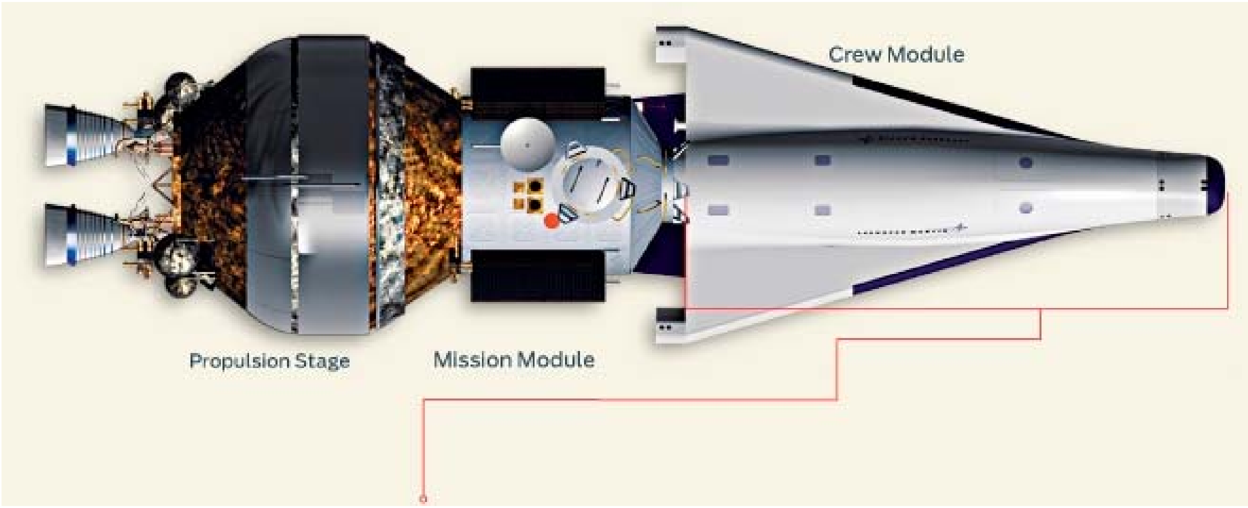
The lessons learned from the foam loss occurrences during the shuttle program are more likely to result in a different design concept for future spacecraft than a different ablative material choice. This point will become clear as the following future spacecraft concepts demonstrate. The X-33 concept utilizes a similar thermal protection system to the space shuttle. Figure 10 illustrates that this concept incorporates the fuel tanks into the body of the spacecraft, which eliminates the concern of damage from falling debris.



Source: Wikipedia, Online Encyclopedia

Figure 10 X-33 Concept

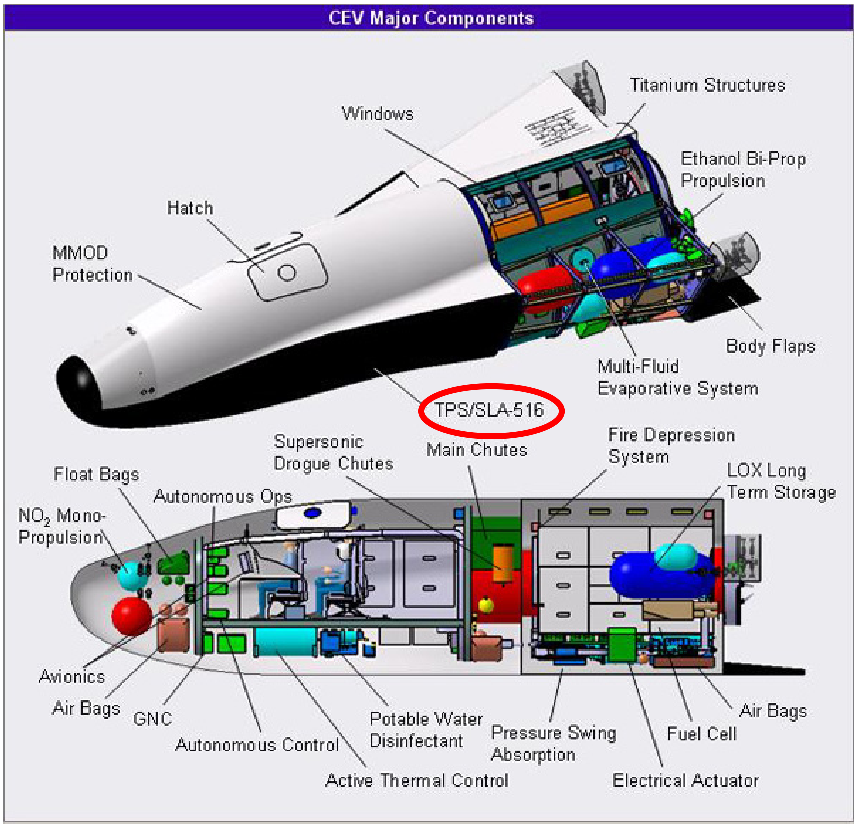
Currently, Lockheed Martin and the Northrop Grumman - Boeing team are competing for the Crew Exploration Vehicle (CEV) contract that will replace the space shuttle. Each company has different ideas but one theme is common to each of them. Both concepts return to a classic rocket style configuration where the crew compartment is on top of the propulsion system and fuel storage. Figures 11, 12, 13, and 14 show the concepts from the each design team. These concepts do not eliminate the need for a thermal protection system and/or ablative materials but they eliminate the threat to the crew created by debris from it's own propulsion system.



Source: Wikipedia, Online Encyclopedia

Figure 11 Lockheed Martin Concept

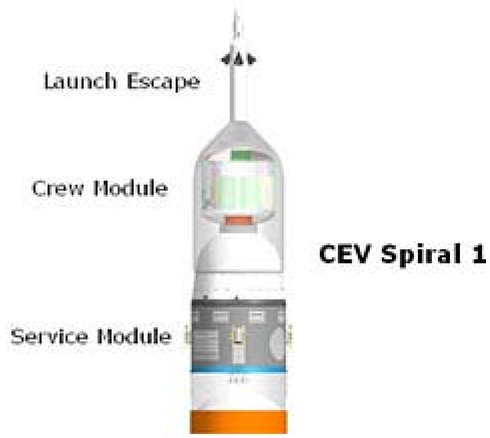
The Crew Module of the Lockheed Martin CEV Concept, shown in Figure 11, has seating room for 6 astronauts and living quarters for 4. It has a lifting body shape, similar to the space shuttle, which increases maneuverability and reduces the heat build up during reentry. Figure 12 shows that the crew and the CEV structure will be protected from that heat by SLA-516 in this concept. Although there's no information currently available on this product, it would be safe to assume that it has a similar composition and properties to the other SLA products covered in this paper.



Source: Wikipedia, Online Encyclopedia

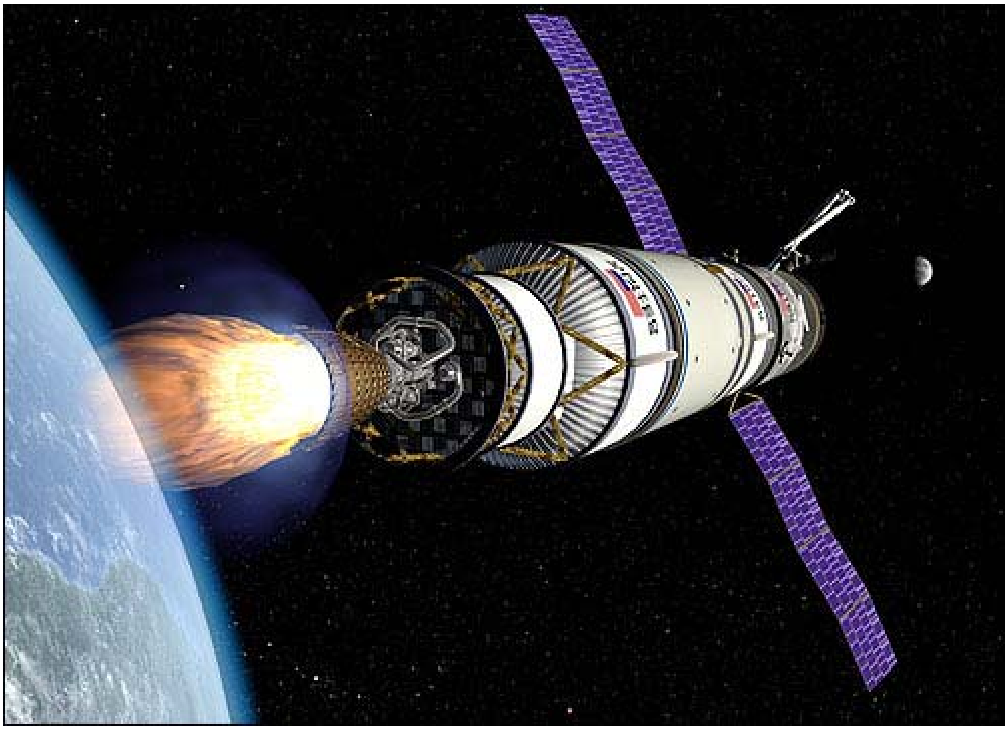
Figure 12 Lockheed Martin Crew Module Concept

The Northrop Grumman – Boeing team has limited the amount of information publicly released on their CEV concept. The artist renderings shown in Figures 13 and 14 provide the only available insight into what their design will have to offer.



Source: Wikipedia, Online Encyclopedia

Figure 13 Crew & Service Modules from Northrop Grumman – Boeing Team

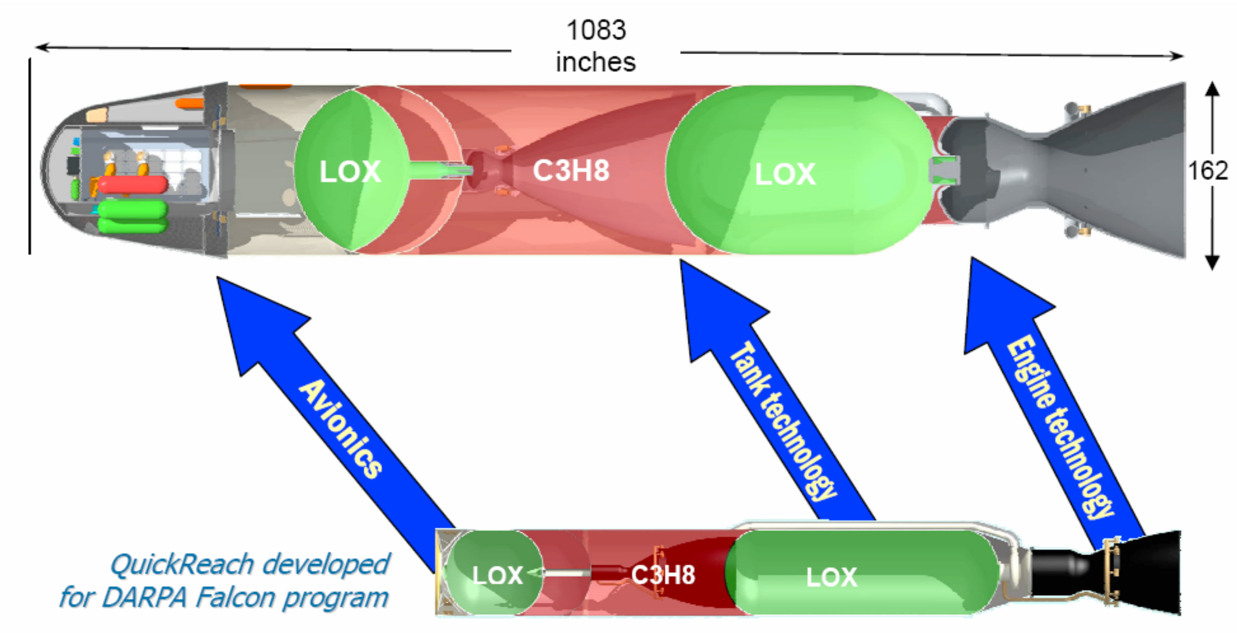


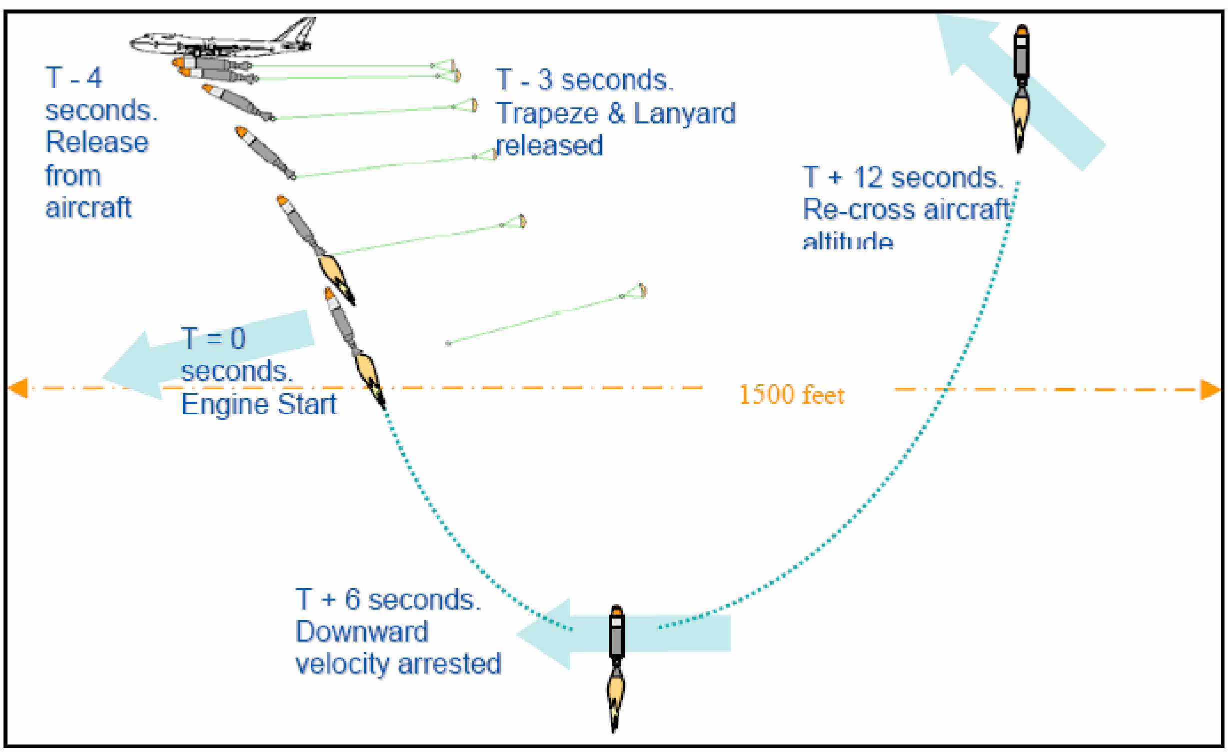
Source: Wikipedia, Online Encyclopedia

Figure 14 Northrop Grumman - Boeing Team Concept

Although there is no information currently available on the Northrop Grumman – Boeing team's CEV concept, the rendering still reveals a spacecraft design that protects its crew from potential falling debris by isolating the crew module from the propulsion system.

While these teams are competing for the contract to replace the space shuttle, Transformational Space Corporation (t/Space) is developing a low cost space vehicle to fill the gap between the decommission date of the shuttle and the first launch of CEV. The t/Space alternative is very similar to the CEV concepts but in order to reduce cost and schedule, it doesn't meet all the same requirements levied on CEV. Figure 15 shows the t/Space design and launch concept for a crew launch vehicle.





Source: Popular Science

Figure 15 T/Space Design and Launch Concept

This concept differs from the others in that it requires a carrier aircraft to host it's launch. Scaled Composites successfully demonstrated the carrier plane idea as they won the X-Prize with SpaceShipOne and its carrier White Knight. Scaled Composites has also completed preliminary tests for t/Space and will do most of the construction for both vehicles. T/Space has the first engine test scheduled for August 2007, its first flight in 2008, and the first manned flight in 2009. With this schedule, the t/Space spacecraft would be ready for service well before the scheduled retirement of the space shuttle, presently scheduled for September 2010.

The discussion on thermal protection and/or ablative materials is limited because most of these concepts don't reveal the details of their designs. Even without those details, its clear that future designs will prevent the tragedies that have occurred due to the loss of foam from the ET during the shuttle program.

9 RECOMMENDATIONS AND CONCLUSION

9.1 Recommendations and Future Research

9.1.1 Insulating Foam Alternative

Although this research did not result in a suitable alternative for the foam insulation products used in existing ET design, that does not mean there are no alternatives. As discussed in Section 7.1, changing the ET design to resemble Figure 9 is an alternative, but it introduces the unknown risks associated with a new design. Blowing agents were also discussed in Section 7.1, and should be considered the most promising solution to the problem. By changing the blowing agent for the existing materials, different properties can be achieved after the foam cures. This could result in better adhesive quality or a stronger product. Improved strength would make the foam less susceptible to damage during manufacturing and transportation. A series of tests are recommended to determine if the existing products with various blowing agents could achieve the desired results. These tests should include:

- Verification of the material density
- Destructive compression testing
- Destructive tensile strength tests
- Adhesive quality tests
- Thermal conductivity test
- Flammability test

9.1.2 Ablative Material Alternative

Section 7.2 resulted in insufficient evidence to eliminate SLA-220 as an alternative ablative material for utilization on the ET. Therefore, thorough testing of SLA-220 is recommended. These tests should include:

- Verification of the material density
- Destructive compression testing
- Destructive tensile strength tests
- Adhesive quality tests
- Thermal conductivity testing
- Flammability testing
- Specific heat capacity testing
- Applicable temperature range testing
- Backside temperature testing

9.1.3 Testing Considerations

As noted in the previous two sections, any product change would require compressive and tensile strength testing. Due to the extremely large size of the ET, it is not practical to use a full size test article. Therefore, a representative section of the tank should be used for the strength tests. The test section should retain the same structural properties of the entire tank in order to provide actuate results. It should also receive the same foam application process as the full ET. If the area of interest on the ET would receive several layers of foam and then be machined to a specific thickness, the test section should be treated exactly the same way. This is important because of the interlaminar stresses that exist between the foam layers. At the edges of the foam layers, where it ends for access panels or protruding parts, very high interlaminar shear stress can cause debonding between layers. These interlaminar stresses could cause an otherwise acceptable alternative to be rejected due to the required application thickness on the ET.

9.2 Conclusion

In Section 1, a general description of the ET and its thermal protection system provided the background required to derive the material requirements discussed in Section 3. Section 1 also provided some insight into recent problems associated with the foam products used on the ET. Table 1 summarized the evolution of the ET structural materials and inert weight. The material changes implemented for the SLWT, used for STS90, could have resulted in a more flexible frame or changed the natural frequency of the structure. Allowing the structure to flex while the foam remained rigid would result in foam separation. While this seems like a logical conclusion, another change took place in the same time frame that is a more likely contributor to the problem. In order to comply with EPA regulations, the blowing agent was changed to HCFH-141b for STS87 and all subsequent flights. As described in Section 7.1, the blowing agent will affect the properties of the final product. Both of these changes were necessary but they should have been independently tested and then tested together prior to implementation.

The details of the foam products currently in use were covered in Section 2 and then compared to the functional requirements in Section 4. Sections 5 and 6 reviewed some of the available products on the market that could be used as alternative products. The effectiveness and feasibility of those alternatives were evaluated and compared to the functional requirements in Section 7. That evaluation resulted in no suitable alternative for the insulating foam, however one possible ablative material alternative was determined. While researching future applications for Section 8, it has become clear that a product change would merely mask the inherent design flaw at the source of the problem. There is no way to protect the shuttle structure, and inherently protect the crew from ET debris in the current space shuttle and ET configuration. The only way to be sure that the ET will stop shedding foam is to eliminate the foam completely. With only 5 years and 19 missions remaining until the scheduled shuttle retirement, it doesn't seem reasonable to spend the time and money required for a complete ET design change. Therefore, the tests previously mentioned in Section 9.1 are recommended and if the desired results are achieved, the changes should be implemented. It is also recommended that t/Space funding continue to ensure space flights will not be interrupted between the shuttle retirement and beginning of the CEV program.

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