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INFORMATION BRIEF

**Title:** Metallic and Non-metallic Materials for the Primary Support Structure

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**Summary:** The primary support structure (PSS) is required for mechanical support of reactor module (RM) components and mounting of the RM to the spacecraft. The PSS would provide support and accept all loads associated with dynamic (e. g., launch and maneuvering) or thermally induced loading. Prior to termination of NRPCT involvement in Project Prometheus, the NRPCT Mechanical Systems team developed preliminary finite element models to gain a basic understanding of the behavior of the structure, but optimization of the models, specification of the final design, and materials selection were not completed. The Space Plant Materials team had evaluated several materials for potential use in the primary support structure, namely titanium alloys, beryllium, aluminum alloys and carbon-carbon composites. The feasibility of application of each material system was compared based on mass, stiffness, thermal expansion, and ease of fabrication. Due to insufficient data on environmental factors, such as temperatures and radiation, and limited modeling support, a final materials selection was not made.

**Background:** The primary support structure (PSS) is the structural system that provides the load paths required to provide physical support and maintain alignment of reactor module components during launch and operation. The PSS would have been required to connect the shield, reactor, and power conversion systems (PCS), serve as the mounting location for protective (e. g., micrometeoroid and/or thermal) shields, and attach the RM to the spacecraft.

In considering the design of the PSS, the NRPCT Mechanical Systems (MS) team evaluated three structure types: truss, sheet stringer, and honeycomb.<sup>1</sup> Finite element models were generated for the truss and sheet stringer designs to gain a basic understanding of the behavior for each structure. The NRPCT assessed three common space-application materials in their studies: beryllium, titanium alloys, and carbon-carbon composite. Due to NRPCT program termination, the sensitivity studies did not utilize materials selection for design optimization. Instead, titanium alloys were assumed as the baseline material due to the availability of an extensive material property database. Also due to termination of NRPCT involvement, designs did not progress to accounting for the temperature and radiation fields that the PSS would experience over the life of the Prometheus mission.

**Primary Properties of Concern:** Space primary support structures require low mass, high stiffness, high strength, low coefficient of thermal expansion (CTE) and dimensional stability over their operational lifetime. The PSS would also need to accommodate thermally induced stresses and strains associated with long runs of hot and cold piping. For truss and platform structures mechanical loads should be low; however, they should be stiffness-compatible to minimize stresses caused by any imposed loads. Also, since the PSS is required to operate in low earth orbit or similarly harsh environments it must be chemically stable (e. g., atomic oxygen) and tolerant of radiation exposure.

**Secondary Properties of Concern:** There are additional characteristics that are of secondary concern in considering the PSS material selection, which could provide significant functional benefits in addition to supporting the reactor module components. Some of these are high thermal conductivity, ease of joining between both the supporting elements and plant components, and an extensive material property database to aid in mechanical design. The latter may be particularly important if the program schedule is aggressive, as was the case for Project Prometheus. Under some circumstances, primarily dependent upon the operating temperature, it could be advantageous to consider a material with low creep resistance. This could allow stress relaxation during the mission and reduce the applied stresses on the structure.

If a material with high thermal conductivity is used in the primary support structure, it could also serve in the role of heat rejection. This might allow some portion of the heat rejection system (i. e., the radiator panels) to be replaced by the now dual purpose support structure. The high thermal conductivity could also reduce the magnitude of the thermal stresses imposed on the support structure. As components of the reactor plant operating at different temperatures are attached to the support structure, the proximate regions in the support structure will differentially expand. With a highly conductive support structure the thermal gradients in the structure will be reduced, thus decreasing the thermally induced stresses.

Another useful characteristic of the support structure material would be ease of joining, both to itself to ease fabrication of the structure, and to the individual plant components. If there is difficulty joining the parts of the support structure to each other, there may be an increased chance that problems will develop in the joints in service.

If a large, stable manufacturing base, consisting of multiple suppliers, exists for the material of choice, there may be substantial schedule advantages and potential cost savings. Some materials, such as beryllium, require special handling in manufacturing and are available only from a sole source, which could be problematical.

**Primary Support Structure Materials:**

1. Metallic

Only a few classes of materials were identified as potentially meeting the structural requirements for the primary support structure of the space nuclear power plant (SNPP). The limiting requirements are high stiffness to weight ratio and reasonable yield strength at high temperatures (probably up to 950 K). The two types of metal alloys meeting these requirements are beryllium alloys and titanium alloys. There are concerns with each group of

materials. Beryllium has a very high specific stiffness, but it is difficult to handle in manufacturing due to environmental, safety, and health (ES&H) issues. Titanium alloys are well characterized, have a lower specific stiffness than beryllium, but require substantial care and control in joining. Since some of the titanium alloys are two-phase materials, operating temperatures and lifetime, relative to thermal effects on microstructural stability, need to be considered. The other common aerospace alloy system is aluminum, which has a similar specific stiffness to titanium alloys; however, it may not be useable at the upper end of the expected temperature regime. Table 1 summarizes typical room temperature properties of representative alloys from each alloy class.

**Table 1: Thermal-Mechanical Properties of Metallic Materials**

Alloy	Composition	Density (g/cc)	Modulus (GPa)	UTS (MPa)	YS (MPa)	$\alpha$ ( $10^{-6}/C$ )	Stiffness/Density	Conductivity (W/m K)	$\nu$
Pure Be (S-200, Rod)	-	1.85	303	765	414	11.5	163.9	216	0.07
Pure Ti	ASTM Grade 1	4.51	102.7	240	250	9.7	22.7	16	0.34
Alpha Ti	Ti-11Sn-1Mo-2.25Al-5Zr-0.2Si	4.82	113.8	1050	945	9.4	23.6	-	-
Near Alpha	Ti-6Al-2Sn-4Zr-2Mo-0.15Si	4.54	113.8	940	860	8.1	25.1	7.1	0.32
Alpha+Beta Ti	Ti-6Al-4V	4.43	113.8	1172	1103	9.5	25.7	6.7	0.342
Beta Ti	Ti-3Al-8V-6Cr-4Mo-4Zr	4.82	105.5	1448	1379	9.6	21.9	-	-
AlBeMet 162	Be-38Al (MMC)	2.1	196.5	-	-	13.9	93.6	212	0.17
AlBeMet 140	Be-60Al (MMC)	2.28	158	-	-	16	69.3	210	-
Al alloy (7075 T6)	Al-1.6Cu-2.5Mg-0.23Cr-5.6Zn	2.8	71.7	570	505	25.2	25.6	130	0.33

## 1.1 Beryllium Alloys:

Structural beryllium is mainly one composition, at least 99% pure. It is processed in a number of ways including powder metallurgy, extrusion, and rolling. Structural Be is designated with an S, and the two main types are made by Brush Wellman. The S-200 types have a maximum of 1.5 wt.% beryllium oxide, S-65 grades have a maximum of 1 wt.% beryllium oxide. The S-65 grade (see Table 2 for composition) has been formulated and processed so that it has a higher ductility than S-200, but a lower tensile strength. There are two main ways that bulk Be is fabricated, one is vacuum hot pressing (VHP), and the other is hot isostatic pressing (HIP). An advantage Be has over other alloys under consideration is its high stiffness to weight ratio. It has a significant history as an aerospace alloy because of high specific stiffness, so there is some precedent for using it in the Prometheus project.<sup>2</sup> In spite of its good physical properties, Be has not seen wide usage due to environmental, safety and health (ES&H) issues associated with handling of fine particulate material, and the metal is difficult to process due to the stability of its oxide.<sup>3</sup>

**Table 2: Composition of S-65 Beryllium**

<b>Element (max unless stated otherwise)</b>	<b>Wt%</b>
Be (min %)	99
BeO	1.0
Al	0.06
C	0.10
Fe	0.08
Mg	0.06
Si	0.06
Other metallic impurities	0.04

### 1.1.1. Thermal-Mechanical Properties

Beryllium has a Young's Modulus of 303 GPa and a density of 1.84 g/cc. The specific stiffness of Be is about 160 (E/ρ), which is about eight times that of the other metallic alloys under consideration. It also has a very high thermal conductivity (216 W/m K). One downside of Be is that, in spite of its stiffness, it has a comparatively low strength with a tensile strength of 765 MPa and a yield strength of 414 MPa. One problem with using Be as a structural material is its anisotropic nature (ν is about .07), which can be a problem both from a manufacturing and structural standpoint. The thermal expansion coefficient of Be is  $11.5 \times 10^{-6}$ .<sup>4,5</sup>

### 1.1.2 Joining, Fabrication, and Cost

Beryllium essentially is available from only one source, Brush-Wellman. Though not a common structural alloy, it has been used in space applications similar to the potential application in the Prometheus

support structure, primarily due to its high specific stiffness and low density. Beryllium alloys are available in both rod and sheet form. One serious problem with the manufacturing of these alloys are the ES&H hazards associated with handling beryllium. Inhalation of beryllium dust can cause chronic beryllium disease (CBD) in a portion of the population. Because of the ES&H issues, the cost of beryllium products can be high.

Another problem associated with structural Be alloys is joining. Be alloys are difficult to join due to their HCP structure and its lack of slip systems, which do not allow thermal stresses to be relieved in the joint. There are several methods of surmounting this. One method is to use a lower melting point shim in the joint, which of course limits its application to lower temperatures. Laser welding combined with an appropriate preheat can also be used to form a solid joint. The preheat can improve ductility in the surrounding material and the laser can give a joint with a narrow heat affected zone (HAZ). By manipulating some of the parameters associated with this method, an improved joint can be created. One major problem faced during welding is the creation of oxide particles. Be oxidizes very easily, and if the weld is not well protected large amounts of oxide particles can be formed. If these oxides are formed in the joint they can severely reduce the mechanical properties of the joint. Joining appears to be an area of concern for Be alloys if they are to be applied in high temperature service, and there is an apparent need for additional development in this area.<sup>6</sup>

## 1.2 Titanium Alloys

There are numerous titanium alloys that are commonly used in aerospace applications, which could be considered for the PSS. Titanium alloys can be broken down into three classes based on their microstructures. Alpha phase alloys have an HCP structure, beta phase alloys have a BCC structure, and alpha-beta alloys have both types present in their microstructure. Pure titanium undergoes a phase transition from HCP to BCC at 882° C upon heating. This means that for an alpha phase titanium alloy to be stable above this temperature, alloying elements must be added to stabilize the alpha phase at temperatures above the phase transformation. Conversely, for the beta phase to be stable below 882° C, different elements must be added to stabilize the BCC phase at lower temperatures. Generally, the strongest titanium alloys are the alpha-beta alloys.

Specific stiffness of titanium alloys is about 23 ( $E/\rho$ ), and the tensile strengths and yield strengths are much higher than beryllium. The tensile strength for titanium alloys can range from 1050 to 1450 MPa and the yield strength ranges from 935 to 1370 MPa, which is more than double the UTS and YS values for the S-200 Be alloy. The thermal expansion coefficient of titanium alloys is  $9.6 \times 10^{-6}$  and its Poisson's ratio is 0.34.<sup>7,8</sup>

Titanium alloys considered for the primary support structure would have primarily been alpha-beta alloys. The common aerospace alloy Ti-6Al-

4V is included in this group; it is easily procured and its properties are well documented due to its ubiquitousness. This alloy derives much of its strength from age hardening, so use at elevated temperatures could have adverse effects on its mechanical properties. The aging treatment produces a mixture of the alpha and beta phases, which is responsible for the high strength of the alloy. This alloy also has a drastic drop in creep strength at about 250° C. This temperature may be lower than portions of the primary support structure. Under certain circumstances this could be a small advantage. If during heat up of the plant there is significant thermal expansion, creep of the support structure could absorb some of the strain imposed on the system thus lowering the stress in the long-term.<sup>9</sup>

Beta alloys would also have been considered for the support structure. They are among the strongest of the titanium alloys, especially at low temperatures; however, there is significant degradation of their mechanical properties with increasing temperature. Beta alloys also have lower specific stiffness versus other Ti alloy classes by about a sixth, although their specific strength is much higher than the other Ti alloys. The room temperature properties of a particularly good beta titanium alloy (Ti-3Al-8V-6Cr-4Mo-4Zr) are presented for comparison in Table 1. This class of alloys has traditionally been difficult to successfully join, however, the particular alloy cited has moderate weldability. Typically, the greatest advantage of using beta alloys is their fracture toughness and their response to heat treatment. Due to the possible elevated temperatures involved in the primary support structure, this may be a liability for the Prometheus PSS.<sup>10</sup>

A near-alpha Ti alloy to consider would be Ti-6Al-2Sn-4Zr-2Mo-0.15Si. This alloy is frequently used in aerospace components due to its higher strength at elevated temperatures and better creep resistance than other Ti alloys. Its useful temperature limit is generally identified as 450° C.<sup>7</sup> These near-alpha alloys are easier to join than the beta alloys. The material properties of this alloy are also provided in Table 1.<sup>11</sup>

### 1.2.1 Thermal-Mechanical Properties

For most of the titanium alloys considered, the thermal-mechanical properties are very similar. The beta titanium alloy, Ti-3Al-8V-6Cr-4Mo-4Zr, has a somewhat lower Young's modulus than the alpha phase alloys, such as Ti-11Sn-1Mo-2.25Al-5Zr-0.2Si. This could favor the higher modulus alpha alloys because of the need for vibrational stability and good damping in the spacecraft structure. The tensile strengths would be greater for the beta alloy due to its heat treatment, but at elevated temperature this potential advantage could be negated, as noted above. The near alpha alloy, Ti-6242, seems to have the best high-temperature capability, especially with the 0.15% Si addition. Its lower tensile strength compared to the other candidate alloys could be accounted for in design, albeit, perhaps at a small mass penalty. The thermal conductivity of the titanium alloys is the lowest of the alloy choices, but their thermal expansion coefficients are also the smallest of the candidate alloys.

### 1.2.2 Joining and Fabrication

Most titanium alloys are readily obtainable because of their widespread use in a variety of structural applications, and they can be fabricated in almost any shape for such use. Because their strength to weight ratio is greater than that of aluminum, they have seen wide usage in aerospace applications and there is extensive literature available related to their usage. Some titanium alloys are much more difficult to join than others. The alpha and near alpha alloys are the easiest to join followed by the alpha-beta alloys. Beta alloys are the most difficult to join because their retained beta structure can result in cracking. They can be joined but special processing is required for pre- and post-weld heating.

### 1.3 Aluminum Alloys

The classic aerospace alloys are aluminum-based. These alloys are typically used in low-temperature applications because of the relatively low melting point of aluminum (660° C). The strongest of these alloys are age-hardened with low aging temperatures (~120° C), so operating temperatures should be well below this to prevent Ostwald ripening with an accompanying loss of strength. Because the thermal conditions of the PSS were not conclusively defined, aluminum alloys were considered as possible candidates for the PSS, with the caution that temperature limitations could ultimately lead to their rejection.

One variant on aluminum alloys with improved mechanical properties is a metal matrix composite (MMC) made from aluminum and beryllium. The matrix is made from aluminum and the strengthening phase is beryllium. The material is based upon the fact that aluminum and beryllium are immiscible and that no intermetallic compounds are formed. Two different MMC compositions are commercially available, one with 38 wt.% Al called AlBeMet 162, and the second, AlBeMet 140, with 60 wt.% Al. Due to their composite structure, they have a stiffness intermediate between aluminum and beryllium. They also display the high thermal conductivity of beryllium. In addition, they are easily machined and formed. The major constraint foreseen to application of these MMC's for the Prometheus PSS is the Al-Be eutectic at 644° C, meaning it has temperature limitation concerns similar to aluminum, which might preclude its use in the PSS.

#### 1.3.1 Thermal-Mechanical Properties

For an example of aluminum alloy properties, 7075 aluminum with a T6 temper has been selected for comparison purposes based on its high strength. Aluminum has a density of 2.8 g/cc and a Young's modulus of 71 GPa. At 25° C, 7075-T6 has an ultimate tensile strength of 570 MPa and a yield strength of 505 MPa. Its thermal conductivity is 130 W/m K, and the coefficient of thermal expansion is  $25.2 \times 10^{-6}$ . The Poisson's

ratio of aluminum is 0.33, which makes it easy to form and use structurally.

### **1.3.2 Joining, Fabrication, and Cost**

Aluminum alloys are readily available and are supplied by many different vendors, resulting in low cost compared to other aerospace alloys. In addition, it can easily be formed into almost any shape and is available in rod, tube, and sheet form, which would be the most likely forms in the PSS. 7075 in the T6 temper is difficult to weld in the aged condition, but is easier to weld in its solution treated state. It might have been possible to weld the entire structure in its solution treated state, and then age it for strength.

## **2. Non-Metallic Materials**

### **2.1 Carbon-Epoxy Composites**

Fiber reinforced composites have become an increasingly attractive, and more widely used, option for space applications because they are strong, stiff, damage tolerant, and offer significant weight savings. A major advantage of composite materials is that they can be tailored to meet specific design load requirements, accomplished by optimally orienting the fibers based on the distribution of the applied load. In general, the structural properties of composites are controlled by the orientation, volume fraction, and properties of the fibers, although fiber-matrix interactions also play a significant role in determining the primary properties.

The design of composite materials typically begins with selection of the fibers and matrix. Conventional space structural systems have made use of S-glass, aramid, or carbon/graphite fiber reinforcements in a resin matrix. The primary role of the matrix is to maintain fiber orientation and distribute the applied load evenly among fibers. The matrix is the weak link in the composite and generally determines the overall service temperature limitations and environmental resistance of the material. Resin matrices are limited to a maximum service temperature of approximately 250°C, at which point they reach their glass transition temperature.<sup>12</sup> This relatively low temperature probably precludes the adoption of carbon fiber/epoxy matrix composites for the PSS.

### **2.2 Carbon-Carbon Composites**

Carbon-carbon (C/C) composites make use of the excellent high-temperature capabilities of carbon-based material by utilizing carbon fiber reinforcement in a carbon matrix. C/C composites exhibit high-strength at high temperatures, low creep, high thermal conductivity, and low CTE. C/C composites are unique in that their mechanical properties do not typically degrade with increasing temperature until 2000°C in a non-oxidizing environment.<sup>13</sup>



C/C composites present the opportunity to tailor their mechanical and thermal properties primarily by fiber selection and fiber orientation. Carbon fibers are available with a range of CTE, moduli, and strength properties. Because of the wide range of properties available (Table 3), carbon fiber is used extensively in space structures where the capability to specifically tailor structural characteristics, such as dimensional stability and high specific stiffness, while minimizing mass, is particularly advantageous. For these applications, either polyacrylonitrile (PAN)-based or mesophase pitch-based precursors are used to make the fibers. Also, advances in fiber architecture have evolved to produce composites with widely varying stress-bearing capabilities. Unidirectional lay-ups exhibit a high degree of anisotropy and are often used in laminate form. Laminates can be cross-plyed at different angles to form a two-dimensional (2D) composite. Two-dimensional composites may also be produced by weaving methods. Multi-dimensional lay-ups, which display a more isotropic nature, are often produced by orthogonal weaving. The flexibility and adaptability of composite design, especially fiber architecture, lends significant advantage in terms of optimization of mechanical properties for specific stress distributions.

**Table 3: Axial Properties of Carbon Fibers<sup>14</sup>**

Fiber		Density (g/cc)	Tensile Modulus (GPa)	Tensile Strength (MPa)	Thermal Conductivity (W/m-K)	CTE (10 <sup>-6</sup> /K)
PAN	Low Modulus	1.76	230	3300	8.5	-0.7
	High Modulus	1.9	390	2400	70	-0.5
Meso-phase Pitch	Low Modulus	1.9	160	1400	-	-
	Intermediate Modulus	2.0	380	1700	100	-0.9
	High Modulus	2.15	725	2200	520	-1.6

The carbon matrix plays a significant role in determining the properties of the composite, primarily in any direction in which the fibers are not axially loaded. Much like the fibers, the carbon matrix can exhibit a range of properties by varying the precursor and processing methods. Two processes have been developed to produce high-performance carbon-carbon composites: liquid impregnation and chemical vapor infiltration (CVI).<sup>15</sup> The liquid impregnation method commonly uses resins as the matrix precursor to form a prepreg, which is a ready-to-mold component consisting of the resin matrix and carbon fiber. The prepreg matrix is transformed into carbon residue by a high-temperature heat treatment (pyrolysis). The type of resin precursor selected will

affect the carbon-yield, microstructure, and fiber-matrix interaction of the composite.

The CVI of carbon uses gaseous hydrocarbons, such as methane, to deposit a carbon matrix on the surfaces of a porous carbon fiber preform. The microstructure is controlled by adjusting the processing parameters: temperature, pressure, gas composition, and flow rate. The major drawback of CVI is the very slow rate of deposition leading to high final cost. Therefore, using impregnation for initial densification to produce a structure with relatively uniform open pores, followed by CVI for final densification is an attractive option.

## 2.2.1 Mechanical Behavior

### Strength and Modulus

Although the structural properties of C/C composites are generally controlled by the fibers, it is often process-induced stresses, heat treatments, and fiber-matrix interactions that play a significant role. Typical room temperature properties are summarized in Table 4. When the bonding between the fibers and matrix is strong, cracks that form in the matrix will propagate across the fiber-matrix interface resulting in brittle fracture. Conversely, weak interfaces between the fibers and matrix allow matrix cracking to occur without crack propagation through the fibers. Intact fibers bridge the matrix cracks and maintain a load-bearing capability until the load initiates fiber fracture. This type of failure exhibits pseudo-plastic behavior due to matrix cracking and fiber movement.<sup>13</sup>

Typically, thermoset resin precursors yield low-modulus, brittle isotropic carbons upon pyrolysis. Pyrolysis strongly influences the strength of the fiber-matrix interface due to densification and shrinkage of the matrix, which provides open porosity. This accessible porosity provides the ability to realize significant improvements in mechanical properties by increasing density through repeated impregnation/pyrolysis cycles. In order to improve the properties of isotropic carbon, heat treating is utilized to develop a graphitic structure at the fiber-matrix interface. In general, increasing the heat treatment temperature (HTT) for a thermoset resin will increase the strength and modulus of the composite.<sup>13</sup>

Pitch-based precursors generally transform to a mesophase state, which aligns parallel to the fiber axis upon pyrolyzation. A highly oriented, dense graphitic matrix is produced upon graphitization, which provides a high-modulus contribution along the fiber axis. For pitch precursors, the strength is observed to fall as the HTT is increased. This is due to strong interfacial bonding between matrix and fiber, which results in brittle failure or behavior more nearly typical of a monolithic material. Therefore, graphitization of pitch precursors aids in densification but at the price of lower strength.<sup>13</sup>

For CVI-densified C/C composites, three types of carbon microstructure - smooth laminar, rough laminar, and isotropic - can be produced depending on the processing parameters. The smooth laminar matrix has a strong fiber-matrix interface and produces composites with high strength and stiffness but brittle fracture behavior. The rough laminar matrix exhibits a more graphitic microstructure and pseudo-plastic fracture behavior due to a loosely bonded fiber-matrix interface. An isotropic CVI matrix exhibits less desirable mechanical properties due to lower density and closed porosity.<sup>13</sup>

### Density

One of the major factors determining the strength, as well as other characteristics, of C/C composites is the density of the carbon matrix material. Increasing density will increase strength by reducing the size and number of voids, thus reducing the number and the intensity of the stress concentration regions. In tensile testing, a more nearly uniform stress field is generated, and low, uniformly distributed overall porosity consisting of minimum size pores is the key factor. The compressive response is typically controlled by interlaminar shear strength, which increases with density much like tensile strength.

Fracture toughness is interpreted as the ability of a material to resist crack propagation from existing voids. Since C/C has numerous internal voids, the fracture toughness depends strongly on the type of carbon fiber used, the density of the composite, and the orientation of the initial crack. If crack propagation is perpendicular to the fibers, crack blunting and delamination are observed.

### Fatigue

Composite materials exhibit complex fatigue failure mechanisms due to their anisotropic nature. Fatigue may be a problem due to extensive matrix microcracking that is present before loading. Fatigue failure is usually accompanied by extensive damage that propagates throughout the specimen, in contrast to the localized formation of a predominant, single crack as is common in monolithic, isotropic brittle materials. The four basic failure mechanisms of a composite are layer cracking, delamination, fiber breakage, and fiber-matrix interfacial debonding. Any combination of these can be characteristic of fatigue damage that will result in reduced strength and stiffness.<sup>16</sup>

### Mechanical Properties at High temperature

The high-temperature, in-plane strength is dominated by the properties of the fibers, but the properties of the matrix and fiber-matrix interface often dictate the effect of temperature on the shear, cross-fiber tensile, and compressive strengths of the composite. Generally, the properties improve with increasing temperature, which is attributed to the annealing of matrix microcracks. Creep behavior has received little attention to date, but is predicted to be at least four orders of magnitude lower than that of most monolithic ceramics.<sup>15</sup>

**Table 4: Typical Mechanical Properties of C/C Composites at Room Temperature<sup>a</sup>**

Mechanical property	Hitco <sup>b</sup>	ASM <sup>c</sup>			Carbon <sup>d</sup>					
					2D			3D		
		UD	2D	3D	CP-M	CP-T	WO	ROD-L	ROD-H	WO
Tensile Strength (MPa)	276	1000 (x) 2.0 (z)	350 (x-y) 5.0 (z)	170 (x-y) 300 (z)	180.3	129.2	161.1	161	151	225
Tensile Modulus (GPa)	90	260 (x) 3.4 (z)	115 (x-y) 4.1 (z)	55 (x-y) 96 (z)	90.2	57.2	66.9	116	116	85
Compression Strength (MPa)	207	620 (x) --- (z)	150 (x-y) --- (z)	--- (x-y) 140 (z)	-	-	-	-	-	-
Compression Modulus (GPa)	-	250 (x) --- (z)	100 (x-y) --- (z)	--- (x-y) 90 (z)	-	-	-	-	-	-
Shear Strength (MPa)	-	-	-	-	31.9	43.9	31.4	17.6	18.4	17.1
Shear Modulus (GPa)	-	-	-	-	5.4	5.4	5.4	0.56	0.89	1.5

<sup>a</sup> Presented as typical data for C/C composites, although preform design, fiber type, matrix precursor, and processing influence properties.

<sup>b</sup> Hitco Carbon Composites, Inc. *Chemcarb Properties* [Electronic Data Sheet]. Available November 2005: www.hitco.com

<sup>c</sup> ASM International (ref 15). UD = One-dimensional composite, 2D = Fabric laminate, 3D = Woven orthogonal. Load directions (x-y) and (z) denote in-plane and through-plane values, respectively. Approximately 60% PAN fiber volume assumed for each set.

<sup>d</sup> Aly-Hassan, M.S. *et al. Carbon* 41 (2003) pp. 1069-1078. 2D-CP-M = Cross-ply 90° High Modulus fiber-Mesophase pitch matrix, 2D-CP-T = Cross-ply 90° High Strength fiber-Mesophase pitch matrix, 2D-WO = Woven High-Strength Fiber-Phenolic resin matrix, 3D-ROD = Pitch-based rods arranged in orthogonal three-directions-Pitch matrix (L=low density, H=high density), 3D-WO = Woven PAN fibers-Pitch matrix.

## 2.2.2 Thermal Properties

### Thermal Conductivity

Carbon-carbon composites present the opportunity to tailor thermo-physical properties, which can be tailored by the various fiber, matrix, and/or processing options available. For instance, conductivity in the fiber direction is greater than the transverse conductivity. Also, carbon-carbon processing methods can affect conductivity values such that a more graphitic matrix exhibits higher conductivities than an isotropic matrix.<sup>13</sup>

For a CVI matrix, the graphitic rough laminar microstructure exhibits higher thermal conductivity than the smooth laminar or isotropic microstructures. For a thermoset-derived carbon matrix, the fibers will dominate the thermal conductivity due to the low thermal conductivity of isotropic carbon. A pitch-derived carbon matrix will exhibit high thermal conductivity due to its dense, graphitic microstructure.<sup>13</sup>

### Thermal Expansion

The thermal expansion of unidirectional C/C composites tends to be dominated by the fibers parallel to the fiber axis. Thermal expansion varies from being slightly negative at room temperature for high-

modulus fibers to slightly positive for low-modulus fibers. The CTE becomes positive at higher temperatures but in all cases remains low. The CTE in the transverse direction will depend on the matrix and fiber properties, and the extent of porosity in the matrix. Typical thermal properties are summarized in Table 5.

**Table 5: Typical Thermal Properties of C/C Composites<sup>a</sup>**

Thermal property	Hitco	ASM <sup>c</sup>			Toyo <sup>d</sup>	
		UD	2D	3D	2D	Felt
CTE (10 <sup>-6</sup> /K)	1.4	1.1 (x) 10.1 (z)	1.3 (x-y) 6.1 (z)	1.3 (x-y) 1.3 (z)	< 1 (x-y) 7.7 (z)	1.7 (x) 2.3 (y) 5.3 (z)
Thermal Conductivity (W/m-K)	34	125 (x) 10 (z)	95 (x-y) 4 (z)	57 (x-y) 80 (z)	35 (x-y) 5 (z)	390 (x) 320 (y) 190 (z)

<sup>a</sup> Presented as typical data for C/C composites, although pre-form design, fiber type, matrix precursor, and processing influence properties.  
<sup>b</sup> Hitco Carbon Composites, Inc. *Chemcarb Properties* [Online Data Sheet]. Available November 2005: [www.hitco.com](http://www.hitco.com)  
<sup>c</sup> ASM International (ref 15). UD = One-dimensional composite, 2D = Fabric laminate, 3D = Woven orthogonal. Load directions (x-y) and (z) denote in-plane and through-plane values, respectively. Approximately 80% PAN fiber volume assumed for each set.  
<sup>d</sup> Toyo Tanso, Co. *Characteristics of C/C composite* [Online Data Sheet]. Available November 2005: [www.toyotanso.co.jp](http://www.toyotanso.co.jp)

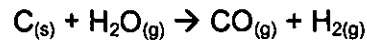
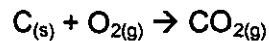
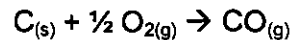
### 2.2.3. Modeling Considerations

Although the NRPCT constructed a model for a metallic PSS, predicting failure of a composite material is more complex due to the nature of composite systems. For instance, unlike stiffness which depends on average properties, the initiation of failure is highly affected by flaws that are distributed randomly and unpredictably throughout the structure, creating localized regions of high stress. In general, these regions are too numerous to be readily characterized or modeled. Second, the strength of composites is not only affected by the initiation of failure at flaw sites, but also by the progressive growth and accumulation of microfailures which result in stiffness changes and stress redistribution.

Finite element analysis can be used to create simple models of the composite's structural elements. A simplistic approach to modeling anisotropic materials is to estimate properties based on the rule of mixtures. This approach takes into account the volume fraction and properties of the fibers and matrix, independently. For the primary support structure, further development of current models would have been necessary for adequate evaluation of composite materials.

### 2.2.4 Corrosion Concerns

Although carbon-carbon displays excellent high-temperature capabilities in inert environments, there are major concerns with application at elevated temperatures in an environment with significant oxygen-potential, such as low-earth orbit. The primary consequence of carbon corrosion is that solid carbon can be gasified via the reactions:<sup>17</sup>



As the solid carbon is lost, the interfacial bond between the fiber and matrix becomes debonded and a significant reduction in mechanical and thermal properties of the composite becomes unavoidable. Carbon-carbon corrosion is governed by structural defects or stress regions within the matrix as a result of carbonization shrinkage. The reaction will commence at edge sites or porosity, then proceed through the matrix, and consume the fibers. Graphitic carbon, with its denser, crystalline structure and lower proportion of reactive edge sites, does not begin to corrode until slightly higher temperatures than isotropic carbon. In general, the gasification rate is increased by increasing temperature and reduced by increasing heat treatment temperature. The latter is believed to occur as a result of reducing reactive edge sites, retained impurities, and residual carbonization stresses.

The gasification of carbon-carbon typically begins at 350°C and the corrosion rate is found to increase exponentially with temperature. Depending on the temperature regime, gasification attack can be uniform throughout the material or limited to the geometrical surface. At low temperatures (< ~500°C), the rate-controlling steps of the reaction are chemical in nature and the reactions are so slow that corrosive gas can penetrate the carbon in depth. Corrosion occurs primarily at the high-energy reactive sites (edges and microcracks) causing rather uniform attack. At higher temperatures (> ~900°C), the rate-controlling step changes to diffusion controlled as gas diffuses through the boundary layer close to the solid carbon. In this regime, chemical reactivity is so high that all corrosive gas penetrating the boundary layer reacts immediately with the hot carbon surface, causing geometrical changes.

Protective coatings have been demonstrated to mitigate the concern with C/C corrosion in certain operating regimes. Silicon carbide coated C/C has been used extensively in the aerospace industry for corrosion resistance. SiC exhibits chemical compatibility with the carbon substrate, good adhesion, and ease of application. Although SiC has a low CTE, there are concerns over crack formation as a result of thermal expansion mismatch with the C/C substrate. These open cracks provide paths for the ingress of corrosive species. Also, although SiC forms a protective SiO<sub>2</sub> scale in high oxygen potential environments, the oxide formed in low oxygen potential environments is the monoxide, SiO, which is volatile and does not provide a protective function. Therefore, it is necessary to determine the environmental factors and structural effects of coating the C/C composite system prior to coating selection.<sup>18</sup>

### 2.2.5 Material Availability

Carbon-carbon composites are readily available and are primarily used in the aerospace and defense industries for aircraft brakes, rocket nozzles, and heat shields. Aircraft braking materials capture the majority of the market and are the cheapest, whereas high-density, three-dimensional composites used for space structural applications cost substantially more. Composite materials have been used in space structures for satellite trusses and platforms with proven success.

The price of carbon-carbon varies considerably depending on the end-use and method of production. Carbon-carbon raw material costs vary according to the type and geometries of the fibers and matrix precursor. Epoxy resins are less expensive than other high-carbon-yield polymers, and high density composites are more costly due to increased impregnation cycles and CVI furnace times. Chopped, low-strength fibers are less expensive than continuous high-modulus fibers, and the cost of weaving varies according to the weave geometry, number of dimensions, and type of fiber.<sup>19</sup>

### 2.2.6 Joining

The structural limits of a composite structure are largely established by the properties of its joints. Joints in C/C structures can be produced in a variety of ways. Brazing of C/C composites is the preferred method for high-temperature applications, and nickel-based brazes have been dominant in this category.<sup>20</sup> Another method of connecting C/C composites is to fabricate splices in the laminate at predetermined locations in the structure. This allows the possibility to create numerous lap joints or strap joints and then bond the composites together. Finally, using mechanical fasteners such as bolts is another option, but may be a problem because of the brittle nature of the composite.<sup>21</sup>

Another joining concern is any requirement for a C/C to metallic bond. The CTE mismatch between C/C and metal interfaces may create excessive thermally-induced stresses causing catastrophic failure at the joint. Although methods<sup>22,23</sup> have been developed to accommodate a C/C to metallic bond, the joining technology is underdeveloped and unproven for high-temperature joint reliability over a long mission lifetime, and further research would have been required if such joints were a necessity for the Prometheus PSS.

Perhaps another concern involved with utilizing C/C composites as the primary support structure material is the potential for intimate contact with hot refractory metal or superalloy piping. Since C/C has a very low CTE and long lengths of piping will experience substantial growth when put in service at elevated temperature, there is a possibility that piping could come into contact with the C/C structure. At elevated temperatures, there is a risk that the carbon-carbon PSS could react with the metals to form surface carbides or interstitially embrittle refractory metals. Either of these mechanisms could be detrimental to the creep or fracture toughness properties of the piping.

**Conclusions:**

The operating temperature range of the PSS components would have been a significant factor in the material selection. If high temperatures were a factor in local areas of the structure, then titanium alloys would probably have been removed from consideration because they experience substantial drops in strength at about 500-600° C. In addition, they are weak in creep which could be a problem considering the long mission lifetime. If a titanium alloy were selected for the support structure, it is tentatively concluded that Ti-6Al-2Sn-4Zr-2Mo-0.15Si could have been a reasonable choice. It has been used in many structural aerospace applications, so that it would have a good manufacturing base and a large property database. Since it is a near-alpha alloy, it would have had reasonable joinability as well. The main benefits of using this material over the other candidates would have been its ease of joining and large manufacturing base. The negatives of using this material are its lower specific stiffness compared with the other candidates and its limited high temperature capability.

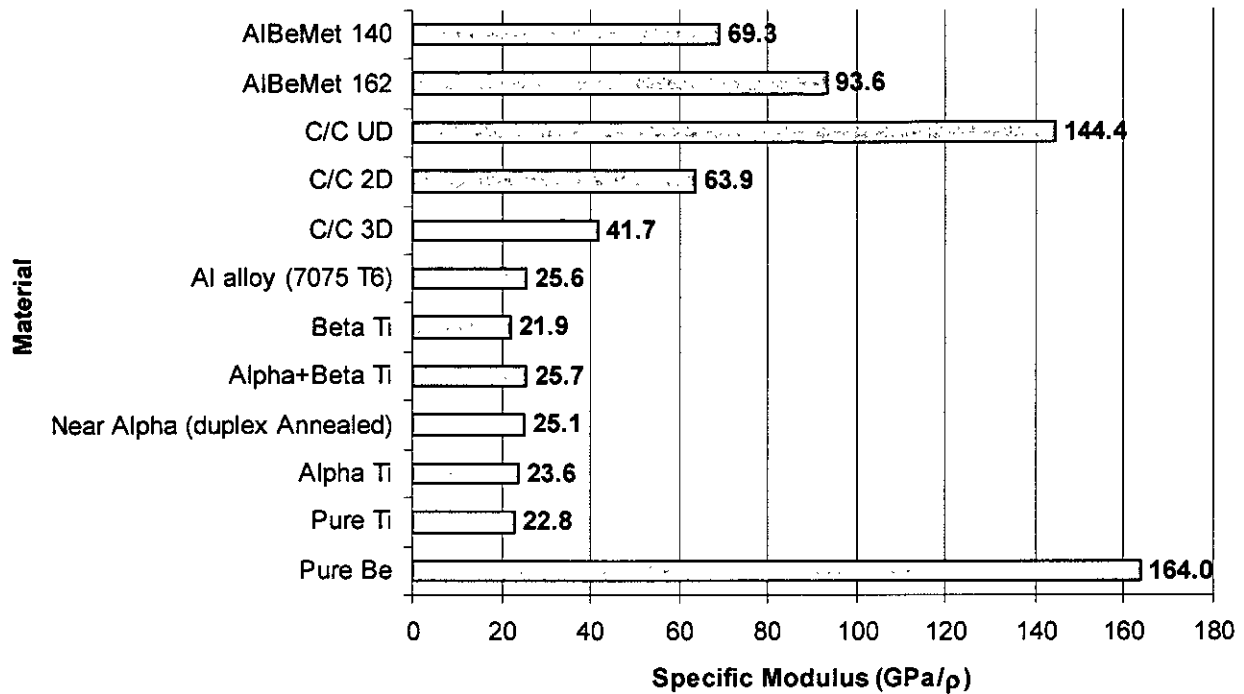
Structural grade beryllium is an excellent choice based on its high specific stiffness and its high thermal conductivity. It does have several drawbacks such as joining difficulties, lower strength than Ti alloys, and a single supplier. Its specific strength is higher than the Ti alloys under consideration so there could still be significant mass savings. It does have a history of use as a structural material in aerospace applications so its use is documented and most joining and fabrication issues have already been addressed. There seems to be a lack of high temperature data for beryllium due to the stability of its oxide and safety problems regarding any testing of beryllium at high temperatures. If thermal modeling of the system determined that the PSS needed to function at temperatures over 300°C, extended thermal testing would need to be done.

Aluminum alloys could be a candidate for the PSS if the structure would not see temperatures much in excess of room temperature. It probably has the largest database of material properties of any aerospace material under consideration and is available from numerous vendors. Liabilities associated with selection of an aluminum alloy would have been its lower strength and specific modulus. Titanium exceeds aluminum in most properties, especially at higher temperatures. Therefore, it would appear that aluminum would be a poor choice for the PSS, especially if it would see elevated temperatures.

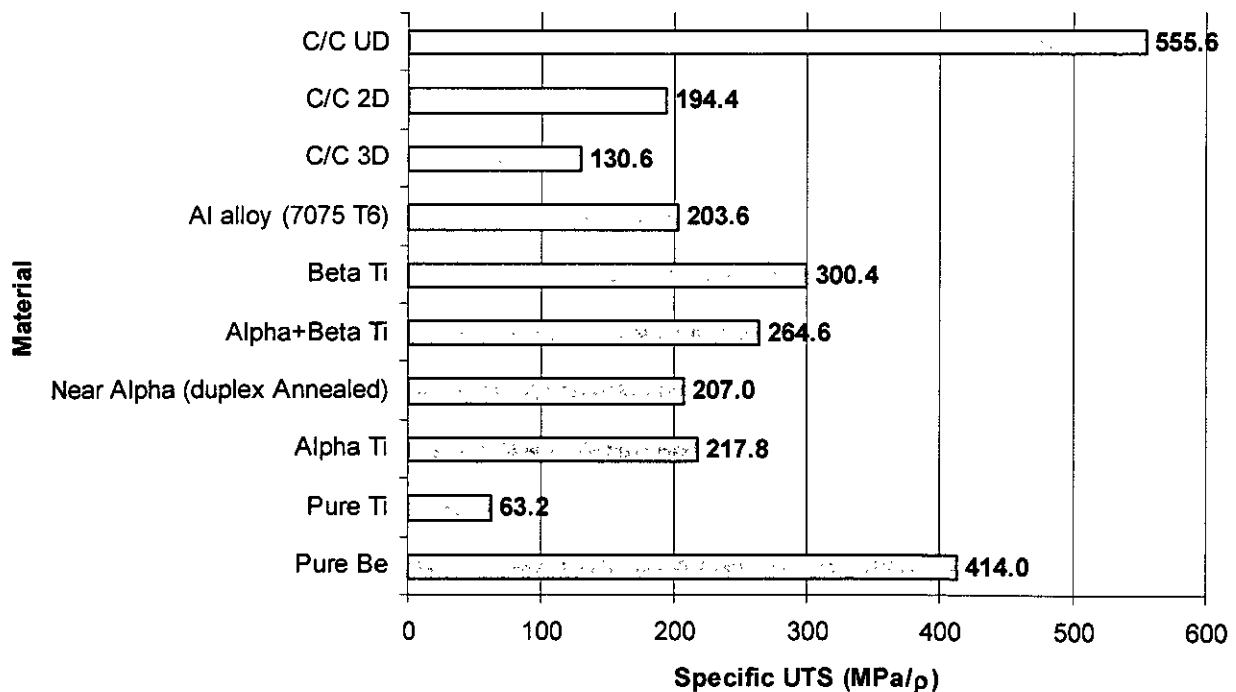
Carbon-carbon composites exhibit excellent high-temperature capabilities, including high specific strength and stiffness, low creep, high thermal conductivity, and low CTE. C/C composites are unique in that their mechanical properties do not typically degrade with increasing temperature until 2000°C in a non-oxidizing environment. The key to applying carbon-carbon composites to spacecraft is in carbon fiber selection and orientation. The selection of matrix precursor and processing methods is also important for properties that are not in the direction of the fibers. C/C material is readily available and can be fabricated into many forms, although joining may be a concern for applications at high temperatures and long service times. The major problems with carbon-carbon composites would have been high-temperature oxidation and low off-fiber-axis properties, which must be taken into account in the design. Figures 1 - 3 show the relationships between materials of interest and the primary properties of concern.

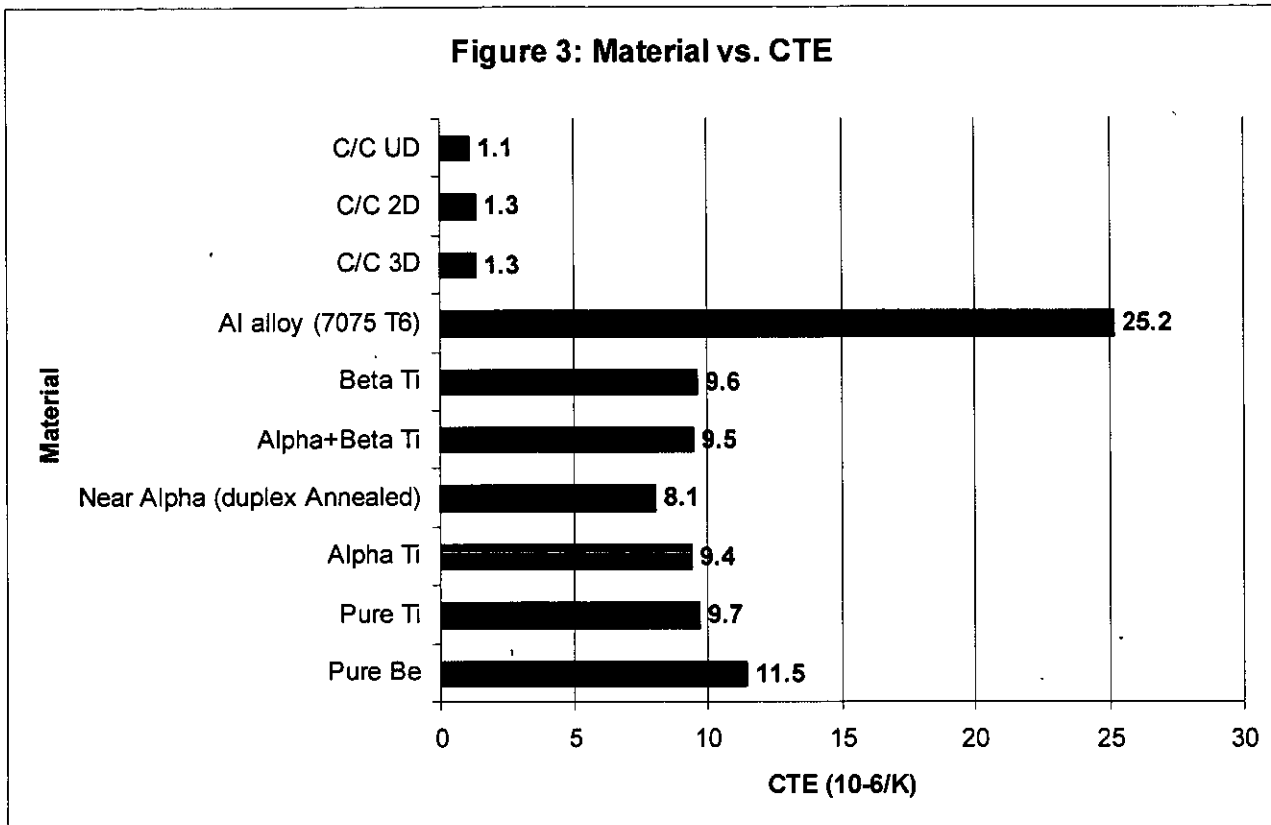


**Figure 1: Material vs. Specific Modulus**



**Figure 2: Material vs. Specific UTS**





In conclusion, titanium alloys are relatively inexpensive and have the largest material property database. Unfortunately, they exhibit poor high-temperature properties and poor weldability. Beryllium has the highest specific stiffness and good high-temperature properties, but fabrication is expensive due to ES&H issues and a limited vendor base. Carbon-carbon composites exhibit excellent high-temperature capabilities and high specific strength and stiffness. Thermal expansion is extremely low over a wide range of temperatures. Fabrication is versatile and relatively inexpensive, although there are serious concerns over joining C/C structures with metallic system components.

**Future Actions:**

In order to make conclusive material recommendations and final selection, the service environment of the PSS would have to be defined. Most important would have been establishing the temperature field envisioned for the PSS. If the temperatures throughout the structure were determined to be relatively low, other materials could have been included in the NRPCT sensitivity studies including aluminum alloys or carbon/epoxy composites. If the temperature were expected to be higher, titanium alloys would be excluded from consideration.

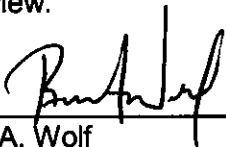
Due to the complex nature of composite systems, the NRPCT structural models would have required substantial development to accommodate C/C composite analysis. Also, additional data would have been necessary for the high-temperature properties of beryllium, or to qualify a specific C/C material due to the variance in mechanical property data as a result of fabrication and material selection details. Once adequate capability for structural analysis was

available, facilitating suitable comparison of all material classes, additional concerns such as cost, fabrication, and joining would have been taken into account in the final material selection.

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