

Materials evaluation for the Origins Space Telescope

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Abstract. The Origins Space Telescope (Origins) study team prepared and submitted a Mission Concept Study Report for the 2020 Decadal Survey in Astrophysics. During the study, a Materials Working Group was formed to evaluate materials for Origins. The Materials Working Group identified material candidates and evaluated the candidates using driving requirements and key material considerations. The evaluation resulted in several options to aid the study team in making a materials selection for the mission concept. Our paper details the approach to the materials evaluation and the results. © The Authors. Published by SPIE under a Creative Commons Attribution 4.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.JATIS.7.1.011011](https://doi.org/10.1117/1.JATIS.7.1.011011)]

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1 Introduction

1.1 Origins Space Telescope

The Origins Space Telescope (Origins) traces our cosmic history, from the formation of the first galaxies and the rise of metals to the development of habitable worlds and present-day life. Origins does this through exquisite sensitivity to infrared radiation from ions, atoms, molecules, dust, water vapor, and ice, and observations of extra-solar planetary atmospheres, protoplanetary disks, and large-area extragalactic fields. Origins operates in the wavelength range 2.8 to 588 μm and is more than 1000 times more sensitive than its predecessors due to its large, cold (4.5 K) telescope and advanced instruments.¹

1.2 Materials Evaluation

A materials evaluation was completed for the mission's main optical and structural elements. The evaluation team, which included Origins team members and industry partner materials experts, developed an iterative process to identify suitable material candidates. The material candidates under consideration were chosen based on their material properties, spaceflight mission heritage, and knowledge of current manufacturing and processing capabilities. The evaluation criteria were determined by the driving requirements for Origins, material performance—particularly at cryogenic temperatures—and relevant manufacturing challenges.

An initial assessment of primary mirror material candidates yielded five potential options: beryllium, aluminum, AlBeMet[®], silicon carbide (SiC), and fused silica. The team conducted

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further trade studies to better understand the material performance needed to meet Origins' requirements. Structural materials were also evaluated in a broader framework. This paper describes the approach to the evaluations and the results, ultimately leading to a materials selection.

2 Evaluation Criteria

2.1 Driving Requirements

The telescope, including the backplane, is expected to be isothermal so it must be composed of materials with relatively high thermal conductivity, greater than $4 \text{ W/m} \cdot \text{K}$ at 4.5 K. It must have low overall mass, namely $<900 \text{ kg}$, to be consistent with the 6643 kg payload mass established for the design,¹ a large primary mirror with a light collecting area $>25 \text{ m}^2$, and the materials themselves should have a relatively high technology readiness level (TRL) ≥ 4 , where component validation exists in a laboratory environment.

2.2 Evaluation Criteria

The evaluation criteria include key material properties that drive performance for the Origins' primary mirror and additional considerations. The criteria include the following: density, stiffness, thermal conductivity, coefficient of thermal expansion (CTE), outgassing, and manufacturability.

2.2.1 Density

Telescope mass is driven by two factors: size and material density. The size is driven by the science objectives, including the aperture diameter of the primary mirror and number and types of instruments. Density is one of the most significant material properties for systems launching to space. Materials with a low density and high overall material performance are ideal for meeting Origins' overall mass budget.

2.2.2 Stiffness

Stiffness, or Young's modulus, is an especially important material property for optical elements and some structural elements. High stiffness provides dimensional stability, allowing mirrors and structural components to hold their shape over long periods. Stiffness is also critical for maintaining optical alignments in the system, especially during launch and deployment when a telescope experiences severe vibrations.² Specific stiffness, or specific modulus, is Young's modulus per mass density. Materials with high specific stiffness are generally favored because components have maximum stiffness at minimum weight, an attractive goal for Origins when considering the mass budget, elements, and gravity impacts while verifying the 0-g optical system in 1 g.

2.2.3 Thermal conductivity

A unique objective of Origins is achieving a temperature of 4.5 K on the cold side of the telescope. Materials with high thermal conductivity can transfer heat faster and cool down uniformly. The primary mirror is one example of where thermal conductivity is critical. Cryocooler heat exchangers are strategically placed on the back of the Origins primary mirror structure and need to cool down the entire mirror, including mirror segments further away from the cryocoolers. The connecting elements of the mirror—segment frames and struts—should also have a reasonable thermal conductivity to enable them to reach 4.5 K and be isothermal under reasonable ($\sim 10 \text{ mW}$) heat flows at operating temperature. It is estimated that it will take only a few days for the telescope and instruments to reach operating temperature.¹ On the other hand, the warm areas of Origins need to be isolated from the cold components to prevent heat transfer. Therefore, some sections of the telescope need to be made from materials with very low thermal conductivity.

2.2.4 Coefficient of thermal expansion

The CTE is used to determine how a material changes dimensionally as a function of temperature. It is a critical property for structures comprised of different materials, especially for bonds and joints that use polymers or metal nodes. Using materials with similar CTEs can reduce or eliminate issues with thermomechanical stresses at interfaces or in bonding materials. Some materials, such as Invar, have an extremely low CTE and are typically used as fittings to mitigate CTE mismatch between structural components, such as composites tubes, rather than using polymers or metals with large thermal expansions. It is important to consider the CTE over the entire temperature range, from room temperature to 4.5 K, to account for dimensional changes during cool down. It is also crucial to account for the CTE at 4.5 K, to design a stable and functioning system at operating temperature. A related property, thermal strain, is the strain in the material caused by the temperature change, from room temperature to 4.5 K for Origins. The CTE at 4 K and the thermal strain from 293 to 4 K are plotted against specific stiffness for five potential materials in Sec. 3.3. Steady-state gradient thermal stability (thermal conductivity/CTE) and long-term stability (thermal diffusivity/CTE) are two other significant thermal considerations that compound with CTE at 4 K and drive long-term operating stability and gradient stability. Both are also plotted in Sec. 3.3.

2.2.5 Outgassing

It is crucial for the optics to remain clean before launch and in space so they can provide clear images and high-quality data during operation. Some materials may outgas in a vacuum environment depending on their material composition and temperatures. Outgassing is a concern because the released gasses, including water vapor, can potentially condense on cold optical surfaces and distort images and data. During deployment, materials may outgas when in direct view of the sun. The outgassing properties of all organic materials need further evaluation, including adhesives and resin matrix materials in composites such as carbon fiber reinforced polymer (CFRP), polyether ether ketone (PEEK), Ultem[®], and Vespel[®].

2.2.6 Manufacturability

When selecting a primary mirror, whether it is a monolithic mirror or a segmented mirror, the material choice can have significant impacts on development. For example, a monolithic mirror made of a material with limited heritage may require an extensive facility development program to accommodate the size and material selected whereas a material with heritage may allow for the use of existing equipment. A segmented mirror may instead require a lengthy segment development program, where the first segment is manufactured and tested and the remaining segments are manufactured subsequently. James Webb Space Telescope (JWST) underwent an extensive segment development program for the 18 beryllium segments for its 6.5-m primary mirror.³

The team considered heritage and meter-class mirror manufacturability for point to point hexagonal segments for all material candidates. Cryogenic testing is also a lengthy process for mirror development. However, Origins' relaxed requirements in comparison to JWST—Origins is diffraction limited at 30 μm compared to JWST at 2 μm —may eliminate the need for some testing, such as cryo-null testing and figuring for mirror shape, which helps reduce the cost and schedule for mirror development.

3 Mirror Materials

3.1 Preliminary Assessment

The mirror material evaluation was prioritized over the structural material evaluation due to the inherent complexity of assessing mirror manufacturing. A preliminary list of material candidates is shown in Table 1. Candidate mirror materials were systematically evaluated, resulting in five potential options. Major advantages and disadvantages were noted for each material with respect to manufacturability and material performance for Origins. The candidates were selected due to

Table 1 Candidate mirror materials were systematically evaluated, resulting in five potential options.

Material	Advantages	Disadvantages
Potential materials		
Beryllium O-30	Superior stiffness, extremely lightweight, and low CTE over temperature range	Expensive, brittle, toxic, and long machining time
Aluminum 6061	Good structurally, good fabrication time, and inexpensive	Heavy, reactive surface, and low stiffness
AlBeMet®	Good stiffness, lightweight, and low CTE over temperature range	Limited information and heritage, toxic
SiC	Excellent stiffness, excellent strength, and low CTE over temperature range	Brittle, heavy, expensive, and long machining time
Fused Silica	Low CTE over temperature ranges and lightweight	Low stiffness and low thermal conductivity
Eliminated materials		
Titanium	Excellent strength and good thermal performance	Extremely heavy and low machinability
ULE	Low CTE and lightweight	Poor thermal performance and low strength
Zerodur	Low CTE	Poor thermal performance and low strength
Borosilicate	Lightweight	Poor thermal performance and low strength
Composite/CFRP	Extremely lightweight and low CTE can be achieved	Limited manufacturability technology and creep

their material properties, mirror material heritage, and the knowledge of current manufacturing capabilities.

Traditional mirror materials include glasses, ceramic materials, and fused quartz while nontraditional mirror materials include metals, metal alloys, SiC, and CFRP composites. Nontraditional mirror materials offer opportunities to reduce weight and cost. In the case of Origins, nontraditional mirror materials also provide thermal advantages over traditional mirror materials.⁴ The first assessment was primarily driven by Origins' 4.5 K operating temperature. The first materials eliminated were any that were not ideally suited for cryogenic temperatures. This included the glasses and glass ceramics: Ultra Low Expansion (ULE) glass (titania-silicate glass), Zerodur (lithium-aluminosilicate glass-ceramic), and Borosilicate (glass with silica and boron trioxide). However, fused silica was not eliminated because of its prominent heritage as an optical substrate and its potential to perform in cryogenic temperatures. Other materials eliminated include titanium because of its extremely high density and CFRP based on its limited manufacturability technologies. Five mirror material candidates remained: beryllium, aluminum, fused silica, SiC, and aluminum, and beryllium metal matrix composite (AlBeMet®).

3.1.1 Fused silica

Fused silica has extensive heritage as an optical substrate. It also has the lowest CTE at 4.5 K, nearly indistinguishable from beryllium, the lowest strain at 4.5 K and relatively low specific stiffness. However, it has poor thermal conductivity and thermal diffusivity, which is critical for Origins. Thermal diffusivity is the thermal conductivity divided by density and specific heat capacity at constant pressure, measuring the rate of heat transfer in a material. In terms of manufacturability, it is roughly equivalent to ULE glass with boule production, light-weighting, and polishing.

3.1.2 Silicon carbide

Silicon carbide (SiC) has high specific stiffness, low strain at 4.5 K—significantly higher than fused silica but lower than others—low CTE at 4.5 K, and excellent thermal conductivity and diffusivity. It also has the potential for many segments to be created from a single mold using a cladding process. SiC has spaceflight heritage through the Herschel Space Observatory, a large 3.5-m sintered SiC primary mirror.⁵ Other examples of SiC heritage include a SiC bench for near-infrared spectrograph Instrument on JWST and SiC mirrors have been demonstrated on GAIA of the European Space Agency (ESA).^{6,7}

3.1.3 Beryllium

Beryllium has the highest performance because of its high specific stiffness, low CTE at 4.5 K, and excellent thermal conductivity and diffusivity. It also has the most relevant heritage through the JWST with a large, segmented primary mirror operating at cryogenic temperatures. It also requires significant schedule lead time to develop segments and imposes higher costs, mainly associated with manufacturing. Even though beryllium is high TRL based on its JWST heritage, it requires extra care in manufacturing due to the human health complexity factor in grinding and light-weighting.

3.1.4 Aluminum 6061

Aluminum 6061 has good thermal conductivity and diffusivity. It is also excellent for manufacturability because it can be machined easily, polished, and heat-treated. However, its high density, extremely high strain at 4.5 K—highest of all the materials—and relatively high CTE at 4.5 K make it an overall poor performer for Origins. An athermal design, both optically and structurally, would minimize some issues associated with strain and CTE mismatch, but then mass is an issue. Options exist to improve light-weighting for an aluminum mirror but there is also chemical stability to consider because of its highly reactive surface. Spaceflight heritage exists for apertures below 0.5 m.

3.1.5 AlBeMet[®]

AlBeMet[®] is a metal matrix composite of aluminum and beryllium. Its materials properties fall between beryllium and aluminum and while it has a better performance than aluminum, it still has some of the disadvantages of low manufacturability due the toxicity of beryllium while also being lower TRL. It also lacks heritage, with little-to-no spaceflight heritage and no meter class heritage.⁸

3.2 Mirror Material Trade Matrix

A material trade matrix was created for the top choices among the remaining material candidates. This trade matrix was initially designed for consideration of passive mirror segments for a 9.1-m aperture, where the actuators are used once to optically phase the mirror segments. The matrix is shown in Table 2 and assesses each material on a scale of 1 to 5 for performance, schedule, and cost, using NASA standard values. The materials are listed in order of preference, showing fused silica and SiC as the top choices.

Additionally, the results of the mirror material trade matrix show beryllium as the highest performing, despite programmatic challenges. SiC also has high performance and is another viable option for Origins. AlBeMet[®] offers the opportunity to improve the manufacturability of beryllium but would ultimately weigh more overall and have a lower stiffness than beryllium. Fused silica has the strongest optical heritage among the candidates, which would greatly reduce cost and schedule, but its lower thermal conductivity makes it less ideal for cooling than the other candidates. Aluminum has relatively good properties and machinability, but overall poorer thermal contraction performance and lower specific stiffness than the top candidates.

Table 2 A material trade matrix assisted the Origins team in identifying the top primary mirror materials. (On a scale of 1 to 5 with the higher values being better.)

Material	Performance	Schedule	Cost	Heritage
Fused Silica	3	5	4	Glass has max heritage as optic substrate
SiC (multiple)	4	4	3	Herschel heritage
Beryllium	5	2	2	JWST heritage
Aluminum 6061	2	5	5	All-Al telescope studied, found to be too massive
AlBeMet [®]	4	2	1	No meter-class heritage

3.3 Material Performance for Origins

The team created material performance plots to further evaluate the five potential material candidates. Figure 1 shows critical material properties plotted against specific stiffness at room temperature for beryllium, AlBeMet[®], SiC, fused silica, and aluminum. It is important to note that measured material properties vary at 4.5 K from test to test and alloy to alloy. The properties also vary based on purity, grade, and manufacturer. Where 4 K data is unavailable, values measured at temperatures in the range 4.5 to 30 K were used in these figures.

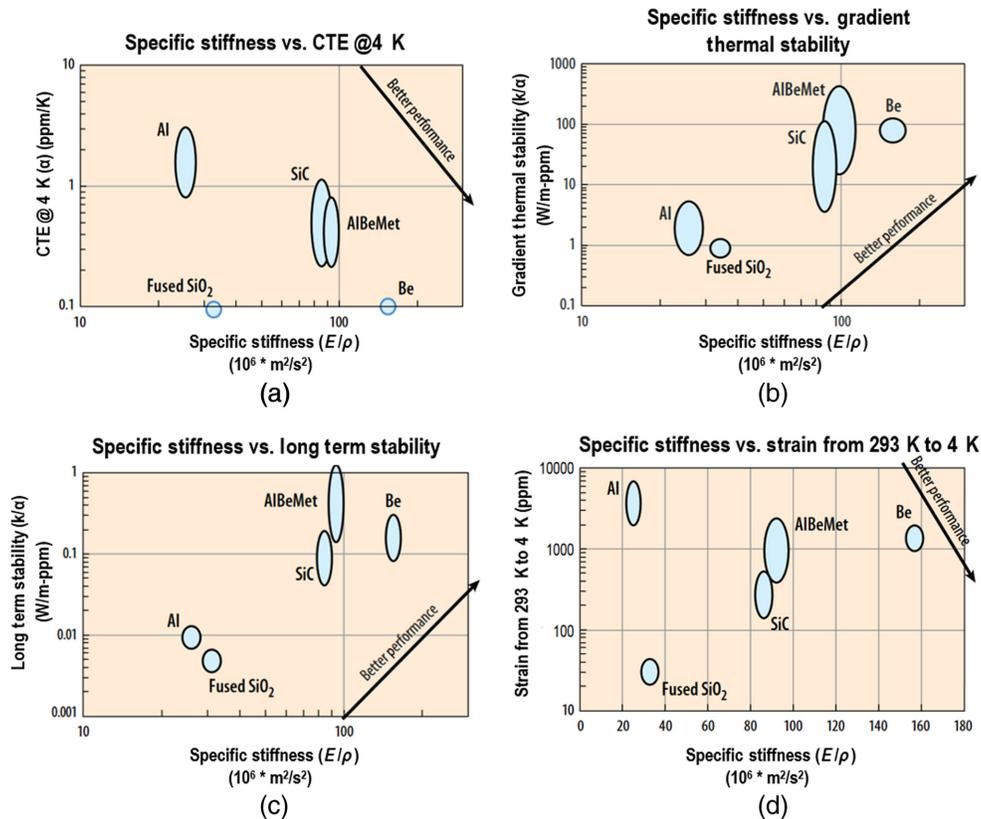


Fig. 1 (a) The CTE at 4 K plotted against specific stiffness shows beryllium (Be) is the best performer, followed by AlBeMet[®], SiC, fused silica, and aluminum (Al). (b) Steady-state gradient thermal stability plotted against specific stiffness shows Be, AlBeMet[®], and SiC as the best performers. (c) Long-term stability plotted against specific stiffness shows Be, AlBeMet[®], and SiC as the best performers. (d) Strain from room temperature (293 K) down to 4 K against specific stiffness shows trade-offs between Be, AlBeMet[®], SiC, and fused silica, with Al as the lowest performer.

Table 3 The advantages and disadvantages of each structural material were considered.

Material	Advantages	Disadvantages
Aluminum	Good fabrication time, inexpensive, and high thermal conductance	Heavy in comparison to CFRP and low stiffness
Copper	Excellent thermal properties	Extremely heavy
Composite/CFRP	Extremely lightweight and low CTE can be achieved	Creep and outgassing
Titanium	Excellent strength and good thermal properties	Extremely heavy and machining ability
Invar	Near zero CTE, excellent stiffness, and strength	Heavy
Stainless steel	Excellent structural material	Extremely heavy
Beryllium	Superior stiffness, extremely lightweight, low CTE, and high thermal conductance	Expensive, brittle, toxic, and long machining time
SiC	Excellent stiffness, excellent strength, and low CTE	Brittle, expensive, and long machining time

4 Structural Material

Ideal structural materials share many of the same characteristics as ideal mirror materials—strong, lightweight, and a near-zero change in thermal expansion. The team considered aluminum, copper, CFRP, titanium, Invar, stainless steel, beryllium, and SiC as the possible structural materials to use on Origins. Table 3 summarizes the overall appraisal.

Standard metals are typically strong and have excellent thermal properties but are generally too heavy to be used in large components. Lightweight materials, such as beryllium and SiC, are ideal but require more design development for large structural components. CFRP is strong, lightweight, but has low thermal conductance and is not suitable for Origins without also providing extensive thermal strapping to isothermalize the structure. Its other weakness is that it will produce water outgassing when warm (>160 K).

4.1 Final Materials Selection

For the 4.5 K structure, beryllium was selected. There are several potential issues with the use of beryllium that will be taken into account. Beryllium is more brittle compared to traditional materials such as aluminum so it requires special care in design (sharp corners, proper clearance holes, etc.). Beryllium dust is toxic, so fabrication is limited to certain places. These dangers do not exist after fabrication though, and a safety and handling plan would be created to address transport and handling of the parts.

Several organizations that have used large beryllium structures were consulted and offered guidance for Origins. These organizations would not hesitate to use beryllium again. Ball Aerospace developed the beryllium mirrors and the beryllium Aft Optics Subsystem (AOS) bench for the JWST⁹ as well as the beryllium mirror and structure for Spitzer.^{10,11} Lockheed Martin developed the beryllium bench of near-infrared camera (NIRCam) on JWST.² Origins plans to work with vendors early to qualify workmanship and design details. A segment of the primary mirror would be used to validate performance and then again after integrating the segments to the mirror backplane. Origins recognizes the need to restore the beryllium processing facilities used by JWST.

For the spacecraft structure, the team selected CFRP whenever possible. Origins has critical structures on the warm side [spacecraft bus module (SBM)] and the cold side (mirror and instrument thermally isolating support structures). While the observatory is warm before cool down, water vapor will outgas from CFRP. On the cold side, this vapor could condense onto the mirror

and instruments, impacting optical throughput. As a result, the team avoided using CFRP as much as practicable on the cold side, opting instead for metals.

Therefore, CFRP is an advantageous choice for the SBM, whereas metals are more suited for the cold side structures. An exception to this are the 4.5 K bipods, which are made of the CFRP M55J to provide the necessary stiffness to thermal conductivity in the range of 4.5 to 35 K. In contrast, high thermal conductance is critical for the backplane, which will be cooled conductively to 4.5 K, so the team sought a metal with good thermal conductivity down to 4.5 K. The mirror structures would also ideally be made from the same material as the mirror segments to avoid CTE mismatch between structures on the cold side. Thus, an athermal design of beryllium on the cold side is favorable.

5 Conclusion

The materials selection is a trade-off process. The most important parameters for the Origins primary mirror are specific stiffness (high stiffness and low density) and thermal performance (high thermal conductivity and low CTE). Beryllium O-30 has excellent specific stiffness and adequate thermal performance for Origins' needs. It is also the highest TRL material and has the most relevant cryogenic heritage, which advances the manufacturability and development. SiC is an attractive alternative option, but requires trades on the design and processing. Further assessments to address face sheet thickness, rib thickness, cell size, and mounting configuration of the mirror segments are recommended for either material option.

For structural materials, an athermal design is an attractive solution for CTE matching but greatly increases the mass. As a result, the team recommends composites whenever possible. For the backplane and other cold side structures, thermal performance is more important than mass. Therefore, the team recommends these structures be made of the same material as the primary mirror. However, beryllium and SiC require more design development in comparison to most metals and composites, so early work with potential designs and vendors is needed to ensure larger structures made of these materials will meet performance requirements and survive launch.

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