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Mirror Material Properties Compiled for Preliminary Design of the Next Generation Space Telescope (30 to 294 Kelvin)

P.L. Luz and T. Rice
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

National Aeronautics and
Space Administration

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TECHNICAL MEMORANDUM

MIRROR MATERIAL PROPERTIES COMPILED FOR PRELIMINARY DESIGN OF THE NEXT GENERATION SPACE TELESCOPE (30 to 294 KELVIN)

1. INTRODUCTION

In February 1996, the Program Development Directorate at NASA Marshall Space Flight Center (MSFC) began studying the feasibility of a Next Generation Space Telescope (NGST) and developed the prephase A program for it. After finishing some initial studies and concepts development work on the NGST,[1] Program Development handed this work to the Observatory Projects Office at NASA MSFC. NASA Goddard Space Flight Center (GSFC) was later given leadership of the NGST program.[2] NASA GSFC then issued a Cooperative Agreement Notice in April 22, 1996, to solicit proposals from industry to join in feasibility assessments related to the development of an NGST.[3] On August 19–21, 1996, "teams led by Lockheed Martin, TRW, and the GSFC concluded that an NGST was not only feasible and affordable, but that it could be made powerful using recent breakthroughs in space technologies."[4]

1.1 Mirror Material Tasks

From April 1996 to June 1997, the Optical Telescope Assembly (OTA) materials team performed a number of tasks for the prephase A (Advanced Studies) design of the NGST, including (1) identifying viable mirror material candidates, (2) identifying valid comparison factors, (3) compiling an initial mirror material properties database, (4) trading and comparing the materials, and (5) identifying critical issues and concerns.

1.2 Scope of This Report

This NASA technical memorandum reports on the mirror material properties that were compiled from April 1996 to June 1997 for preliminary design of the NGST. This work was performed by the Preliminary Design Office and Materials & Processes Laboratory at NASA MSFC for the NGST OTA team which was led by John T. Humphreys, manager of the AXAF Telescope Office at NASA MSFC, in support of NASA GSFC.

2. MIRROR MATERIAL PROPERTIES THAT ARE CITED

Refer to appendices A through I for detailed mirror material properties.

2.1 Literature Survey

Several sources were consulted for mirror material property data—textbooks; Internet databases; Redstone Scientific Information Center (RSIC) databases, including NASA RECON, DTIC, and CPX WEB; and industrial suppliers of the mirror materials. Information from at least 6 industrial suppliers, 16 textbooks, 44 technical papers, and 130 abstracts were reviewed for mirror material property information.

2.2 Overview

Requirements from NASA GSFC, the lead center for the NGST study, specify a "scientific requirement for telescope temperatures in the range 40 to 60 K."[5] Table 1 identifies the *lowest* temperature at which mirror material properties data was found during our survey of literature, the Internet, and industrial suppliers. Overall, the expected temperature range of the NGST is approximately 30 to 300 K.

Table 1. Lowest temperature at which material properties data is cited.

Type	Optical Material	Abbrev.	Lowest Temperature (K) at Which Data is Available							
			Density	CTE	k	Cp	E	Poisson's	YTS	UTS
	Be Spherical Powder									
Metal	Beryllium I-70A	Be I-70A	10*	10*	10*	20*	10*	10*	Room	Room
	Beryllium O-50	Be O-50	10*	5*	10*	20*			Room	Room
	Pure Nickel	Ni	Room	24*	24*	20*	20*	Room	Room	Room
	Electrodeposited Nickel	EdNi	Room	Room	30*	30*	Room	Room	78*	78*
Glass	Boro Silicate	Boro Si								
	Fused Silica Glass	SiO_2 (pc)	Room	Room	100*	150*	Room	Room		
	Fused Quartz, GE 214	SiO_2 (c)	Room	Room	Room	Room	Room	Room	Room	
	ULE 7971	ULE	Room	198*	223*	Room	73*	73*		
	Zerodur M	Zerodur	Room	75*	Room	Room	150*	Room		
Ceramic	CVD Silicon Carbide™	CVD SiC™	123*	133*	123*	123*	273*	Room	133*	
	Reaction-Bonded SiC	RB SiC								
Composite	Carbon/ Silicon Carbide	C/SiC	Room	4***	Room	Room	Room	Room		Room

Unfortunately, low temperature properties for many of the mirror substrate materials were not found in the literature surveyed up to June 1997. The property information cited in literature was typically at room temperature. Refer to the appendices for detailed material properties for the mirror materials in table 1. The text below gives some general information about the mirror materials.

- Beryllium. Beryllium "has flown on some of the most ambitious spacecraft programs undertaken, from the Apollo landers to deep space probes like Voyager" and has been used as an optical substrate on many missions, including Voyager, the Relay Mirror Experiment, and AOA.[6] Brush Wellman, the main supplier of beryllium, has the capability to produce near-net-shape beryllium optical substrates by hot isostatic pressing (HIP), cold isostatic pressing (CIP), and cold pressing of beryllium powders.[7] Please refer to appendices A and B for Beryllium I-70A and Beryllium O-50 material properties.

- Pure Nickel. Nickel was recommended for the NGST study by the Optics Lab (EB52) at NASA MSFC. Cold-worked nickel is one of the most ductile materials available. It has an advantage over some other optical materials under consideration, in that it can be machined and joined easily. However, it also has some disadvantages, including a high-mass density, low-specific stiffness, and thermal deformation parameters that are not favorable until the material becomes very cold. There are many factors to consider when choosing a material, and these may influence the selection of a baseline mirror material as the project's life cycle proceeds.

Some forms of nickel that are available include, but are not limited to, Nickel 200 (commercially pure-wrought nickel), Nickel 201 (low-carbon grade), and Inco's Duranickel™ alloy (containing 4.4% Al and 0.6% Ti). One may also hear about electroless nickel. Do not confuse this with pure nickel because it is a coating. "Electroless nickel plating is a controlled autocatalytic reduction of nickel ions by a suitable reducing agent, such as sodium hypophosphite, on a catalytic surface such as iron or aluminum. The resulting deposit is not a pure nickel, but essentially an alloy of nickel and phosphorus (if the normally used hydrophosphite salt is utilized as a reducing agent)." [8] Refer to appendix C for pure nickel material properties.

- Electrodeposited Nickel (EdNi). Beginning in October 1996, MSFC's Optics Lab (EB52) was working on an NGST mirror replication task in which their charter was to "produce high-quality subscale prototype normal incidence mirror elements for the NGST".[9] For the replication, they used an aluminum mandrel, deposited a layer of electroless nickel on it, a layer of gold, and then the final electrolytic nickel mirror surface. They produced the electrolytic nickel in-house using the Barrett process and sulfamate nickel.[10] However, since material properties for their nickel have not been determined yet through a material test program, some material property data for EdNi will be quoted as a representative sample.

EdNi "is a dense, essentially pure form of nickel. Because of the nature of the electrodeposition process, intricate contours can be readily and economically reproduced or covered with this form of nickel. EdNi can be deposited in thicknesses ranging from thin films to 1 inch or more. Mechanical properties of annealed EdNi are comparable to those of wrought Nickel 200. In the as-deposited form, the strength and hardness are higher than those of Nickel 200."[11] Refer to appendix D for EdNi material properties.

- Chemical Vapor Deposition (CVD) Silicon Carbide™ (SiC). CVD SiC™ is a free-standing, monolithic single-phase cubic material with high purity, no porosity, superior chemical resistance, thermal conductivity, stiffness, and polishability. It is a result of Morton International's bulk CVD process.[12] Other vendors and forms of SiC—like reaction bonded SiC, hot pressed SiC, and sintered SiC—are available. CVD SiC™ only represents one possible candidate out of many.

- Fabrication: "CVD SiC™ parts up to 60 inches (1.5 m) in diameter and 1 inch (25 mm) thick are available."[13] Engineers in NASA MSFC's cost group are currently checking on the cost of enlarging these facilities for NGST. Refer to appendix E for CVD SiC™ material properties.

- Silicon Dioxide Glass (Fused Silica & Fused Quartz). Fused silica is the common name for the polycrystalline form of silicon dioxide, a common glass material. Silicon dioxide is also known as quartz, but quartz should not be confused with fused silica because its structure is crystalline and its material properties (thermal conductivity at least) are orthotropic.[14] Refer to appendices F and G for fused silica and fused quartz material properties.

- ULE 7971. ULE™ is Corning Incorporated's Code 7971 Ultra Low Expansion titanium silicate glass.[15] The Hubble Space Telescope's 2.4-m diameter primary mirror blank was made from lightweighted ULE.

  - Fabrication: From a *single boule*, solid shapes up to 1.4 m in diameter by 15 cm thick can be fabricated. In addition, Corning's *flowout process* can be used to produce sizes up to 2.8 m in diameter; and a *hex sealing* process can be used to manufacture sizes up to 10 m in diameter. Hex seal technology was used to produce the 8.3-m ULE mirror blank for the Subaru Telescope which will be located atop Mauna Kea, Hawaii. In 1995, Corning completed the first 8.1-m ULE mirror blank for the Gemini 8-M Telescopes Project which will construct twin telescopes on Mauna Kea and on Cerra Pachon, Chile.[16] Refer to appendix H for ULE 7971 material properties.

- Zerodur. Zerodur is a glass ceramics material that Schott Glass Technologies, Inc., has developed for optical, optoelectronic, and precision engineering applications.[17] It is an inorganic, nonporous material which has a crystalline phase and a glassy phase. Zerodur mirror substrates have been built for various telescopes, including NASA's Advanced X-Ray Astrophysics Facility (AXAF) telescope, the ESO New Technology Telescope, and several telescopes for the Max-Planck-Institute for Astronomy in Heidelberg. Fabrication of parts up to 8.2 m in diameter is possible.[18] Refer to appendix I for Zerodur material properties.

3. MATERIAL SELECTION COMPARISON FACTORS

Many factors should be considered when trying to determine a suitable material for the mirror substrate of a space-based telescope. An effort was undertaken to identify many of the comparison factors, or figures of merit, which are pertinent to the selection of a telescope's mirror material. Table 2 lists these comparison factors, their definitions, and metric units. The table is loosely divided into seven categorical groupings of comparison factors: (1) structural figures of merit, (2) life cycle factors, (3) material homogeneity and stability, (4) thermal deformations, (5) optical scatter measurements, (6) reflectance, and (7) cost.

Table 2. Telescope mirror materials: some factors to consider.

Parameter	Definition	Units	Critieria
Specific Stiffness	E/rho	MJ/kg	High is Good
Specific Strength	YTS/rho	kJ/kg	High is Good
Microyield Strength (Temporal Stability Due to Creep)	Stress Producing 1% Creep in 100,000 Hours	MPa	High is Good
Fracture Toughness	K1c		
Anisotropy (Property homogeneity)	Ratio of Directional Mat'l Properties	Dimensionless	Near 1 is Good
Hysteresis Due to Thermal Cycling	Optical Figure Change	Waves r.m.s.	Low is Good
Steady State Thermal Distortion	CTE/k	cm/Megawatt	Near 0 is Good
Transient Thermal Distortion	(CTE-rho-Cp)/k	μ sec/cm ^{2}-K	Near 0 is Good
Surface Figure –Peak-to-Valley Deformation –Curvature Tilt	Δ (Deformed- Undeformed Shape	 mm (Microns) Micro-Radians	 Low is Good Near 0 is Good
Surface Microroughness	Departure of Surface From Plane	Angstroms r.m.s.	Low is Good
Optical Scatter	Scatter From Reflecting Surface	Angstroms r.m.s.	Low is Good
Reflectance (Normal Incidence)	$R=[(n\ \lambda-1)^2+\lambda k^2]/[(n\lambda+1)^2+\lambda k^2]$	percent (%)	High is Good
Cost	Price/Diameter	$/cm	Low is Good

- Stress and Deformations. The structural figures of merit, specific stiffness and specific strength, are good indications of how different materials can be compared in terms of stress and deformation due to structural loads. Structural loads which must be considered are quasi-static, random vibration and acoustic loads (from launch), thermal, crew-induced loads (if any, on orbit), and shock from transportation and separation events.

- Thermal. Thermal loads and their impact on thermal deformations and figure changes have always been an important consideration for space-based telescopes. Thermal loads for mirrors can be characterized as bulk temperature excursions, axial (through the thickness) gradients, and diametrical (across-the-span) gradients.

3.1 Other Considerations

Studies must consider many other factors as their telescope projects mature. Two of the most important questions concern material availability (their technology readiness level) and ease of fabrication to the telescope's desired size and precision. These factors have been difficult to quantify for the NGST study. As of June 1997, engineers in the NASA's cost group have been attempting to get quotes from private industry optical firms to estimate the cost of producing facilities large enough to handle the NGST optics.

Packaging considerations also lead to some very important questions, such as; will the design fit within a launch vehicle? Will there be any deployment mechanisms? There are also programmatic considerations such as budget, mass, and volumetric constraints; service life; and repair and maintenance.

4. CONCLUSION

This NASA technical memorandum reports on the mirror material properties that were compiled from April 1996 to June 1997, for preliminary design of the NGST. Detailed material properties are included in the appendix.

The careful and systematic selection of a mirror material for a space-based telescope is a difficult task because of the many interactions that exist due to structural, thermal, optical, and configuration considerations during the telescope's design. Mirror material selection is very important because it will also affect the selection of materials for the telescope's reaction structure, mirror support, and metering structure. The combination of mirror material and metering structure materials is critical in determining the total system performance. A strain-free and thermally insensitive mirror has little benefit if the metering structure is sensitive to thermal loads. But if the mirrors and metering structure are the same material, or are otherwise athermalized, then temperature soaks can be compensated.

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8. Downloaded on August 2, 1996 from http://www.metalogic.be/: METALogic N.V. , a spin-off company of K.U. Leuven Dept. MTM Kapeldreef 60–3001 HEVERLEE–Belgium, telephone +32–16–298.330, fax +32–16–298.319, e-mail: webmaster@METALogic.be.

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11. Anonymous: "Material Properties Manual," Rockwell International: Rocketdyne Div., Materials Engineering & Tech., Vol. IIA, 4th Ed., January 31, 1987.

12. Morton Advanced Materials: 185 New Boston Street, Woburn, MA 01801-6203. telephone (617) 933–9243, toll free sales (800) 552–2283, fax (617) 933–5142, WWW=http://www.mortoncvd.com/

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19. Anonymous: "Metallic Materials and Elements for Aerospace Vehicle Structures," MIL–HDBK–5F, Department of Defense, pp. 1–8 to 1–9, November 1990.

APPENDIX A

Beryllium I-70A
Material Properties

In October 1997, the authors intended for appendices A and B to contain material properties for Beryllium I-70 and Beryllium O-50. However, after a review of our sources for these properties, we realized that the major contributing source was export controlled.

After discussions with our management and export control officers, we decided in March 1998 to remove the table of beryllium material properties. Instead, we will list the sources of the properties for your reference.

Beryllium sources that are NOT export controlled.

Contained CTE vs. temperature data for Beryllium O-50
Swenson, "HIP beryllium: Thermal expansivity from 4 to 300 K and heat capacity from 1 to 108 K," Journal of Applied Physics, 70(6), Sept. 1991.

Contained Poisson's ratio and Elastic Modulus vs. temperature data for Beryllium I-70
J. Focht and D. Caldwell, "Beryllium Materials Characterization Report," Report No. K89-72U(R), Kaman Science Corp., Colorado Springs, CO, Aug. 4, 1989.

The major source which DOES contain Export Controlled Information.

D.H. Killpatrick, "Report on the Properties of Beryllium," prepared by RDA Logicon for MODIL, Oak Ridge National Laboratory, Purchase Order 90X-SE860V, May 1990.

"*WARNING—This document contains technical data whose export (including transmission to non-resident aliens) is restricted by the Arms Export Controls Act (22 USC 2751 et seq) or the Export Administration Act of 1979, as amended (50 USC 2401 et seq).*

Violations of these export laws are subject to criminal penalties."

A Supplier of Beryllium.

Brush Wellman, Beryllium/Mining Division, 14710 W. Portage River S. Rd., Elmore, Ohio 43416, (419) 862-4205. http://www.brushwellman.com/www/homepage.html

APPENDIX B

Beryllium O-50
Material Properties

In October 1997, the authors intended for appendices A and B to contain material properties for Beryllium I-70 and Beryllium O-50. However, after a review of our sources for these properties, we realized that the major contributing source was export controlled.

After discussions with our management and export control officers, we decided in March 1998 to remove the table of beryllium material properties. Instead, we will list the sources of the properties for your reference.

Beryllium sources that are NOT export controlled.

<u>Contained CTE vs. temperature data for Beryllium O-50</u>
Swenson, "HIP beryllium: Thermal expansivity from 4 to 300 K and heat capacity from 1 to 108K," Journal of Applied Physics, 70(6), Sept. 1991.

<u>Contained Poisson's ratio and Elastic Modulus vs. temperature data for Beryllium I-70</u>
J. Focht and D. Caldwell, "Beryllium Materials Characterization Report," Report No. K89-72U(R), Kaman Science Corp., Colorado Springs, CO, Aug. 4, 1989.

The major source which DOES contain Export Controlled Information.

D.H. Killpatrick, "Report on the Properties of Beryllium," prepared by RDA Logicon for MODIL, Oak Ridge National Laboratory, Purchase Order 90X-SE860V, May 1990.

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APPENDIX C

Pure Nickel
Material Properties

This appendix contains material properties for pure nickel.

Properties. Listed in the following charts are mass density, thermal properties (specific heat, thermal conductivity), and mechanical properties (CTE, modulus of elasticity, Poisson's ratio, and material strength). When available, properties are given over the temperature range of interest for the NGST, from 30 to 294 K.

Average CTE values. To assist structural analysts, we calculated average CTE values for the different materials, where possible, for a temperature drop from room temperature down to the NGST's operating temperature range. We numerically integrated the CTE curve to get thermal strain and then divided by the change in temperature to get an average CTE from 294 to 30 K. If available, these average CTE values are shown below the CTE plots for the various mirror materials.

Caution. The listed material strengths are often denoted as being average, typical values. When a telescope project matures, we advise that A-Basis properties be used instead. A-Basis values represent the value at which at least 99 percent of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95 percent.[19]

Special notations by the data. If a text notation appears next to a value, *calc.* indicates that the value was calculated from other data in the table, *int.* means that the value was linearly interpolated, and *assume* indicates that the density was assumed to be relatively constant versus temperature. All other values represent data that was measured in a laboratory.

MATERIAL PROPERTIES: Structural & Thermal.

NASA MSFC. PD21 / Paul L. Luz

Material: Pure Nickel

SUPPLIER: Thomas Register of American Manufacturers listed 33 "Nickel: Pure" suppliers, downloaded 11-15-96 from WWW at http://www.thomasregister.com:8000/index.html

BASIS (as defined in "Metallic Materials and Elements for Aerospace Vehicle Structures", MIL-HDBK-5G, Department of Defense, November 1994, pp 1-8 to 1-9.):

S-Basis properties = the minimum value specified by the governing industry specification or federal or military standards for the material.
A-Basis properties = at least 99% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
B-Basis properties = at least 90% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
Typical properties = average values with no statistical assurance associated with them.

MATERIAL PROPERTIES: 15-Nov-96

Direction =													
Basis =		Typical	Typical	Typical	Typical.	Typical.		Typical	Typical	Typical		
Type =												
Temperature (C)	(°K)	**Density** rho (kg/m^3)	**Ultimate Strength** UTS (MPa)	**Yield Strength** YTS (MPa)	**Elastic Modulus** E (GPa)	**Poisson's Ratio** mu (—)	**Microyield Strength**	**CTE** (per °K)	**Thermal Conductivity** k (W/m-K)	**Specific Heat** Cp (J/kg-K)	**Radiative Absorptivity** alpha	**Radiative Emmissivity** epsilon
-253 C	20 °K				214.2					5.2		
-249 C	24 °K	Assumed 8913						8.64E-6	860	10.5		
-240 C	33 °K	Assumed 8913			214.2			8.79E-6	657.6	16.7		
-224 C	49 °K				214.2			int. 9.17E-6		62.8		
-212 C	61 °K	Assumed 8913						9.46E-6	257.2	105		
-184 C	89 °K	Assumed 8913						1.01E-5	173.1	209		
-173 C	100 °K	Assumed 8913						int. 1.03E-5	164	230		
-156 C	117 °K							1.05E-5	138.5			
-143 C	130 °K							1.08E-5				
-129 C	144 °K	Assumed 8913			206.8			1.10E-5	123.6	335		
-73 C	200 °K	Assumed 8913						1.12E-5	108.9	387		
-45 C	228 °K							1.15E-5	103.8			
-33 C	240 °K				197			int. 1.19E-5		418		
21 °C	**294 °K**	**8913**	**689.5**	**344.7**	**197**	**0.287L, 0.281T**		**1.35E-5**	**88.96**	**460**		
1455 C	1728 °K											

FABRICATION: Maximum = parts up to TBD diameter and TBD thick.
Minimum = somewhere in the ballpark of TBD.

REFERENCES:

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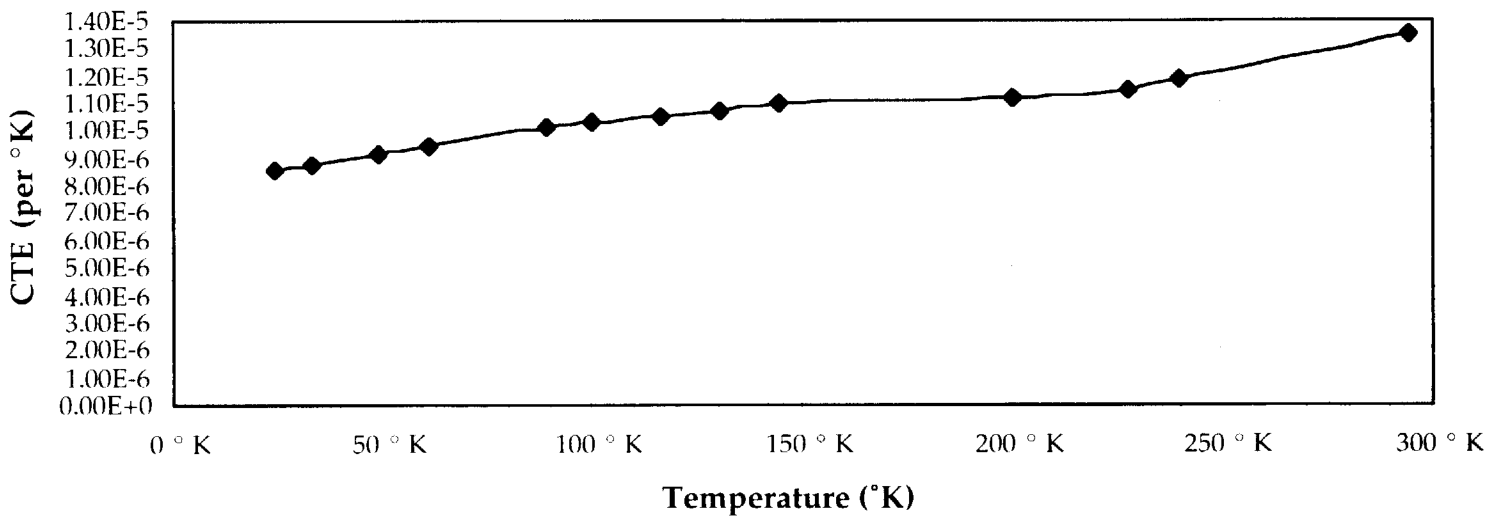
- Poisson's ratio — For Ni 200: Anon., "Material Properties Manual", Rockwell International: Rocketdyne Div., Materials Engineering & Tech., Vol IIA, 4th Ed., 1-31-87.

CTE of PURE NICKEL

The CTE is a calculated value, derived by taking the derivative of the measured thermal strain plot with respect to temperature.

Pure Nickel CTE vs. Temperature



Likewise, the test specimen's thermal strain from point T1 to point T2 can be calculated by integrating the CTE curve. This strain can then be divided by the change in temperature (T1–T2) to get an *average* CTE that can be used by analysts to simply their thermal strain calculations for other structural configurations.

For a bulk temperature drop from 294 °K to 60 °K, the *average* CTE=11.23 E-6 per °K; and from 294 °K to 30 °K, the *average* CTE=11.01 E–6 per °K.

Material FIGURES OF MERIT: Structural & Thermal.

NASA MSFC. PD21 / Paul L. Luz

Material: Pure Nickel

SUPPLIER: Thomas Register of American Manufacturers listed 33 "Nickel: Pure" suppliers, downloaded 11-15-96 from WWW at http://www.thomasregister.com:8000/index.html

BASIS (as defined in "Metallic Materials and Elements for Aerospace Vehicle Structures", MIL-HDBK-5G, Department of Defense, November 1994, pp 1-8 to 1-9.):

S-Basis properties = the minimum value specified by the governing industry specification or federal or military standards for the material.
A-Basis properties = at least 99% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
B-Basis properties = at least 90% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
Typical properties = average values with no statistical assurance associated with them.

FIGURES OF MERIT: **15-Nov-96**

Direction =						
Basis =		*Typical*	*Typical*	*Typical*		
Type =		Strength Driven	Strength Driven	Deflection Driven	Thermal Deform.	Thermal Deform.
Temperature		**Specific *Strength***	**Specific *Strength***	**Specific *Stiffness***	**Steady-state *Distortion***	**Transient *Distortion***
		UTS / rho	YTS / rho	E / rho	CTE / k	CTE-rho-Cp / k
(°C)	(°K)	(kJ/kg)	(kJ/kg)	(MJ/kg)	(cm/MW)	E-6(sec/cm^2-K)
-253 °C	20 °K					
-249 °C	24 °K				1.00	0.09
-240 °C	33 °K			24.0	1.34	0.20
-224 °C	49 °K					
-212 °C	61 °K				3.68	3.44
-184 °C	89 °K				5.83	10.87
-173 °C	100 °K				6.25	12.82
-156 °C	117 °K				7.58	
-143 °C	130 °K					
-129 °C	144 °K			23.2	8.90	26.57
-73 °C	200 °K				10.28	35.48
-45 °C	228 °K				11.08	
-33 °C	240 °K					
21 °C	294 °K	77.4	38.7	22.1	15.18	62.22
1455 °C	1728 °K					
		^ high is good	^ high is good	^ high is good	^ near zero is good	^ near zero is good

APPENDIX D

Electrodeposited Nickel
Material Properties

This appendix contains material properties for electrodeposited nickel.

Properties. Listed in the following charts are mass density, thermal properties (specific heat, thermal conductivity), and mechanical properties (CTE, modulus of elasticity, Poisson's ratio, and material strength). When available, properties are given over the temperature range of interest for the NGST, from 30 to 294 K.

Average CTE values. To assist structural analysts, we calculated average CTE values for the different materials, where possible, for a temperature drop from room temperature down to the NGST's operating temperature range. We numerically integrated the CTE curve to get thermal strain and then divided by the change in temperature to get an average CTE from 294 to 30 K. If available, these average CTE values are shown below the CTE plots for the various mirror materials.

Caution. The listed material strengths are often denoted as being average, typical values. When a telescope project matures, we advise that A-Basis properties be used instead. A-Basis values represent the value at which at least 99 percent of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95 percent.[19]

Special notations by the data. If a text notation appears next to a value, *calc.* indicates that the value was calculated from other data in the table, *int.* means that the value was linearly interpolated, and *assume* indicates that the density was assumed to be relatively constant versus temperature. All other values represent data that was measured in a laboratory.

MATERIAL PROPERTIES: Structural & Thermal.

NASA MSFC. PD21 / Paul L. Luz

Material: Electrodeposited Nickel (EdNi)

SUPPLIER: N/A

BASIS (as defined in "Metallic Materials and Elements for Aerospace Vehicle Structures", MIL-HDBK-5G, Department of Defense, November 1994, pp 1-8 to 1-9.):

- **S-Basis** properties = the minimum value specified by the governing industry specification or federal or military standards for the material.
- **A-Basis** properties = at least 99% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
- **B-Basis** properties = at least 90% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
- **Typical** properties = average values with no statistical assurance associated with them.

MATERIAL PROPERTIES: 22-Nov-96

Direction =														
Basis =		Typical	Exp. Min.	Exp. Min.	Typical	Typical		Typical	Typical	Typical			Exp. Min. as-deposited
Type =			As-Deposited	As-Deposited									
Temperature		**Density** rho	**Ultimate Strength** UTS	**Yield Strength** YTS	**Elastic Modulus** E	**Poisson's Ratio** mu	**Microyield Strength**	**CTE**	**Thermal Conductivity** k	**Specific Heat** Cp	**Radiative Absorptivity** alpha	**Radiative Emmissivity** epsilon	**Compressive Strength**
(°C)	(°K)	(kg/m^3)	(MPa)	(MPa)	(GPa)	(—)		(per °K)	(W/m-K)	(J/kg-K)			(MPa)
-243 °C	30 °K								605	30			
-228 °C	45 °K								380	40			
-213 °C	60 °K								295	55			
-195 °C	78 °K		855	483					200	75			459
-173 °C	100 °K		814	476					170	90			452
-151 °C	122 °K		772	469					145	105			448
-129 °C	144 °K		738	455					130	120			441
-107 °C	166 °K		717	448					120	130			434
-84 °C	189 °K		690	441					110	140			428
-62 °C	211 °K		669	434					100	150			421
-40 °C	233 °K		655	428					90	160			417
-18 °C	255 °K		641	421					85	170			410
5 °C	278 °K		634	414					85	175			403
22 °C	**295 °K**	**8854**	**614**	**414**	**180**	**0.264**		**1.47E-5**	**83.04**	**180**			**400**
1435 °C	1708 °K												

FABRICATION:
Maximum = parts up to TBD diameter and TBD thick.
Minimum = somewhere in the ballpark of TBD.

REFERENCES:

- At NASA/MSFC, EB52 produces electrolytic nickel with the Barrett process from sulfate nickel (11-22-96).
- Anon., "Material Properties Manual", Rockwell International: Rocketdyne Div., Materials Engineering & Tech., Vol IIA, 4th Ed., 1-31-87.

Material FIGURES OF MERIT: Structural & Thermal.

NASA MSFC. PD21 / Paul L. Luz

Material: Electrodeposited Nickel (EdNi)

SUPPLIER: N/A

BASIS (as defined in "Metallic Materials and Elements for Aerospace Vehicle Structures", MIL-HDBK-5G, Department of Defense, November 1994, pp 1-8 to 1-9.):

S-Basis properties = the minimum value specified by the governing industry specification or federal or military standards for the material.
A-Basis properties = at least 99% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
B-Basis properties = at least 90% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
Typical properties = average values with no statistical assurance associated with them.

FIGURES OF MERIT: **22-Nov-96**

Direction =						
Basis =		Exp. Min.	Exp. Min.	Typical.		
Type =		Strength Driven	Strength Driven	Deflection Driven	Thermal Deform.	Thermal Deform.
Temperature		**Specific Strength**	**Specific Strength**	**Specific Stiffness**	**Steady-state Distortion**	**Transient Distortion**
		UTS/rho	YTS/rho	E/rho	CTE/k	CTE-rho-Cp/k
(°C)	(°K)	(kJ/kg)	(kJ/kg)	(MJ/kg)	(cm/MW)	E-6(sec/cm^2-K)
-243 C	30 K					
-228 C	45 K					
-213 C	60 K					
-195 C	78 K					
-173 C	100 K					
-151 C	122 K					
-129 C	144 K					
-107 C	166 K					
-84 C	189 K					
-62 C	211 K					
-40 C	233 K					
-18 C	255 K					
5 C	278 K					
22 C	295 K	69.3	46.8	20.3	17.70	28.21
1435 C	1708 K					
		^ *high is good*	^ *high is good*	^ *high is good*	^ *near zero is good*	^ *near zero is good*

APPENDIX E

CVD Silicon Carbide™ Material Properties

This appendix contains material properties for CVD Silicon Carbide™.

Properties. Listed in the following charts are mass density, thermal properties (specific heat, thermal conductivity), and mechanical properties (CTE, modulus of elasticity, Poisson's ratio, and material strength). When available, properties are given over the temperature range of interest for the NGST, from 30 to 294 K.

Average CTE values. To assist structural analysts, we calculated average CTE values for the different materials, where possible, for a temperature drop from room temperature down to the NGST's operating temperature range. We numerically integrated the CTE curve to get thermal strain and then divided by the change in temperature to get an average CTE from 294 to 30 K. If available, these average CTE values are shown below the CTE plots for the various mirror materials.

Caution. The listed material strengths are often denoted as being average, typical values. When a telescope project matures, we advise that A-Basis properties be used instead. A-Basis values represent the value at which at least 99 percent of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95 percent.[19]

Special notations by the data. If a text notation appears next to a value, *calc.* indicates that the value was calculated from other data in the table, *int.* means that the value was linearly interpolated, and *assume* indicates that the density was assumed to be relatively constant versus temperature. All other values represent data that was measured in a laboratory.

MATERIAL PROPERTIES: Structural & Thermal.

NASA MSFC. PD21 / Paul L. Luz

Material: CVD Silicon Carbide™

SUPPLIER:

Morton Advanced Materials
185 New Boston Street
Woburn, MA 01801-6203

tel: (617) 933-9243
contact = Lee Burns at (617) 937-9102
fax: (617) 933-5142

Morton International WWW = http://www.mortoncvd.com/

BASIS (as defined in "Metallic Materials and Elements for Aerospace Vehicle Structures", MIL-HDBK-5G, Department of Defense, November 1994, pp 1-8 to 1-9.):

S-Basis properties = the minimum value specified by the governing industry specification or federal or military standards for the material.
A-Basis properties = at least 99% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
B-Basis properties = at least 90% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
Typical properties = average values with no statistical assurance associated with them.

MATERIAL PROPERTIES: 1-Jul-97

Direction =												
Basis =		Typical		Typical	Typical	Typical		Typical	Typical	Typical		
Type =				4-point flexural strength	4-point flexure							
Temperature		**Density** rho	**Ultimate Strength** UTS	**Yield Strength** YTS	**Elastic Modulus** E	**Poisson's Ratio** mu	**Microyield Strength**	**CTE**	**Thermal Conductivity** k	**Specific Heat** Cp	**Radiative Absorptivity** alpha	**Radiative Emmissivity** epsilon
(°C)	(°K)	(kg/m^3)	(MPa)	(MPa)	(GPa)	(—)		(per °K)	(W/m-K)	(J/kg-K)		
-273 °C	0 °K											
-150 °C	123 °K	calc. 3202							360	146		
-140 °C	133 °K	int. 3206		460				4.00E-7	396	175		
-100 °C	173 °K	calc. 3223		465				8.00E-7	485	301		
0 °C	273 °K	calc. 3223		470	460			1.90E-6	333	574		
21 °C	**294 °K**	**3210**		**470**	**461**	**0.21**		**2.20E-6**	**300**	**640**		
100 °C	373 °K	calc. 3329						2.90E-6	272	817		
200 °C	473 °K	calc. 3180		480	457			3.70E-6	221	952		
300 °C	573 °K	calc. 3226						4.10E-6	192	1044		
400 °C	673 °K	calc. 3192						4.40E-6	157	1093		
500 °C	773 °K			500	450			4.60E-6	137	1134		
700 °C	973 °K			515	440			4.90E-6	110	1189		
1000 °C	1273 °K	calc. 3282		540	435			5.00E-6	78	1251		
1200 °C	1473 °K	calc. 3243		555	422			5.10E-6	63	1295		
1500 °C	1773 °K			575	415				48	1355		

FABRICATION:

Maximum = parts up to 60" (1.5m) diameter and 1" (25mm) thick.
Minimum = somewhere in the ballpark of 1-2 mm (dependent on diameter of substrate, curvature, surface finish, etc.).

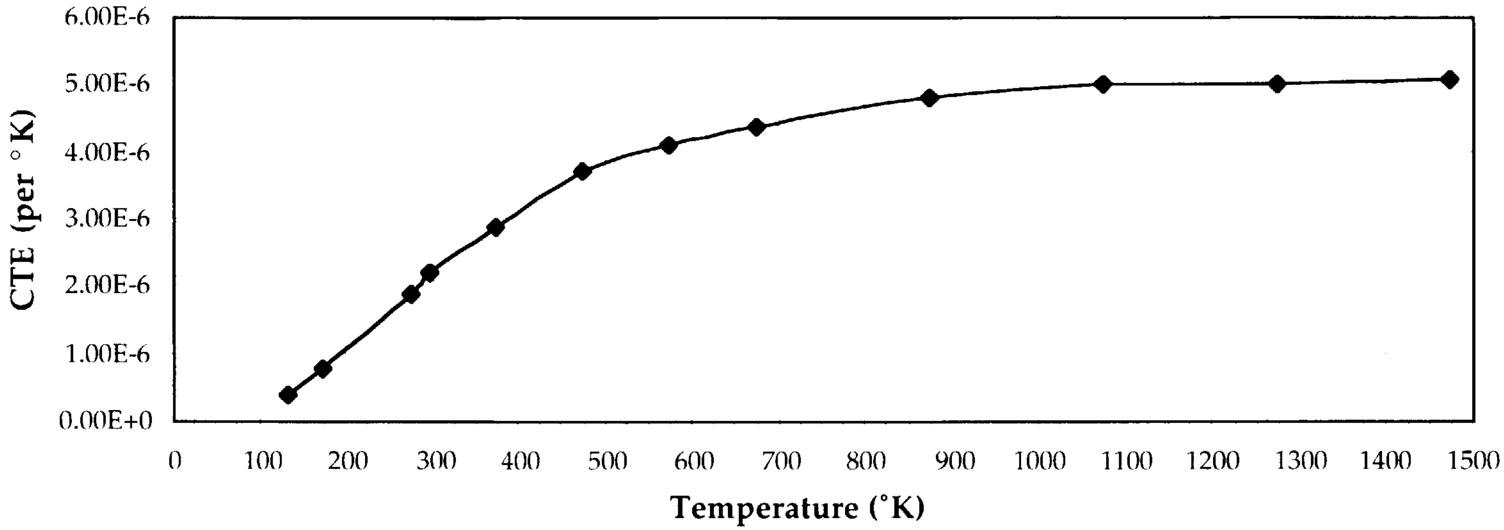
REFERENCES:

(1) Anon., "CVD Silicon Carbide™", Material specification SC-001, Morton Advanced Materials, Woburn, MA, October 1996.
(2) Anon., "CVD Silicon Carbide™", CVD Materials Technical Bulletin #996, Revision 1, Morton Advanced Materials, Woburn, MA, September 1996.
(3) http://www.nashville.net/~ceramics/morton/cvdsic.html, August 8, 1996. Verified existing properties and was able to add more properties at different temperatures.
(4) Cp, k, CTE, E, Strength from measurements at Morton Advanced Materials, University of Dayton Research Institute, Thermophysical Properties Research Laboratory at Purdue University, and a number of other commercial and university laboratories (see ref 2, page 2).

CTE of CVD™ SILICON CARBIDE

The CTE is a calculated value, derived by taking the derivative of the measured thermal strain plot with respect to temperature.

CVD Silicon Carbide™ CTE vs. Temperature



Likewise, the test specimen's thermal strain from point T1 to point T2 can be calculated by integrating the CTE curve. This strain can then be divided by the change in temperature (T1–T2) to get an *average* CTE that can be used by analysts to simply their thermal strain calculations for other structural configurations.

The *average* CTE for CVD Silicon Carbide™ during the NGST temperature drop from 294 °K to 30 °K could *not* be calculated because we have data from a CTE curve that only goes down to 133 °K.

Material *FIGURES OF MERIT* : Structural & Thermal.

NASA MSFC. PD21 / Paul L. Luz

Material: CVD Silicon Carbide ™

SUPPLIER:

Morton Advanced Materials
185 New Boston Street
Woburn, MA 01801-6203

tel: (617) 933-9243
contact = Lee Burns at (617) 937-9102
fax: (617) 933-5142

Morton International WWW = http://www.mortoncvd.com/

BASIS (as defined in "Metallic Materials and Elements for Aerospace Vehicle Structures", MIL-HDBK-5G, Department of Defense, November 1994, pp 1-8 to 1-9.):

S-Basis properties = the minimum value specified by the governing industry specification or federal or military standards for the material.
A-Basis properties = at least 99% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
B-Basis properties = at least 90% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
Typical properties = average values with no statistical assurance associated with them.

FIGURES OF MERIT: 1-Jul-97

Direction =						
Basis =			*Typical*	*Typical.*		
Type =		Strength Driven	Strength Driven	Deflection Driven	Thermal Deform.	Thermal Deform.
Temperature		**Specific Strength**	**Specific Strength**	**Specific Stiffness**	**Steady-state Distortion**	**Transient Distortion**
		UTS/rho	YTS/rho	E/rho	CTE/k	CTE-rho-Cp/k
(°C)	(°K)	(kJ/kg)	(kJ/kg)	(MJ/kg)	(cm/MW)	E-6(sec/cm^2-K)
-273 °C	0 °K					
-150 °C	123 °K					
-140 °C	133 °K		143.5		0.10	0.06
-100 °C	173 °K		144.3		0.16	0.16
0 °C	273 °K		145.8	142.7	0.57	1.06
21 °C	294 °K		146.4	143.6	0.73	1.51
100 °C	373 °K				1.07	2.90
200 °C	473 °K		150.9	143.7	1.67	5.07
300 °C	573 °K				2.14	7.19
400 °C	673 °K				2.80	9.78
500 °C	773 °K				3.36	
700 °C	973 °K				4.45	
1000 °C	1273 °K		164.6	132.6	6.41	26.32
1200 °C	1473 °K		171.1	130.1	8.10	34.00
1500 °C	1773 °K					
		^ *high is good*	^ *high is good*	^ *high is good*	^ *near zero is good*	^ *near zero is good*

APPENDIX F

Fused Silica Glass
Material Properties

This appendix contains material properties for fused silica glass.

Properties. Listed in the following charts are mass density, thermal properties (specific heat, thermal conductivity), and mechanical properties (CTE, modulus of elasticity, Poisson's ratio, and material strength). When available, properties are given over the temperature range of interest for the NGST, from 30 to 294 K.

Average CTE values. To assist structural analysts, we calculated average CTE values for the different materials, where possible, for a temperature drop from room temperature down to the NGST's operating temperature range. We numerically integrated the CTE curve to get thermal strain and then divided by the change in temperature to get an average CTE from 294 to 30 K. If available, these average CTE values are shown below the CTE plots for the various mirror materials.

Caution. The listed material strengths are often denoted as being average, typical values. When a telescope project matures, we advise that A-Basis properties be used instead. A-Basis values represent the value at which at least 99 percent of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95 percent.[19]

Special notations by the data. If a text notation appears next to a value, *calc.* indicates that the value was calculated from other data in the table, *int.* means that the value was linearly interpolated, and *assume* indicates that the density was assumed to be relatively constant versus temperature. All other values represent data that was measured in a laboratory.

MATERIAL PROPERTIES: Structural & Thermal.

NASA MSFC. PD21 / Paul L. Luz

Material: Fused Silica—Silicon Dioxide, Polycrystalline.

SUPPLIER: N/A

BASIS (as defined in "Metallic Materials and Elements for Aerospace Vehicle Structures", MIL-HDBK-5G, Department of Defense, November 1994, pp 1-8 to 1-9.):

S-Basis properties = the minimum value specified by the governing industry specification or federal or military standards for the material.
A-Basis properties = at least 99% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
B-Basis properties = at least 90% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
Typical properties = average values with no statistical assurance associated with them.

MATERIAL PROPERTIES: **1-Jun-92**

Direction =												
Basis =		Typical			Typical	Typical		Typical	Typical	Typical		
Type =												
Temperature		***Density*** rho	**Ultimate *Strength*** UTS	**Yield *Strength*** YTS	**Elastic *Modulus*** E	**Poisson's *Ratio*** mu	**Microyield *Strength***	***CTE***	**Thermal *Conductivity*** k	**Specific *Heat*** Cp	**Radiative *Absorptivity*** alpha	**Radiative *Emmissivity*** epsilon
(°C)	(°K)	(kg/m^3)	(MPa)	(MPa)	(GPa)	(—)		(per °K)	(W/m-K)	(J/kg-K)		
-273 °C	0 °K											
-223 °C	50 °K											
-173 °C	100 °K								0.69			
-123 °C	150 °K									418.655		
-73 °C	200 °K								1.14	544.252		
-23 °C	250 °K									661.475		
0 °C	273 °K											
21 °C	**294 °K**	**2200**			**72**	**0.244**		**5.50E-7**	**1.38**	**745**		
27 °C	300 °K											

FABRICATION: Maximum = parts up to TBD diameter and TBD thick.
Minimum = somewhere in the ballpark of TBD.

REFERENCES:

- rho, CTE, Cp, E, Poisson'r ratio. Y.S. Tououkian, "Thermophysical Properties of High Temperature Solids".
- k Incropera and DeWitt. Fundamentals of heat and Mass Transfer, Third Edition, 1990, Appendix A, p A8.
- Doubled-checked 294K props. Dibble, M.A. (ed.), "material Selection", Machine Design: 1992 Basics of Design Engineering Reference Volume, Vol. 64, No. 12, June 1992, p 969.

Material FIGURES OF MERIT: Structural & Thermal.

NASA MSFC. PD21 / Paul L. Luz

Material: <u>Fused Silica—Silicon Dioxide, Polycrystalline.</u>

SUPPLIER: N/A/

BASIS (as defined in "Metallic Materials and Elements for Aerospace Vehicle Structures", MIL-HDBK-5G, Department of Defense, November 1994, pp 1-8 to 1-9.):

- **<u>S-Basis</u>** properties = the minimum value specified by the governing industry specification or federal or military standards for the material.
- **<u>A-Basis</u>** properties = <u>at least 99%</u> of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
- **<u>B-Basis</u>** properties = <u>at least 90%</u> of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
- **<u>Typical</u>** properties = <u>average values</u> with no statistical assurance associated with them.

FIGURES OF MERIT: **1-Jun-92**

Direction =						
Basis =				*Typical*		
Type =		Strength Driven	Strength Driven	Deflection Driven	Thermal Deform.	Thermal Deform.
Temperature		**Specific *Strength***	**Specific *Strength***	**Specific *Stiffness***	**Steady-State *Distortion***	**Transient *Distortion***
		UTS/rho	YTS/rho	E/rho	CTE/k	CTE-rho-Cp/k
(°C)	(°K)	(kJ/kg)	(kJ/kg)	(MJ/kg)	(cm/MW)	E-6(sec/cm^2-K)
-273 °C	0 °K					
-223 °C	50 °K					
-173 °C	100 °K					
-123 °C	150 °K					
-73 °C	200 °K					
-23 °C	250 °K					
0 °C	273 °K					
21 °C	294 °K			32.7	39.86	65.32
27 °C	300 °K					
	0 °K					
	0 °K					
	0 °K					
	0 °K					
	0 °K					
	0 °K					
		^	^	^	^	^
		high is good	*high is good*	*high is good*	*near zero is good*	*near zero is good*

APPENDIX G

Fused Quartz Glass
Material Properties

This appendix contains material properties for fused quartz glass.

Properties. Listed in the following charts are mass density, thermal properties (specific heat, thermal conductivity), and mechanical properties (CTE, modulus of elasticity, Poisson's ratio, and material strength). When available, properties are given over the temperature range of interest for the NGST, from 30 to 294 K.

Average CTE values. To assist structural analysts, we calculated average CTE values for the different materials, where possible, for a temperature drop from room temperature down to the NGST's operating temperature range. We numerically integrated the CTE curve to get thermal strain and then divided by the change in temperature to get an average CTE from 294 to 30 K. If available, these average CTE values are shown below the CTE plots for the various mirror materials.

Caution. The listed material strengths are often denoted as being average, typical values. When a telescope project matures, we advise that A-Basis properties be used instead. A-Basis values represent the value at which at least 99 percent of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95 percent.[19]

Special notations by the data. If a text notation appears next to a value, *calc.* indicates that the value was calculated from other data in the table, *int.* means that the value was linearly interpolated, and *assume* indicates that the density was assumed to be relatively constant versus temperature. All other values represent data that was measured in a laboratory.

MATERIAL PROPERTIES: Structural & Thermal.

NASA MSFC. PD21 / Paul L. Luz

Material: Fused Quartz, GE Type 214 — Silicon Dioxide, Crystalline Silica (From Sand or Rock).

SUPPLIER:

General Electric
GE Willoughby Quartz Plant
Willoughby, OH

tel = ?
fax = ?
e-mail = quartz@lighting.ge.com

General Electric Quartz WWW = http://www.ge.com/quartz/catalog.htm
Fused Quartz WWW = http://www.users.fast.net/~wa3key/gedata.html

BASIS (as defined in "Metallic Materials and Elements for Aerospace Vehicle Structures", MIL-HDBK-5G, Department of Defense, November 1994, pp 1-8 to 1-9.):

S-Basis properties = the minimum value specified by the governing industry specification or federal or military standards for the material.
A-Basis properties = at least 99% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
B-Basis properties = at least 90% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
Typical properties = average values with no statistical assurance associated with them.

MATERIAL PROPERTIES: **7-May-97**

Direction =													
Basis =		*Typical*		*Typical*	*Typical*	*Typical*		*Typical*	*Typical*	*Typical*			*Typical*
Type =				Design Tensile Strength									Design
Temperature		**Density** rho	**Ultimate Strength** UTS	**Yield Strength** YTS	**Elastic Modulus** E	**Poisson's Ratio** mu	**Microyield Strength**	**CTE**	**Thermal Conductivity** k	**Specific Heat** Cp	**Radiative Absorptivity** alpha	**Radiative Emmissivity** epsilon	**Compressive Strength**
(°C)	(°K)	(kg/m^3)	(MPa)	(MPa)	(GPa)	(—)		(per °K)	(W/m-K)	(J/kg-K)			MPa
-273 °C	0 °K												
-150 °C	123 °K												
-140 °C	133 °K												
-100 °C	173 °K												
0 °C	273 °K												
21 °C	**294 °K**	**2200**		**48.3**	**72.4**	**0.17**		**5.50E-7**	**1.4**	**670**			**1100**
100 °C	373 °K												
200 °C	473 °K												
300 °C	573 °K												
400 °C	673 °K												
600 °C	873 °K												
800 °C	1073 °K												
1000 °C	1273 °K												
1200 °C	1473 °K												
1500 °C	1773 °K												

FABRICATION:

Maximum = parts up to TBD diameter and TBD thick.
Minimum = somewhere in the ballpark of TBD

REFERENCES:

- 294K props http://www.users.fast.net/~wa3key/gedata.html (Downloaded 5-7-97. Web page revision = August 6, 1996).

Material FIGURES OF MERIT: Structural & Thermal.

NASA MSFC. PD21 / Paul L. Luz

Material: Fused Quartz, GE Type 214—Silicon Dioxide, Crystalline Silica (From Sand or Rock).

SUPPLIER:

General Electric
GE Willoughby Quartz Plant
Willoughby, OH

tel = ?
toll-free sales = (800) 438-2100
fax = ?
e-mail = quartz@lighting.ge.com

General Electric Quartz WWW = http://www.ge.com/quartz/catalog.htm
Fused Quartz WWW = http://www.users.fast.net/~wa3key/gedata.html

BASIS (as defined in "Metallic Materials and Elements for Aerospace Vehicle Structures", MIL-HDBK-5G, Department of Defense, November 1994, pp 1-8 to 1-9.):

S-Basis properties = the minimum value specified by the governing industry specification or federal or military standards for the material.
A-Basis properties = at least 99% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
B-Basis properties = at least 90% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
Typical properties = average values with no statistical assurance associated with them.

FIGURES OF MERIT: **7-May-97**

Direction =						
Basis =			*Typical*	*Typical*		
Type =		Strength Driven	Strength Driven	Deflection Driven	Thermal Deform.	Thermal Deform.
Temperature		**Specific Strength**	**Specific Strength**	**Specific Stiffness**	**Steady-state Distortion**	**Transient Distortion**
		UTS/rho	YTS/rho	E/rho	CTE/k	CTE-rho-Cp/k
(°C)	(°K)	(kJ/kg)	(kJ/kg)	(MJ/kg)	(cm/MW)	E-6(sec/cm^2-K)
-273 °C	0 °K					
-150 °C	123 °K					
-140 °C	133 °K					
-100 °C	173 °K					
0 °C	273 °K					
21 °C	294 °K		22.0	32.9	39.29	57.91
100 °C	373 °K					
200 °C	473 °K					
300 °C	573 °K					
400 °C	673 °K					
600 °C	873 °K					
800 °C	1073 °K					
1000 °C	1273 °K					
1200 °C	1473 °K					
1500 °C	1773 °K					
		^ *high is good*	^ *high is good*	^ *high is good*	^ *near zero is good*	^ *near zero is good*

APPENDIX H

ULE 7971
Material Properties

This appendix contains material properties for ULE 7971.

Properties. Listed in the following charts are mass density, thermal properties (specific heat, thermal conductivity), and mechanical properties (CTE, modulus of elasticity, Poisson's ratio, and material strength). When available, properties are given over the temperature range of interest for the NGST, from 30 to 294 K.

Average CTE values. To assist structural analysts, we calculated average CTE values for the different materials, where possible, for a temperature drop from room temperature down to the NGST's operating temperature range. We numerically integrated the CTE curve to get thermal strain and then divided by the change in temperature to get an average CTE from 294 to 30 K. If available, these average CTE values are shown below the CTE plots for the various mirror materials.

Caution. The listed material strengths are often denoted as being average, typical values. When a telescope project matures, we advise that A-Basis properties be used instead. A-Basis values represent the value at which at least 99 percent of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95 percent.[19]

Special notations by the data. If a text notation appears next to a value, *calc.* indicates that the value was calculated from other data in the table, *int.* means that the value was linearly interpolated, and *assume* indicates that the density was assumed to be relatively constant versus temperature. All other values represent data that was measured in a laboratory.

MATERIAL PROPERTIES: Structural & Thermal.

NASA MSFC. PD21 / Paul L. Luz

Material: ULE™—Corning's Code 7971 Ultra Low Expansion Titanium Silicate Glass

SUPPLIER:

Corning Incorporated
Advanced Materials Business
HP CP-08
Corning, NY 14831

Sales = (607) 974-7440.
Customer service = (607) 974-7597.
Fax = (607) 974-7210.

WWW = http://www.corning.com/

BASIS (as defined in "Metallic Materials and Elements for Aerospace Vehicle Structures", MIL-HDBK-5G, Department of Defense, November 1994, pp 1-8 to 1-9.):

S-Basis properties = the minimum value specified by the governing industry specification or federal or military standards for the material.
A-Basis properties = at least 99% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
B-Basis properties = at least 90% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
Typical properties = average values with no statistical assurance associated with them.

MATERIAL PROPERTIES: **5-Jul-96**

Direction =													
Basis =		Typical		Typical	Typical	Typical		Typical	Typical	Typical		
Type =												
Temperature		**Density** rho	**Ultimate Strength** UTS	**Yield Strength** YTS	**Elastic Modulus** E	**Poisson's Ratio** mu	**Microyield Strength**	**CTE**	**Thermal Conductivity** k	**Specific Heat** Cp	**Radiative Absorptivity** alpha	**Radiative Emmissivity** epsilon
(°C)	(°K)	(kg/m^3)	(MPa)	(MPa)	(GPa)	(—)		(per °K)	(W/m-K)	(J/kg-K)		
-243 °C	30 °K											
-228 °C	45 °K											
-213 °C	60 °K											
-200 °C	73 °K				64	0.158						
-173 °C	100 °K											
-150 °C	123 °K											
-100 °C	173 °K											
-75 °C	198 °K							-2.70E-7				
-60 °C	213 °K											
-50 °C	223 °K				66			-1.80E-7	1.3			
-25 °C	248 °K							-1.00E-7				
0 °C	273 °K							-3.00E-8				
21 °C	294 °K											
25 °C	298 °K	2210	49.8		67.6	0.17		2.00E-8	1.31	767		
1000 °C	1273 °K											

FABRICATION:

Maximum = monolithic solids up to 10 m diameter and TBD thick.
Minimum = somewhere in the ballpark of a few centimeters diameter and TBD thick.

REFERENCES:

• Anonymous, "Zero Expansion Glass ULE™", Corning Incorporated, Corning, NY 14831, dated March 1996.

Material FIGURES OF MERIT: Structural & Thermal.

NASA MSFC. PD21 / Paul L. Luz

Material: ULE™ - Corning's Code 7971 Ultra Low Expansion Titanium Silicate Glass.

SUPPLIER:

Corning Incorporated
Advanced Materials Business
HP-CP-08
Corning, NY 14831

Sales = (607) 974-7440.
Customer service = (607) 974-7597.
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BASIS (as defined in "Metallic Materials and Elements for Aerospace Vehicle Structures", MIL-HDBK-5G, Department of Defense, November 1994, pp 1-8 to 1-9.):

S-Basis properties = the minimum value specified by the governing industry specification or federal or military standards for the material.
A-Basis properties = at least 99% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
B-Basis properties = at least 90% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
Typical properties = average values with no statistical assurance associated with them.

FIGURES OF MERIT: **5-Jul-96**

Direction =						
Basis =			*Typical*	*Typical*		
Type =		Strength Driven	Strength Driven	Deflection Driven	Thermal Deform.	Thermal Deform.
Temperature		**Specific *Strength***	**Specific *Strength***	**Specific *Stiffness***	**Steady-state *Distortion***	**Transient *Distortion***
		UTS/rho	YTS/rho	E/rho	CTE/k	CTE-rho-Cp/k
(°C)	(°K)	(kJ/kg)	(kJ/kg)	(MJ / kg)	(cm/MW)	E-6(sec/cm^2-K)
-243 °C	30 °K					
-228 C	45 K					
-213 C	60 K					
-200 C	73 K					
-173 C	100 K					
-150 C	123 K					
-100 C	173 K					
-75 C	198 K					
-60 C	213 K					
-50 C	223 K				-13.85	
-25 C	248 K					
0 C	273 K					
21 C	294 K					
25 C	298 K	22.5		30.6	1.53	2.59
1000 C	1273 K					
		^ *high is good*	^ *high is good*	^ *high is good*	^ *near zero is good*	^ *near zero is good*

APPENDIX I

Zerodur
Material Properties

This appendix contains material properties for Zerodur.

Properties. Listed in the following charts are mass density, thermal properties (specific heat, thermal conductivity), and mechanical properties (CTE, modulus of elasticity, Poisson's ratio, and material strength). When available, properties are given over the temperature range of interest for the NGST, from 30 to 294 K.

Average CTE values. To assist structural analysts, we calculated average CTE values for the different materials, where possible, for a temperature drop from room temperature down to the NGST's operating temperature range. We numerically integrated the CTE curve to get thermal strain and then divided by the change in temperature to get an average CTE from 294 to 30 K. If available, these average CTE values are shown below the CTE plots for the various mirror materials.

Caution. The listed material strengths are often denoted as being average, typical values. When a telescope project matures, we advise that A-Basis properties be used instead. A-Basis values represent the value at which at least 99 percent of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95 percent.[19]

Special notations by the data. If a text notation appears next to a value, *calc.* indicates that the value was calculated from other data in the table, *int.* means that the value was linearly interpolated, and *assume* indicates that the density was assumed to be relatively constant versus temperature. All other values represent data that was measured in a laboratory.

MATERIAL PROPERTIES: Structural & Thermal.

NASA MSFC. PD21 / Paul L. Luz

Material: Glass Ceramics Zerodur

SUPPLIER:

Schott Glass Technologies, Inc.
400 York Avenue
Duryea, PA 18642

Contact = Bob Chamberlain
(717) 457-7485 Ext. 305
(717) 457-6960

BASIS (as defined in "Metallic Materials and Elements for Aerospace Vehicle Structures", MIL-HDBK-5G, Department of Defense, November 1994, pp 1-8 to 1-9.):

S-Basis properties = the minimum value specified by the governing industry specification or federal or military standards for the material.
A-Basis properties = at least 99% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
B-Basis properties = at least 90% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
Typical properties = average values with no statistical assurance associated with them.

MATERIAL PROPERTIES: 30-Jun-97

Direction =												
Basis =		Typical			Typical	Typical		Typical	Typical	Typical		
Type =												
Temperature		**Density** rho	**Ultimate Strength** UTS	**Yield Strength** YTS	**Elastic Modulus** E	**Poisson's Ratio** mu	**Microyield Strength**	**CTE** (per °K)	**Thermal Conductivity** k	**Specific Heat** Cp	**Radiative Absorptivity** alpha	**Radiative Emmissivity** epsilon
(°C)	(°K)	(kg/m^3)	(MPa)	(MPa)	(GPa)	(—)			(W/m-K)	(J/kg-K)		
-243 °C	30 °K	assumed 2530						about - 6.7E-7	0.2	about 50		
-228 °C	45 °K							int. - 5.8E-7	0.4	about 100		
-213 °C	60 °K							int. - 4.9E-7	0.6			
-198 °C	75 °K							about - 4.0E-7	0.7			
-173 °C	100 °K							about - 2.0E-7	0.9			
-123 °C	150 °K				88.3			int. - 1.4E-7				
-103 °C	170 °K				88.65			int. - 1.2E-7				
-83 °C	190 °K				89			about - 1.0E-7		about 500		
-63 °C	210 °K				89.3			about - 1.0E-7				
-43 °C	230 °K				89.6			int. - 9.8E-8				
-23 °C	250 °K				89.85			int. - 9.5E-8				
-3 °C	270 °K				90			int. - 9.3E-8				
0 °C	273 °K				90.05			int. - 9.3E-8				
21 °C	**294 °K**	**2530**			**90.3**	**0.243**		**-9.0E-8**	**1.46**	**800**		
600 °C	873 °K											

FABRICATION:

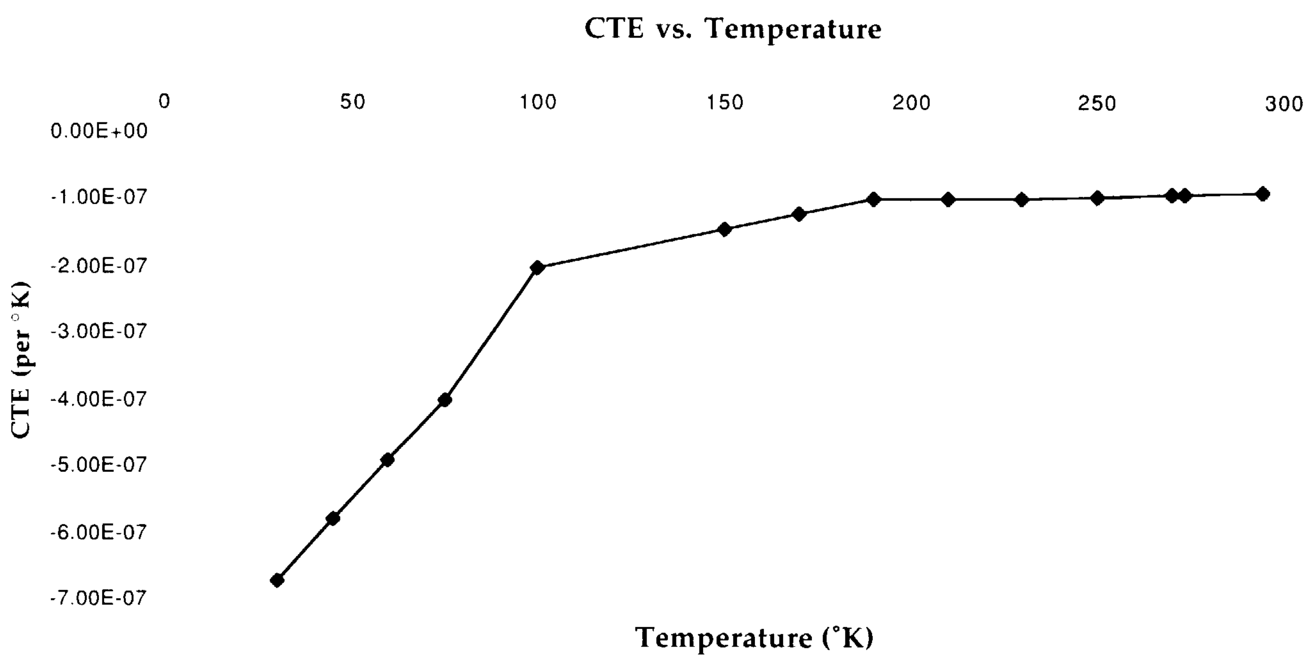
Maximum = parts up to 8.2 m diameter and TBD thick.
Minimum = somewhere in the ballpark of TBD.

REFERENCES:

• Anon., "Zerodur - Precision from glass ceramics", Product brochure 10041, Schott Glass Technologies, Inc., Duryea, PA, date 10-91?

CTE of Glass Ceramics Zerodur

The CTE is a calculated value, derived by taking the derivative of the measured thermal strain plot with respect to temperature.



Likewise, the test specimen's thermal strain from point T1 to point T2 can be calculated by integrating the CTE curve. This strain can then be divided by the change in temperature (T1–T2) to get an *average* CTE that can be used by analysts to simply their thermal strain calculations for other structural configurations.

For NGST's temperature drop from 294 ° K to 30 ° K, the *average* CTE=0.208 E–6 per ° K.

Material FIGURES OF MERIT: Structural & Thermal.

Material: Glass Ceramics Zerodur

SUPPLIER:

Schott Glass Technologies, Inc.
400 York Avenue
Duryea, PA 18642

Contact = Bob Chamberlain
(717) 457-7485 Ext. 305
(717) 457-6960

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- S-Basis properties = the minimum value specified by the governing industry specification or federal or military standards for the material.
- A-Basis properties = at least 99% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
- B-Basis properties = at least 90% of the population of values is expected to equal or exceed the material property allowable, with a statistical confidence of 95%.
- Typical properties = average values with no statistical assurance associated with them.

FIGURES OF MERIT: **30-Jun-97**

Direction =						
Basis =			*0*	*Typical*		
Type =		Strength Driven	Strength Driven	Deflection Driven	Thermal Deform.	Thermal Deform.
Temperature		**Specific Strength**	**Specific Strength**	**Specific Stiffness**	**Steady-state Distortion**	**Transient Distortion**
		UTS/rho	YTS/rho	E/rho	CTE/k	CTE-rho-Cp/k
(°C)	(°K)	(kJ/kg)	(kJ/kg)	(MJ/kg)	(cm/MW)	E-6(sec/cm^2-K)
-243 °C	30 °K				-335.00	-42.38
-228 °C	45 °K				-145.00	
-213 °C	60 °K				-81.67	
-198 °C	75 °K				-57.14	
-173 °C	100 °K				-22.22	
-123 °C	150 °K					
-103 °C	170 °K					
-83 °C	190 °K					
-63 °C	210 °K					
-43 °C	230 °K					
-23 °C	250 °K					
-3 °C	270 °K					
0 °C	273 °K					
21 °C	294 °K			35.7	-6.16	-12.48
600 °C	873 °K					
		^ *high is good*	^ *high is good*	^ *high is good*	^ *near zero is good*	^ *near zero is good*

APPROVAL

MIRROR MATERIAL PROPERTIES COMPILED FOR PRELIMINARY DESIGN OF THE NEXT GENERATION TELESCOPE (30 TO 294 KELVIN)

P.L. Luz and T. Rice

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

A. Roth
Director, Program Development Directorate

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13. ABSTRACT *(Maximum 200 words)*

This technical memorandum reports on the mirror material properties that were compiled by NASA Marshall Space Flight Center (MSFC) from April 1996 to June 1997 for preliminary design of the Next Generation Space Telescope (NGST) study. The NGST study began in February 1996, when the Program Development Directorate at NASA MSFC studied the feasibility of the NGST and developed the prephase A program for it. After finishing some initial studies and concepts development work on the NGST, MFSC's Program Development Directorate handed this work to the Observatory Projects Office at MSFC and then to NASA Goddard Space Flight Center (GSFC). This technical memorandum was written by MSFC's Preliminary Design Office and Materials and Processes Laboratory for the NGST Optical Telescope Assembly (OTA) team, in support of NASA GSFC. It contains material properties for 9 mirror substrate materials, using information from at least 6 industrial suppliers, 16 textbooks, 44 technical papers, and 130 technical abstracts.

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