TERTIARY MIRROR BLANK SPECIFICATIONS

TMT.OPT.SPE.06.006.REL02

12 January 2010

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1. INTRODUCTION

This document defines the mirror blank requirements for the Tertiary Mirror (M3) of the Thirty Meter Telescope (TMT). The M3 Blank will be fabricated into the solid meniscus M3 Mirror that is shown in the Tertiary Mirror Assembly (M3A) in Figure 1.

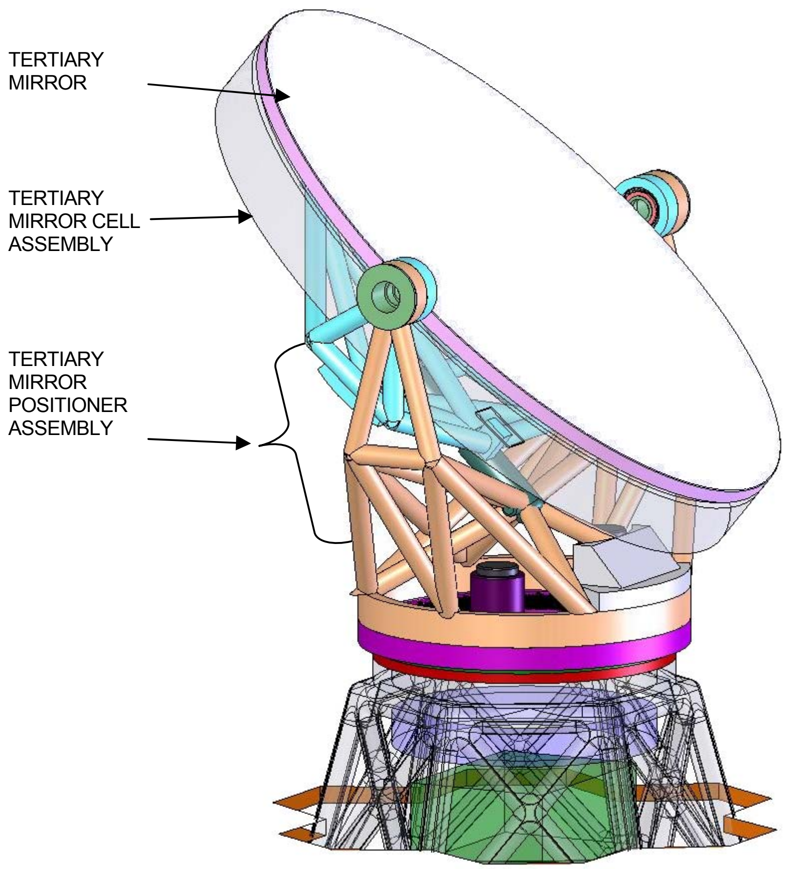

Figure 1. Tertiary Mirror Assembly including the M3 Positioner and M3 Mirror Cell Assemblies.

1.1 PURPOSE

This document specifies requirements for the Tertiary Mirror Blank for the Thirty Meter Telescope Tertiary Mirror.

1.2 SCOPE

This specification defines the requirements for the M3 Blank only. The requirements for the finished Tertiary Mirror are described in a separate specification.

1.3 CHANGE RECORD

Revision	Date	Section	Modifications
REL01	April 17, 2007		Original release
REL02	Jan. 12, 10		This is the initial version of this specification since the change of the TMT telescope baseline design

1.4 ABBREVIATIONS

CTE Coefficient of Thermal Expansion
CTE_e Effective Coefficient of Thermal Expansion
CTE_i Instantaneous Coefficient of Thermal Expansion
ºC Degrees Centigrade
ΔL Change in Length
L Length
M3A Tertiary Mirror Assembly
M3CA Tertiary Mirror Cell Assembly
M3M Tertiary Mirror
mm millimeter
MPa megapascal
RMS Root Mean Square
ΔT Change in Temperature
TMT Thirty Meter Telescope

1.5 DEFINITIONS

- **Back Surface:** The Back surface is the flat surface of the Blank that is on the opposite side of the M3 Optical Surface. The Back Surface will have pads bonded to it during final mirror assembly.
- **Basic Dimension:** a theoretically exact value used to describe the ideal size, profile, orientation or location of a feature. Geometric Dimensioning and Tolerancing shall be interpreted per ANSI Y-14.5M-1994.
- **Blank**: The blank is the piece of glass or glass-ceramic from which the TMT Tertiary Mirror will be fabricated.
- **Blank Supplier:** the manufacturer that will supply the Blank
- **Blister:** A Blister is a flat void in a seam between boules of material that have been fused together to make the Blank.
- **Bubbles:** See inclusions.
- **Chip:** A Chip is defined as a hollow depression in the surface of the M3 Blank. A ground out spherical depression shall be considered to be a Chip, as defined in this specification. Chips

occur only on the surface of the Blank material. The size of a chip shall be its Mean Diameter.

- **Crack:** A crack is defined as a separation of the material of the blank. The length of the crack shall be defined as the longest dimension of the separation area.
- **Critical Zone:** The Critical Zone is defined as the volume of material directly under the Optical Surface. This zone shall be 10mm in thickness, and shall extend over the surface to within 10mm from the edge, as shown in Figure 2.
- **CTE Axial Gradient:** The CTE Axial Gradient is defined as the slope of the linear least squares fit of the Operating Range Average CTE for each CTE Specimen plotted versus the axial distance of the measured material from the center of the M3 Blank. The sign of the axial distance is defined in the positive direction as denoted by the Z-Blank arrow in Figure 2. An example of this calculation is provided in Appendix 7.4
- **CTE Lateral Variation:** The CTE Lateral Variation is defined as the absolute value of the difference between the Operating Range Average CTE of all the CTE Specimens of the M3 Blank (averaged together) and the Operating Range Average CTE of each CTE Specimen.
- **CTE Specimen:** CTE Specimen is defined as a sample of glass or glass-ceramic material used to derive the CTE metrics in the Blank. CTE Specimens shall be taken from material immediately adjacent to the Blank material. For a Blank material whose CTE can be measured in-situ, references in this document to CTE Specimens shall include in-situ CTE measurements made at specific locations, where applicable.
- **Defects:** Defects are defined as chips or cracks on the surface or cracks inside the M3 Blank material.
- **Generating:** machining the surfaces of the M3 Blank by fixed-abrasive grinding or similar technique
- **Inclusions:** Inclusions are defined as any foreign matter in the M3 Blank that is not the zero-expansion material from which the M3 Blank is made. For purposes of this specification, bubbles are considered to be Inclusions. The size of an Inclusion shall be its Mean Diameter.
- **Instantaneous CTE:** Instantaneous CTE is defined as the first derivative with respect to Temperature of the curve of $\Delta L/L$ plotted versus Temperature. This is illustrated in Appendix 7.2..
- **Ion Figuring:** an optical figuring method in which the optical surface is shaped by bombarding it with an ion source.
- **M3 Blank:** A piece of glass or glass-ceramic from which the Tertiary Mirror will be fabricated.
- **Mean Diameter:** The Mean Diameter is defined as the diameter of a sphere having the same volume as an Inclusion or a Chip.
- **Observatory:** the facility located at Mauna Kea that will include the Thirty Meter Telescope
- **Operating Range Average CTE:** The Operating Range Average CTE is defined as the average of a set of Instantaneous CTE measurements taken at the specific temperatures: -5ºC, 2ºC, and 9ºC within the Operating Temperature Range. An Operating Range Average CTE will be calculated for each CTE Specimen. The Operating Range Average CTEs of all the CTE Specimens will be averaged together to calculate the Operating Range Average CTE for the M3 Blank. This is illustrated in Appendix 7.3.2.
- **Operating Temperature Range:** The Operating Temperature Range is defined as the temperature range experienced by the M3 Mirror during Astronomical Observing. The limits of this temperature range are the warmest and coldest predicted temperatures that will be experienced at the M3 Mirror during collection of Astronomical Data. The Operating Temperature Range is defined as -5ºC to 9ºC.

- **Optical Surface:** the flat surface of the Tertiary Mirror that will be polished to meet the required reflectivity requirements and that will reflect the telescope light.

- **Shop-Op Effective CTE:** The Shop-Op Effective CTE is defined for each CTE Specimen as the change in length per length of the CTE Specimen between the high limit and low limit of the Shop-Op Temperature Range divided by ΔT of the Shop-Op Temperature Range. The Blank Shop-Op Effective CTE is defined as the average of all the CTE Specimens Shop-Op Effective CTEs. This is illustrated in Appendix 7.3.1.

- **Shop-Op Temperature Range:** The Shop-Op Temperature Range is defined as the temperature range experienced by the M3 Mirror. The upper limit of the Shop-Op Temperature Range is the average of the temperatures that will be experienced during assembly, installation, and maintenance. The Shop-Op upper limit is defined as 20ºC. The lower limit of the Shop-Op Temperature Range is the average of the temperatures that will be experienced during Astronomical Observing on the telescope. The Shop-Op lower limit is defined as 2ºC. The Shop-Op Temperature Range is defined as 2ºC to 20ºC having a ΔT of 18 ºC.

- **Strain-Induced Birefringence:** The difference (retardation) between the path length of light propagating in the direction of maximum strain and that propagating in the transverse direction, per unit length. It is a result of the different indices of refraction, which are caused by inherent or imposed strains in the material.

- **Subsurface Damage:** Cracks in the glass below the surface caused by machining or grinding, whether visible or not.

2. OVERALL DESCRIPTION

2.1 PERSPECTIVE

The M3 Blank will be fabricated into the solid meniscus TMT Tertiary Mirror (M3M). The M3M will be supported in the M3 Mirror Cell (M3CA) with passive lateral supports attached to the edge and active axial supports attached to the back surface. The axial supports will be controlled to maintain the M3 Optical Surface as the M3 Assembly rotates with respect to gravity and also experiences a changing thermal environment.

The M3CA will be supported by a positioning assembly that will control the rigid body position of the M3 Optical Surface.

The Optical Surface of the M3 mirror is flat. Table 1 below provides a summary of the optical and dimensional properties of the M3 Mirror and M3 Mirror Blank for reference only. The dimensions provided in Figure 2, take precedence over any values provided here.

Table 1. Summary of Optical and Dimensional Properties of the M3 Mirror and M3 Mirror Blank

Mirror Element	Optical Beam Dimensions	Coated Clear Aperture Dimensions	Mechanical Dimensions	Thickness	Optical Surface Spherical Radius of Curvature	Conic Constant
Finished M3 Mirror	ellipse major Φ: 3.508 m minor Φ: 2.450 m	ellipse major Φ: >3.544 m minor Φ: >2.485 m	ellipse major Φ: 3.594 m minor Φ: 2.536 m	100 mm	N/A (flat)	N/A
M3 Mirror Blank	N/A	N/A	ellipse major Φ: 3.596 m minor Φ: 2.538 m	103 mm	N/A (flat)	N/A

3. SPECIFIC REQUIREMENTS

Paragraphs appearing in italics and beginning with "Discussion" are explanations rather than requirements.

Discussion: TMT reserves the right to test the Blank material to verify that it meets the requirements in Section 3.

3.1 MATERIAL PROPERTIES

3.1.1 M3 Blank Material

[SPE-M3.BLK-1100] The M3 Blank material shall be a low-thermal-expansion glass or glass-ceramic. No other material is allowed in the M3 Blank, except as noted in Section 3.6 Inclusions and Defects.

3.1.2 Chemical Resistance

Discussion: The Optical Surface of M3M will be subject to periodic cleaning throughout the life of the Observatory.

Discussion: The cleaning process will include any combination of CO_2 snow, and/or liquids including alcohol, acetone, detergents and water.

[SPE-M3.BLK-1210] The M3 Blank material shall not show any damage or increase of surface roughness on the polished surfaces after being subjected to 2000 cleaning cycles using CO2 snow and 1000 cleaning cycles using liquids.

Discussion: The reflective coating on the M3 will be subject to periodic removal throughout the expected life of the Observatory.

[SPE-M3.BLK-1220] The M3 Blank material shall not show any damage or increase of surface roughness on polished surfaces after being subjected to 30 coating removals. Materials that may be used during coating removal include:

- Hydrochloric acid (37% concentration)
- Cupric Sulfate
- Potassium Hydroxide
- Nitric Acid (70% concentration)
- Ceric Ammonium Nitrate
- Calcium Carbonate
- Potassium Ferrocyanide solutions
- Sodium Thiosulfate solutions

3.1.3 Dimensional Stability

[SPE-M3.BLK-1310] The M3 Blank material shall be dimensionally stable over the anticipated 50-year lifetime of the Observatory.

Discussion: the intention of this requirement is to limit changes due to aging: long-term dimension changes due to, for example, subtle equilibrium or phase changes within the material.

[SPE-M3.BLK-1320] The Material shall undergo no permanent dimensional changes after mechanical cycling 10 times over a stress range of -10 to +10 MPa, and/or after thermal cycling 10 times over a temperature range from -40°C to 105°C. This requirement applies under the following measurement conditions:

- Thermal condition: reference temperature (isothermal) = 2°C
- Mechanical condition: no external mechanical loads applied
- Prior to taking any dimensional measurements to determine possible dimensional changes, the Material shall be allowed to fully relax any residual stresses that may have been induced by handling or test cycling.

3.1.4 Polishing Compatibility

[SPE-M3.BLK-1410] The M3 Blank material shall be able to be polished using conventional optical finishing processes and materials to a surface roughness of 1 nanometer RMS or less.

[SPE-M3.BLK-1420] The material in the M3 Blank shall be compatible with Ion-Figuring processes.

Discussion: This compatibility shall be considered proven if samples of the material that have been polished to a surface roughness of 1 nanometer RMS can have 5 microns of material removed by Ion Figuring while maintaining a surface roughness of less than 1.2 nanometers RMS.

3.1.5 Coefficient of Thermal Expansion (CTE)

3.1.5.1 Samples of M3 Blank Material for CTE Specimens

[SPE-M3.BLK-1501] The M3 Blank Supplier shall define a CTE Specimen sampling scheme for collecting CTE Specimens that will enable calculation of all the CTE metrics required within Section 3.1.5. Appendix 7.1 illustrates a possible (but not required) sampling scheme.

[SPE-M3.BLK-1505] The M3 Blank Supplier shall retain all CTE Specimens for the duration of the M3 Blank production period, and shall deliver all CTE Specimens to TMT upon request.

3.1.5.2 Measurements and calculations required for M3 Blank CTE definition

[SPE-M3.BLK-1510] The M3 Blank Supplier shall define a measurement scheme that will enable calculation of all the CTE metrics required within Section 3.1.5. Measurement accuracy shall be sufficient to demonstrate compliance with all requirements within Section 3.1.5.

[SPE-M3.BLK-1515] The M3 Blank Supplier shall calculate all the CTE metrics required within Section 3.1.5. The M3 Blank Supplier shall provide processed CTE test data to TMT in an electronic format that will be mutually agreed on by the Blank Supplier and TMT.

3.1.5.3 Instantaneous CTE of each CTE Specimen

[SPE-M3.BLK-1520] Measurements of the CTE Specimens shall characterize the Instantaneous CTE of each CTE Specimen over the temperature range from -10°C to 20°C.

Discussion: An example of the method to be used to calculate Instantaneous CTE is provided in Appendix 7.2.

[SPE-M3.BLK-1525] The absolute value of the Instantaneous CTEs of each CTE Specimen shall be <100 x 10^{-9}/ºC at every temperature from -10°C to 20°C, inclusive.

[SPE-M3.BLK-1527] The absolute value of the difference between the Instantaneous CTEs of each CTE Specimen and the M3 Blank Operating Range Average CTE shall be <50 x 10^{-9}/ºC at temperatures within the Operating Temperature Range.

3.1.5.4 Shop-Op Effective CTE

[SPE-M3.BLK-1530] The Shop-Op Effective CTE of each CTE Specimen shall be calculated. These values shall be recorded and reported to TMT. This is illustrated further in Appendix 7.3.1.

[SPE-M3.BLK-1535] The M3 Blank Effective CTE shall be calculated from the Shop-Op Effective CTEs of all the CTE Specimens. This value shall be recorded and reported to TMT.

3.1.5.5 Operating Range Average CTE

[SPE-M3.BLK-1540] The Operating Range Average CTE of each CTE Specimen shall be calculated using the Instantaneous CTE of the CTE Specimen at the Observatory Temperatures: -5°C, 2°C and 9°C. This is illustrated in Appendix 7.3.2. These values shall be recorded and reported to TMT.

[SPE-M3.BLK-1545] The M3 Blank Operating Range Average CTE shall be the average of the Operating Range Average CTEs of all the CTE Specimens and shall be within the range of $\pm$ 50 x 10^{-9}/ºC .

3.1.5.6 CTE Lateral Variation within the M3 Blank

[SPE-M3.BLK-1550] The CTE Lateral Variation for any CTE Specimen of the M3 Blank shall be calculated at the Observatory Temperatures: -5°C, 2°C and 9°C. The CTE Lateral Variation for each CTE Specimen equals the difference between the M3 Blank Operating Range Average CTE and the Operating Range Average CTE for each CTE Specimen. These values shall be recorded and reported to TMT.

[SPE-M3.BLK-1555] CTE Lateral Variation for any CTE Specimen of the M3 Blank shall be within the range +/-20 x 10^{-9} / ^{o}C relative to the M3 Operating Range Blank Average CTE.

3.1.5.7 CTE Axial Gradient within the M3 Blank

[SPE-M3.BLK-1560] While generating the meniscus, the blank shall be oriented based on the calculated CTE Axial Gradient so the Average CTE of CTE Specimens from the Optical Surface is equal to or greater than the Average CTE of CTE Specimens at the Back Surface.

Discussion: This process is discussed further in Appendix 7.4.

[SPE-M3.BLK-1565] The CTE Axial Gradient shall be calculated as described in Appendix 7.4, based on Instantaneous CTE values of the CTE Specimens measured at the temperatures: -5°C, 2°C and 9°C. The positive axial direction is in the direction of the Z-Blank axis shown in Figure 2. The absolute value of the CTE Axial Gradient shall be less than or equal to 45 x 10^{-9} per ºC per meter.

[SPE-M3.BLK-1567] If the Blank is formed by fusing together separate boules of glass or glass-ceramic, the CTE Axial Gradient of each boule shall be measured and the Blank shall be assembled with the CTE Axial Gradients of all the boules having the same sign (i.e., the same direction).

Discussion: The calculation is further detailed in Appendix 7.4.

3.1.5.8 CTE Stability

[SPE-M3.BLK-1570] The M3 Operating Range Average CTE shall not change by more than 10 x 10^{-9}/ ^{o}C after the CTE Specimens are subjected to ten temperature cycles of -40°C to 105°C, at a temperature rate of 50ºC/hr, and two temperature cycles of -40°C to 105°C, at a temperature rate of 1ºC/hr.

3.2 RESIDUAL STRESS

[SPE-M3.BLK-2010] The Strain-Induced Birefringence shall be measured through the thickness of the M3 Blank at no fewer than seven points, with a goal of taking one measurement at the center and at least six required measurements approximately equally spaced every 60 degrees around the perimeter of the M3 Blank, approximately 20 cm from the edge. The M3 Blank shall be supported during measurement to ensure the support-induced stress is less than 0.08 MPa.

[SPE-M3.BLK-2020] The absolute value of residual stress in the M3 Blank material shall be less than 0.4 MPa at all points in the Blank.

[SPE-M3.BLK-2030] The Blank Supplier shall provide documentation that validates the stress optical coefficient used in the calculation of stress.

3.3 Dimensions

Discussion: The Drawing TMT.TEL.OPT.M3S.CA.BLND-0001 (the "Drawing") included in this specification as Figure 2 shows the complete dimensional requirements for the M3 Blank. In case of discrepancies between dimensions provided elsewhere within this document and dimensions on the Drawing, information on the Drawing takes precedence.

[SPE-M3.BLK-3020] The M3 Blank supplier shall perform an inspection of the M3 Blank before shipment, using equipment and methods adequate to ensure that all dimensional tolerances have been met. During this inspection, the M3 Blank shall be supported in a manner that produces no more than 0.5 mm of deflection at any point due to gravity.

3.4 Surface Condition

[SPE-M3.BLK-4010] To control the depth of Subsurface Damage, the final figure of the M3 Blank shall be Generated with care based upon the experience of the Blank Supplier. The Blank Supplier shall provide TMT with documentation justifying the recommended approach to control Subsurface Damage.

[SPE-M3.BLK-4020] The Subsurface Damage of the final figure of the M3 Blank shall penetrate into the Blank material no more than 50 microns. The Blank Supplier shall demonstrate that their Generating approach will consistently result in surfaces with Subsurface Damage that meets this specification.

3.5 Fiducial Markings

[SPE-M3.BLK-4010] A fiducial mark shall be placed on the M3 Blank that will be used to orient the optical surface and locations of CTE Specimens and will be referenced in the inspection report. The fiducial mark shall be located on the edge of the blank or away from the optical surface of the polished M3 mirror.

3.6 Inclusions and Defects

3.6.1 Inclusions

[SPE-M3.BLK-6105] Inclusions with a Mean Diameter smaller than 0.5 mm are not restricted in this specification, and do not need to be documented.

[SPE-M3.BLK-6110] Inclusions with a Mean Diameter greater than 2.5 mm are not allowed within or partially within the Critical Zone.

[SPE-M3.BLK-6120] The number of Inclusions of mean diameter greater than 0.5 mm and less than 2.5 mm, partially or totally within the Critical Zone, shall total 5 or less per any 1,000,000 mm^3 volume. The volume shall be defined as a 316 mm square area having the Critical Zone thickness (10 mm x 316 mm x 316 mm).

[SPE-M3.BLK-6130] The total number of Inclusions of mean diameter greater than 0.5 mm and less than 2.5 mm, partially or within the Critical Zone shall total less than 50 for the entire Critical Zone

[SPE-M3.BLK-6140] No visible refractory material shall be allowed within the Critical Zone.

[SPE-M3.BLK-6150] Outside of the Critical Zone, Inclusions with a Mean Diameter greater than 10 mm shall not be allowed.

[SPE-M3.BLK-6160] Outside of the Critical Zone, the number of Inclusions of mean diameter greater than 0.5 mm and less than 5 mm shall total 1000 or less for the entire volume.

[SPE-M3.BLK-6165] Outside of the Critical Zone, the number of Inclusions of Mean Diameter greater than 0.5 mm and less than 5 mm shall total 10 or less per any 900,000 mm^3 volume defined as a square area of 100mm x 100mm having the thickness from the Back Surface to the Critical Zone (100mm x 100mm x 90mm).

[SPE-M3.BLK-6170] Outside of the Critical Zone, the number of Inclusions of mean diameter greater than 5 mm and less than 10 mm shall total 100 or less for the entire volume.

[SPE-M3.BLK-6175] Outside of the Critical Zone, the number of Inclusions of mean diameter greater than 5 mm and less than 10 mm shall total 2 or less per any 900,000 mm^3 volume defined as a square area of 100mm x 100mm having the thickness from the Back Surface to the Critical Zone (100mm x 100mm x 90mm).

[SPE-M3.BLK-6180] If the M3 Blank is constructed by fusing together pieces of glass from separate boules, the fusion seams between boules must be 99% sealed, defined as follows: the area occupied by blisters and Inclusions, collectively, as measured in the plane of the fusion seam shall not exceed 1.0 % of the total area of such fusion seam.

Discussion: The Inclusion Limits are summarized in Table 2*.*

[SPE-M3.BLK-6190] The location of all Inclusions shall be documented with respect to the Fiducial Mark on the Blank and reported to TMT.

3.6.2 Defects: Surface Chips and Cracks

[SPE-M3.BLK-6210] All surfaces of a Chip must be ground out to remove sharp edges and cracks, then etched to remove Subsurface Damage. The final size of the chip is determined after this process has taken place.

[SPE-M3.BLK-6220] No Chips are allowed on the optical surface of the M3 Blank.

[SPE-M3.BLK-6230] The Chip size shall not exceed 20 mm in Mean Diameter after grinding and no more than three Chips are allowed over all the surfaces of the entire M3 Blank.

[SPE-M3.BLK-6240] Within or partially within the Critical Zone, no Defects are allowed.

[SPE-M3.BLK-6250] Within the entire M3 blank volume outside the Critical Zone, no Cracks equal to or larger than 10 mm in length are allowed.

[SPE-M3.BLK-6255] Within the entire M3 blank volume outside the Critical Zone, the number of Cracks smaller than 10 mm in length shall be less than 5. The Cracks must be separated by 0.5 meters from other Cracks within the volume.

[SPE-M3.BLK-6260] No visible Cracks shall be allowed on the surface of the M3 Blank. Any Crack on the surface shall be ground out leaving a depression that is approximately spherical then etched. Any resulting depression shall be counted as a chip and shall satisfy Specification [SPE-M3.BLK-6230].

[SPE-M3.BLK-6270] The depth of any ground spherical depression shall be less than half the diameter of the sphere.

Discussion: The Defect Limits are summarized in Table 2*.*

[SPE-M3.BLK-6280] The location of all Cracks and Chips shall be documented with respect to the Fiducial Mark on the Blank and reported to TMT.

Table 2. Inclusion and Defect Limits

INCLUSION LIMITS

INSPECTION REGION	MEAN DIAMETER	INSPECTION VOLUME	MAX QUANTITY
Inside Critical Zone*	<0.5mm	Entire Zone	Any
	0.5mm to 2.5mm	Entire Zone	50
	0.5mm to 2.5mm	Any 1,000,000mm^3 vol.	5
Outside Critical Zone	<0.5mm	Entire Volume	Any
	0.5mm to 5mm	Entire Volume	1000
	0.5mm to 5mm	Any 900,000mm^3 vol.	10
	5mm to 10mm	Entire Volume	100
	5mm to 10mm	Any 900,000mm^3 vol.	2

* Within or partially within the Critical Zone

DEFECT LIMITS

	INSPECTION REGION	SIZE	INSPECTION ZONE	MAX QUANTITY
Cracks	**Inside Critical Zone***	Any	Volume of Critical Zone	None
Cracks	**Outside Critical Zone**	<10mm length	Entire Volume excluding Crit. Zone	5
Chips	**Entire Surface of Critical Zone**	Any	Entire Surface of Critical Zone	None
Chips	**Entire Surface except Critical Zone**	≤20mm Mean Diameter	Entire Surface except Critical Zone	3
Cracks	**Entire Surface**	Any	Entire Surface of Blank	None

* Within or partially within the Critical Zone

4. DOCUMENTATION REQUIREMENTS

An inspection report shall be provided for the M3 Blank, and shall include all of the measurements related to the requirements of this specification, including the requirements related to:

- Coefficient of Thermal Expansion
- Residual Stress
- Dimensions
- Surface Condition
- Bubbles and Inclusions
- Cracks and Chips

5. PACKAGING AND DELIVERY

A proposal shall be submitted for the final Packaging and Transfer Plan of the M3 Blank. This plan shall be subject to review and approval by TMT. The Blank Supplier shall provide the shipping container to be used for moving the M3 Blank from the fabricator's facility to the polishing vendor's facility.

6. M3 BLANK DRAWING

Discussion: In case of disagreement between the information in the M3 Blank Drawing and the information in the text, the information in the drawing shall have precedence.

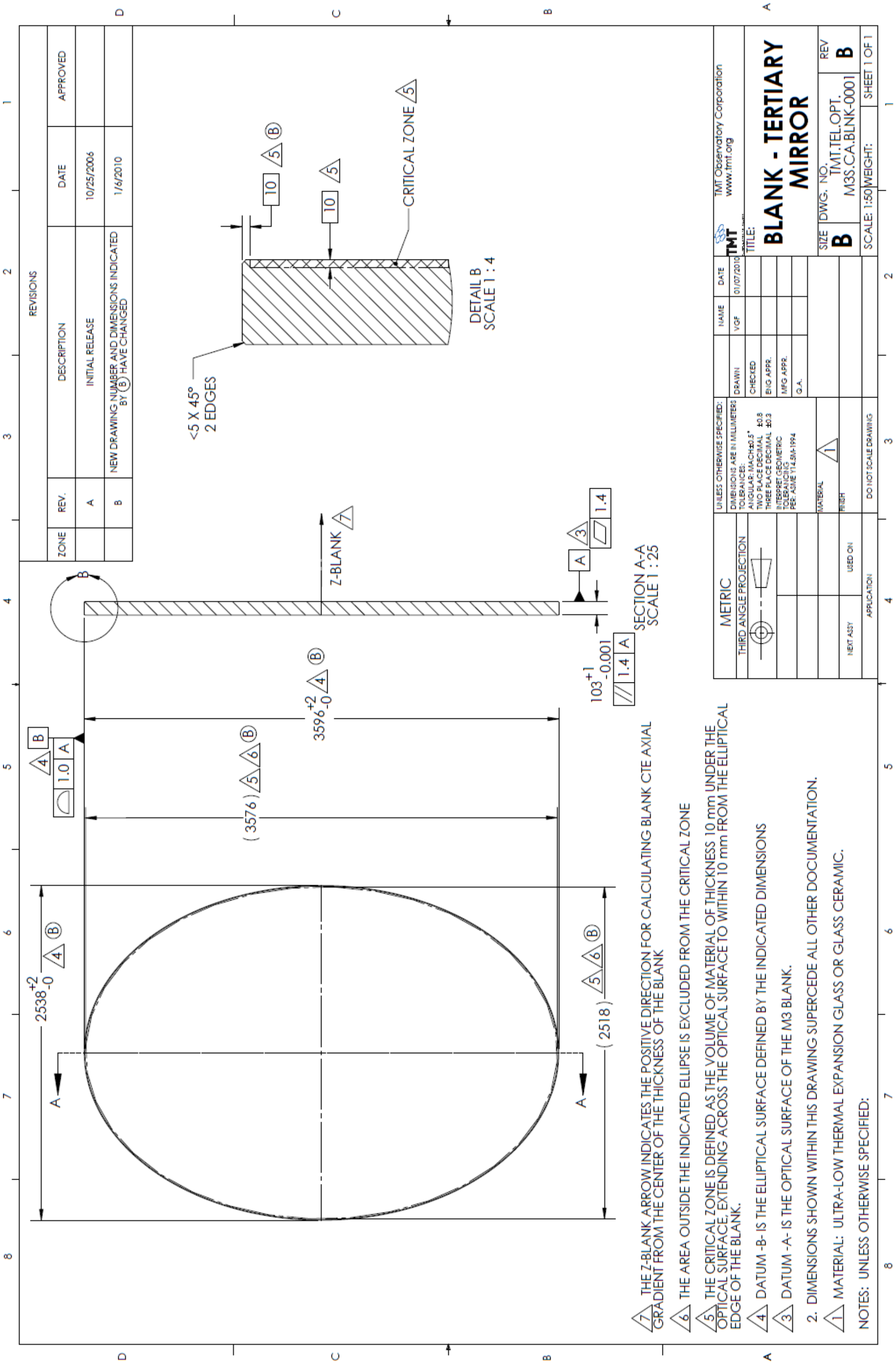

Figure 2. Tertiary Mirror Blank Drawing

7. APPENDICES

7.1 CTE SPECIMEN SAMPLING GEOMETRY

Per requirement [SPE-M3.BLK-1501] The M3 Blank Supplier shall define a CTE sampling scheme for collection of CTE Specimens that will enable calculation of all the required CTE metrics. A possible sampling geometry is shown below in Figure 3 for illustration only. **This particular sampling geometry is *not* required, and is provided only as an example. The Z-BLANK direction is as specified in** Figure 2. Tertiary Mirror Blank Drawing**.**

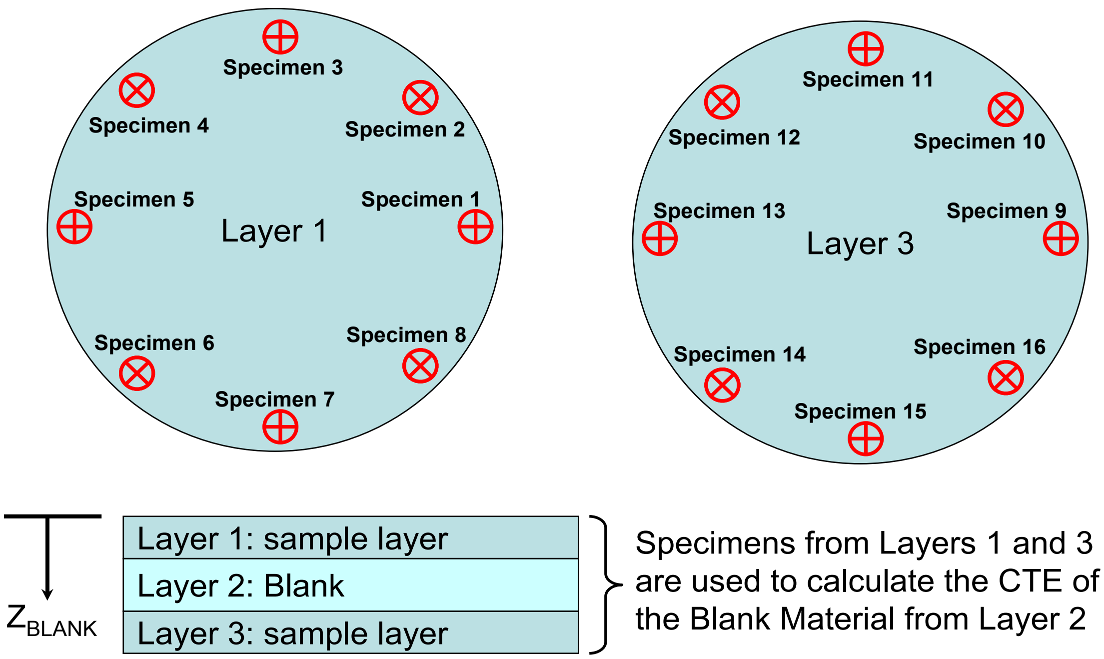

Figure 3. A possible CTE sampling geometry within a boule or casting

7.2 INSTANTANEOUS CTE MEASUREMENT

For each CTE Specimen, the requirements in Section 3.1.5.3 specify that instantaneous CTE calculations be made. The conventional measurement technique would produce ΔL/L data as shown in Figure 4. The instantaneous CTE is the first derivative of the ΔL/L curve with respect to Temperature.

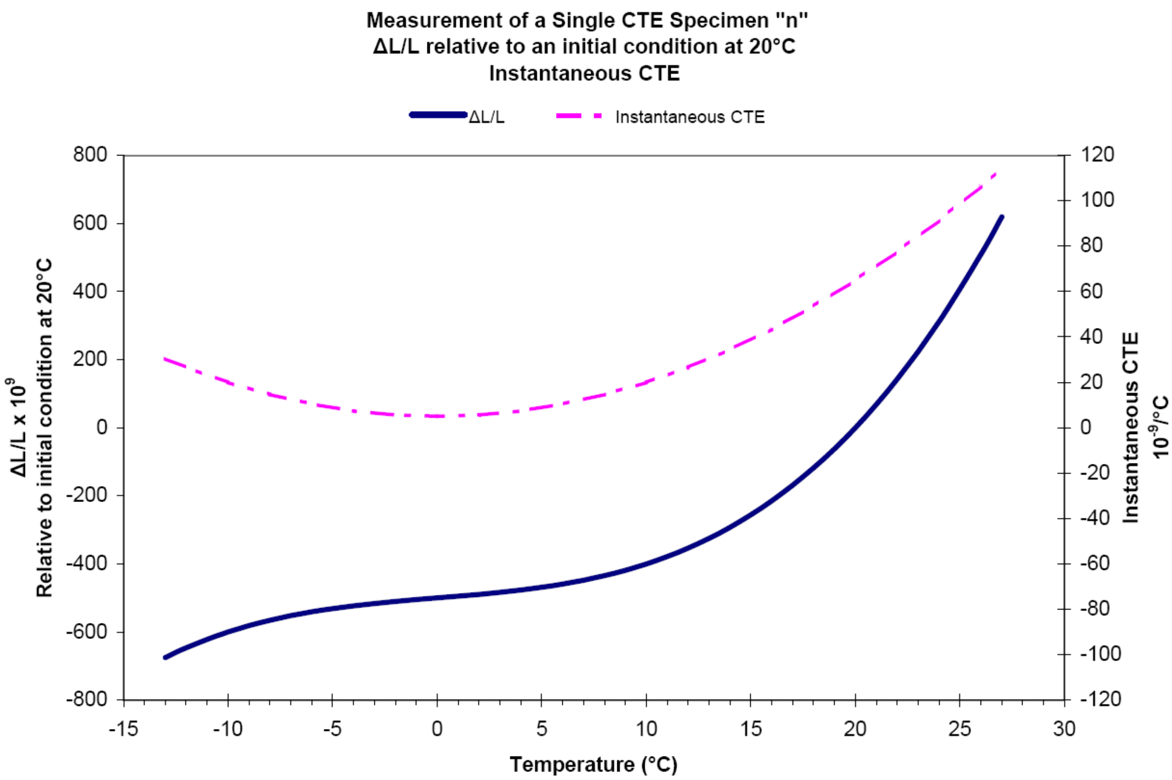

Figure 4. ΔL/L and Instantaneous CTE measurement data of a hypothetical specimen "n"

7.3 Calculating Shop-Op Effective CTE and Operating Range Average CTE

7.3.1 Shop-Op Effective CTE

The requirements in Section 3.1.5.4 require calculation of the Shop-Op Effective CTE of each CTE Specimen over the Shop-Op Temperature Range from 2°C to 20°C. Figure 5 graphically illustrates the calculation of the Effective CTE for each CTE Specimen for the M3 Blank.

The Shop-Op Effective CTE of the M3 Blank shall be the average of the Shop-Op Effective CTEs of all the CTE Specimens.

7.3.2 Operating Range Average CTE

The requirements in Section 3.1.5.5 require calculation of the Operating Range Average CTE of each CTE Specimen using the Instantaneous CTE measurements of the CTE Specimen. For the purposes of this specification, Operating Range Average CTEs shall be calculated using Instantaneous CTE values at the Observatory Temperatures: -5°C, 2°C and 9°C. This is graphically illustrated in Figure 5 for one CTE Specimen.

The M3 Blank Operating Range Average CTE is calculated by averaging the calculated Operating Range Average CTE values from all the CTE Specimens (calculated only at the Observatory Temperatures: -5°C, 2°C and 9°C). This is done by summing the CTE Specimen Operating Range Average CTEs then dividing the sum by the number of CTE Specimens. For the sampling example in Figure 3, one would use the CTE Specimens in layer 1 and the CTE Specimens in layer 3 to calculate the Average CTE of the M3 Blank.

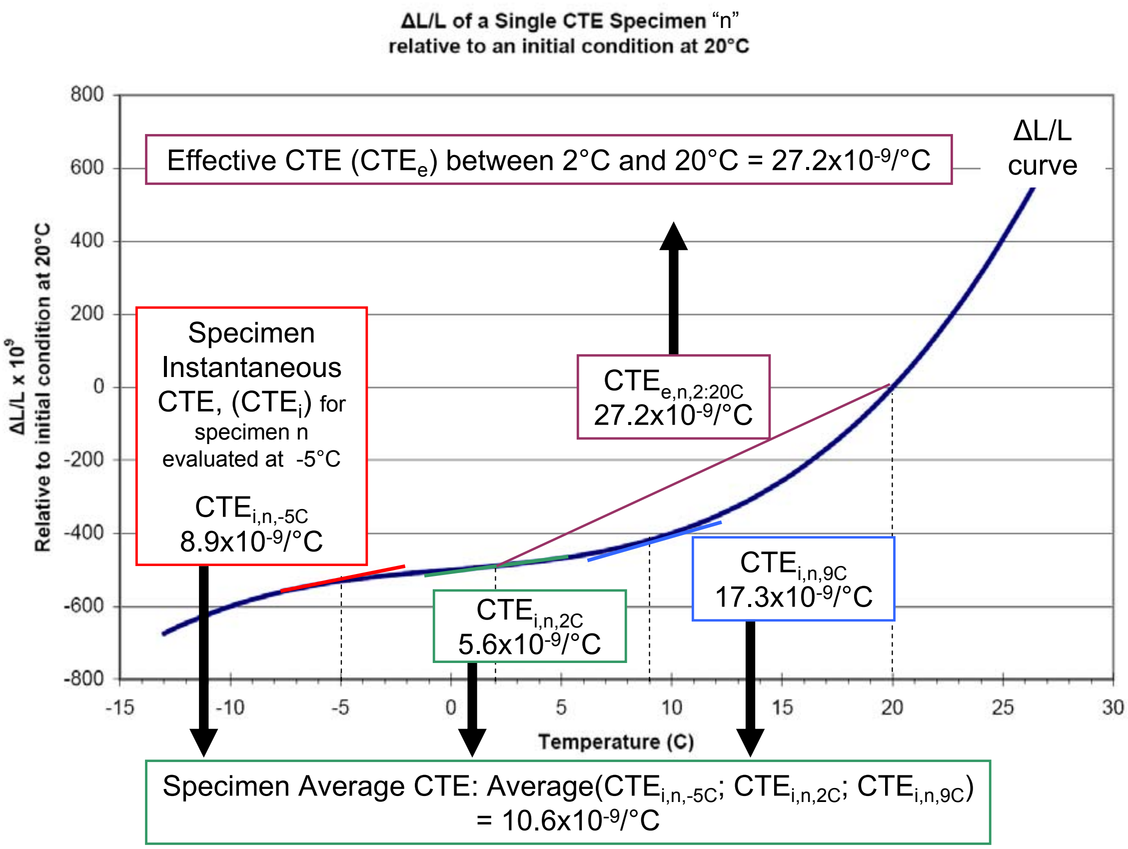

Figure 5. Calculation of Shop-Op Effective CTE andOperating Range Average CTE of a hypothetical CTE Specimen

7.4 CALCULATING CTE AXIAL GRADIENT

Per the requirements specified in Section 3.1.5.7, the Blank Supplier is required to make CTE measurements and calculate CTE Gradient metrics based upon measured data. The Operating Range Average CTEs of the CTE Specimens, as described above in Section 7.3, are to be used for these calculations.

Per requirement [SPE-M3.BLK-1501], the Blank Supplier is responsible for defining a CTE sampling and measurement scheme that will enable calculation of CTE Axial Gradient. TMT has developed a spreadsheet tool for evaluating candidate sampling schemes, and will provide it to potential Blank Suppliers upon request.

The evaluation of CTE Axial Gradient metrics shall be performed as follows. For the purposes of illustration, the sampling geometry shown above in Figure 3 is used. **This particular sampling scheme is *not* required, and is provided only as an example.**

1. For the M3 Blank, plot the Operating Range Average CTEs for the CTE Specimens versus the axial distance from the center of the material of the M3 Blank to the locations where the Instantaneous CTE measurements were taken from the CTE Specimens. The Z-Blank direction from Figure 2 shall be used to establish the positive and negative distance directions. The

example shown uses measurements taken from four locations located in layers above and below the center of the Blank (the final locations will be based on the Blank Supplier's specific sampling plan). Referring to the example shown in Figure 3, to calculate the Blank CTE Axial Gradient of Blank material from Layer 2, use the CTE Specimens Operating Range Average CTEs from Layers 1 and 3 to create 8 data points.

2. Perform a linear least squares fit of the data. Calculate the slope of the fit line. This slope is the CTE Axial Gradient from the set of data. This is illustrated using hypothetical data in

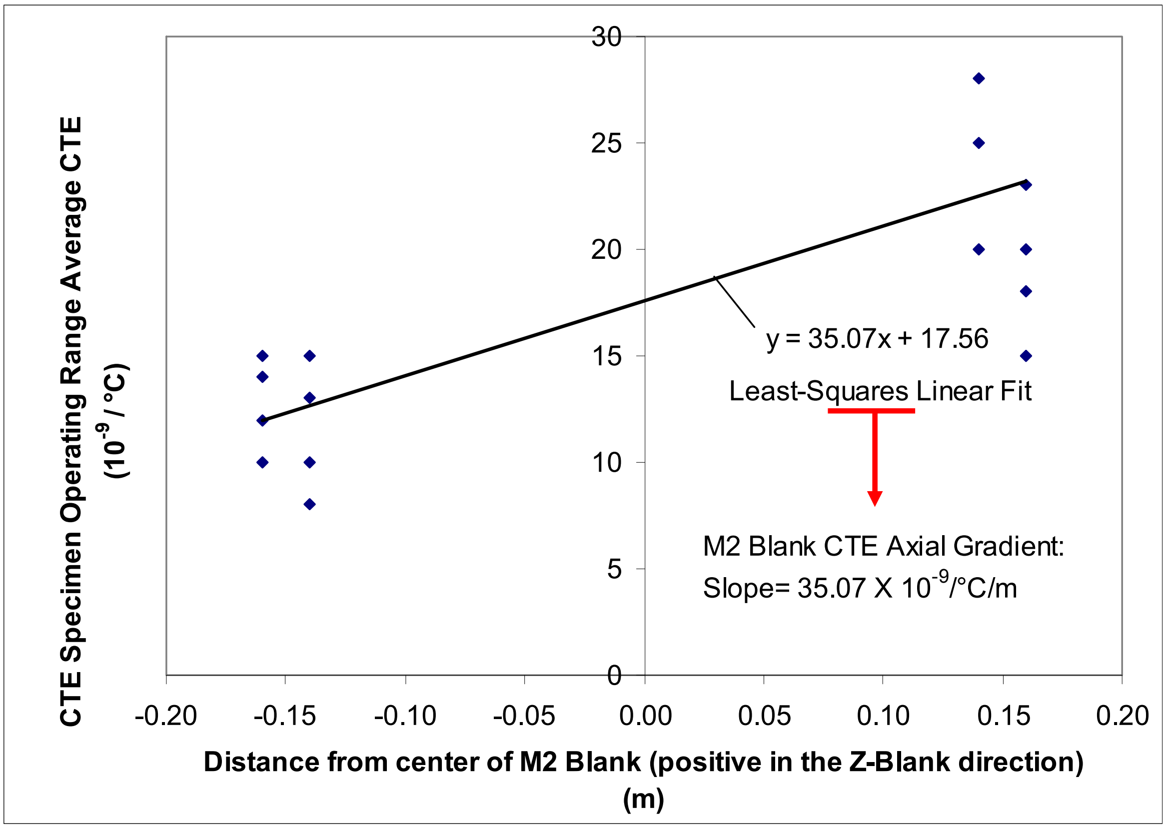

Figure 6. Example of CTE Axial Gradient Calculation

3. Choose the orientation of the M3 Blank to satisfy [SPE-M3.BLK-1560]. I.e., if the measured gradient in the Z_{Blank} direction is <0, flip the blank. The final resulting CTE Axial Gradient shall be ≥ 0.