DESIGN REQUIREMENTS DOCUMENT

FOR

TELESCOPE OPTICAL COATINGS

TMT.OPT.SPE.06.004.DRF02

September 18, 2009

Note: A draft version of this document was temporarily released with the following document number: TMT.OPT.DRD.09.003.DRF02.

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FIGURES

TABLES

1. INTRODUCTION

1.1 INTRODUCTION

This design requirements document (DRD) contains requirements for the optical coatings for the Thirty Meter Telescope (TMT). It describes the constraints and functional performance requirements of the optical coatings on mirrors of the telescope assembly: the primary mirror segments (M1), the secondary mirror (M2) and the tertiary mirror (M3). These requirements drive the coating design and the details of the coating processes and thereby guide the coating facility requirements.

This document captures requirements specified in the top level requirements documents, Observatory Architecture Document (OAD), Observatory Requirements Document (ORD), Operations Concept Document (OCD), and system engineering error budgets and provides flow down and interpretation at the level of the optical coatings. Also included are requirements that originate at the level of this document.

Where the requirements from the applicable documents (AD1, AD2, and AD3) are listed herein, they retain their original requirement numbering configuration and are duplicated here verbatim. Specific requirements that originate within this document are assigned requirement numbers within this document.

1.2 PURPOSE

This document describes requirements for the coatings that will be applied to the telescope mirrors when the observatory is first commissioned, i.e., at “first light”, and additionally describes goals for feasible future improved coatings that would enable enhanced science capability.

The document will guide the design and verification of the first light optical coatings for the telescope mirrors during the design and construction phase of the TMT Observatory. During this process, attention to requirements for future upgraded coatings will ensure that the upgrade will be feasible in the future.

1.3 SCOPE

The scope of this document is shown schematically in Figure 1. This document covers requirements for the deliverable of the TMT.TEL.OPT.COAT work breakdown structure (WBS) element.

Included are the requirements for the optical coatings that will be applied to the telescope mirrors: M1 segments, M2, and M3.

Not included are requirements for instrument optical coatings.

Not included are requirements for the coating and handling equipment that will be designed and constructed for the purpose of handling the telescope mirrors and removing and applying the coatings onto the surfaces of the telescope mirrors.

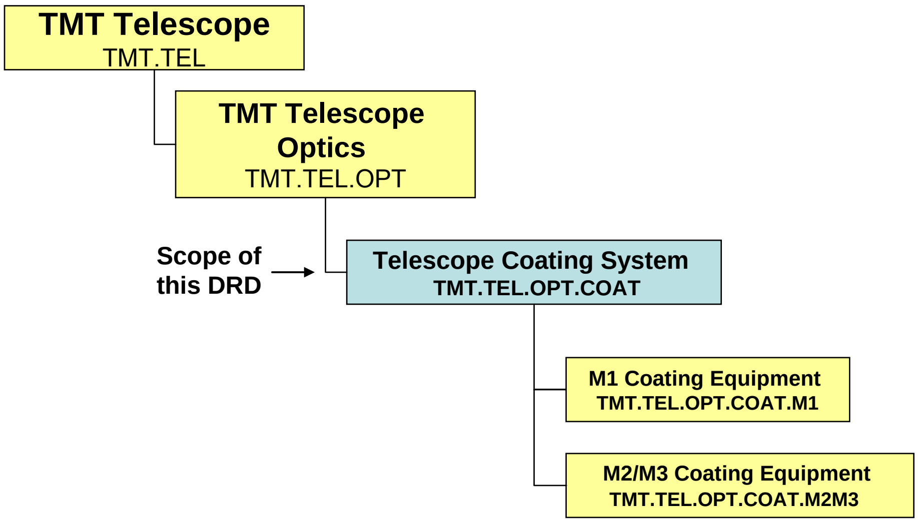

Figure 1. Scope of this DRD relative to TMT WBS

1.4 APPLICABLE DOCUMENTS

Applicable documents contain information that shall be applied in the current document. In the event of a conflict between this document and the Applicable documents below, the Applicable documents take precedence.

AD1 – Operations Concept Document (OCD), (TMT.OPS.MGT.07)

AD2 – Observatory Requirements Document, (TMT.SEN.DRD.05)

AD3 – Observatory Architecture Document, (TMT.SEN.DRD.05)

1.5 REFERENCE DOCUMENTS

RD1 – M1 Optics System Requirements (TMT.OPT.DRD.07.001)

RD2 – Secondary Mirror System Requirements (TMT.OPT.DRD.07.004)

RD3 – Tertiary Mirror System Requirements (TMT.OPT.DRD.07.006)

RD4 – Ritchey-Chrétien Baseline Design (TMT.SEN.SPE.06.001)

RD5 – Coating Facility Requirements (draft) (TMT.OPT.TEC.05.036)

RD6 – Baseline Optical Design of the Thirty Meter Telescope (TMT.SEN.TEC.05.002)

RD7 – Draft Coating Requirements for the TMT Mirrors (TMT.OPT.SPE.06.004)

RD8 – Gemini Coating Specification - Informal (TMT.OPT.SPE.09.003)

RD9 – Notes from discussion with Jacques Sebag (TMT.OPT.COR.09.004)

RD10 – Notes from the Optics Coating & Cleaning Conference, Ensenada, B.C., 10/20-21/03 (TMT.OPT.TEC.05.007)

RD11 – Coating the 8-m Gemini telescopes with protected silver (TMT.OPT.JOU.09.005)

1.6 Change Record

Revision	Date	Section	Modifications
DRF01	14 Aug 2009	All	Initial draft

1.7 Abbreviations

AIV – Assembly, Integration & Verification

FOV – Field of View

CLN – Optical Cleaning System

COAT – Optical Coating System

CTE – Coefficient of Thermal Expansion

HNDL – Optical Handling System

LLNL – Lawrence Livermore National Laboratory

M1 – Telescope Primary Mirror

M2 – Telescope Secondary Mirror

M3 – Telescope Tertiary Mirror

N/A – Not Applicable

OAD – Observatory Architecture Document

ORD – Observatory Requirements Document

OCD – Operations Concept Document

PNNL – Pacific Northwest National Laboratory

REQ – Requirements

TBC – To Be Confirmed

TBD – To Be Determined

TMT – Thirty Meter Telescope

WBS – Work Breakdown Structure

Ø – diameter

Units:

m – meter

mm – millimeter

nm – nanometer

μm – micrometer

2. OVERALL DESCRIPTION

2.1 PERSPECTIVE

The Thirty Meter Telescope is a three mirror design configured as shown in Figure 2. All three telescope mirrors consist of active optical assemblies with thin mirror elements made of low-expansion glass or glass ceramic. The Primary Mirror (M1) consists of an assembly of 492 hexagonal optical mirror segments, each mounted on an actuated support assembly that provides rigid body position correction and surface figure correction for each segment. The Primary Mirror will have 82 spare segments which are used to facilitate efficient recoating of the primary mirror. The Secondary Mirror (M2) and the Tertiary Mirror (M3) both have mirror cell assemblies with axial and lateral support actuators that also enable surface figure correction. The M2 and M3 mirror cell assemblies are both positioned with separate mechanisms and control systems that maintain correct rigid body positions.

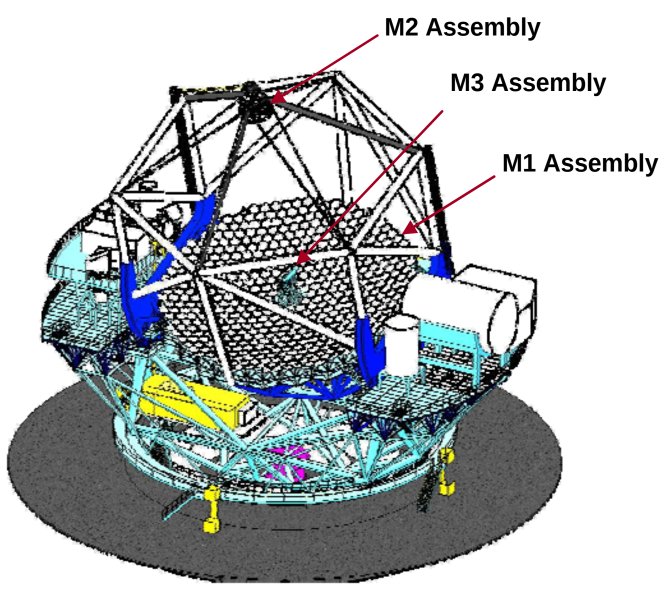

Figure 2. Thirty Meter Telescope

2.1.1 Telescope Mirror Sizes and Optical Prescription

The outer dimensions, thicknesses and optical parameters of the three telescope mirror elements are shown below in Table 1 and are extracted from RD1, RD2, RD3 and RD4. Also, based on REQ-1-

OAD-1000 of AD2, the telescope optical design shall be a Ritchey Chrétien configuration as shown in Figure 3. The aperture stop is located at the Primary Mirror.

Table 1. Dimensions and Optical Parameters of the TMT Telescope Mirrors

Mirror Element	Optical Surface Size and Shape	Coated Clear Aperture	Thickness	Radius of Curvature*	Conic Constant
M1 Segment	Hexagon, 1.44 m across diagonal	Hexagon 1.44 m across diagonal	45 mm	-60 meters	-1.00095
M2	Circular, 3.120 m diameter	Circular, >3.060 m diameter	100 mm	- 6.23 meters	- 1.32
M3	Elliptical, long axis 3.530m short axis 2.514 m	Elliptical, long axis >3.508 m short axis >2.446 m	100 mm	∞	N/A
* Sign convention: positive curvature is convex toward the sky					

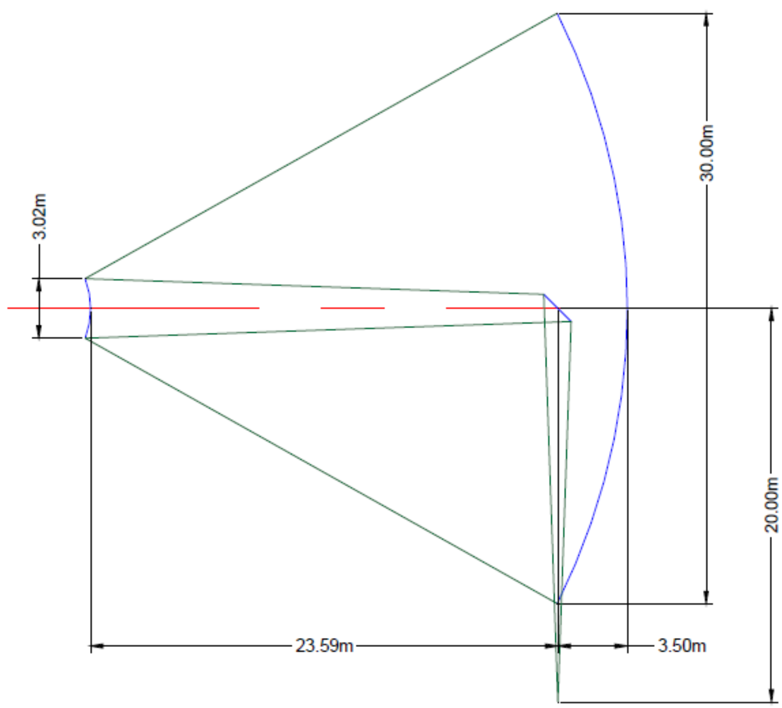

Figure 3. Telescope Optical Design

2.1.2 Background and Reflectivity Goals

The Thirty Meter Mirror Telescope (TMT) Project has an aggressive goal for the reflective coatings on M1, M2, and M3 mirrors of the telescope optics. Previous studies have indicated that this specification may be beyond the current state-of-the-art. Therefore, the TMT Project has adopted a more readily-achievable specification for the initial mirror coatings at the observatory "first light", based on the performance of the 4-layer protected silver coating developed for the Gemini Telescope. The set of requirements in this document flow down from the observatory requirements that are listed in the high level requirements documents. The performances listed as goals apply to coatings that will be developed and applied in the future for significant coating performance improvement.

Protected Silver and Aluminum, with and without enhancing layers, are the standard coatings for astronomical mirrors. The emissivity of an Aluminum coating in the Infrared is too high for the sensitive IR instruments and the reflectivity of a Silver coating in the UV is too low for the UV instruments. An enhanced Silver coating was developed for the Gemini Telescope that has held up well for > 2 years, however, its reflectivity in the near UV does not meet the TMT goals. Lawrence Livermore National Laboratory (LLNL) developed a modified Gemini-type coating that was good in the near UV but had a large emissivity spike at about 10 microns that also did not meet the TMT goals. The reflectivity of the Gemini and LLNL coatings from the UV to the near IR is shown in Figure 4. The infrared reflectivity dip (demonstrating the 10 micron emissivity spike) of the LLNL coating is shown in Figure 5.

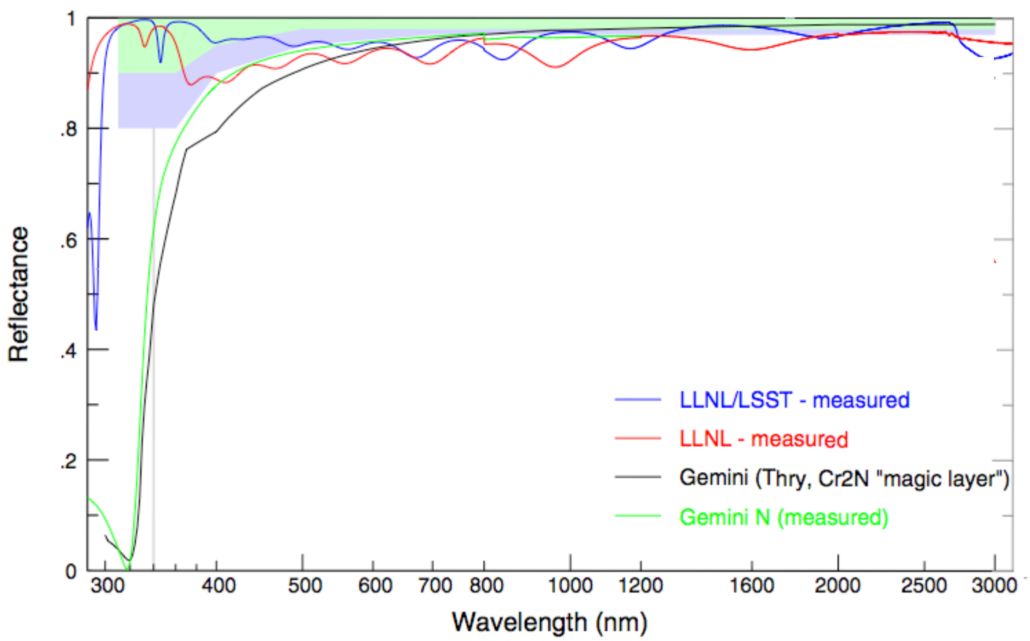

Figure 4. Reflectivity of the Gemini and LLNL coatings

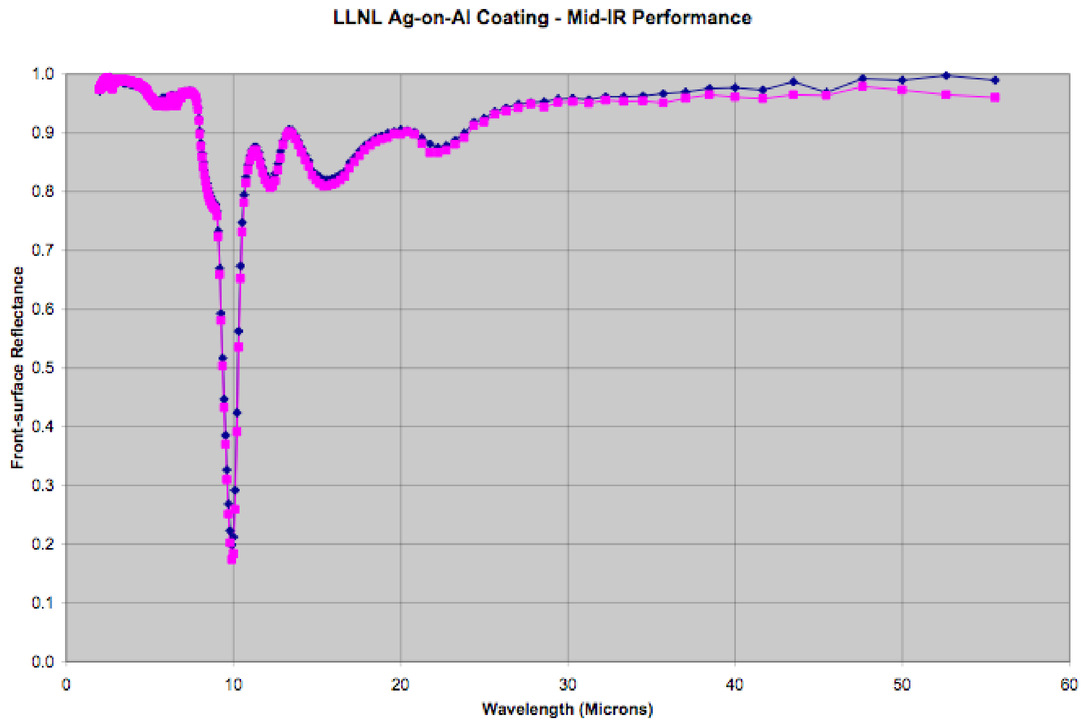

Figure 5. Reflectivity dip of the LLNL coating in the Infrared

Coating development efforts have also shown that the reflectivity, as a function of wavelength, is process dependent. In particular, surface Plasmon resonances were observed in some coating samples of Gemini-type coatings developed at Pacific Northwest National Laboratory (PNNL). Plasmon resonance is a quantum-mechanical effect that takes place in the interface between Ag and the overlying dielectric. The result is a dip in reflectivity at visible wavelengths, as shown in Figure 6 with the PNNL coatings compared to the standard Gemini coating. The surface Plasmon problem seems to be a strong function of Ag grain size. Some improvement was made by faster deposition rates and lower temperature deposition. This problem appears to be very solvable but is something to consider when designing a coating process and a coating chamber.

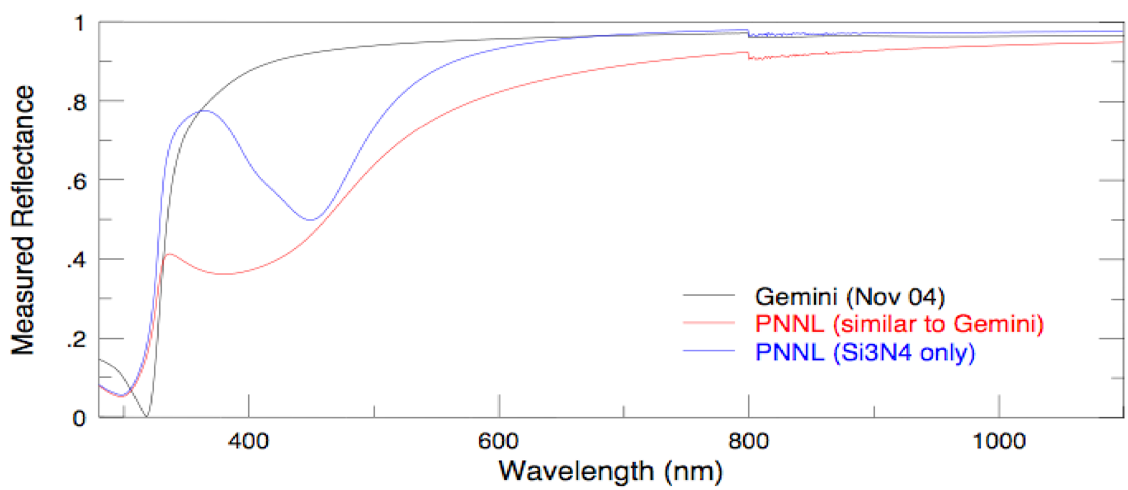

Figure 6. Dip in reflectivity caused by surface Plasmon resonances on Gemini-type coating samples

2.1.3 Maintenance

Experience at existing observatories indicates that the reflectivity of the mirror coatings decreases by ~0.25% per month due to dust and other surface contaminations. Removing contamination requires regular cleaning with CO_2 snow; however, Figure 7 shows that CO_2 snow cleaning only recovers about half of the loss in reflectivity. H_2O cleaning recovers almost all of the loss in reflectivity. These data show why it is important for the mirror coating to withstand many cleanings with both CO_2 snow and a liquid, such as water.

The coated mirror surfaces will be cleaned while the optical elements are installed in the telescope (in situ) using CO_2 snow. The mirrors will also be washed periodically using cleaning fluid, most likely soap and water. Cleaning for each mirror assembly will follow a maintenance schedule and will require cleaning support equipment.

Additionally, all of the telescope mirrors must be recoated periodically on the mountain at the telescope site. Therefore, it is necessary to develop a coating design, coating process and coating equipment suitable for use at the telescope site. Coating equipment will include two coating facilities – one for the M1 segments and another for the M2 and M3 mirrors. The schedule for recoating M1 segment mirrors requires recoating 5 mirror segments every week in order to recoat all the segments within two years, thus requires a high through-put facility. M2 and M3 are larger than the M1 segments and will be recoated approximately once every two to five years, thus will require a larger chamber, but not require equipment to achieve the same high through-put.

Mirror cell removal, handling equipment and coating support equipment will be required to support the coating process. Prior to recoating, the mirrors must have the previous coatings stripped off. The mirror surfaces must not be damaged by the stripping process. After recoating, the mirror surfaces must perform as well as the original coated reflective surfaces. The coating design and process must be transferable to the telescope operations staff.

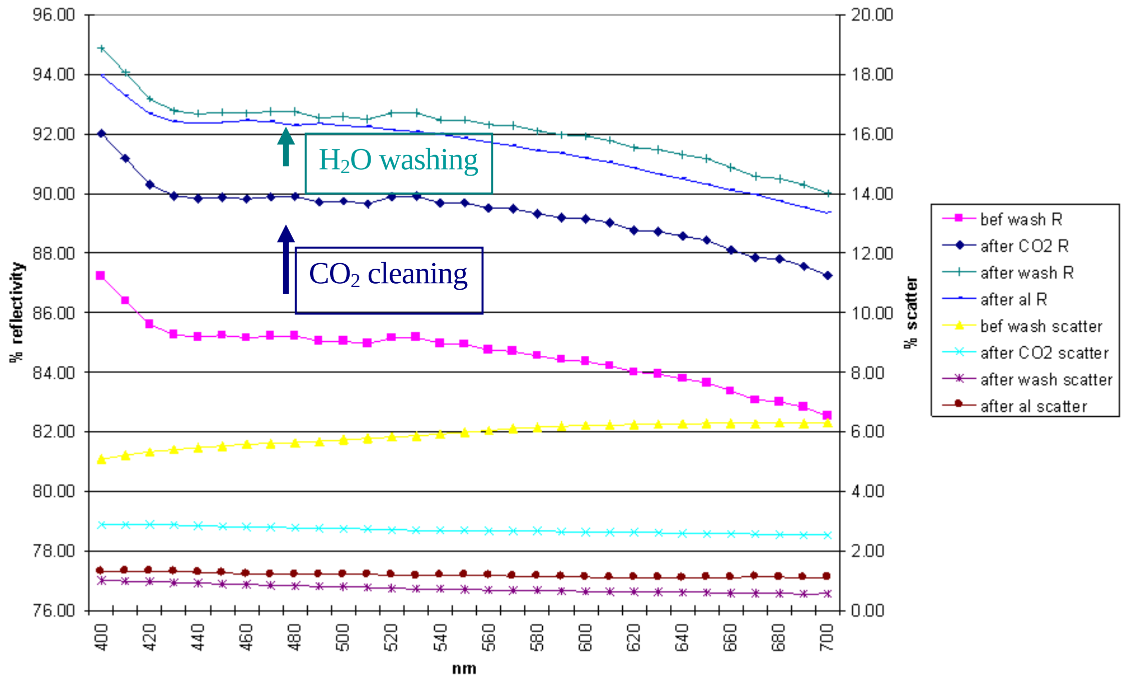

Figure 7. Example (from the CTIO 36" telescope) of how CO2 snow and de-ionized water cleaning improves the reflectivity of a bare Aluminum coated telescope mirror.
Data courtesy of Cerro Tololo InterAmerican Observatory.

2.1.4 General Coating Constraints

The TMT coatings must meet the following general constraints:

- Coatings must be efficient for science:
  - Must be highly reflective
    - Must work over wide wavelength range (0.31 -- 28 µm).
    - Must have low IR emissivity (i.e., reflectance in IR must be high)
  - Reflectance shall vary slowly with wavelength to enable data interpretation
  - Coating must work at a range of incidence angles.
- Coating must have excellent longevity to reduce operation costs and risks:
  - With 492 M1 segments, recoating every two years requires coating 5 segments per week. Longer lasting coatings will significantly reduce operational cost.
  - Risk of damage to segments increases with frequency of removal, stripping, coating and reinserting. Less frequent recoating will significantly reduce risk.
  - Coating should be easily strippable with no resultant damage to the optical substrate.
- Coating must be mechanically robust to withstand ~2-5 yrs regular cleaning with CO_2 snow and washing.
  - Coating should adhere well to substrate
  - Coating shall not be soft
  - Coating must not react or corrode when exposed to CO_2 or the fluids used for washing.
- Coating stress should be low and predictable:
  - With thin substrates, stress induced between the coating and the mirror element can deform the optical figure.

- Non-uniformity or non-repeatability in the resulting stress may deform the optical figure in a manner that may not be fully compensated using the actuators for each element.

The currently-known coating that comes closest to meeting the TMT requirements is Gemini protected Ag, but its throughput in UV/blue is inadequate.

The TMT first light coating requirements listed herein are nearly met by the Gemini protected silver coating. TMT expects to improve the Gemini coating to meet the requirements at first light. Future coating development will enable upgrade to an advanced coating that will meet all of the TMT goals.

2.2 SYSTEM FUNCTIONS

The reflectance of the coatings on the telescope mirrors across the TMT wavelength band will impact the performance of the instruments and their ability to collect astronomical data. The coating performance through different wavelength bands must be balanced to an acceptable compromise to enhance the scientific objectives of the Thirty Meter Telescope Observatory.

Environmentally, the coatings must be durable, cleanable, and replaceable so that the reflectivity is maintained on a schedule that enables the telescope operations to proceed as required in AD1.

Finally, the coatings must not create uncorrectable changes to the mirror surface shapes. If the stress produced by the coating interaction with the optical surface is too high, too non-uniform or too unpredictable, then the resulting deformation of the thin mirror elements may be uncorrectable. Additionally, if the thickness of the coating varies significantly over the optical surfaces, the resulting surface variation may be uncorrectable.

2.3 USER AND OPERATOR CHARACTERISTICS

Three maintenance processes will be performed to maintain coating reflectivity: CO_2 snow cleaning, fluid cleaning, and recoating. The personnel who perform these operations must be highly trained optical technicians to avoid damage to the mirror elements.

2.4 CONSTRAINTS

Some coatings may contain hazardous materials. Any coating design chosen for TMT that contains hazardous materials must comply with local material regulations covering safe deposition, handling, and disposing of the materials.

The mirror assemblies for M1 segments, M2 and M3 are constrained to temperature limits. The temperature of the surfaces of the elements where support system components are attached during the coating process is constrained to be less than 80ºC to prevent the adhesive from over-heating. The glass or glass ceramic material of the mirror substrate is limited to temperatures less than 100ºC to prevent the substrate from changing shape. The purpose of the temperature constraints is to prevent possible damage or deformation to the mirror assembly during the coating process.

2.5 ASSUMPTIONS AND DEPENDENCIES

The reflectivity of the coating is dependent on the required throughput of the telescope that is needed by each instrument. Reflectivity decreases as the coating collects dust and contaminants or is scratched or corroded. Cleaning the coated surface restores some of the reflectivity that was lost due to removable contaminants. Scratches and corrosion are only removed when the optical surface is recoated.

Because the TMT primary mirror is composed of segments, TMT has the ability to continuously recoat segments. This will cause non-uniform reflectivity across the primary mirror. The recoating schedule is timed to contain this effect to the temporal variation of the coating reflectivity as it gradually degrades after a series of in-situ cleaning cycles. The ability to recoat primary mirror segments continuously has the beneficial effect that the entire primary mirror will never be at the worst reflectivity degradation state, but will always be composed of a set of segments ranging from clean freshly coated surfaces to those nearing maximum lifetime.

Because reflectivity drives the cleaning and coating schedule for the telescope mirrors, any change in reflectivity requirements will impact the timing for these operations. The reflectivity requirements are derived from the requirements of the instruments, thus any changes in instrument reflectivity requirements may impact the requirements in this document that are related to reflectivity, cleaning and recoating and all maintenance schedules.

3. SPECIFIC REQUIREMENTS

3.1 PERFORMANCE REQUIREMENTS

3.1.1 Reflectivity Requirements

[REQ-2-CO-1100] The reflectivity of a freshly applied coating for M1 segments, M2 and M3 at first light shall equal or exceed the values given in the Requirement column of Table 2 for the wavelength bands specified.

Table 2. Minimum reflectivity as a function of wavelength for fresh coatings at the prescribed angles of incidence shown in Table 3.

Range	Requirement	Goal
0.31 - 0.34 μm	N/A	0.8
0.34 - 0.36 μm	0.8	0.9
0.36 - 0.40 μm	0.8 → 0.9	0.9 → 0.95
0.4 - 0.5 μm	0.9 → 0.95	0.95 → 0.98
0.5 - 0.7 μm	0.95 → 0.97	0.98
0.7 – 1.8	0.97	0.98
1.8 - 28 μm	0.97	0.98

Discussion: An arrow in the Requirement column indicates that the reflectivity requirement in that range varies linearly from the first value specified at the lower end of the wavelength range to the second value specified at the higher end of the wavelength range.

Discussion: This distribution of reflectance is nearly met by the performance of the Gemini protected silver coating as reported in RD8.

[REQ-2-CO-1102] The reflectivity of a freshly applied coating as a function of wavelength presented in Table 2 shall diminish <0.5% as the angles of incidence change across the mirror element surfaces over the ranges shown in Table 3.

Table 3. Range of angles of incidence for reflection at each mirror surface.

Mirror Element	**Angles of Incidence**	
	Minimum	**Maximum**
M1 Segment	0°	14.4°
M2	0°	14.1°
M3	32°	48°

[REQ-2-CO-1103] For fresh new coatings, the reflectance of the coating at a single angle of incidence over the surface of the coated element over the wavelength range from 0.31 to 28 μm shall be uniform within the following limits:

M1 segments:

±0.3% across the segment surface averaged from discrete measurements of roughly 10 mm diameter spots

M2:

±0.3% across the element surface averaged from discrete measurements of roughly 10 mm diameter spots

M3:

±0.2% across the element surface averaged from discrete measurements of roughly 10 mm diameter spots

3.1.2 Emissivity Requirements

[REQ-2-CO-1200] The emissivity of a freshly applied coating for M1 segments, M2 and M3 at first light, over the wavelength range of 0.7 to 28 um, shall be less than or equal to 0.015.

Discussion: The performance of the Gemini coating complies with this requirement per RD8.

Discussion: As a goal, the emissivity of each surface should be less than 0.013.

3.1.3 Change of reflectivity with wavelength

[REQ-2-CO-1300] The variation of reflectivity of the coating with wavelength shall be less than 0.003 per nm of wavelength.

3.1.4 Polarization

[REQ-2-CO-1400] The phase shift of light shall be less than 22º when reflected with an angle of incidence of 45º off a freshly coated optical surface.

Discussion: The performance of the Gemini coating complies with this requirement per RD8.

3.1.5 Coating thickness uniformity

[REQ-2-CO-1500] The optical surface figure change of the M1 segments, due to total coating thickness non-uniformity, shall be segregated into two types: correctable and non-correctable. The correctable low spatial frequency thickness variation up to Zernike 3rd order shall be less than 50nmRMS (TBC). The non-correctable thickness variation for 4th order and above shall be less that 5nm RMS (TBC)

Discussion: The M1 segments have active supports that are able to correct low-spatial-frequency shape errors up to and including 3rd order Zernikes. Shape errors having spatial frequencies above 3rd order are not correctable by the supports, and therefore they impact performance more significantly.

[REQ-2-CO-1501] The optical surface figure change of the M2 and M3, due to total coating thickness non-uniformity, shall be segregated into two types: correctable and non-correctable. The correctable low spatial frequency thickness variation up to Zernike 3rd order shall be less than 50nmRMS (TBC). The non-correctable thickness variation for 4th order and above shall be less that 5nm RMS (TBC)

Discussion: The M2 and M3 low-spatial frequency errors are correctable by reshaping the M1 to compensate. Higher-spatial frequency errors are not correctable on the M1 and therefore they impact performance more significantly.

3.1.6 Coating-induced deformation of optical surface

[REQ-2-CO-1600] For the M1 segments, the allowable amount of repeatable defocus of the optical surface from coating-induced stress shall not exceed 200 nm peak-to-valley.

[REQ-2-CO-1602] Relative to the average optical surface defocus of all the M1 segments caused by coating-induced stress, the optical surface defocus of any individual segment shall not deviate by more than 40 nm peak-to-valley.

[REQ-2-CO-1604] For the M1 segments, the allowable amount of optical surface deformation, described by Astigmatism, Coma, and Trefoil, from coating-induced stress shall not exceed 20 nm peak-to-valley.

[REQ-2-CO-1605] For the M1 segments, the allowable amount of optical surface deformation, described by 4^{th} order Zernikes and higher, from coating-induced stress shall not exceed 5 nm peak-to-valley.

[REQ-2-CO-1606] For the M2, the allowable amount of repeatable defocus of the optical surface from coating-induced stress shall not exceed 200 nm peak-to-valley.

[REQ-2-CO-1608] For the M2, the variation in defocus of the optical surface from coating-induced stress, from one coating application to the next, shall not exceed 100 nm peak-to-valley.

[REQ-2-CO-1610] For the M2, the allowable amount of optical surface deformation, described by Astigmatism, Coma, and Trefoil,, from coating-induced stress shall not exceed 40 nm peak-to-valley.

[REQ-2-CO-1611] For the M2, the allowable amount of optical surface deformation, described by 4^{th} order Zernikes and higher, from coating-induced stress shall not exceed 5 nm peak-to-valley.

[REQ-2-CO-1612] For the M3, the allowable amount of repeatable defocus of the optical surface from coating-induced stress shall not exceed 400 nm peak-to-valley.

[REQ-2-CO-1614] For the M3, the variation in defocus of the optical surface from coating-induced stress, from one coating application to the next, shall not exceed 200 nm peak-to-valley.

[REQ-2-CO-1616] For the M3, the allowable amount of optical surface deformation, described by Astigmatism, Coma, and Trefoil, from coating-induced stress shall not exceed 80 nm peak-to-valley.

[REQ-2-CO-1617] For the M3, the allowable amount of optical surface deformation, described by 4^{th} order Zernikes and higher, from coating-induced stress shall not exceed 5 nm peak-to-valley.

Discussion: Neither the final coating nor the coating process shall induce excessive non-uniform stress (surface warping) in mirror substrates, in excess of the optical uniformity requirement. Some defocus is acceptable, provided it is repeatable from segment to segment.

3.1.7 Coating process constraints

[REQ-2-CO-1700] At no time during the coating process shall the temperature of any portion of the glass or glass ceramic mirror substrate exceed 100° C.

Discussion: This is to ensure dimensional stability of the substrate

[REQ-2-CO-1702] At no time during the coating process shall the temperature of the adhesive used to bond attachments to the back surface of the glass or glass ceramic substrate exceed 80° C.

Discussion: This is to ensure stability of the adhesive.

[REQ-2-CO-1704] The coating deposition shall be compatible with a coating plant that can achieve a base pressure of *1 x* 10^{-7} torr with the optic loaded and pumped down..

Discussion: For example, contamination of silicon nitride layers with oxygen and H_2O *is a concern. Pumping down to lower than 3 x* 10^{-7} *torr has been recommended.*

[REQ-2-CO-1706] The deposition rate for the silver layer shall be high enough to avoid a reduction in reflectivity caused by surface plasmons.

Discussion: Rates higher than 2 nm per second have been recommended.

3.1.8 Coating Durability

[REQ-2-CO-1800] The coating shall meet the performance requirements specified herein, during normal operation, for a period of no less than two years (5 years as a goal) when maintained using the cleaning methods and frequencies specified in 3.2.3.

3.2 ENVIRONMENTAL, CHEMICAL AND PHYSICAL CONSTRAINTS

3.2.1 Coating Visual Inspection

[REQ-2-CO-2100] Visual inspection shall be performed per MIL-C-48497 Revision A, Section 4.5.2.5.2.

[REQ-2-CO-2102] The freshly applied coatings shall have no pinholes larger than 10 µm in diameter, fewer than 5 pinholes that are approximately 5-10 µm in diameter, and fewer than 5 pinholes that are < 5 µm in diameter within any 30mm x 30 mm area within the clear aperture of the coated substrate as determined by visual inspection.

Discussion: As stated in RD11, section 4.5, pinholes are caused by dust on the surface during coating deposition. By keeping the coating chamber and mirror substrates free of dust, the pinholes in the coating will be minimized. The facility for coating TMT mirrors will have a clean room at the coating plant load/unload stations.

Discussion: The pinhole size and quantity listed above are from RD11 and were obtained during Gemini coating deposition when the substrate was blown clean using CO2 snow as it was installed into the coating chamber. In addition, the coating chamber was outfitted with a HEPA-filtered air system and maintained at a positive pressure. The clean room approach adopted by TMT should improve the cleanliness conditions, thus should improve the pinhole size and frequency. The pinhole size and quantity affect the durability of the coating, thus should be minimized.

[REQ-2-CO-2104] The freshly applied coatings shall cover 100% of the clear aperture and shall have combined defects within the clear aperture <0.1% of the clear aperture area. The maximum size of any one single defect shall be <5mm^2.

Discussion: Defects are defined in MIL-C-48497 Revision A and shall also include stains, streaking, smears and other coating features that would affect the spectral response of the coated surface.

Discussion: The Gemini 4-layer coating passes this inspection.

3.2.2 Environmental, Chemical and Physical Testing

[REQ-2-CO-2200] Five (TBC) witness samples made of the same substrate material as each mirror element, and prepared in the same manner, shall be coated along with each mirror element during every coating run, under process conditions identical to the conditions existing at the mirror surface. The witness samples will be labeled.

[REQ-2-CO-2202] TBD witness samples that were coated along with the mirror element shall pass the following tests, conducted in the order presented in Table 4. The state of operation (defined per the ISO specification) is not applicable for all tests.

Table 4. Environmental, Chemical and Durability Testing of the Optical Coating

Description	Test Specification	Test pass criteria
Salt Mist: 5% NaCl solution at 35ºC for 2 days	ISO 9022-40-05	no reflectivity loss
Damp Heat: 16 hours at 55ºC 90%-95% relative humidity	ISO 9022-12-07	no reflectivity loss
Slow Temperature Change: 5 cycles from -10ºC to 40ºC, 2.5 hour dwell at each end, temperature change rate 0.2ºC/minute	ISO 9022-14-01	no reflectivity loss
H_2S exposure: 5 ppm at 35ºC, 75% relative humidity, for 4 days	ISO 9022-42-08	>88% reflectivity at $\lambda \leq 0.5\mu m$, no reflectivity loss at $\lambda > 0.5\mu m$
Coating environmental durability test for Abrasion	ISO 9211-4-01-01	No scratches discernable
Coating environmental durability test for Adhesion	ISO 9211-4-02-02	No coating removal discernable

3.2.3 Maintainability

3.2.3.1 Cleaning Maintenance

[REQ-2-CO-2310] The coating on M1 segments, M2, and M3 shall be capable of being cleaned with CO_2 snow at weekly intervals over a two-year period (104 cleaning processes total).

Discussion: The proposed cleaning schedule is not dictated by throughput performance as much as by a desire to prevent dust and contaminants from adhering to the coating and reducing its lifetime per page 4 of RD10.

[REQ-2-CO-2312] The coating on TMT M1 segments M2, and M3 shall be capable of being cleaned with fluids at monthly intervals over a five-year period (60 cleaning processes total). The fluids to be used may include water, water with detergent, alcohol (methanol and ethanol), and acetone.

Discussion: The proposed cleaning schedule is not dictated by throughput performance as much as by a desire to prevent dust and contaminants from adhering to the coating and reducing its lifetime per page 4 of RD10.

[REQ-2-CO-2314] After a two year period, the total reduction in reflectivity caused by all cleanings (CO_2 snow and fluid combined) shall be less than 2%.

Discussion: Based on RD8, the Gemini coating experiences no discernible reflectivity, adhesion and durability change when exposed to the listed fluids. Figure 9 of RD11 indicates that the 4-layer Gemini coating meets this requirement.

Discussion: The reduction in reflectivity does not include the effect of dust collection over time. It is assumed that the cleaning removes the dust.

3.2.3.2 Recoating Maintenance

[REQ-1-OCD-2320] The interval between M2 and M3 recoating events shall be no less than 24 months (TBC), i.e. it shall be possible to meet the mean net reflectivity requirement for at least 24 months based on M2 and M3 considerations alone. During the design phase, consideration shall be given to allowing M2 and M3 recoating to be completed within the same TBC window (goal: 5 days maximum).

[REQ-2-CO-2322] The coating shall be completely strippable with chemicals within an elapsed time of no more than two hours, with no damage to the underlying substrate.

[REQ-2-CO-2324] The chemicals required to strip the coating shall not be hazardous to personnel or equipment, though protective masking, respirator, and clothing may be required.

Discussion: Materials used to strip Gemini coatings are Hydrochloric Acid and Ammonium Cerium Nitrate. Per RD8, these materials are able to strip the 4-layer Gemini coating within 30 minutes.

REQ-2-CO-2326] The M1 segment coating shall be designed so that substrate and chamber preparation and coating application can all be accomplished in less than 4 hours.

Discussion: This allows the continuous processing of M1 segments to occur within normal working hour shifts during operations, and the coating of two segments per day during Assembly, Integration and Verification.

[REQ-2-CO-2328] The coating shall be designed so that substrate and chamber preparation and coating application for the M2 and M3 can all be accomplished in less than 24 hours (three 8-hour shifts) with a goal of 16 hours.

Discussion: This allows time for careful chamber preparation, mirror cell disassembly and large mirror handling steps while leaving 2 days worth of normal working hour shifts for installation and removal of the mirrors from the telescope.

3.2.4 Safety and Health

[REQ-1-ORD-7000] The observatory shall comply with all applicable local and national safety regulations and standards.

[REQ-2-CO-2400] The TMT coating deposition and removal processes shall not endanger the health and safety of personnel, nor cause damage to the M1 segments, M2 and M3.

[REQ-1-ORD-7200] The observatory shall comply with all applicable local and national environmental and occupational health regulations and standards.