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LIGO Laboratory / LIGO Scientific Collaboration

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Core Optics Components
Design Requirements Document

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1 Introduction

1.1 Purpose

This Design Requirements Document (DRD) for the Core Optics Components (COC) subsystem identifies the information necessary to define the COC subsystem and quantify its relationship to other LIGO subsystems. Requirements, formally flowing down from the Systems (SYS) task, are stated to provide a full description of the COC and their optical and physical properties. As of this draft, the exact quantities or tolerances that are required for some COC properties are unknown. These are identified with TBD rather than a specific number.

2 Scope

This document will detail requirements on the 9 or 11 (LHO 2k) “Core” optical elements necessary for each Advanced LIGO interferometer. Reference to other subsystems will be made only to define interfaces, clarify rationale for requirements, and provide justification of required parameters.

The plan for development, manufacture and test of the optics is presented in the COC development plan, LIGO-T000128. The design that specifically meets the requirements of this document and is the baseline for the Advanced LIGO COC is described in the COC Reference Design, LIGO-T000098.

2.1 Definitions

2.1.1.1 Physical Definitions

Physically, the COC subsystem consists of the following items:

Cylindrical substrates:

- Test Masses (TM) of two types: Input TM (ITM) and End TM (ETM).
- Beamsplitter (BS).
- Power Recycling Mirror (PRM).
- Signal Recycling Mirror (SRM)
- Compensation Plates (CP)
- Folding Mirrors (FM) to be incorporated only into the second Hanford IFO.

Thin film optical coatings applied to faces of the substrates:

- Anti reflectance coating applied to surface 2 of each optic.
- High reflectance coating applied to surface 1 of each optic.

2.2 Acronyms

- Throughout this document items will be mentioned whose existence, scope, or value are yet to be determined. A symbol $^{\text{TBD}}$ represents this status.
- IFO= Interferometer
- SUS= Suspension design system.
- IO= Input optics.
- ASC= Alignment sensing and control subsystem.
- AOS= Auxiliary Optics System
- YAG= 1.06 micron laser or laser light (wavelength λ if not otherwise specified).

- SYS= Detector Systems Engineering/Integration.
- λ_s = optical surface spatial wavelength.
- GW= gravitational wave.
- G= Power recycling cavity gain: G_c for carrier power; G_{sb} for side band power
- CD= Contrast defect: CD_c for carrier power; CD_{sb} for side band power.
- w_0 = Primary cavity's beam Gaussian waist radius. w_{xx} indicates beam Gaussian radius at location xx. For example w_{ETM} will be the end test mass beam radius.
- Reff= the effective radius of curvature for a mirror surface as seen by an incident Gaussian beam.
- ϕ, δ, = diameter, thickness of optics. ϕ_s, δ_s would specify substrate diameter and thickness.
- HTM= higher transverse modes.
- FFT model: the standard computer simulation of the static LIGO IFO
- "in-line" and "out-line": refer to the two IFO arms. The in-line arm is the one colinear with the PRM-BS axis.

2.3 Applicable Documents

2.3.1 LIGO Documents

Core Optics Components Reference Design Document: LIGO-T000098

Advanced LIGO Coating Program and Specification: LIGO-E000487

Advanced LIGO Coating Development Plan: LIGO-C030187-00-R

COC Subsystem Development Plan: LIGO-T000128

Test Mass Material Downselect PlanLIGO-T020103

Advanced LIGO Systems Design LIGO-T010075

Polarization Scatter Through Sapphire Substrates: LIGO-T030189-00-D

Thermal Compensation Update, LIGO-G020502-00-R and MIT thesis, R. Lawrence, 2003.

Thermal Noise in Interferometric Graviational Wave Detectors Due to Dielectric Optical Coatings: LIGO-P020005-00-Z

Many requirements are developed from earlier, generic studies:

LIGO I Science Requirements Document: LIGO-E950018-00-E

COC (LIGO I) sizes meetings notes: LIGO-L960112

Optical Wave front Distortion Specification notes (R. Weiss) LIGO-T952009-00-E

Electrostatic Charging on TMs (FJR) L960044-00-E

AR/ER coating properties (H. Yamamoto) LIGO-G950043

FFT model description (B. Bochner, Y. Hefetz) LIGO-G950061-01-R and Thesis, B. Bochner, MIT, 2000.

2.3.2 Non-LIGO Documents

VIRGO Final Design (report) ver 0. June 1995

Thesis, P. Hello. University of Paris, 1994.

W. Winkler,et. al., Optics Comm.,112, 245(1994).

W. Winkler, et. al., Phys. Rev. A44, 7022

3 General description

Product Perspective

The Core Optics Components (COC) provide a framework of stable, low loss optical cavities that are used for the optimal detection of gravitational waves within the design bandwidth. Thus the COC interfaces optically with the Input Optics (IO) subsystem. COC are aligned via optical interface with sensing systems provided by Auxiliary Optics System (AOS). The only mechanical interface is to Suspensions (SUS) (specified by the SUS DRD) via contacting suspension elements. There are no direct electrical connections to COC.

3.1 Product Functions

The main functions of the COC are:

- Provide a high performance TEM_{00} (optimally matched to the IO beam TEM_{00} mode) mode optical cavity interferometer, which is maximally sensitive to gravitational waves.
- Provide appropriate beam pick-off points, allowing routing of samples of the optical cavity light to various gravitational wave, length and alignment sensing detectors.
- Minimize stray/scattered light from the optical cavities and surfaces.
- Minimize thermal mode noise from the body and face of the optic and the interfacing suspension components.
- Optimize the overall optical configuration to minimize or minimize the effects of optical distortions due to beam heating at full power operation.

3.2 General Constraints

Realistic feasibility constraints have guided the nature of the requirements from the outset of the Advanced LIGO program. We mention the main ones here:

3.2.1 Simplicity

The basic GW IFO configuration, specified by SYS, should be simple in terms of COC number and type:

- Each optic contributes additional wave front distortion, which degrades performance.
- Each COC optic necessitates an additional control servo and suspension system, which degrades performance.
- Contamination potential is proportionally reduced.
- Overall system design is significantly eased, clear optical lines of sight are increased.
- Physically similar COC simplify optical fabrication, IFO construction, spares inventory, handling fixtures and testing.

This document assumes a minimal IFO component count comprising two optics in each arm cavity; and five optics in the recycling cavity (seven for the second Hanford IFO).

3.2.2 Basic Shape

The COC are to be fabricated within the constraints of the ultra high precision optical industry. This framework virtually determines the choice of substrate geometrical shape (circular cylinder, possibly with wedged faces). Additional reasons for this shape include:

- The natural shape for the COC optical faces is circular, matching the TEM_{00} mode symmetry.
- Understanding of the internal mechanical mode spectrum and influence is simplified by this choice.

We therefore assume without further detailed discussion that the all COC are of the basic right circular cylinder shape.

3.2.3 Continuous operation

LIGO must operate with high availability; therefore the COC must be designed with high reliability and low mean time to repair. Spares will be prepared to provide required availability, since the fabrication of precision optics is a lengthy process.

3.2.4 Substrate material

Sapphire is chosen as the COC test mass material baseline. This is because its high thermal conductivity reduces thermal lensing problems from high optical power. A high Young's modulus, mechanical Q, thermal conductivity, and density mean that both substrate and coating thermal noise will be low, in addition.

Fused silica is chosen as an alternate test mass material. The material that promises the best performance will be selected for use in Advanced LIGO. Details of material comparison can be found in the Test Mass Material Downselect Plan, LIGO-T020103.

Fused silica is chosen as the material for all other COC [recycling cavity] elements due to the body of optical industry and LIGO experience with this material.

3.3 Assumptions and Dependencies for this document

- The primary laser beam light is at 1064 nm (YAG).
- A stable, curved-curved arm cavity configuration with cavity length = 4000 m is assumed.
- The two IFO arm cavities are oriented in the same plane at 90^o. This requires a 45^o oriented BS element. This BS is assumed to split the two arm beams at the coating on its front surface, which faces the Power Recycling mirror.
- The primary optical HR and AR coatings on the COC substrates will be multilayer, dielectric thin films.

- With the exception of the recycling mirrors (PRM, SRM) All COC will be mounted by attachment of glass ribbons or fibers.
- All COC are of the right circular cylinder form (with only slight departure for interface to other subsystems, for instance AR surfaces at small wedge angles with respect to the normal to the interferometer plane.
- All COC optical surfaces are to have nominally flat surfaces except for the primary (HR) ETM, ITM, PRM and SRM surfaces which are assumed to be sections of spheres with the effective radii of curvature adjusted to maintain a stable, w_{mir}=6.0cm Gaussian mode.
- The input beam entering the IFO will be polarized such that its electric field is normal to the plane of the IFO. This effects the specification of the coating of non-normal incidence COC; the beam splitter and fold mirrors. This will also influence the crystal orientation in the event sapphire is chosen as the test mass material.

4 Requirements

4.1 Introduction

Primarily the COC requirements flow down from those determined by SYS to be appropriate for the Advanced LIGO. Of secondary consideration are requirements for engineering of other subsystem components. For instance the specification of wedge angles for the TM surface 2 to facilitate implementation of the sensing systems is strictly subordinate to this specification and should not negatively impact the TM optical cavity performance. Table 1 summarizes such flow down from primary requirements of the detector (or subsystems) to requirements of COC and other subsystems.

Table 1 Performance requirement flow down

Requirement on COC	Other Subsystem	Other Subsystem Requirement Category	Primary Requirement Mechanism
Number of pick-off surfaces for length control	SYS	IFO configuration	Necessity of inter cavity signal for orientation & length control
Substrate bulk optical quality	SYS	IFO Cavity Power gains	Minimize loss to bulk scattering mechanisms
Element optical surface quality			Minimize loss to surface scatter out of TEM$_{00}$
Substrate bulk optical quality	SYS	Dark port contrast defect	Wave front distortion: bulk inhomogeneities
Element optical surface quality			Wave front distortion: surface irregularities
Coating absorption	SYS	Arm cavity intensity limitation.	Minimize thermal distortion of elements.
	AOS	Compensation	
Element mass and aspect ratio	SYS	Circulating cavity power	Balance radiation pressure
		Scattering loss to baffles	Optimum substrate Diameter Optimum effective optical Diameter
Substrate and coating bulk mechanical & chemical quality	SYS	IFO thermal noise from substrate fluctuation-dissipation	Minimize substrate and coating loss angles.
Substrate dimensions			Choose high internal mode resonant frequencies
Secondary surface AR	SYS	Stray light beam control	Generate ghost beams from

reflectivity & wedge angle		and scattered light noise	secondary surfaces
AR reflectivity & wedge angles	ISC	Signals for length and orientation control servos	Select ghost beams of desired properties
ETM residual transmission			
Mean surface reflectivity	SYS	Optimum IFO operation parameters	Specific mirror reflectivity values
Surface reflectivity tolerances		Contrast defect	Coating uniformity
Element surface contamination control (cleaning, handling)	SYS	IFO sensitivity degradation	Lowering of Qs Increased light scatter
		Advanced LIGO down time	Damage of optical surfaces

4.2 Characteristics

4.2.1 Performance Characteristics

The discussion of the COC requirements will be broken down into the following characteristic areas:

- Physical Size and Shape.
- Mechanical loss.
- Matching to Interferometer parameters.
- Distortion of the wave front: light scattering (including birefringence)
  - ⇒ Matching losses
  - ⇒ Prompt loss.
  - ⇒ Diffraction due to finite TM size
- Absorption (losses): thermal effects.

4.2.2 Physical Characteristics

Requirements on the COC follow a nominal physical prescription as summarized in table 2.

4.2.2.1 Size and Shape

The exact right circular cylindrical geometry is required to be slightly altered as follows:

- Edges are to be beveled in accordance with standard optical fabrication safety practice (reducing the face diameters from the cylindrical diameters).
- Each surface will have a wedge angle with respect to the cylindrical axis for ghost beam aiming, to suppress stray light and to facilitate pick-off of signals for servo control.
- The BS wedge angles are small. A 1° wedge produces a thickness variation of 11% across the full diameter. This is an assumed limit for thermal and mechanical integrity.
- The ITM, ETM, PRM, and SRM primary, HR, surfaces will be slightly spherical concave. All secondary (AR) surfaces are taken to be nominally flat.
- Flat areas are required on the cylindrical sides of all but the Recycling optics to facilitate suspension.

4.2.2.1.1 Diameter and Thickness

The Test Masses are required to weigh 40 kg in order to meet the Advanced LIGO detection sensitivity goals. The diameter and mirror radii of curvature are selected to minimize TEM_{00} mode diffraction loss and thermal noise. An additional margin of at least 0.6 cm is included to allow for suspension settling and centering tolerance. The aspect ratio is chosen to ensure sufficiently high internal mode frequencies.

4.2.2.1.1.1 Beam Splitter

Similar to the LIGO I requirements the geometrical loss for the beamsplitter is required to not exceed 10 ppm.

4.2.2.1.1.2 Test Masses

The test mass diameter is chosen to be as large as technically feasible and consistent with having no internal normal modes below 5 kHz. The radii of the beams at the test masses will be chosen so that the 1 ppm energy contour lies with the diameter of the optic.

4.2.2.1.1.3 Recycling Mirrors

Table 2 Physical Parameters of 4000m COC

Physical Quantity	**Test Mass** **ETM**	**ITM**	**Beam splitter**	**Recycling mirrors**
Diameter of substrate, ϕ_s (cm)	31.4	31.4	35	26.5
Substrate Thickness, d_s (cm)	13	13	6	10
1 ppm intensity contour diameter (cm)	31.5	31.5		31.5
Lowest internal mode frequency (kHz)	9.35	9.35		
Weight of Suspended Component (kg)	40	40	12.7	12.5

Wedge angle (deg)	0.5	1.2	1.0	2.4
Nominal surface 1 radius of curvature (km) and g+ factor	2.076 g_2=-.9265	2.076 g_1=-.9265	Flat	2.106 g=-.9212

4.2.2.2 Internal resonances, Qs, thermal noise and quantum limit.

4.2.2.2.1 Quantum limit.

What is termed the standard quantum limit for IFO sensitivity depends on the mass of the test masses. Test Masses are required to be 40 kg for optimum sensitivity given the design 125 Watt beam input to the interferometer.

4.2.2.2.2 Thermal noise

Only the thermal noise of the TM substrates will be considered here since the contribution of the other COC is much less important. The TM’s thermal motion can be modeled using Levin’s theorem, and will depend on the mechanical loss of the substrate material, the coating, and any attachments to the optic. Internal normal modes of the optics will be designed to be out of the gravitational wave band.

4.2.2.2.2.1 Substrate mechanical and thermal properties

The mechanical loss angle relevant to thermal noise calculations for sapphire, which will depend on the choice of axis, the intrinsic loss of the substrate, and any surface loss will be less than 10^{-7}.

The specification is stated in terms of loss angle rather than Q. This is because the thermal noise will be determined by the loss from a specific distribution of energy, namely that of the static Gaussian pressure specified in Levin's theorem. While measuring a modal Q is a rough guide to the expected thermal noise, the parameter of interest is the effective loss angle to be used in Levin's theorem.

Thermoelastic noise calculated from Braginsky’s formula will be no more than 5 x 20^{-21} m/$Hz^{1/2}$ per optic at 100 Hz, which may be affected by the choice of sapphire grade and axis.

4.2.2.2.2.2 Coating mechanical and thermal properties

The optical coating will be chosen so that the combined Brownian thermal noise, calculated with the Nakagawa/Gretarsson formula, and the thermoleastic noise, calculated from the Braginsky/Fejer formula, will be no more than 3 10^{-21} m/$Hz^{1/2}$ per optic at 100 Hz. This will be affected by the coating mechanical loss, its Young’s modulus, thermal conductivity, and other mechanical and thermal properties. The coating must also satisfy an optical loss and scatter requirements specified in Section 4.2.2.5.

4.2.2.2.2.3 Substrate diameter and thickness

These dimensions determine the mode resonance frequency spectrum. The choices of shape and aspect ratio determine an initial mode sequence. These Test Mass resonances should occur at the same frequency and be above 5 KHz. Shape perturbations (face wedges, bevels, substrate imperfections) are assumed to not significantly modify the spectrum.

4.2.2.2.2.4 Attachments and contamination

Any contacting material (coatings, contamination, etc) or coupling to external systems (SUS) can cause increased thermal noise. The loss angle and Young's modulus of any contacting material must not cause an increase in thermal noise.

4.2.2.3 Matching to SYS IFO parameters

The overall optical design of the IFO depends on the average effective optical characteristic values of each optical surface on which the main beam impinges. Matching of such characteristics between the two IFO arms is required.

4.2.2.3.1 HR-ITM reflectivity

The SYS arm storage time determines the HR-ITM coatings. Current design is for the HR coating to have a transmission of .005. The criteria for the arm to arm match, and therefore the coating tolerance is that the maximum storage [fractional] time difference be .01 as described in E950099-04-D appendix D1.

4.2.2.3.2 HR-PRM reflectivity

The current best informed 1064 nm Bench and FFT model runs yield suggest an optimized transmission for the HR-PRM coating of 0.06. A tolerance of .005 (TBD) will be required for the ultimately selected transmission value.

4.2.2.3.3 HR-SRM reflectivity

An optimized transmission for the HR-SRM coating is 0.05. A tolerance of .005 (TBD) will be required for the ultimately selected transmission value.

4.2.2.3.4 HR-ETM transmission

The HR-ETM would nominally have unit reflectivity. However a small leakage transmission is desired in order to aid in locking and IFO monitoring. The transmission should be greater than 1ppm to ensure ample monitor/servo signal. The transmission should also be small compared to the dominant cavity loss mechanism, which is scattering loss due to the cavity mirror surface quality. This loss may be ≤ 25 ppm per surface. A reasonable goal requirement is $T< 10$ ppm, which is believed to be consistent with achievable coating technology.

4.2.2.3.5 AR coating reflectivity

In order that the ghost beam loss from the recycling cavity AR coated faces (surface 2) be small compared to the arm cavity (visibility) loss their reflectivity should be ≤ 200 ppm. This bound will provide adequate signal for control and diagnostics and allow a coating design whose reflectivity is inherently insensitive to surface position variations coating layers.

4.2.2.3.6 HR-BS coating

The HR-BS coating must perform a beam splitting of 45^{o} incident light (S polarized), such that the exit beams are equal in power within 2% (including the effects of absorption and the AR-BS coating). See appendix D.3 of E950099-04-D.

4.2.2.3.7 Effective TM curvature radii

The TM radii of curvature are determined by the Gaussian beam size (at TMs) as prescribed by SYS. The effective TM primary surface curvature radii are required to satisfy $g_{1,2} < 0$ ($g_i = 1 - L/R_i$). For the 4km arm interferometers this results in equal TM ROC of approximately 2075m. Any difference in TM primary surface ROC due fabrication tolerance variations will also mismatch the arms. This, however, may also be regarded as a wave front distortion and is treated in 4.2.2.4.3

4.2.2.4 Distortion of the wavefront: scattering losses

Imperfections of the COC surface profiles, their finite diameter, as well as the combined influences of the substrate, coating and bulk index and birefringence inhomogeneities, contribute to distortion of an ideal TEM$_{00}$ mode wave front propagating in the IFO. All such distortions may be regarded as scattering losses (to HTMs). The total scatter loss budget will critically dertermine the arm cavity TEM$_{00}$ mode gain and hence the interferometer sensitivity. Table 3 summarizes required limits to these distortions.

4.2.2.4.1 Contrast Defect loss.

In a properly aligned IFO the CD$_c$ will result predominantly from scattered components of the TEM00 beam which substantially remain within the COC aperture. Experience with LIGO I indicates that CD is a small fraction (few x 10^{-4}) of the total carrier IFO loss. This is of the same order loss (~few 100s ppm) as that allocated for RC AR coating/pick-off loss: entirely negligible. In this section we assume the value CD$_c \leq 1 \times 10^{-3}$ for the requirement on the contrast defect.

Table 3 Required limits on sources of wave front distortion (surface 1)

Descriptive section	**Requirement**	**Test masses**		**Beam splitter, Fold mirrors**	**Recycling mirror**
		ITM	**ETM**		
4.2.2.4.2	Arm-arm match of R_{eff} (fractional)	0.015	0.015	0.015	N/A
4.2.2.4.3	rms surface errors for w > λ_s> 2.3 mm out to ~2*w* diameter [6]	λ/1200	λ/1200	λ/600	λ/600
4.2.2.4.4	rms surface errors for 2w > λ_s > 2.3 mm past 2*w* diameter$_b$	λ/600	λ/600	λ/300	λ/300
4.2.2.4.5	rms surface error for 2.3mm > λ_s> 1.3mm out to ~ 3*w* diameter	<0.2 nm	<0.2 nm	<.4 nm	< .4 nm
4.2.2.4.6	rms surface errors for λ_s > 3-4*w*	λ/160	λ/160	λ/320 [7]	λ/160
4.2.2.4.7	rms transmission OPD for 2*w* > λ_s > 2.3 mm out to ~ 2*w* diameter$_b$	λ/50	λ/20	λ/100	λ/50
4.2.2.4.8	Birefringence (transmission) δ (mrad)	20	N/A	< 10 / NA	< 50

4.2.2.4.2 Effective radius of curvature

As a typical example consider the arm cavity forming mirrors. The input laser beam from IO may be matched equally into both arms if the mirror spacings and effective curvatures are identical. If not, only a mean matching can be achieved. The R_{eff} matching tolerances in table 3 limit the curvature mismatch contribution to CD to $\leq 1.5\ 10^{-3}$ (analysis similar to appendix F of E960099-04-D). Such an R_{eff} matching requires that absorptive losses in the TMs (causing thermal distortions, as in sections 4.2.2.5.1, 4.2.2.5.2) be balanced (appropriate total of surface and bulk absorption) to within ~ 25%.

4.2.2.4.3 Mid λ_s central errors

These are the imperfections seen by the 86% energy foot print of the beam. They produce approximately this proportion of the diffractive loss. The specific requirement values are derived from FFT modeling results. Scattering in this band is neither promptly lost from the arms (see 3.2.2.4.4) nor entirely contained (resulting in CD and arm mode mismatch to TM_{00}). The FFT code, using actual fabrication arm cavity surface distortion maps, is used to model this. Using benchmark LIGO I as built maps (suitably scaled for advanced LIGO beams and optics) this model predicts that such non-prompt scattering (excluding finite ϕ_s) contributes < 15ppm effective loss per arm cavity. Since we expect somewhat better TM surface 1 polish distortions (by judicious choice of polishers) we tentatively budget $\leq 12\,ppm$ per arm for this contribution to scatter loss.

4.2.2.4.4 Mid λ_s peripheral errors

Only 14% of the beam energy lies outside of $\phi = 2w$. It is therefore expected that surface imperfections in this periphery will contribute much less to diffractive loss from the TEM_{00} beam. This is borne out by FFT modeling which is the basis for the requirement values. We may include in this category the diffractive loss suffered by the TEM_{00} beam due to the finite COC diameter ϕ_s. for this diffraction we budget ~ 5ppm per TM (geometric TEM_{00} cutoff loss of 3.2 ppm at $\phi_s = \phi - 2x6mm = 30.2$ cm then roughly doubled for the known diffractive enhancement). We note here that in simple paraxial diffraction theory (level of the FFT model) results are identical for $\pm|g|$ cavity configurations, so that, for example, the negative “g” cavities required for Advanced LIGO have the same finite aperture diffraction as in the more familiar positive “g” situation.

4.2.2.4.5 Micro-roughness: prompt loss

In order to reduce the requirement for all short λ_s (cutoff = 2.3mm) imperfections to a single rms value, some reasonable assumptions (appendix H of E950099-04-D) are needed, based on the condition λ_s,cutoff << $2w$. When defined this way, the micro-roughness merely parameterizes prompt diffuse scatter loss, which, at 1064 nm, would 6 ppm/surface for isotropic polished surface micro-roughness rms = 0.2nm (appendix H of E950099-04-D). In situ measurements of the LIGO I performance have indicated a much larger prompt loss, tentatively traced to large numbers of point defect scatter points embedded in the multi-layer coatings (with potentially significant additional contributions from surface cleaning abrasion and contamination). This anomalous prompt loss amounts to $\geq 60\,ppm$ per HR surface. Leaving this loss category to saturate a total arm loss budget of 75 ppm forces it to be required less than 20 ppm per HR surface.

The very long arm length cavities are effective spatial filters rejecting diffuse scatter contribution to CD_c < 10 ppm. This does not necessarily hold for recycling cavity elements where a substantial fraction of their diffuse loss may channel out the dark port. Allowing $CD_c \leq 10^{-4}$ from this as an upper limit drives the non-arm cavity values in table 3 (but not the net loss requirement of table 4, 4.2.2.5.3).

4.2.2.4.6 Long λ_s errors.

For surface error Fourier components of λ_s 4*w*, one anticipates only a contribution to beam matching effects (as taken into account by 4.2.2.4.2). This is because sines and cosines of periods 4*w* are very good approximations to planes and paraboloids respectively, over a central half wave span (representing most beam energy). Plane contributions are tilt effects removed by ASC. Paraboloids affect the axisymmetric mode matching and are part of the consideration of 4.2.2.4.2. In general the Fourier decomposition is two-dimensional so that a matching between dimensions (astigmatism requirement) is inferred and included in the rms requirement.

The BS carries a tighter requirement since wave front curvature generated by reflection off it is additive between the arms. That is, an intrinsic mismatch is created by splitting surface curvature in this element.

4.2.2.4.7 Transmission OPD errors

Both the cold and additional hot (due to beam absorption) bulk index inhomogeneities in sapphire are too large to go uncorrected (unlike for the FS in LIGO I: see appendix I of E950099-04-D) at Advanced LIGO power levels. The thermal lensing contribution will be discussed separately in 4.2.2.5.1

However native sapphire boules available in the size we require have strong, crystal plane oriented inhomogeneity striae (P010014) which have been measured to exceed ~50nm rms OPD over volumes critical to beam matching into the arm cavities. This distortion would scatter light out of the TM00 mode both upon entering and on exiting the arm cavities. If not corrected this effect would cause diminution of the GW sensitivity by 5-10%. We plan on ameliorating this native OPD with a compensation polish on the AR side 2 of the ITMs. We have identified process which will reduce the net OPD to <10nm rms, reasonably curing the carrier diminution.

In contrast, side band wave fronts have a substantial, if not dominant, distortion from ITM (double pass) and BS transmission. For DC readout of the GW signal, this will have no direct consequence for the interferometer sensitivity. We assume the compensation polish will be sufficient also for the proper excitation of any recycling cavity SB fields.

4.2.2.4.8 Birefringence Effects

Birefringence effects have been considered by Winkler, et al (2.3.2.) These may be: intrinsic, heating strain induced, or mechanical stress induced. We place a nominal requirement on intrinsic material birefringence, however the thermally induced effects are expected to dominate by a large margin. Particularly for the [non-perfect] sapphire crystals available there is the possibility for birefringence due to “wandering” of the optic axis. This has been studied experimentally for a sapphire substrate similar to that believed typical of our TM boules (LIGO T030189). Scatter into the wrong polarization state, as well as induced inhomogeneities (since the n varies with $\underset{\sim}{k}$ in this biaxial system) was show to be negligible compared with the chemical inhomogeneities. Nonetheless our sapphire TMs will be hung with a preferred, c, crystal axis parallel to the beam polarization. This will require correct hanging to within ~1° (TBD) of beam vertical (see section 4.2.3.1.2).

4.2.2.5 Absorption: losses and thermal effects

Absorption, as in LIGO I, is anticipated (based on the known quality of LIGO I coatings, and absorption tests to date on available sapphire substrates) to be a minor contributor to the net loss budget. However its indirect effect via thermal distortion scatter loss to the TEM_{00} mode is now much worse. The thermal distortions at full power in Advanced LIGO would significantly deteriorate (R. Lawrence, MIT thesis, 2003) the carrier fields (not just side bands as in LIGO I). Concern that the absorption may not be sufficiently uniform, as well as mixed success with the "point design" compensation polish (of the RM) approach in LIGO I lead to the entirely new design here of active compensation with auxiliary correction plates (LIGO-G020502-00-R).

In addition the total (bulk plus surface) absorption of beam power will significantly raise the TM mean temperature. The absorption goal values (for sapphire) described below will raise their temperature ~10^{o} K above [radiative] ambient. This alone will increase the thermodynamic noise contribution in the signal channel by 3-4%.

Table 4 Specified limits to losses (in ppm) in COC optics

Section reference	**Loss Source**	**Input TM**	**End TM**	**BS & Fold Mirrors**	**Recycling Mirror**
4.2.2.5.3	Bulk scattering of transmitted beams (ppm)	<50	N/A	< 50	< 50
4.2.2.5.2	Total surface absorption Surface 1 (ppm)	< 1.0	< 1.0	<1	< 1
4.2.2.5.4	Surface scattering from effective mirror micro-roughness (ppm)	<20	<20	<100	<200
4.2.2.5.5	Ghost beam loss (surface 2 origin, ppm)	<200	N/A	~100	<1000
4.2.2.5.6	Accumulated contamination scattering + absorption (ppm)	< 1	< 2	<10	<10
4.2.2.5.1	Substrate bulk absorption, single pass	< 260	N/A	<5 /NA	<60
4.2.2.3.4	ETM transmission	N/A	<10	N/A	N/A
4.2.2.4.4	Finite COC apertures, ϕ_e diffraction loss	5	5	9	N/A
4.2.2.4.3	Mid scale surface scattering losses	<12		<100	

4.2.2.5.1 Bulk absorption

Thus the requirement for thermal distortion through the COC substrates is subsumed into the AOS subsystem requirement. However it is clear that low average substrate absorption will be crucial to make the entire design work. In this spirit we require the ITMs to have mean central ($\phi = 2w$) absorption of $\leq 20\, ppm/cm$. This may be regarded as a goal requirement whose realization is flexible since it matches no "point designed" optics. For the case of the (FS) BS element, we anticipate holding the magnitude of lensing to manageable levels by specifying ultra low absorption material (SV grade).

4.2.2.5.2 Surface absorption

The low beam power and arm finesse of LIGO I made [HR coating] absorption only significant for the SB field distortion. The situation for Advanced LIGO is qualitatively different. Since surface absorption contributes *equally* as bulk absorption to (ITM) lensing distortion it must be similarly limited. The goal limit imposed in the previous section gives then an equal lensing limit of 2.6 ppm (= 2x20 ppm/cm x 13cm x T_{ITM}) absorption in the HR coating.

Further, the surface absorption (as well as some smaller bulk absorption contribution) causes an HR *surface deformation*. Even if the absorption is uniform, this *increase* of the surface radius of curvature with heating will alter the cavity mode and hence beam matching into the arm cavities. The simple model of Winkler, et al. may be applied here, with the assumption that the bulk heating contributes the same surface deformation. Then for the Advanced LIGO arm cavity sapphire parameters and *requiring* <1.0 ppm surface absorption the hot arm mode will have ~34% reduction in mode Gaussian radius. Unfortunately the FS plate *lensing* compensators will not compensate this effect. One approach is to “point design” this problem (start, cold, with TM ROCs which give 34% larger beams). However, as a practical matter, this cold “point design” would be very close (within reasonable fabrication tolerances ?) to the stability limit (both TM ROC = 2000 m).

4.2.2.5.3 Bulk scattering

It is assumed that this category of loss does not contribute to substrate heating. The requirement value is chosen to make this contribution to loss much smaller than that from other mechanisms. Expected scattering loss from high homogeneity FS is much less (< 2ppm/ cm)

4.2.2.5.4 Surface scattering

Operationally this includes all non-absorptive loss at the IFO surfaces, which cannot be explicitly accounted for by diffraction modeling (e.g. the FFT wave front code). FFT model analysis shows that values of this loss of up to ~22 ppm per arm cavity surface can be tolerated to maintain G_R 17.

4.2.2.5.5 Ghost beams

Here the transmission residual beam through the HR-ETM is not included (see 4.2.2.3.4). Then all other ghost reflections are recycling cavity losses. Single ghost losses 1000ppm become comparable to contrast defect and to total absorption and surface scatter loses. The table 4 values are required to keep this balance. Although AR coatings could be obtained to limit reflection to ~ 50 ppm, the resultant ghost wave fronts would have poor phase stability (1.5.1.9). The requirement allows coating design to avoid this. Since ghost beams will be used for length control pick-off a significant$^{\text{TBD}}$ detectable signal is required (100 mW for table 4 values). For beams transiting the AR coatings a full analysis shows that there is no similar sensitivity to coating uniformity variation. It would therefore be permissible to use minimum reflectance AR coatings e.g. on the BS (does not supply control signals) where uncontrolled beam loss is a possible problem (1.5.1.6).

4.2.2.5.6 Contamination loss

This requirement derives from 4.2.2.5.2: any acquired surface loss should be substantially less than that intrinsically desired. A time scale needs to be attached to such accumulation.

4.2.3 Interface Definitions

The main interface for COC occurs with the suspension subsystem. The COC subsystem includes the substrate and all coatings that are applied to it. There are only mechanical and optical interfaces to the COC.

4.2.3.1 Interfaces to other LIGO detector subsystems

4.2.3.1.1 Mechanical Interfaces

Mechanical interfaces SUS-COC are:

- Location and surface quality of the flat polished onto the edge of each core optic. This flat is used for attaching the suspension mechanism. From SUS
- Location of alignment reference marks must be located ± TBD in order to guarantee proper placement of the optic within the suspension. From SUS
- Mass tolerance and therefore dimensional tolerances must be negotiated with SUS.

Mechanical interfaces SUS-COC-AOS are:

- Size of thermal compensation plates. From SUS and AOS.

4.2.3.1.2 Optical Interfaces

Optical interfaces SUS-COC-IO are:

- Clocking alignment of sapphire crystal axis. The primary IFO beams interface the COC with the input and output optics system. These beams are to have polarization, aligned to within ±1° TBD, to the c-axis of the input mass, and also with respect to the plane defined by the two IFO arms.

Optical interfaces COC-ASC are:

- Diagnostic beams which interface to the ASC subsystem and are either input to COC from the ASC or derivative from the primary IFO beams (e.g. ghost beams off wedged AR surfaces). Each COC must have some minimum wedge to keep second surface reflections out of the main beam path. The requirement for pointing the ghost and diagnostic beams determines the wedge angles of the COC.
- AR coatings may be designed to reflect ASC positioning beams. ASC requirements shall not compromise the performance of the COC.

Optical interfaces COC-AOS are:

- Optical absorption of thermal compensation plates. Coatings, material quality and surface quality of thermal compensation plates will be determined by COC and will be in accordance with the loss budget for the recycling cavity.
- The absorption profile of compensation plates and ITMs will be measured by COC and reported to AOS.

4.2.3.1.3 Stay Clear Zones

To maintain the good optical performance required of the COC optical faces it will be necessary to maintain a stay clear cone whose vertex is on the optical axis and whose surface intersects the ~ 1ppm contour of the Gaussian beam intensity at any mirror face. This prescription is to include a ~ 5mm margin for imperfect alignment and suspension settling. Intrusion within these [cylindrically symmetric] cones can be tolerated as long as the intruders for one face “clip” geometrically no more than ~ 1ppm of the impinging beam intensity.

4.2.3.2 Interfaces external to LIGO detector subsystems

There are no interfaces to COC aside from those to other LIGO subsystems.

4.2.4 Reliability

- It is expected that the COC have no inherent hard failure mechanisms. Reliability will be essentially dependent on the extent that they remain free of contamination from external sources.
- An adequate protocol for handling, storing, cleaning, and working around the COC elements must be formulated and assured in practice to avoid breakage or degradation of the optical surfaces. It is to be noted that a single inadvertent scratch on a coated surface will likely constitute breakage.

4.2.5 Maintainability

It will not be possible to “repair” COC elements. The only form of maintenance will be in cleaning the optical surfaces. There is no inherent contamination mode so that a MTTR for cleaning will not be a requirement imposed on the COC.

It will be required that effective cleaning procedures for the specific COC materials (fused silica and the optical thin film coating materials) be developed which can be invoked to clean the surfaces when they are determined to be contaminated.

Tests (e.g. in-situ ring down, ellipsometry, etc.) must be developed to unambiguously signal contamination since in-situ cleaning or change out of COC elements will cause major LIGO down time.

Given the COC operational environment (UHV) it is anticipated that the only mechanism for dealing with contaminated elements will be to change them out. However every effort will be made to investigate and develop possible in situ cleaning procedures.

Consistent with the on time requirements of a LIGO interferometer at the nominal initial LIGO strain sensitivity, is that contamination equivalent to that in table 5 not accrue in less than 2 months operating time. This estimate is based on the assumption that replacing or cleaning the contaminated mirrors will cost an effective observation down time of one month.

4.2.6 Environmental Conditions

COC elements must be exposed at all times to only the cleanest possible environments.

For storage and transport, individual, specially designed hermetic containers will be provided which assure an environment of at least a Class10 clean room environment.

For open handling, transfer to the IFO chambers, cleaning, and auxiliary examination or testing the elements will be exposed to no worse than a Class 100 clean room environment.

The cleanliness requirement for the COC is particularly critical, since first, contamination can lead to *cumulative* irreversible degradation of the optical performance and hence extremely small detectable amount is of concern. Second, cleanliness of the entire LIGO vacuum environment is specified by its impact on the COC, so that all other subsystems are in turn specified in this respect by the COC requirements.

4.2.6.1 Natural Environment

4.2.6.1.1 Temperature and Humidity

Table 5 Environmental Performace Characteristics

Operating	Non-operating (storage)	Transport
+0 C to +50 C, 0–90 % RH	40 C to +70 C, 0–90 % RH	40 C to +70 C, 0–90 % RH

4.2.6.1.2 Atmospheric Pressure

4.2.6.1.3 Seismic Disturbance

4.2.6.2 Induced Environment

Certain materials shall not be put in close proximity of the optical surfaces for extended periods of time (even short term placement is to be checked with cognizant optical engineer)

Synthetic rubber products

4.2.6.2.1 Electromagnetic Radiation

All COC Coatings are extremely sensitive to UV radiation. Severe, non-reversible damage to the coatings can occur with even short term exposure to UV sources. UV sources include direct exposure to welding flash, UV curing lamps, high UV output lamps, UV lasers/markers, plasma discharges, intense direct sunlight, etc. Consult the appropriate optical engineering staff before a potential exposure.

4.2.6.2.2 Acoustic

Equipment shall be designed to produce the lowest levels of acoustic noise as possible and practical. As a minimum, equipment shall not produce acoustic noise levels greater than specified in Derivation of CDS Rack Acoustic Noise Specifications, LIGO-T960083.

4.2.6.2.3 Mechanical Vibration

Mechanical vibration from the subsystem shall not increase the vibration amplitude of the facility floor within 1 m of any other vacuum chambers and equipment tables by more than 1 dB at any frequency between 0.1 Hz and 10 kHz. Limited narrowband exemptions may be permitted subject to LIGO review and approval.

4.2.7 Transportability

All items shall be transportable by commercial carrier without degradation in performance. As necessary, provisions shall be made for measuring and controlling environmental conditions (temperature and accelerations) during transport and handling. Special shipping containers, shipping and handling mechanical restraints, and shock isolation shall be utilized to prevent damage. All containers shall be movable for forklift. All items over 100 lbs. which must be moved into place within LIGO buildings shall have appropriate lifting eyes and mechanical strength to be lifted by cranes.

4.3 Design and Construction

Minimum or essential requirements that are not controlled by performance characteristics, interfaces, or referenced documents. This can include design standards, requirements governing the use or selection of materials, parts and processes, interchangeability requirements, safety requirements, etc.

4.3.1 Materials and Processes

Such items as units of measure to be used (English, Metric) should be listed and any other general items, such as standard polishing procedures and processes.

4.3.1.1 Finishes

Examples:

Ambient Environment: Surface-to-surface contact between dissimilar metals shall be controlled in accordance with the best available practices for corrosion prevention and control.

External surfaces: External surfaces requiring protection shall be painted purple or otherwise protected in a manner to be approved.

- Metal components shall have quality finishes on all surfaces, suitable for vacuum finishes. All corners shall be rounded to TBD radius.
- All materials shall have non-shedding surfaces.
- Aluminum components used in the vacuum shall not have anodized surfaces.
- Optical table surface roughness shall be within 32 micro-inch.

4.3.1.2 Materials

A list of currently approved materials for use inside the LIGO vacuum envelope can be found in LIGO Vacuum Compatible Materials List (LIGO-E960022). All fabricated metal components exposed to vacuum shall be made from stainless steel, copper, or aluminum. Other metals are subject to LIGO approval. Prebaked viton (or fluorel) may be used subject to LIGO approval. All materials used inside the vacuum chamber must comply with LIGO Vacuum Compatibility, Cleaning Methods and Procedures (LIGO-E960022-00-D).

The only lubricating films permitted within the vacuum are dry platings of vacuum compatible materials such as silver and gold.

4.3.1.3 Processes

4.3.1.3.1 Welding

Before welding, the surfaces should be cleaned (but baking is not necessary at this stage) according to the UHV cleaning procedure(s). All welding exposed to vacuum shall be done by the tungsten-arc-inert-gas (TIG) process. Welding techniques for components operated in vacuum shall deviate from the ASME Code in accordance with the best ultra high vacuum practice to eliminate any “virtual leaks” in welds; i. e. all vacuum welds shall be continuous wherever possible to eliminate trapped volumes. All weld procedures for components operated in vacuum shall include steps to avoid contamination of the heat affected zone with air, hydrogen or water, by use of an inert purge gas that floods all sides of heated portions.

The welds should not be subsequently ground (in order to avoid embedding particles from the grinding wheel).

4.3.1.3.2 Cleaning

All materials used inside the vacuum chambers must be cleaned in accordance with Specification Guidance for Seismic Component Cleaning, Baking, and Shipping Preparation (LIGO-L970061-00-D). To facilitate final cleaning procedures, parts should be cleaned after any processes that result in visible contamination from dust, sand or hydrocarbon films.

Materials shall be joined in such a way as to facilitate cleaning and vacuum preparation procedures; i. e. internal volumes shall be provided with adequate openings to allow for wetting, agitation and draining of cleaning fluids and for subsequent drying.

4.3.1.4 Component Naming

All components shall be identified using the LIGO Naming Convention (LIGO-E950111-A-E). This shall include identification (part or drawing number, revision number, serial number) physically stamped on all components, in all drawings and in all related documentation.

4.3.2 Workmanship

Standard of workmanship desired, uniformity, freedom from defects and general appearance of the finished product.

4.3.3 Interchangeability

Specify the level at which components shall be interchangeable or replaceable.

4.3.4 Safety

This item shall meet all applicable NSF and other Federal safety regulations, plus those applicable State, Local and LIGO safety requirements. A hazard/risk analysis shall be conducted in accordance with guidelines set forth in the LIGO Project System Safety Management Plan LIGO-M950046-F, section 3.3.2.

4.3.5 Human Engineering

Note: For many detector subsystems, this section is not applicable.

Specify any special or unique requirements, e.g., constraints on allocation of functions to personnel, and communications and personnel/equipment interactions. Also include any specified areas, stations, or equipment that require concentrated human engineering attention due to the sensitivity of the operation, i.e. those areas where the effects of human error would be particularly serious.

Example: Seismically isolated platforms or points must accommodate addition, removal and adjustment of equipment with a minimum of force or torque applied to the platforms. This requires that adequate space be provided surrounding the optics platform for an individual to move into proper position for the work intended. Equipment mounted to the optics platform should be provided with fasteners that can accommodate these force/torque requirements.

4.4 Assembly and Maintenance

Example:

Assembly fixtures and installation/replacement procedures shall be developed in conjunction with the SEI hardware design. These shall include (but not be limited to) fixtures and procedures for:

- SEI component insertion and assembly into the vacuum chambers without load support from the chambers
- assembly of the in vacuo components in a clean room (class 100) environment
- initial alignment of the SEI components
- installation/removal/replacement of the bellows
- installation/removal/replacement of the actuator components
- installation/removal/replacement of the SEI stage elements

4.5 Documentation

Requirements for documentation of the design, including types of documents, such as operator manuals, etc.

4.5.1 Specifications

List any additional specifications to be provided during the course of design and development, such as Interface Control Documents (ICD) and any lower level specifications to be developed.

4.5.2 Design Documents

List all design documents to be produced, including installation and commissioning plans, standards documents, etc.

Example:

- LIGO SEI System Preliminary Design Document (including supporting technical design and analysis documentation)
- LIGO SEI System Final Design Document (including supporting technical design and analysis documentation)
- LIGO SEI Prototype/Test Plans
- LIGO SEI Installation and Commissioning Plans and Procedures

4.5.3 Engineering Drawings and Associated Lists

A complete set of drawings suitable for fabrication must be provided along with Bill of Material (BOM) and drawing tree lists. The drawings must comply with LIGO standard formats and must be provided in electronic format. All documents shall use the LIGO drawing numbering system, be drawn using LIGO Drawing Preparation Standards, etc.

4.5.4 Technical Manuals and Procedures

4.5.4.1 Procedures

Procedures shall be provided for, at minimum,

- Initial installation and setup of equipment
- Normal operation of equipment
- Normal and/or preventative maintenance
- Installation of new equipment
- Troubleshooting guide for any anticipated potential malfunctions

4.5.4.2 Manuals

Any manuals to be provided, such as operator’s manual, etc.

4.5.5 Documentation Numbering

All documents shall be numbered and identified in accordance with the LIGO documentation control numbering system LIGO document TBD

4.5.6 Test Plans and Procedures

All test plans and procedures shall be developed in accordance with the LIGO Test Plan Guidelines, LIGO document TBD.

4.6 Logistics

The design shall include a list of all recommended spare parts and special test equipment required.

4.7 Precedence

The following lists the principle COC requirements in decending order of importance

- Primary optical surface quality requirement (both substrate polish and coatings)
- Cleanliness requirements
- Substrate material homogeneity for primary beam transmitting elements
- Mechanical Q requirements
- Physical dimension tolerance requirements.

4.8 Qualification

Acceptance of the COC elements from the optical fabricator and the thin film coating provider will be subject to a full array of tests which will assure that the requirements of section 4.2.1 above have been met. These tests will be partially conducted by verified tests conducted by the vendors and subsequently completed and supplemented by LIGO “in house” tests.

5 Quality Assurance Provisions

This section includes all of the examinations and tests to be performed in order to ascertain the product, material or process to be developed or offered for acceptance conforms to the requirements in section 3.

5.1 General

This should outline the general test and inspection philosophy, including all phases of development.

5.1.1 Responsibility for Tests

Who is responsible for testing.

5.1.2 Special Tests

5.1.2.1 Engineering Tests

- Absorption test of HR coated surfaces @ 1.06 microns.
- Scattering test of AR and HR coated surfaces to determine net normal incident 1.06 micron light scattered from specular.
- Q measurement of characteristic internal substrate resonance modes
- Interferometric mapping of the optical surfaces.
- Inspection, ellipsometry, etc $^{\text{TBD}}$ to determine the state of optical surface contamination.

5.1.2.2 Reliability Testing

Reliability evaluation/development tests shall be conducted on items with limited reliability history that will have a significant impact upon the operational availability of the system.

5.1.3 Configuration Management

Configuration control of specifications and designs shall be in accordance with the LIGO Detector Implementation Plan.

5.2 Quality conformance inspections

Design and performance requirements identified in this specification and referenced specifications shall be verified by inspection, analysis, demonstration, similarity, test or a combination thereof per the Verification Matrix, Appendix 1 (See example in Appendix). Verification method selection shall be specified by individual specifications, and documented by appropriate test and evaluation plans and procedures. Verification of compliance to the requirements of this and subsequent specifications may be accomplished by the following methods or combination of methods:

5.2.1 Inspections

Inspection shall be used to determine conformity with requirements that are neither functional nor qualitative; for example, identification marks.

5.2.2 Analysis

Analysis may be used for determination of qualitative and quantitative properties and performance of an item by study, calculation and modeling.

5.2.3 Demonstration

Demonstration may be used for determination of qualitative properties and performance of an item and is accomplished by observation. Verification of an item by this method would be accomplished by using the item for the designated design purpose and would require no special test for final proof of performance.

5.2.4 Similarity

Similarity analysis may be used in lieu of tests when a determination can be made that an item is similar or identical in design to another item that has been previously certified to equivalent or more stringent criteria. Qualification by similarity is subject to Detector management approval.

5.2.5 Test

Test may be used for the determination of quantitative properties and performance of an item by technical means, such as, the use of external resources, such as voltmeters, recorders, and any test equipment necessary for measuring performance. Test equipment used shall be calibrated to the manufacture’s specifications and shall have a calibration sticker showing the current calibration status.

6 Preparation for Delivery

Packaging and marking of equipment for delivery shall be in accordance with the Packaging and Marking procedures specified herein.

7 Preparation for Delivery

Packaging and marking of equipment for delivery shall be in accordance with the Packaging and Marking procedures specified herein.

7.1 Preparation

- Vacuum preparation procedures as outlined in LIGO Vacuum Compatibility, Cleaning Methods and Procedures (LIGO-E960022-00-D) shall be followed for all components intended for use in vacuum. After wrapping vacuum parts as specified in this document, an additional, protective outer wrapping and provisions for lifting shall be provided.
- Electronic components shall be wrapped according to standard procedures for such parts.

7.2 Packaging

Procedures for packaging shall ensure cleaning, drying, and preservation methods adequate to prevent deterioration, appropriate protective wrapping, adequate package cushioning, and proper containers. Proper protection shall be provided for shipping loads and environmental stress during transportation, hauling and storage. The shipping crates used for large items should use for guidance military specification MIL-C-104B, Crates, Wood; Lumber and Plywood Sheathed, Nailed and Bolted. Passive shock witness gauges should accompany the crates during all transits.

For all components which are intended for exposure in the vacuum system, the shipping preparation shall include double bagging with Ameristat 1.5TM plastic film (heat sealed seams as practical, with the exception of the inner bag, or tied off, or taped with care taken to insure that the tape does not touch the cleaned part). Purge the bag with dry nitrogen before sealing.

7.3 Marking

Appropriate identification of the product, both on packages and shipping containers; all markings necessary for delivery and for storage, if applicable; all markings required by regulations, statutes, and common carriers; and all markings necessary for safety and safe delivery shall be provided.

Identification of the material shall be maintained through all manufacturing processes. Each component shall be uniquely identified. The identification shall enable the complete history of each component to be maintained (in association with Documentation “travelers”). A record for each component shall indicate all weld repairs and fabrication abnormalities.

For components and parts which are exposed to the vacuum environment, marking the finished materials with marking fluids, die stamps and/or electro-etching is not permitted. A vibratory tool with a minimum tip radius of 0.005" is acceptable for marking on surfaces which are not hidden from view. Engraving and stamping are also permitted.

8 Notes

This section should contain information of a general or explanatory nature, and no requirements shall appear here. This could be such items as modelling data/results, R&D prototype information, etc.

Appendix A Quality Conformance Inspections

Appendixes are used to append large data tables or any other items which would normally show up within the body of the specification, but, due to their bulk or content, tend to degrade the usefulness of the specification. Whenever an Appendix is used, it shall be referenced in the body of the specification.

Appendix 1 shall always contain a table which lists the requirements and the method of testing requirements. An example table follows. Additional appendixes can contain other information, as appropriate to the subsystem being specified.

Table 6 Quality Conformance Inspections

Paragraph	Title	I	A	D	S	T
3.2.1	Performance Characteristics					X
3.2.1.1	Controls Performance		X			
3.2.1.2	Timing Performance‘		X			X