LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-E010613-v2*

Advanced LIGO

4 Jan 2012

Generic Requirements & Standards for Detector Subsystems

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Distribution of this document: LIGO Science Collaboration
This is an internal working note of the LIGO Project.

* ***N.B.: This document was erroneously referred to as E010123-00 in the past.***

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Change Record

Revision	Date	Changes
00	1 Jul 2001	Initial release, coincident with the Systems Design Requirements Review
01	5 Jun 2005	1) Completed the section on earthquakes 2) Added a section on acoustic noise emission requirements 3) Completed the section on EMI/EMC requirements
02/v1	7 Apr 2008	1) Defined the document scope more clearly and dropped sections on guidance covered in other documentation, specifically configuration control, change control, and review requirements. 2) Added some naming convention references. 3) Added some guidelines, procurement, safety plan, contamination control, environmental disturbance and optics cleaning references to the applicable documents list. 4) Combined testing requirements with QA and cited T950065-A, Guidelines for Design Requirement Documents, for the compliance verification matrix (rather than repeating in this document). 5) Added some guidance regarding weld quality requirements. 6) Added requirements on the quality of commercial, commodity parts such as fasteners and cabling. 7) Added some guidance on contamination control.
v2	4 Jan 2012	Corrected the default proof test level in section 3.4.4.1.1

Table of Contents

List of Figures

List of Tables

1 Introduction

The intent of this document is to provide a common set of guidelines, standards and requirements for the LIGO Detector (science instrument). Since this document has been written after the Initial LIGO construction phase, it applies to new designs (Advanced LIGO (AL) and Initial LIGO (IL) upgrades) but is not retroactive in scope. The scope of this document is principally on the engineering and implementation requirements and not the performance requirements.

Each AL Detector subsystem, or major IL upgrade project, should write a set of requirements which call out the provisions in this document which apply, or state how and why a deviation from these requirements is needed.

1.1 Purpose

This document defines the generic requirements and standards for all subsystem designs for the Advanced LIGO (AdL) detector. The AdL detector is currently defined as a single major upgrade to the Initial LIGO (InL) Detector. These requirements apply even for more modest upgrades to the InL Detector.

1.2 Scope

This document defines, or refers to, the requirements and standards that transcend any particular subsystem and are thus generic. More detailed requirements or standards are referenced where applicable. The scope includes all aspects (mechanical, electrical, optical, etc.) and all phases (design, analysis, test, fabrication, assembly, installation) of the Detector. This document is meant to compliment the following managerial or policy guidance documents with technical/engineering guidance:

- M050303-03, Advanced LIGO Project Execution Plan
- M070102-02, Advanced LIGO Change Control Procedure
- M050220-07, Guidelines for Advanced LIGO Detector Construction Activities
- M950046-D, LIGO Laboratory System Safety Plan
- M960076-A, LIGO Project Quality Assurance Plan
- TBD (E960099-B for now; see note in section 1.4.9), LIGO Reliability Program Plan
- M080036-00, Advanced LIGO Project Procurement Guidelines
- TBD (E030350-A, section 4 for now), Configuration Control Procedure

1.3 Acronyms & Naming Convention

A standard naming convention for all subsystem components shall be developed, documented and uniformly applied in all subsystem documentation, in order to avoid confusion and conflicts with names from other LIGO subsystems.

Documents which compliment the current LIGO Naming Convention, E950111-A document(which needs revision):

- Pendulum Parameter Descriptions and Naming Convention, T040072-01

- Channel Naming Convention, T990033-00 (needs revision for Adl)
- Naming convention for the optics in the stable recycling cavities, see M080038-03
- HAM chamber numbering for AdL, see T010076-02 (until revised Vacuum Equipment (VE) drawings are available)
- Rack naming convention per DAQ (pending revision to T980030-00)

40m Lab	R&D/Test Facility at LIGO/Caltech
AC	Alternating Current
ADC	Analog to Digital Converter
ADCU	Analog Data Collection Unit
AL	Advanced LIGO
AM	Amplitude Modulation
AOS	Auxiliary Optics System (subsystem in AL)
API	Application Programmer's Interface
ASC	Alignment Sensing / Control (detector subsystem)
ATM	Asynchronous Transfer Module
BS	Beamsplitter (optical component)
BSC	BeamSplitter Chamber (large vacuum chamber)
BPCU	Beam Pointing Control Unit
BT	Beam Tube
BTE	Beam Tube Enclosure
CA	Channel Access (EPICS Control & Monitoring system network protocol)
CC	Civil Construction
CDS	Control and Data System (detector subsystem)
CIT	California Institute of Technology
CMS	Control and Monitoring System (a part of CDS)
COC	Core Optics Components (detector subsystem)
COS	Core Optics Support (detector subsystem)
CP	Chiller Pad (part of FAC)
CP	Compensation Plate (optical element part of TCS)
DAQS	Data Acquisition System
DC	Direct Current (steady state - low frequency)
DCC	Document Control Center
DCU	Data Collection Unit
DET	Detector system
DIA	Data Information Area (of reflected memory)
DMA	Direct Memory Access
DRD	Design Requirements Document
EDCU	EPICS Data Collection Unit
EDSU	EPICS Data Server Unit
EMC	Electro-Magnetic Compatibility
EMI	Electro-Magnetic Interference
EOM	Electro-Optic Modulator (optical hardware)
EPICS	Experimental Physics and Industrial Control System

ETM	End Test Mass (optical component)
FAC	Facilities (part of CC)
FCMS	Facility Control and Monitoring System
FCR	Facility Control Room
FFT	Fast Fourier Transform
FI	Faraday Isolator (optical component)
FIFO	First In First Out
FM	Frequency Modulation
FM	Fold Mirror
FR	Faraday Rotator (optical component)
GDS	Global Diagnostic System
GPS	Global Positioning System
GUI	Graphical User Interface
GW	Gravitational Wave
HAM	Horizontal Access Module
HVAC	Heating Ventilation and Air Conditioning
HWCI	Hardware Configuration Item
HWP	Half-Wave Plate (optical hardware)
Hz	Hertz
ICD	Interface Control Document
IFO	Interferometer
IL	Initial LIGO
INS	Installation
I/O	Input/Output
IOO	Input Optics (detector subsystem, formerly named Input / Output Optics)
IP	Internet Protocol
ISR	Interrupt Service Routine
ITM	Input Test Mass (optical component)
IXS	Information eXchange Services
LA	Louisiana
LASTI	LIGO Advanced Systems Test Interferometer (test facility at LIGO/MIT)
LDAS	LIGO Data Analysis System
LHAM	Horizontal Access Module at Louisiana Site
LHO	LIGO Hanford Observatory
LIGO	Laser Interferometer Gravitational-Wave Observatory
LLO	LIGO Livingston Observatory
LSC	Length Sensing / Control (detector subsystem)
LOS	Large Optic Suspension
LVEA	Laser and Vacuum Equipment Area (of the LIGO observatories)
MAP	Memory Allocation Pointer (reflected memory)
MC	Mode Cleaner
MCM	Mode Cleaner Mirror
MIT	Massachusetts Institute of Technology
MMT	IFO Mode Matching Telescope
MSR	Mass Storage Room
MTBF	Mean Time Between Failures

MTTR	Mean Time To Repair
MZ	Mach-Zender Interferometer
NDS	Network Data Server
Nd:YAG	Neodynium doped Yttrium Aluminum Garnet (laser gain medium)
OSB	Operations Support Building
PDD	Preliminary Design Document
PDH	Pound-Drever-Hall (reflection locking technique)
PEM	Physics Environment Monitoring
PM	Phase Modulation
POSIX	Portable Operating System Interface (IEEE Standard 1003.1)
PSL	Pre-Stabilized Laser (detector subsystem)
PZT	Piezo-electric Transducer (mechanical hardware)
RAID	Removable Array of Independent Drives
RAM	Random Access Memory
RC	Radius of Curvature of a Reflective Mirror
RF	Radio Frequency
RM	Recycling Mirror
SAH	Sensor Actuator Heads
SCSI	Small Computer Standard Interface
SEI	Seismic Isolation
SOS	Small Optic Suspension
SRD	Science Requirements Document
SRS	Software Requirement Specification
SUP	Support Equipment
SUS	Suspension Subsystem (sometimes also Suspension assembly)
SYS	Detector Systems Engineering
TBD	To Be Determined (or To Be Done)
TCP	Transport Control Protocol
TCS	Thermal Compensation System
TGG	Terbium-Gallium-Garnet (optical material used in Faraday Isolators)
TFP	Thin Film Polarizer (optical hardware)
TNI	Thermal Noise Interferometer (R&D/Test interferometer at LIGO/Caltech)
UDP	User Datagram Protocol
UF	University of Florida
VE	Vacuum Equipment
VEA	Vacuum Equipment Area
VME	Versa Module Eurocard
WA	Washington
WFS	Wave Front Sensors

1.4 Applicable Documents

1.4.1 Management & Procurement

Document #	Title
M050220-07	Guidelines for Advanced LIGO Detector Construction Activities (supersedes M950090-A)
M050303-03	Advanced LIGO Project Execution Plan
M070102-02	Advanced LIGO Change Control Procedure
E030647	Advanced LIGO Detector Subsystem Interface Control Document
M040004-00	Record of Decision/Agreement (RODA)
NA	RODA Status Web Page
M080036-00	Advanced LIGO Project Procurement Guidelines

1.4.2 Configuration Control & Documentation

The documentation associated with contracting and fabrication is controlled so that the effect of changes (on cost, schedule, interfaces, etc.) can be ascertained and tracked. This documentation applies to all engineering specifications, drawings, procedures, development plans, test plans, interface control documents, etc. Generally in the LIGO document numbering scheme, it is the E and D documents which are approved for release and are controlled through the Document Change Notice (DCN) process (though all documents can be handled with a DCN). Once a document is formally released, the changes (for all lettered, or controlled, revisions – not numbered, or "draft", revisions) must be recorded with new revisions through additional DCNs.

Most project and technical documentation is uncontrolled and unreleased (which does not mean it is not valuable or available). These include technical memoranda (T documents), letters (L documents), etc.

Document #	Title
L960237-00	LIGO Document Change Notice
L960641-05	Electronic Submissions to the Document Control Center
G960249-00	Electronic Submissions to the Document Control Center
Form DCN-04 (06/2004)	Document Change Notice (DCN) Form
L950003-B	LIGO Document Numbering System
	Inspection Form
	Traveler Form
T960051-02	Integrated Layout Drawings: Usage & Maintenance
E000037-00	Detector Configuration Control Procedures

	N.B.: The configuration control approach defined in this document was never fully implemented; A simpler process was developed but never documented well
M950005-00	LIGO Configuration Management Plan *N.B.: This document defines both change control and configuration control. For Adv. LIGO, change control is superseded by the M070102, Advanced LIGO Change Control Procedure. The configuration control approach defined in this document was never fully implemented; A simpler process was developed but never documented well.*
E030350-A	LIGO Drawing Requirements *N.B.: The general configuration control approach that has actually been used in LIGO, and that is proposed for use in Adv. LIGO , is defined in this document. It really should be extracted and placed into a separate document and not "buried" in a Drawing Requirements document. Furthermore, we should seriously consider whether it is time for the LIGO Lab to finally augment our Document Change Notice (DCN) process with an Engineering Change Request (ECR) process.*
T950065-A	Guidelines for Design Requirement Documents

1.4.3 Mechanical & General Technical

Document #	Title
T980044-10	Determination of Global and Local Axes for the LIGO Sites
E950111-A	LIGO Naming Conventions
D980226-00	HAM Chamber Port Designations
D980227-00	BSC Chamber Port Designations
D980229-00	BSC Chamber Door Port Designations
D980228-00	Adaptor Port Designations
E950084-01 [DCC only has –00 and not electronic]	LIGO System Specification (for Initial LIGO, but facility limits all apply)
C961574-00 need scanned DCC copy	Civil Construction, Facilities: Design Configuration Control Document, Final Issue
E970063-01	Seismic Isolation System: Fabrication Process Specification, E970063
DOT/FAA/AR-MMPDS-01	"Metallic Materials Properties Development and Standardization (MMPDS)", Jan 2003 (Note: This is the replacement for MIL-HDBK-5.)
MSFC-00000254	Astronautics Structures Manual (lots of useful tables on fastener strengths, etc.)

NASA-STD-5001	Structural Design and Test Factors of Safety for Space Flight Hardware
	T050047-00, Preliminary Results from the Measurement of Creep in Maraging Blades
Mil-Std-2219	Fusion Welding for Aerospace Applications, 18 Jul 2005
T080071-00	Outgassing from Aluminum Weld Samples

1.4.4 Optical

Document #	Title
E070292-00	Optics Cleaning Specification - First Contact™
E050157-00	4ITM05 Cleaning Procedure
E990035-C	Large Optics and COC Cleaning Procedures
E990034-C	Small Optics Cleaning Procedure
E010355-00	Cleaning Procedure for Uncoated and Ion Beam Sputtered Optics Only
E000007-00	Cleaning Procedures for LIGO Commercial Optics (Other Than Core or IO Optics)
E990316-00	CO2 Cleaning Procedures
E990190-01	Viewports Cleaning and Baking Procedure

1.4.5 Electrical

Document #	Title
E960036-A	LIGO EMI Control Plan and Procedures
T960177-00	LIGO Cable Numbering and Marking Standard
E020986-01	LIGO Interferometer Electronics EMC Requirements
E060231-06	Printed Circuit Board Check-list Prior to Manufacture

1.4.6 Software

Document #	Title
T970130-F	Specification of a Common Data Frame Format for Interferometric Gravitational Wave Detectors (IGWD)
T960004-A	CDS Software Development Plan & Guidelines (SDP)

1.4.7 Vacuum & Contamination

Document #	Title
E960022-B	LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures
E960050-B	LIGO Vacuum Compatible Materials List
M990034-C	LIGO Hanford Observatory Contamination Control Plan
E048228-A	Process Specification for AdLIGO Seismic Isolation System In-Vacuum Mechanical Elements Contamination Control
T040111-00	Galling Tendencies and Particles Produced by Ultra Clean Screw Threads
SLAC-TN-86-6	SLAC Technical Specification for Vacuum Systems [NON-BINDING]
C981212-00 need electronic copy in DCC	Cleaning Process Control Procedures: S/S Support Tubes and Alum HAM & BSC Weldments
D972202-E	SEI "weld configuration & weld procedure" drawing
T040001-00	Vacuum Hydrocarbon Outgassing Requirements *N.B.: Pending revision. This analysis does not account for the extremely large pumping speed (and essentially infinite capacity) of the beam tubes. The requirements are not as tight as stated in this document and should be comparable to initial LIGO requirements.*
MIL-STD-1246C	Product Cleanliness Levels and Contamination Control Program
IEST-STD-CC1246D	
FED-STD-209	Airborne Particulate Cleanliness Classes in Cleanrooms and Clean Zones

1.4.8 Environment

Document #	Title
T010074-03	The LIGO Observatory Environment
T030075-00	Notes on the Acoustic Emission of VME Crates at LIGO
T98?	Initial environmental data from the Hanford facilities
Number?	Environmental Disturbances: E5, E6 and E7 Investigations
G040391-00	Progress since March on S3 Environmental Disturbances
G050217-00	S4 Environmental Disturbances

G070581-00	S5 Environmental Disturbances: March to July 07
T030091-00	Study of wind behavior in Hanford and its influence on the seismic motion excitation
P040015-00	Long Term Study of the Seismic Environment at LIGO
G010208-00	Earthquake Risk & Recovery: Lessons from the 28 Feb 2001 Olympia, WA Quake

1.4.9 Quality Assurance, Reliability, Transportability, Packaging

Document #	Title
M960076-A make external link	LIGO Project Quality Assurance Plan
E960099-B	LIGO Reliability Program Plan *N.B.: This plan is too theoretical; We need to write a plan which can be used more readily to act upon and make decisions.*
MIL-C-104B	Crates, Wood; Lumber and Plywood Sheathed, Nailed and Bolted

1.4.10 Safety

Document #	Title
M950046-D	LIGO Laboratory System Safety Plan
	M960001, LIGO Laser Safety Program
	M980140, LIGO Hanford Observatory Emergency Action Plan
	M990148, LIGO Livingston Observatory Laser Safety Plan
	M990184, LIGO Livingston Observatory Emergency Action Plan
	M000009, LIGO Livingston Observatory Security Procedures
	M020131, LIGO Hanford Observatory Laser Safety Plan with Added Engineering Controls and Interlock Hardware
	M040112, LIGO Livingston Laser Safety Plan
M070360-04	Advanced LIGO Safety: Processes and Guidelines

2 Documentation Requirements

The types and extent of documentation required for the various phases of the project are defined in M050220-07, Guidelines for Advanced LIGO Detector Construction Activities (supersedes M950090-A). The Configuration Control requirements are defined in TBD (E030350-A, section 4 for now), Configuration Control Procedure.

2.1 Documentation Numbering & Electronic Filing

All documents shall be numbered and identified in accordance with L950003-B, LIGO Document Numbering System.

All documents (regardless of type or whether the documents are under configuration control) shall be filed electronically in the LIGO Document Control Center (DCC) database in Adobe AcroBat (*.pdf) format. This includes all correspondence with contractors (including email), all specifications, all RFQs/RFPs, all bids, all invoices, all drawings, all incoming inspection reports, all certifications, etc.; i.e. all documents – no exceptions.

2.2 Source Files

All engineering documents shall have their source document(s) filed into the DCC as well, unless there is a separate, project maintained and sanctioned file repository. (For mechanical drawings this repository is a PDMWorks™ vault.) For example,

- When an engineering specification is filed electronically into the DCC, not only is the Adobe Acrobat (*.pdf) version filed, but if created with (for example) Microsoft Word, then the *.doc file is submitted to the DCC as well. (Note that the *.doc file can be attached to the *.pdf file instead of filing separately if desired.)
- When an analysis is documented in a technical memo (T document), the memo is filed in *.pdf and source (say *.doc) format. In addition, source file(s) associated with the analysis should also be filed, such as Matlab m-files, or Mathematica notebook files, or finite element files (if of reasonable size).

2.3 Archival

The DCC archives (saves) all submissions, including all revisions.

For source files in separate project maintained and sanctioned document repositories (e.g. SolidWorks™ drawings and associated data in PDMWorks™), all files including all revisions must be saved. If storage of the files becomes a problem, then archival records must be made before removing old files. Moreover, archival snapshots at significant milestones (e.g. Final Design Review, RFQ package, As-Built Documentation …) are encouraged. These archives can be in the form of a DVDROM collection and submitted to the DCC (for off-line storage). Translation of the source files from native format to a universal format (e.g. from SolidWorks™ parts files, SLDPRT to STEP format) is required for the as-built configuration; The Adobe Acrobat file, native source file and universal format file are then all filed together in the DCC.

2.4 Engineering Drawings and Associated Lists

All LIGO engineering drawings must comply with the preparation standards/requirements defined in E030350-A, LIGO Drawing Requirements. As stated in this document, in addition to a complete set of drawings suitable for fabrication, one must provide an associated Bill(s) of Material (BOM) and drawing tree list(s).

2.5 Technical Manuals and Procedures

2.5.1 Procedures

In general procedures shall be provided for, as required:

- Initial assembly
- Functional test (check-out) of equipment
- Initial installation and setup of equipment
- Normal operation of equipment
- Normal and/or preventative maintenance
- Test of new equipment
- Troubleshooting guide for any anticipated potential malfunctions
- Acceptance testing procedures and criteria

2.5.2 Manuals

Any manuals to be provided, such as an operator's manual, shall be provided with delivery of the detector subsystem equipment.

3 Mechanical Characteristics & Standards

3.1 Part Numbers

All fabricated LIGO parts shall have a part number designation number. The part number is identical to the drawing number, including the revision letter. See sections 3.1.5 and 3.2.12 of E030350-A, LIGO Drawing Requirements.

3.2 Serial Numbers

Parts for which data is to be collected for individual items (inspection data, performance data, characteristics, etc.) need to have individual serial numbers. See sections 3.1.5 and 3.2.12 of E030350-A, LIGO Drawing Requirements.

3.3 Coordinate Systems

The coordinate system definition shall be in accordance with T980044-10, Determination of Global and Local Coordinate Axes for the LIGO Sites. If needed, additional subsystem specific local coordinate systems can be defined (e.g. chamber referenced), but should be right-handed it should be clear how to transform to the coordinate frames defined in T980044.

3.4 Structural Safety Factor

All Factors of Safety (FS) are to be used with minimum ("S basis" or equivalent) yield and ultimate values for the material[1].

The factors of safety given in the sections below are not meant to cover large uncertainties in the environment and loads, nor are they meant to accommodate unevaluated stress concentration factors. In general for the LIGO Detector components, the service environment and loads are well known (controlled). The material properties, composition and history are likewise (generally) well known and controlled. Engineering judgment should be used if situations arise for which an increased factor of safety might be warranted due to uncertainties in the material, environment or loading conditions.

For safety critical structures (personnel or machine safety), detailed finite element analysis of stress is required.

Discussion/background (not a requirements statement): The factors of safety in the following sections, as well as the proof test magnitude for brittle or bonded structures, is based upon NASA-STD-5001, "Structural Design and Test Factors of Safety for Space Flight Hardware". However, this is not called out as a binding document here – only a reference. NASA-STD-5001.

3.4.1 Metal (other than maraging steel)

For metallic structures other than maraging steel, the FS should be a minimum of 1.25 for yield and 1.4 for ultimate.

[1] S-Basis material values are defined as the value for which 99% of a normal distribution have a higher value with a 95% confidence. S-basis material properties are provided in "Metallic Materials Properties Development and Standardization (MMPDS)", Jan 2003, DOT/FAA/AR-MMPDS-01 (Note: This is the replacement for MIL-HDBK-5.)

3.4.2 Maraging Steel

For maraging steel components which form flexural elements of a LIGO passive isolation system, use a FS or 1.8 for yield. See also section 3.6.2 on maraging heat/load treatment to accelerate creep.

Background/discussion (not a statement of requirement): LIGO uses maraging steel for cantilevered blade spring flexures, in plate form, and for suspended pendulum links/flexures, in rod or wire form. Generally these are safety critical structures (non-redundant and supporting a heavy load and/or an expensive asset, such as a core optic.). In addition, these maraging steel elements form passive vibration isolation elements in proximity to the sensitive, low noise, optical elements. Noise due to creep or relaxation must be minimized in part by keeping stresses low. Discussions on maraging steel in these applications can be found in the following references:

G050099-00, Maraging Steel: SUS perspective

G050211-00, Maraging Steel: SEI Perspective

3.4.3 Bonds

For the bonds of composite structures (metallic or non-metallic), the FS shall be a minimum of 2.0 for ultimate.

3.4.4 Glass & Ceramics

For non-metallic, brittle structures, the FS should be a minimum of 3.0 for ultimate stress.

3.4.4.1.1 Proof Testing

For all components or assemblies that are to be placed into the LIGO vacuum system, proof testing on the actual end article must be performed for all structural bonds (to metallic or non-metallic components) and all non-metallic, brittle structures. For non-pressurized applications, proof testing is to be done to a factor of 1.2 over the maximum service load. For pressurized applications the minimum proof test factor shall be 2.0. All proof testing shall be short duration with rapid release of load and performed in an inert environment, to minimize flaw growth.

3.4.4.1.2 Inert Environment for Fused Silica Fibers or Ribbons

To minimize flaw growth, the fused silica fibers or ribbons are to be kept in an inert environment (free of moisture) as much as possible. In particular the fibers are to be stored in a moisture free environment. Ribbons or fibers are to be proof tested before welding into a suspension assembly.

3.5 Materials

All materials used in the LIGO vacuum system, or in safety critical structures, must have material certifications.

All materials used in the LIGO vacuum system must comply with E960050-B, LIGO Vacuum Compatible Materials List.

3.6 Processes

3.6.1 Cleaning

All materials used inside the vacuum chambers will be cleaned in accordance with E960022-B, LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures. Final cleaning & vacuum preparation of parts should be performed after all processing has been completed, if at all possible. Cleaning shall be performed at intermediate steps to insure cleanliness when subsequent fabrication or assembly steps limit the effectiveness of final cleaning; For example the OSEM coil former and coil wire will be cleaned and vacuum baked prior to winding. Care will be taken to insure proper handling in processing steps following intermediate cleaning steps.

The various suspensions will use 2 or 3 different types of Optical Sensor and Electro-Magnetic actuator (OSEM) assemblies. The assembly procedure for the "Hybrid OSEM" (used on the Recycling Mirrors Suspension and Mode Cleaner Suspension), including cleaning steps in given in E030084-02, "Hybrid OSEM Assembly Specification". A similar procedure will be developed for all OSEM variants used in the suspension assemblies.

Parts or assemblies shall be capable of disassembly for cleaning, or 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.

All SUS parts will be detergent and solvent cleaned in ultrasonic baths and then vacuum baked, and qualified for LIGO vacuum service with an RGA measurement, with the exception of the lower structure of all BSC suspensions (and potentially the upper structure of the combined FM/ITM suspension). These large components will be detergent cleaned and air baked, with qualification for LIGO vacuum service via an FTIR test. In all cases the procedures will comply with E960022.

SEI Part Cleaning – or generalize

3.6.2 Creep Acceleration

Maraging steel flexural elements used for passive isolation in the suspension systems (close to the final isolated test mass/optic) shall be treated to bake out creep in advance of installation. In the final clamp assembly, under its nominal loading, the maraging steel shall be baked at 100C to 200C for 7 days. The load must then remain applied to the maraging steel.

Background/discussion (not a statement of requirement): LIGO uses maraging steel for cantilevered blade spring flexures, in plate form, and for suspended pendulum links/flexures, in rod or wire form. These maraging steel elements form passive vibration isolation elements in proximity to the sensitive, low noise, optical elements. Noise due to creep or relaxation must be minimized in part by keeping stresses low. The creep rate should also be reduced by appropriate heat and load treatment to accelerate creep. Discussions on maraging steel creep can be found in the following reference:

T050047-00, Preliminary Results from the Measurement of Creep in Maraging Blades

3.7 Welding and Brazing for UHV

The scope of this section is non-vacuum pressure vessels. None of the detector system component welds form a pressure vessel. In general the SUS components are stiffness critical structures, not strength critical, so that weld strength is not an issue. The principal concern for SUS welds is vacuum cleanliness and stiffness.

3.7.1 Welding Metal

3.7.1.1 General

Before welding, the surfaces should be cleaned (but baking is not necessary at this stage) according to the UHV cleaning, or similar, procedure(s). All welds, which will subsequently be exposed to the LIGO vacuum, shall be done by the tungsten-arc-inert-gas (TIG) process. Welding techniques for components operated in vacuum shall be in accordance with the best ultra high vacuum practice, such as the SLAC "Technical Specification for Vacuum Systems", SLAC-TN-86-6 (section VI. Welding and Brazing and Appendix I.D)

In particular all vacuum welds shall be full penetration wherever possible to eliminate trapped volumes or difficult to clean crevices, i.e. virtual leaks. 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).

The Initial LIGO Seismic Isolation System: Fabrication Process Specification, E970063, can serve as a guide for welding requirements and process sequence, as well as the associated detailed processing procedures developed by Allied Engineering to implement E970063 (e.g. "Cleaning Process Control Procedures: S/S Support Tubes and Alum HAM & BSC Weldments", C981212-00).

Weld preparation details shall be called out on the drawings. Each of these welds should be developed with a welder experimentally to insure full penetration and minimal heat distortion of the parts (e.g. as part of the prototype development efforts). The specific examples in the SEI "weld configuration & weld procedure" drawing, D972202 can serve as guidance for welding details. These weld preparation details are all for full penetration welds suitable for in-vacuum service. They are typically for joining aluminum plate from 0.25 to 0.75 inches thick.

3.7.1.2 Weld Quality

The weld preparation, processing and welders should be qualified against Mil-Std-2219, Fusion Welding for Aerospace Applications, for Class A welds (or an equivalent specification) for sample welds which are similar to the actual part welds. Once the process is certified (by both non-destructive evaluation and cross-sectioning), then the production article welds only require a visual inspection, by unaided eye, i.e. the non-destructive evaluation required for Class A certification does not apply to the production articles. The welders and process should be re-checked/re-certified during the course of the production run. The frequency of this re-certification depends on the complexity of the welds and should be determined by the cognizant engineer.

Ideally outgassing from the weldment would be checked, after cleaning and vacuum baking, by a Residual Gas Assay (RGA) if it can fit into a suitable vacuum chamber.

Basis for the requirement: Mil-Std-2219 defines the quality of welds as Class A, Class B or Class C, where Class A is the highest quality and Class the lowest. The Brookhaven LS project has selected class A of Mil-Std-2219 as the most appropriate weld qualification specification for their project. There is no known published standard for TIG welding of aluminum vacuum vessels. At the Argonne National Lab for the Advanced Photon Source (APS) production facility, MIL-STD-2219 for Class A welds was adopted (LS254, Quality Issues). This was the toughest specification against which APS aluminum welding performance could be judged. Some weak justification for specifying Class A welds for LIGO is given in T080071-00, on the basis of some extremely limited and suspect outgass measurements of small weld samples, and some order-of-magnitude analysis of allowable porosity.

Mil-Std-2219, Class A welds in aluminum requires 100% x-ray evaluation. Any weld regions failing to meet the Class A inclusion, void and porosity limits must be cut out and re-welded and re-examined by x-ray. Generally this process must repeat three or four times before the entire weldment passes as Class A. This drives the cost up considerably.

For InL no similar weld specification was applied. Good practice, weld sample evaluation and visual examination (unaided eye) were deemed adequate.

3.7.2 Welding Fused Silica

Requirements for welding fused silica fibers or ribbons to fused silica ears (which are bonded to a suspended mass) are pending completion of the enabling R&D.

3.7.3 Dip Brazing

Due to the high porosity and inability to guarantee removal of all salts and fluxes, dip brazing is not acceptable for parts intended for LIGO vacuum service.

3.8 Finishes

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

Surfaces requiring protection (and outside of the vacuum system) shall be painted LIGO blue or otherwise protected in a manner to be approved.

Metal components intended for vacuum service shall have quality finishes on all surfaces, suitable for vacuum. All sharp edges and corners shall be rounded. All materials shall have non-shedding surfaces. Aluminum components used in the vacuum shall not have anodized surfaces.

Tight fit/tolerance sliding contacts should be avoided if possible in the LIGO vacuum. If necessary then low outgassing, vacuum compatible, solid, non-organic lubricants should be used, in accordance with E960050, LIGO Vacuum Compatible Materials List.

3.9 Bolted Joints & Threaded Fasteners

All fasteners used in vacuum and in critical applications must be high quality and have certifications delivered with the fasteners; High quality, certified fasteners are encouraged for all applications.

3.9.1 In-Vacuum Fasteners

To prevent cold welding or galling, use stainless fasteners into aluminum, and use silver coated stainless fasteners into ftainless. In addition all in-vacuum fasteners shall use oversize tapped threads to prevent galling, in accordance with E030350, Drawing Requirements.

Unless other overriding design considerations dictate an alternate set of materials, or thread treatment, all in-vacuum fasteners shall comply with the following requirements to prevent galling. If an alternate design choice is recommended, then this choice must be shown by test[2] not to gall after LIGO cleaning procedures and service in vacuum:

> Aluminum: LIGO aluminum in-vacuum parts that are expected to be disassembled (such as clamps for securing optical table components into the aluminum optics table) must use stainless steel screws in Nitronic-60 (N60) thread inserts for the tapped holes, to reduce the amount of generated particles and to reduce the risk of galling. For parts that are disassembled rarely, stainless steel screws shall be used in 0.005" oversize tapped aluminum parts.
>
> Stainless Steel: Silver-plated, stainless steel screws shall be used in 0.005" oversize tapped stainless parts.

3.9.2 Seismic Isolation Subsystem

Holo-Krome or Unbrako are specified for all commodity (non-custom) fasteners used for the seismic isolation subsystem. Both provide high quality rolled threads to ASTM specifications, run in-process statistical process control and perform a final inspection on random samples taken from each lot. Both perform a full compliment of laboratory tests, as required by ASTM specifications - including decarburization, hardness, and wedge tensile strength. The fasteners are then UHV cleaned, bagged, and kitted for its specific assembly by LIGO Lab.

3.9.3 Suspension Subsystem

All of our vented and silver plated hardware is purchased from UC Components. They specialize in cleaned high vacuum hardware. The screws, washers and bolts come with specifications and are pre-cleaned. We clean and bake them again per our specification. If UC Components specifications are still not tight enough, we procure MIL spec hardware, have them etched to a tight tolerance and then have them plated to a tight tolerance.

All other fastener hardware is bought to a mil-spec or equivalent. For example, in non-precision applications we buy from McMaster Carr hardware that is "MIL-16999-11 or equivalent" for stainless socket head cap screws or "NAS-620-4 or equivalent" for washers. They provide certification as such.

---

[2] Testing similar to that reported in T040111, Galling Tendencies and Particles Produced by Ultra Clean Screw Threads

In precision situations, we buy from Lavender Fasteners, who specialize in high quality military fasteners. Specs are provided with each order. In these applications, we buy to the appropriate mil spec and ask for specs with the parts.

3.10 Drawing & CAD Standards

E030350-A, LIGO Drawing Requirements.

3.11 Units

Drawings shall be dimensioned in inches, except for layouts where dual dimensions are preferred, in the following format: inches [mm]. (per section 3.2.6 of E030350-A, LIGO Drawing Requirements) Exceptions may be granted by the System Engineer to foreign contributors and subcontractors.

3.12 Preparation for Delivery

3.12.1 Preparation

3.12.2 Bar Codes

LIGO will implement a bar code system for tracking and inventory control. Procedures and system description are TBD.

3.12.2.1 In-Vacuum Parts/Assemblies

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.

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, or equivalent. 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 if the components absorb water.

3.12.2.2 Electronic Components

Electronic components shall be wrapped according to standard procedures for such parts, including electrostatic protection, as appropriate.

3.12.3 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.

3.12.4 Marking

see E030350-A

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.

All component parts shall be marked with their part number and, if appropriate, serial number.

4 Electrical Characteristics & Standards

4.1 EMI/EMC, Grounding & Shielding

All LIGO Detector electrical/electronics equipment shall meet the Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC) requirements of the following two documents:

- LIGO EMI Control Plan and Procedures, E960036-A
- M. Zucker, "LIGO Interferometer Electronics EMC Requirements", E020986-01

In particular, as stated in E960036-A:

- LIGO digital electronics shall conform to FCC Part 15, Subpart J regulations for radiated and conducted emissions form Class B computing devices
- LIGO digital and analog electronics shall conform to the selected portions of MIL-STD-461E called out in LIGO-E960036-A, for both electromagnetic emission and susceptibility to ambient environment
- LIGO-E960036-A also calls out requirements on DC Power Supplies, Circuit Shielding and Grounding (digital, baseband analog and RF) as well as cabling standards.

Relevant examples of the implementation of LIGO acceptable EMI/EMC practice are included in the following documents:

- M. Zucker, J. Heefner, "EMC, “Shielding and Grounding Retrofit Plan”, E020350-08
- B. Abbott, "Installation of RFI Mitigated HEPI System at LLO", E040288-00, 18 Jun 04

4.2 Cabling & Connectors

see T960177-00, LIGO Cable Numbering and Marking Standard

4.2.1 in-vacuum

All in-vacuum materials, processes and suppliers are strictly controlled. Qualification of a kapton insulated cable from one company does not mean that all kapton insulated cables are approved; All sources are qualified by supplier and part number. All parts are cleaned and vacuum baked by LIGO Lab. All parts are 100% tested by LIGO for vacuum compatibility by mass spectrometry.

All in-vacuum cables are 100% continuity tested by the manufacturer and all come with material certifications and (if appropriate) a statement of compliance with our drawing and specification.

The LIGO Lab also performs 100% testing on all cables after LIGO Lab completes UHV cleaning and baking.

4.2.2 exo-vacuum

Custom and commercial off-the-shelf cable assemblies are to be procured only from sources which have been confirmed to deliver high quality and high reliability cables. All must perform 100% testing and guarantee their product.

The LIGO Lab also performs 100% testing on all cables.

4.2.3 Electrical Vacuum Feedthroughs

All electrical vacuum feedthroughs are certified to meet the manufacturer's or our drawings and processes (as appropriate) and are 100% He leak tested.

LIGO Lab will also 100% leak test after LIGO Lab completes UHV cleaning and baking.

4.2.4 Commercial Off-The-Shelf (COTS) Components & Modules

4.2.4.1 Electronics Modules

Commercial off-the-shelf electronics modules come with manufacturer warranties and implied or explicit certifications that they meet the manufacturer's specifications. Upon receipt, LIGO Lab performs 100% testing of these components.

4.2.4.2 Electronic Component Parts

Electronic component parts for LIGO custom board/module designs

4.2.4.2.1 Critical Passive Components

This category includes thin film resistors, polycarbonate capacitors. For critical applications like high tolerance thin film resistors, we purchase from companies that use MIL-PRF-55342 (the military standard for high reliability resistors). Our critical capacitors are custom made, and 100% tested.

4.2.4.2.2 Photo-detectors

As these components are essential to the operation of LIGO, they are ordered as custom products, and come with a paper-trail of individual testing.

4.2.4.2.3 Semi-conductors and Integrated Circuits

If the application requires critical parameters to be met, then components must be purchased from sources that guarantee these specifications. In addition, LIGO Lab will perform 100% in-house testing of critical component parameters.

4.2.4.2.4 Printed Circuit Boards

Prior to manufacturing printed circuit boards, the design is checked against E060231-06, Printed Circuit Board Check-list Prior to Manufacture.

We order circuit boards only from qualified, reliable manufacturers who perform 100% visual checking per IPC-600F (or similar). We also rely on 100% testing of printed circuit boards once they are complete the manufacturing phase, either by LIGO Lab or by a testing house in accordance with a LIGO Lab specified test procedure.

5 Software Characteristics & Standards

5.1 Software Development Plan & Guidelines

See T960004-A, CDS Software Development Plan & Guidelines (SDP)

5.2 GUI Human Engineering

TBD

5.3 Software Configuration Control

TBD

5.4 Testing

TBD

6 Contamination Control

6.1 In-Vacuum, Non-optical Parts and Assemblies

Cleanliness Requirements are as follows:

- Achieve a Non-Volatile Residue (NVR) level of A/50 or better (per MIL-STD-1246C or IEST-STD-CC1246D) on piece parts before clean assembly
- Achieve a Particulate Cleanliness Level of 50 or better (per MIL-STD -1246C or IEST-STD-CC1246D) on piece parts before clean assembly
- Perform clean assembly and all steps through UHV Packaging in a Class 100 Clean Room (per FED-STD-209)
- Comply with Contamination Control Protocols defined in E048228-A, "Process Specification for AdLIGO Seismic Isolation System In-Vacuum Mechanical Elements Contamination Control", or similar procedures.
- Comply with M990034-C, "LIGO Hanford Observatory Contamination Control Plan", for assembly and installation work at the LIGO Observatories. In particular, this document defined the requirements for cleaning tooling (Class B) which contacts parts which are installed into the vacuum system (Class A).
- Package the Clean Parts per E048228-A, "Process Specification for AdLIGO Seismic Isolation System In-Vacuum Mechanical Elements Contamination Control", or similar procedures.

Contractors must certify the cleaning and baking process with representative parts to demonstrate 1246 Level 50-A/50. The NVR level must be confirmed via FTIR (Fourier Transform Infrared analysis). The particulate level must be confirmed by particle sizing and counting or equivalent particle area coverage per MIL-STD -1246C or IEST-STD-CC1246D. LIGO Lab will independently assess the contractor's cleaning/baking process with representative parts by RGA (mass spectrometer outgassing analysis) per E960022.

Cleanliness requirements relate to the manufacturing process as illustrated in Figure 1. Practical implementation requirements during manufacturing:

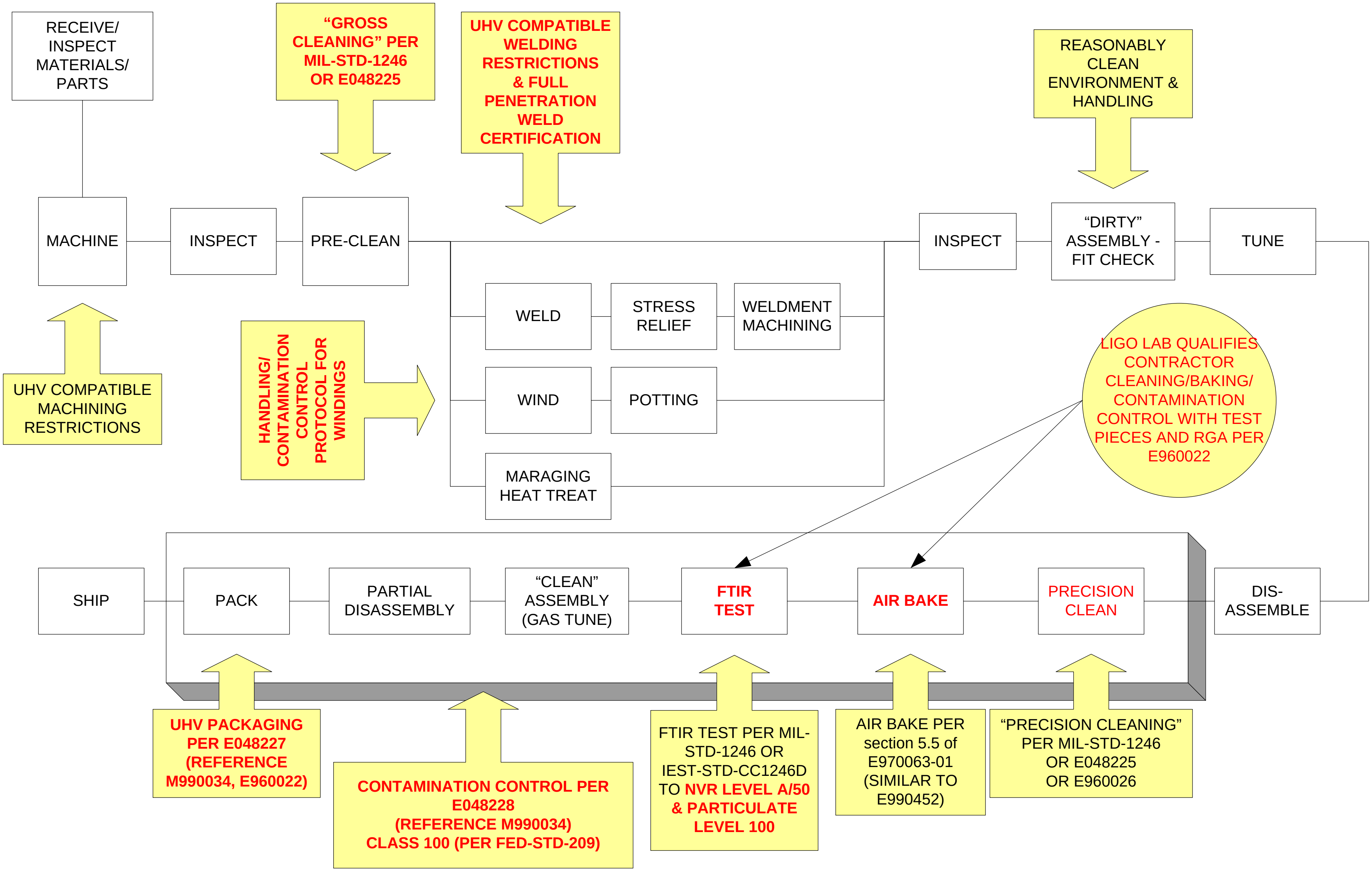
1) Must pre-clean parts before welding and winding
2) Must clean parts multiple times during fabrication
3) Must thoroughly clean parts:
    a) "gross" clean with solvents and acids
    b) Mechanical clean (scrub) parts especially tapped holes – multiple times, with powered rotary tool – during "gross" and "precision" clean steps
    c) "precision" clean with hot, water soluble detergents (steam or hot water spray) – multiple times
    d) Never let parts dry with detergent
    e) Multiple rinses with Deionized water

8) Must bake parts (air or vacuum) after "precision" cleaning
9) Must maintain parts in a class 100 clean room
    a) or keep wrapped in "UHV Foil" and keep in at least a class 10,000 clean area)
    b) limit exposure, keep wrapped /covered when possible
10) Must Control Contamination with Good Clean Room Practice
    a) All tools must be cleaned, air baked, wrapped & kept in Class 100 areas
    b) All personnel must wear full clean room garb, including hair net, face mask and gloves

6.2 Optical Components

Procedures for cleaning and contamination control for LIGO optics are given in section 1.4.4.

Figure 1: Ultra-High Vacuum (UHV) Cleanliness Requirements Related to Manufacturing Processes



7 Vacuum Compatibility Requirements

7.1 In-Situ Low Temperature Bake

All components and assemblies placed into the LIGO vacuum system shall be able to sustain a 30C, non-operating bake for an extended period of time (order of days) without damage or degradation.

7.2 Tribology

See section 3.9.1, In-Vacuum Fasteners

7.3 Materials

See E960050-B, LIGO Vacuum Compatible Materials List

7.4 Qualification of Materials and Processes

See E960022-B, LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures

7.5 Fabrication Restrictions

See E960022-B, LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures

7.6 Cleaning

See E960022-B, LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures

8 Environment

References on the LIGO environment and environmental disturbances are given in section 1.4.8, Environment.

8.1 Acoustic Requirements

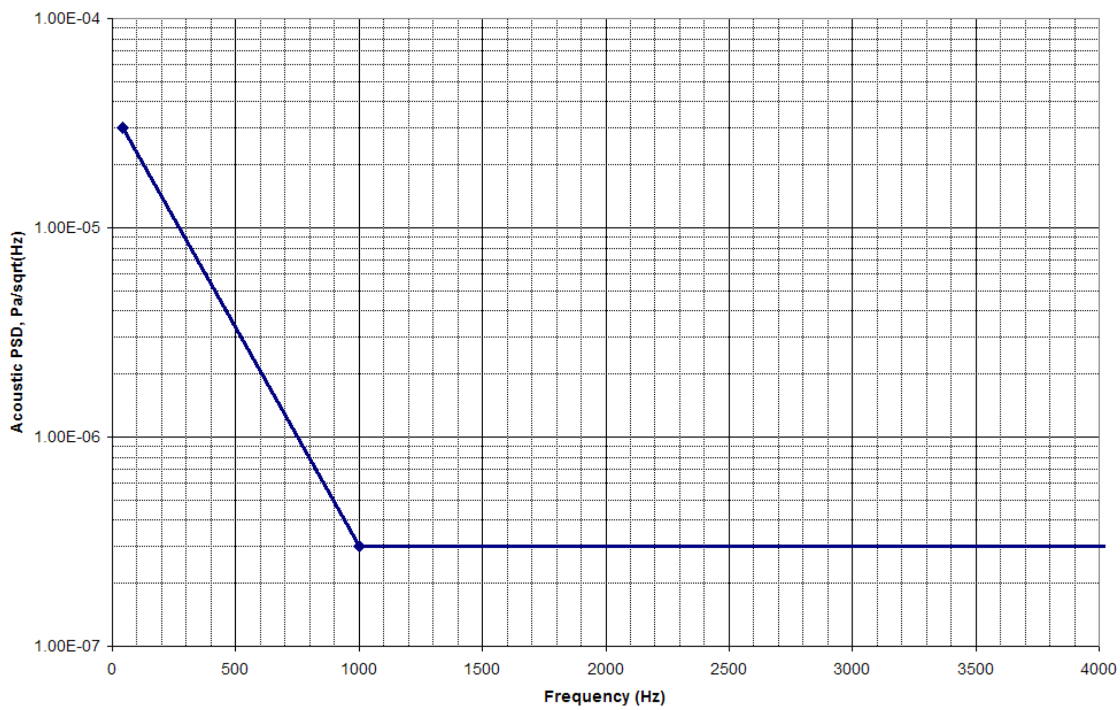
8.1.1 Emission in the LVEA and VEA Areas

Requirement:

Equipment shall be designed to produce the lowest levels of acoustic noise as possible and practical. Electronic cooling fans are not permitted in the LVEA or VEA areas. The acoustic noise level from any one subsystem is limited to the power spectral density shown in the Figure below, i.e.

3×10^{-5} Pa/√Hz at 10 Hz , 3×10^{-7} Pa/√Hz at 1 kHz and above

Figure 2: Acoustic Broadband Noise Limit



Derivation of the Requirement:

Acoustic measurements[3] in the LVEA and VEA for Initial LIGO indicate that a broadband acoustic power spectral density level of 10^{-4} Pa/√Hz, for frequencies > 40 Hz, is marginal (i.e. just adequate) to achieve the Initial LIGO Science Requirements Document (SRD) sensitivity. Given that:

[3] R. Schofield, et. al., S4 Environmental Disturbances, LIGO-G050217-00

- Advanced LIGO is expected to achieve a sensitivity that is a factor of up to 15 better than Initial LIGO and up to a factor of 4 lower in frequency, and
- technical noise sources should be a factor of 10 below the level which compromises the interferometer noise floor

then a simple linear scaling for Advanced LIGO yields a broadband acoustic noise level requirement of 7 x 10^{-7} Pa/√Hz, for frequencies > 10 Hz. However, in Advanced LIGO the sensitive readout optics and electronics are planned to be in vacuum and so not sensitive to acoustic noise levels in the LVEA & VEA areas. There may still be some readout optics in air (and acoustically shielded as is the case for Initial LIGO). Consequently this level is overly conservative.

At LLO where all of the electronics racks (fan noise) were removed from the LVEA, the ambient noise level varies linearly from 10^{-4} Pa/√Hz at 40 Hz to 10^{-6} Pa/√Hz at 1 kHz. Advanced LIGO Detector equipment should not compromise on this building/facility background acoustic level[4]. Since on the order of 10 subsystems can contribute to this overall acoustic noise in a root-sum-squared sense, the acoustic noise limit for each subsystem is set to 1/3 the above facility level.

N.B.: The derivation of acceptable electronic rack acoustic noise specification for Initial LIGO[5] does not apply for advanced LIGO.

8.1.2 Emission in the MSR and CDS Rack Areas

Requirement:

Racks and crates in the CDS Rack Area shall be no noisier than the EMI-tight Dawn crate and Knurr Rack currently used at LLO.TBD.

Derivation of the Requirement:

Some electronics can exhibit microphonic sensitivity. As a consequence the acoustic noise level in the rack areas of the LIGO facility should be held to a reasonable limit. In addition, these areas are not far from optics in the LVEA and VEA areas, which are acoustically sensitive. Measurements[6] after the Science #4 run indicated that at the initial LIGO interferometer sensitivity level, acoustic noise at a level much higher than the (considerable) fan noise associated with the LLO EMI-tight racks and crates, does not present a problem. Since we may use these (or similar) crates (Dawn) and racks (Knurr) for advanced LIGO, we'll assume that the acoustic noise emission from these crates and racks are acceptable, or that they can be made acceptable for advanced LIGO with some added sound dampening to the walls. The acoustic emission levels of the Dawn VME crates[7] are documented in T030075-00.

[4] Note that this level is not precisely the facility/building background level in the LVEA and VEA areas, since Detector electronic racks in the adjacent CDS Rack Room may still be contributing to the ambient acoustic level.

[5] A. Lazzarini, Derivation of CDS Rack Acoustic Noise Specifications, LIGO-T960083-A.

[6] R. Schofield, LLO elog Entry: Acoustics, LVEA Electronics Room, 25 Mar 2005.

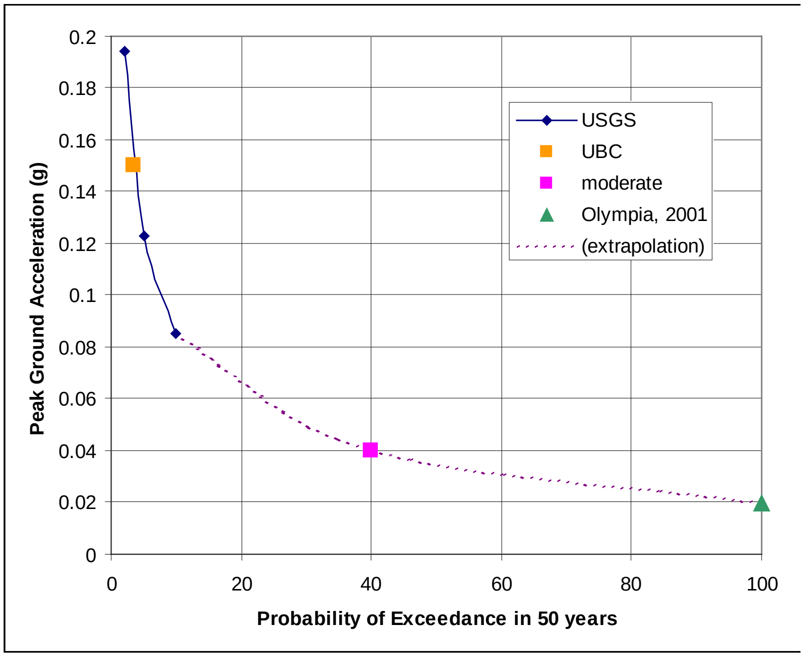
[7] S. Marka, Notes on the Acoustic Emission of VME Crates at LIGO, 25 Apr 2003, LIGO-T030075-00.

8.2 Earthquake Requirements

The LIGO interferometers are subjected to earthquakes of varying magnitudes. The interferometers are subjected to small micro-tremors and low amplitude accelerations, due to distant high magnitude earthquakes, as frequently as daily. Moderate and severe earthquakes are rare events. Requirements are defined in the following sections for three levels of earthquake motion: (i) Severe, (ii) Moderate and (iii) Minor.

A plot of the approximate probability of exceeding a peak ground acceleration (PGA) is shown below. The PGA associated with the severe motion design requirement from the Uniform Building Code (UBC) is 0.15 g and has a probability of exceedance of 3.5% in 50 years. The moderate earthquake PGA level chosen for design criteria is 4% of g and (very roughly) has a probability of ~40% in 50 years (or ~8% in the approximate 10 year lifetime between major detector changes).

Figure 3: Peak Ground Velocity Probability
Values for high Peak Ground Acceleration (PGA) versus the probability of exceedance for Hanford WA are from the USGS[8]. Strong ground motion is much less likely to occur at the LIGO Livingston site. Data was not found in the literature (with a limited time search) on the probability of moderate to low amplitude ground motion (though it seems likely that such data exists). In fact an analysis of the LIGO seismometer data from the Observatories might be able to establish the low to moderate ground motion probabilities. The Olympia, WA 28 Feb 2001 event, which caused extensive "minor" damage to the Initial LIGO Detector and many months of Observatory downtime[9], had a PGA of 2% of g; For the purpose of approximate extrapolation the Olympia event is assumed to be a 1 in 50 year event. The moderate ground motion level for design requirements was set to be 4% and it is guessed that the probability of exceeding this level is about 8% in 10 years. The PGA level associated with the UBC design criteria is also indicated in the plot.



[8] Frankel, Arthur, Mueller, Charles, Barnhard, Theodore, Perkins, David, Leyendecker, E.V., Dickman, Nancy, Hanson, Stanley, and Hopper, Margaret, 1997, Seismic-hazard maps for the conterminous United States, U.S. Geological Survey Open-File Report 97-131-F.

[9] D. Coyne, Earthquake Risk & Recovery: Lessons from the 28 Feb 2001 Olympia, WA Quake, G010208-00

8.2.1 Severe Earthquake Motion: Maintaining Structural & System Integrity

The high magnitude earthquake load requirement imposed on the detector equipment is modeled on the civil construction requirements which were applied to the design of LIGO buildings and derive from the Uniform Building Code (UBC).

8.2.1.1 Failure Levels

Each system, subsystem, assembly and component shall be designed to resist severe earthquake motion (at the magnitude defined in the next section) without "catastrophic damage"; In this context catastrophic damage is defined to be:

- fracture of structural members (exceeding ultimate strength), or
- failure of high value components or assemblies (assemblies or components whose replacement cost exceeds ~$250K each or whose replacement time exceeds 1 year), or
- failure of the integrity of the vacuum system.

Acceptable levels of damage are as follows:

- fracture or yielding (plastic deformation) of components which can be repaired or replaced with a cost of less than ~$250K for each instance and a replacement time (including vacuum and cleanroom operations, preparation staging and procurement activities, installation, alignment and integrated test) of less than 1 year

Examples of unacceptable levels of damage:

- Fracture of a core optic component (COC), for example by failure of it's caging structure which causes the optic to fall
- Failure of the SEI support structure which in turn would (could) lead to failure of the support tube bellows and compromise the vacuum system

Examples of acceptable levels of damage:

- Failure of a suspension fiber/ribbon or wire
- Failure of a bonded magnet/standoff from a suspended mass
- Ear to COC bond failure if the COC is re-usable, or if the probable number of non-re-usable COC is covered by acceptable delivered spares
- Failure of an SEI actuator

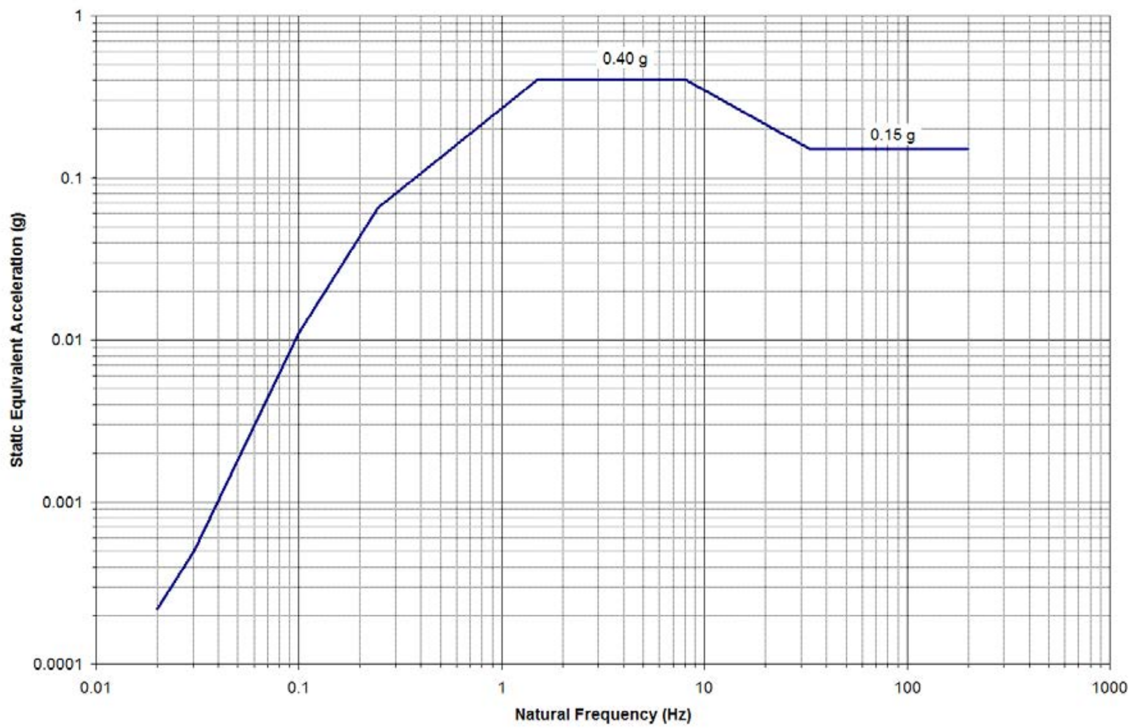
It is the responsibility of each subsystem to perform a failure effects and modes (FEMA) study and to propose the acceptable levels of damage in the event of a high magnitude earthquake. The subsystem should, if appropriate, plan for adequate delivered spares to be consistent with the proposed damage mitigation strategy. Recovery from the damage defined as acceptable above, could take a year or more of observatory downtime.

8.2.1.2 Base Shear

Requirement: All LIGO Detector assemblies must meet the failure criteria defined in section 9.1.1 when subjected to the static-equivalent, horizontal load indicated in Figure 2 as a function of the lowest natural frequency of the structural system that couples to horizontal motion. This load applies to any horizontal direction.

Figure 4: Elastic Design Response Spectrum for Severe Ground Motion

The design response spectra gives the static equivalent load that a structural system, with the indicated first natural frequency, must sustain in terms of the gravitational acceleration, g. The methodology given in A. Chopra[10] was used to develop this elastic design spectrum.



If meeting this requirement is difficult for a particular structural assembly, then assumptions with regard to allowable plasticity and inherent damping may be used to reduce the static equivalent loading (see derivation below) with review and approval. Another alternative to this static equivalent load, is a transient dynamic analysis with a time series realization of a canonical event with the equivalent peak ground motion.

Derivation of the Requirement: The static equivalent base shear (horizontal lateral force), V_b, that the system must survive is defined in the Uniform Building Code (UBC)[11], 1994 edition, as:

$$V_b = \left(\frac{ZIC}{R_W} \right) W$$

where

[10] A. Chopra, Dynamics of Structures: Theory and Applications to Earthquake Engineering, Prentice Hall, 1995, pg. 220-224.

[11] Uniform Building Code (UBC), Vol. 2, 1994. There have been a number of revisions to the UBC culminating in the 1997 version. The UBC is now superceded by the International Building Code (IBC).
Note: Tthe latest International Building Code (IBC) should be reviewed to insure that the strong earthquake base shear load herein is still applicable.

- W = the total dead load
- Z = the seismic zone factor; Z = 0.15 for zone 2B (Hanford,WA; it is zero for Livingston, LA)
- I = the structure importance factor; I = 1 for LIGO detector components
- R_w = the structural system coefficient and accounts for the ductility capacity and inelastic performance of the materials and system. In building wall design Rw might vary from 4 to 12; R_w is 6 for the LIGO buildings. For a completely elastic system, R_w =1. Since the Detector designs are typically stiffness critical designs, and have no detailing for ductile connections, the default for LIGO Detector components should be R_w =1.
- C = elastic seismic coefficient; $C = \frac{1.25S}{T_1^{2/3}} \le 2.75$ The upper limit of 2.75 corresponds to the elastic amplification factor for acceleration for a structure with 5% damping (Q = 20) typical of bolted, welded or riveted construction.
- T1 = fundamental natural vibration period of the structure (sec)
- S = site soil coefficient; S = 1.2 (CHECK!) for the Hanford, WA LIGO site[12]

The UBC does not specify a vertical motion (load) requirement.

For the default assumptions that there is no plastic deformation to absorb the seismic loading (R_w = 1), the first natural frequency is greater than 2.5 Hz, and damping is 5%, then C = 2.75 and the base shear, V_b = 0.4 W, or the static equivalent base shear acceleration is 0.4 g (where g is the gravitational acceleration).

Using the methodology given in A. Chopra to define an elastic design spectrum, with a Z = 0.15 g as the peak ground acceleration, results in Figure 2. The maximum static equivalent acceleration is 0.4 g, consistent with the UBC result above.

8.2.2 Moderate Earthquake Motion: No Damage Threshold

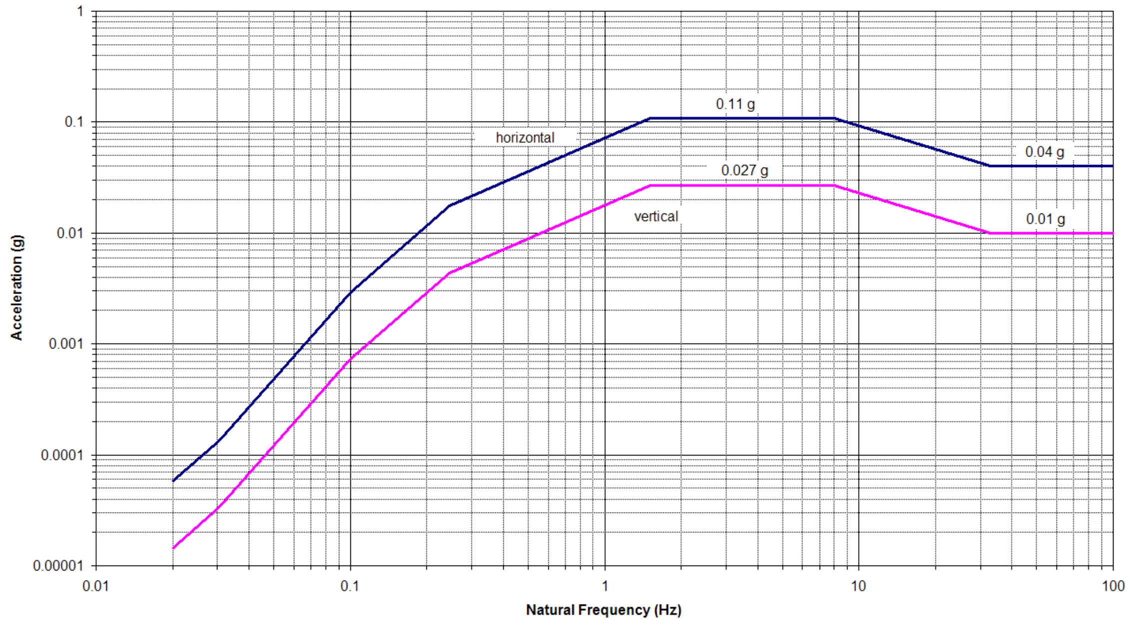
Requirement: No damage should occur to any Detector structural assemblies when subjected to the static-equivalent, horizontal load indicated in Figure 3 as a function of the lowest natural frequency of the structural system that couples to horizontal motion. This load applies to any horizontal direction.

In addition to this horizontal motion, a simultaneous vertical motion equal to ¼ of the horizontal motion must also be sustained without damage.

It is recognized that misalignment of the interferometer optics may occur at this level (without damage) and this is considered acceptable. The expected time to recover interferometer alignment is on the order of 4 months.

Figure 5: Elastic Design Response Spectrum for Moderate Ground Motion
The design response spectra gives the static equivalent load that a structural system, with the indicated first natural frequency, must sustain in terms of the gravitational acceleration, g.

[12] REF Parsons Engineering Report for LIGO



Derivation of the Requirement: More frequent, though still rare, moderate magnitude motion should not cause long term downtime for the observatories. As indicated in the discussion in Section 9.1, we choose to set the no-damage threshold at the ground motion level for which the probability of exceedance in 10 years (the approximate lifetime between major upgrades) is about 8%. Based on available data the corresponding peak ground acceleration (PGA) at this probability level for the Hanford, WA site is about 0.04 g. The methodology in A. Chopra was used to define the elastic design response spectrum consistent with this PGA level which appears in Figure 3.

The USGS and the UBC do not define vertical ground motion for earthquake hazard definition. However, it seems prudent to consider a non-zero vertical acceleration level acting simultaneously with the horizontal acceleration for the purpose of defining the no-damage threshold criteria. Based on the 95 percentile r.m.s velocity values for the Hanford site in the 1-3 Hz band from E. Daw's study[13], the vertical motion might be expected to be about ¼ the magnitude of the horizontal motion. It is recognized that the sources of the ground noise in E. Daw's study is a mixture of anthropogenic and (micro)seismic events and may not apply to the moderate ground motion level under consideration. No source for better data was found in a limited time search.

8.2.3 Minor Ground Motion: Maintaining Operation

All Detector systems must be able to operate through the 95th percentile limits of ground motion defined in P040015-00, Long Term Study of the Seismic Environment at LIGO.

[13] E. Daw, Long Term Study of the Seismic Environment at LIGO, Class. Quantum Grav., 11 Mar 2004, P040015-00

9 Quality Assurance & Testing Requirements

All subsystems must comply with M960076-A, LIGO Project Quality Assurance Plan. This section includes provides some additional guidance regarding Quality Assurance (QA).

See also:

section 3.9, Bolted Joints & Threaded Fasteners

section 4.2, Cabling

section 4.2.4, Commercial Off-The-Shelf (COTS) components

9.1 Commercial Component Testing

High value, or “mission critical” commercial components (such as the seismic isolation system sensors), must all be 100% inspected, tested, and certified to meet their advertised performance and come with calibration and characterization data.

9.2 Machined Parts

By default all machined parts are 100% dimensionally checked by the fabricator's QC department. For large procurements we require a QA plan. For smaller shops, less critical parts we still require dimensional inspection, though not always 100% but limited to key dimensions. We inspect their facilities for QC capabilities and practices.

All variances must be submitted to LIGO Lab for review. If the variance is not approved the part must be re-machined.

All parts are supplied with material certifications, heat treat certifications (if appropriate) and at least a general statement of compliance to our drawings (dimensional) and our process specification (if appropriate). Usually a complete dimensional inspection report is required.

9.3 Fit Check

Every item shall be fit checked (or at least dimensionally checked) to the extent practical in assembly tests before delivery to the installation effort.

9.4 Assembly

Assembly tooling and procedures shall be developed, and documented, for each subsystem and tested prior to delivery of first article and production hardware. The delivery of special assembly tooling is the responsibility of each subsystem. Each subsystem is also responsible for coordinating facility or infrastructure support requirements (including standard lab tool needs and space) with the Facilities Modification and Preparation (FMP) subsystem leads (for AdL), or the relevant Observatory staff for non-AdL activities.

9.5 Function

Functional tests must be performed for every assembly or subsystem.

9.6 Performance

Performance of the delivered assembly or subsystem can either be:

- tested (if/as practical) on each unit (preferred method), or
- assured by similarity to a prototype system, if all components have been separately tested against their performance requirements, or
- assured by analysis (if appropriate and only with the approval of the Systems Engineer)

9.7 Self-Test

The provision for health/status monitoring and self-test or diagnosis is encouraged for all complex subsystems.

9.8 Acceptance Test

Acceptance testing of the articles (components, assemblies, subsystems, etc.) delivered by the subsystems to the installation and commissioning effort, must first pass acceptance testing. The procedures for acceptance testing, and the acceptance criteria, must be documented, reviewed and approved. The quantitative results of the acceptance testing and characterization must also be documented.

9.9 Quality conformance inspections

Design and performance requirements identified in the subsystem requirements document shall be verified by inspection, analysis, demonstration, similarity, test, or a combination thereof, as defined in T950065-A, Guidelines for Design Requirement Documents. Verification method selection shall be specified by individual specifications, and documented by appropriate test and evaluation plans and procedures.

10 Reliability

A revised reliability plan is pending (E960099-B is the published LIGO reliability plan; however see note in section 1.4.9). In the interim, the following guidance is given.

10.1 Reliability Requirements

Each subsystem shall derive requirements on the reliability of their subsystems from system level imposed availability requirements (TBD). These derived requirements shall further be compared to the expected reliability of the subsystem designs by assessing the reliability of the components which are likely to limit availability of the subsystem. A complete failure effects and modes analysis (FEMA) is not required, as long as simple bounding analyses indicate that the required subsystem availability is adequate. Emphasis should of course be placed on active components and especially active components in the vacuum system (due to the long mean-to-to-repair (MTTR)).

10.2 Reliability Testing

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

10.3 FEMA

A Failure Effects and Modes Analysis (FEMA) is required from every subsystem with active components in the vacuum system, or which act upon systems in the vacuum system. For subsystems, comprised of multiple, non-interacting systems or assemblies, separate FEMAs on each system or assembly may be more suitable. The FEMA will then serve as the basis for a qualitative assessment of the unlikelihood of failure scenarios and decisions on pro-active measures to prevent, or recover quickly from, the failure mode.

11 Maintainability & Reparability

Consideration must be given in the design to allow for access to maintain and repair the installed components, assemblies and systems. This is a particularly important point for in-vacuum equipment.

12 Safety

All subsystems must comply with M950046-D, LIGO Laboratory System Safety Plan, as well as all relevant Observatory/site safety plans and procedures (see section 1.4.10). In particular hazard analyses are required for all procedures for which there are risks to personnel or equipment.