

# LIGO VACUUM EQUIPMENT FINAL DESIGN REPORT

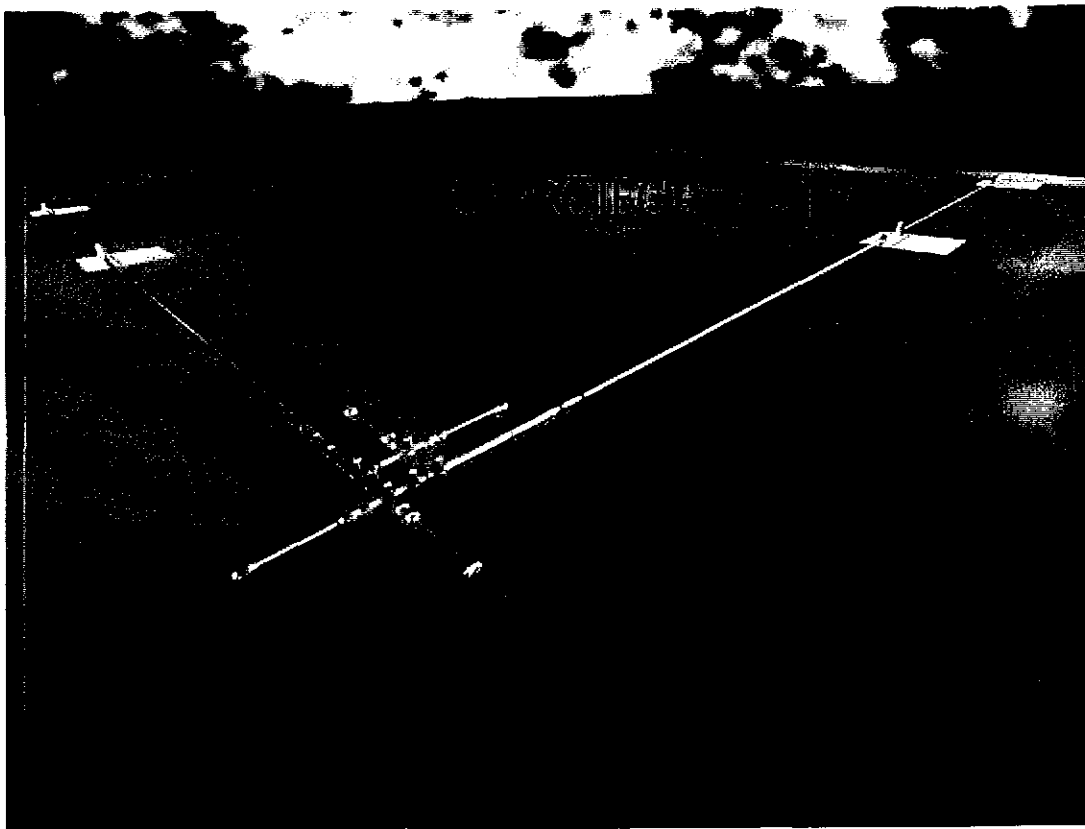
## VOLUME II DESIGN

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CDRL NO: 03

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CALIFORNIA INSTITUTE OF TECHNOLOGY  
MASSACHUSETTS INSTITUTE OF TECHNOLOGY



**LIGO PROJECT**

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**LIGO VACUUM EQUIPMENT  
FINAL DESIGN REPORT  
VOLUME II DESIGN**

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**LIGO PHASE B  
FINAL DESIGN  
CDRL 03**

**TABLE OF CONTENTS**

**Volume II**

**Vacuum Equipment Design**

**SECTION**

**1.0 SYSTEM DESIGN SUMMARY**

- 1.1 Key Design Decisions
- 1.2 FDR Action List
- 1.3 Design Requirements
- 1.4 Design Verification
- 1.5 Project Q.A. Plan
- 1.6 Safety and Reliability
- 1.7 Status of Bench Scale Qualification Testing
- 1.8 Codes and Standards

**2.0 VACUUM PERFORMANCE**

- 2.1 Leak Rate
- 2.2 Outgassing and Ultimate Pressures
- 2.3 Pumpdown
- 2.4 Bakeout Capability

**3.0 DESIGN**

**3.1 Station Design**

- 3.1.1 Equipment Arrangement
  - 3.1.1.1 WA Corner Station
  - 3.1.1.2 WA Mid Station
  - 3.1.1.3 WA & LA End Station
- 3.1.2 Utilities
  - 3.1.2.1 Electrical Power
  - 3.1.2.2 Cooling Water
  - 3.1.2.3 Instrument Air
- 3.1.3 Interfaces to Buildings and Utilities
  - 3.1.3.1 Electrical
  - 3.1.3.2 Mechanical
- 3.1.4 Interfaces to Process Control System
  - 3.1.4.1 WA Corner Station
  - 3.1.4.2 WA Mid Station
  - 3.1.4.3 WA End Station

## **3.2 Vacuum Enclosure**

### **3.2.1 Design**

- 3.2.1.1 Beam Splitter Chamber
- 3.2.1.2 Horizontal Access Module
- 3.2.1.3 Beam Tube Manifolds
- 3.2.1.4 Mode Cleaner Tubes
- 3.2.1.5 80 K Cryopumps
- 3.2.1.6 Common Items
  - 3.2.1.6.1 Materials
  - 3.2.1.6.2 Cleaning
  - 3.2.1.6.3 Welding
  - 3.2.1.6.4 Alignment and Dimensions
  - 3.2.1.6.5 Mechanical Loads
  - 3.2.1.6.6 Flanges and Ports
  - 3.2.1.6.7 Flange Annuli
  - 3.2.1.6.8 Access Connectors
  - 3.2.1.6.9 Fasteners
  - 3.2.1.6.10 Bellows

## **3.3 Pumps**

- 3.3.1 Main Roughing System
- 3.3.2 Main Turbomolecular Pump System
- 3.3.3 Auxiliary Turbomolecular Pump System
- 3.3.4 Main Ion Pumps
- 3.3.5 Annulus Ion Pumps
- 3.3.6 80 K Pumps

## **3.4 Valves**

- 3.4.1 Large Gate Valves
- 3.4.3 Small Valves

## **3.5 Vent and Purge System**

- 3.5.1 Clean Air Supply
- 3.5.2 Portable Softwall Cleanrooms/Systems

## **3.6 Bakeout/Heating System**

- 3.6.1 Bakeout Blankets
- 3.6.2 Bakeout Control System

### **3.7 Monitor and Control System**

- 3.7.1 Vacuum Gauging
- 3.7.2 Other Instruments
- 3.7.3 Cabinets
- 3.7.4 Interlocks
- 3.7.5 Required Controls by Others

## **4.0 SHOCK, VIBRATION AND ACOUSTICS**

- 4.1 Shock
- 4.2 Vibration
- 4.3 Acoustics
- 4.4 Technical Approach to Shock, Vibration and Acoustics/Risk Mitigation
- 4.5 Source Measurement and Transmission Analysis

## **ATTACHMENTS**

### **Attachment 1**

#### **Calculations**

Structural Design Criteria

BSC's - Structural

General - Structural

HAM - Structural

### **Attachment 2**

#### **Calculations**

80K Cryopump - Structural

Adapters and Spools - Structural

### **Attachment 3**

#### **Calculations**

Adapters and Spools - Structural

### **Attachment 4**

#### **Calculations**

Vacuum and Process Calculations

Safety and Reliability Analysis

### **Attachment 5**

#### **Specifications/Miscellaneous**

Shock, Vibrations and Acoustics

Design Goals/Requirements

Specifications

# FINAL DESIGN REPORT

## VOLUME II DESIGN

### 1.0 SYSTEM DESIGN SUMMARY

The purpose of this Final Design Report is to document and validate the PSI design of the LIGO Vacuum Equipment. The criterion for system design throughout this effort has been to assure that the LIGO Vacuum Equipment achieves the required level of vacuum performance as defined in the LIGO/PSI contract. As you read through this Final Design Report, you will note that PSI's understanding of the design philosophy presented in LIGO specification No. E940002-02-V and subsequent addenda, is accurately and efficiently reflected in the detailed design.

The following points are addressed in this report:

- Key Design Decisions
- PDR Action Item Resolution
- LIGO Requirements vs. PSI Design
- Design verification through testing and/or analysis (ISO-9001 approach)
- Project Quality Assurance Program
- Safety and Reliability

The scope of the attached drawing package is limited to the Washington site design. The Louisiana drawing package will be completed upon approval of the Washington design and the issuing of the Louisiana building drawings.

## 1.1

### Key Design Decisions

Throughout the execution of the proposal, preliminary design, and the final design process, PSI has made a number of key decisions to manage technical risk and optimize system performance. These decisions are summarized below along with the basis for the decision.

<b>Key Decision</b>	<b>Issue</b>	<b>Justification</b>
1. Double Viton O-rings	Vacuum performance	<ul style="list-style-type: none"><li>• Metal O-rings present an unacceptable risk, since potential vendors will not guarantee performance.</li><li>• Metal O-rings of the size required for LIGO have not been used in UHV service.</li><li>• Gasket seating loads for metal O-rings are not well understood. Very high seating loads are required resulting in very thick flanges with many bolts.</li><li>• Viton O-rings with a pumped annulus can provide predictable vacuum performance. Gas loads from permeation and outgassing can be predicted with confidence.</li></ul>
2. Place all roughing equipment in mechanical room	Noise and vibration	<ul style="list-style-type: none"><li>• Moves a major source of noise and vibration on a separate foundation away from the optics.</li></ul>
3. Investigate cleaning methods	Vacuum performance	<ul style="list-style-type: none"><li>• Identification of suitable detergents.</li><li>• Develop cleaning protocol.</li><li>• Define washing equipment requirements.</li></ul>
4. Prototype vessel	Design verification	<ul style="list-style-type: none"><li>• Verify flange design.</li><li>• Verify manufacturing methods.</li><li>• Verify stress relieving effectiveness.</li><li>• Measure cryopump vibration.</li></ul>



5. Bench scale prototype	Early verification of design data	<ul style="list-style-type: none"> <li>• Verify effectiveness of cleaning techniques by measuring outgassing rates from the metal.</li> <li>• Verify that stress relieving protocol does not adversely affect H<sub>2</sub> outgassing.</li> <li>• Verify O-ring outgassing and permeation rates.</li> <li>• Verify O-ring bakeout protocol.</li> <li>• Verify O-ring groove design.</li> <li>• Verify O-ring manufacturing method.</li> </ul>
6. Noise & vibration testing program	Design data for vibration model	<ul style="list-style-type: none"> <li>• Provide realistic source data to improve confidence level in vibration models.</li> </ul>
7. Oversized vessel nozzles	Alignment	<ul style="list-style-type: none"> <li>• 60" nozzles are oversized to accommodate manufacturing tolerances.</li> </ul>
8. Alignment slots	Alignment	<ul style="list-style-type: none"> <li>• Slots have been added to flange bolt holes between fixed sections to allow for some angular misalignment.</li> </ul>
9. Plasma welding	Alignment	<ul style="list-style-type: none"> <li>• Reduction in weld distortion by reduced heating of weld joint.</li> </ul>

## 1.2 Action Item Resolution List

There were two sets of action items resulting from the PDR Update meeting.

- A list of 12 action items of which 9 were assigned to PSI and which are addressed in this section.
- A second list of 22 items from TDM 03 related specifically to the text of the PDR. These items have been previously addressed and have been included in the final version of the PDR Update, CDRL 01, and are therefore not discussed here.

Table 1.2 summarizes the resolution of the nine action items assigned to PSI from the PDR Update meeting.

**TABLE 1.2**

<b>Action Item</b>	<b>Issue</b>	<b>Resolution</b>
1. Foreign Materials	LIGO QA suggested that materials from foreign sources require independent lab analysis of the material properties.	This item is included in the QA Plan V049-2-029.
3. Water Outgassing Rate	The water outgassing rate at 10 minutes of $2 \times 10^{-8}$ Tl/sec $\text{cm}^2$ may be optimistic. What is the impact of 10x higher on the pumpdown?	All of the pumpdown calculations have been updated for the FDR and are included in Attachment 4. The outgassing rate at the end of the 100 hour pumpdown is considered to be more important than the 10 minute rate. The design values used after 100 hours of pumping are: <ul style="list-style-type: none"><li>• Viton: <math>3 \times 10^{-9}</math> torr-l/s-<math>\text{cm}^2</math> for 0.5 hour reexposure to air.</li><li>• Stainless: <math>5 \times 10^{-11}</math> torr-l/s-<math>\text{cm}^2</math></li></ul>
5. Low Emissivity Liner	PSI was requested to check the calculations of the low e liner by an independent means.	The liner calculations were confirmed by an independent model. These calculations can be found in Attachment 4.
6. Electric Gate Valves	PSI was requested to consider using electric actuators on all of the large gate valves.	The definition of the size and type of gate valves was determined by LIGO and provided to PSI by TIM 9.

- |                                     |   |   |
|-------------------------------------|---|---|
| 7. Ion Pump<br>Vibration            | It was suggested that the analysis of potential vibration sources include the ion pumps. The unregulated power supplies used in most ion pumps might couple 60 Hz or multiples thereof into the ion pump structure.                   | Ion pump vibration will be measured as part of vibration source data collection included in CAA scope of work.  |
| 8. Post Weld<br>Stress Relief       | It has been suggested that the furnace treatment can have a positive or negative impact on the vessel outgassing. (Positive if done in a clean environment, potentially negative, if hydrocarbons are baked onto the vessel surface.) | Steam cleaning prior to stress relief and control of the furnace to provide excess O <sub>2</sub> is included in the stress relief procedure, V049-2-046 which is included in Volume III Fabrication.<br><br>The verification of the post weld stress relief process is included in the bench scale prototype and BSC prototype testing programs.   |
| 9. CH <sub>4</sub> Pumping<br>Speed | CH <sub>4</sub> Pumping speed data in ion pumps was requested. Why is the CH <sub>4</sub> speed greater than air.   | The pumping speed of CH <sub>4</sub> has been confirmed to be greater than the pumping speed of N <sub>2</sub> by Varian, the supplier of the ion pumps. The reason for the high pumping speed is the methane molecule is cracked and transformed into smaller compounds such as C, CH <sub>3</sub> ,...H. The lighter compounds always have a higher pumping speed than N <sub>2</sub> . |

**10. QA Audit Points**

LIGO requested definition of suggested QA audit points of PSI and PSI subcontractors.

This item is included in the following documents.

- QA Plan V049-2-029 Sections 4.3.2- Vendor Surveillance and 4.10.2-QA requirements.
- BSC Procurement Plan V049-2-080.
- HAM Procurement Plan V049-2-081.

**11. All Metal Foil**

Investigate all metal aluminum foil as insulation on 80 K cryopumps

As part of the engineering analysis it was determined that the heat load contribution from the ambient temperature walls is a relatively small portion of the total heat load. Additional shielding would provide only marginal benefit (app 2 %) and makes the assembly of the vessel more difficult.

## **1.3 Design Requirements**

### **1. ISO-9001 Approach**

The LIGO system will be designed, fabricated and installed using ISO-9001 type philosophies including design input verification, design review, independent analysis, etc.

### **2. Designs Goals**

Each component or subsystem has been reviewed for compliance to the specification via a "Design Goals/Requirements Form". The specification requirements are listed along with a specific method meeting the requirements, and identifies the engineer responsible to complete any action items. This document is a working document that is updated and revised at each design review. The Design Goals are detailed in Volume II, Attachment 5.

### **3. Equipment Specifications**

Equipment specifications are generated for each major component. These specifications are reviewed against the project specification for compliance using the Design Goals/ Requirements Form.

### **4. Design Reviews**

Each major component or subsystem undergo internal design reviews, where the cognizant engineer and other members of the design team review the design for technical feasibility, specification compliance, safety, and operability.

## **1.4 Design Verification**

### **1. Analyses**

Design verification is provided by analysis where applicable by codes and standards or where adequate methods exist. All analyses are checked independently. Analyses necessary to support the design are included in the attachments. Analyses are organized as follows:

- Attachment 1, 2, 3 - Structural
- Attachment 4 - Vacuum and Process
  - - Safety and Reliability
- Attachment 5 - Shock, Vibration, and Acoustics
  - - Design Goals/Requirements Specifications

Where insufficient data exists to depend on analyses alone, additional testing has been or will be undertaken to provide the necessary supporting data. Examples in this category include:

- Outgassing from metal and elastomers
- O-ring permeation
- Gate valve shock
- Source vibration from turbopumps, ion pumps, and cryopumps
- Flange design under internal pressure

### **2. Bench Scale Testing**

- PSI has continued the cleaning evaluation program initiated during the Preliminary Design. A washing station has been constructed that allows testing of various cleaning agents.
- A Bench Scale prototype has been constructed and is being used for qualification testing of welding techniques, cleaning methods, outgassing rates, O-ring performance and baking protocol, clean room assembly methods, and leak detection methods.
- A test setup was constructed and vibration characteristics of two phase flow simulating the flow regime entering the 80K cryopumps were measured.
- The O-ring sealing under tension loading will be verified by pressure testing a flange with the same geometry as the full scale design.

### **3. Prototype Testing**

A prototype BSC is being constructed. This unit will provide full scale verification of the fabrication methods including, welding procedures, fixturing, stress relieving, and cleaning. The BSC prototype will also provide a test vehicle for 80 K cryopump vibration testing.

### **4. First Article Fabrication Approach**

The LIGO vessel designs and procedures will be validated on one unit before the entire order is released for fabrication. A HAM first article will be constructed prior to release of the production lot. As with the BSC prototype, confirmation of the fabrication methods will be verified.

## **1.5 Project Quality Assurance Program**

The overall project quality assurance strategy is detailed in V049-2-029 "Project Q.A. Plan".

Project Quality Assurance begins with understanding the contract requirements and ends with accurately recording performance data. In between the Quality Assurance program forms the backbone of a strategic risk management plan.

Timely reviews of engineering, design, procurement, vendor performance greatly increase the probability of a successful project. PSI has adopted this philosophy in its execution of design engineering and throughout the entire project.

PSI Q.A. program includes the following:

- ISO-9001 Design Approach
- Component Design Reviews
- Station Design Reviews
- Vendor Q.A. Requirements
- Vendor Audits
- Vendor Inprocess and Final Inspection
- Vendor Performance Tests

## **1.6 Safety and Reliability**

PSI has generated a Hazards Analysis as required by the Statement of Work and detailed in the LIGO System Safety Plan. The major types of equipment and operations were analyzed with respect to hazards that result in injury to personnel, or damage to equipment or the environment. A Failure Modes, Effects, and Criticality Analysis has also been performed.

The complete Preliminary Hazards Analysis, Document V049-2-093 and the associated Failure Modes, Effects, and Criticality Analysis, Document V049-2-094 can be found in Volume II, Attachment 4.

## **1.7 Status of Bench Scale Qualification Testing**

As part of the design qualification, several test programs have been initiated. Interim test results are discussed below.

### **1. Cleaning**

A number of detergents have been tested for effectiveness by measuring surface contamination by XPS analysis. A detergent was selected for use on the 10" Bench Scale prototype vessel based on a number of factors including ease of disposal. Conclusions reached to date are:

- The first choice detergent (217 pressure wash) although not the most effective cleaner is adequate based on the outgassing results obtained on the 10" vessel.
- The most effective detergent based on multiple sets of tests is KOH (DET-O-Jet) which has consistently shown lower levels of carbon and higher levels of oxygen.
- As expected none of the pressure washed samples have been able to duplicate the cleanliness of the best results achieved during phase 1 testing. We believe that this difference is attributable to the washing method. The phase 1 samples were cleaned in ultrasonic baths which are impractical for this application because of the equipment size.



## 2. Bench Scale Vessel

The first set of vacuum tests have been completed on the 10" Bench Scale vessel. These tests were made on a vessel that has a mill finish, was detergent cleaned with a pressure wash, and was not stress relieved. The purpose of this testing was to establish baseline outgassing rates after a 48 hour bake at 150C.

Although the data has not been totally reduced preliminary indications suggest that the outgassing rates for H<sub>2</sub>, H<sub>2</sub>O, CO, CO<sub>2</sub>, and CH<sub>4</sub> are about as expected. Based on RGA measurements using a Faraday cup detector, outgassing rates are as follows:

Species	Outgassing Rate torr-l/s-cm <sup>2</sup>
H <sub>2</sub>	10 <sup>-11</sup>
H <sub>2</sub> O	10 <sup>-12</sup>
CO	<10 <sup>-12</sup>
CO <sub>2</sub>	<10 <sup>-12</sup>
CH <sub>4</sub>	<10 <sup>-12</sup>

The second test vessel which has been made from the same lot of material, but has been stress relieved at 550C in a natural gas fired furnace in accordance with the planned stress relieving procedure is being assembled for bakeout as this report is being written. Data is expected by the FDR.

The first vessel is being converted to test Viton outgassing. Data is also expected to be available by the FDR.

## 1.8 Codes and Standards

The following standards are incorporated as applicable. Requirements as set forth in the specification have final precedence.

1. **American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code**
  - Materials, Section II
  - Pressure Vessels, Section VIII, Division 1 and 2.
  - Welding and Brazing Qualifications, Section IX.
2. **American Society for Testing and Materials**
  - ASTM E498-Standard Test Methods for leaks using the Mass Spectrometer Leak Detector.
3. **Handbook of Acoustical Measurements and Noise Control**
  - Chapter 43, Noise Criteria for Heating, Ventilation, and Air Conditioning Systems.
4. **International Standards Organization**
  - ISO Standard 2861-Flange Standards.
5. **American Society of Civil Engineers**
  - Minimum Design Loads for Buildings and Other Structures, ASCE 7-88
6. **Expansion Joint Manufacturer's Association (EJMA)**
  - Standards for Expansion Joint Manufacturer's Association.
7. **National Fire Protection Association (NFPA) Standards**
  - No. 70-National Electrical Code.
8. **Government Standards**
  - Federal Standard 209 for clean rooms.
9. **American Institute of Steel Construction**
  - Manual of Steel Construction, Allowable Stress Design, Ninth Edition

## 2.0 VACUUM PERFORMANCE

### 2.1 Leak Rate

Specification Section 4.1 requires leaks greater than  $1 \times 10^{-9}$  torr-l/s of helium to be repaired. To demonstrate leak integrity of any individual chamber or tube section, the total leak will be measured per ASTM E498, to be less than  $1 \times 10^{-9}$  torr-l/s of helium at PSI.

Specification Paragraph 5.1.14 requires that leaks on each chamber or tube section be repaired at the site of manufacture. Leak checking will be performed in stages prior to shipment from the factory. A preliminary leak check will be done prior to final cleaning. Since leaks can develop in apparently tight systems following a bake [Welch, 1994, LEP Group, 1990]. PSI will conduct the final shop leak test on each chamber and tube section after it has been baked at 150C for several days.

Each vacuum enclosure will be delivered to the field site as a clean and dry unit under vacuum. Valves attached to the chamber at the plant will allow a check of the vacuum level and a leak check prior to opening the chamber to confirm that no shipping damage has occurred.

As each vacuum enclosure is installed, the O-ring annulus of each adjacent section will be pumped to operating pressure to provide a qualitative indication of O-ring joint integrity.

The objective of these procedures is to do as much work as possible prior to the final assembly so that potential leaks in each isolatable volume are minimized. This will significantly reduce costs, schedules, and risks of overruns and delays.

A baked vacuum section can have its air leak rate directly measured by a Residual Gas Analyzer (RGA). The air signature amplitudes are compared with those from a calibrated air leak. The bakeout will eliminate or greatly reduce the level of CO and other gases etc. which can interfere with this direct measurement in unbaked systems. This RGA measurement is especially helpful when testing a complex section with many chambers. Definite knowledge that a leak exists, and the size of the leak, has a remarkable effect on the efficiency of the search for leaks. PSI plans that the total leak rate of each vacuum section be initially measured with an RGA. If no leak is detected with the air signature, then the section meets the leak requirement. Otherwise a search with a helium leak detector is initiated.

The bakeout in the shop will be done using the heater blankets developed for requirement of Specification Section 4.5; and that the LIGO main turbomolecular pumps (TMP), and auxiliary TMP's be used in the shop as far as practical. Any wear on the equipment would be far outweighed by the operating experience gained in its use.

Leak testing a chamber sealed with double O-rings requires three separate measurements: the leak from atmosphere to annulus, that from within the chamber to annulus, and that from atmosphere directly into the chamber. Permeation of helium through the Viton seals will occur in a few minutes, so all three measurements must be completed quickly.

Detailed leak test plans are included as attachments to Volume II (Fabrication) and Volume IV (Installation) and are integrated with the plans for cleaning, baking, and outgassing measurements.

## **2.2 Outgassing Rates And Ultimate Pressures**

### **2.2.1 Water & Surface Desorption**

The vacuum envelope will be baked at 150C to drive off surface contaminants and to potentially reduce the concentration of hydrogen in the steel.

Since the surfaces are exposed to air after the bake-out process, the surface will reabsorb water. The outgassing rates obtained when the volume is re-evacuated will vary depending on the time of exposure and the dewpoint of the air.

For design purposes the outgassing rates for water after 100 hours of pumping are:

Viton:  $3 \times 10^{-9}$  torr-l/s-cm<sup>2</sup> for 0.5 hour re-exposure to ambient air

Stainless:  $5 \times 10^{-11}$  torr-l/s-cm<sup>2</sup>

The basis of selection of the outgassing rates are discussed in detail in the "Pumpdown and Ultimate Pressure Analysis" V049-1-078 which is included in Attachment 4.

### 2.2.2 Hydrogen Outgassing

Since the vessel wall is baked at low temperature (150C), hydrogen outgassing rates will remain essentially as manufactured. Rates as high as  $5 \times 10^{-10}$  torr-l/s-cm<sup>2</sup> have been reported, and as low as and lower than,  $2 \times 10^{-12}$  torr-L/s-cm<sup>2</sup> (VIRGO - Final Design). Since these rates are dictated by the diffusion and/or recombination of atomic hydrogen from the bulk of the metal vessel wall which is at room temperature, the hydrogen outgassing rates will be almost unchanged over the 100 hours of pumpdown and will change less than one decade over many years (see Santeler). There are several independent sources of outgassing data that suggest that ordinary 304L stainless will have outgassing rates of less than  $1 \times 10^{-11}$  torr-l/s-cm<sup>2</sup>. Santeler reports a 200 hour bakeout time at 150C to obtain an outgassing rate of  $2 \times 10^{-11}$  torr-l/s-cm<sup>2</sup> and at 250C to obtain an outgassing rate of  $2 \times 10^{-12}$  torr-l/s-cm<sup>2</sup> for hydrogen. VAT valve reports achieving outgassing rates of  $2 \times 10^{-13}$  mbar - l/Scm<sup>2</sup> after baking for 24 hours at 150C. The VIRGO Final Design reports hydrogen outgassing rates of  $2-3 \times 10^{-12}$  mbar-l/s-cm<sup>2</sup> after baking at 150C for one week.

For design purposes a H<sub>2</sub> outgassing rate of  $1 \times 10^{-11}$  torr-l/s-cm<sup>2</sup> was used.

For the design outgassing rate of  $1 \times 10^{-11}$  torr-L/s-cm<sup>2</sup>, a surface area of 814 m<sup>2</sup> in the corner station and 20,000 l/s of ion pump speed, the achievable partial pressure of hydrogen will be about  $4 \times 10^{-9}$  torr.

There will be three near term opportunities to verify the water and H<sub>2</sub> outgassing rates; the bench scale prototype, the BSC prototype, and the HAM first article. The HAM first article will provide the best data since it will be fabricated from the same material as the early production chambers.

### 2.2.3 Leakage

#### **Corner Station**

Assuming that the leakage and diffusion from a single chamber with its adjacent tube or chamber interconnecting flange joint is  $1 \times 10^{-9}$  torr-l/s each and that there are 100 joints per isolatable volume, then the total leakage will be  $1 \times 10^{-7}$  torr-l/s. The required pumping speed to hold  $1 \times 10^{-9}$  torr will be about 100 l/s, which corresponds to about 1% of the ion pumping capacity in the section. This value is conservative since the leakage should be better than  $1 \times 10^{-9}$  torr-l/s per joint.

#### **End And Mid Stations**

Assuming that the leakage and diffusion from a single chamber with its interconnecting flange joint to an adjacent tube or chamber is  $1 \times 10^{-9}$  torr-l/s each and that there are 25 joints, the total leakage will be  $0.25 \times 10^{-7}$  torr-l/s. The required pumping speed to hold  $1 \times 10^{-9}$  torr will be about 25 l/s, which also corresponds to about 1% of the ion pumping capacity in each station.

#### 2.2.4 Ultimate Pressures

To achieve a partial pressure of  $5 \times 10^{-9}$  torr for hydrogen, the outgassing rate for hydrogen must be less than  $1 \times 10^{-11}$  torr-l/s-cm<sup>2</sup> with the available ion pump capacity. Since the outgassing rate for hydrogen will not decay very quickly the achievable ultimate partial pressure can be predicted by measuring the hydrogen outgassing rate after the bakeout process.

Depending on initial conditions for water content on the vessel-wall surface, it may not be possible to meet the partial pressure of  $5 \times 10^{-9}$  torr for water after 100 hours of pump down. However, if the partial pressure of water is only several times larger than the required partial pressure, then the desired partial pressure may be reached in a reasonable amount of time because of the quick decay of the outgassing rate for water. If the partial pressure is an order of magnitude higher, a low temperature bake out may need to be repeated.

It is difficult to predict the exact partial pressure of species other than water and hydrogen after 100 hours of pumpdown. Various investigators have measured the partial pressures of the other species after a bake out or after a pumpdown (see Dylla et al. and Moraw and Dobrozemsky). Surface outgassing rates of other species were estimated from Dylla's pumpdown measurements for partial pressures of other species after 100 minutes of pumping. A  $1/t$  decay behavior was used for the surface outgassing rates of the other species in the pumpdown calculations.

Maximum partial pressure goals for each isolatable volume from Specification section 4.3:

Gas Species	Partial Pressure (Torr)	Comments
H <sub>2</sub> O	$5 \times 10^{-9}$	Varies depending on air purge conditions and bakeout
H <sub>2</sub>	$5 \times 10^{-9}$	Depends on H <sub>2</sub> content of stainless steel as manufactured
N <sub>2</sub>	$5 \times 10^{-10}$	Vary depending on cleaning and bakeout
CO	$5 \times 10^{-10}$	Vary depending on cleaning and bakeout
CO <sub>2</sub>	$2 \times 10^{-10}$	Vary depending on cleaning and bakeout
CH <sub>4</sub>	$2 \times 10^{-10}$	Vary depending on cleaning and bakeout
Others	$5 \times 10^{-10}$	Vary depending on cleaning and bakeout



### **Partial Pressure Measurement**

Partial pressure of the various species will be measured at the Ion pumps. With the outgassing rate dominated by water a pressure gradient for water will establish itself along the beam manifold since the cryopump is located at the far end. The partial pressure of water will vary by approximately one order of magnitude throughout the isolatable section. Partial pressure for water could be measured at two locations, one near the cryopump and another at the other end of the isolatable section. Pumpdown curves are based on the partial pressure of water near the cryopump.

### **Cryopumping Of Carbon Dioxide**

The vapor pressure of CO<sub>2</sub> at 80K is about 10<sup>-7</sup> torr. CO<sub>2</sub> will be cryopumped onto the 80K pump surface during pumpdown if a lot of CO<sub>2</sub> is present and will re-evaporate when the pressure drops below 10<sup>-7</sup> torr, thus becoming an outgassing source in the UHV range. To minimize this effect the startup of the cryopump is delayed until the pressure is less than 1x10<sup>-5</sup> torr.

## **2.3 Pumpdown**

### **2.3.1 Pumpdown From 760 Torr to 0.1 Torr**

To obtain a total roughing time of less than four hours for crossover to Turbo molecular pumping, the capacity of the roughing pump must average about 100 l/s. The main roughing pump package which is comprised of a roots blower with hydrokinetic drive, backed by a multistage dry pump, provides a pumpdown from atmosphere to  $10^{-2}$  torr of approximately 2 hours for the largest isolatable volume.

### **2.3.2 Pumpdown From 0.1 Torr to $10^{-6}$ Torr**

For a clean, dry system, the 1000 l/s net pumping speed at the chamber provided by a single TMP, is adequate for pumpdown of the isolatable section in 24 hours. If moisture is present in the chamber because of improper cleaning, bake out, or purging with less dry air; then either a second TMP connected at the roughing port or, operation of the 80K cryopump may be necessary in order to lower the pressure below  $10^{-5}$  torr.

### **2.3.3 Pumpdown From $10^{-6}$ Torr to $10^{-9}$ Torr**

Using the 80K cryopump and Ion pumps, reaching the desired ultimate partial pressures within 100 hours of pumping will be dictated by the outgassing rates and is dependent on proper cleaning and bakeout of the surfaces. To achieve the required partial pressures the outgassing rate for water, after 100 hours, needs to be about  $5 \times 10^{-11}$  torr-l/s-cm<sup>2</sup>. The outgassing rate for hydrogen needs to be about  $1 \times 10^{-11}$  torr-l/s-cm<sup>2</sup>, and the total outgassing rate for the other gasses needs to be about  $1 \times 10^{-12}$  torr-l/s-cm<sup>2</sup>.

### **2.3.4 Pumpdown Curves**

Thirty two (32) hour and 100 hour pumpdown curves of the corner, mid, and end stations are shown in V049-1-078 which can be found in Attachment 4.

## **2.4 Bakeout Capability**

Degassing of the vacuum chamber walls requires a bake-out temperature of  $150\text{C} \pm 20\text{C}$ . Requirements and design criteria for the bakeout blanket system are dictated by bakeout temperature, warm-up time, maximum allowable surface temperature, practical blanket thickness and available space for installation, insulation type, cost effective design, and end effects such as gate valve's gate and vacuum envelope support legs. Additionally, higher power density heating jackets are required for baking the pressure gauges at  $250\text{C}$ .

### **2.4.1 Blanket Design**

#### **2.4.1.1 Insulation thickness**

To be able to reach a temperature of  $150\text{C}$  asymptotically a certain insulation thickness/value is required for a given power input. Selection of the insulation thickness involves tradeoffs between power density, heat-up time, cooldown time, maximum allowable surface temperature and available space for installation. To maintain a reasonable cost of the blanket system and manageability of the blankets (a thick blanket makes it difficult to install onto the complex curvature of the vacuum envelope), 2 inch fiberglass insulation has been specified.

#### **2.4.1.2 Warm-up Time**

Because the warm-up is controlled to maintain temperature uniformity over the bakeout system, warm-up of the vacuum envelope will be dictated by the thickest section. At a power density of  $350 \text{ W/m}^2$  it takes less than 48 hours to heat the thickest flange (1.5 inch). The specification requires a maximum ramp of  $1.8\text{C}/\text{hour}$  and requires it to be controllable. Power density is limited to provide fail safe protection.

#### **2.4.1.3 Cooldown Time**

With a 2 inch fiberglass insulation the cooldown is estimated to take over 48 hours to approach room temperature.

#### **2.4.1.4 Power Density**

A 2 inch fiberglass insulation with a design margin of 2 for the insulating value, and a surface emissivity of 0.9 requires a power density is  $350 \text{ W/m}^2$  to hold a temperature at  $170\text{C}$ . The system is currently specified to have an average power density of no more than  $450 \text{ W/m}^2$ .

#### 2.4.2 Special Blankets

To ensure that all surfaces can be heated to at  $150\text{C} \pm 20\text{C}$ , certain sections need to have blankets with higher power density to maintain the required temperature on the vacuum surface.

Due to end effects on the gate spool sections, in the adjoining isolatable section next to gate valves, require a higher power density blanket in order to allow the gate being baked to reach the required temperature.

Vessel support legs which are made from carbon steel (higher thermal conductivity than stainless steel) requires a blanket system to allow the vacuum surface to reach temperature.

Pressure gauge pair bakeout at  $250\text{C}$  requires a higher power density jacket.

#### 2.4.3 Power Requirements

The power requirement will be the highest for the most massive isolatable section used in the bake-out. However, if sufficient amount of time is allowed for warm-up to a steady state temperature of  $150\text{C}$ , then the minimum power requirements will be dictated by the section with the largest surface area.

The corner station in WA or LA has an isolatable section with an approximate area of  $400\text{m}^2$ , and at a power density of  $450\text{ W/m}^2$  requires a power of  $180\text{ kW}$ .

The end station which has an approximate area of  $119\text{ m}^2$  requires a power of approximately  $53\text{ kW}$ .

The mid station which has an approximate area of  $162\text{ m}^2$  requires a power of approximately  $72\text{ kW}$ .

Further information on the blanket design and control is given in section 3.6 and Document V049-1-065.

## **3.0 DESIGN**

### **3.1 Station Design**

#### **3.1.1 Equipment Arrangement**

The basic equipment arrangement and dimensional requirements have been determined by LIGO in the Vacuum Equipment Specification LIGO-E940002-02-V, Rev. 2 and various LIGO TDM's and LIGO Preliminary ICD's to the beam tube contractor and civil contractor.

The drawings listed below at the various section headings are the PSI drawings for each station that depict the locations of the PSI Vacuum Equipment, vacuum/purge air and utility piping at the Corner, Mid and End Stations.

In general, PSI has been responsible for the location and arrangement of the following items at all the stations:

1. PSI's electrical instrumentation and control work, as shown on the drawings, provides LIGO with a complete installation, enabling proper operation of vacuum equipment. All devices and raceways are shown installed in such a way so as to avoid stay clear areas and to avoid interferences with vacuum equipment and piping systems while providing some flexibility due to possible field corrections.
2. The layout of the vacuum pump piping, the purge air/air shower piping and the utility air and cooling water headers. The piping has been routed under the beam tube manifolds and is supported 6 in. above the floor surface on pipe supports which are anchored to the floor.
3. The design and layout of the 80K cryopumps, the LN<sub>2</sub>/GN<sub>2</sub> piping and the LN<sub>2</sub> storage tanks and associated equipment. The LN<sub>2</sub>/GN<sub>2</sub> piping is supported on tee posts approximately eight feet above the floor. Note the 80K pump shell rupture disc vent line, the GN<sub>2</sub> relief valve discharge and the Dewar pressure regulator vent are all piped to a safe discharge zone outdoors and within a fenced off area around the LN<sub>2</sub> systems. The suggested fence is to be provided by LIGO.
4. The port locations for the main turbo and roughing pump carts.
5. The port locations of the main ion pumps.
6. The layout of the equipment and piping in the mechanical/vacuum support equipment rooms.
7. PSI has included circumferentially slotted holes for flange bolts on certain spools. This feature will allow easier alignment of the spools. An example of this is shown on drawing V049-4-060.

8. PSI has increased the ID's of the following items to assure LIGO minimum apertures to allow for manufacturing tolerances.

BSC's to 104.5 in. ID, from 104 in. ID

HAM's to 84.25 in. ID, from 84 in. ID

Manifolds to 72.25 ID, from 72 in. ID

Manifolds to 60.5 in ID, from 60 in. ID

Manifolds to 48.25 in. ID, from 48 in. ID

Manifolds to 44.625 in. ID, from 44 in. ID

Manifolds to 30.5 in. ID, from 30 in. ID

### 3.1.1.1 Washington Corner Station

*Reference PSI Drawings V049-5-001 (2 Sheets), V049-5-012, V049-5-013 and V049-5-014.*

The equipment has been arranged per Figure 4 of Specification LIGO-E940002-02-V Revision 2. The Final Design Review drawings reflect the following updates to the original scope drawings.

1. The HAM support saddles are anchored directly to the concrete floor.
2. The elevation of the floor surface was lowered 3 in. (measured at the vertex). This gives a dimension of 73 in. (1854 mm) between the floor surface to the beam axis centerline.
3. The 72 in. beam tube manifolds are now arranged similar to the Louisiana long tube sections to save costs on flanged sections. (Reference change order #11).
4. The HAM 60" end covers now have a symmetrical pattern vs. Figure 9 details. The HAM 84" doors have the ports spread at greater horizontal intervals to avoid nozzle reinforcement problems. (Approved per TIM 21).
5. Beam tube manifold changes in diameter are made with flat plate transitions instead of cone shaped sections. (Approved per TIM 26).
6. The orientation of LIGO vibration isolation supports for the detector equipment at BSC1 and BSC3 have been turned 90<sup>0</sup> to allow easier removal of adjacent beam tube manifold sections.
7. The main ion pumps are mounted on top of the 30 in. mode cleaner tubes and the 48 in. diagonal beam tube manifolds. This was done to free up space around the BSC's which are very congested, and avoid mounting them on top of the HAM's above the optics.
8. The 30 in. x 60 in. adapter cone sections on the ends of the mode cleaner tubes have been deleted. The 30 in. diameter sections are extended to a 30 in. x 60 in. transition plate on each end of the mode cleaner tubes. This transition plate connects directly to the HAM flanges.
9. The four (4) cone style view port adapters, as depicted in view "C-C", of LIGO Spec. E940002-02-V, Figure 4, have been changed to a flat flange plate style. Details of these can be seen on dwg. V049-4-A15 & A1. The flat plate concept will allow more viewing area. Note that on A15 the size of the view ports are in 3 in. tube on a 55 1/4" dia. circle because of the 60.5" ID nozzle on the BSC.

10. The HAM 75 l/s annulus ion pumps are located on top of the HAM chambers to free up floor space. For details, refer to dwg. V049-4-054.
11. The BSC 75 l/s annulus ion pumps are located at grade. For annulus tubing layout on the BSC chamber, refer to dwg. V049-4-025.
12. The 25 l/s annulus ion pumps for the gate valves and the 75 l/s pumps for the beam tube manifold annuli, will be supported near grade adjacent to the beam tube manifold. For details of the 25/75 l/s pump/manifolds, refer to dwgs. V049-4-077 & 078.
13. The mode cleaner tubes have had a third central support point added which limits the amount of axial thermal movement into the bending type supports. This has created the need for an additional bellows in the 30 in. section near the vertex end. This was approved by LIGO in Change Order No. 19.