Quarterly Report

(March 1997 through May 1997)

The Construction, Operation, and Supporting Research and Development of a Laser Interferometer Gravitational-Wave Observatory (LIGO)

NSF Cooperative Agreement No. PHY-9210038

June 1997

Table of Contents

List of Figures

List of Tables

Quarterly Report

(March 1997 - May 1997)

THE CONSTRUCTION, OPERATION, AND SUPPORTING RESEARCH AND DEVELOPMENT OF A LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY (LIGO)

NSF COOPERATIVE AGREEMENT No. PHY-9210038

June 1997

CALIFORNIA INSTITUTE OF TECHNOLOGY

This Quarterly Report is submitted under NSF Cooperative Agreement PHY-9210038[1]. The report summarizes Laser Interferometer Gravitational-Wave Observatory (LIGO) Project activities from March 1, 1997 through May 31, 1997.

1.0 Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) Project will open the field of gravitational-wave astrophysics through the direct detection of gravitational waves. LIGO detectors will use laser interferometry to measure the distortions of the space between free masses induced by passing gravitational waves. The design, construction, and operation of LIGO is being carried out by scientists, engineers, and staff at the California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT). Caltech has prime responsibility for the project under the terms of the Cooperative Agreement[1] with the National Science Foundation (NSF). LIGO will become a national facility for gravitational-wave research, providing opportunities for the broader scientific community to participate in detector development, observations and data analysis. LIGO welcomes the participation of outside scientists at any of these levels. The initial LIGO facility will comprise one three-interferometer detector system. The site allows for expansion of the facility to a multiple-detector configuration to enable simultaneous use by several gravitational-wave detectors.

The LIGO Project was described in the LIGO Proposal[2] submitted to NSF in December 1989, and the Technical Supplement[3] submitted to NSF in May 1993. Project organization is described in the LIGO Project Management Plan[4]. The cost of the construction activities for the observatory facilities and the initial detector equipment was presented in the LIGO Cost Book[5], which was reviewed in September, 1994.

This quarterly report covers activities accomplished during the second quarter of the sixth year (LIGO fiscal year 1997) of the Design and Construction Phase of the LIGO Project, and the related Research and Development. This phase includes facility construction, support equipment acquisition, initial interferometer design and fabrication, and the concurrent research to refine the initial detectors and data algorithms. LIGO Design/Construction began December 1, 1991 as defined in the Cooperative Agreement and will end with the acceptance of the vacuum systems at both sites and completion of the fabrication of the third interferometer.

2.0 Executive Summary

The project continues to make excellent progress. The project is 54 percent complete. The rate of accomplishment, as measured by our Performance Measurement tracking systems, now reflects active subcontracts for the construction of facilities at Hanford, Washington and Livingston, Louisiana as well as subcontracts for the design and fabrication of Detector components.

An NSF Semi-Annual Technical Review was held at Caltech on April 15, 16, and 17. On April 13 and 14, just prior to this review, a subset of the NSF Review committee visited the Hanford, Washington site for a Cost/Schedule overview and a site tour. A draft report was issued early in May.

Washington Site Construction. The civil construction is proceeding overall on schedule with the Arm-1 mid- and end-stations nearing completion. At the corner station, the Laser and Vacuum Equipment Area (LVEA) will be completed in time for Vacuum Equipment installation by Process Systems International (PSI). The Arm-2 beam tube installation has been completed and the leak testing of the first module began in May. Preliminary data indicates that this leak rate is well within the specified parameters. Installation of the beam tube on Arm-1 is continuing on schedule. Chicago Bridge and Iron (CB&I) has completed all of the tube forming required for the Washington site, and the spiral mill is being shipped to Louisiana. PSI has continued the fabrication, bake out and leak testing of the large vacuum vessels, spool pieces, and cryo pumps. A contractor has been selected for the installation of this equipment at the Washington site and is scheduled to start during the next quarter.

Louisiana Site Construction. The civil construction in Louisiana is well underway, and both contractors are on schedule despite the heavy rains encountered throughout this period. The concrete work for the Arm-1 end-station, both mid-stations and the Operational Support Building (OSB) has been completed and steel erection has begun at the end-station and at the corner station. The service roads along both arms have been completed. The cement treatment performed along both berms proved to be an excellent and cost effective way to maintain the overall schedule for both contractors. CB&I has been able to lease an excellent facility about 25 miles west of the LIGO site for the fabrication of the beam tubes. Installation of the tube fabrication equipment has begun and beam tubes are scheduled to be fabricated during the next quarter.

Detector. Several key detector design and fabrication activities were accomplished this quarter. The first Nd:YAG 10W light source brassboard was produced and tested with very promising results; some LIGO performance targets were exceeded. The polishing of several to-be-installed optics was completed, and they are ready for metrology. Many of the practical challenges in the fabrication of the seismic isolation internally-damped coil springs were resolved, and performance of the test pieces meets our requirements for damping and acoustic feedthrough. A complete prototype of the LIGO data acquisition system was finished and tested using the 40-meter test interferometer as a signal source; data frames saved in the final LIGO data format will be used in the development of data handling algorithms.

The Preliminary Design Review of the Seismic Isolation, and the Design Requirements Review for the Core Optics Support were successful, enabling further design activities.

R&D. The configuration of the test interferometers on both campuses were changed this quarter. The 40-meter interferometer successfully locked the low-finesse cavities appropriate for the recycling experiment. This enabled LIGO to select and order the correct transmission for the recycling mirror. The Phase Noise Interferometer is being converted to the Nd:YAG 1064 nm wavelength, and first measurements were made using a low-power pre-stabilized laser and a suspended 1064 nm cavity; the performance of the laser exceeds that of the Argon pre-stabilized laser it replaced.

Integration. The Science and Integration Meeting was held on May 22 and 23, 1997 at Caltech. This quarterly meeting is used as a forum to discuss a variety of technical issues. Highlights from this session included discussions on (i) how to structure the Advanced R&D Program at both Caltech and MIT as LIGO moves from construction into operation; (ii) strategies to design interferometer mirrors to accommodate anticipated thermal lensing effects at the expected operational powers; (iii) the planning and design of the initial LIGO I data analysis system (DAS); (iv) prototype activities on the 40 meter facility for data acquisition and analysis; (v) development of advanced control systems identification tools to improve instrument availability and sensitivity through adaptive controls methodologies; (vi) exploitation of spectral cross correlations and linear regression techniques to improve sensitivity and remove instrumental effects in interferometer performance; (vii) the deferral of fabrication of seismic isolation subsystems for the vacuum chambers associated with the interferometer output optics that are not needed for the initial interferometer.

During the last quarter, LIGO successfully completed a time-critical review of shedding by the beam tube baffles. The review isolated the problem and identified the work-around required. New baffles will be fabricated using a high temperature (850C) air bake as a method of reducing reflectivity and improving optical isolation properties of the baffles. By the end of the quarter, procurement of the new baffles had started, and improved cleaning methods were being used to maintain the optical properties.

2.1 Project Milestones

The status of the significant milestones identified in the Project Management Plan (PMP) for the LIGO Facilities is summarized in Table 1.

TABLE 1. Status of Significant Facility Milestones

Milestone Description	Project Management Plan Date[a]		Actual (A)/Projected (P) Completion Date	
	Washington	Louisiana	Washington	Louisiana
Initiate Site Development	03/94	08/95	03/94 (A)	06/95 (A)
Beam Tube Final Design Review	04/94		04/94 (A)	
Select A/E Contractor	11/94		11/94 (A)	
Complete Beam Tube Qualification Test	02/95		04/95 (A)	
Select Vacuum Equipment Contractor	03/95		07/95 (A)	
Complete Performance Measurement Baseline	04/95		04/95 (A)	
Initiate Beam Tube Fabrication	10/95		12/95(A)	
Initiate Slab Construction	10/95	01/97	02/96 (A)	12/96 (A)
Initiate Building Construction	06/96	01/97	08/96 (A)	12/96 (A)
Accept Tubes and Covers	03/98	03/99	01/98 (P)	12/98 (P)
Joint Occupancy	09/97	03/98	09/97 (P)	02/98 (P)
Beneficial Occupancy	03/98	09/98	10/97 (P)	06/98 (P)
Accept Vacuum Equipment	03/98	09/98	04/98 (P)	10/98 (P)
Initiate Facility Shakedown	03/98	03/99	04/98 (P)	12/98 (P)

a. Project Management Plan, Revision B, LIGO-M950001-B-M approved by NSF in October 1996

Table 2 shows the status of the significant milestones for the Detector. The projected completion date for the *Core Optics Support Final Design Review* is now December 1997 (vs. April 1997). Significant scope originally in this task has been moved to the Suspension task. This defers some need dates. The delay does not affect the expected date for first operation of the LIGO interferometers. A better understanding of the requirements and design for the Core Optics Support (reviewed and documented in the Design Requirements Review held in April 1997) has reduced the expected fabrication time, and all critical components are expected to be ready in time to avoid installation delays.

The *Core Optics Components Final Design Review* has also been delayed by approximately three months. In this case, an aggressive procurement strategy has been instituted which permits initial fabrication steps to be started prior to the FDR without incurring significant risk and, in fact, reduces costs by allowing time for rework of any parts damaged during fabrication as opposed to requiring additional spares.

These projections were presented during the April Semi-Annual Review.

As of the end of May 1997, all significant project milestones can be achieved.

TABLE 2. Status of Significant Detector Milestones

Milestone Description	Project Management Plan Date		Actual (A)/Projected (P) Completion Date	
	Washington	Louisiana	Washington	Louisiana
BSC Stack Final Design Review	07/97		08/97 (P)	
Core Optics Support Final Design Review	04/97		12/97 (P)	
HAM Seismic Isolation Final Design Review	07/97		08/97 (P)	
Core Optics Components Final Design Review	07/97		10/97 (P)	
Detector System Preliminary Design Review	12/97		04/98 (P)	
I/O Optics Final Design Review	04/98		05/98 (P)	
Prestabilized Laser Final Design Review	08/98		07/98 (P)	
CDS Networking Systems Ready for Installation	09/97		07/97 (P)	
Alignment (Wavefront) Final Design Review	04/98		02/98 (P)	
CDS DAQ Final Design Review	04/98		05/98 (P)	
Length Sensing/Control Final Design Review	05/98		12/97 (P)	
Physics Environment Monitoring Final Design Review	06/98		08/97 (P)	
Initiate Interferometer Installation	07/98	01/99	07/98 (P)	01/99 (P)
Begin Coincidence Tests	12/00		12/00 (P)	

2.2 Financial Status

Table 3 summarizes costs as of the end of May 1997. It has been recognized that the Caltech Financial systems have not been relieving commitments in a timely manner when special processing has been requested for payments (e.g., Electronic Funds Transfers). The commitments for subcontracts are, therefore, overstated on internal reports and are not reported here. We are working with Caltech Finance to review and correct commitments. In addition, the Caltech Internal Audit function is assisting us to assure that project reporting is consistent with internal control and reporting systems.

TABLE 3. Costs and Commitments as of the End of May 1997

(All values are $Thousands)

WBS	Description	Costs Thru Nov 1996	First Quarter FY 1997	Mar-97	Apr-97	May-97	Cumulative	Open Encumbrances	Total Cost Plus Commit-ments
1.1.1	Vacuum Equipment	21,254	956	1,993	1,603	50	25,856		
1.1.2	Beam Tube	17,262	4,795	1,309	1,342	1,036	25,743		
1.1.3	Beam Tube Enclosure	6,237	958	596	1,033	1,304	10,128		
1.1.4	Civil Construction	14,117	4,705	1,953	2,941	2,660	26,377		
1.2	Detector	6,270	1,521	850	598	820	10,058		
1.3	R&D	16,816	845	265	228	309	18,463		
1.4	Project Office	16,288	1,452	843	607	652	19,841		
	Unassigned (see note)	2	-	4	3	-	10		
	TOTAL	98,246	15,231	7,813	8,355	6,832	136,477		
	Cumulative Actual Costs	98,246	113,477	121,289	129,645	136,477			
	Open Commitments	91,492	109,800	106,249					
	Total Costs plus Commitments	189,738	223,277	227,538		-			
	NSF Funding	*208,468*	*265,389*	*265,389*	*265,389*	*265,389*			

Note: “Unassigned costs” have not been assigned to specific LIGO Work Breakdown Structure element, but are continually reviewed to assure proper allocation.

(All entries in $ Thousands)

Run Date: 30JUN97	COST / SCHEDULE STATUS REPORT (CSSR)							Page 1
CONTRACTOR: Caltech LOCATION: Pasadena, CA	CONTRACT NUMBER: PHY-9210038		CONTRACT BUDGET BASELINE 292, 100, 000		REPORTING PERIOD: 30APR97-31MAY97	PROJECT FILE NAME: LIGO Master Merged PMB - WBS 1.0		
PERFORMANCE DATA (K$s)								
REPORTING LEVEL	CUMULATIVE TO DATE					AT COMPLETION		
MPR LEVEL	BUDGETED COST		ACTUAL COST	VARIANCE		BUDGET	ESTIMATE	VARIANCE
	WORK SCHEDULED	WORK PERFORMED	WORK PERFORMED	SCHEDULE (2-1)	COST (2-3)	(BAC)	(EAC)	(6-7)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1.1.1 : Vacuum Equipment	26819	26390	25856	(429)	534	42113	42113	0
1.1.2 : Beam Tubes	25155	25981	25743	826	238	44746	44746	0
1.1.3 : Beam Tube Enclosur	11093	11059	10128	(34)	931	19943	19943	0
1.1.4 : Facility Design &	23584	27832	26377	4248	1455	48624	48624	0
1.1.5 : Beam Tube Bake	0	0	0	0	0	3240	3240	0
1.2 : Detector	12746	10877	10058	(1868)	819	52840	53609	(769)
1.3 : Research & Developme	19182	18922	18463	(259)	459	23490	23490	0
1.4 : Project Office	19297	19297	19841	0	(545)	27074	27074	0
SUBTOTAL	137875	140358	136467	2483	3892	262072	262841	(769)
CONTINGENCY						0	29259	(29259)
MANAGEMENT RESERVE						30028	0	30028
TOTAL	137875	140358	136467	2483	3892	292100	292100	0

COBRA (R) by WST Corp.

FIGURE 1. Cost Schedule Status Report (CSSR) for the End of May 1997

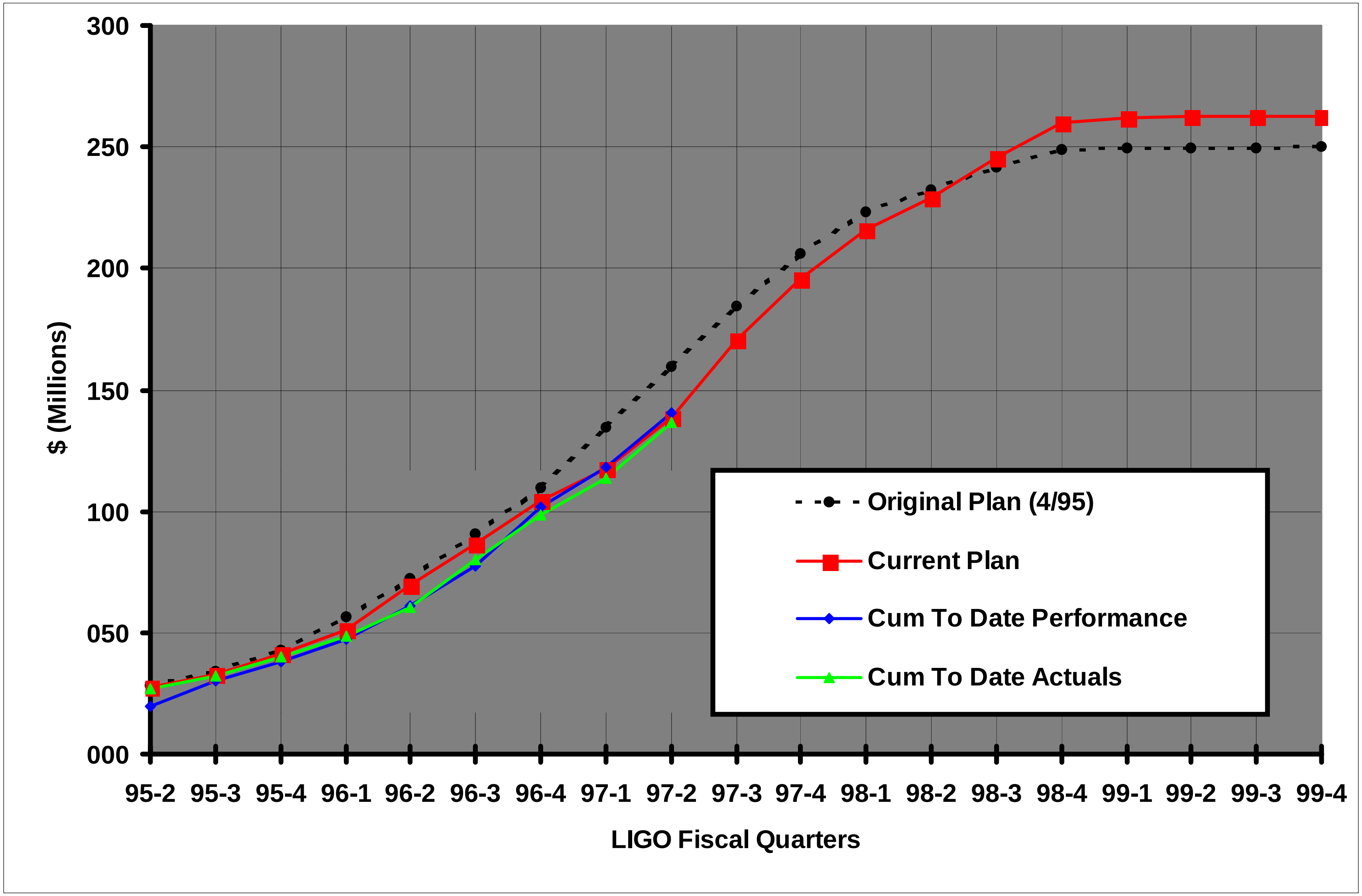

FIGURE 2. LIGO Project Budget, Earned Value, and Actual Costs as a Function of Time

2.3 Performance Status (Comparison to Project Baseline)

Figure 1 on page 8 is a Cost Schedule Status Report (CSSR) for the end of May. The CSSR shows the time-phased budget to date, the earned value, and the actual costs through the end of the month for the NSF reporting levels of the WBS. The schedule variance is equal to the difference between the budget-to-date and the earned value and represents a “dollar” measure of the ahead (positive) or behind (negative) schedule position. The cost variance is equal to the difference between the earned value and the actual costs. In this case a negative result indicates an overrun. Figure 2 shows the same information as a function of time for the LIGO Project.

Vacuum Equipment. (WBS 1.1.1) Vacuum Equipment is slightly behind schedule. A large number of components have been fabricated, several large chambers have been cleaned and checked for leaks, and vacuum bake activities began in May. Process Systems International (PSI) and its subcontractor, GNB, have rescheduled gate valve deliveries to ensure that contractual needs are met. Two Washington gate valves will be delayed to assure that the first two Louisiana gate valves are delivered in time to support CB&I requirements. All Washington gate valves will be delivered by September 15, 1997.

The favorable cost variance reflects normal delays in processing invoices.

Beam Tube. (WBS 1.1.2) The favorable schedule variance reflects purchases of stainless steel that were made in advance of the schedule date to take advantage of favorable prices.

The favorable cost variance reflects normal delays in processing invoices.

Beam Tube Enclosure. (WBS 1.1.3) Installation of the Beam Tube Enclosure (BTE) has been behind schedule in Hanford. Levernier, the subcontractor responsible for installing the enclosures, has been delayed by the rate at which CB&I can align the Beam Tube. (Note: the first arm of the beam tube at Hanford was aligned and the Beam Tube Enclosure segments installed during June.)

The favorable cost variance reflects normal delays in processing invoices.

Civil Construction. (WBS 1.1.4) Favorable cost and schedule variances are reported. Civil Construction is ahead of schedule at both sites. However, the subcontractors are being monitored closely as we enter the last phases of construction at Hanford to assure availability of the facilities to PSI.

New schedules have been developed based on detailed plans provided by the subcontractors selected in Louisiana, and these new schedules have been incorporated into the LIGO baseline.

The favorable cost variance reflects normal delays in processing invoices.

Beam Tube Bake. (WBS 1.1.5) Note that a change request has been processed to create a new third level work breakdown structure (WBS) element to track the Beam Tube Bake. The change request moved $3.2 million into 1.1.5 from the Beam Tube (WBS 1.1.2) where the budget for the vacuum bake had been held.

Detector. (WBS 1.2) The Detector is behind schedule and under cost. LIGO has been hiring additional staff, but this has not been accomplished quickly enough to avoid some delays. In addition personnel have been diverted to R&D tasks. It will be noted that a year ago the R&D effort was approximately six months behind relative to the plan proposed in September 1994, but during the past year the status of these R&D tasks has improved dramatically. Priorities are being adjusted to assure that all critical milestones will be met.

Specific Detector tasks that are behind schedule include:

- The vendor laser development activity is behind schedule relative to the internal LIGO plan. However, this reflects the fact that the vendor's plan included a longer time for development and a correspondingly shorter time for production with an unchanged final delivery date.
- Other issues that affect the status of the Laser and Optics include a delayed start on the Input Optics contract by the University of Florida (approval of the contract was received from NSF during May) and late optic blank deliveries from Corning. All final milestones are on track.
- The Alignment Sensing and Control (ASC) effort is behind schedule because resources have been shared to accomplish R&D tasks supporting interferometer development. The original budget estimate (labor and materials) is not adequate for the Length Sensing Control (LSC) effort, and this is being addressed through the normal change control process.

2.4 Change Control and Contingency Analysis

Twenty Change Requests (CRs) shown in Table 4 were approved and incorporated into the baseline during the first half of this year. The net effect of these change requests was to allocate $2.06 million from contingency. The contingency as of the end of this reporting period is $30.0 million.

TABLE 4. Approved Change Requests

Change Request No.	Description	Submitted By	Submittal Date	Current Status	Disposition Date
CR-970003	WBS 1.1.4 Facilities - Air Handling Ducts cleaning procedures and specifications	O. Matherny	February 12, 1997	Approved $150,000 NTE	February 13, 1996
CR-970004	WBS 1.1.2 - Beam Tube, Transformers	L. Jones	March 12, 1995	Approved ($44,110)	March 25, 1997 L9700163
CR-970005	WBS 1.1.2 - Beam Tube Miscellaneous	L. Jones	March 12, 1995	Approved $51,200	March 25, 1997 L9700163
CR-970006	WBS 1.1.2 - Beam Tube, BDF Air Monitoring	L. Jones	March 12, 1995	Approved $46,130	March 25, 1997 L9700163
CR-970007	WBS 1.1.2 - Beam Tube, Hanford Labor Rates	L. Jones	March 19, 1995	Approved $61,316	March 25, 1997 L9700163

TABLE 4. Approved Change Requests

Change Request No.	Description	Submitted By	Submittal Date	Current Status	Disposition Date
CR-970008 Rev A	WBS 1.1.4 - Cement Treatment of Berm, Livingston, Louisiana Site	F. Asiri	March 21, 1997	Approved $667,087	May 29, 1997 L9700281
CR-970009	WBS 1.2 - Core Optics Components, Reduced Number of Components	G. Billingsley	March 20, 1997	Approved ($881,636)	March 25, 1997 L9700163
CR-970010	WBS 1.2 - Input/Output Optics, Delete Output Mode Cleaners	J. Camp	March 21, 1997	Approved ($471,000)	March 25, 1997 L9700163
CR-970011	WBS 1.1.2 - Beam Tube, WA Module End Conditions	L. Jones	April 1, 1997	Approved $75,787	May 6, 1997 L970263
CR-970012	WBS 1.1.2 - Beam Tube, WA X1 Module Gate Valve Contamination	L. Jones	April 24, 1997	Approved $9,550	May 6, 1997 L970263
CR-970013	WBS 1.1.2 - Beam Tube, WA X1 and X2 Module Cleaning	L. Jones	April 25, 1997	Approved $7760	May 6, 1997 L970263
CR-970015	WBS 1.1.2 - Beam Tube Baffles, Change-over to Bright Annealed Stainless Steel	A. Sibley	May 2, 1997	Approved $665,800	May 6, 1997 L970263
CR-970016	WBS 1.1.4 - Civil Construction, Sound Trap Cleaning - Hanford	F. Asiri	May 12, 1997	Approved $55,000	May 29, 1997 L970281
CR-970017	WBS 1.1.1 - Vacuum Equipment, Additional Pumpcarts	J. Worden	May 2, 1997	Approved $650,000	May 29, 1997 L970281
CR-970018	WBS 1.1.2 - Beam Tube, Move Funds for Bake to Planning Package	F. Fernandez	May 13, 1997	Approved	May 29, 1997 L970281
CR-970019	WBS 1.1.4 - Civil Construction, Livingston, Reduced Taxes	F. Asiri	May 20, 1997	Approved ($280,000)	May 29, 1997 L970281
CR-970020	WBS 1.1.3 - Beam Tube Enclosure, Livingston, Reduced Taxes	F. Asiri	May 20, 1997	Approved ($332,500)	May 29, 1997 L970281

2.5 Staffing

The LIGO staff currently numbers 106 (full time equivalent). Of these, 22 are contract employees. Eighty-nine LIGO staff are affiliated with CIT including three graduate students. Seventeen are located at MIT including three graduate students. Six LIGO staff are now permanently located at the Hanford, Washington site, and three are located in Livingston, Louisiana.

3.0 Vacuum Equipment (WBS 1.1.1)

Significant accomplishments during this quarter

- Mechanical completion of an additional six Beam Splitter Chambers (BSCs) (total to date is eight).
- Mechanical completion of an additional seven Horizontal Access Modules (HAMs) (total to date is eight).
- Mechanical completion of an additional five 80K pumps (total to date is six).
- Cleaned, baked and vacuum tested four chambers (two BSCs and two HAMs).
- Cleaned, baked and vacuum tested one short 80K pump.
- Selected the Washington site installation contractor (Apollo Sheet Metal).
- Completed five large liquid nitrogen dewars (eight required for Washington).
- Received of six 2500 liter/second main ion pumps from Varian.
- Completed large component bake oven.
- Received the first production bake-out blankets from Heat Trace.

Discussion of accomplishments and work in progress

Process Systems International (PSI) continued to fabricate chambers for the Washington site. In April cleaning and leak testing was started in preparation for the commissioning of the large component bake oven. Figure 3 and Figure 5 show a Beam Splitter Chamber (BSC) cleaned, assembled and being pumped down for leak testing prior to bake. Figure 4 shows a completed Horizontal Access Module (HAM) chamber ready for bake.

During this period PSI also received the first production bake blankets which are being fabricated by Heat Trace, Inc. Figure 6 shows the styrofoam template used to manufacture the HAM blankets. Figure 7 is the finished product fitted to a HAM chamber. To help speed the bake and testing process PSI has procured and installed a large component bake oven. This hot air oven allows bakeout of several chambers at once without the labor intensive fitting of bake blankets. Figure 8 shows this oven at PSI.

In late May PSI made the final selection of an installation contractor for the Washington site. The contractor is Apollo Sheet Metal of Kennewick, Wa. Plans are to begin site mobilization in mid-September. An installation readiness review is planned in August.

Work planned to be accomplished next quarter

- Complete the fabrication and testing of all Washington left arm components.
- Complete all liquid nitrogen storage dewars for Washington.
- Receive the prototype cleanroom curtains and begin the production quantities.
- Hold an installation readiness review in Richland, WA.

FIGURE 3. Production Beam Splitter Chamber after Cleaning.

FIGURE 4. Horizontal Access Module Ready for Vacuum Bake and Test.

FIGURE 5. Initial Leak Check of Beam Splitter Chamber.

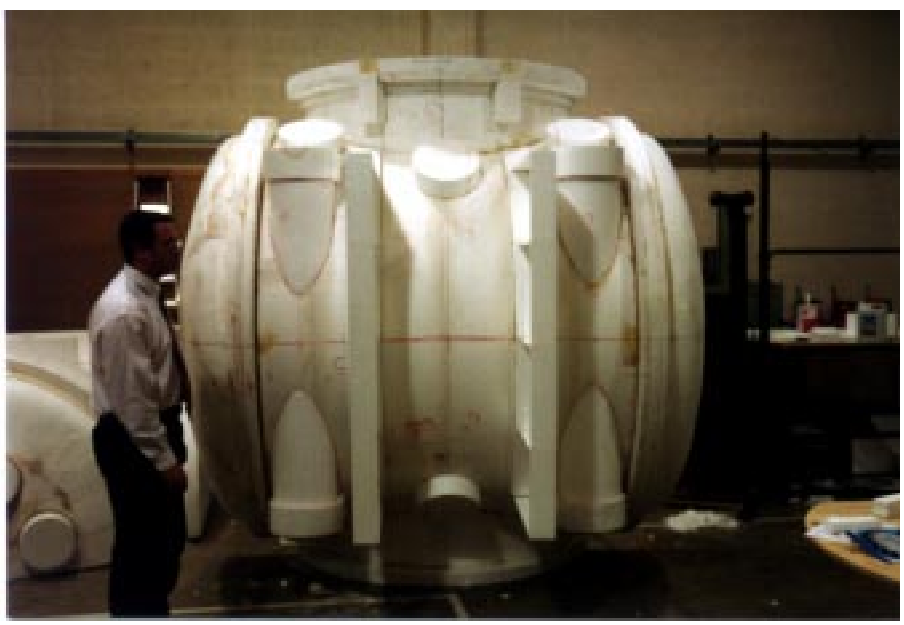

FIGURE 6. Bake Blanket Template for HAM Chamber.

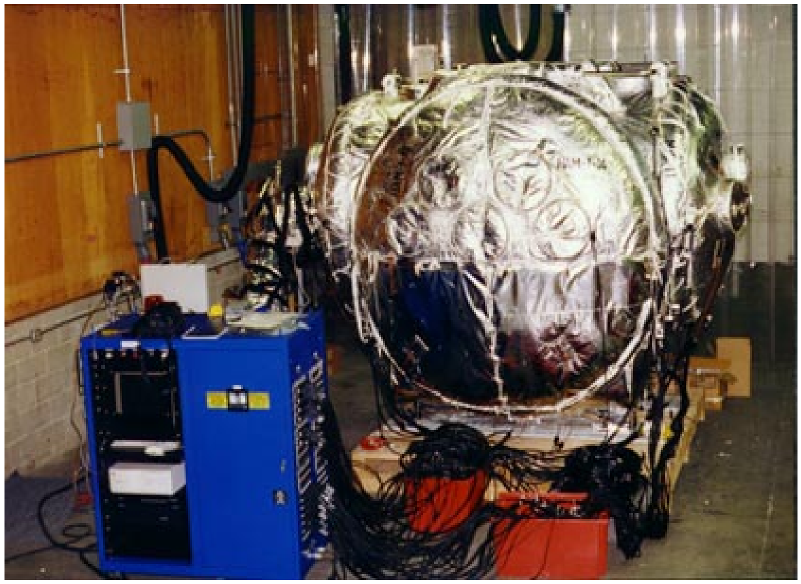

FIGURE 7. Finished HAM Blankets.

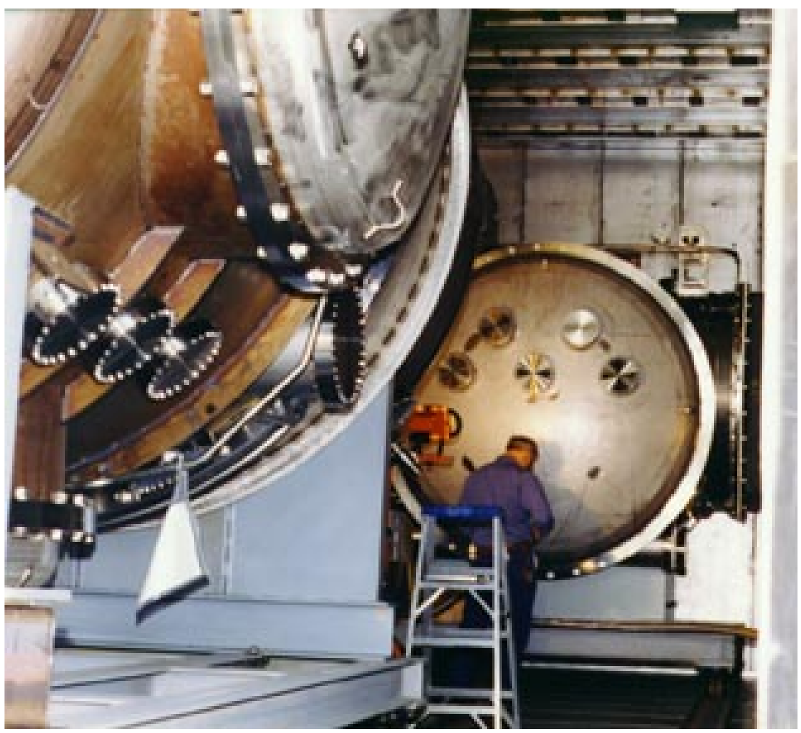

FIGURE 8. Inside the Large Component Bake Oven at PSI.

4.0 Beam Tube (WBS 1.1.2)

Significant accomplishments during this quarter

- Completed intallation of X Arm modules at Hanford.
- Completed installation of concrete enclosure over the X Arm modules.
- Began pumpdown of the longest high vacuum system on record.
- Began installation of Y Arm beam tube modules.
- Began moving the beam tube spiral weld facility from Washington State to Louisiana.

Discussion of accomplishments and work in progress

Installation of the two beam tube modules on the X Arm at Hanford was completed on April 23. This included over 16 km of spiral weld and 302 girth seams (with a total length of over 1 km), all of which passed rigorous helium mass spectrometer leak tests at 1×10^{-10} tl/s! This achievement was due to the consistent welding performance and careful visual inspection by the beam tube contractor, Chicago Bridge & Iron (CB&I). The concrete enclosure cover segments were installed over the X arm modules.

CB&I commenced installation of beam tube modules on the Hanford Y Arm after moving the clean air blowers and field installation enclosures. Initial shipments of improved baffles have been received at Hanford and the baffles are being installed as the tube sections are installed. Forty-four of the 200 tube sections on the Y Arm have been installed as of the end of May.

CB&I set up vacuum pump carts on the X2 module to prepare for the first module acceptance test. Of the nine pump ports distributed along the X2 module, special test hardware including cold traps, residual gas analyzers (RGAs) and vacuum gaging was installed and leak tested on ports 1, 4, 5, 6, and 9. Roughing pump carts were installed at ports 4 and 6 and main turbopump carts were installed at ports 1 and 9 (see Figure 9). These pump carts had been contractually provided by the vacuum equipment contractor, Process Systems International, Inc. (PSI); all pumps are of the "dry" design to preclude beam tube contamination by pump oil in the event of a pumping mishap. Each cart uses a chiller system to keep the pumps cool and an oil-free compressor to pressurize rotational seals.

A data collection system and RGA control systems were installed in a field trailer near port 5. A fiber-optics cable was run the two km length of the module for RGA control and data transmission. Temperature sensors were installed on the module in 18 positions, and the open doorways in the concrete enclosure cover were covered to minimize tube temperature variations.

Since this was the first LIGO module experiencing pumpdown, the beam tube termination supports were instrumented with dial indicators to measure movement. Supports at the module terminations are the only beam tube supports that are loaded by atmospheric pressure (> 7000 N) when the beam tube module is pumped down.

Pumpdown of the longest high vacuum system on record started on May 3. The roughing pumps reduced module pressure to 1×10^{-2} torr in 21 hours of pumping (spread over three days). Figure

10 plots the roughing pumpdown pressures as seen from ports 4, 5, and 6, with the pumps stationed at ports 4 and 6. Minor problems were experienced with blown fuses and thermal trips of one of the backing pumps. Adjustments were made to correct these. Termination supports deflected 4-5 mm; this magnitude had been anticipated by the designers.

Ion pumps were installed on the annular space between the double O-ring seals of the large gate valves at each end of the module, as is planned for the operational mode to minimize seal leakage.

The main turbopump carts were started and run for four hours on May 14. Operation has been continuous since May 15, except for short durations. Again, minor problems were experienced which caused cart shutdowns. Since the pumps are of “dry” design, no contamination was experienced. Unfortunately, data collection problems prevented recording the initial turbo pumping results, but manual logging shows that over two decades of reduction (torr) were achieved in the first four hours. Figure 11 shows module pressure (Port 4) and turbopump inlet pressure (Port 1) for subsequent pumping. This indicates some of the excursions in pressure at cart shutdowns and the pressure drop between Port 4 and the pump inlet at Port 1. Also apparent are the daily variations in pressure due to temperature changes affecting the water outgassing rate.

When the RGA was activated, it was apparent that the measurement system was contaminated as seen by the multiple peaks at typical hydrocarbon AMU numbers. Heating tape and insulation were installed and the measurement system was baked to enable sufficient sensitivity for the module leak check and outgassing measurements required in the acceptance test.

This test of the X2 module is expected to be completed in June with testing of the X1 module to follow. During the next quarter, acceptance testing of modules X1 and X2 will be completed, as well as installation of the two modules on the Y arm. The replacement of glass coated baffles on the X arm with the improved design will then be started.

The CB&I fabrication shop spiral welded the final tube section for Hanford, and has begun disassembly of the spiral mill for shipment to Louisiana. Other operations at the shop are winding down, with all but tube cleaning expected to be completed in June. By the end of the quarter, all equipment will be moved to Louisiana.

Work planned to be accomplished next quarter

- Complete the vacuum test of the X1 and X2 beam tube modules.
- Begin replacement of the glass coated baffles in the X1 and X2 modules.
- Complete all beam tube processing in Washington.
- Move all beam tube processing equipment to Louisiana.

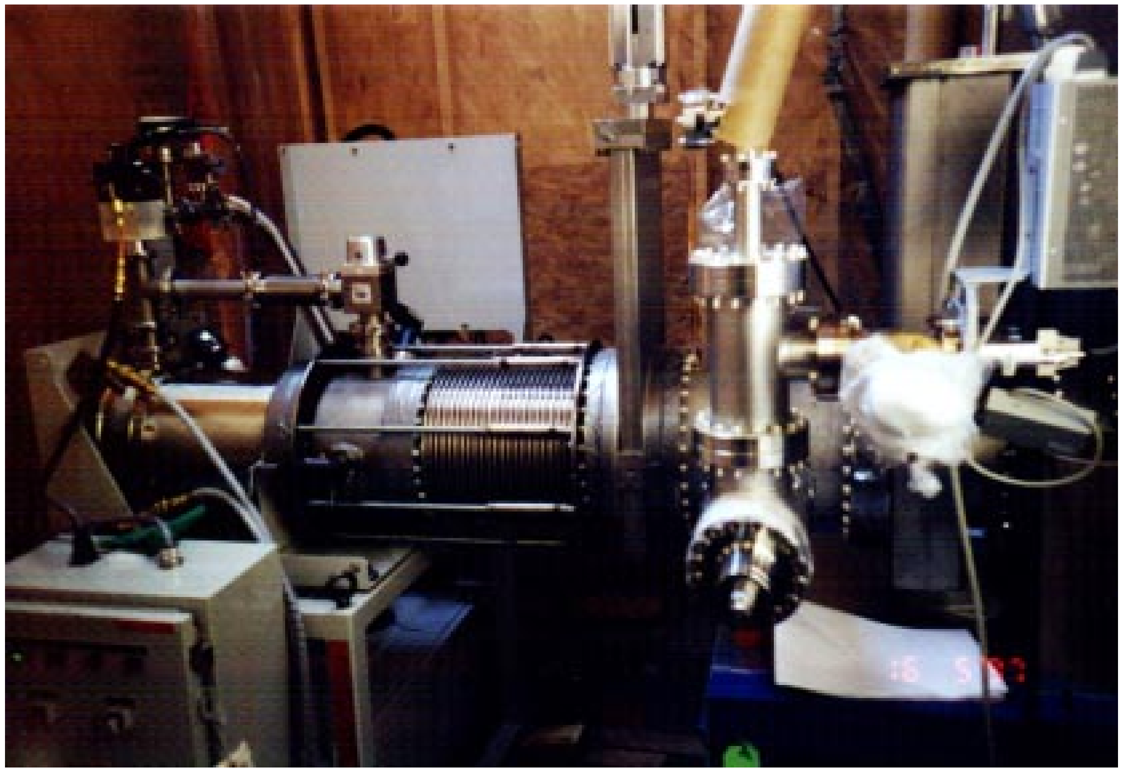

FIGURE 9. Turbopump Cart Installed at Port 1.

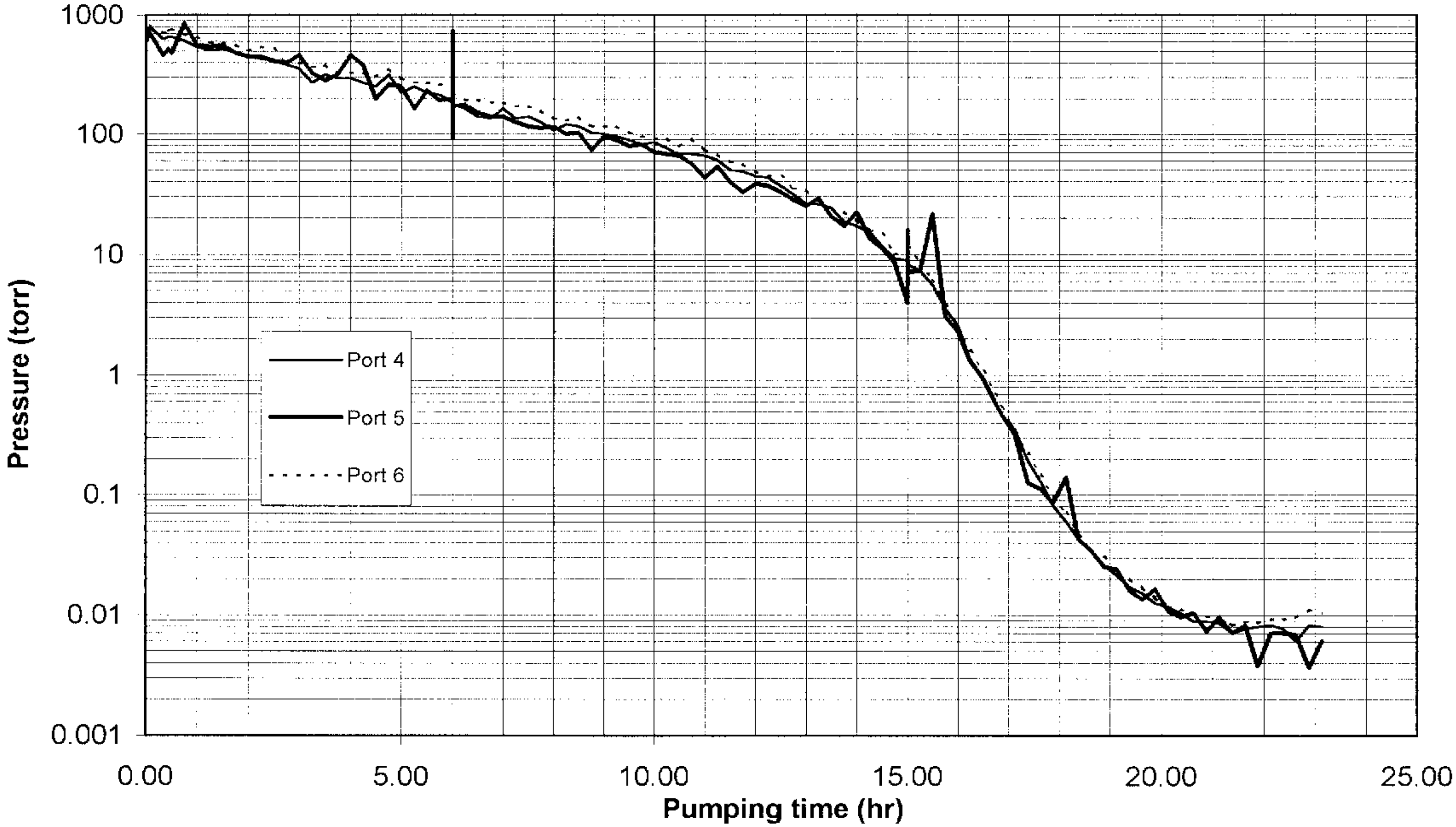

FIGURE 10. Initial Pumpdown of Hanford X2 Module.

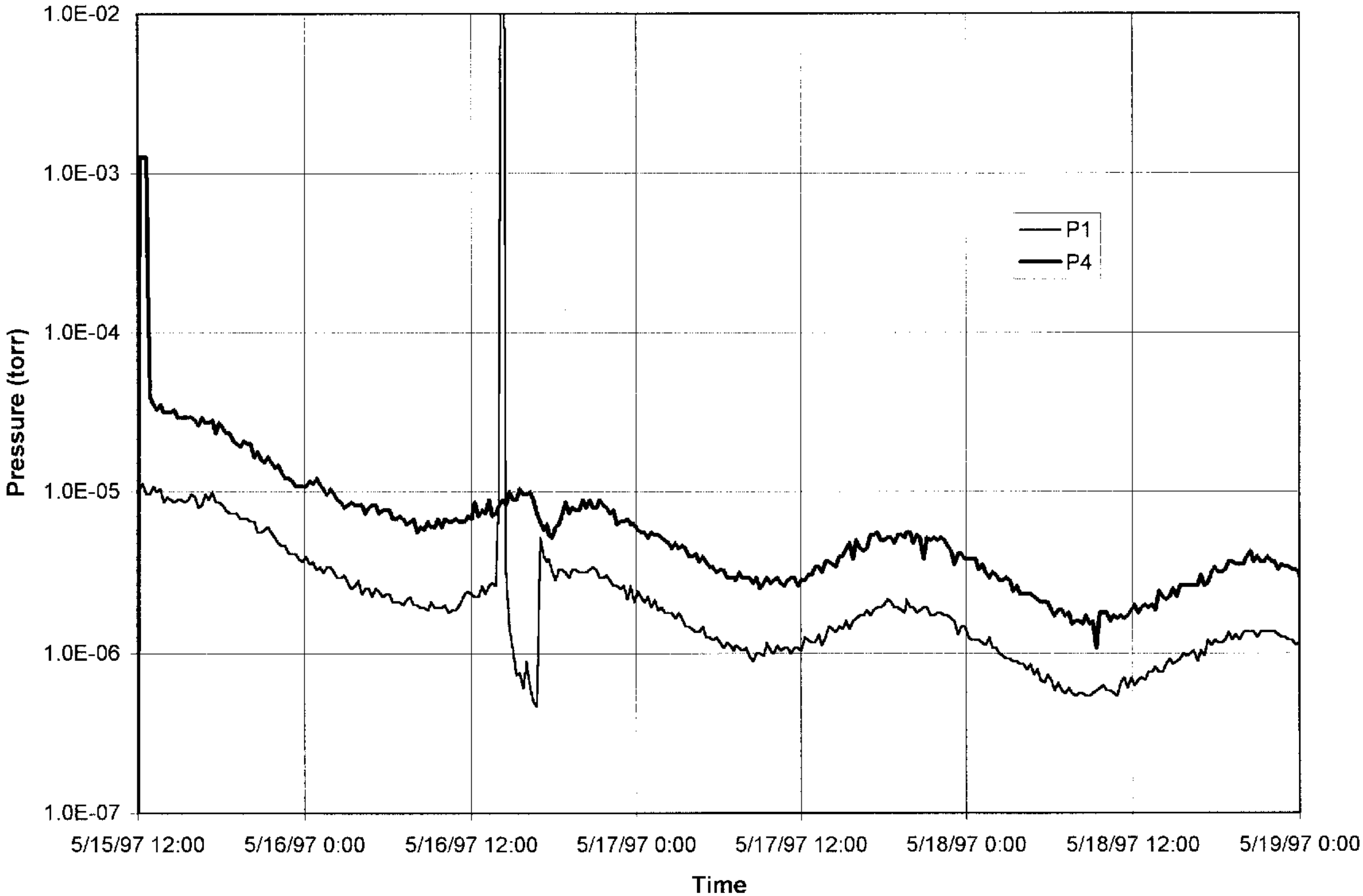

FIGURE 11. Turbopumping the Hanford X2 Module.

5.0 Beam Tube Enclosure (WBS 1.1.3)

Significant accomplishments during this quarter

Hanford Site:

- Fabrication of the pre-cast beam tube enclosure segments for the Hanford site was completed.
- Placement of the beam tube enclosure segments was completed on the northwest arm at the Hanford site.
- Started the installation of the beam tube enclosure on the southwest arm at the Hanford site.

Livingston Site:

- Construction of the service roads, fabrication and installation of the beam tube enclosures has began and proceeding on schedule.
- Completed the soil cement treatment of the top surface of the berm.
- Completed aggregate base for the service roads, the temporary access road and peripherally road at the corner station.
- Poured concrete for the termination foundations at mid and end of the southeast arm.

Discussion of accomplishments and work in progress

Hanford Site. Precast fabrication of the beam tube enclosure (BTE) segments were completed by the end of this period. This included pre-casting of about 2,600 enclosure segments (each 10ft long). Placement of BTE segment over the beam tube started slowly due to start-up problems with installation of the beam tubes and weather. However, the rate of installation exceeded the plan at the end. And the placement of the segments over the beam tube on the southwest arm was completed one month late. The placement of the BTE segments over the beam tube on the southwest arm has began and, by the end of this reporting period, was about 10 percent complete.

Livingston Site. Construction of the service road along southeast arm started slowly due to soft conditions on the top surface of the berm as well as inclement weather. However, after treatment of the top surface of the berm with cement the construction work proceeded efficiently and by the end of this period the aggregate base for the service roads as well as the temporary access road was completed. Concrete for the termination foundation at the mid and end of the southeast arm has been poured (Figure 15 on page 25).

Work planned to be accomplished next quarter

- Proceed with the installation of the beam tube enclosure segments on the southwest arm of the LIGO Hanford site and reach about 80 percent completion level.
- Pour concrete the termination foundation at the mid- and end-stations on the southwest arm at the Livingston site.
- Place concrete for the beam tube enclosure slab along both arms at the Livingston site.

FIGURE 12. Partial View of Completed Beam Tube Enclosure along Northwest Arm at Hanford Site.

FIGURE 13. View of the Access Road along Southeast Arm at Livingston.

FIGURE 14. Installation of Beam Tube Enclosure Segments along Southwest Arm

FIGURE 15. View of the Termination Foundation on Southwest Arm at the Corner Station.

6.0 Civil Construction (WBS 1.1.4)

Significant accomplishments during this quarter

Hanford Site:

- Reached the 90 percent completion level for construction of the mid- and end-stations on the southwest arm.
- Poured concrete for the technical and building foundations for the mid- and end-stations on the northwest arm.
- Completed the steel framing, siding and roofing for the corner station (Figure 16).

Livingston Site:

- Completed approximately 65 percent of all submittals and shop drawings for the buildings at the Livingston site
- Poured concrete for the operation building support foundation at the corner station.
- Completed the excavation and underground utilities work at the corner station.
- Placed concrete for the technical and building foundations at the end station on the southeast arm (Figure 17).

Discussion of accomplishments and work in progress:

Hanford Site. Construction of the buildings and infrastructure is 60 percent complete. Progress was affected during this period by several factors including cleanliness requirements for all HVAC system for the Laser and Vacuum Equipment Area (LVEA) and Vacuum Equipment Area (VEA), and delays in delivery of the building metal siding. The mid- and end-stations on the southwest arm continue to be behind schedule. Progress has improved in the LVEA area since the last quarter and it is expected that joint occupancy will occur in September 1997.

Livingston Site. After a slow start due to site conditions and the weather, progress on the construction of the buildings and infrastructure has improved. All foundation work has been completed for the end station on the southeast arm as well as for the operation support building. There was significant progress in site and underground work at the corner station during this period. Overall the construction effort is 25 percent complete.

Work planned to be accomplished next quarter

- Reach 75 percent completion level at the mid and end stations on the northwest arm at the Hanford site.
- Reach 90 percent completion level for the LVEA at the Hanford site.
- Complete construction work at the mid and end stations on the southwest arm at Hanford site.
- Complete construction work at the mid and end stations on the southeast arm at the Livingston site.
- Complete construction work at mid station on the southwest arm at the Livingston site.

FIGURE 16. The Corner Station from Main Entrance at Hanford Site.

FIGURE 17. Finishing the Concrete Work at End Station at the Livingston Site.

7.0 Detector (WBS 1.2)

Detector activities are organized according to the LIGO WBS as follows:

- WBS 1.2.1 Interferometer System, organized into three major task groups, each responsible for several subsystems:
  - Suspensions and Isolation
    - Seismic Isolation
    - Suspension Design
  - Lasers and Optics
    - Prestabilized Laser
    - Input/Output Optics
    - Core Optics Components
    - Core Optics Support
  - Interferometer Sensing/Control
    - Alignment Sensing/Control
    - Length Sensing/Control
- WBS 1.2.1.9 Detector System Engineering/Integration
- WBS 1.2.2 Control and Data Systems
- WBS 1.2.3 Physics Monitoring System
- WBS 1.2.4 Support Equipment

While we continue to report progress separately for R&D activities and Detector activities, the task groups enumerated above include the relevant R&D (most laboratory activities and exploratory modeling) with the objective of concentrating the activity on a given domain. In addition, the Detector Site Implementation and Operations task group reports activities focussed on these topics and also the activities in the 40-meter Interferometer facility, which is a primary tool for tests of operations and integration for the Detector group.

7.1 Suspensions and Isolation

Significant accomplishments during this quarter

- Completed the Preliminary Design Review of the Seismic Isolation System.
- Performed tests of the Small Optics Suspension in the 40-meter interferometer.

Discussion of accomplishments and work in progress

Seismic Isolation. The Preliminary Design Review was held on March 5, and Hytec, Inc. initiated final design. The review was supported by a complete set of documentation and analyses which provide important information for the interferometer controls design.

There was significant progress to report in the spring design and test activities. Practical manufacturing approaches addressing a number of fabrication difficulties were found. Structural materials and glues for the interior of the coil springs were identified; an electron-beam welding process was tested for the hermetic seals on the coil ends; and several design and test cycles resulted in a design for the Fluorel (elastomer) seats which is mechanically stable and adds to the damping of the spring. Tests of springs in isolation and in one-stage isolation systems at the University of New Mexico, Sandia, and Caltech demonstrated acceptable damping and acoustic feedthrough, all within specifications.

A prospective vendor for the bellows was identified (Senior Flexonics, Inc.), and orders were placed for initial units for testing. The support and actuator system design was refined to add tilting degrees-of-freedom and to stiffen the overall structure and make it more compact. A detailed installation scenario was developed, and the design of installation fixtures began.

Suspension Design. The Small Optic Suspension prototype was installed in the 40-meter interferometer (suspending the beamsplitter), where it was subjected to system and noise tests. The measured *Q*s of the suspension wires and the optic substrate are acceptable for the 40-meter and for LIGO when scaled for the mass size. An alternative 'dumbbell'-shaped standoff for the magnets was developed which makes the assembly more robust without loss of performance. A counterbalancing scheme was developed to allow the initial tilt of the mirror to be brought to a small fraction of the dynamic range of the suspension actuators allowing greater tolerance in initial assembly and greater servo robustness (via the larger available headroom).

Finite-element modeling of the Large Optic Suspensions (test mass and beamsplitter) continued with the objective of stiffening the structure and improving 'manufacturability.'

Work planned to be accomplished next quarter

- Seismic Isolation. Prototype readiness reviews; start of fabrication of first article.
- Suspension Design. Small Optics Suspension completion of Final Design.

7.2 Lasers and Optics

Significant accomplishments during this quarter

- Prestabilized Laser. Completed and tested 10W Brassboard lasers by Lightwave, Inc.
- Input Optics. Prototyped the phase modulation scheme.
- Core Optics. Polished several production test masses.
- Core Optics Support. Performed the Design Requirements Review.

Discussion of accomplishments and work in progress

Prestabilized Laser. Lightwave, Inc. continued development of the LIGO 10W Nd:YAG laser, and the Preliminary Design Review was held on April 25. Brassboard prototype lasers have been constructed which easily provide 10W with good beam quality (95 percent of the power in the TEM_{00} mode) and stability. The final design is underway with the Final Design Review planned early during the next quarter. Some reliability problems with the lower-powered 700mW lasers used as the light source for the 10W laser (and some laboratory activities, see below) are being addressed by a Lightwave reliability plan with the objective to increase the lifetime at the rated power. No net effect on schedule or performance is expected.

The requirements and conceptual design work for the complete Pre-Stabilized Laser has progressed. A prototype stabilized laser based on these conceptual designs, using a Lightwave 700mW laser as the light source, was tested and is now installed on the Phase Noise Interferometer at MIT for high-sensitivity measurements of frequency noise and subsequent use in that experiment. The results are encouraging; the performance requirements for the initial LIGO have been met in a wide range of detection frequencies. As the quarter closes, preparations are underway for the Design Requirements Review. A collaborative effort continues with Stanford University for the design of a spatial and temporal filtering cavity which may be needed for the laser subsystem.

Input Optics. The University of Florida group responsible for the Input Optics is continuing the Preliminary Design. Visits by both LIGO and University of Florida staff are maintaining the close contact needed for integration of the effort which is focused on the design of the mode-matching telescope between the mode cleaner and the main interferometer optics. One of the challenges is to accommodate the thermal lensing anticipated in components on both sides of the optics chain, and a three-mirror ‘zoom’ configuration has been identified which gives ample margin. Detailed layouts (using the common design tools selected by the LIGO detector engineering team) are used to verify interfaces and dimensions. Prototypes have been developed that demonstrate two approaches to the modulation system: a Mach-Zehnder parallel-arm interferometer, where the multiple modulations are imposed on spatially separated beams and then interferometrically recombined, and a system of phase- and amplitude-modulators in series in which cross-products of the modulation frequencies are canceled through linear additions. A meeting will be convened early next quarter at MIT to discuss the requirements and the conceptual designs for this aspect of the Input Optics.

Core Optics Components. The first polished substrates for the optics to be installed in LIGO were completed. General Optics (GO) and the Commonwealth Scientific and Industrial Research Organization (CSIRO) both delivered parts for pre-coating metrology. The suppliers of substrate material, Heraeus GMBH and Corning Inc., are experiencing delays in production of material; this has not yet affected the overall schedule but is being monitored. On-campus work has concentrated on studies of thermal lensing due to substrate and coating absorption. A compensation approach has been identified which optimizes for our anticipated power and absorption, and gives a wide tolerance for variation about that point. In addition, the first coatings from REO have been analyzed and the results provided to REO for the second round of pre-production test mass coating trials. In-house metrology activities included a review of detailed construction drawings of the reflection-transmission scanner and the receipt of bids for the 1064 nm phase-shifting interferometer.

Core Optics Support. A Design Requirements Review was held on April 4 for the core optics support subsystem which is responsible for handling the light leaving the interferometer including the principal output beams from which the gravitational-wave will be read and the other control signals developed, and also the stray light within the end and vertex stations, and the design of baffling for its control. In addition to a set of requirements, specific conceptual designs have been developed for telescopes used to couple the light out and for baffling stray light. The preliminary design is now underway.

Work planned to be accomplished next quarter

- Prestabilized Laser (PSL). Hold the Design Requirements Review for the Pre-Stabilized Laser.
- Input Optics. Complete and review the preliminary design.
- Core Optics. Complete and review the preliminary design.
- Core Optics Support. Continue the preliminary design.

7.3 Interferometer Sensing/Control

Significant accomplishments during this quarter

- Alignment Sensing/Control. Began prototyping the initial alignment tools.
- Length Sensing/Control. Identified photodiodes for the main strain calibration sensing.

Discussion of accomplishments and work in progress

Alignment Sensing/Control. Final Design activities, which started this quarter, concentrated on the initial alignment which is the first component of the system scheduled to be installed. Coordination with the overall installation scenario was required (e.g., some initial alignment requires that the vacuum equipment be at atmospheric pressure while at other times a vacuum is required). Once these issues were resolved, beams were laid out and the optical ports for optical levers were assigned; detailed part drawings were produced, fabrication of prototype parts started, and orders were placed for commercial pieces. There was also some work on the systems/sensor design including optimization of sensor positions for robustness, interaction with the quadrant photodetector manufacturer regarding layout details, and generation of requirements for beam quality to aid in the design of the Core Optics Support output coupling telescopes.

Length Sensing/Control. The rate of progress in this subsystem has been slower than planned largely due to the assignment of staff to critical experiments taking place in the 40-meter (recycling) and six-meter (phase noise) suspended interferometer experiments. These experiments provide information required for the length control design, and progress there is directly relevant to the subsystem design. Progress has been made on the preliminary design with the development of detailed servo-control system models (integrating our best knowledge of the seismic noise, performance of the Hytec seismic isolation stacks, and detailed models of the suspension transfer functions), the exploration of locking scenarios through numeric modeling, the development of requirements and a conceptual design for the primary and secondary strain sensitivity calibration systems, and the characterization of photodiodes. The indium-gallium-arsenide photodetectors which have a very high quantum efficiency for 1064 nm light are a relatively young technology, and the manufacturers know little about performance limits. In-house measurements have shown that commercial units demonstrate remarkable linearity at very high fluxes (roughly 0.5 W for a 2mm-diameter device) and electrical characteristics allowing use at the planned 25 MHz modulation frequency. This eases the LIGO photodetector design, which will use several (but not many!) devices to detect the average 600mW at the output of the interferometer. These photodiodes were also used to measure the technical noise in a Lightwave 700mW laser with an unprecedented precision providing information for the Pre-Stabilized Laser design work.

Work planned to be accomplished next quarter

- Alignment Sensing/Control. Continue final design; test initial alignment prototypes.
- Length Sensing/Control. Complete and review the Preliminary Design.

7.4 Detector System Engineering/Integration

Significant accomplishments during this quarter

- Contamination studies were planned and started.

Discussion of accomplishments and work in progress

A new initiative was started to qualify in-vacuum materials and processes for their optical contamination properties. There are two measurement approaches: precision outgassing measurements and surface characterization, and direct optical contamination measurements. The outgassing measurements involve the establishment of a very clean vacuum system instrumented with a Residual Gas Analyzer, and means for calibration, bake-out, control of pump speed, and overall pressure. Direct optical measurements require high-finesse Fabry-Perot cavities in an initially very clean vacuum chamber, a laser source, and a servo-control system to maintain resonance. In either experiment, samples of possible contaminants are introduced after establishing a baseline performance. These systems were designed and components ordered during this quarter, and some initial measurements made on partial setups.

The integrated layout drawing set including the optical layout became standard tools during this quarter, ensuring interface consistency. Several inter-subsystem issues were resolved, notably the length control interfaces and sensor/actuator hierarchy for the Pre-Stabilized Laser, Input Optics, Length Sensing/Control, and Suspensions/Seismic Isolation.

Work planned to be accomplished next quarter

- System Design Requirements. Complete the second Design Requirements Review.
- Contamination. Review first results from optical and non-optical testing.

7.5 Control and Data Systems (CDS) Activities (WBS 1.2.2)

Significant accomplishments during this quarter

- The computer network at Hanford was established.
- A complete LIGO data acquisition system was completed and successfully operated.

Discussion of accomplishments and work in progress

There is now a significant CDS presence at the LIGO Hanford site, and the complete computer network is installed at the site. Vacuum Controls hardware and software were being developed this quarter with, at one point, one-half of the CDS staff located on-site. Four of seven racks of Vacuum Controls electronics were finished and are being tested.

Support for Interferometer Subsystems. The CDS Design Requirements Review was held this quarter for the Alignment Sensing and Control system, which represents probably the most complicated design problem for the interferometer. A breakthrough in the design for the analog output amplifier of the suspension controller has allowed the large dynamic range requirements of this subsystem to be met; this system must not add displacement noise to the masses, yet must have sufficient control 'authority' to allow initial alignment and tracking of medium-term drifts.

Global System and Data Acquisition. Development of the full prototype data acquisition system was finished this quarter, and some initial data was acquired from the 40-meter interferometer. This involved hardware design and construction (e.g., anti-aliasing filters and interface amplifiers) as well as software (e.g., a 50-channel software oscilloscope for monitoring locking transients). The system writes data 'frames' using the standard developed by VIRGO and LIGO, and refinements in that format were made based on the experience gained with this system.

Work planned to be accomplished next quarter

- Interferometer Controls. Complete the Design Requirements Review for the Pre-Stabilized Laser and the Length Sensing and Control; complete the Preliminary Design Review for the Suspensions.
- CDS integration and global systems. Complete the Final Design Review for the Global CDS; issue requests for proposals (RFPs) for the Hanford fiber optics and control room systems.
- Data acquisition. Complete the Preliminary Design Review for Data Acquisition.
- Vacuum system controls. Complete Hanford system assembly and test including software; procure components for Livingston system and begin assembly.

7.6 Physics Environment Monitor (WBS 1.2.3)

Significant accomplishments during this quarter

- Using computer models, demonstrated that the number of false alarms from cosmic muons will not be important.

Discussion of accomplishments and work in progress

The final design continued for the Physics Environmental Monitor. Much of the activity targeted early measurements of correlations of variables (seismic, magnetic, radio-frequency signals) to be made before there is significant 'self-pollution' of the environment. High-sensitivity magnetometers were designed, protoypes were constructed, and plans for measurements were developed. A Monte-Carlo study of cosmic muons led to a refined estimate for the disturbance of the test masses due to energy deposited in them by passing particles; it appears that this will contribute an insignificant number of 'false alarms' in coincidence between sites.

Work planned to be accomplished next quarter

- Complete the Final Design Review.
- Make on-site measurements of possible inter-site correlated environmental effects.

7.7 Support Equipment (WBS 1.2.4)

Definition of the required Support Equipment will continue.

8.0 Research and Development (WBS 1.3)

Significant accomplishments during this quarter

- Successful locking with high-transmission cavities in the 40-meter Interferometer
- First measurements made with the 1064 nm Phase Noise Interferometer
- Confirmation of length-control model on the Fixed Mass Interferometer

Discussion of accomplishments and work in progress

40-meter Interferometer Investigations. The intermediate configuration of the 40-meter for recycling (a non-recycled Fabry-Perot Michelson, using asymmetry readout) was the focus of research this quarter. The low-finesse arm cavities (appropriate for the recycling experiment) required significant changes to the servo-control system, and interactions between the arm cavities and the Argon pre-stabilized laser resulted in new insights into these control systems. Once reliable locking was obtained, data needed to establish the power recycling mirror characteristics were obtained from measurements of visibility, ringdown, beam splitter transmission-loss and mode matching studies. The transmission of the input mirrors was inferred from observations of the input coupling and losses in each arm. This task proved more difficult than anticipated because of initial discrepancies found between these inferences and direct measurements of transmission made earlier in the Optics Test Facility. This motivated a refinement of the ringdown measurement technique which resolved the apparent discrepancies and allowed the coating of the recycling mirror to be specified. Enhanced understanding of the ringdown technique may be useful in the future development of diagnostic techniques for LIGO. A 15 percent transmission (factor of eight recycling) was selected.

A new RF reference source with a modulation frequency of 32.7 MHz was installed. The change from 12.3 MHz to 32.7 MHz is required for operation in power re-cycling mode. The tuned circuit driving the Pockels cell was also changed to be compatible with the new 32.7 MHz reference source.

The wave front sensor electronics used in the wave front sensing experiment at MIT have all been shipped to Caltech for installation in the 40-meter interferometer to improve reliability and to study the wavefront sensor system in a long-storage-time interferometer. The transfer functions of the end mass and vertex test mass suspensions have been measured so that the servo loops can be designed.

Development of Data Acquisition and Analysis Techniques. As reported above, the prototype LIGO data acquisition system was deployed for use with the 40-meter, and this was a joint effort of the CDS and 40-meter team. It is now being used as a powerful debugging tool, and some data has also been acquired for post-analysis as a system test.

Phase Noise Research. The first phase of the research using the Phase Noise Interferometer with Nd:YAG Infrared light started this quarter. The system consists of the 700mW pre-stabilized laser (see Pre-Stabilized Laser in the Detector section), and two suspended in-vacuum masses forming a quiet reference Fabry-Perot to allow sensitive tests of the laser. Initial measurements have been made with this configuration, and the performance of the laser (and thus the overall system) are very encouraging. Figure 18, shows the frequency noise of the laser measured using the separate

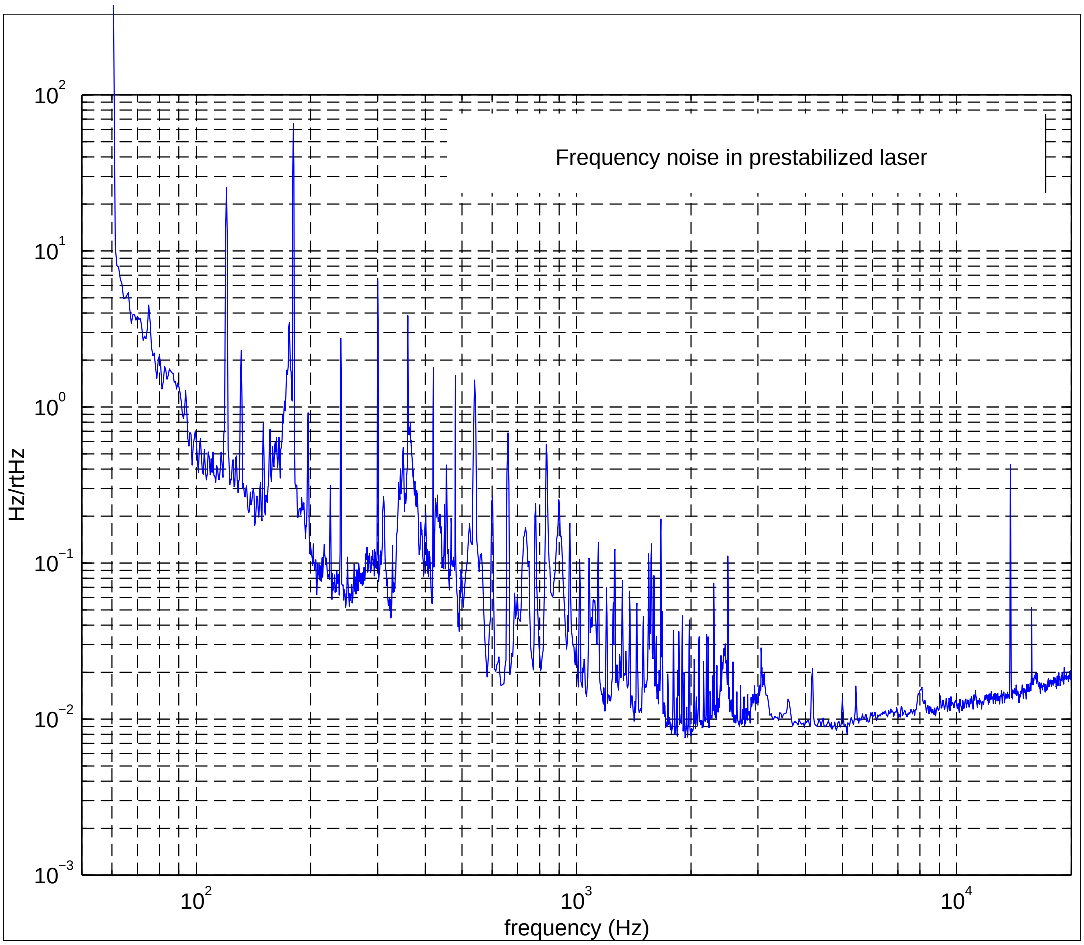

FIGURE 18. Frequency Noise in Prestabilized Laser

suspended cavity. The servo configuration for this measurement is a simplified one in which the laser is only stabilized to its own reference (and not to the suspended cavity); the performance is close to that required for the initial LIGO Pre-Stabilized Laser, reaching $10^{-2}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ in abroad range of frequencies. The Phase Noise Interferometer will require a stabilization to some $6\times10^{-3}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ over the measurement band, but using the suspended recycling cavity as a secondary reference. The configuration is being changed to that one as the quarter closes.

Some important technical work was carried out to allow this measurement. In particular, wavefront sensing and closed loop alignment controls were introduced, and a very careful diagonalization of the suspension sensor-to-controller matrix made. These efforts both help to reduce cross-coupling from undesired motions (angular, transverse) to the sensitive longitudinal axis.

Interferometer Alignment Investigations. One last measurement was made on the Fixed Mass Interferometer which had been constructed for alignment investigations: A carefully calibrated measurement of the length control matrix was performed, and good agreement with the model achieved. A letter for publication was drafted.

Thermal Noise Investigations. No significant activity to report this quarter.

Work planned to be accomplished during the next quarter

- 40-meter Interferometer:
  Recombination and Recycling. The recycling mirror will be installed and the shakedown of the full recycled interferometer will begin.
  Data Acquisition and Analysis. The data acquisition system will be thoroughly exercised. A datastream of moderate length will be taken to test streaming to multiple tapes and to allow use of analysis routines designed to look for trends in data.
- Phase Noise Demonstration: The remaining optical components will be installed in the vacuum system, and full Phase Noise Interferometer characterization started.

9.0 Systems Engineering (WBS 1.4.3)

9.1 Integration (WBS 1.4.3.1)

Significant accomplishments during this quarter

- Developed a detailed schedule and cost estimate for the Beam Tube Bake.
- Issued draft Reliability Prediction Reports for the Suspension System and the Physics Environment Monitoring System; draft Reliability Prediction Report for Data Acquisition is in-process. Preliminary reliability allocations and fault trees were developed for the Pre-stabilized Laser in support of the Design Requirements and Conceptual Design Documents.
- Completed the redesign and validation of the new beam tube baffles. Resumed installation of baffles into the beam tube, developed a recovery plan in concert with the facilities group to place baffles into the first X module affected by the discovery of the glaze shedding problem.
- Completed the mock-ups for the chamber shells (Horizontal Access Module and Beam Splitter Chamber); now developing mock-ups for the Seismic Isolation systems.
- Completed the design and initiated fabrication of Core Optics Containers for transportation of finished test masses from polishers to LIGO and to the observatories.
- Jointly with the Science Team held a quarterly LIGO Science and Integration Meeting at Caltech at the end of May. A continuing dialog on various key issues regarding future Advanced R&D plans and the use of the Caltech and MIT facilities was initiated at that meeting. (See the proceedings issued for the two-day session for more details.)

Discussion of accomplishments and work in progress

Vacuum Equipment - Civil Construction Interface Control Document (ICD). A revised LIGO block diagram has been developed, and the ICD is being revised to reflect modifications in electrical interfaces.

Integration Planning - WA site schedule. Systems Engineering and Hanford Observatory management are developing schedules for integration of the detector components into the WA observatory. The first schedule being developed is for the vertex Michelson configuration of the 2km interferometer.

Beam Tube Bake. A detailed schedule and cost estimate for the Beam Tube Bake has been developed. LIGO is hiring additional staff to carry out the vacuum bake at the Hanford site, which will be baked first. A GFE source (Fermi National Accelerator Laboratory) for DC current supplies capable of providing sustained power to the beam tubes for resistive heating during the bake has been identified.

Reliability Support. Reliability data was obtained from a number of Physics Environment Monitoring (PEM) System equipment suppliers and VME circuit board suppliers. This information was then incorporated into preliminary Reliability Prediction Reports for the Suspension System and the PEM System. In addition, preliminary reliability allocations and fault trees were developed for the Pre-stabilized Laser in support of the Design Requirements and Conceptual Design Documents.

LIGO Core Optics Containers. Eight core optic component carriers were completed and shipped in fitted shipping containers. (See Figure 19 and Figure 20 below.)

FIGURE 19. Core Optics Shipping Container

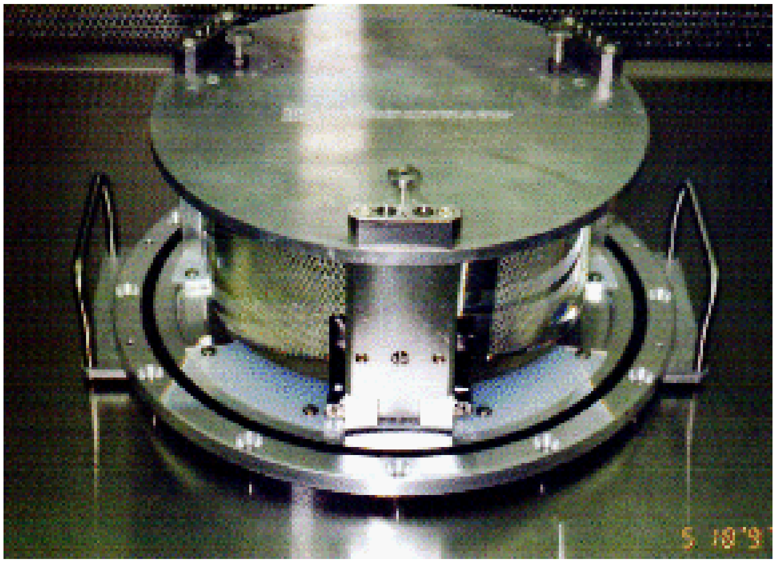

FIGURE 20. Core Optics Carrier

Mock-up Development. The Horizontal Access Module (HAM) seismic isolation system mock-up has been completed and is installed. The Beam Splitter Chamber (BSC) seismic isolation system mock-up design is 60 percent complete; large components have been sent out for fabrication.

Integrated Layout Drawing. The Hanford, Washington Laser and Vacuum Equipment Area (LVEA) integrated layout drawing has been updated to reflect as-built details for both Process Systems International (PSI) vacuum chambers and civil construction details. Work is proceeding on the Vacuum Equipment Area (VEA) layouts for the mid- and end-station buildings.

Work planned for the next quarter

- Complete the draft Reliability Prediction Reports on the Suspension Systems, Physics Environment Monitoring Systems, and Data Acquisition Systems. Continue development of subsystem fault trees and reliability predictions as Preliminary Design Review information becomes available.
- Completed Seismic isolation system mock-up and integrate with the BSC chamber mock-up.
- Support Detector integration planning by identifying installation sequences needed to be checked with the mock-up facilities. Identify potential integration problems before they are discovered in the field. Identify support equipment/jigs/etc., needed to permit component installation.

9.2 Simulation, Modeling and Data Analysis

Significant accomplishments during this quarter

- Received first version of the time-domain (dynamic) modal model code for LIGO; completed the first test suite for validation and verification of the working code.
- Completed a detailed analysis of computational requirements to be implemented at the LIGO sites for on-line analysis.
- Outlined the initial LIGO data analysis system conceptual design and implementation.
- Completed a data analysis run using the new prototype data acquisition system at the 40-meter laboratory.
- Incorporated the LIGO/VIRGO Common Data Format into the 40-meter prototype acquisition system hardware and software. It is now possible to share data sets with VIRGO in this common format.

Discussion of accomplishments and work in progress

The time domain model of the LIGO interferometer provides length and alignment degrees of freedom. This code is cross-platform compatible--between SUN and PCs--and includes the interfaces for Fortran and C. The code is being validated and attempts made to improve processing speed.

The astrophysical analysis of LIGO data as a function of different computational system configurations was modeled using theoretical estimates of the number of templates required as a function of the minimal mass of a compact binary component. The model included the details of all floating point operations performed in the baseline optimal filtering scheme, the data storage requirements for the large number of template waveforms predicted by theory, and the I/O performance for data transfer between storage and nodes in a parallel computing environment. Based on this study LIGO expects to be able to look for binary inspiral objects greater than one solar mass.

During May the 40-meter interferometer was run to collect data using the newly installed prototype data acquisition system. The interferometer would not lock during this run, but the system was still exercised (without the gravitational wave channel) to demonstrate integration of components including the real-time acquisition system, the common LIGO/VIRGO data format (FRAME) software, quick-look channel visualization software, the tape archival system, and the on-line data analysis software. Even without interferometer locking, the exercise turned out to be a major success for demonstrating LIGO's ability to handle gravitational physics data.

The GRASP (Gravitational Radiation Analysis and Simulation Package) data analysis software has been upgraded to work with frames from the common LIGO/VIRGO data format I/O library. This has allowed GRASP to work with data analogous to LIGO data. These two software packages (Frame I/O library and GRASP) are now available to an increasing audience of users. Both software packages were originally developed on Sun and Alpha computing platforms. In an effort to increase the number of platforms supported and demonstrate the portability of the software, both packages were ported to a PC running the LINUX operating system. The port was successful and opens the door for prototyping LIGO data analysis on a widening arena of hardware platforms.

Work planned to be accomplished next quarter

- Validate and document the end-to-end model framework. The 40-meter experiment results will be compared with model predictions to understand the quality/reliability of the model. The strategy of including the alignment degree of freedom in the cavity calculation and in the control system model will be studied and implemented.
- Implement an object-oriented graphical user’s interface (GUI) front end for the full LIGO interferometer model.
- Finalize a formal specification jointly with the VIRGO Experiment to define and implement a controlled Common Data Frame Format.

10.0 LIGO Visitor's Program

Richard Gustafson, Keith Riles - University of Michigan. Richard Gustafson has been resident at the 40-meter facility since October 1996. Gustafson and Riles are preparing an amendment MOU for LIGO I. Both plan to be heavily involved in the commissioning and data analysis activities. The critical path to gravity wave detection lies substantially in operational progress with the hardware, dealing with noise sources, and advancing the art at the 40-meter facility and the sites.

Keith Riles is obtaining the GRASP software (see below) and an early 40-meter tape to start analysis at the University of Michigan.

Bruce Allen - University of Wisconsin, Milwaukee. Dr. Allen has been at LIGO as a visitor/collaborator since August 1996, and plans to stay through August 1997. He also visited LIGO for five months at the end of 1995. Dr. Allen's work is in data analysis. This work is important for the timely development of a LIGO data-analysis infrastructure. The techniques which he is developing are being tested on data from the 40-meter prototype.

During Dr. Allen's visit, he has developed a data analysis package called GRASP (Gravitational Radiation Analysis and Simulation Package). This is a C-language object library of functions, together with documentation and source code. These functions are designed to allow analysis of interferometer data using the standard and specialized techniques described in the literature. The package can be used to compare new data analysis techniques with existing ones, and to study the behavior of data analysis algorithms on simulated noise or on real interferometer output. It can also be used to study such practical issues, such as the choice of whitening filters, the effect of non-linearities in the detector transfer function, effects of quantization noise in the analog to digital conversion, etc.

Work accomplished during this quarter

- On eight LIGO workstations, used MPI "multi-filter" code to filter five hours of 40-meter data through an optimally-spaced filter bank in three hours and four minutes (new record!). The 66 filters covered the mass range from 1.2 to 1.6 solar masses. Optimized code for Intel paragon machine. Can filter five hours of 40-meter data in 10.3 minutes on 256 processors.
- Wrote translator code that converts data from the old 40-meter format to the new LIGO/VIRGO frame format. Resolved time-stamp problems with the old-format data.
- Ported GRASP to DEC alpha, LINUX, Intel Paragon, IBM SP2, and HP UNIX operating systems. Implemented/tested spectral line removal algorithm. Successfully tracks/removes all 60 Hz harmonics, violin modes. Section on black hole ring-down searching added.
- Created frame format versions of all GRASP examples. Assisted VIRGO to identify and repair memory "leaks" (subroutines that terminate without returning memory allocated) and other problems with the FRAME library.
- Created real-time versions of all GRASP code for the 40-meter lab.

11.0 REFERENCES

1. Cooperative Agreement No. PHY-9210038 between the National Science Foundation, Washington, DC 20550 and the California Institute of Technology, Pasadena, CA 91125, May 1992.

2. *The Construction, Operation, and Supporting Research and Development of a Laser Interferometer Gravitational-Wave Observatory,* proposal submitted to the National Science Foundation, December 1989.

3. *Technical Supplement to the LIGO Construction Proposal (1989)*, dated May 1993.

4. *LIGO Project Management Plan*, LIGO-M950001, Revision B, April 24, 1996.

5. *LIGO Cost Book*, dated September, 1994.

6. *LIGO Supplement for Installation, Commissioning and Operations*, LIGO-M950039, August 1995.

7. Cooperative Agreement No. PHY-9210038 between the National Science Foundation, Washington, DC 20550 and the California Institute of Technology, Pasadena, CA 91125, Amendment No. 5, April 20, 1995.

8. Cooperative Agreement No. PHY-9210038 between the National Science Foundation, Washington, DC 20550 and the California Institute of Technology, Pasadena, CA 91125, Amendment No. 11, August 23, 1996.

9. Report of the Panel on the Use of the Laser Interferometer Gravitational Wave Observatory, Boyce McDaniel, Chair, United States National Science Foundation, June, 1996.