Quarterly Progress Report

(June 1996 through August 1996)

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

NSF Cooperative Agreement No. PHY-9210038

September 1996

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

NSF COOPERATIVE AGREEMENT No. PHY-9210038

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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 June 1, 1996 through August 31, 1996.

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

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1.0 Executive Summary

Notable progress continued this quarter as the Project approaches full construction activity. LIGO staff have begun to relocate to the Hanford site. Otto Matherny, Washington Site Manager, relocated to Hanford during the last quarter. This quarter he was joined by John Worden, Cecil Franklin, and Richard Riesen who will oversee installation of the Beam Tube and Vacuum Systems.

A prototype Beam Splitter Chamber (BSC) has now been fabricated and tested for leaks by Process Systems International (PSI). This chamber is being 'baked' to remove residual gases. The process of baking also provides an opportunity to evaluate the heater blankets and control system which will be used to bake all of the large vacuum vessels. The BSC and the bake equipment both appear to be working well. Evaluation of the ultra-high vacuum (UHV) cleaning process will follow. The first large ion pump has been delivered to PSI for testing.

Vacuum Equipment deliverables required to support the Beam Tube contract are also being delivered to the site. Pump carts and chiller carts have already been delivered and inspected. The first large gate valve which terminates a Beam Tube module is in final test at GNB. It is scheduled to be shipped to the Washington site on September 13.

The spiral mill was shipped from Pacific Roller Die (PRD) and received at the Chicago Bridge and Iron (CB&I) Big Pasco facility on July 8. The spiral mill has been commissioned and almost all of the equipment in the factory is now operational. A successful preliminary Fabrication Readiness Review was held August 21 at the Big Pasco facility. Fifteen production quality Beam Tubes have been welded.

A total of 300 baffles have been fabricated by Capital Industries, and shipped to West Coast Porcelain. West Coast has coated 200 of the baffles (as of early September) and will complete the remaining 100 early in September. One hundred baffles are being cleaned at the Jet Propulsion Laboratory (JPL) and will be shipped to Hanford during the first half of September. All baffles required for the first arm will be at the site in Washington by the end of September.

Concrete slabs for both arms at Hanford were completed early in June. Acme has also fabricated over 900 of the precast Beam Tube Enclosure (BTE) sections.

The contract for the construction of the buildings at Hanford was awarded to Levernier Construction, Incorporated, on July 17, 1996. Excavation of the area for the corner station is complete, and concrete footers for the mid- and end-stations are now being poured.

Levernier also submitted the winning bid for installation of the BTE, and the contract has been submitted to NSF for approval.

Parsons completed the bid package for the BTE, site work, and precast fabrication of the enclosure segments for the Livingston, LA site. Parsons also completed the bid package for the buildings at Livingston. The bid packages were issued to 68 potential bidders as of the end of August. The job walk occurred on August 28. The bid opening is scheduled for October 15, 1996.

One hundred thirty-one days have been lost due to inclement weather and wet soil conditions in the Livingston, LA rough grading work. However, only 65,000 cubic yards of dirt remain to be moved, and it is estimated that this work can be finished in less than ten dry working days.

Bids have been received for the mirror blanks, and contracts have been awarded to Corning Glass and to Heraeus Amerisil for different types of material. A total of nearly one-half ton of fused silica has been ordered. The National Institute of Standards and Technology (NIST) has completed all large aperture (15-centimeter diameter) absolute phase-map measurements of the Pathfinder surfaces provided to them. Agreement with the results previously provided by the polishing vendors is good. Solicitations for polishing the Optics are now being prepared.

A review of the HYTEC, Incorporated, design effort on the Seismic Stack was conducted at Caltech on June 28, 1996. The follow-on contract for design and fabrication of prototypes has been approved by NSF.

The Phase Noise Interferometer at MIT has been converted to a recycled configuration. A wavefront sensor was installed on the output of the interferometer to improve the alignment. The total power incident on the Beam Splitter is about 90 W. Preliminary noise measurements give a phase sensitivity of about 5×10^{-10} rad/Hz$^{-1/2}$ at high frequencies.

An active LIGO Visitors Program has been proposed, roughly equivalent to three full-time equivalents (FTEs) each year (more during later years), with individuals involved in research for periods of time six months or longer. Professor Kris Sliwa of Tufts University has just completed a 'sabbatical year' at MIT.

A collaboration with the University of Florida has started. Professor Douglas Tanner and Professor David Reitze have come to Caltech to participate actively in the development of the Input-Output Optics (IOO).

Figure 1 summarizes the cost performance status as of the end of August. The earned value (Cumulative-to-date Performance curve) indicates that the project is slightly behind schedule (approximately one month) and the actual costs are lagging the performance (less than one month), due to normal invoicing delays. Two budget plans are shown for comparison purposes: the April 1995 plan is that which was reviewed by NSF during the May 1995 Semi-annual review; the January 1996 plan reflects all change requests that have been approved since the May 1995 review, including those adjustments of the budgets implemented to reflect the negotiated prices for major contracts, the switch to the Nd3:YAG laser, the reorganization of the Detector and R&D efforts, and experience to date. The new plan was reviewed by NSF during the April 1996 Semi-annual Review.

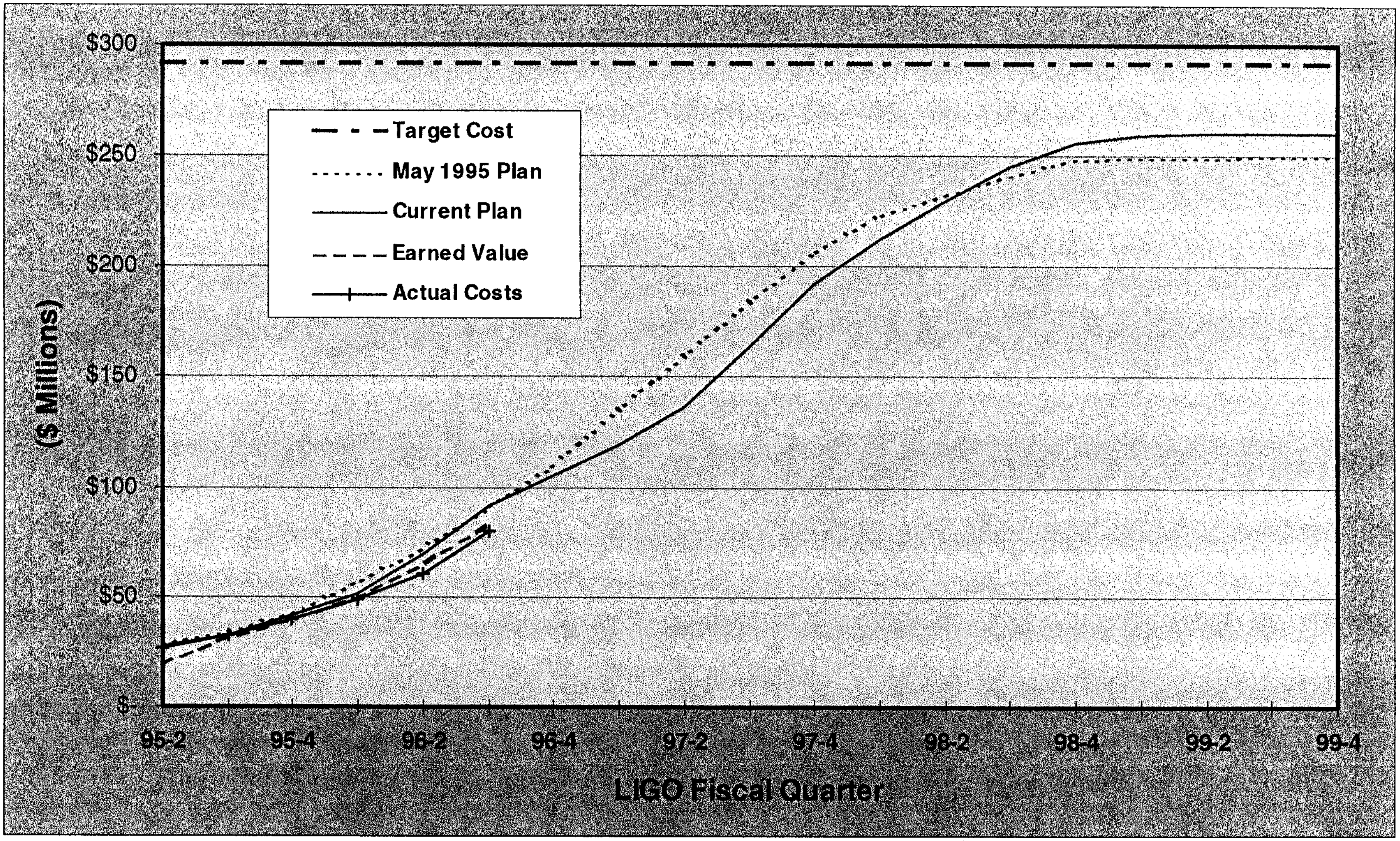


FIGURE 1. Cost Performance Status as of the End of August 1996

2.0 Facilities and Vacuum System (WBS 1.1)

2.1 Vacuum Equipment (WBS 1.1.1)

Significant accomplishments this quarter:

- Approved the Process Systems International (PSI) final design package.
- Received the Beam Splitter Chamber (BSC) prototype bake-out blankets and control cart.
- Completed fabrication of prototype BSC vessel by Ranor.
- Cleaned and leak tested prototype BSC vessel at PSI facilities.
- Received rough and turbo molecular pump carts at Washington.
- Completed fabrication of first two large gate valves at GNB.
- Began acceptance testing of first two large gate valves.
- Prototype main ion pump shipped from Varian in Italy to PSI.
- Began fabrication of Washington vessels.

Discussion of accomplishments and work in progress:

In June 1996 LIGO approved the PSI final design presented on May 22. PSI is currently updating the final design drawings to be consistent with the Washington civil construction package and the Louisiana bid package. These drawings will be submitted in September as the final version of CDRL 03. Also in June, PSI completed the first bake-out control cart and received most of the BSC prototype bake-out blankets. Figure 2 shows the bake-out control cart.

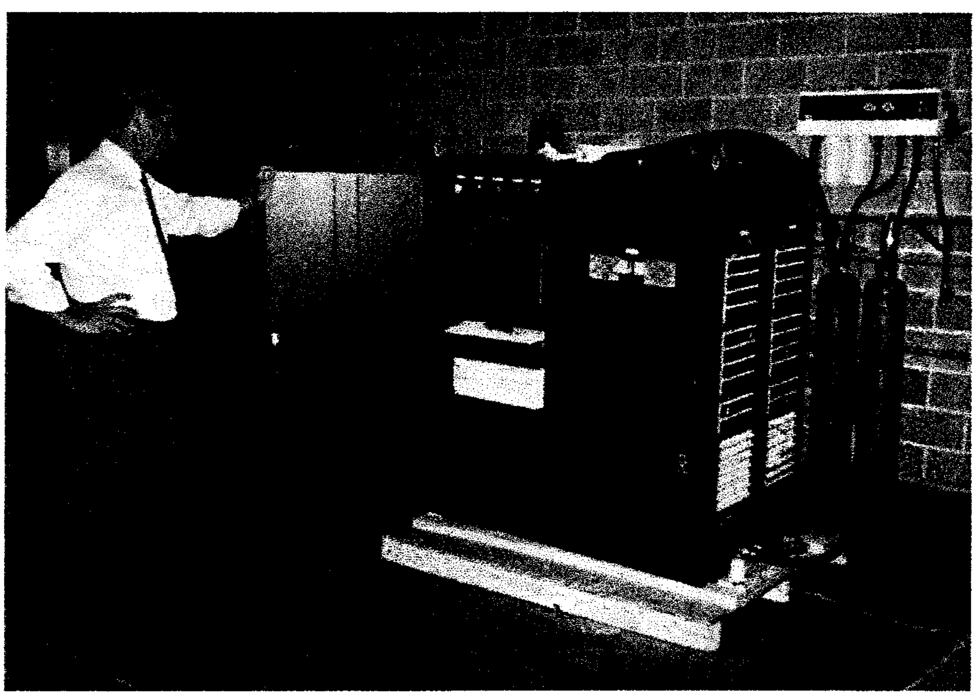


FIGURE 2. Bake-out Control Cart

In July fabrication of the prototype BSC was completed and the chamber was moved to PSI facilities. Figure 3 shows the completed prototype BSC at PSI. The prototype BSC has been cleaned and checked for leaks. Baking is under way as of the end of August, and residual gas analyzer (RGA) data will be available by mid-September.

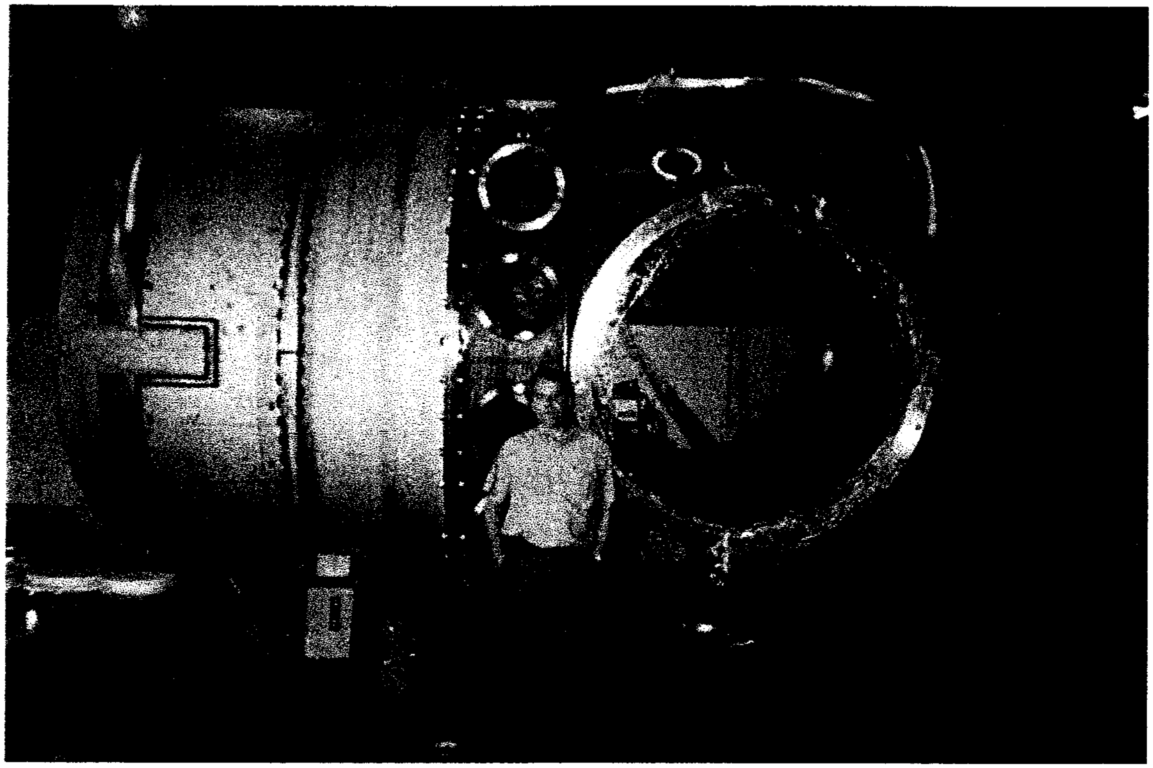


FIGURE 3. Prototype Beam Splitter Chamber

All pumping equipment required for pumping down the Beam Tube has been received at the Washington site. Figure 4 shows a turbo molecular pump cart ready for use at the PSI shop (identical to the turbo molecular carts shipped to the site).

The first two gate valves have been completed but testing is ongoing. The correction of problems, detected during testing of the prototype unit (valve 1), has resulted in a delay in completing the testing and subsequent shipping of the valves. However, the valves are expected to reach the Washington site before they are needed by the Beam Tube contractor, Chicago Bridge and Iron (CB&I). The prototype valve body can be seen in Figure 5 and the gate mechanism in Figure 6. Fabrication, assembly and testing of the prototype valve is currently proceeding at GNB in Hayward, California.

In August, after testing a prototype ion pump, Varian Vacuum Products of Italy shipped the first main ion pump to PSI. This pump will be subjected to further testing at PSI and the results will be presented at the end of September.

PSI started the production fabrication of the Washington vessels. Horizontal Access Module (HAM) chambers and the 80K pumps will be fabricated by PSI while the Beam Splitter Chambers (BSCs) will be subcontracted out to Ranor (who fabricated the prototype BSC). PSI has also

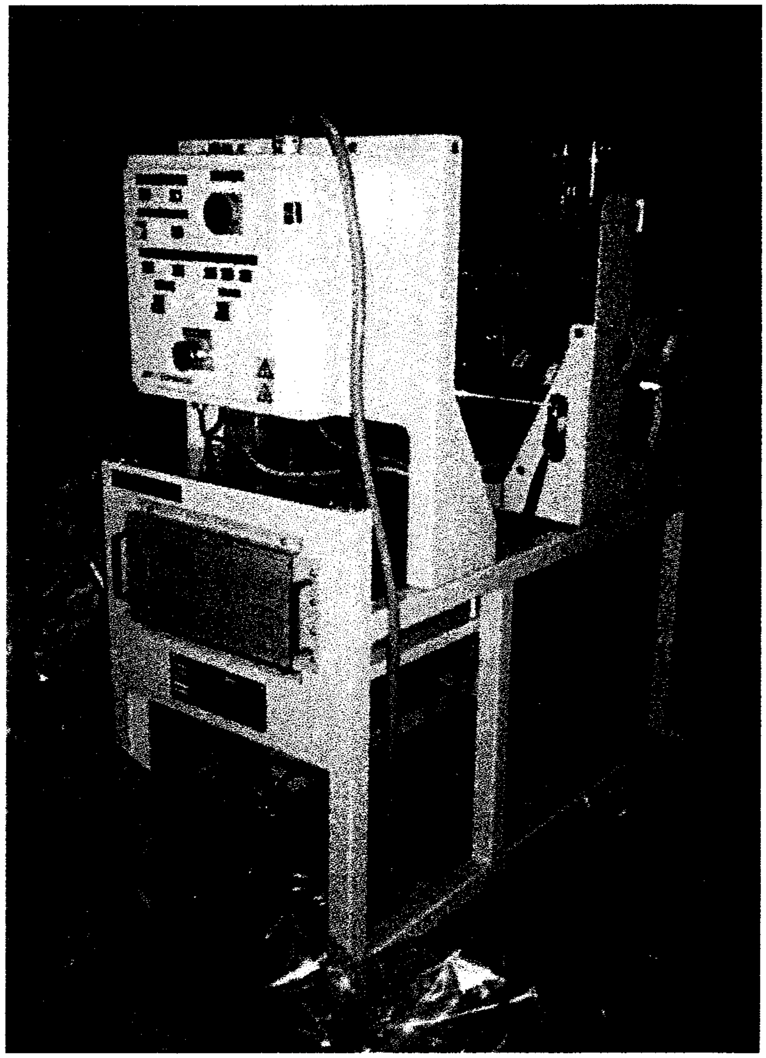


FIGURE 4. Turbo Molecular Pump Cart

decided to manage the fabrication of the portable clean rooms with the aid of a clean-room consultant.

Most major equipment orders have been placed, and recently a large order for stainless steel for the vessels was placed.

The preparation of final design drawings consistent with the Washington and Louisiana civil packages was the primary engineering activity this period.

Work planned next quarter:

- Deliver eight large gate valves to Washington site.
- Complete first 80K pump.
- Complete vacuum testing of prototype BSC.
- Complete vibration measurements related to boiling noise in first 80K pump.
- Complete testing of main ion pump.

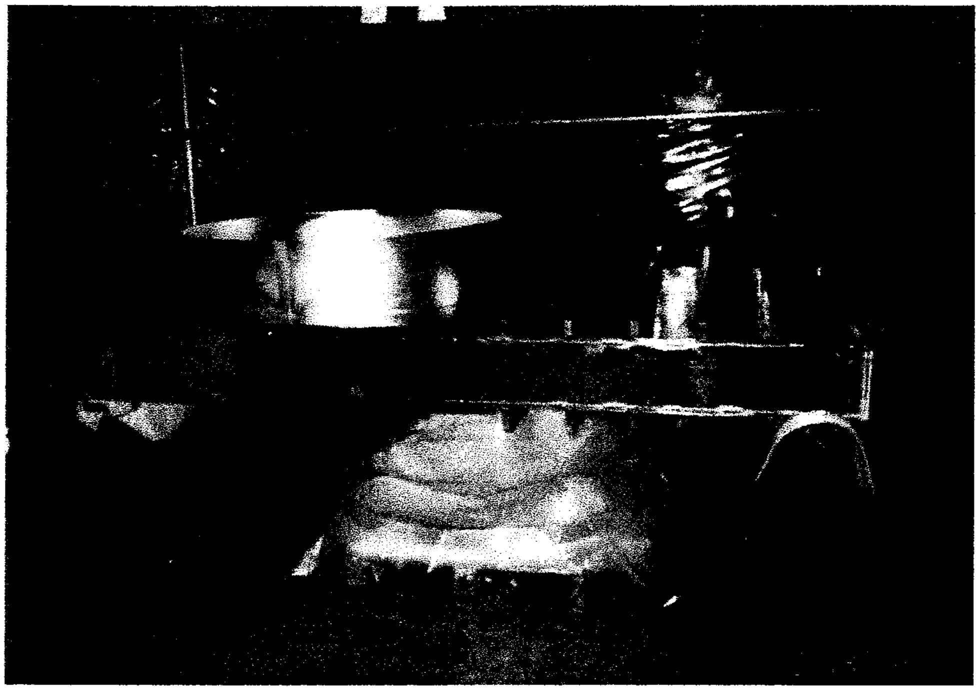


FIGURE 5. Gate Valve Body

- Present all results from prototype program.
- Place order for production quantities of bake-out system.
- Fabricate first article HAM chamber.

One significant milestone has been missed. The large gate valves were due to be shipped to the Washington site in mid-August. Instead, they will be shipped mid-September in time for the Beam Tube installation work.

FIGURE 6. Gate Mechanism

2.2 Beam Tube (WBS 1.1.2)

Significant accomplishments this quarter:

- Incorporated recommendations from updated design review into Beam Tube design.
- Completed fabrication facility modifications for production.
- Qualified spiral tube mill performance, including effect on hydrogen outgassing of weld material.
- Qualified most fabrication equipment and fixtures.
- Processed stainless steel coil batch #2; batch #3 partially processed.
- Fabricated and tested sixteen expansion joints.
- Began Beam Tube fabrication: spiral welded ten tube sections (each 20 m long).
- Fabricated and coated over 80 baffles.

Discussion of accomplishments and work in progress:

Chicago Bridge and Iron (CB&I), the Beam Tube contractor, requested and was granted permission to use all qualified tube sections, produced prior to the Fabrication Readiness Review, as production sections. This action will allow a more thorough demonstration of readiness and provides effective use of shop labor during start-up when some items experience schedule slippage.

All fabrication equipment was purchased and installed in CB&I's fabrication shop at Big Pasco, WA. When the contractor for hoists revealed that his installation could not meet CB&I's schedule, CB&I assumed responsibility for the installation task for the structural steel rails and supports (Figure 7) and met the schedule. A rail conveyor system was installed to efficiently move the long tube sections between building columns.

The custom spiral mill was fabricated and qualified at the Pacific Roller Die (PRD) facility in Haywood, California, using both 24-inch wide and 36-inch wide coils. Outgassing measurement coupons were cut from spiral welds of 20 in/min and 40 in/min; testing confirmed that hydrogen outgassing levels were significantly less than that experienced during the qualification test. The mill was moved and set up in CB&I's fabrication facility at Big Pasco, WA. Figure 8 shows the spiral tube mill installed at Pasco. Ten tube sections were spiral welded and started through the subsequent production processes.

Custom equipment was purchased, set up, and programmed for welding the stiffening rings to the tube sections. Figure 9 shows the stiffening rings being welded to the Beam Tube. The program indexes the weld equipment between rings and rotates the tube according to the tube's helix angle to prevent the ring weld from overlapping the spiral weld.

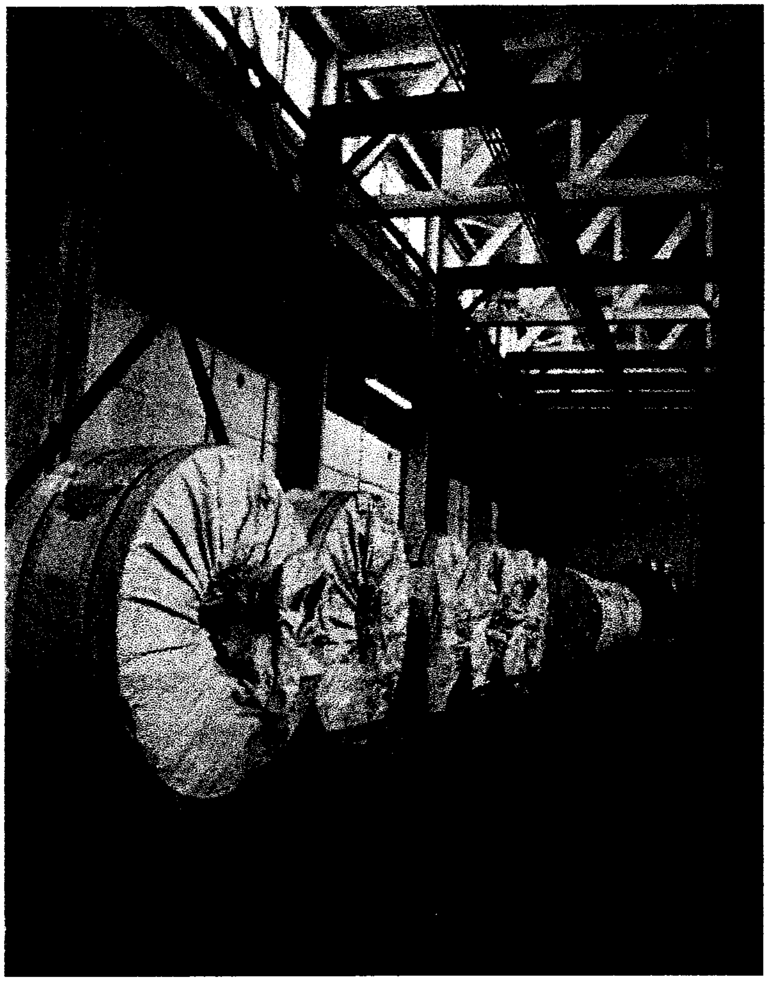


FIGURE 7. Stainless Steel Coils Waiting to be Processed Under Hoist Rail

FIGURE 8. Spiral Tube Mill Installed at Big Pasco Facility

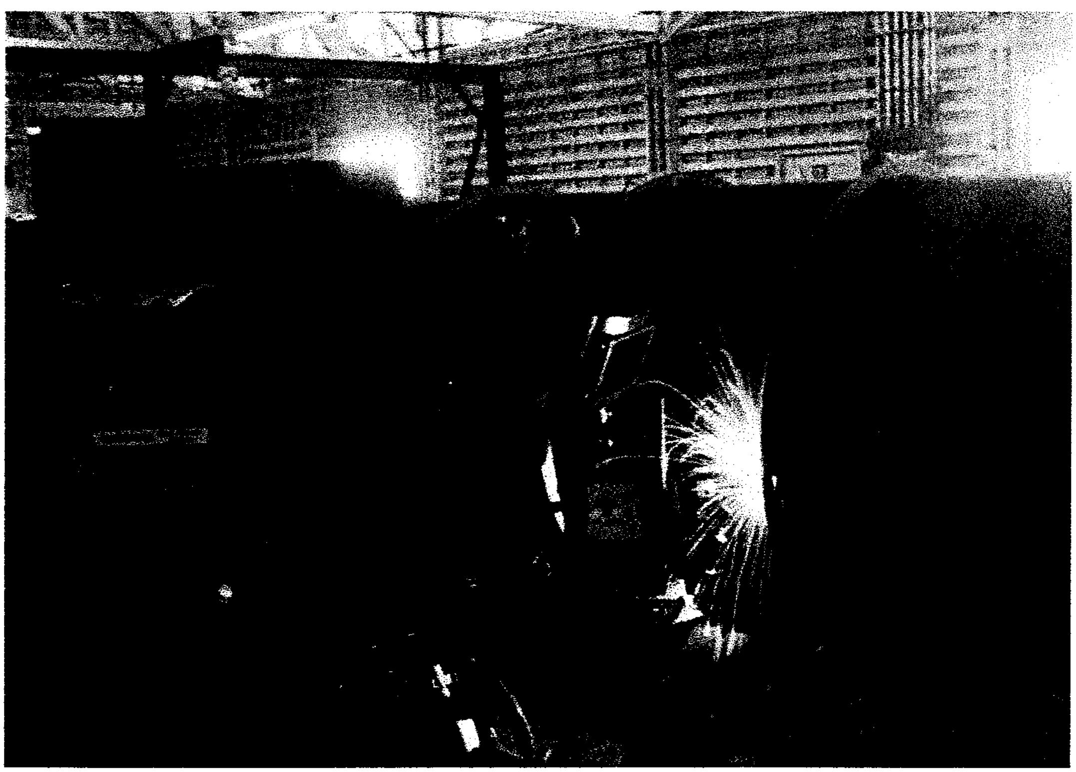


FIGURE 9. Stiffening Rings Being Welded

Two custom units, shown in Figure 10, were purchased and installed to expand the ends of the tube sections to a precision circumference to facilitate field welding of the sections. These units then trim the tube ends for a tight fit.

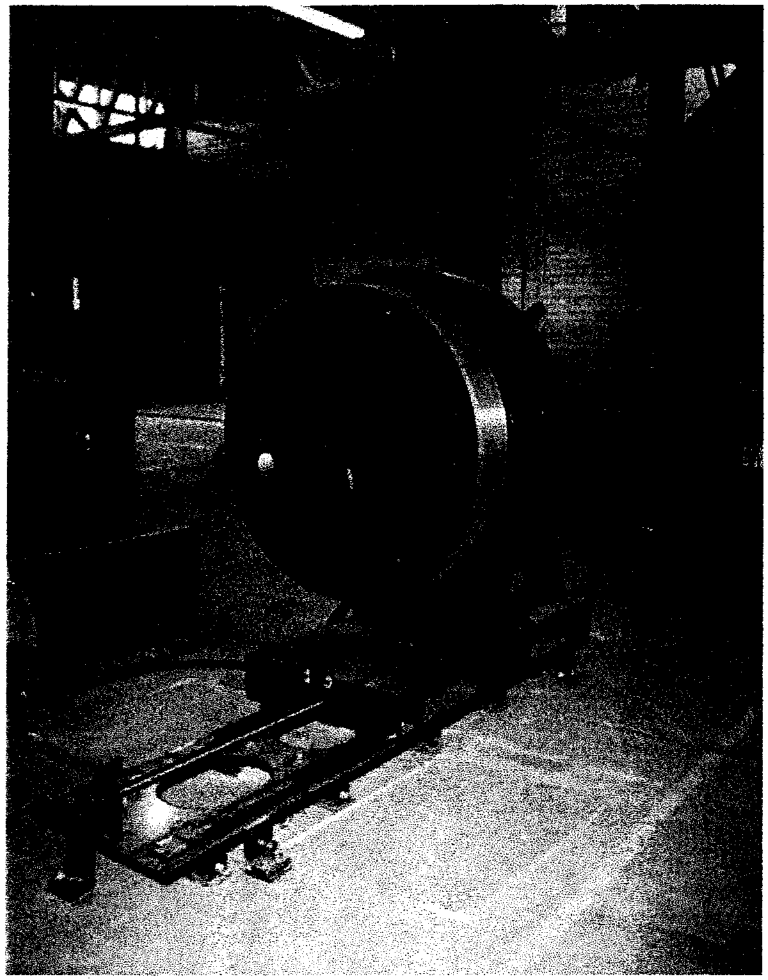


FIGURE 10. Tube End Expander/Cut-off Machine

Special equipment was designed and built by CB&I, such as the lift table shown in Figure 11, for fitting expansion joints to half of the tube sections.

Insulated panels were installed to create a large, air-conditioned room for leak testing the fabricated tube sections. Three test stations are provided, complete with pumping systems, helium mass spectrometers (HMS), and slip-on tube end closures. Special test enclosures, shown in Figure 12 in the test room, surround the tube sections with helium for high-sensitivity testing. A separate control room helps keep the background signal low in the HMS units.

FIGURE 11. Lift Table with Expansion Joint Fit-up

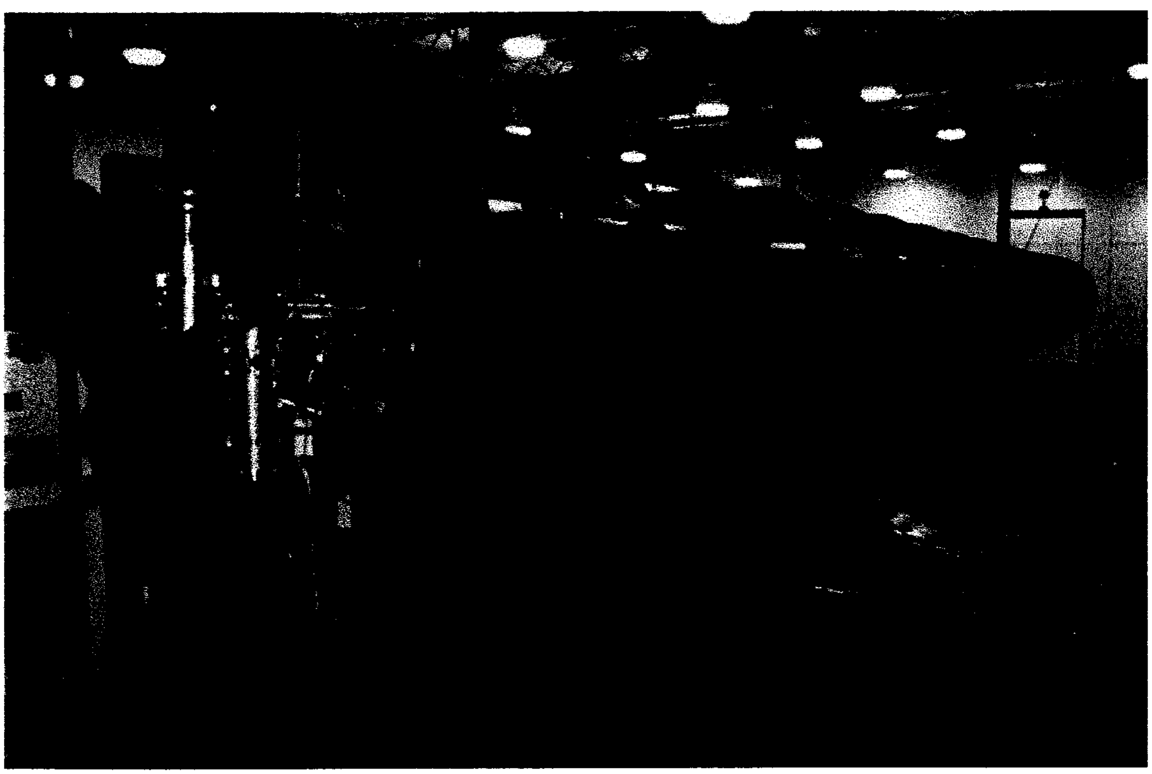


FIGURE 12. Pumping System and Test Enclosure for Tube Section Leak Check

A separate room, shown in Figure 13, was built to house the tube section cleaning process. A system was installed to provide deionized water, and a steam generator and hose reel were installed to provide detergent and water to a rotating spray unit that traverses the tube section.

FIGURE 13. Beam Tube in Position for Cleaning

All of the fabrication shop equipment and fixtures were qualified, with the exception of the cleaning equipment. This delay resulted when priority was assigned to other, higher-risk processes, and does not indicate a technical problem.

The batch #2 coils, 100 tons of 24-inch wide Type 304L stainless steel material, were processed through hot rolling, annealing and pickling, air bake, stretching and leveling, coupon testing, and slitting-to-width for spiral tube fabrication. All subsequent coils will be 36 inches wide to reduce weld content (thereby lowering the risk of leaks and hydrogen outgassing) and increase production efficiency. Batch #3, 300 tons, has been processed through stretching and leveling.

The terms of the Beam Tube contract require the LIGO Project to assume the risk of stainless steel price increases. However, the price of stainless steel, based on the Producer Price Index, was at a peak and has since declined significantly. To capitalize on an opportunity to reduce costs, we have asked CB&I to evaluate the impact of purchasing the remaining 2300 tons of material and storing it.

Initial expansion joint production is slower than expected, due to the vendor's problems implementing a leak test fixture. This is not expected to effect Beam Tube production.

Baffle fabrication is running smoothly. Problems experienced during start-up of the porcelain coating process are now under control. A cleaning step has been added to remove dust contamination, deposited by the coating environment.

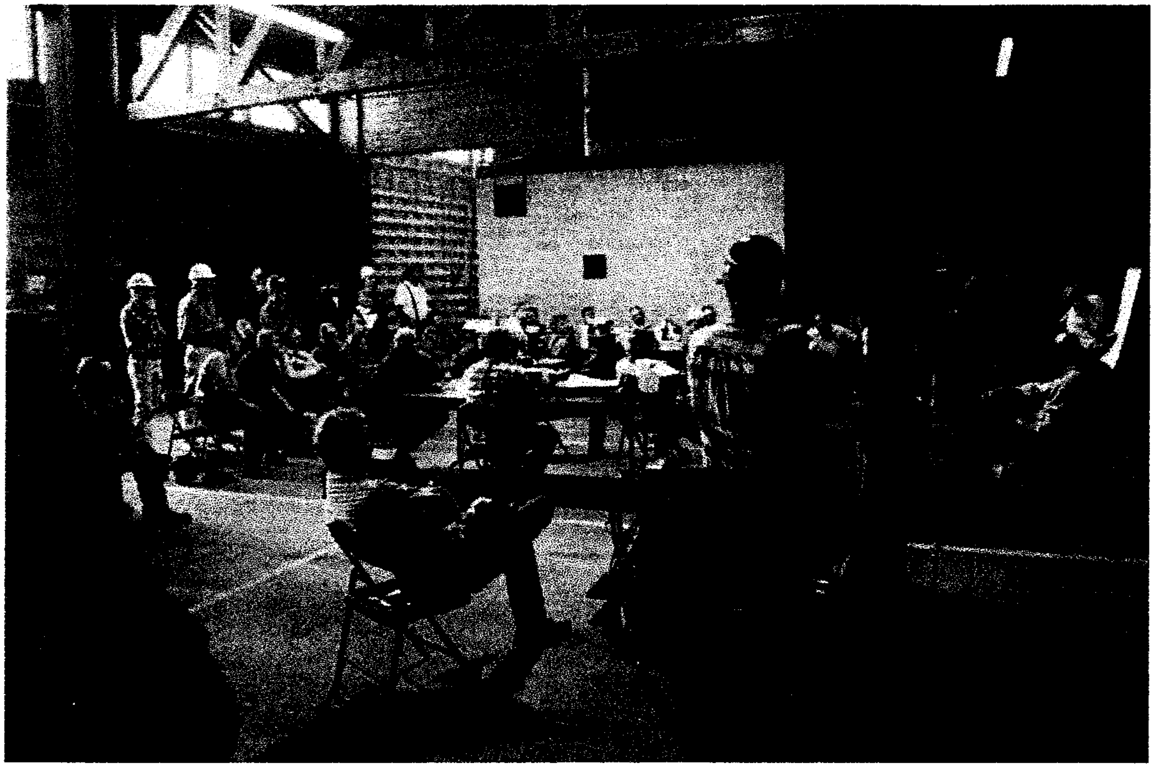


FIGURE 14. Professor Weiss of MIT, Lecturing CBI Boilermakers on Gravity-wave Theory

Work planned for the next quarter:

- Qualify cleaning equipment and installation equipment.
- Provide physical reference points to indicate ends of Beam Tube modules.
- Conduct Fabrication and Installation Readiness Reviews.
- Deliver first 300 baffles to Hanford site.
- Fabricate and install first fifty tube sections.

2.3 Beam Tube Enclosure (WBS 1.1.3)

Significant accomplishments during this quarter:

- Issued Request for Proposal (RFP) for Beam Tube Enclosure (BTE) installation at Hanford site.
- Completed proposal evaluation process and selected contractor for Beam Tube installation at Hanford site.
- Completed design and bid package for precasting and installation of BTE, including concrete slab and service road along arms at Livingston site.
- Initiated bid process for BTE and installation at Livingston site.
- Completed service road along both arms at Hanford site.
- Completed precasting of 800 segments of BTE at Hanford site.
- Completed fabrication of lifting device and successfully demonstrated installation of three segments of enclosure.

FIGURE 15. Completed Beam Tube Enclosure Segments at Contractor's Site

Discussion of accomplishments and work in progress:

During this quarter the construction of the Beam Tube Enclosure proceeded on schedule, and all the major schedule milestones were achieved.

Parsons I&T, the A/E contractor, completed the design and prepared the bid package for fabrication and installation of the BTE for the Livingstone site. They also prepared the RFP for the BTE

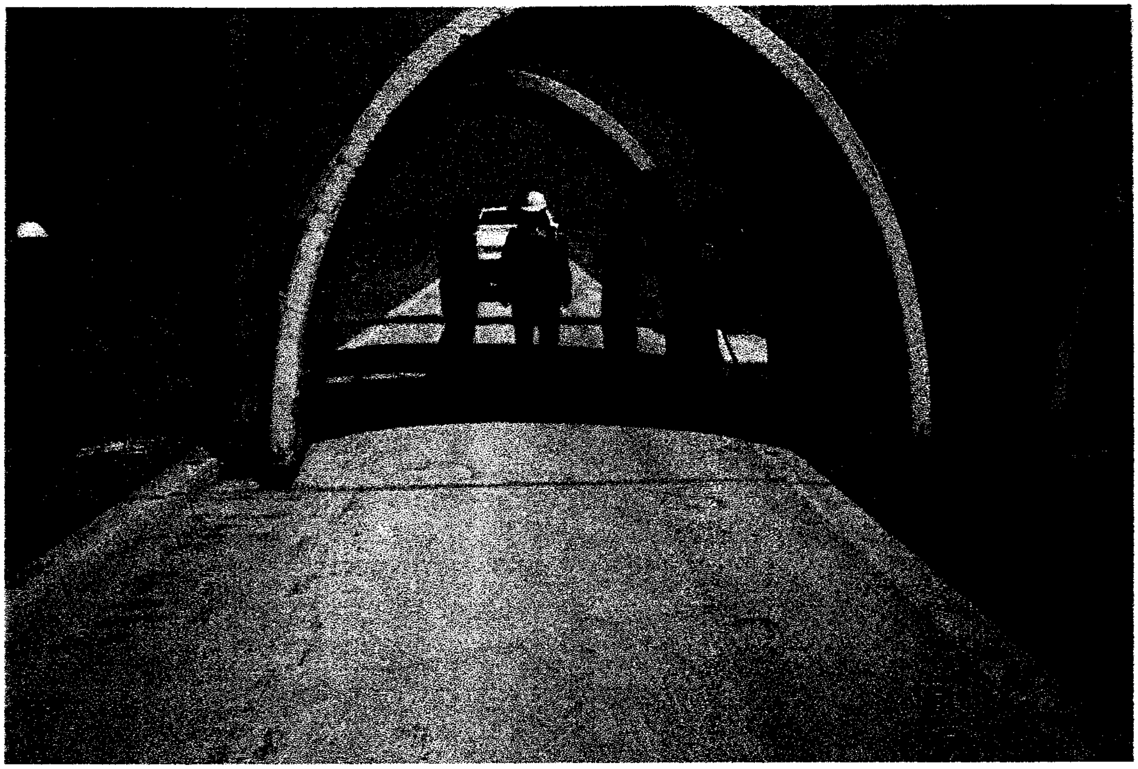


FIGURE 16. Demonstration of Enclosure Segment Installation at Hanford

installation at the Hanford site.

The Invitation to Bid for the BTE fabrication and installation for the Livingston site was issued to 26 plan holders, ten of them being general contractors. The bidders conference/job walk took place at the Livingston, LA on August 28, 1996. The public bid opening will take place at Baton Rouge, LA on October 15, 1996.

Work planned for the next quarter:

- Award contract for BTE installation for Hanford site.
- Award contract for site work and precast fabrication and installation of BTE for Livingston site.

2.4 Civil Construction (WBS 1.1.4)

Significant accomplishments during this quarter:

- Selected general contractor and awarded contract for construction of Facility (buildings) at Hanford site.
- Started construction of Facility (buildings) at Hanford site.
- Completed about 40 percent of excavation work for building foundations at Hanford site.
- Completed detailed design package for Facility (buildings) at Livingston site.
- Conducted Final Design Review (FDR) for Facility (buildings) at Livingston site.
- Prepared bid package for Facility (buildings) for Livingston site.
- Initiated bid process for Facility (buildings) for Livingston site.
- Completed final design package for Facility (buildings) for Hanford site.
- Completed electric power distribution at Hanford.
- Dixie Electric Membership Corporation raised electric power line at two locations that cross LIGO arms at Livingston site.

Discussion of accomplishments and work in progress:

Parsons I&T, the A/E contractor, completed the final design of the Facility (buildings) for the Livingston site. This design consisted of drawings, specifications, calculations and cost estimates for the two-interferometer arrangement. Parsons I&T also completed and submitted a bid package along with the design. The Final Design Review and approval process for the Livingston site took place during this quarter.

The Invitation to Bid for the Facility (buildings) at the Livingston site was issued to 33 plan holders, ten being general contractors. The bidders conference and job walk occurred at Livingston, LA on August 28, 1996. The public bid opening will take place at Baton Rouge, LA on October 15, 1996.

Hanford Site. Levernier Construction, Incorporated, was awarded the contract for the Civil Construction-Facilities (Buildings) for the Hanford site. Levernier has mobilized and started construction work at the site (Figure 17).

Livingston Site. One hundred thirty-one days have been lost due to inclement weather and wet soil conditions. However, only 65,000 cubic yards of dirt remain to be moved, and it is estimated that this work can be finished in less than ten dry working days. Current activities continue to focus on drying the site, installing the culvert pipes, and constructing the berm along the arms. Late completion of this activity is not expected to delay building construction.

Work planned during the next quarter:

- Select general contractor and award contract for construction of Facility (buildings) at Hanford site.
- Complete detailed design package for Facility (buildings) at Livingston site.
- Conduct Final Design Review for Facility (buildings) at Livingston site; approve design.
- Prepare bid package for Facility (buildings) for Livingston site.
- Initiate bid process for Facility (buildings) for Livingston site.

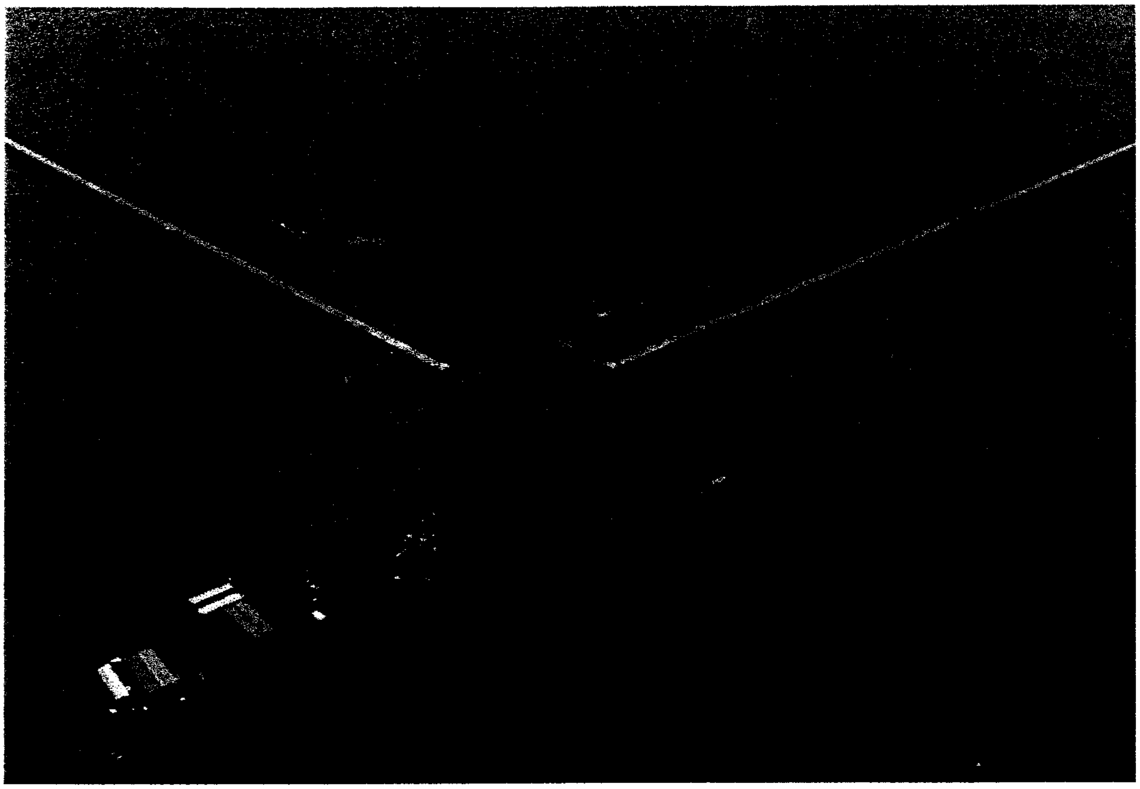


FIGURE 17. Laser and Vacuum Equipment Area (LVEA) Construction at Hanford

3.0 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 40m Interferometer facility, which is a primary tool for tests of operations and integration for the Detector group.

3.1 Suspensions and Isolation

Significant accomplishments during this quarter:

- Preliminary Design Review (PDR) for Suspension Subsystem occurred on June 6.

Seismic Isolation. Preliminary design activities continued. A trade study of the Suspension and Seismic Isolation Subsystems was initiated to allocate the total adjustment range between the Seismic Isolation and Suspension actuators. Statistical fluctuations in the microseismic peak amplitude at the Livingston site have been a particular focus since storm activity there determines the total actuator range required to maintain the interferometer in lock.

HYTEC, Incorporated, the subcontractor executing the preliminary design of the Seismic Isolation Subsystem, has made significant progress on several fronts. Detailed finite-element models of the various components of the Seismic Isolation Subsystem and support structures have been completed. Monte-Carlo studies of the sensitivity of the projected isolation to variations of the individual spring elements were performed, with encouraging results. Two innovative spring designs, one of which is shown in Figure 18, are being investigated to improve the isolation performance: a coil spring and a leaf spring, both using constrained-layer damping in a vacuum-tight envelope. The first fabrication tests of the coil spring manufacturing process have been made (coiling of a phosphor-bronze tube). Fabrication of a leaf spring prototype will begin next quarter.

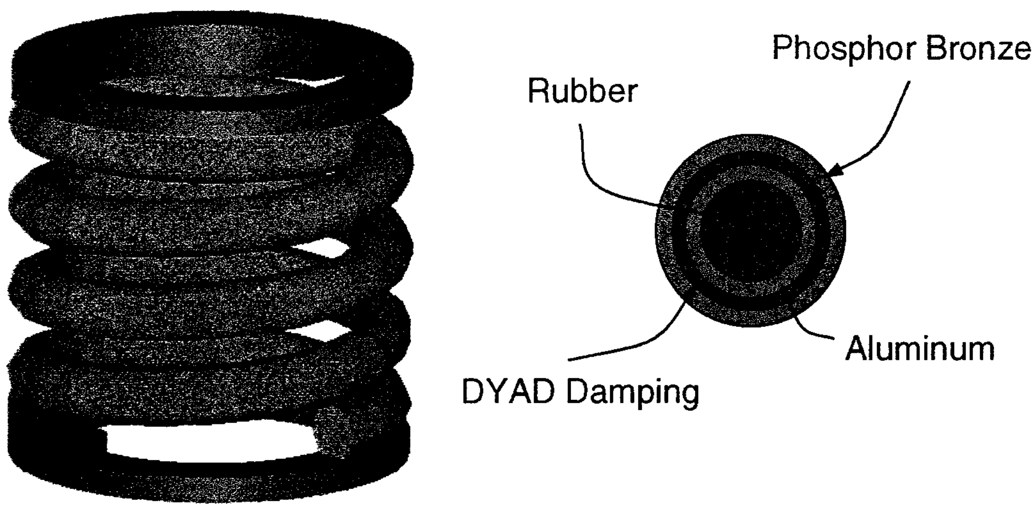


FIGURE 18. Coil Constrained-layer Damped Spring Design

Suspension Design. The preliminary design phase of the Suspension Subsystem culminated in a Preliminary Design Review on June 6. The mechanical design presented, critical to controlling thermal noise and limiting the effect of mechanical resonances, was found to be well-matched to the requirements. The actuator requirements are being refined in a trade study that includes the Seismic Isolation Subsystem to investigate the possibility of shifting part of the large microseismic peak requirement to the seismic actuators, thus easing the low-noise design at gravitational-wave frequencies. A successful test of a reduced-scale model of the suspension in the 40m Interferometer is discussed in section 4.2.

Work planned for the next quarter:

- Seismic Isolation. Complete actuator trade study. Continue preliminary design of the Beam Splitter Chamber (BSC) and Horizontal Access Module (HAM) Isolation Subsystems.
- Suspension Design. Continue prototype fabrication and tests of both Small and Large Optics Suspensions, with Prototype Test Review early in 1997.

3.2 Lasers and Optics

Significant accomplishments during this quarter:

- Core Optics. Selected substrate materials for Core Optics; placed orders.

- Core Optics Metrology. Completed measurement and analysis of substrates polished under Pathfinder task (very encouraging results).
- Prestabilized Laser. Initiated development of 10W diode-pumped Nd:YAG laser.

Prestabilized Laser. A kick-off meeting was held with Lightwave Electronics, our vendor for the LIGO 10W diode-pumped Nd:YAG laser. Lightwave has placed orders for long-lead items for their experimental prototype. As the quarter closes, materials are arriving, and the initial experiments are beginning.

Input Optics. A group from the University of Florida is developing the Design Requirements Document (DRD) for the Input Optics during extended visits to LIGO. As this quarter closes, work is starting on the document per se and will culminate in a review in October.

Core Optics. The polished Pathfinder substrates were characterized by the Optical Metrology group at the National Institute of Standards and Technology (NIST) during this quarter. A careful examination of the data from the polishers and NIST showed that three of the polishers involved in the Pathfinder process can meet our requirements, and, in fact, exceed them, giving us some procurement flexibility. A procurement strategy is being developed to give the best balance of quality, price, and schedule performance, the latter being particularly important since the production of the optics is the critical path for the Detector.

Collaborative interaction on coating uniformity with Research Electro Optics (REO) continued with both in-house testing and measurements at REO. An example of data from that effort is shown in Figure 19. This is a map of the phase height inferred from reflectivity measurements of

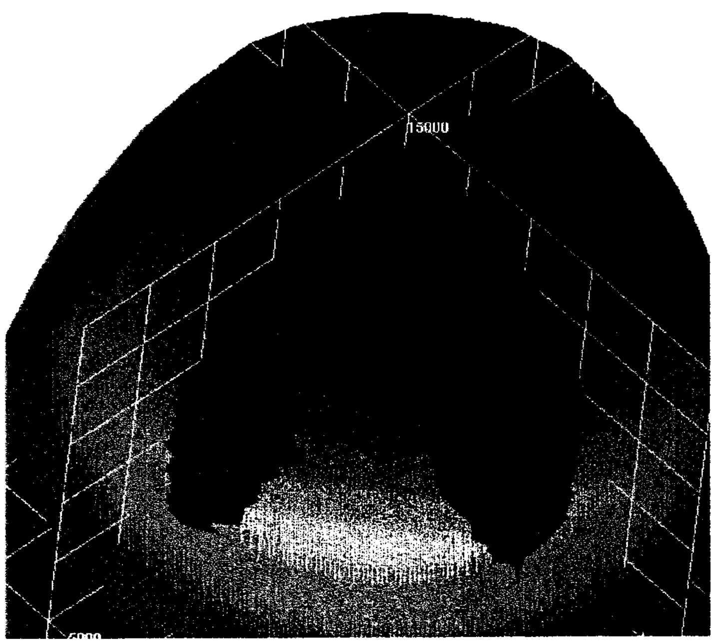


FIGURE 19. Coating Uniformity Test Map

an anti-reflective coating and shows a periodic structure with six azimuthal nodal lines and a fractional variation of roughly one percent. This information is provided to REO to influence the design of the planetary motion, used in the coating process, and which is thought to be the cause of the periodic variation.

Specifications for the substrate material for each of the Core Optics were defined. Bids were solicited, and two orders were placed, well in advance of the schedule. The first is for those optics which have low transmitted-light power (end test masses, folding mirrors, and the recycling mirror) and was placed with Corning. The second, for those optics experiencing high transmitted-light power (Beam Splitter, near test masses), was placed with Heraeus Amerisil. Deliveries begin in November and continue for approximately one year.

Work planned for the next quarter:

- Core Optics Metrology. Concentrate metrology effort on measurements of coating uniformity and interaction with coating vendor.
- Core Optics. Prepare and issue Specifications and Requests for Proposal (RFPs) for polishing of LIGO substrates; select contractors for polishing.
- Input Optics. Complete Design Requirements Document (DRD); perform review.
- Prestabilized Laser (PSL). Develop, document, and review requirements for PSL Subsystem.

3.3 Interferometer Sensing/Control

Significant accomplishments during this quarter:

- The requirements, interfaces, and the conceptual design of the Alignment Sensing/Control Subsystem were documented in a Design Requirements Document (DRD), and successfully reviewed.

Alignment Sensing/Control (ASC). There was progress in all aspects of this complex subsystem during this quarter. A model of the paths for angular excitation of the test-mass angular motion was developed, and estimates were revised for the levels of the environmental input. A visual representation of the model is shown in Figure 20.

The environmental input is shown at the bottom of the page; the transfer functions and couplings lead to the final variable of interest, the Θ motion of the mirror. The wavefront-sensing system design advanced with the calculation of the sensor-to-actuator matrix and the design of the servo-loop to maintain the required alignment. The initial alignment procedure was expanded, and the role of optical levers in both initial and operational modes was refined to facilitate implementation. The requirements and conceptual design were reviewed on August 29. Preliminary design will now begin.

Length Sensing/Control (LSC). The preliminary design of the Length Sensing/Control Subsystem continued. An important question concerns the extent to which the end test masses will be actuated. It will be a challenge to transmit signals of the required dynamic range over the 4km path from the vertex to the end stations. A study was made of different actuation topologies and of the ways in which the requirements can be relaxed for this communication link. A review on

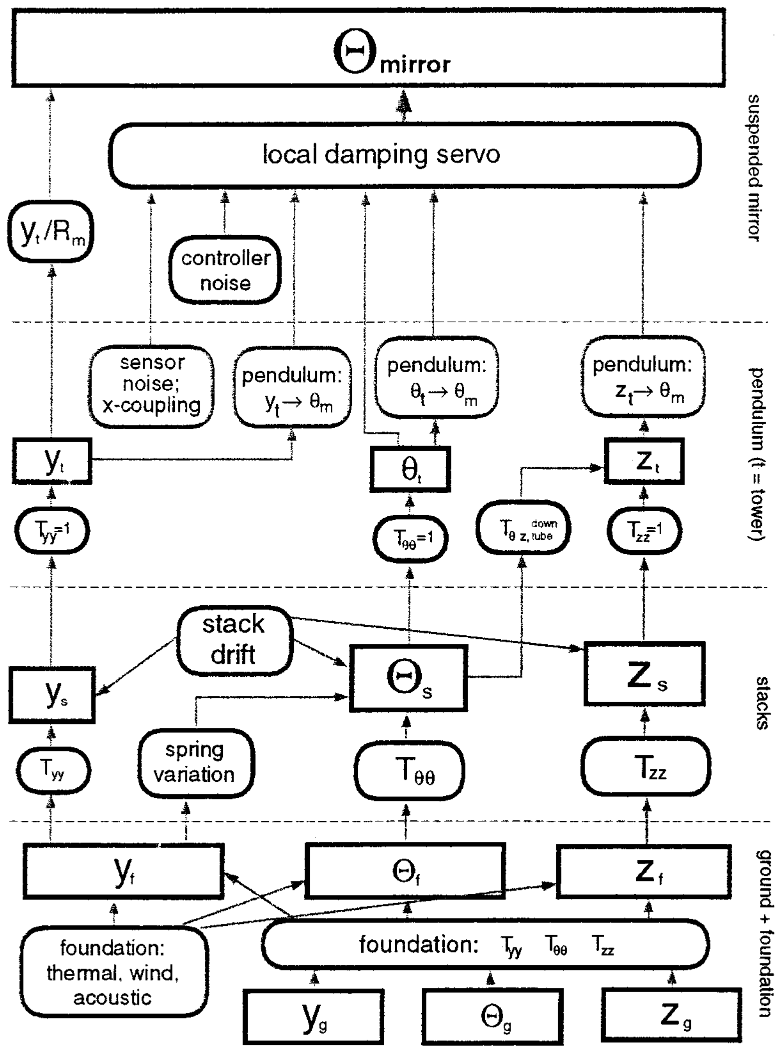


FIGURE 20. Coupling Paths from Ground Motion to Mirror Tilt

August 26 marked the completion of the development of the tools for modeling the acquisition of length control.

Work planned for next quarter:

- Alignment Sensing/Control. Begin preliminary design of overall system; optical lever prototyping will culminate in Prototype Test Review.
- Length Sensing/Control. Continue design work culminating in PDR.

3.4 Detector System Engineering/Integration

The Detector Systems Engineering/Integration has continued to address the requirements flowdown and the trade studies required to deliver the sensitivity of the initial LIGO detector. Design Requirements Reviews (DRRs) for the Alignment Sensing/Control Subsystem and the Control ducted this quarter, as was the PDR for the Suspension Subsystem. A draft version of the Detector Subsystems DRD has been circulated and is in use for assuring consistency between subsystems.

Work planned for next quarter:

- System Design Requirements. Conduct Detector Subsystems DRR; then focus on subsystem interfaces.
- Optical Layout. Produce and review preliminary optical layout.

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

Significant accomplishments during this quarter:

- Documented (in DRDs) and reviewed requirements, interfaces, and conceptual design of Data Acquisition and Interferometer (IFO) Diagnostics System.

Requirements and Preliminary Design. Issues related to determining the Data Acquisition strategy were addressed this quarter. Some Interferometer Diagnostics requirements were also defined. Both of these CDS activities require input from the interferometer designers, and the resulting dialogue has helped both the Interferometer System and the CDS. A review was held on July 24 leading to the start of the preliminary design for the Data Acquisition System. Figure 21, taken from the DRD, illustrates the organization of the interfaces to the Data Acquisition System. A prototype system, designed to test the architecture of Data Acquisition, using the 40m Interferometer as a signal source, has been configured and the components have been ordered. The format for recording LIGO data is being discussed with VIRGO with the objective of establishing a common approach; some tests of the efficiency of the VIRGO format have been made, and it was found to be satisfactory.

Many CDS design efforts are underway; of particular note are the following:

- Vacuum Cabling is in prototype stage. Sample 'cables' of multi-conductor copper-on-Kapton are being fabricated and will be tested for electrical properties and for outgassing.
- Vacuum Controls involve close cooperation with PSI, the Vacuum Equipment subcontractor. Progress has been made in defining interfaces and choosing implementations. The preliminary design is nearly complete.
- Small Optics Suspension prototype electronics are being fabricated, based on experience gained in tests of the suspension in 40m Interferometer.

Prototyping and R&D Support. The CDS group made significant contributions to the R&D effort this quarter. The Alignment Fixed-Mass Interferometer is using demodulators fabricated by the CDS group and delivered during the quarter. The suspension tests conducted in the 40m Interferometer used control electronics and cabling designed and fabricated by the CDS group. Electronics to support the conversion of the 40m Interferometer to a recycled configuration are being designed and fabricated, as are elements of the medium-power Nd:YAG frequency-stabilized laser. The control system for the Argon Pre-Stabilized Laser was reviewed on 25 July, providing scientists and engineers with an opportunity to learn about human interfaces and real-life implementation challenges.

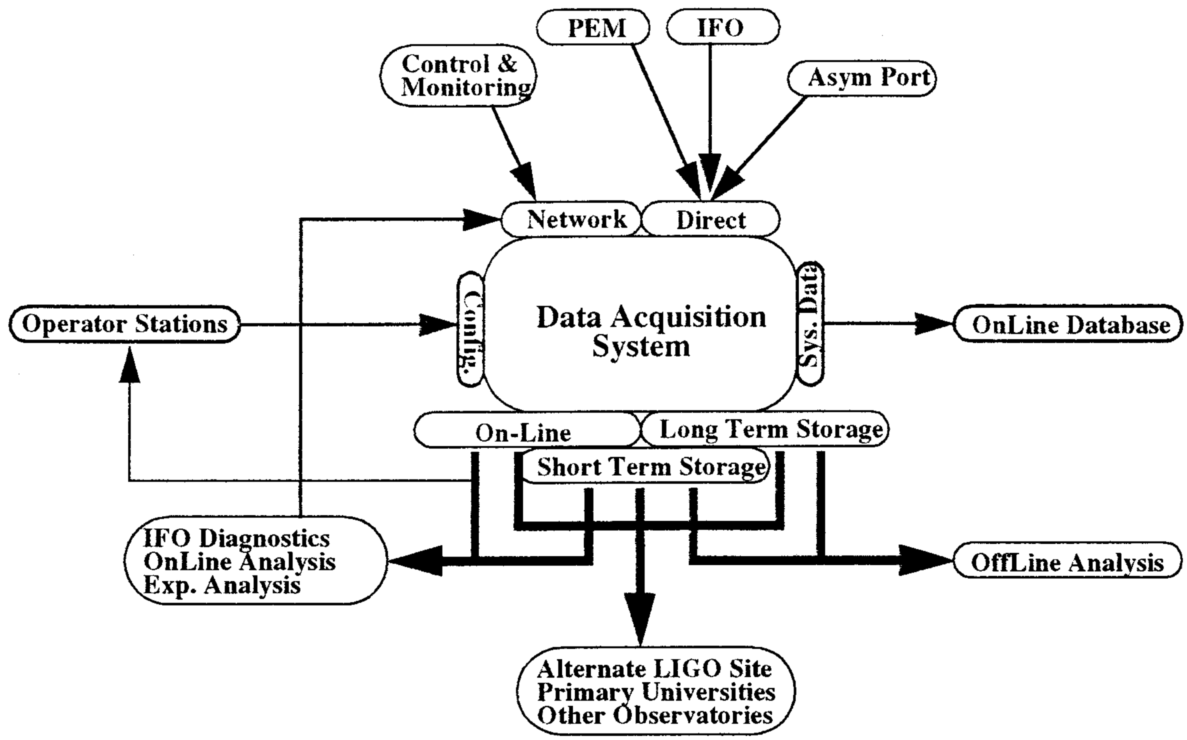


FIGURE 21. **Data Acquisition System Interfaces and Organization**

Work planned for next quarter:

- Design Requirements Reviews (DRRs). Develop requirements and conceptual designs, document, and conduct conceptual design reviews for Length Sensing/Control, Core Optics Suspension Controls, and the Physics Monitoring Subsystems.
- Preliminary Design Reviews (PDRs). Perform preliminary design and prototyping, documentation, and review for Global Control and Monitoring, Vacuum Feedthrough and Cabling, and Vacuum Controls.
- Conceptual and Preliminary Design. Perform conceptual and preliminary design for Nd:YAG Pre-Stabilized laser, Alignment and Length Sensing/Control, Seismic Controls, Data Acquisition and Interferometer Diagnostics System, and Timing and Network.

3.6 Physics Monitoring (WBS 1.2.3)

During this quarter, the Physics Monitoring System requirements and design were finalized for review. The environment at the LIGO sites has been documented, and the requirements and conceptual designs for sensors developed. A staged implementation of the system is planned, with an early presence at the sites in the form of a portable self-contained monitoring system. The DRR is scheduled early next quarter.

3.7 Support Equipment (WBS 1.2.4)

Definition of the required Support Equipment will continue.

4.0 Research and Development (WBS 1.3)

Significant accomplishments during this quarter:

- Demonstrated record level of phase sensitivity in Phase Noise Interferometer (significant step forward).
- Performed first measurements with Alignment Fixed-Mass Interferometer.
- Concluded work on non-recycled, recombined 40m configuration.
- Installed, tested, and characterized LIGO-like Small Optics Suspension on 40m Interferometer.

Discussion of accomplishments and work in progress:

The primary goal of the LIGO R&D program is to understand the noise sources which affect interferometer gravitational-wave detectors and to develop methods to control them. We have instituted a wide variety of research efforts which include experimental investigations using interferometers with suspended mirrors, development of new interferometer techniques starting with table-top interferometers, and R&D in vacuum science, materials properties, seismic isolation, and optics. At the current stage of the project, the majority of these investigations are directed at achieving the initial LIGO interferometer sensitivity goals. However, an important longer-term goal of the R&D program is to lay the groundwork for more advanced interferometers by developing a fundamental understanding of noise mechanisms which can serve as a starting point for advanced developments as soon as the initial LIGO performance is assured.

A secondary goal of the R&D program is to develop technology needed for the operation of large interferometers by building and testing LIGO-scale models of interferometer subsystems. While many of the aspects of the full-scale LIGO interferometers cannot be demonstrated on a laboratory scale, it is possible to develop subsystem requirements and evaluate full-scale (or near full-scale) subsystems against those requirements. The results of these development activities are interpreted through an ongoing program of modeling, including optical, control, and system modeling. Highlights of this quarter's activities are given below.

4.1 40m Interferometer Investigations

Optical Recombination. Research on the recombined, non-recycled, Fabry-Perot Michelson configuration was brought to a close. New information on length-lock acquisition, tolerances to deviations from the optimal operating point, and the sensitivity of the configuration to various defects in the laser source (intensity, frequency fluctuations) was obtained. Using this information, the design parameters for the recycled system were refined, and the instrument was then made available for suspension characterization. All available staff took 'shifts' on the interferometer, with the result that a wide range of experience was focussed on the research challenges while the base of experienced instrument operators was broadened, which will be crucial to the installation and operations phase of LIGO.

Suspension Tests. A new test-mass suspension, incorporating the key features planned for the suspensions on the full-size interferometers, was installed in the 40m Interferometer at one of the vertex test-mass positions. Tests of the control performance, noise, and isolation were performed.

The design was found to be satisfactory, and will be replicated to replace all test-mass suspensions in 1997. The objective is to gain experience with these LIGO-like suspensions, and it is also anticipated that the improved control and seismic isolation will allow better low-frequency noise performance in the 40m Interferometer.

Preparations for Recycling. The next phase of the 40m research will be to complete the conversion to the LIGO optical configuration by adding power recycling to the recombined interferometer. New test masses have been coated for higher transmission, allowing a compromise between recycling gain and arm storage time. The servo-system has been translated into an electronics design and is being fabricated.

Integration of LIGO Argon PSL. The testing of the Argon Prestabilized Laser, with the Control and Monitoring System planned for the LIGO sites, was completed during this quarter and reviewed on 25 July. It now becomes part of the standard equipment of the 40m Interferometer, with information gained going into the new design for the Nd:YAG Prestabilized Laser.

4.2 Suspension Development

In addition to the tests discussed above, measurements of the Q of suspended test masses with magnets attached, as planned for LIGO, were made. The results confirm the scaling of the losses with test-mass size that had been used to predict the internal thermal noise in the LIGO test masses. The results show that losses due to magnet attachment should not limit initial LIGO sensitivity.

A summer research project, carried out by an undergraduate student, has provided us a better understanding of suspension fibers for test masses. The student surveyed several metals for suitability as suspension wires. The best choices turn out to be steel (the current LIGO baseline), tungsten, and Invar. This work highlighted the importance of clamping suspension wires tightly.

4.3 Phase Noise Research

To attain the high sensitivity to gravitational-wave strains in the frequency range of interest, the LIGO interferometers must provide a very precise measurement of the optical phase of the light ($\sim 10^{-10}$ rad/$\sqrt{\text{Hz}}$). This research effort is designed to develop and demonstrate the technology for the shot-noise limited-interferometer operation at initial LIGO power levels, using the 5m facility at MIT, configured as a Phase Noise Interferometer. During this quarter, research on the recycled Michelson configuration entered the measurement phase.

Automated Alignment. To date, the prototype interferometers used in LIGO have either depended on a quiet environment or an auxiliary pointing system to maintain a satisfactory alignment of the optical system. Initial measurements with the recycled Phase Noise Interferometer showed that this would not be sufficient to achieve the measurement goals, and thus a system for automated alignment was incorporated, using the techniques and designs developed for the Fixed-Mass Interferometer alignment test and to be used on LIGO. A special-purpose servo-system optimizes the gain in the frequency regime most critical in terms of excitation, and wavefront sensor heads and demodulators were fabricated. The implementation, put into place late in this quarter, performed exactly as designed, and reduced dramatically the fluctuations in circulating power and coupling to laser imperfections, thus enabling the next step in the phase noise measurement.

Present Status. The interferometer is now operating with roughly 200 mW of input power (514 nm green light from an Argon laser source). The recycling factor of roughly 450 leads to the order of 90 W of circulating power in the recycling cavity. With this set of parameters, a phase noise sensitivity of roughly 3×10^{-10} rad/$\sqrt{\text{Hz}}$ should be obtained. Initial measurements (made in the last week of this quarter) with the interferometer with automated alignment show a noise level corresponding to shot noise at high frequencies and a net noise of $\sim 6\times10^{-10}$ rad/$\sqrt{\text{Hz}}$; the discrepancy in sensitivity from that calculated is in the signal size, and is under study. This very encouraging result is, to our knowledge, the highest phase sensitivity of any interferometer to date. Figure 22 shows the present performance and the best result obtained without recycling; note that the factor of roughly 10 in phase sensitivity required a factor of roughly 100 in the circulating power. The increase in the noise at low frequencies is under investigation.

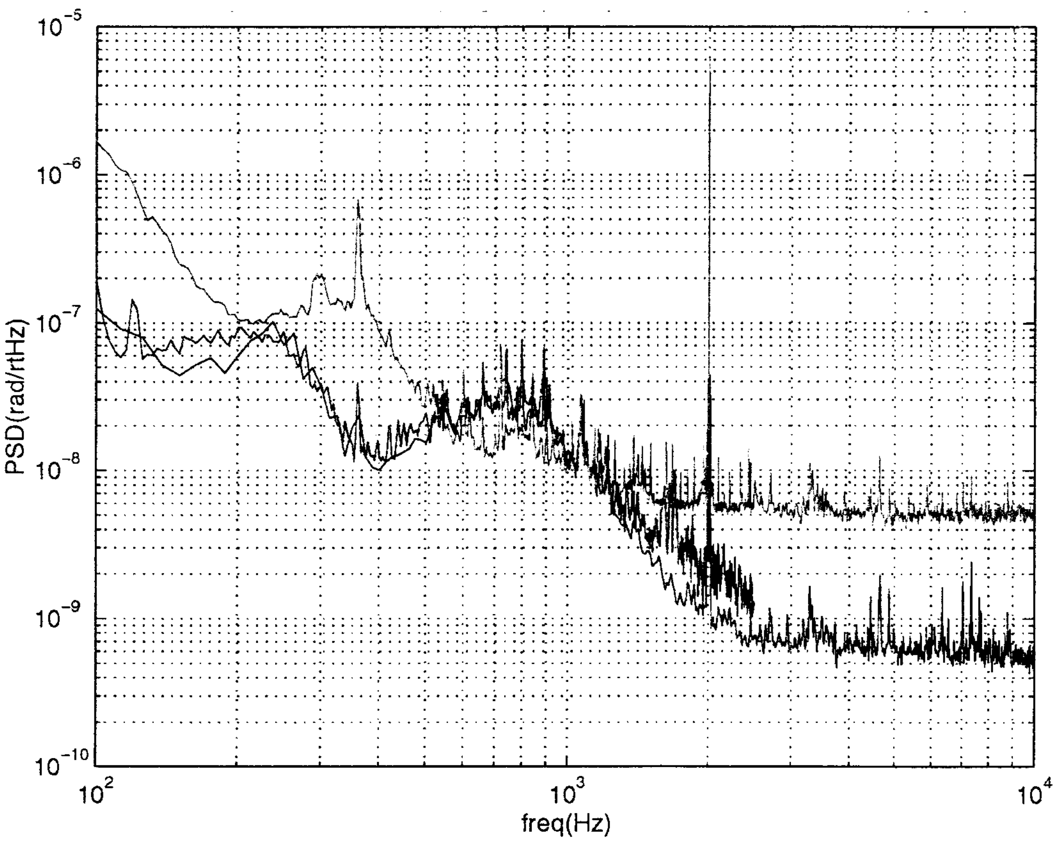


FIGURE 22. Phase Noise Interferometer Performance with (Bottom) and without (Top) Recycling

Preparations for upgrades. Work to convert the interferometer to 1064 nm is underway as part of the test of Nd:YAG lasers for LIGO. The suspended optics were coated and delivered this quarter, and the characterization of other optical components is proceeding. The Nd:YAG laser development is described in a later section.

4.4 Interferometer Alignment Investigations

This research effort is directed toward developing the operational system of alignment for the initial LIGO interferometer. A test of the target wavefront-sensing system is underway on the MIT Fixed-Mass Interferometer, where the discriminants at all interferometer ports will be measured and compared with a semi-analytical model.

In this quarter, the programming of the Data Acquisition System was completed; routines both for normal acquisition and also for on-line set-up and debugging of the optics and alignment sensors were written. Construction and alignment of the alignment-sensing hardware (wavefront sensors and demodulators) is largely complete. At the close of this quarter, the first sample data was taken, providing alignment information both from wavefront sensors and from a pointing monitor.

4.5 Nd:YAG Characterization and Stabilization

To gain familiarity with infrared techniques and to develop a basis for the LIGO Nd:YAG Laser Subsystem design, moderate-power (700 mW) commercial lasers are being prepared for use in the campus laboratories. These lasers, with frequency and intensity stabilization, will be used in the Phase Noise Interferometer (where precision tests of the performance of the 700 mW and later 10W laser will be performed), in mirror-contamination testing (where long-term exposure of mirrors to possible contaminants will be evaluated in the presence of high-circulating optical powers), and in the 40m Interferometer (where systems tests will be performed).

During this quarter, work continued on the test of prototype control systems and the fabrication of electronics modules for the operational configuration.

R&D Work planned for the next quarter:

- Installation in 40m Interferometer of new high-transmission, vertex-arm input-coupling mirrors to be used in recycling. Design and fabrication of control electronics for recycled interferometer, using LIGO CDS standards.
- Completion of measurements with recycled Phase Noise Interferometer with Argon laser. Continued preparations for conversion to Nd:YAG/1064 nm.
- Measurements of complete alignment matrix for Alignment Fixed-Mass Interferometer configuration; comparisons of alignment signals with detailed theory.

5.0 Project Office

5.1 Project Management (WBS 1.4.1)

Staffing. The LIGO staff currently consists of 91 equivalent employees. Of these, 14 are contract employees. During the quarter LIGO added the following personnel:

TABLE 1. New LIGO Employees (June 1996 - August 1996)

Edward Chargois	Property Management, CIT
Shinji Miyoki	R&D, CIT
Richard Riesen	Facilities, Hanford, WA
Brent Ware	R&D, CIT
Haisheng Rong	R&D, MIT
Alex Marin	Detector, MIT

Seventy-four LIGO staff are located at CIT, including four graduate students. Seventeen are located at MIT, including five graduate students. Figure 23 shows the staffing history since January 1995.

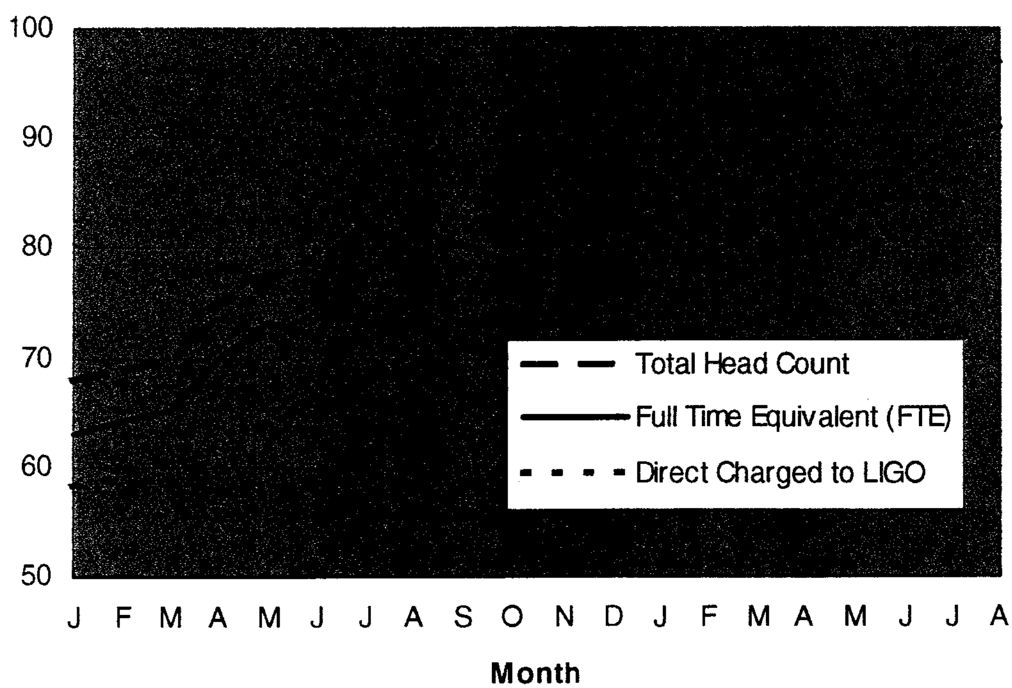


FIGURE 23. LIGO Staffing History since January 1995

Schedule Status. The status of the significant milestones identified in the Project Management Plan (PMP) for the LIGO Facilities is summarized in Table 2. The milestone dates projected in this table have been updated to reflect delivery dates negotiated with Vacuum Equipment, Beam

Tube, and Beam Tube Enclosure subcontractors as well as the efforts to integrate these schedules with the plans for constructing the buildings. The projected milestone dates were presented in detail during the NSF review in April and in Revision B to the Project Management Plan submitted to NSF on April 24, 1996.

TABLE 2. 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		03/95 (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)	01/97 (P)
Initiate Building Construction	06/96	01/97	07/96 (A)	01/97 (P)
Accept Tubes and Covers (Post B/O)	03/98	03/99	03/98 (P)	03/99 (P)
Joint Occupancy	09/97	03/98	09/97 (P)	03/98 (P)
Beneficial Occupancy	03/98	09/98	03/98 (P)	09/98 (P)
Accept Vacuum Equipment	03/98	09/98	03/98 (P)	09/98 (P)
Initiate Facility Shakedown	03/98	03/99	03/98 (P)	03/99 (P)

a. Project Management Plan, Revision B, LIGO-M950001-B-M submitted April 1996

Table 3 shows the status of the significant milestones for the Detector. This schedule was also presented in detail at the April NSF Review, and was included in the proposed revision to the Project Management Plan. The projected completion date for the *Core Optics Support Final Design Review* is now June 1997 (vs. April 1997). However, the current plan simplifies the subsequent fabrication effort so the overall schedule for installing the interferometers is not affected.

Note that as of the end of August 1996, all significant milestones can be achieved.

TABLE 3. 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		07/97 (P)	
Core Optics Support Final Design Review	04/97		06/97 (P)	
HAM Seismic Isolation Final Design Review	07/97		07/97 (P)	
Core Optics Components Final Design Review	07/97		07/97 (P)	
Detector System Preliminary Design Review	12/97		12/97 (P)	
I/O Optics Final Design Review	04/98		04/98 (P)	
Prestabilized Laser Final Design Review	08/98		08/98 (P)	
CDS Networking Systems Ready for Installation	09/97		09/97 (P)	
Alignment (Wavefront) Final Design Review	04/98		04/98 (P)	
CDS DAQ Final Design Review	04/98		04/98 (P)	
Length Sensing/Control Final Design Review	05/98		05/98 (P)	
Physics Environment Monitoring Final Design Review	06/98		06/98 (P)	
Initiate Interferometer Installation	07/98	01/99	07/98 (P)	01/99 (P)
Begin Coincidence Tests	12/00		12/00 (P)	

Financial Status Report. Table 4 summarizes costs for the third quarter and commitments as of the end of August 1996. Figure 24 on page 37 shows the costs and commitments as a function of time.

Performance Status. Figure 25 on page 38 is a Cost Schedule Status Report (CSSR) for the end of August. 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. In addition, Figure 26 on page 39 shows the same data graphically as a function of time. The revised plan is in place and was used for reporting progress as of the end of August.

TABLE 4. Costs and Commitments as of the End of August 1996

(All Entries are $ Thousands)

WBS	*Costs Thru Nov 1995*	*First Half LFY 1996*	*Jun-96*	*Jul-96*	*Aug-96*	*Cumulative Costs*	*Open Commitments*	*Total Cost Plus Commit-ments*
1.1.1	4,081	5,942	3,982	60	4,440	18,506	22,700	41,205
1.1.2	2,736	3,562	299	2,062	898	9,558	36,437	45,995
1.1.3	468	1,447	1,306	1,143	28	4,391	3,879	8,270
1.1.4	6,677	2,833	1,128	543	478	11,658	19,279	30,937
1.2	2,430	1,770	295	257	298	5,050	3,475	8,525
1.3	13,321	1,974	231	315	444	16,284	1,248	19,759
1.4	10,152	3,265	361	436	482	14,696	1,741	15,944
Unassigned	79	(123)	6	(4)	(0)	(43)	55	12
TOTAL	39,943	20,670	7,608	4,812	7,067	80,099	88,814	168,914
Cumulative Actual Costs	39,943	60,612	68,220	73,033	80,099			
Open Commitments	44,993	86,515	80,350	76,703	88,814			
Total Costs Plus Commitments	84,935	147,127	148,571	149,735	168,914			
NSF Funding	*138,089*	*167,089*	*208,089*	*208,089*	*208,469*			

Note: Unassigned costs have not been assigned to a LIGO WBS, but are continually reviewed to assure proper allocation.

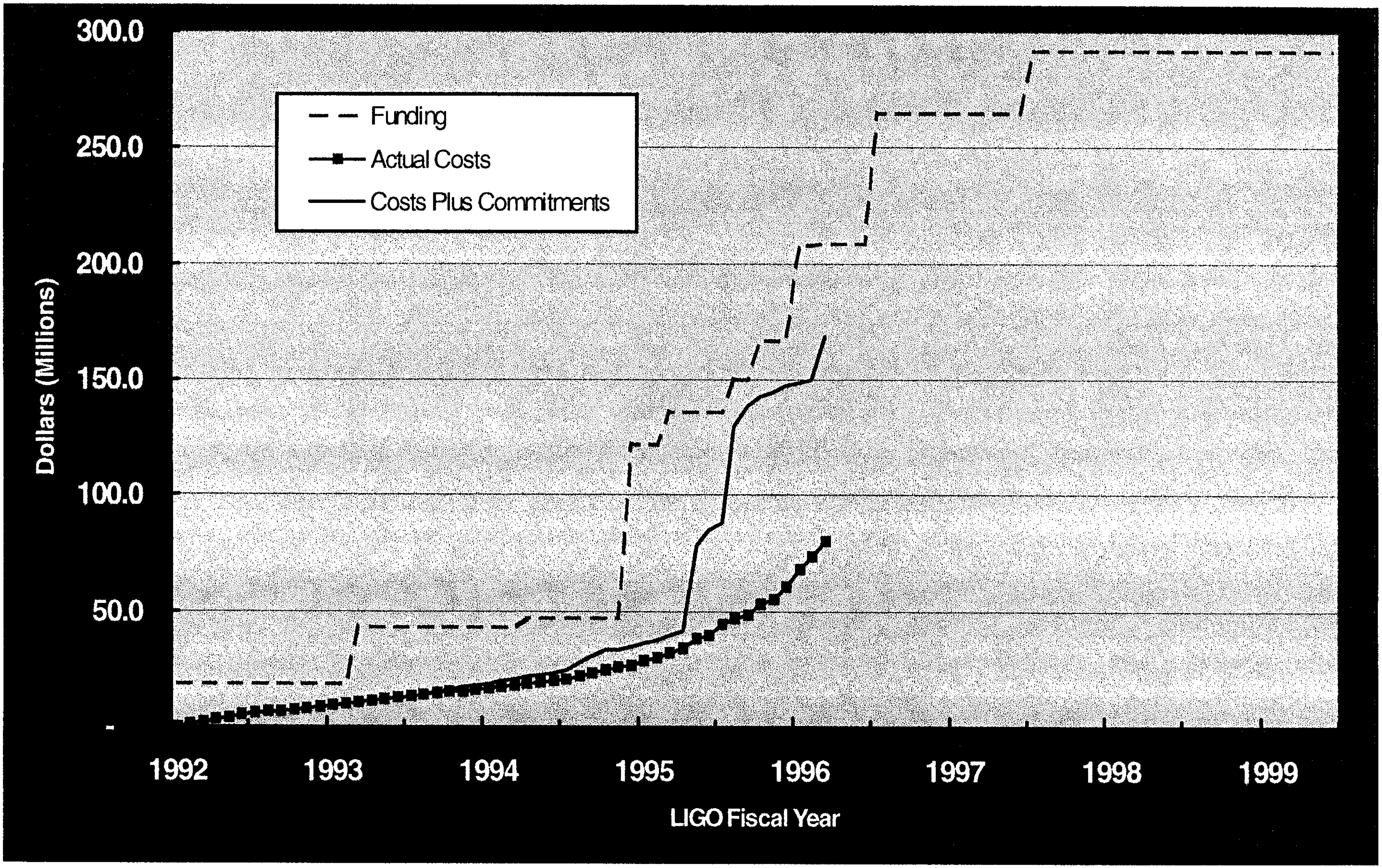
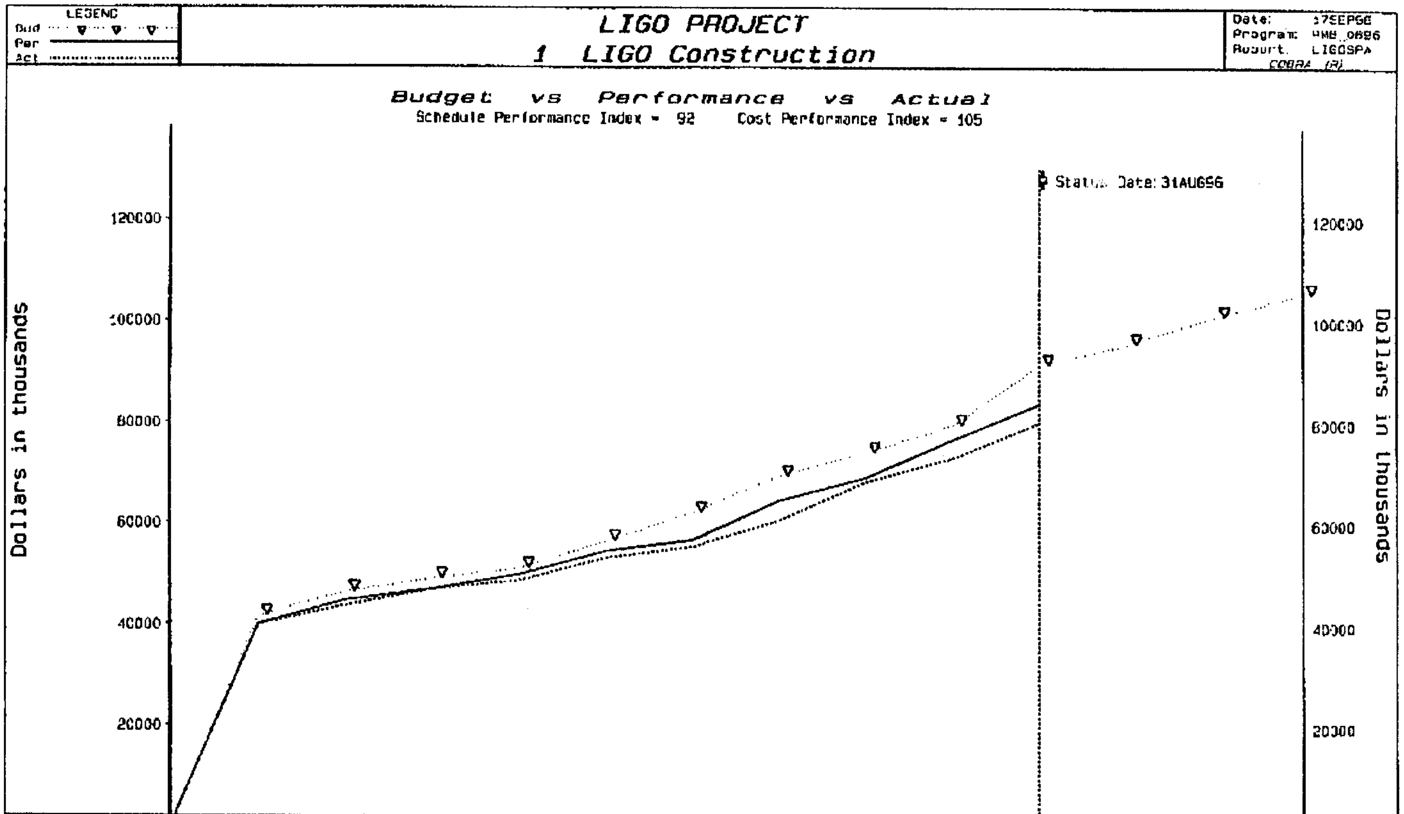


FIGURE 24. Costs and Commitments as a Function of Time

Run Date: 17SEP96	COST / SCHEDULE STATUS REPORT (CSSR)							Page 1
CONTRACTOR: Caltech LOCATION: Pasadena, CA	CONTRACT NUMBER: PHY-9210038		CONTRACT BUDGET BASELINE 292, 100, 000		REPORTING PERIOD: 31JUL96-31AUG96	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	22094	18189	18506	(3906)	(317)	42113	42113	0
1.1.2 : Beam Tubes	12873	10976	9558	(1897)	1419	47708	47708	0
1.1.3 : Beam Tube Enclosur	4395	4551	4391	156	160	19384	19384	0
1.1.4 : Facility Design &	13775	13379	11658	(396)	1721	47681	47681	0
1.2 : Detector	6411	5780	5011	(632)	768	52568	53336	(768)
1.3 : Research & Developme	17069	16011	16284	(1059)	(274)	23490	23490	0
1.4 : Project Office	14897	14897	14696	0	201	27074	27074	0
SUBTOTAL	91515	83782	80104	(7732)	3678	260019	260787	(768)
CONTINGENCY						0	31307	(31307)
MANAGEMENT RESERVE						32075	0	32075
TOTAL	91515	83782	80104	(7732)	3678	292094	292094	0

COBRA (R) by WST Corp.

FIGURE 25. Cost Schedule Status Report for the End of August 1996



	FY95	DEC95	JAN96	FEB96	MAR96	APR96	MAY96	JUN96	JUL96	AUG96	SEP96	OCT96	NOV96	SCALE
Planned Budget	41,556	46,348	49,027	51,168	56,547	62,162	69,351	74,102	79,650	91,515	95,647	101,021	105,592	K$
Performance	40,003	44,706	47,046	49,962	54,586	56,741	64,526	69,091	76,784	83,782				K$
Actuals	39,863	43,730	47,029	48,777	53,219	55,432	60,656	68,220	73,037	80,104				K$
Schedule Variance	-1,553	-1,642	-1,981	-1,206	-1,961	-5,421	-4,825	-5,011	-2,866	-7,733				K$
Cost Variance	140	976	17	1,185	1,367	1,309	3,870	871	3,747	3,678				K$

Schedule Variance = Perf-Budg Cost Variance = Perf-Actual Schedule Performance Index = Perf/Budg Cost Performance Index = Perf/Actual

FIGURE 26. End of August 1996 Performance Measurement Chart

There is a significant unfavorable (behind) schedule variance in the Vacuum Equipment (WBS 1.1.1). Process Systems International (PSI) has missed payment milestones relating to subcontracts for the large gate valves, for the portable clean rooms, and for the bake-out systems. The contractor's schedule for early milestones relating to the purchase of major material items was very aggressive and provided significant float for subsequent activities. PSI believes the schedule variances for the clean rooms and the bake-out systems should not affect the completion of major project milestones. LIGO has been closely monitoring PSI's progress on the large gate valves since these are required to support Beam Tube installation. The first gate valve will be shipped to the Hanford site on September 13, 1996. The second gate valve will be shipped to Hanford in October in time to support the installation of the first Beam Tubes. The remaining gate valves will be delivered later in the fourth quarter in time for the installation of subsequent Beam Tube modules.

Table 5 lists the significant Facilities milestones (including the Vacuum Equipment) that are currently behind schedule, the current projected date that the milestones will be completed, and the approximate performance value assigned to the milestone. It is expected that most of the unfavorable schedule variance will be recovered during September and October.

TABLE 5. Projected Completion Dates for Facilities Milestones Currently Behind Schedule

Description	Planned Date	Projected Completion	Approximate Value ($M)
VACUUM EQUIPMENT			
Order Bake System	May 1996	Oct 1996	0.7
Order Clean Rooms	May 1996	Oct 1996	0.6
First Article Test Complete	Jul 1996	Oct 1996	0.7
Gate Valves (8) Delivered to Washington	Aug 1996	Nov 1996[a]	0.7
Receive Steel Vessel Material for Washington	Aug 1996	Sep 1996	0.4
Receive Steel Vessel Material for Louisiana	Aug 1996	Sep 1996	0.4
BEAM TUBE			
Deliver 300 Baffles to Glazing Contractor	Jul 1996	Sep 1996	0.1
Deliver 200 Baffles to Glazing Contractor	Aug 1996	Sep 1996	0.1
Beam Tube Fabrication Readiness Review	Aug 1996	Sep 1996	1.7
CIVIL CONSTRUCTION			
Rough Grading - Louisiana	Aug 1996	Oct 1996[b]	0.3

a. Two Gate Valves will be delivered in time to support Beam Tube installation.

b. Depending on weather

There is also an unfavorable schedule variance in the Beam Tube (WBS 1.1.2). The CB&I schedule included a milestone for a Fabrication Readiness Review (FRR) in August. This milestone has been slipped to September 18. A preliminary FRR was conducted at the CB&I Big Pasco facility in August, and it was apparent that preparations for fabrication are well advanced. Partial credit was conservatively taken for the milestone. The remainder will be earned in September.

The Beam Tube Enclosure (WBS 1.1.3) is ahead of schedule. The roads have been completed at the Hanford site, and the site work is complete.

Facility Design and Construction (WBS 1.1.4) is behind schedule. One hundred thirty-one days have been lost due to inclement weather and wet soil conditions in the Livingston, LA rough grading task. However, only 65,000 cubic yards of dirt remain to be moved, and it is estimated that this work can be finished in less than ten dry working days. Late completion of this activity is not expected to delay building construction.

There is a favorable cost variance in Facilities. This variance is primarily due to the delays in the processes of invoicing and payment and does not translate into a projected underrun at the end of the project. Recent efforts to expedite payments have significantly reduced this effect.

The Detector (WBS 1.2) is slightly behind schedule. LIGO has been attempting to hire additional personnel, but this has not been accomplished quickly enough to avoid some delays in the Interferometer Sensing and Control effort, Vibration Isolation, and the Control and Data Systems. Priorities are being set to assure that all critical milestones will be met. Currently there is sufficient float in many of the tasks to avoid impacting any major project milestones.

The R&D effort (WBS 1.1.3) is six months behind schedule relative to the plan that was presented in September 1994. However, progress has been steady over the last six months as more personnel have become involved. Primary behind-schedule tasks include the Phase Noise Research effort at MIT and the effort in the 40m facility for recombination and recycling.

Change Control and Contingency Allocation. The Change Requests (CRs) in Table 6 have been approved. These CRs allocated $887,234 from the contingency pool and added to the budget baseline that was used for preparing the end of August 1996 reports.

TABLE 6. Approved Change Requests

Change Request No.	Description	Date Approved	Allocated From/(To) Contingency
CR-960022 Rev A	WBS 1.4.3.2 Document Control Center - adds FTEs (5N507)	August 13, 1996	$624,950
CR-960023 Rev A	WBS 1.4.1.2 Project Controls - add Technical Configuration Manager, address rate variance (5N502)	July 8, 1996	$1,365,103
CR-960024 Rev A	WBS 1.4.4.1 Administrative Support (5N509) - adds budget to cover additional FTE at MIT, and Supplies and Expenses	August 13, 1996	$592,622
CR-960026 Rev A	WBS 1.1 Facilities and Vacuum Equipment - adjust budget for cognizant scientist support	July 8, 1996	($498,245)
CR-960027	WBS 1.2.1.2 Move IOO and COS fabrication budget into new Suspension Fabrication WBS elements	July 8, 1996	(No cost)
CR-960028 Rev A	WBS 1.2 Detector - increased management costs	July 25, 1996	$470,000
CR-960029	WBS 1.2.1 Seismic Isolation System	July 25, 1996	$763,000
CR-960030 Rev A	WBS 1.2.1 Detector - HTES contract	July 25, 1996	$140,000
CR-960032	WBS 1.1.1 Beam Tube - Primary adjustment is for Stainless Steel Pricing	September 16, 1996	($1,025,530)
CR-960034	WBS 1.1.4 Civil Construction - Adjustment for Negotiated Contract	September 16, 1996	($1,544,666)

5.2 Support Services (WBS 1.4.2)

The Jet Propulsion Laboratory (JPL) Office of Engineering and Mission Assurance (OEMA) continues to provide staff to support LIGO Quality Assurance (QA), Reliability, Product Assurance, and Environmental Safety and Health (ES&H).

Quality Assurance (QA). During the third quarter the primary focus for LIGO quality assurance has been to support the activities of the Facilities group. QA effort included monitoring the stretching and leveling of stainless steel coils for the Beam Tube; monitoring spiral mill development and acceptance at Pacific Roller Die (PRD) in Haywood, CA; participating in the Parsons QA Audit/Surveillance Review of the Hanford final design drawings; and observing the vendor leak tests of the initial production expansion joint.

LIGO QA also reviewed the Process Systems International (PSI) Final Design Review (FDR) documents, supported the development and qualification of the baffle coating process, and proposed requirements for receiving and acceptance of LIGO procured hardware for the Vacuum Equipment pump carts. LIGO QA has completed first article and initial production run acceptance inspections of the baffles and witnessed the demonstration of the Beam Tube Enclosure lifting and handling equipment at the Hanford site. LIGO QA is currently providing source acceptance inspection at the baffle coating vendor and has assisted with final cleaning for the first 300 baffles to be shipped to Chicago Bridge and Iron (CB&I).

The draft LIGO QA Plan was also completed during the third quarter and was distributed to LIGO staff members for review and comment.

Safety Office. The primary emphasis this quarter has been to establish the LIGO System Safety Program and establish the requirements for the System Hazard Analysis. An externally supported safety review process that will determine the adequacy of the hazard analysis has been established.

At this time the LIGO System Safety Program has identified eight top-level hazards that will be monitored and controlled before the observatories can be operational. In addition, PSI, the Vacuum Equipment manufacturer, has provided an analysis that identifies and recommends methods to control Vacuum Equipment hazards. These two analyses comprise the initial hazard identification effort that ultimately will identify methods needed to assure equipment and personnel safety. This initial hazard identification will be the subject of a review, scheduled for September 25, 1996, to be chaired by Dr. John R. Orr and including noted vacuum systems manager Mr. Thomas Beat from the Lawrence Livermore National Laboratory. Dr. Orr has been project leader for the Deviatory Project at Formable and is an expert on the various safety issues that occur with this type of project. Likewise, Mr. Beat is a recognized expert on vacuum safety issues. The initial Safety Review will occur next quarter and be complete for presentation at the NSF Semi-annual Review in October.

The Laser Safety Program has conducted five training classes and is currently providing individual training, as required. The training of LIGO personnel, 40 to date, includes a medical clearance (eye check) to perform duties in the LIGO laser facilities. The Laser Safety Program is still in the start-up phase. However, the Safety Standard Operating Procedures will become the basis for the

Laser Safety Program at the observatory facilities. The Laser Safety Program will be monitored and comply with OSHA safety requirements by the second quarter of next year.

CB&I will be providing information to the LIGO Safety Office concerning safety procedures that will be used during Beam Tube fabrication and installation to ensure compliance with LIGO safety requirements.

5.3 LIGO Research Community

A proposal for a LIGO Visitors Program to support three scientists per year for five years was submitted to the National Science Foundation on June 5, 1996.

The LIGO Program Advisory Committee (PAC) is being formed. Suggestions for membership have been solicited and received from the LIGO Research Community (LRC).

The LIGO Newsletter is now being published on the World Wide Web. The newsletter covers recent LIGO activities at a level of interest to specialists and casual readers alike. The response has been favorable.

6.0 Systems Engineering (WBS 1.4.3)

6.1 Integration (WBS 1.4.3.1)

Significant accomplishments during this quarter:

- Completed first article production and acceptance testing of baffles for Beam Tube (BT).
- Completed full-scale mock-ups of Beam Splitter Chamber (BSC) and Horizontal Access Module (HAM) chambers for use in integration planning and assembly jig/fixture design.
- Completed Electromagnetic Interference/Compatibility Plan (EMICP).

Description of accomplishments and work in progress:

Beam Tube Baffles. Although the responsibility for the production of Beam Tube baffles was assigned to the Facilities group, the Integration group was active in resolving fabrication issues and performing (back-scatter) acceptance tests.

Major Interface Definition and Control Documents (ICDs). Further revisions and finalization of the ICDs are underway, with almost all subcontracted/vendor design input in-hand. Completion of the ICDs and their revisions is an ongoing activity with high priority.

Integrated Layout Drawings. The integrated layout drawings for the Facility have been updated and maintained as contractor information has become available and as the definition process for the Detector System has evolved.

EMI/EMC Plan Development. An Electromagnetic Interference/Compatibility Plan (EMICP), written jointly by the Systems Engineering and Control and Data Systems (CDS) groups, has been broadly reviewed and approved by the Project.

Ambient Magnetic Field Calculation. A calculation of the expected 60Hz (and harmonics) magnetic field in proximity to the worst-case chamber has been made. This calculation, together with a composite of broadband magnetic field spectra measurements, defines the environment within which the LIGO equipment must perform.

Reliability Plan Development. A draft Reliability Plan has been widely reviewed by the Project and is currently being revised, with release scheduled next month. After reviewing the Failure Modes and Effects Criticality Analysis (FMECA) delivered by the Vacuum Equipment contractor, Process Systems International (PSI), work on the FMECA for the Vacuum Equipment System is underway. The functional FMECA for the Vacuum Control and Monitoring System, to be provided by the Control and Data Systems group, has also been initiated. The preliminary system-level fault tree analysis has also been started. The top-level events identified to date are: the failure to operate in the three identified operating modes, i.e., single coincidence, double coincidence, and triple coincidence. The fault tree analysis will identify the equipment-level failure modes which contribute to the top-level events.

Vacuum Compatibility, Cleaning Methods and Procedures for LIGO Instrumentation Materials Specification Document. A LIGO vacuum-compatible materials list has been prepared and approved. This document will be used to guide Detector System designers. It will be updated as new data becomes available through planned extensive tests of the candidate materials being used by the Detector System. A companion document which defines the procedures and methods to be employed in establishing material compatibility and cleanliness for LIGO is under development in collaboration with the Detector group.

Naming Conventions. A draft of a naming conventions document for LIGO components, systems, and coordinate systems has been issued by the project.

Core Optics Carrier (COC) and Shipping Container. The Core Optics carrier and shipping container design, used in the Pathfinder effort, is being tested and analyzed to determine if it is acceptable for use in LIGO and to make modifications, as required.

Alignment. The alignment requirements for LIGO sites have been defined and documented. Systems Engineering and Facilities agreed on how to proceed with the survey of the LIGO sites in support of the Vacuum Equipment and Beam Tube contractor requirements. The Facilities group has prepared the Statement of Work for the site survey.

Work planned for next quarter:

- Revise and finalize Interface Definition and Control Documents.
- Issue System Design Requirements Document (DRD).
- Issue (first draft) Detector Integration Plan.
- Expand Beam Splitter Chamber and Horizontal Access Module mock-ups with representations of the Seismic Stack and clean room enclosure; plan utilization of Beam Splitter Chamber and Horizontal Access Module mock-ups.
- Continue updating the integration drawings; implement 3D integrated layout drawings for chamber.
- Conduct Design Requirements Review (DRR) in November for initial design by Systems Engineering group of Beam Tube bake-out.
- Continue developing relational database for Hardware Configuration Item list.
- Bring Reliability Plan under configuration control.

6.2 Simulation and Modeling

Summary of significant accomplishments:

- Held follow-up meeting with Benoit Mours of VIRGO to review development on common LIGO/VIRGO data format.
- Studied optimal parameters for design of 2km Interferometer and found little gain could be achieved by making 2km Interferometer significantly different from 4km Interferometer.
- Analyzed anti-reflective coating on 9-inch mirror, provided by Research Electro Optics (REO), to estimate uniformity of phase map.

Description of accomplishments and work in progress:

The 226 parameters that appear in the LIGO noise model were reviewed and updated for accuracy and consistency with the current designs for LIGO. The LIGO noise model was also compared with the model being developed for VIRGO, particularly the results in the thermally dominate regions of the noise curves. The two models were shown to be in good agreement.

Benoit Mours of VIRGO visited Caltech in early August to continue the joint development of a common data format with LIGO. At the earlier meeting in April, LIGO personnel made several suggestions for modifications to the data format library which were incorporated in time for the August meeting. The code was shown to be compatible with the major hardware systems being used by the two groups, and data sharing was demonstrated. The data format library will continue to evolve, and plans have been made to develop documentation and establish version control for the library. The planned prototype Data Acquisition System for the 40m facility is scheduled to use this data format library.

Two separate numerically intensive modeling codes, in use by the LIGO modeling team, were recast into the Message Passing Interface (MPI) standard. These codes are used to calculate the optimal geometry for the test masses to reduce thermal noise for a given beamspot size, and to optimize the interferometer configuration for a given set of mirror surface irregularities. Both codes were modified with the assistance of a Caltech undergraduate student, working under the Sponsored Undergraduate Research Fellowship (SURF) program. The new codes have been shown to be compatible on a massively parallel supercomputer, the Caltech Paragon, and on the LIGO array of networked Sun Sparcstations configured to run the MPI standard. A trade study determined what sensitivity could optimally be achieved in the 2km Interferometer at Hanford by varying the shape and mass of the test masses and the optical coating. The study showed that only insignificant reductions in the thermal noise could be achieved by changing the test-mass geometry. The study also showed the thermal noise to be so dominate over the shot noise in the region of the cavity pole frequency that changes in the cavity storage time, made by varying the optical coatings, would not contribute to an improved sensitivity.

Research Electro Optics (REO) provided a 9-inch mirror, with an anti-reflective coating (SiO_2 and Ta_2O_5 on the SiO_2 surface). This coating was designed so that the thickness variation can be determined very accurately. From the first measurement, using 12-degree incident angle P and S polarization light, the thicknesses of the two layers proved to be 10 percent different from design values. From the deduced thicknesses, the phase map variation was calculated. The phase variation due to the coating turned out to be several times worse than the requirement. Further measurements are planned to reduce the uncertainties in both measurement and analysis.

End-to-end model building continued with two new tasks. The first is an effort to include a control loop on top of the Twiddle-based interferometer modeling. (Twiddle is a computer model developed by LIGO.) The second effort is to prototype the 40m Interferometer Data Acquisition System along the lines of the end-to-end model. This will help to clarify the necessary components of the end-to-end model for LIGO. As a part of end-to-end modeling effort, the radiation pressure noise was calculated. Also, Twiddle was improved to handle an arbitrary number of sidebands and was used to validate other simulation packages.

Development of the time-domain interferometer model continued under subcontract, including both the longitudinal and alignment degrees of freedom. An Interim Status Review was held at MIT on June 19.

Work planned for next quarter:

- Port noise model to avs/express software environment and integrate noise model with LIGO end-to-end model.
- Continue work on common data format with VIRGO. Efforts to specify scientific goals, technical hurdles, and scope for Data Analysis System will receive high level of attention during next quarter.
- Proceed on phase variation due to (mirror) coating at higher levels of accuracy, using additional measurements at larger incident angles. Deduced phase map will be used in FFT run to determine acceptability of surface roughness on coating.
- Implement end-to-end model for prototype 40m Interferometer Data Acquisition System, with attention to future evolution of final LIGO model. This model will include simple control loops and possibly time-domain calculation.
- Receive time-domain, large-angle modal model code from Ray Beausoleil, the subcontractor performing this work for LIGO. Significant time will be invested in model validation, including comparison between Twiddle and similar code currently being developed for LIGO by Jet Propulsion Laboratory (JPL).