Proposal to the National Science Foundation

THE CONSTRUCTION, OPERATION, AND SUPPORTING RESEARCH AND DEVELOPMENT OF A

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

Submitted by the
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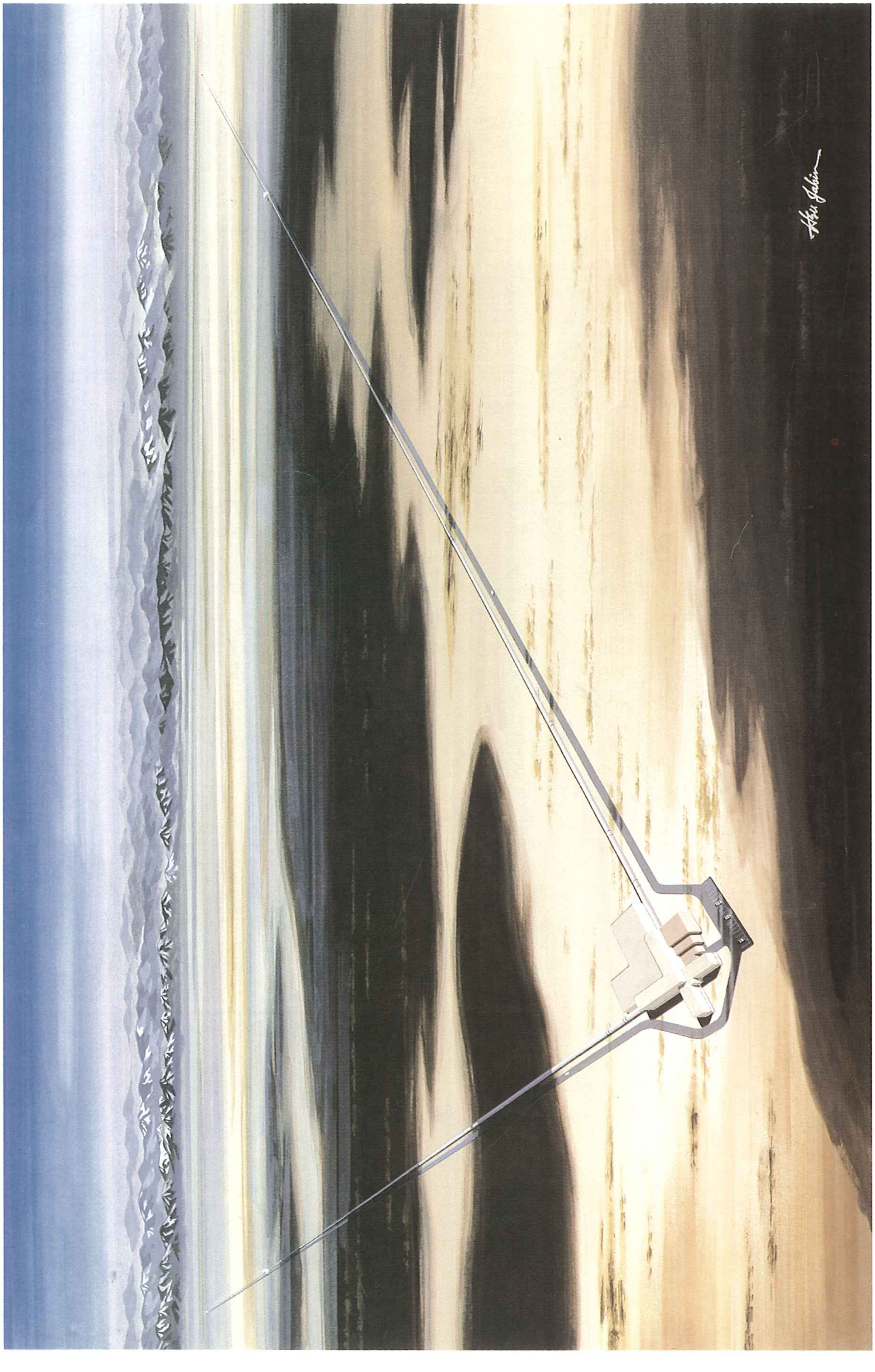

I. INTRODUCTION

This is the second of two volumes of a proposal to construct a Laser Interferometer Gravitational-Wave Observatory (LIGO). An artist's sketch of the facility at one of the sites is presented on the facing page. Volume 1, **LIGO Science and Concepts**, gives the scientific justification for the proposed LIGO, concepts for gravitational-wave detection, a general discussion of the conceptual design, and an overview of the LIGO project organization, budget, and schedule.

Volume 2, **Phase-A Design and Construction Implementation**, addresses the requirements derived from Volume 1 and presents a conceptual design description, a construction implementation plan, and a cost estimate. The LIGO requirements, specifications, and goals are given in Section II, the influence of phased construction on the design is discussed in Section III, and the detailed conceptual design is presented in Section IV. Site considerations are discussed in Section V, a project implementation plan is provided in Section VI, and project costs are presented in Section VII.

The present phase of the LIGO design process has sought to establish a sound basis for estimating the cost of implementation. It was not possible to scale the cost from an existing design because no similar facility has been built before. Therefore, selected design features were investigated at a fairly detailed level. Design priorities were derived primarily from a priori perceptions of cost and cost risk. The resulting design description in Section IV shows differing levels of detail, providing for a balanced cost analysis in Section VII.

II. DESIGN REQUIREMENTS, SPECIFICATIONS, AND GOALS

The LIGO Concept described in Volume 1, Section IV defines key features of the proposed facilities. We outline below the most important design considerations derived from this concept.

The LIGO will consist of two laser interferometer facilities located far apart within the continental United States. Each facility will include a vacuum system, laid out in the form of an "L", that is made up of 4-km tubes for the laser beams that define the interferometer arms and of chambers that house the interferometer components. The tubes will be approximately 1.2 m in diameter and will accommodate up to six primary-interferometer beams. The facilities will also include buildings to protect the vacuum chambers, protective enclosures for the beam tubes, and provisions for isolating sensitive interferometer components from vibration, acoustic noise, dust, and other disturbances.

A. 4-km Arm Length

Specifications associated with the arm length are summarized in Table II–1.

TABLE II–1
LIGO ARM LENGTH SPECIFICATIONS

Parameter	Value
Arm length (nominal)	4 km
Arm length match between sites	0.2 km
Arm length match at each site	2 cm

B. Several Interferometers at Each Site

An essential feature of the LIGO is the capability to operate concurrently several interferometers at each site[1] with minimum interference between the interferometers at a site (Volume 1, Section IV.A.3). Instead of separate vacuum systems for each interferometer, a more economical system has been designed that permits access to the components of any one interferometer while preserving the vacuum environment for the laser beams and components of the other interferometers.

This design is illustrated for the case of two interferometers in Figure II–1. Interferometer 1 has its test masses and optical components at the corner and extreme ends of the vacuum-system arms. Interferometer 2 shares most of this vacuum system, except that its beam splitter and associated optics are contained

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[1] The Phase-C configuration of the LIGO will have 6 interferometers at Site 1 and 3 interferometers at Site 2. (See Appendix A for a discussion of a possible future expansion of the LIGO.)

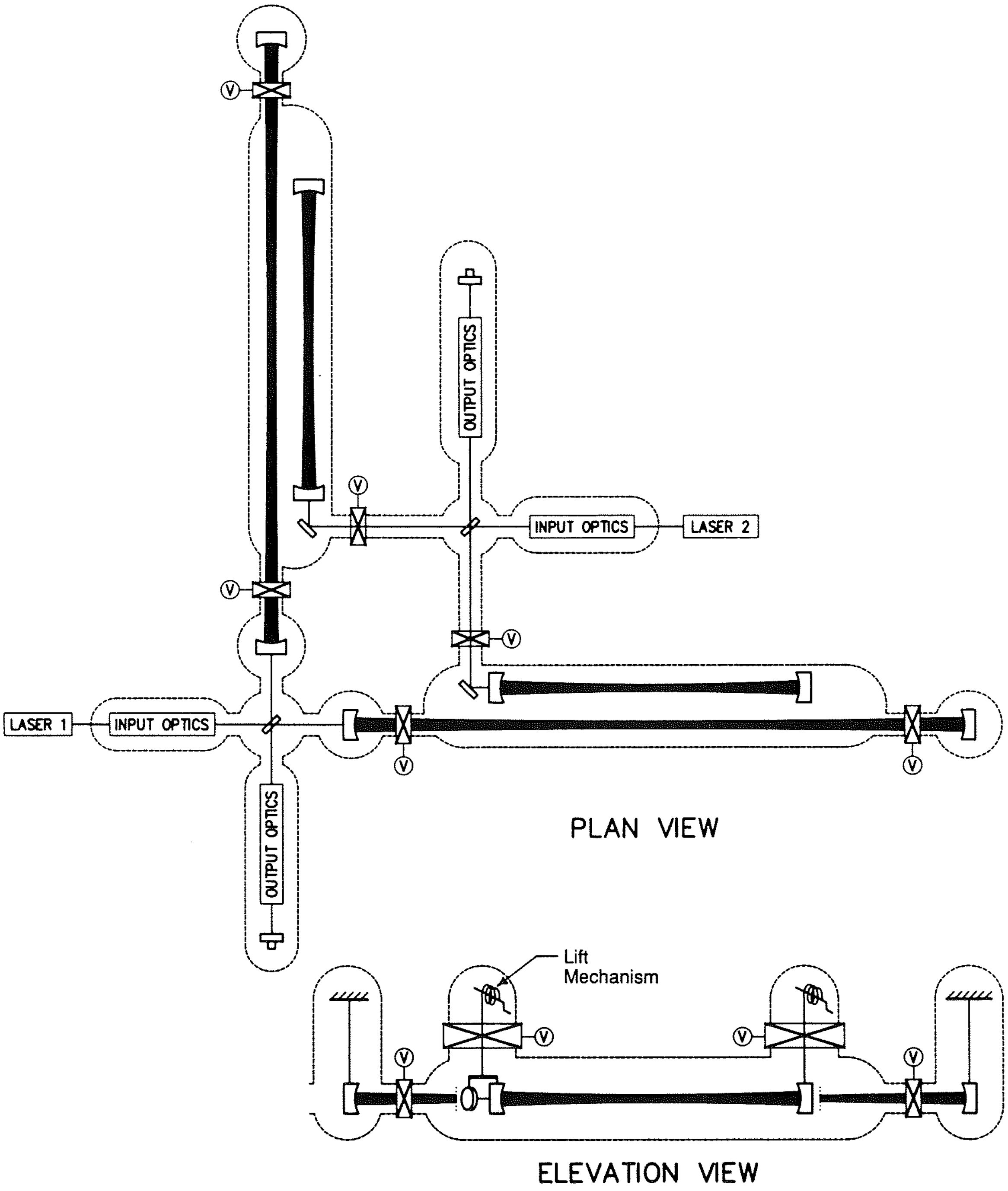

Figure II–1 Schematic illustration of two interferometers sharing the same vacuum system with minimum interference. One interferometer has its beam splitter and associated input and output optics at the intersection of the two arms. The second interferometer shares the vacuum envelope for the arms, but has an adjoining vacuum envelope for its beam splitter and associated optics, situated along the bisector of the arms. Deflection mirrors steer light between the beam splitter and the main cavities. The gate valves ("V") shown in the plan view allow most parts of either interferometer to be isolated for access while the other is operating. The remaining parts (deflection mirrors and main cavity mirrors of the second interferometer) are serviced by lifting them from the vacuum system arms (see elevation view) and closing horizontal gate valves.

in an adjoining vacuum envelope, offset along the diagonal of the "L". The offset is accomplished by deflection mirrors between Interferometer 2's beam splitter and the main cavities. The design allows for the removal or installation of parts of one interferometer, without causing significant disruption to the operation of the other interferometer. Up to six interferometers can be accommodated by extension of this design.

C. Interferometers of Different Arm Lengths

Additional interferometers that do not extend the full length of the "L" can be accommodated by adding vacuum chambers in the corner area and part way down the arms of the "L". We have chosen to provide for additional half-length interferometers at one site (see Volume 1, Section IV, Figure IV–1).

D. Clear Aperture for Laser Beams

The LIGO concept calls for a vacuum enclosure with a *clear aperture* of 1 m to accommodate up to six Fabry-Perot interferometers.[2] The clear aperture is defined as the cross section of the right circular cylinder running the full length of the vacuum system, and is reserved for laser beams and interferometer components. Figure II–2 shows how the test masses and mirrors for six interferometers can be arranged to fit within the 1 m aperture. Test masses up to 50 cm in diameter can be accommodated in four of the six positions. The numbers in the figure indicate the sequence of test masses; the sequence was chosen to prevent the test masses and suspension wires of one interferometer from obscuring the laser beams of another. Positions 1, 4, and 6 correspond to interferometers with arms 4-km long, while positions 2, 3 and 5 are for arms 2-km in length. The clear aperture also accommodates secondary interferometers for monitoring and controlling relative motion of the suspension points of each primary-interferometer's test masses, as illustrated in Figure II–2 and discussed in Volume 1, Section V.A and Volume 1, Appendix C.

As discussed in Volume 1, Appendix F, scattering of light off the tube walls may be a source of noise in more advanced interferometers, if the walls are vibrating. We will reduce the effects of scattered light by (1) choosing an appropriate finish for the tube inner surface, (2) installing optical baffles in the tube at appropriate intervals, (3) choosing low-vibration equipment, and (4) installing an enclosure around the beam tubes to protect them from wind-induced and acoustic vibration.

E. Vacuum System Properties

Statistical fluctuations in the index of refraction of the residual gas can limit interferometer sensitivity, as discussed in Volume 1, Section III.A.3. The effect varies with gas species and is cumulative along the gas column in the optical path. The LIGO pressure specifications are summarized in Table II–2.

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[2] This aperture permits flexibility in interferometer design by accommodating both delay-line or mixed Fabry-Perot/delay-line interferometers, possibly operating at near-infrared wavelengths.

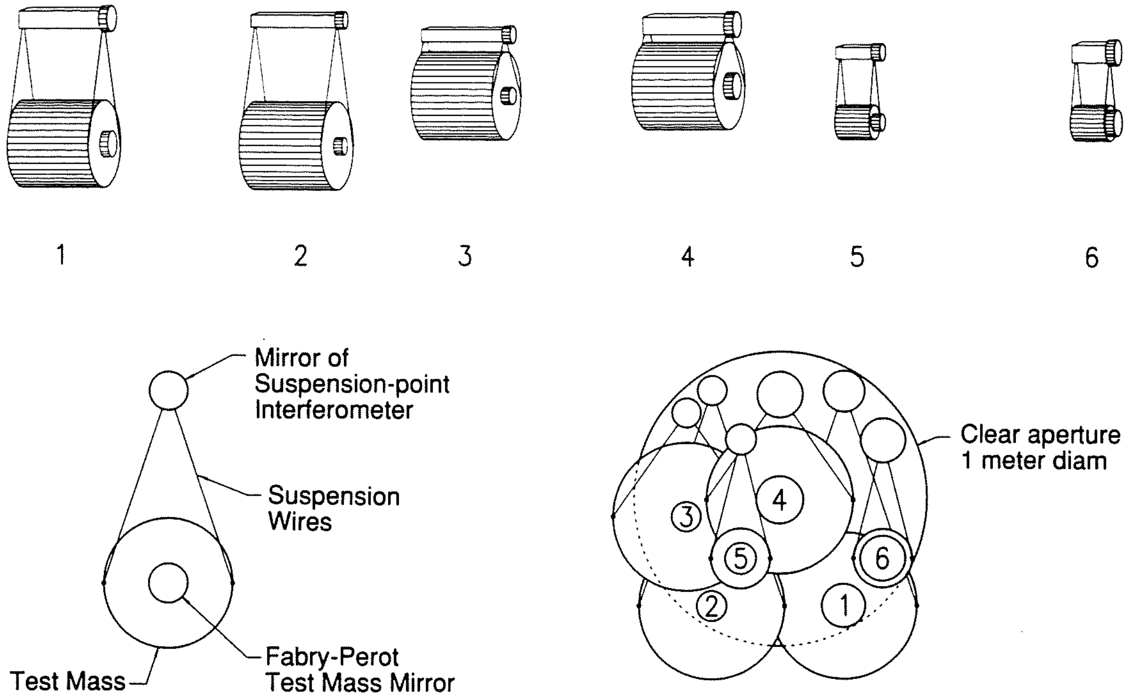

Figure II–2 Arrangement of test masses with attached interferometer cavity mirrors. *Upper:* Arrangement of individual test masses in the corner station that permits most efficient use of the clear aperture. The corresponding end masses at the end or mid stations are in the reverse order. *Lower left:* End-view of a suspended test mass. *Lower right:* A view of the corner station masses as seen from one of the beam tubes, showing the relation to the 1 meter clear aperture.

TABLE II–2
AVERAGE BEAM-TUBE PARTIAL PRESSURES[1]
INITIAL REQUIREMENTS AND GOALS

GAS SPECIES	INITIAL REQUIREMENT	GOAL
	(torr @ 300 K)	
H_2	1×10^{-6}	1×10^{-9}
H_2O	1×10^{-7}	1×10^{-10}
N_2	6×10^{-8}	6×10^{-11}
CO	5×10^{-8}	5×10^{-11}
CO_2	2×10^{-8}	2×10^{-11}

[1] Maximum pressure in chambers = 1×10^{-6} torr.

The initial pressure requirements are set so that residual gas will not limit the sensitivity of the initial LIGO interferometers. They are derived from the design of the initial interferometers, which is described in Volume 1, Section V.A (see also Volume 1, Figure III–2). The vacuum system design must ensure that these *initial requirements* are met with some margin.[3] The *goals* in the table are similarly set (from estimates of the sensitivity achievable with advanced interferometers); the vacuum system design must not *preclude* achieving these goals at some future time, but the goals are not going to become cost drivers in the initial construction of the LIGO.

The vacuum requirements are most demanding in the phase-sensitive paths of the interferometer (from the beam splitter to the distant ends).[4] The requirements are less stringent in the input and output optical paths. The residual gas pressure requirement in the chambers that house the test masses and beam splitters is set to keep the gas damping and acoustic coupling of ground motion at levels below those imposed by the test-mass suspension systems. This is satisfied by operating at pressures below 10^{-6} torr.

F. Vibration and Acoustic Noise

LIGO interferometers have the best chance of achieving ultimate sensitivity in a quiet environment. One environmental limitation is the natural seismic background. Figure II–3 shows the vibration amplitude spectral density of typical ground motion at several representative locations. The dashed line represents the adopted LIGO design environment; the LIGO facilities will be designed to have vibrational motion at the support interfaces for the interferometer vibration-isolation stacks that is lower than this level.

Acoustic noise at the vacuum enclosure and lasers will be limited to a pressure amplitude spectral density of 10^{-4} Pa/$\sqrt{\text{Hz}}$ and 45 dBA rms (about the level of a quiet office).

G. Cleanliness and Dust Control

Some of the optical components of LIGO interferometers are sensitive to dust, and are usually handled in clean room environments. Dust, volatile contaminants, and hydrocarbons can also collect on exposed vacuum-system surfaces during internal-access operations, limiting vacuum-system performance and, perhaps more

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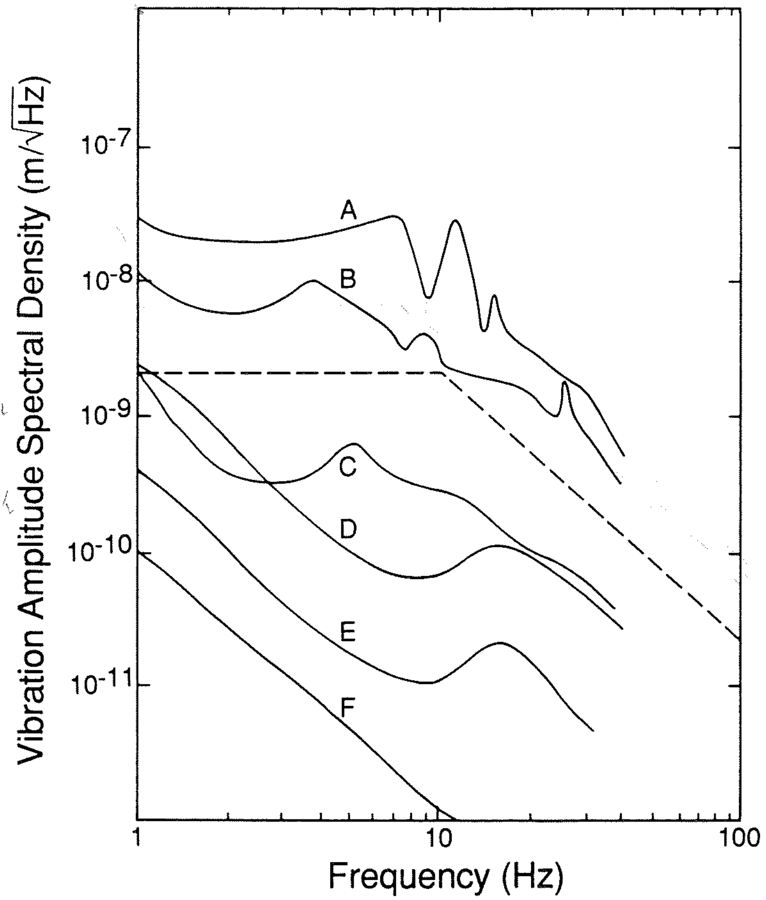
[3] The current vacuum-system design, described in Section IV, can meet these initial requirements even without the bakeout that is planned as part of the installation.

[4] Another consideration is the temporal stability of the gas column density. Although rapid fluctuations in the column density have not been observed in accelerator vacuum systems nor in the prototype interferometers, the LIGO will be many orders of magnitude more sensitive than prior systems, and the short-term stability of the column density merits attention. The optical phase change that results from a pulse of gas in the phase-sensitive part of an interferometer might simulate a gravitational-wave burst. The half-length interferometer should enable discrimination between pulses of gas and valid gravitational-wave signals (see Volume 1, Section VII).

$X(f) = 10^{-7}$ cm/Hz$^{1/2}$

$X(f)$ $10^{-5}/f^2$ = cm/Hz$^{1/2}$



7×10^{-9} m

7×10^{-7}

Figure II–3 Vibration amplitude spectral density data for typical motion of the ground at several locations: (A) MIT laboratory; (B) Caltech laboratory; (C and D) potential LIGO sites; (E) Lajitas, Texas (seismically quietest known location in the United States), with 3–10 mph wind conditions; (F) Lajitas, with no wind. The dashed line is the adopted LIGO specification for vibration measured at the instrument mounting structures.

seriously, exposing the contained optics to sources of contamination during vacuum operation.

The contamination problem is addressed by a hierarchical strategy for limiting dust contamination, beginning with control of building material and pressurization of buildings, and ending with dust filtration and local air curtains in the chambers and critical work areas.

7×10^{-9}

10^{2}

7

H. Site Requirements

The scientific goals of the LIGO constrain the selection of sites; site specifications are summarized in Table II–3.

TABLE II–3
SITE SPECIFICATIONS

Number of sites	2
Distance between sites	
minimum	2500 km
maximum	4500 km
Arm length (nominal)	4 km
Angle between arms	
nominal	90 deg
tolerance	± 15 deg
Slope of arms	< 0.2 deg
Orientation, absolute	No requirement
Orientation, relative	Optimized for average of coincidence projection alignment and Virgo-optimized alignment[1]

[1] Refer to Volume 1, Section V.C for discussion.

The site specifications are satisfied most economically by locations that can accommodate level interferometer arms with a minimum of earthwork. Sites should be sufficiently far from urban development to ensure that they are seismically and acoustically quiet, but near enough for convenient housing of resident and visiting staff. Electrical power and road (or rail) access should be sufficiently close to allow economical construction. Soils and drainage characteristics must be suitable for LIGO construction, and environmental-impact concerns must be addressable.

I. Laser Power

Installed electrical power and cooling capacity limit the optical power available from lasers. The total electrical power allocated to lasers will be 320 kW at a site (see Volume 1, Section IV.B.2). This is sufficient for a total of 20 W of argon-ion laser output, or 3 kW of output from Nd:YAG lasers.

III. PHASED IMPLEMENTATION

In this section, we describe how plans to expand the LIGO facilities beyond the Phase-A period (covered by this proposal) influence the design of the initial facilities. As described in Volume 1, Section IV, we anticipate three phases in the life span of the facilities:

(1) *Phase A, The Exploration/Discovery Phase*, will provide a *one-detector*[1] facility for observation *or* development.

(2) *Phase B, The Discovery/Observation Phase*, will provide a *two-detector* facility and allow concurrent observation *and* development.

(3) *Phase C, The Observatory Phase*, will provide a *three-detector* facility and allow concurrent observation, development, and special investigations. It completes the LIGO evolution to its full capability as presently conceived.

The beam-tube length and diameter are fixed at the outset, and are determined by the needs of the Phase-A configuration. The basis for choosing the beam-tube length is discussed in Volume 1, Section IV. The beam-tube diameter is determined from the requirement for a "clear aperture" for laser beams (see Section II.D) and the need to provide space for baffles and a safety margin for alignment errors and drift.

The principal impact of the phased-implementation approach on the Phase-A design is that the initial vacuum system and enclosures must be configured so as not to preclude increasing the number of interferometers that share the beam tube.

The chambers that house interferometer components are modular; adding interferometers involves building and installing chambers of types already designed for Phase A. The initial vacuum system is designed with removable sections and appropriately placed valves to permit installation of hardware for future phases with a minimum of disruption to operations (see Section IV.C). The vacuum-chamber configurations for Phases B and C are described in detail in Appendix A.

The Phase-A buildings that house the vacuum chambers are designed from the outset to accommodate the full Phase-C vacuum-system configuration. This choice is partly motivated by the consideration that future expansion of an initially smaller building would cost far more than any relatively modest savings realized up front. However, our primary concern is to minimize the disruption that accompanies expansion.

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[1] A *detector* is nominally defined as three laser interferometers, two at Site 1 and one at Site 2.

IV. DESIGN DESCRIPTION

A. Overview

The LIGO will incorporate L-shaped interferometric detectors with arms of 4-km length, located at two widely separated sites. This section of the proposal describes the concepts for design of the LIGO detectors and supporting facilities.

The major elements of each LIGO installation are:

(1) The interferometers.

(2) A vacuum system, which provides the operating environment for the interferometers.

(3) Enclosures, which provide a controlled environment for the vacuum system and for personnel.

(4) Additional supporting equipment and facilities.

The LIGO installation at Site 1 will consist of five *stations* connected by *beam-tube modules* (each 2 km in length); it will be laid out as shown in Figure IV–A–1. The *corner station*, two *end stations* (one each at the end of the right and left arms), and two *mid stations* (one on each arm) will provide access to the vacuum system and contain interferometer components, vacuum equipment, and instruments. The sole function of the beam tubes will be to provide an evacuated path for transmitting light between stations. Because these tubes will be passive, access to their interior will not be required. *Full-length* interferometers will be made up of components installed in the corner stations and end stations; *half-length* interferometer components will be installed at corner stations and mid stations. The Site 2 installation will be identical to that shown in Figure IV–A–1 for Site 1, except that Site 2 will have no half-length interferometers and no mid stations.

The remainder of this section is organized as follows:

B. Initial Interferometer Design Description.

C. Vacuum System: Mechanical Design.

D. Vacuum System: Vacuum Design.

E. Enclosure Design.

F. Instrumentation, Control, and Data System.

G. Electrical Power.

The reader may wish to review Volume 1, Section IV, which presents the rationale for the design features. Also, a quick survey of the remainder of this section may be achieved by scanning the figures and captions; much of the design information is contained in these illustrations.

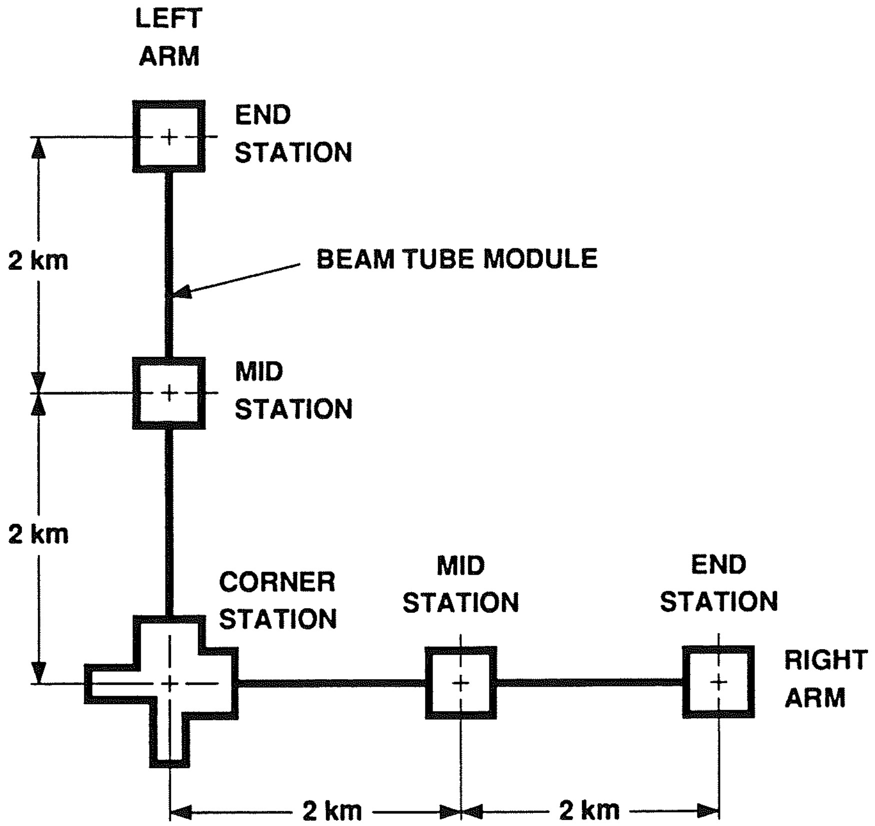

Figure IV–A–1 Layout of LIGO Site 1 facility showing the relationship of corner station, end stations and mid stations connected by beam-tube modules 2-km long (a reduced version of this figure appears in many other figures to help orient the reader). The Site 2 facility has no mid stations.

B. Initial Interferometer Design Description

The goal of the initial interferometer (see Volume 1, Section V.A) is to achieve the highest sensitivity consistent with simple and reliable operation, using a 5-W argon-ion laser and, to the maximum extent possible, using components and techniques proven in the prototypes. The design description presented in this section is in preliminary form; it represents the simplest implementation consistent with minimizing risks in the extension from prototype scales to 4-km arm lengths. LIGO interferometers will contain a number of modular subsystems, each as independent as practicable. The interferometers will be sufficiently flexible to allow switching between different modes of operation, from non-recycling mode in the first tests, to various recycling modes. The principal features for each subsystem in the initial interferometers are described and sample parameters are given.

1. Lasers and extra-vacuum optics

Each interferometer will have its own laser and associated prestabilization system on optical benches that are separate from the main vacuum chambers. Some of the parameters for this subsystem are listed in Table IV–B–1. These parameters are based on the assumption that commercial lasers will be modified by us for improved stability, using techniques developed during prototype research. The modification isolates the laser mirrors from vibrations (resulting from the turbulent flow of cooling water), and adds piezoelectric translators to control the laser frequency. The reference cavity is a length standard defined by a stable spacer between mirrors housed in a small vacuum chamber near the laser. A small fraction of the laser output will be sampled for frequency stabilization of the main beam.

TABLE IV–B–1
PARAMETERS FOR LASER AND EXTRA-VACUUM OPTICS

Parameter	Value	Notes
Laser type	Argon ion	
Wavelength	514 nm	
Power output	5 W	Single longitudinal mode
Reference cavity		
Length	$\approx$ 1 m	
Power	$\approx$ 0.1 W	
Finesse[1]	$\approx$ 1000	

[1] See Section IV.B.2.a

2. Input/output optics

Many of the components within the corner-station vacuum chambers are for conditioning and filtering the interferometer input and output beams. Figure IV–B–1 illustrates how the light is processed.

Figure IV–B–1 (facing page) The path of laser beams (arrows) through the functional units (boxes) in the initial interferometer. Many of the units are replicated several times with only minor modifications (see text). The functional units are grouped into subsystems denoted by dotted borders. The electrical connections are not shown in this figure.

a. Mode-cleaner and filter cavities. There will be one or two[1] (the pair arranged in series) mode-cleaner cavities (see Volume 1, Section III.B.3) at the input, and one at the output. The cavity mirrors for the mode cleaners will be separately suspended and controlled, with alignment controls similar to those for the main cavity mirrors (see below). As indicated in Table IV–B–2, the input mode cleaners must be capable of handling the full power available from the laser, and the output mode cleaner will be exposed to much less power. The optical phase modulation is simplified by choosing the length of the output mode cleaner so that the modulation sidebands and the laser frequency are transmitted by different resonance modes of the cavity. The finesse F ($F \simeq \pi/(1-\sqrt{R_1 R_2})$, where R_i is the intensity reflectivity of mirror i) of the input and output mode cleaners is chosen to obtain the best filtering action without significant transmission loss.

A circulator[2] before the output mode cleaner diverts the light reflected from this mode cleaner into the subcarrier filter system, which contains the output filter cavity. This system separates optical signals with different carrier and modulation frequencies. These signals are used for interferometer control. The optical and mechanical specifications for the filter cavity are less demanding than those for a mode cleaner. The filter cavity may be made from separately suspended components, or from mirrors on the ends of a fixed spacer.

b. Functional units. Six distinct functional units are replicated throughout the input and output conditioning-optics chains:

i. Mode-matching telescope. This unit consists of lenses that match a beam to the TEM_{00} mode of a cavity or reduce the diameter of light beams exiting a cavity and passing through small-aperture components such as Faraday isolators and Pockels cells. Larger components may be used as they become available, especially if their use can reduce the number of mode-matching telescopes.

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[1] The prefiltering mode cleaner may not be required for the initial interferometers. This will be determined from results of prototype experiments.

[2] A circulator (typically made from a polarizing beam splitter and a quarter-wave retardation plate) diverts reflected light from a cavity away from the incident beam axis.

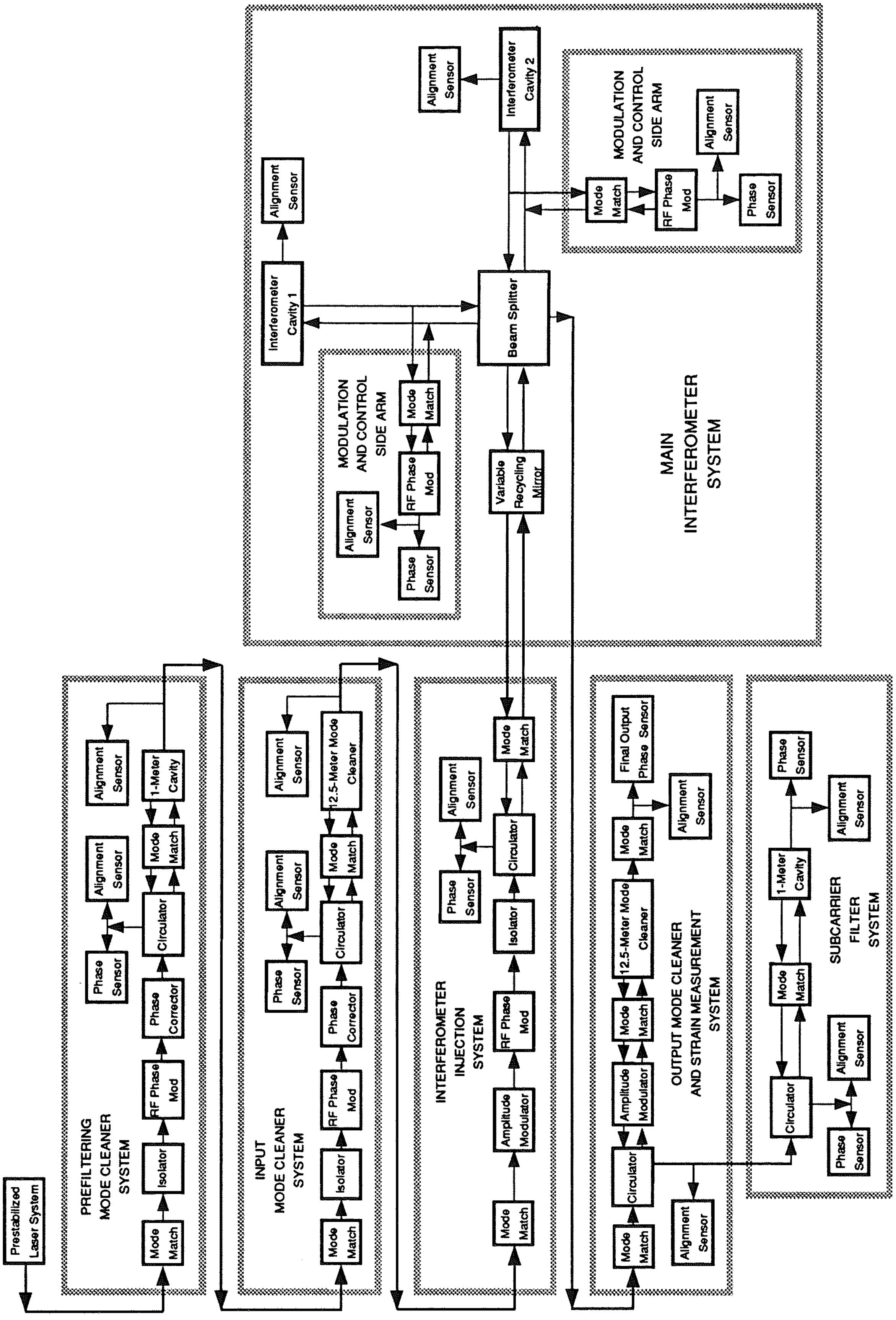
Prestabilized Laser System
PREFILTERING MODE CLEANER SYSTEM
Mode Match
Isolator
RF Phase Mod
Phase Corrector
Circulator
Phase Sensor
Alignment Sensor
Mode Match
1-Meter Cavity
Alignment Sensor
INPUT MODE CLEANER SYSTEM
Mode Match
Isolator
RF Phase Mod
Phase Corrector
Circulator
Phase Sensor
Alignment Sensor
Mode Match
12.5-Meter Mode Cleaner
Alignment Sensor
INTERFEROMETER INJECTION SYSTEM
Mode Match
Amplitude Modulator
RF Phase Mod
Isolator
Circulator
Phase Sensor
Alignment Sensor
Mode Match
OUTPUT MODE CLEANER AND STRAIN MEASUREMENT SYSTEM
Mode Match
Circulator
Alignment Sensor
Amplitude Modulator
Mode Match
12.5-Meter Mode Cleaner
Mode Match
Final Output Phase Sensor
Alignment Sensor
SUBCARRIER FILTER SYSTEM
Circulator
Phase Sensor
Alignment Sensor
Mode Match
1-Meter Cavity
Phase Sensor
Alignment Sensor
MAIN INTERFEROMETER SYSTEM
Variable Recycling Mirror
Beam Splitter
Interferometer Cavity 1
Alignment Sensor
MODULATION AND CONTROL SIDE ARM
Mode Match
RF Phase Mod
Alignment Sensor
Phase Sensor
Interferometer Cavity 2
Alignment Sensor
MODULATION AND CONTROL SIDE ARM
Mode Match
RF Phase Mod
Alignment Sensor
Phase Sensor

TABLE IV-B-2
PARAMETERS FOR MODE-CLEANER AND FILTER CAVITIES

Parameter	Value	Notes
Prefiltering mode cleaner		
Length	1 m	
Finesse	≈ 1000	
Power	5 W	
Main input mode cleaner		
Length	12.5 m	
Finesse	≈ 1000	
Power	5 W	
Output mode cleaner		
Length	12.5 m	For 12-MHz modulation
Power	$\lesssim 1$ W	
Output filter cavity		
Length	≈ 1 m	

ii. Mirror alignment unit. This unit is part of a control system that matches the input light wavefront to a cavity by adjusting the relative orientation between the cavity mirrors and the beam, and also centers the beam on the mirrors by adjusting their relative positions. It uses a pickoff beam splitter to sample a small fraction of the light reflected or transmitted by a mirror.

iii. Cavity stabilization unit. This typically consists of a circulator and a photodetector to sense the phase difference between the input light reflected from the cavity and the light stored in the cavity. The cavity stabilization unit may use Pockels cells for high-frequency phase correction.

iv. RF Phase modulator. Several of these devices generate the various RF subcarriers and sidebands on the main beams that are used to obtain the interferometer output and control signals. The modulation scheme is shown in Figure V-2 of Volume 1.

v. Isolator. Several of these units (typically a Faraday optical rotator between two polarizers) are used to suppress parasitic optical resonances between various components in the optical chain. The key isolators, which decouple adjacent cavities, are shown in Figure IV-B-1. Additional isolators between other components can be added as necessary.

vi. Amplitude modulator. This device is used in the input optics chain to impress amplitude modulation on the light for diagnostic tests, or as part of a servo to remove amplitude fluctuations. It is also employed in the output optics chain as a variable attenuator during initial alignment, and as a shutter to prevent exposure of the photodiode to excessive light power.

3. Main interferometer system

a. Mirrors and beam splitter. The design radius of curvature for the interferometer-cavity mirrors is 3 km. The resulting spot sizes on the mirrors are within a few percent of the minimum possible (confocal geometry) size. The beam diameter is a minimum in the center of the cavity, where it is approximately 60% of the spot size on the cavity mirrors.

The diameter of the mirrors defining the 4-km Fabry-Perot cavities is set so that the diffraction of light does not limit the storage time or the number of recycles. Mirrors of 14 cm diameter are adequate to keep diffraction losses smaller[3] than losses caused by imperfections in the coatings; allowing for a degradation in mirror quality near the edges, the design diameter for cavity mirrors is 20 cm (see Table IV–B–3 for the cavity parameters for full-length and half-length interferometers).

Storage time and loss parameters for the mirror coatings are discussed in Volume 1, Section V.A. The coating-uniformity and substrate-figure requirements listed in Table IV–B–3 follow from the initial interferometer specifications for shot noise, which determines the required storage time and number of recycles. The figure requirement corresponds to $\lambda/30$ ($\lambda = 633$ nm) rms variation from perfectly spherical mirror surfaces.

The diameter of the beam splitter (and associated beam-steering mirrors) will be larger than the interferometer cavity mirrors by a factor of approximately 1.4, to accommodate beams at 45-deg angles. Mechanical properties of the beam splitter are less critical than those of the cavity mirrors.

b. Modulation and control side arms. A compensation/pickoff plate between the beam splitter and each interferometer-cavity input mirror diverts a small fraction of the light inside the interferometer into a side arm. Each side arm is used for locking the adjacent main cavity and for applying phase modulation to the light.[4] Each side arm terminates in an end mirror that sends the light back to the compensation/pickoff plate for reinjection into the interferometer.

4. Seismic isolation stacks

A conceptual design for five-layer isolation stacks for the test masses and beam splitter is shown in Figure IV–B–2, and the parameters are shown in Table IV–B–4. Each pair of layers is separated by four compliant encapsulated-elastomer modules.

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[3] The diffraction loss for a near-confocal, 4-km cavity with 14-cm-diam mirrors is approximately 10^{-6} per reflection. Relaxing the requirement to 10^{-4} per reflection, as needed for initial interferometers, would reduce the required diameter by only $\sim$ 1 cm.

[4] These phase modulations are used in obtaining the gravitational-wave signal and in controlling the separation between the beam splitter and each cavity input mirror, as shown in Figure V–2 of Volume 1.

TABLE IV–B–3
PARAMETERS FOR MAIN OPTICAL CAVITIES

Parameter	Value	Notes[1]
Mirror Coatings		
Cavity storage time	2 msec	
Scattering + absorption	$\lesssim$ 50 ppm	
Surface microroughness	< 3 Å rms	for < 50 ppm scattering
Coating uniformity	$\lesssim$ 1.5%	rms variation of transmission coefficient over central 8 cm
Cavity length L	4.0 km	(2.0 km)
Mirror curvature R	3.0 km	(1.5 km)
Figure error	200 Å	rms over central 8 cm
Cavity stability parameter $g = 1 - \frac{L}{R}$	−0.33	(−0.33)
Spot radius at mirror w_1	2.6 cm	(1.8 cm)
Spot diameter at mirror for 10^{-6} loss	14.1 cm	(10.0 cm)

[1] Parenthetical entries refer to half-length interferometers.

The "less critical" components will use three-layer stacks. The 300 kg capacity for the isolation stacks accommodates the optical benches in the beam-splitter and other chambers. See Volume 1, Appendix D, for an estimate of the achievable performance of this type of seismic isolation.

TABLE IV–B–4
PARAMETERS FOR ISOLATION STACKS

Parameter	Value	Notes
Test-mass and beam-splitter isolation		7-Hz horizontal resonance 15-Hz vertical resonance
Passive stages	5	
Capacity	300 kg	
Isolation for less critical components		
Passive stages	3	
Capacity	300 kg	

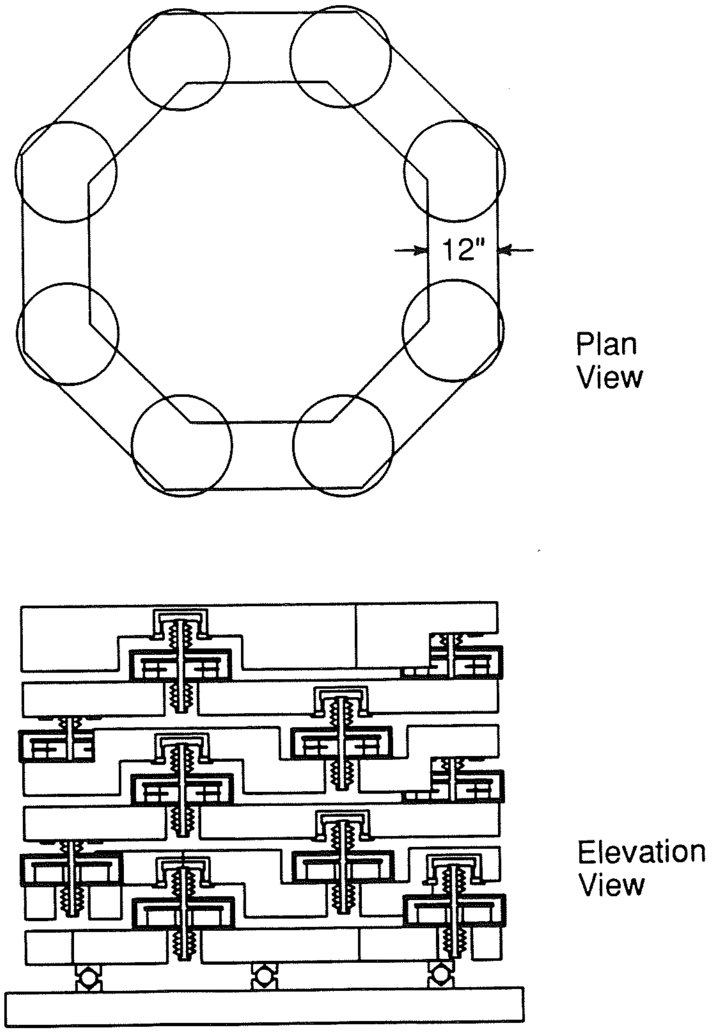

Figure IV–B–2 Five-stage isolation stack for test masses. Isolation between steel layers is provided by cylindrical modules consisting of elastomer elements encapsulated in vacuum-tight canisters with compliant bellows. *Upper:* Plan view of stack, with octagonal steel layers and cylindrical modules. *Lower:* Elevation view, showing offsets of modules and steel layers. The elastomer elements are represented by the rectangles under the horizontal plate in each canister. (The vertical rod, connected to this plate and to the bellows, is not connected to the canister.) The double bellows arrangement on each module provides compensation for forces when the gas pressure changes during pumping or venting.

5. Test masses

The parameters for the initial interferometer test masses are listed in Table IV–B–5. The optimum shape, as discussed in Volume 1, Appendix B, is that which minimizes the internal thermal noise of the mass.[5] The design uses fused-silica test masses (the material used in prototype mirrors and masses), with the cavity mirrors

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[5] The table lists the lowest longitudinal mode resonance, at 16 kHz. A lower resonance, at

coated directly onto the masses.

TABLE IV–B–5
PARAMETERS FOR TEST MASSES

Parameter	Value	Notes
Composition		Monolithic, fused silica
Diameter	20 cm	
Length	14 cm	
Mass	10 kg	
Resonance	16 kHz	Longitudinal mode

6. Control of test-mass and beam position

Each of the four test masses will be hung from identical wire suspensions, connected to one of four identical isolation stacks. The suspension wires are attached to a small metal bar (shown in Section II, Figure II–2) which is controlled by forces between attached magnets and fixed coils. The test mass follows the angular and translational motions of the suspension bar at low frequencies. Fine control of longitudinal position and alignment over a wider bandwidth may be achieved by electrostatic or magnetic forces applied between the test mass and a "reaction mass" (visible in Figure IV–C–7) suspended behind it. The reaction mass is itself isolated and suspended similarly to the test mass, to prevent seismic noise from entering through the test-mass control system.

The "low-frequency" specifications for stability of test-mass orientation and input beam direction and position in Table IV–B–6 refer to slow drifts associated with thermal coefficients of the isolation stacks and position sensors. The upper limit specification stated for angular fluctuations in the signal band ($f \approx 1$ kHz) is determined by predicted first-order effects of beam motion on the interferometer cavity's optical length; higher-order effects may dominate, but the use of mode cleaners is likely to result in smaller fluctuation than this upper limit specification. The stability at intermediate frequencies (≈ 10 Hz) is likely to be intermediate between the values for thermal drift and the specification for motion in the signal band. Local position sensors and feedback transducers, as well as optical levers to determine the angular orientation of the mirrors, provide signals and control for interferometer alignment. When the interferometer is operating, the positions of the test masses and beam splitter are controlled to maintain the proper spacing.

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12 kHz, has a smaller effect. Its contribution to the noise vanishes if the cavity beam center is coincident with the center of this mechanical mode.

TABLE IV–B–6
STABILITY OF CAVITY BEAMS AND TEST MASSES

Parameter	Value	Notes
Pendulum frequency	1 Hz	Nominal; for 30-cm wire suspension
Local position sensors		
Noise	$\lesssim 1 \cdot 10^{-11}$ m/$\sqrt{\mathrm{Hz}}$	$f \lesssim$ 100 Hz
Dynamic range	3 mm	
Test-mass stability		
Angular stability	$< 4 \cdot 10^{-7}$ rad	Peak motion at low frequency
Position stability	$\lesssim$ 0.7 mm	Peak motion at low frequency
Beam stability		
Angular fluctuations	$< 10^{-12}$ rad/$\sqrt{\mathrm{Hz}}$	$f \approx$ 1 kHz
Position stability	$\lesssim$ 0.7 mm	Peak motion at low frequency

Several other components need almost as much vibration isolation as the test masses: the mode-cleaner mirrors, beam splitter, steering mirrors, and recycling mirror. These will be suspended similarly to the test masses. Other optical components will be suspended by pendulums isolated with less elaborate stacks, or none at all. Local position sensors and associated force-feedback transducers are used to damp the pendulum motions and for coarse alignment of suspended components.

Figure IV–B–3 shows a standardized mount and control mechanism for a typical suspended optical component. The self-contained sensing and feedback system is designed to provide adequate accuracy and sufficiently low noise for all but the most critical components. By limiting the number of variations on this design to two or three, automation of interferometer control will be simplified, and economies of scale will be realized in the mechanical and electronic components.

7. Other elements of the design

a. Variable-reflectivity recycling mirror. The design will include the option of operating without the recycling mirror, for diagnostic purposes. The current concept for the recycling mirror is to build it as a composite of two low-loss mirrors, with piezoelectric spacing adjusters. The reflectivity, and consequently the recycling factor, can then be adjusted by varying the separation between the mirrors.

b. Antiseismic suspension-point interferometer. A secondary optical system to reduce seismic noise will be installed either during the initial interferometer construction, or early in the operations phase. This suspension-point interferometer[6] has arms parallel to those of the primary interferometer; it measures the

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[6] See Volume 1, Appendix C for a description.

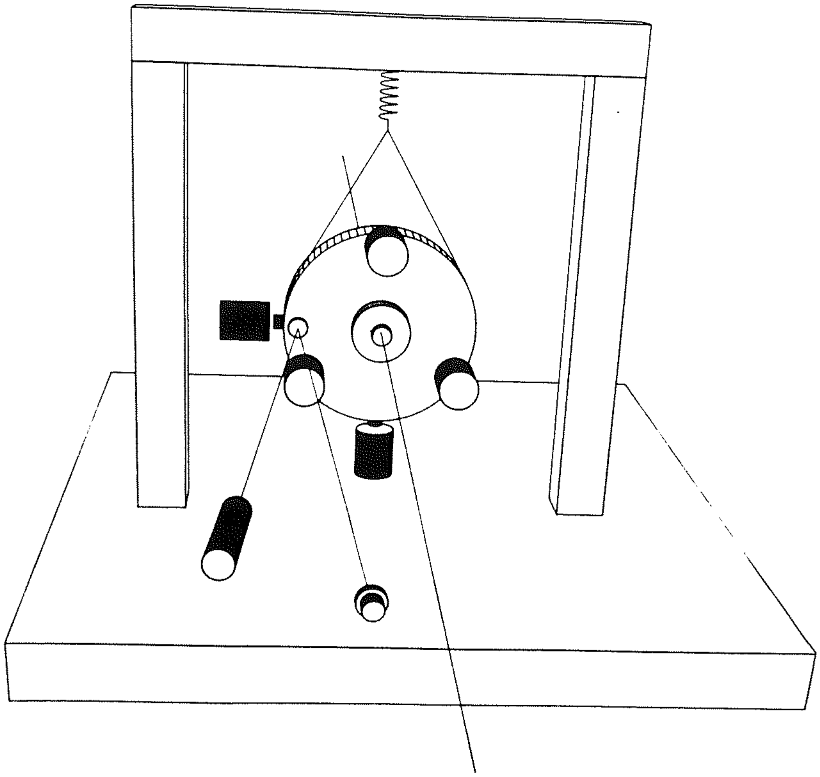

Figure IV–B–3 Alignment, position, and damping control of a typical suspended optical component. A transparent optical component is shown suspended in a holder with five small permanent magnets attached to it. The position of each magnet is sensed optically and controlled with a separate sensing/feedback head, resulting in control of five degrees of freedom (two axes of pendulum motion, vertical position, pitch, and yaw). Also shown is an optical lever consisting of a laser, a mirror at the left edge of the holder, and a position-sensitive photodetector. The optical lever provides enhanced sensitivity for monitoring pitch and yaw motion. Except for small modifications, the same design for sensing and control can be used for almost all of the suspended components in the interferometer.

motion of the bars at the top of the pendulum wires. Its output signal is used to reduce the effect of seismic noise in the main interferometer, either by subtraction from the recorded data stream, or by controlling the longitudinal position of the suspension bars in a closed-loop servo. The overall interferometer design leaves the inclusion of the suspension-point interferometer as an option that can be installed with minimum disruption to operations.

c. Automatic alignment and centering of beams. Although simple controls of the type used in the prototype interferometers should suffice to meet the specifications listed in Table IV–B–6, the highest precision control of the orientation of beams and test masses will be provided by alignment systems based on the main interferometer beams. The complete system, consisting of automatic alignment, centering sensors and controlling transducers, should keep the beams precisely aligned at all times, and stationary relative to the test masses.

d. Detailed design analysis and modeling. During the engineering design of the interferometer, a detailed system-engineering analysis, including the effects of scaling up from 40 m to 4 km, will be carried out. Among the key parameters are: (1) the increased beam sizes that scale with $\sqrt{L}$, (2) the increased precision required in angular alignment, which scales as $1/\sqrt{L}$, and (3) the increased delay times in some of the servo systems, which scale as L.

C. Vacuum System: Mechanical Design

1. General characteristics of the vacuum system

The LIGO vacuum system is designed to meet several key requirements. The beam tubes must:

- Provide a 1-m-diam clear aperture for the optical beams along the 4-km length of each LIGO arm.
- Provide a vacuum good enough that interferometer sensitivity is not degraded by statistical fluctuations in the index of refraction of the residual gas.
- Control the propagation of scattered light.

The chambers in the corner station, end stations, and mid stations must:

- Accommodate a wide variety of interferometer components and configurations.
- Provide access for installation and servicing of interferometer components with minimum disturbance to operating interferometers.
- Assure a clean, low-vibration, high-vacuum environment for interferometer optical components.

The LIGO vacuum system will be constructed entirely of stainless steel. To reduce pumping or bakeout requirements, stainless steel with low hydrogen content has been developed (see Appendix D). We plan to use this type of steel for all internal parts of the vacuum system.

High vacuum throughout the LIGO is achieved and maintained by ion pumps, which are vibration-free and reliable. Condensible gases from interferometer components are pumped by quiet liquid-nitrogen-cooled surfaces.

Gate valves at the ends of the beam-tube modules allow isolation of the major elements of the LIGO vacuum system. Additional gate valves within the stations facilitate installation and servicing of interferometer components and vacuum hardware.

Rough pumping from atmospheric pressure to the range of 10^{-6} torr is done by mechanical-pump/turbomolecular-pump sets, located in the stations at both ends of each beam-tube module. The same rough-pumping sets are used for the beam tubes and the chambers in the stations. Less than 24 hours is required to rough-pump a beam-tube module sufficiently to proceed with leak testing operations. Once the beam tubes are pumped down, they will remain continuously under vacuum. The relatively small chambers in the stations can be rough-pumped to 10^{-6} torr in a few hours; then the noisy pumps can be turned off, permitting unperturbed interferometer operation.

Critical optical surfaces in opened chambers will be protected against particle contamination by local high efficiency particulate air (HEPA) filter showers. Operation of these showers will be integrated with the chamber pumpdown and backfill procedures—they will be gradually turned off after the start of pumpdown, used to backfill the chambers, and left on at all times when at atmospheric pressure.

Operation of the vacuum-system valves and pumps will be manually initiated under the control of a central operator, with interlocks enabled by automatic system-monitoring equipment.

TABLE IV–C–1
2-KM BEAM-TUBE MODULE DESIGN PARAMETERS

Number of modules per LIGO Installation	4
Clear aperture	1 m
Length	2 km
Inside diameter	48 in.
Wall thickness	0.125 in.
Material	Stainless steel, Type 304L
Stiffener spacing	24 in.
Optical baffle spacing	80 in.
Length of finished tube section	40 ft
Weight of finished tube section	3060 lb
Expansion-joint interval	40 ft
Tube-support interval	40 ft
Number of sections per module	160
Vacuum-pump spacing	804 ft
Number of pumps per module	7
Pump-tee length	4 ft

2. Beam tubes

a. Summary. The beam tubes at each site are made up of four identical 2-km-long modules. Key design parameters of the modules are provided in Table IV–C–1, and a segment of a beam-tube module is illustrated in Figure IV–C–1. Beam-tube modules are designed to be supported on a continuous mat foundation and covered with a concrete-arch enclosure after completion of field assembly, alignment, leak testing, and bakeout (see Section IV.E.3 for a description of the cover construction technique). Each module is composed of 40-ft-long sections of tubing, each with an integral expansion joint. The sections are joined by vacuum-compatible welds. Seven ion pumps are distributed along each module at equal intervals.

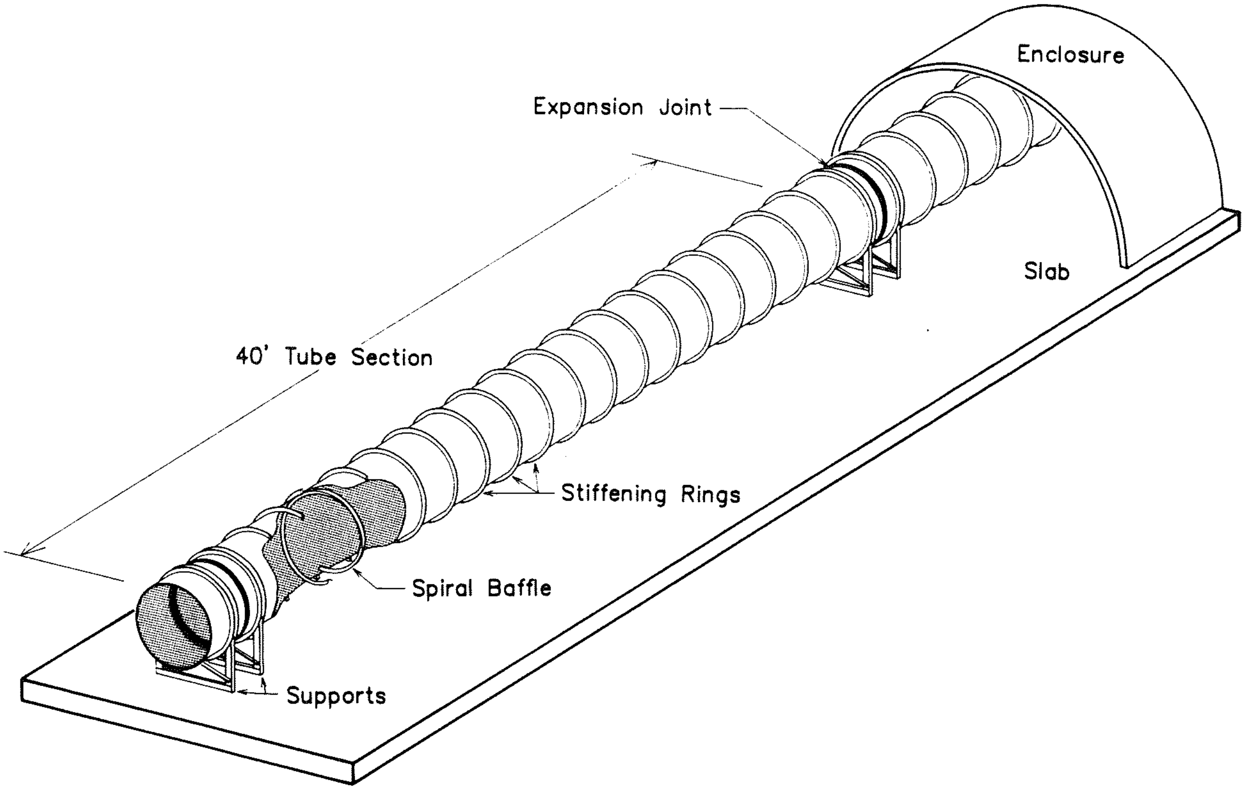

Figure IV–C–1 Segment of a beam-tube module showing stiffening rings and supports. Each prefabricated 40-ft tube section has an integral expansion joint at one end. A portion of the tube section is shown cut away to reveal one of the spiral baffles fitted inside the tube. The semi-cylindrical beam-tube enclosure (shown cut away) is mounted on the slab after the beam-tube module has been fully assembled and tested.

The 48-in. inside diameter tube sections are manufactured at an off-site commercial mill; the 40-ft lengths are the longest that can be readily transported by conventional highway trucks. The tube is spiral-rolled from 1/8-in.-thick stainless steel, type 304L, with carbon-steel stiffening rings installed on the exterior at 24-in. intervals. An expansion joint is welded into each tube section to accommodate construction handling and thermal stresses. The ion pumps are attached to 4-ft-long pump tees spaced one per 20 sections. A 6428-ft-long beam-tube module requires 160 tube sections and seven pump tees. Together with beam-tube extensions incorporated into the stations, the two beam-tube modules along an arm make up a single 4-km-long vacuum envelope.

b. Design and fabrication of the beam-tube elements.

i. Tube section design and fabrication. Figure IV–C–2 shows the principal design features of a 40-ft beam-tube section. The tube is produced in a continuous, automated factory process. Coils of stainless steel sheet, 1/8 in. thick, 4 ft wide, and weighing about 20,000 lbs, are loaded into a machine that simultaneously rolls the sheet into a spiral-formed tube and welds the incoming sheet edge to the outgoing

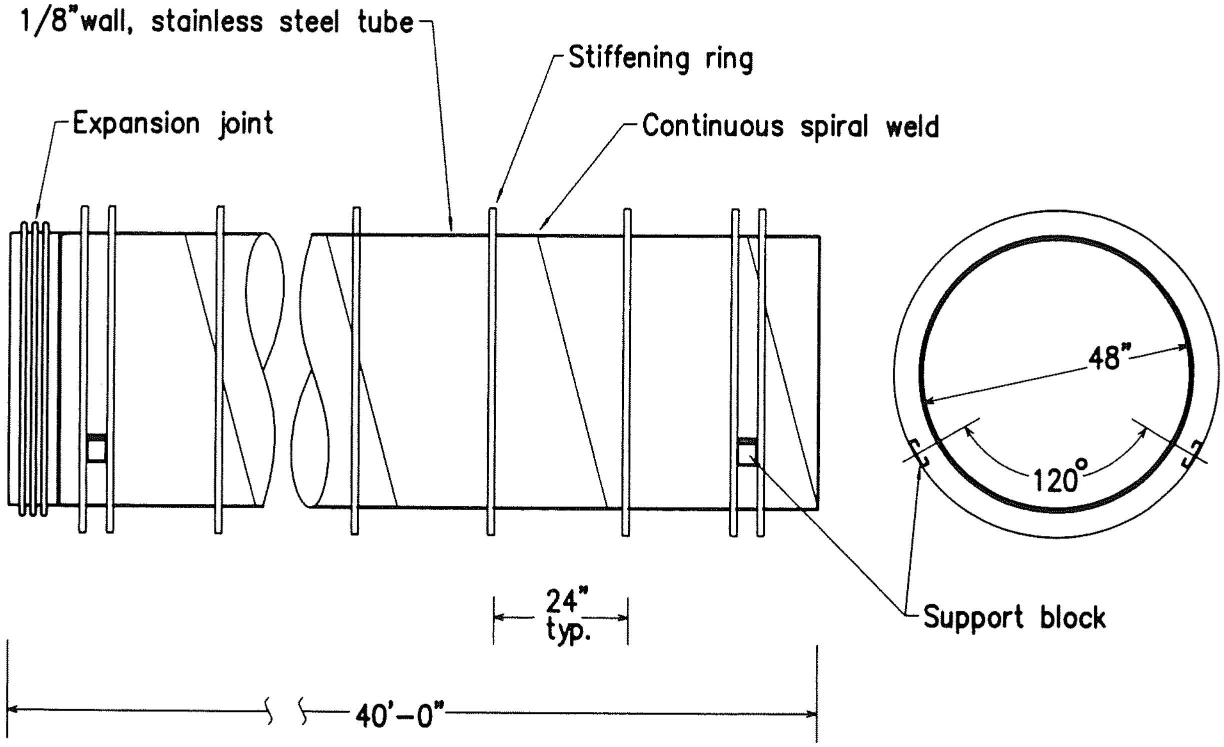

Figure IV–C–2 Principal features of a beam-tube section. *Left:* Side view showing single expansion joint, continuous spiral weld, stiffening rings and support block locations. *Right:* View along cylinder axis. To reduce stress on the thinwall tubing, the tube is held by support blocks mounted between two closely spaced stiffening rings.

tube product[1]. The tube is cut to length and stiffening rings[2] are welded into place. Using a rolling process, each end of the tube section is then expanded for a distance of about 2 in. along the tube axis to a standard circumference to remove diameter variations. The end is faced off to leave a smooth, planar, end surface. The result is a stiffened tube section suitable for subsequent fit-up and butt-welding operations. An expansion joint[3] is butt-welded onto one end of the tube, completing the 40-ft tube-section assembly.

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[1] The process is well established in the piping industry, with about 50 U.S. companies producing carbon steel and stainless-steel pipe in diameters ranging from 4 to 150 in. and wall thicknesses ranging from 0.052 to 0.62 in. A full-penetration tungsten-inert-gas (TIG) weld is applied by machine from the inside of the tube. The weld joint is continuously monitored ultrasonically for weld quality. The output tube product is cut to length by a plasma torch.

[2] The stiffening rings, 1/4 in. wide by 2 in. high, are produced by rolling carbon-steel bar stock into a helix, which is then cut into rings with a small overlap. The rings are expanded to fit loosely over the finished tube product, positioned into place, and released to give a tight fit around the tube. An extra stiffening ring is installed near each end of the tube section to accommodate the tube supports.

[3] The expansion joint, a conventional formed bellows with 0.020 in. wall thickness and five cycles of 1.25-in. period, is fitted with 1-in.-wide rings of expanded, controlled-circumference tubing stock welded to each end by the bellows manufacturer.

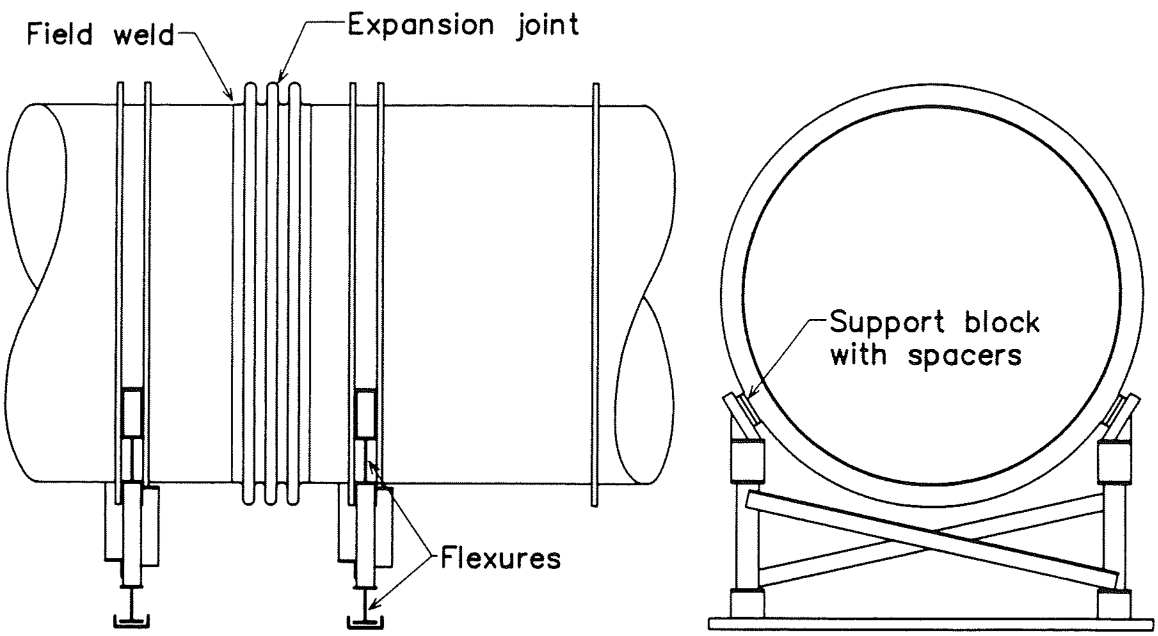

Figure IV–C–3 Sketch showing beam-tube supporting hardware. *Left:* The joint between tube sections. The two sections are butt-welded together in the field. Sections are supported by simple flexible supports that allow thermal expansion without slipping. *Right:* Cross-section of tube and supporting structure. The supports are made of roughly-cut pieces of standard carbon-steel structural members. These are welded together in a jig that defines the spatial relationship between the base-channel and support-block faces; all other dimensions are noncritical. The base-channel piece has two 6-in. slots to allow horizontal adjustment of the tube relative to the base. Vertical adjustment involves inserting spacers between the tube supports and tube sections.

After the tube section is cleaned, temporary covers are clamped onto the ends and the section is pumped down and tested with a residual gas analyzer for leaks and cleanliness. After testing, the tube sections are fitted with shipping covers for transport to one of the LIGO sites.

ii. Tube supports. The tube supports are simple and inexpensive steel structures shown in Figure IV–C–3. Two supports are used for each tube section. The supports are designed to allow adjustment of the beam-tube alignment, with up to 6 in. of adjustment range in both transverse directions.[4] The supports also accommodate thermal stresses of the tube sections by flexing without stick-slip effects.

iii. Baffles. The beam tubes must control the propagation of scattered light, as discussed in Section II.D. This requirement is partially met by random variations in tube diameter, ellipticity, and alignment of the tube wall. These variations will

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[4] Initial alignment of the beam-tube foundations is expected to be within ± 1 in. vertical, so there is ample adjustment-range margin.

arise naturally during the fabrication, field assembly, and alignment of the beam-tube modules.[5] In addition, baffles with a "V" cross section are installed in the beam tubes at 80-inch intervals. The baffles reflect scattered light that approaches the tube walls with small grazing angles into rays that suffer strong attenuation by multiple reflections from the tube walls.[6]

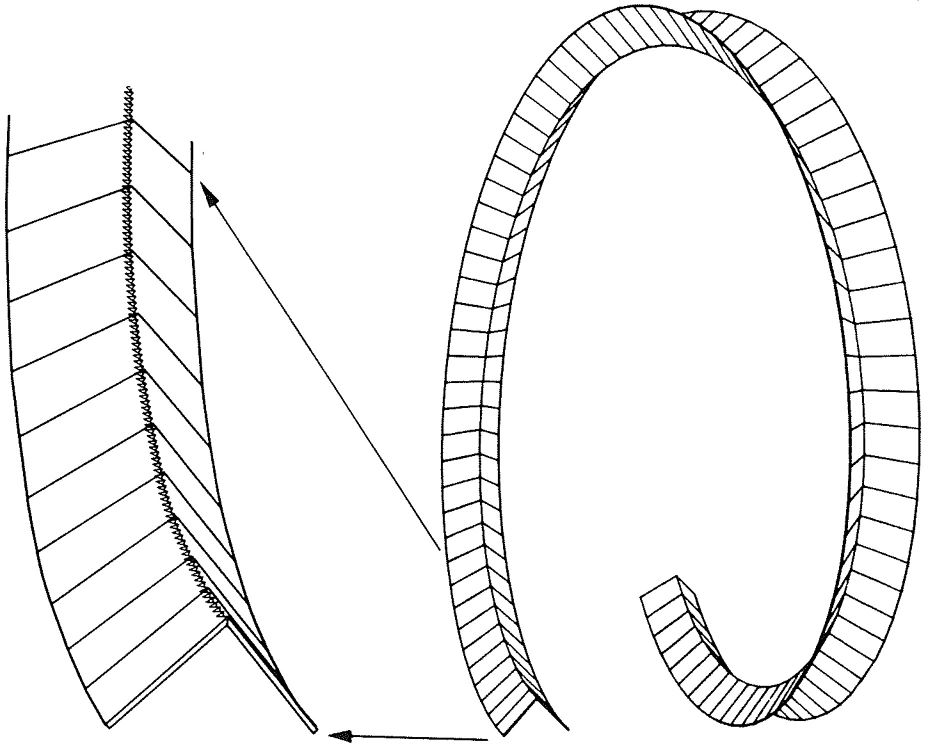

Figure IV–C–4 Spiral baffles. The baffles reflect stray light approaching the tube wall with small grazing angles into steeper angles, leading to absorption by the tube through multiple reflections. The serrated inner edge (exaggerated for clarity) randomizes the phase of paraxial diffracted stray light (see Volume 1, Appendix F). The shape and placement of the baffles is not critical (typical sheet metal tolerances are satisfactory). The baffles are installed by inserting them into the tube in a compressed state and are held in place by friction on the tube walls after being released.

The baffles, illustrated in Figure IV–C–4, are cut from a continuous helix[7] and installed in the beam tube during field assembly.

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[5] Centimeter-scale variations are required; it is actually important to avoid building and aligning the beam tubes as precisely as, e.g., an accelerator beam tube.

[6] For a more detailed discussion, see Volume 1, Appendix F.

[7] Fabrication of the baffles employs a machine-rolled spiral-forming process similar to that used for the tube sections. Coils of 7-in.-wide stainless-steel (processed for low hydrogen content) sheet stock are loaded into the roll-forming machine. As the stock is peeled off the coil, it is first folded 90 deg. along its center line; then the serrations are cut into the folded edge; finally, the folded,

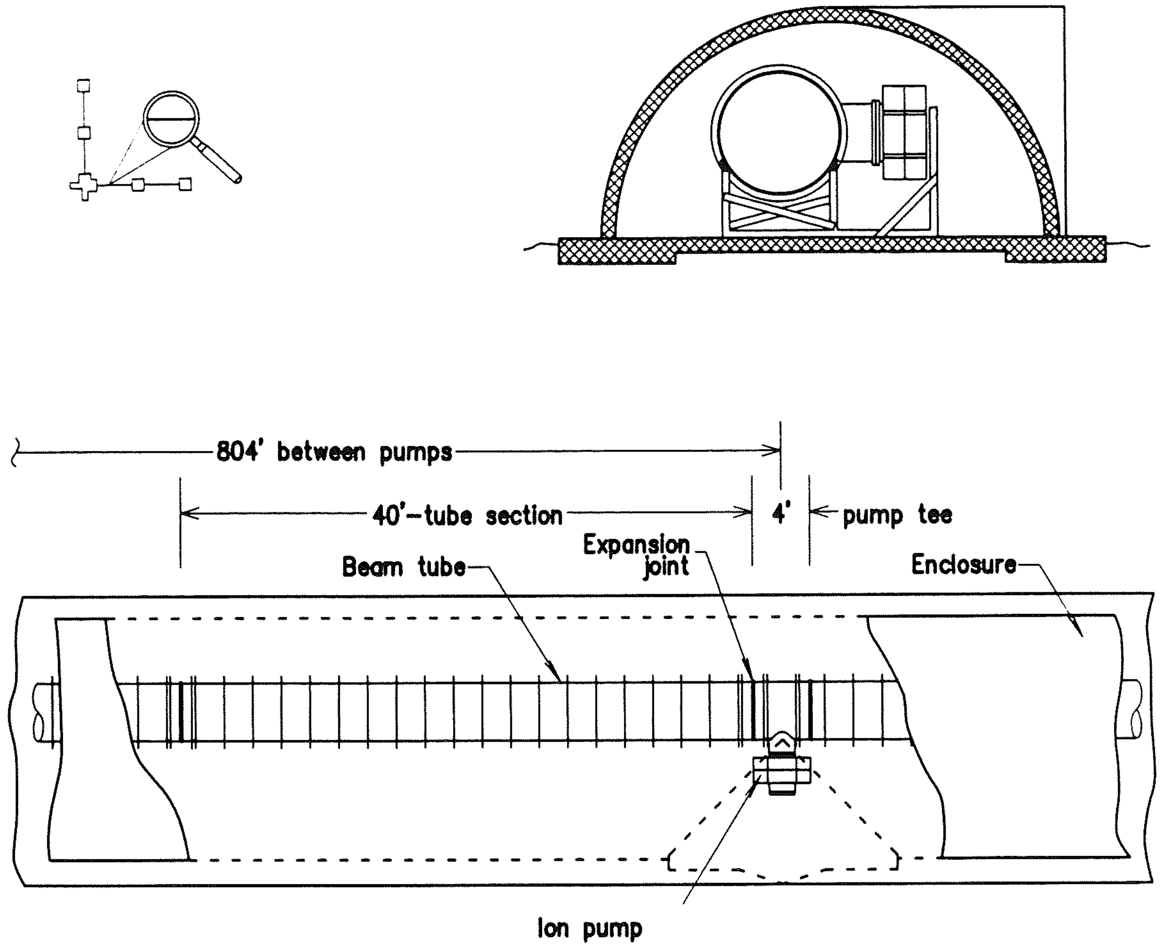

Figure IV–C–5 Attachment of ion pumps to the beam tubes. *Upper:* Section view showing an ion pump connected to the beam tube. *Lower:* Plan view showing pump attached to 4-ft-long tee. There are seven ion pumps installed on each 2-km-long beam-tube module.

iv. Pump stations. A vacuum pumping station is installed between each group of 20 tube sections of a beam-tube module. It uses a 2500 L $\cdot$ s^{-1} ion pump, separately supported, which is installed during field assembly of the beam-tube module. The installation[8] is illustrated in Figure IV–C–5.

c. Field assembly of the beam-tube modules. The design and field

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serrated stock is rolled to produce a continuous helical output of about 50-in. outside diameter. The output product is cut into rings with about 1 ft of overlap to allow for separation of the overlapped area during insertion into the beam tube. Crude sheet-metal processing techniques are adequate to meet the tolerances on shape, fit, surface roughness, and edge definition.

[8] The pump tee, is fabricated in a similar manner to the 40-ft tube sections. A short, flanged nozzle of 18-in.-diam is added to one side to attach the ion pump. A 2.5-in.-diam flanged nozzle is included for attachment of diagnostic instrumentation. The pump tee is installed into the beam tube in the same manner as a tube section.

assembly of the beam-tube modules is considerably simplified by not attempting to control the accumulation of length errors in the assembled portion. The beam-tube modules are simply fitted to the stations at each end with special-length tube sections.

i. Alignment of the tube sections. The continuous mat foundations are constructed as early as possible to give maximum time for settling. The foundation slabs describe a plane with errors of order 3 cm, obtained by using standard construction survey techniques. The tube sections are locally aligned with a precision of about 0.5 cm using reference monuments, located at 250 m intervals. A survey of the monument positions is performed using a kinematic survey technique, which is ideally suited to the needs of the LIGO. This technique relies upon radio signals broadcast by satellites of the Global Positioning System (GPS). A portable GPS receiver, placed on each monument in turn, is used to determine the relative (3-dimensional) locations of the monuments with a precision of a few millimeters. The vertical contour of the slab is traced with a precision of one centimeter by transporting the receiver along the foundation slab between monuments.

With these survey data,[9] field alignment of the tube sections becomes straightforward. A laser leveling transit provides a beam aligned to the clear-aperture axis. The tube section is supported on a movable jack at each end. The mating end is positioned for welding to the tube already installed and the other end is aligned to the laser beam, using the angular freedom of the built-in expansion joint. This procedure will result in alignment of the tube sections within 1 cm.

ii. Welding the tube sections together. Tube sections arrive at the site from the manufacturing plant with shipping covers that protect the inside of the tube section from contamination and prevent damage to the ends that are already prepared for welding.

Portable enclosures[10] are sealed around the new tube section to protect the inside of the tube from wind-carried debris. The shipping covers are removed, an expandable backing ring[11] is inserted into the mating joint, and the new tube section is fitted to the built-up tube. An automatic welding machine[12] is then installed and a TIG weld is made. After the weld is completed, the expandable

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[9] The receiver data are recorded on floppy disk. The field assembly crew will work from instructions generated from these data that specify tube-section alignment relative to the nearest reference monuments.

[10] The portable enclosures have flexible ends wrapped around the adjacent tube walls to obtain an environmental seal.

[11] The pneumatically-actuated expandable backing ring, grooved under the weld joint, is inserted inside the tube to obtain accurate alignment of the joint and to contain the backside inert purge gas for the weld.

[12] The welding machine is guided by a flexible track installed around the tube for accurate tracing of the joint contour. The expandable backing ring and track-guided automatic TIG welder are commercially available.

backing ring is withdrawn through the newly attached tube section. The baffles are installed (see next subsection), and a protective cover with an alignment target is attached to the free end of the tube. The portable enclosures are detached from the tube and moved out of the way.

The reusable shipping covers are returned to the tube manufacturing plant for use on new tube sections.

iii. Installing the baffles. Six baffles are inserted into each tube section, one at a time, by spreading the overlapped ends (thus contracting the diameter of the baffle) with a simple tool on the end of a boom. Once a baffle is located into position, the tool is released and withdrawn, permitting the baffle to spring into place. No additional attachment to the tube wall is required. Baffle spacing is not critical (the tolerance on baffle position is ±1 m).

iv. Installing the supports. The tube supports are positioned on the foundation slab beneath the pair of stiffening rings provided for this purpose (refer to Figure IV–C–3), and fastened to the slab. Support blocks welded to the stiffening rings are bolted to the support via spacers selected to match the tube height.[13]

d. Design tradeoffs.

i. Material. The possible material choices for the LIGO beam tube are stainless steel, carbon steel, and aluminum. Stainless steel is strong and stiff, has good welding characteristics, resists corrosion, and is traditionally used in high-vacuum systems.

Carbon steel, although about 1/6 the cost of stainless steel per unit weight, is generally not used in vacuum systems at pressures below 10^{-6} torr. It is more subject to corrosion than stainless steel, which may lead to excessive outgassing rates. Compared to stainless steel, it has a much higher diffusion rate for hydrogen.[14] The additional pumping speed required to cope with a higher permeation rate would negate any cost advantage. We conclude that using carbon steel for the LIGO beam tubes is too risky.

Aluminum is lightweight but less stiff than stainless steel, requiring either thicker walls or more stiffening rings. At today's prices, an aluminum beam-tube

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[13] The tube section is now supported, aligned, and secured to the slab foundation. Subsequent vertical adjustments (if required by, for example, settlement of the foundation slab) are made by changing the spacers. Horizontal (transverse to the tube axis) adjustment is accomplished by loosening the fasteners that secure the tube support to the slab and sliding the tube support on the slab.

[14] Although room-temperature diffusion-rate data are not available, extrapolation of high-temperature data to room temperature suggests that the diffusion rate of hydrogen in carbon steel may be six orders of magnitude larger than for stainless steel. Our estimate for the permeation rate of hydrogen, generated on the exterior surface due to corrosion from water vapor and permeating through the bulk material to the high vacuum side, is that it might exceed 10^{-12} torr $\cdot$ L $\cdot$ $s^{-1} \cdot$ cm^{-2}.

section would cost about 7% less than the proposed stainless-steel sections. On the other hand, most fittings and flanges for high-vacuum systems are made from stainless steel, and joining aluminum and stainless steel is technically difficult. The additional cost of attaching ion pumps, instrumentation fittings, and valves would offset some or all of the potential cost savings. Aluminum is free of dissolved hydrogen, so that no high-temperature bakeout is needed. The low-hydrogen-content stainless steel proposed for the LIGO beam tubes also requires no high-temperature bakeout. We conclude that there is no advantage to considering aluminum for the beam tubes, and have chosen traditionally favored stainless steel.

ii. Tube-wall thickness. Tube-wall thickness is chosen to balance the cost of stainless steel with the cost of stiffening rings. Although the ASME Boiler and Pressure Vessel Code[15] excludes vacuum vessels from its scope, this standard is commonly used as a guide for design of vacuum tubing and chambers, and was used to determine the wall thickness of the beam tube. The code permits the option of increasing equivalent wall stiffness by the use of external stiffening rings.

Without stiffening rings, the wall thickness of the beam tubes would need to be nearly 1/2 in. By adding inexpensive, external carbon-steel stiffening rings, the thickness of the relatively expensive stainless-steel walls is significantly reduced. Optimization minimizes the sum of the cost of the bulk stainless-steel sheet material and the cost of fabricating and installing the stiffening rings. This, in turn, depends upon the price of steel. Table IV–C–2 displays the recent cost history of stainless steel; the costs include about seven cents per pound for the special low-hydrogen-content processing.

TABLE IV–C–2
COST OF STAINLESS STEEL

Date	Steel price, \$/lb
4/87	0.90
7/88	1.30
11/88	1.54
3/89	1.87
5/89	1.49

At the time of this writing, tube cost optimization has a broad minimum for wall thicknesses in the range of 1/8 to 3/16 in. An increase in the price of stainless steel favors thinner walls. We have chosen the lower end of this range (0.125 in.) to minimize sensitivity to prices of stainless steel and to achieve lower weight, which will result in easier handling and installation. This choice will be reviewed during the detailed design of the beam-tube modules.

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[15] Section VIII, Pressure Vessels; Division 1.

iii. Alternate fabrication methods. We have been investigating corrugated metal pipe (CMP) as an alternative to smooth-wall tubing with stiffening rings. CMP is commercially available as a spiral-formed product for drainage culverts, caissons, and other applications. In the LIGO beam-tube application, spiral-formed stainless-steel corrugated pipe would eliminate stiffening rings, eliminate the need for expansion joints in the tube, reduce wall thickness, and significantly increase attenuation of scattered light.

The required tube wall thickness, using a corrugation profile of 1 in. peak to peak by 5 in. period, is 0.067 in. The major risk involved with this approach lies in the weld integrity. We have initiated an analytical and testing program to characterize the nature of the stresses affecting weld integrity.

3. Vacuum chambers

The vacuum chambers in the corner station, end stations and mid stations provide the operating environment for the interferometer components. To accommodate interferometer evolution (and the anticipated Phase-B and Phase-C expansions of the vacuum system) with minimum disruption, we have adopted a modular approach that provides flexibility in size and geometrical arrangement of the vacuum chambers.

a. Corner station.

i. Site 1 chamber layout. The vacuum system for Site 1 is arranged to accommodate two interferometers during the initial (Phase A) operation of the LIGO, with provisions to add modular vacuum chambers for a total of six interferometers at some future time (see Volume 1, Section IV, for a discussion of the anticipated evolution of LIGO operational capabilities). The Phase-A vacuum-system chamber layout for the corner station at Site 1 is shown schematically in Figure IV–C–6. An array of vacuum chambers is connected to enlarged (6-ft-diam) extensions of the beam tubes that provide space for pointing and alignment beams and will accommodate future expansion of the vacuum system. Gate valves are provided where the beam tubes connect to the vacuum equipment in the corner station, to permit isolation of the major elements of the LIGO vacuum system for servicing, modification, or emergencies. The ability to isolate the beam tubes after initial pumpdown allows them to remain under continuous vacuum.

The chamber array is made up of four basic types of chambers: two types of test-mass chambers, the diagonal chambers, and the horizontal-axis modules. The Type 1 and Type 2 *test-mass chambers*, which house the interferometer test masses and cavity mirrors, are located on the beam-tube extensions. In the Type 1 test-mass chambers, the test-mass assemblies are lowered into position through a horizontal gate valve. In the Type 2 test-mass chambers, which are used only at the extreme ends of the beam tubes, the test-mass assemblies are installed in their final operating locations, isolated from the beam tubes by vertical gate valves. The *diagonal chambers* contain the interferometer beam splitters. One diagonal chamber, located at the intersection of the beam tubes, is connected through large

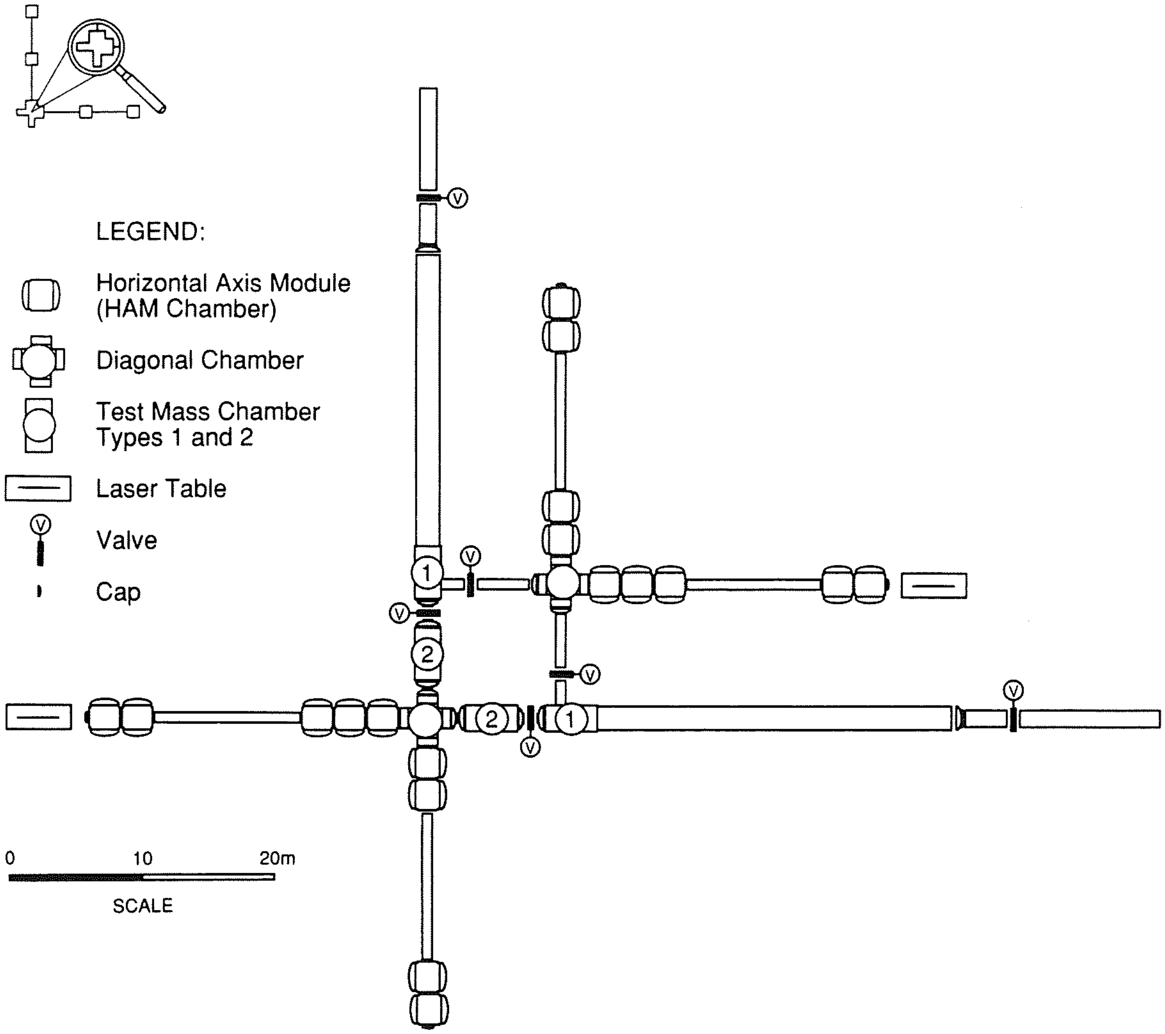

Figure IV–C–6 Layout of the corner-station vacuum chambers for Site 1, Phase A. The beam tubes (entering top and right) can be isolated from the corner-station vacuum chambers by gate valves. An array of modular vacuum chambers and associated gate valves permit the two interferometers to be operated independently. The horizontal-axis module (HAM) chambers, diagonal chamber, and Type 2 test-mass chambers at the vertex (the intersection of the beam tubes) house the input/output optics, beam splitter, and corner-station test masses for the first interferometer. The chambers are interconnected to form a single vacuum envelope, which may be isolated from the rest of the vacuum system by vertical gate valves between the Type 2 and Type 1 test-mass chambers. Components of the second interferometer are housed in the remaining HAM chambers, diagonal chamber, and Type 1 test-mass chambers. The beam splitter and input/output optics for this interferometer are isolated by the gate valves between the diagonal chamber and the Type 1 test-mass chambers. The Type 1 test-mass chambers (illustrated in Figure IV–C–7) include a lifting mechanism and horizontal isolation valve that permit access without disturbing the vacuum in the rest of the system.

apertures to the adjacent Type 2 test-mass chambers. Beams for this interferometer pass directly between the beam splitter and the test masses. The beams for the second interferometer pass through the other diagonal chamber to a Type 1 test-mass chamber. The *horizontal-axis modules* (HAMs) contain input and output optics for each interferometer. The HAMs are separated into groups, connected by beam tubes for the mode-cleaning cavities.

When the appropriate pair of gate valves is closed, all of the components for one of the interferometers are accessible for service or replacement except those in the Type 1 test-mass chambers. A test-mass assembly in a Type 1 test-mass chamber can be serviced by lifting it from the beam tube and closing the horizontal gate valve in the chamber. Thus, any component in either interferometer can be accessed without interfering with the vacuum environment of the other.

The set of HAMs and the diagonal chamber associated with an interferometer function like a single vacuum vessel. Because the HAMs are interchangeable, this part of the vacuum system can grow or shrink as necessary to accommodate the evolutionary development of the interferometer optics chains.

We now describe the design concept and features of each of these chambers in more detail.

(a) Test-mass chamber, Type 1. The Type 1 test-mass chamber assembly is shown in Figure IV–C–7. The vacuum envelope includes an *optics unit* with a 6-ft inside diameter which serves as an expanded extension of the beam tube. The expanded diameter accommodates auxiliary optical beams for position and alignment monitoring. The test-mass assembly can be lowered into the optics unit from above through a horizontal aperture in the *air-lock unit*, which is welded to the top of the optics unit. The 5-ft-diam air-lock aperture accommodates test masses up to 50 cm in diameter (up to 1 ton in mass). The laser beams traveling between the diagonal chamber and the test-mass chamber pass through a port (not shown) in the side of the optics unit, opposite the service-access port.

The air-lock unit contains a horizontally driven air-lock cover and actuator. The cover and actuator are simpler than in a standard gate valve, as they are designed to seal against atmospheric pressure in one direction only. Above the air-lock cover, a pair of support beams that carry the weight of the interferometer apparatus penetrates the side walls of the air-lock unit, sealed by soft bellows. A 2500 $L \cdot s^{-1}$ ion pump is mounted on the air-lock unit. Other features provided by the air-lock unit include vacuum instrumentation ports, a roughing-pump port, and electrical feedthroughs.

The chamber is covered by a removable *dome*.

The interferometer test mass, reaction mass, beam-deflection mirror, and other interferometer components are suspended from a space-frame structure attached to the top of the vibration-isolation stack, described in Section IV.B.[16] The stack is kinematically mounted on three locating blocks attached to the internal support

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[16] The elastomer between the layers of steel in the stack is encapsulated in canisters to protect the vacuum environment from contamination.

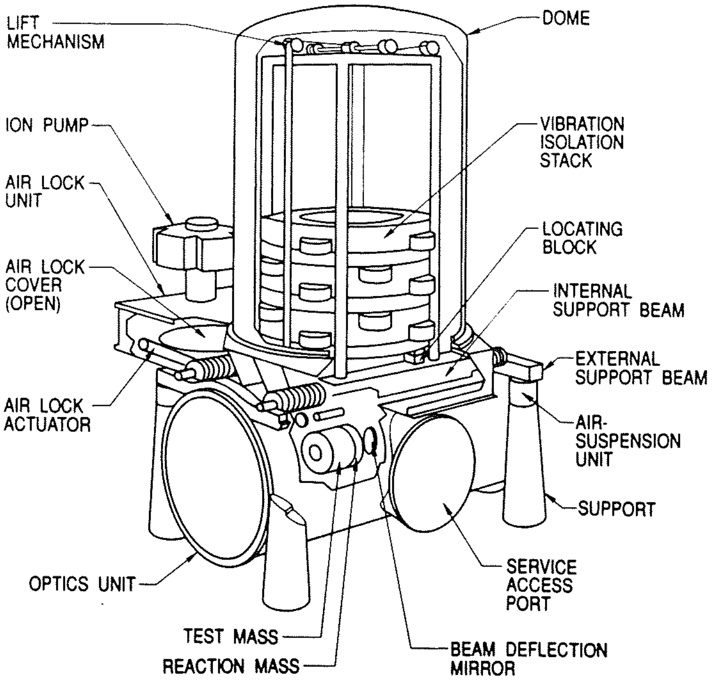

Figure IV–C–7 Representation of Type 1 test-mass chamber (*facing page*), with key components indicated (*above*). Principal elements of the chamber are: (1) the *optics unit* (lower portion) aligned with the beam tube and continuously under vacuum, (2) the *air-lock unit* (welded to the top of the optics unit) containing a horizontally-driven air-lock cover, and (3) the removable *dome*. The vibration-isolation stack and suspended interferometer components are supported by a set of beams resting on four air-suspension units outside of the chamber. Four symmetrically-arranged, soft bellows (*orange*) seal the penetrations through the chamber at the air-lock unit and isolate the interferometer components from external vibration. The interferometer components are serviced by using the lift mechanism (*top*) to raise the vibration-isolation stack and test-mass assembly above the plane of the air-lock cover. Once the air lock is closed the dome can be removed for access to the components leaving the optics unit under vacuum. The *service-access port* (in the side of the optics unit) permits backup access to the system. The optical beams pass to and from the diagonal chamber through a port (not shown) on the opposite side of the service-access port.

beams. This ensures that the stack is positioned accurately when lowered into place. The internal support beams penetrate the vacuum envelope, sealed by soft bellows, and rest on the external support beams, which in turn rest on four air-suspension units.[17] The flexible bellows are symmetrically arranged to provide compensation of atmospheric pressure, so that the support beams do not experience a change in forces when the chamber is evacuated.

This method of supporting interferometer components affords considerable me-

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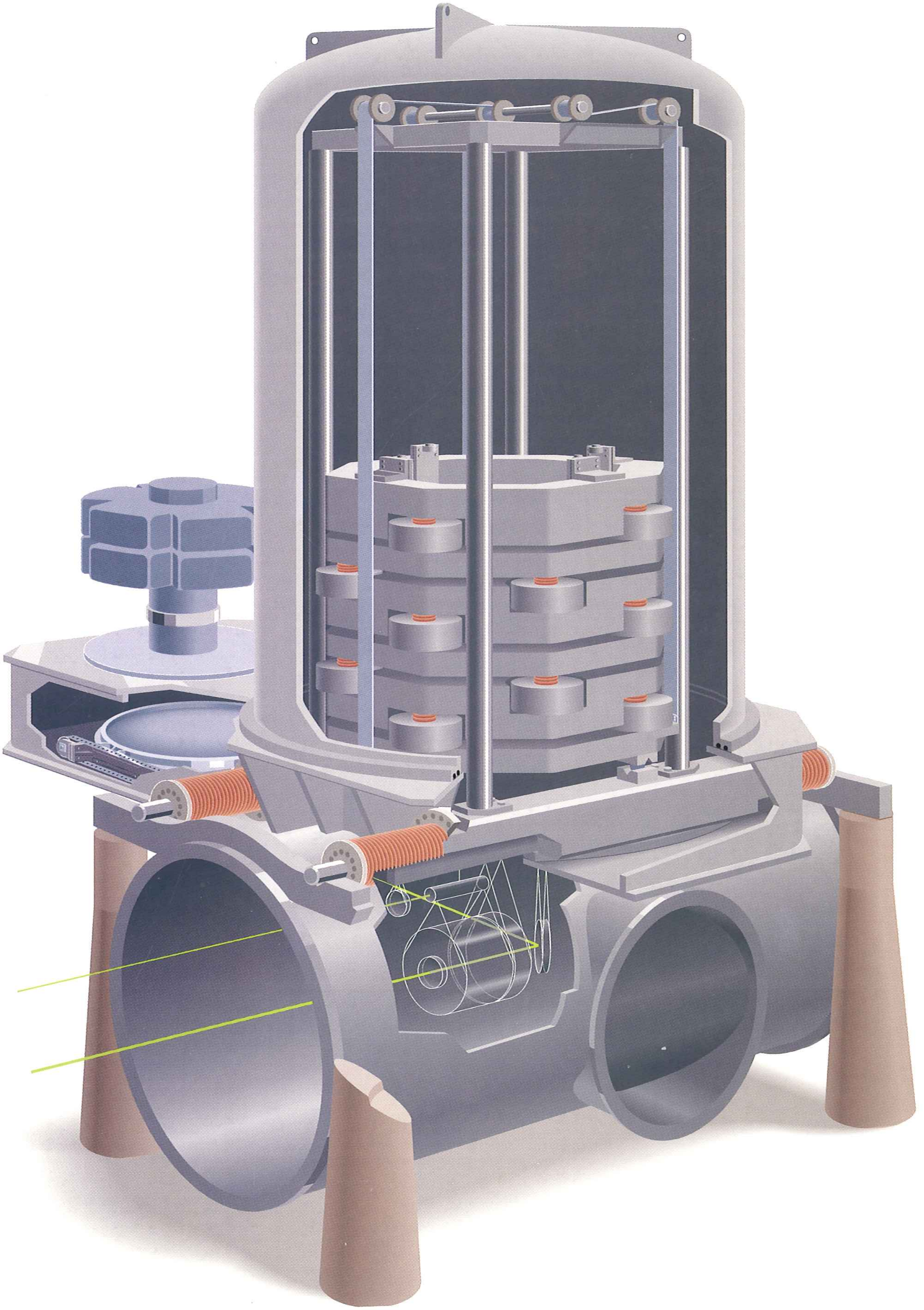
[17] The air-suspension units are mounted on support piers, which carry the weight of the interferometer components, vibration-isolation stack, and support beams. Separate structural supports are provided for the vacuum envelope (not shown in Figures IV–C–7, IV–C–8, IV–C–9, or IV–C–10).



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chanical isolation from both the chamber wall (which unavoidably acts as a microphone, sensitive to ambient acoustic noise), and the building floor and foundations (which transmit seismic vibrations).

In operation, the optics unit of the test-mass chamber assembly is continuously kept under high vacuum, permitting optical beams from other interferometers to pass through freely. To service or replace an interferometer component, the vibration-isolation stack and suspended interferometer components are raised by the lift mechanism until the lowest component clears the plane of the air-lock cover. The air lock is then sealed, and the volume enclosed by the dome and air-lock unit is air-released. The dome is then removed, and work on any part of the installed apparatus may proceed. When the work is completed, the dome is replaced and the upper section of the test-mass chamber assembly is rough-pumped to a pressure suitable for turning on the ion pump. After the outgassing load (mainly water vapor) drops to a suitable level and the absence of contaminating outgassing products is verified, the air lock is opened. The interferometer apparatus is then lowered into the optics unit, and normal operation is resumed.

(b) Test-mass chamber, Type 2. The Type 2 test-mass chamber is illustrated in Figure IV–C–8. It shares many of the design features of the Type 1 test-mass chamber, but is not as complex. The vacuum envelope is a vertical-axis cylinder, 8 ft in diameter and 15 ft in overall height. The upper portion contains a vibration-isolation stack and internal support beams with soft bellows seals, identical in design to those in the Type 1 test-mass chamber. Similar external support beams and air-suspension units are also provided. The lower section, which contains the interferometer test mass and associated components, has four ports, each 5 ft in diameter, for access to the installed components. Two of these ports, aligned along the direction of the optical beam, are coupled through removable adapters to the adjacent diagonal chamber and to a 4-ft-diam gate valve joined to the beam-tube extension. The other two ports are provided with simple covers. A 2500 $\mathrm{L \cdot s^{-1}}$ ion pump is installed on the lower section.

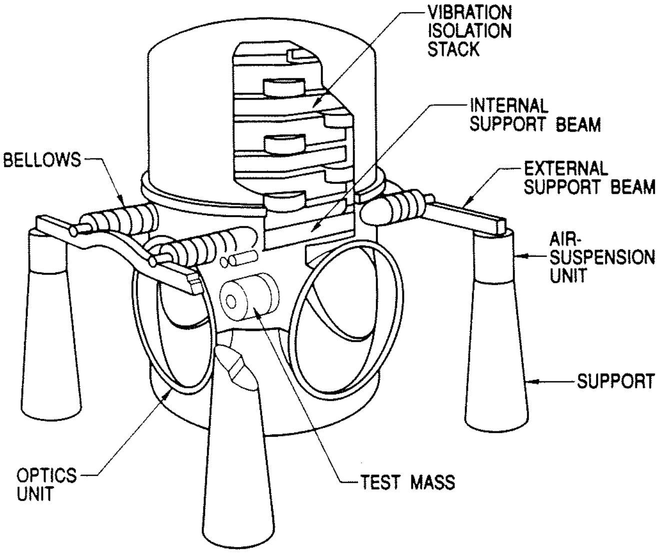
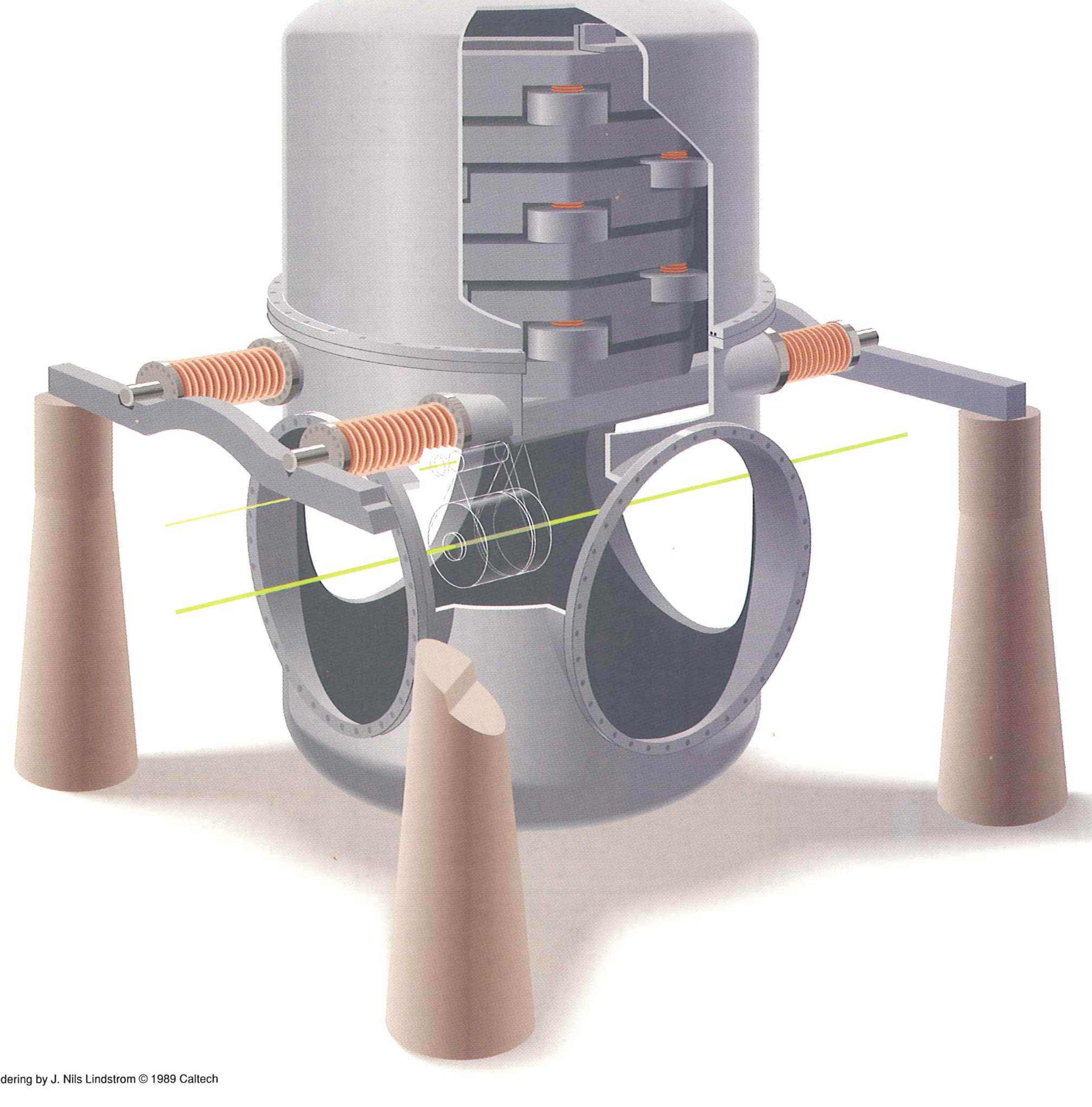


Figure IV–C–8 Drawing of Type 2 test-mass chamber (*facing page*), with key components indicated (*above*). This chamber is used in locations where there are no optical beams from other interferometers. The test-mass assemblies, vibration-isolation stacks, and support beams are nearly identical to those in the Type 1 chamber. The chamber is isolated from the rest of the system by a vertical gate valve in the adjoining beam tube (see Figure IV–C–6). Components are serviced in place through large access ports on all four sides or by removal of the upper section. An ion pump (not shown, but similar to that installed on the air-lock unit of the Type 1 test-mass chamber) is attached to the lower part of the vacuum vessel.

Crane access to the interferometer test-mass assembly and vibration-isolation stack is provided by removal of the upper section. The upper section can be replaced by a taller section (such as the dome used for the Type 1 test-mass chamber) if a larger vibration-isolation stack is necessary.



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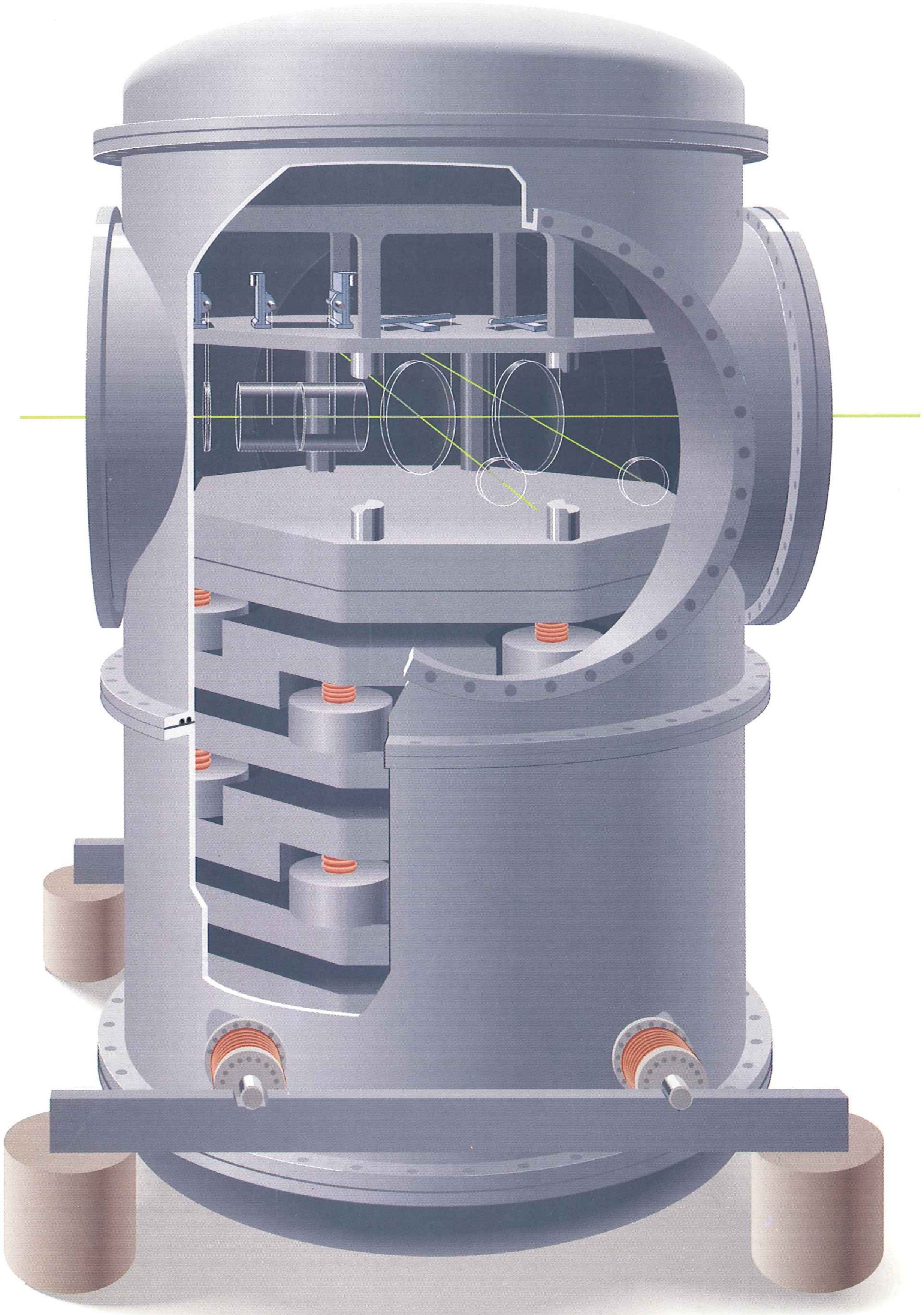

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(c) Diagonal chamber. The diagonal chamber is shown in Figure IV–C–9. The vacuum envelope is a vertical-axis cylindrical chamber of approximately the same size as the Type 1 test-mass chamber, with horizontal separation planes near the midpoint and at the top. The vertical section between the separation planes includes four ports, each 5 ft in diameter, for connection to the adjacent chambers. In addition to passing optical beams, these ports also provide access for minor adjustments and for installation of small interferometer components. The connections between these ports and the adjacent vacuum-system components are made by 2-ft-long flexible bellows couplers, which are removed when access is required.

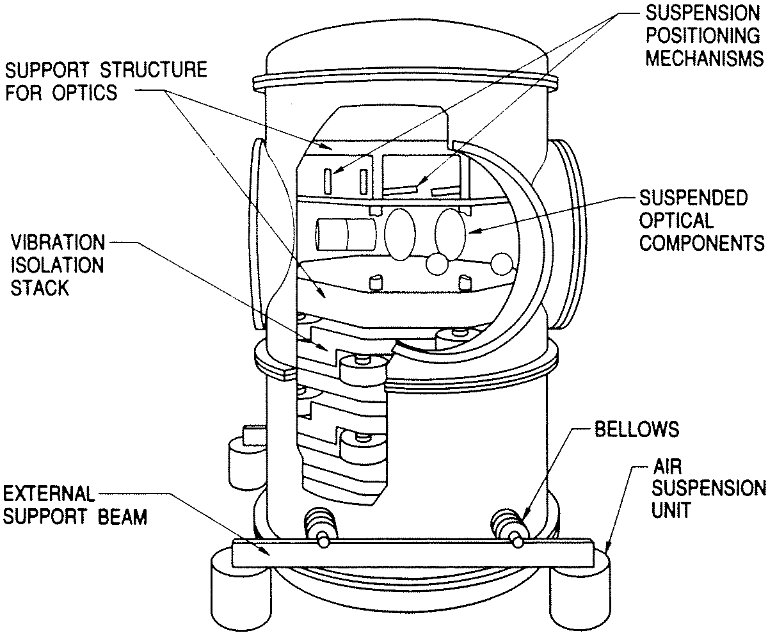


Figure IV–C–9 Illustration (*facing page*) and labeled sketch (*above*) of a diagonal chamber. The cut away section reveals the optical components suspended from a space-frame structure attached to an optical table, that rests on the vibration-isolation stack. The load from the vibration-isolation stack is transferred to the floor by support beams. The support of interferometer optical components is simpler than in the test-mass chambers, because the stack and support beams are below the level of the optical beam.

An optical table rests on the vibration-isolation stack whose design, including internal and external supports, is identical to that in the test-mass chamber.

The diagonal chamber includes two ion pumps (not shown) that provide high-vacuum pumping for the complete vacuum envelope (including the HAMs) connected to it. Ports are provided for vacuum instrumentation, a roughing pump, and electrical feedthroughs.

(d) HAM chamber. The horizontal-axis module (HAM), shown in Figure IV–C–10, is the simplest of the four basic vacuum chambers. The vacuum envelope is a horizontal-axis cylinder, 7 ft in diameter and 6 ft wide, flange to flange, oriented with the cylinder axis horizontal and perpendicular to the optical-beam axis. Removable end caps allow convenient access to the interferometer components inside. The chamber has two flanged ports, each 5 ft in diameter, on opposite sides along the laser-beam axis. One of the ports includes an integral expansion joint, making installation and sealing straightforward. The chamber contains a square vibration-isolated optical table, 6 ft on a side. The design of the vibration-isolation stack is scaled down from the design for the test-mass chambers, but employs the same concept of alternating stainless-steel plates and encapsulated elastomer. A support-beam arrangement with external air-suspension units and compensated sealing bellows completes the assembly. The HAM chambers are pumped through the associated diagonal chamber, so that no other vacuum features except feedthroughs are needed.

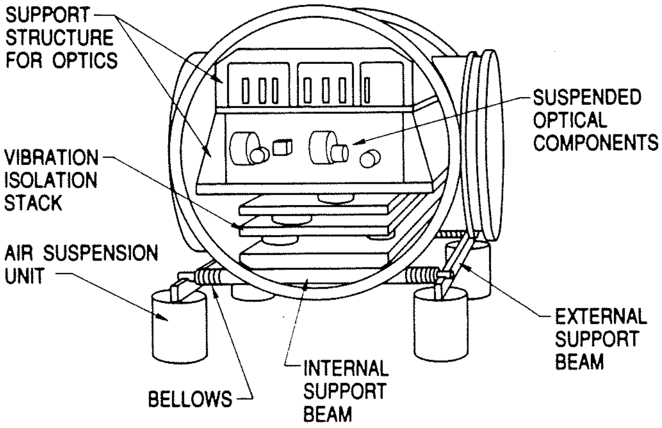
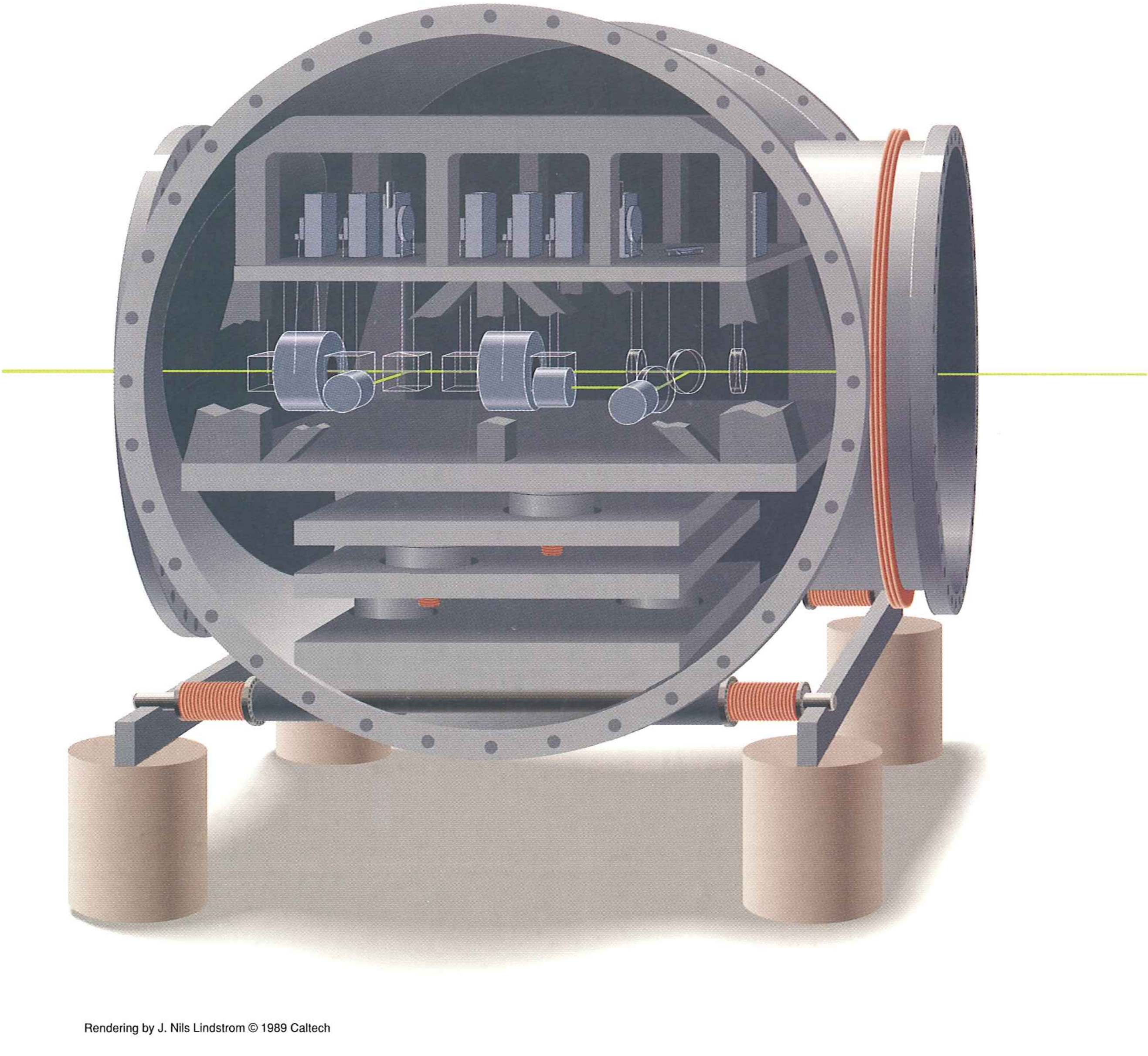


Figure IV–C–10 Representation (*facing page*) and labeled diagram (*above*) of a horizontal-axis module (HAM). One cap is removed showing suspended optical components and the vibration-isolation stack. The principal features of the HAM chamber design are easy access to the optical components, simplicity, and modularity—HAMs can be joined together to allow for a large range of interferometer configurations.



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The complete family of four modular vacuum chambers (and their elevation features) is illustrated in Figure IV–C–11.

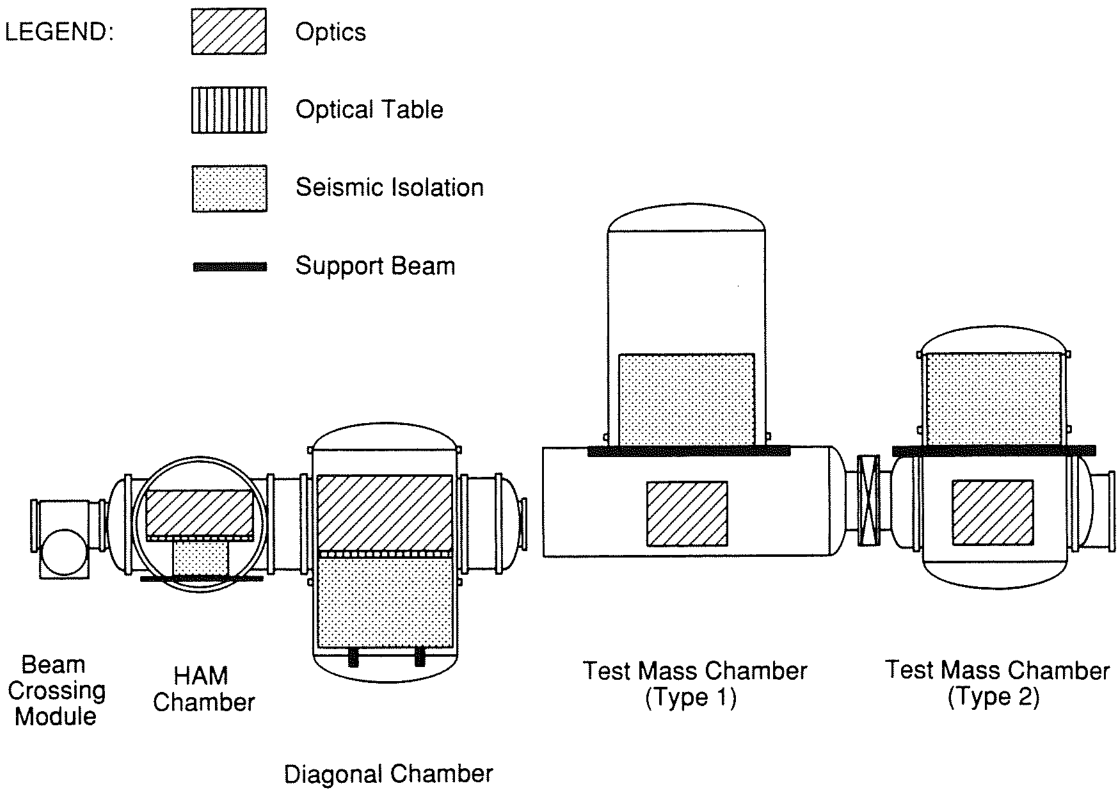


Figure IV–C–11 The family of four modular vacuum chambers, shown in elevation section to illustrate the relative vertical placement of the chambers. The *beam crossing modules* will be used in future expansions of the LIGO vacuum system (see Appendix A).

ii. Site 2 corner-station chamber layout. The vacuum system for Site 2 accommodates one interferometer during the initial (Phase A) operation of the LIGO, with provisions to add modular vacuum chambers for a total of three interferometers. The Phase-A vacuum-chamber layout for the corner station at Site 2 is shown schematically in Figure IV–C–12. The layout is nearly identical to that for Site 1, but without the vacuum chambers for the second interferometer. Type 2 test-mass chambers, a diagonal chamber, and HAM chambers are provided at the intersection of the beam-tube clear apertures in the same manner as at Site 1. The enlarged-diameter beam tube extensions at Site 2 are of the same length as those at Site 1, so that the design of pointing and alignment servos and optics are identical for interferometers at both sites.

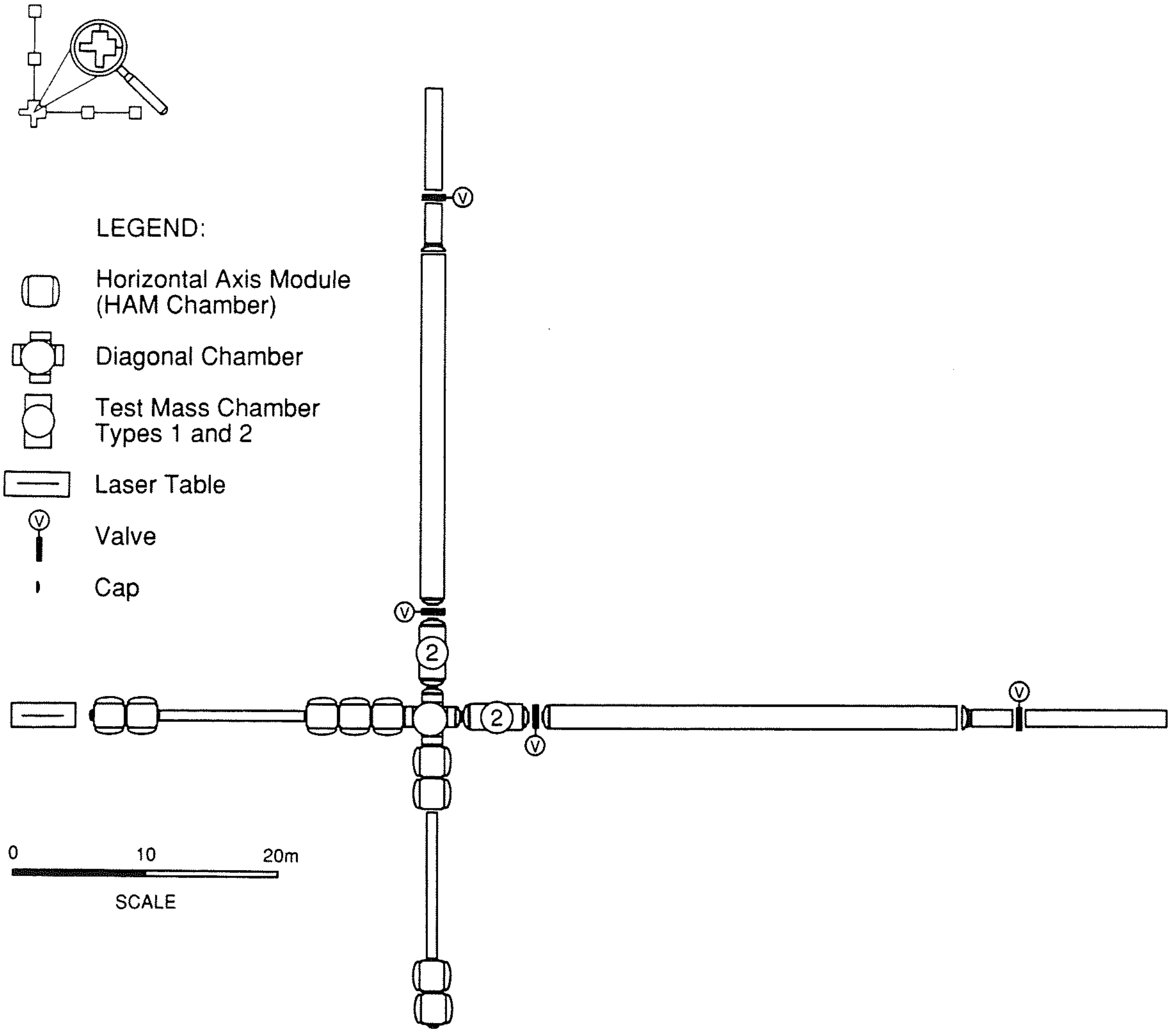


Figure IV–C–12 Layout of corner-station vacuum chambers for Site 2, Phase A. The configuration is identical to that at Site 1 (see Figure IV–C–6) without the Type 1 test-mass chambers and adjoining diagonal and HAM chambers associated with the second interferometer at Site 1.

iii. Illustrative optical configurations. Figures IV–C–13 and IV–C–14 illustrate the layout of optical components in the diagonal and HAM chambers for two interferometer configurations. Figure IV–C–13 shows the layout for the broad-band-recycling configuration that is planned for the initial LIGO interferometers, shown schematically in Figure IV–B–1. Figure IV–C–14 shows the layout for a resonant recycling interferometer which might be installed in the LIGO at some future time (this configuration and its applications are discussed in Volume 1, Appendix C). These figures demonstrate the flexibility and efficiency of the proposed modular vacuum-system arrangement. Growth in complexity of the interferometers tends to require additional linear space along the optical-beam directions between the laser and the beam splitter (input optics), or between the beam splitter and photodetector (output optics); such additional space can be accommodated by installing additional HAM chambers as needed.

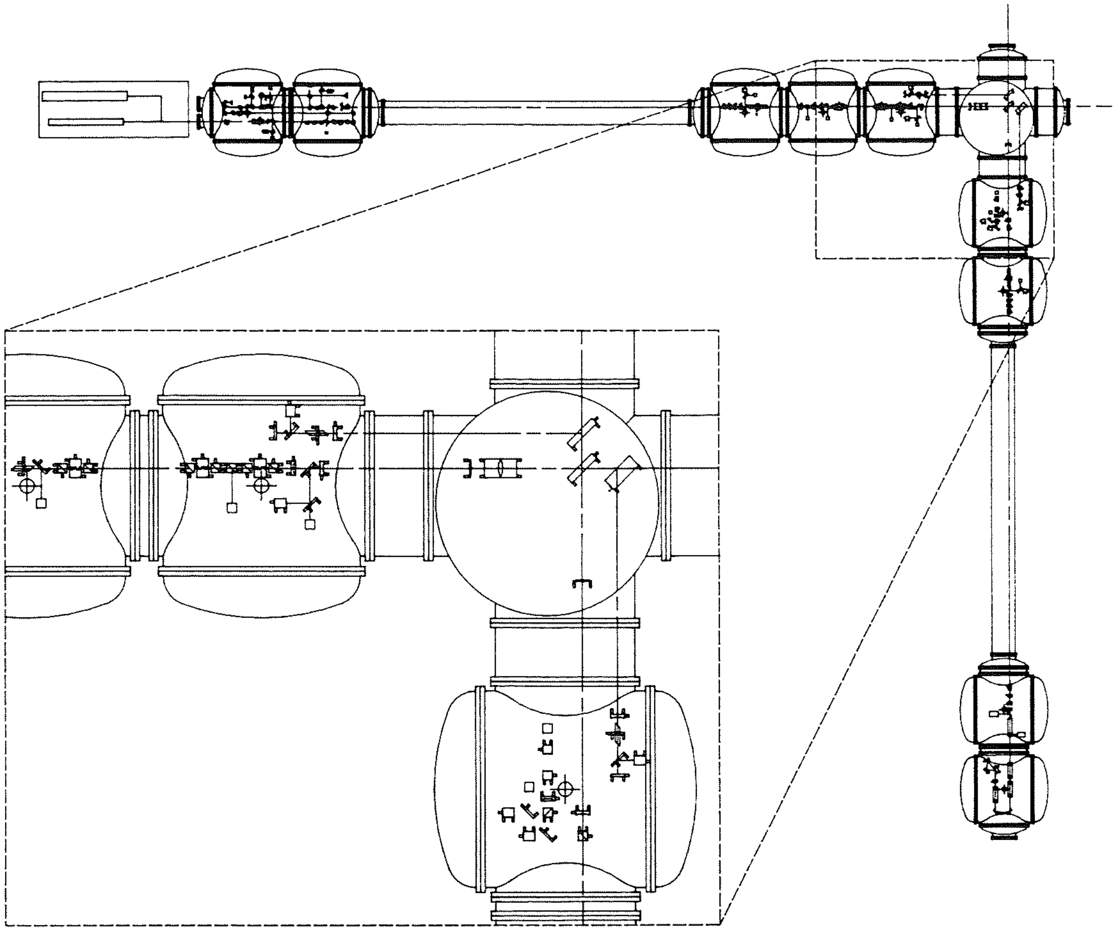


Figure IV–C–13 Layout of input and output optics for a broad-band recycling interferometer, illustrating the optical components located in the diagonal chamber and HAM chambers. Most of the components shown are separately suspended and controlled as illustrated in Figure IV–B–3. The spacing of the components is determined by the beam diameter and the clearances needed for mounts and servo controls (not shown). *Unmagnified view:* The laser and reference cavity are on the optical table at the far left; the HAM chambers adjacent to them contain components to stabilize and filter the laser beam. The two HAM chambers at the bottom contain optics to filter and detect the main interferometer output beam. The long tubes between HAM chambers hold input and output mode-cleaner cavities. *Magnified view:* The light filtered and stabilized by the conditioning optics chain at the left is incident on the recycling mirror in the diagonal chamber. The light propagates to the beam splitter and is then transmitted or reflected to the cavity input mirrors in the two test-mass chambers. The light returned from the cavities is recombined at the beam splitter and directed toward the output optics chain (downwards in the figure).

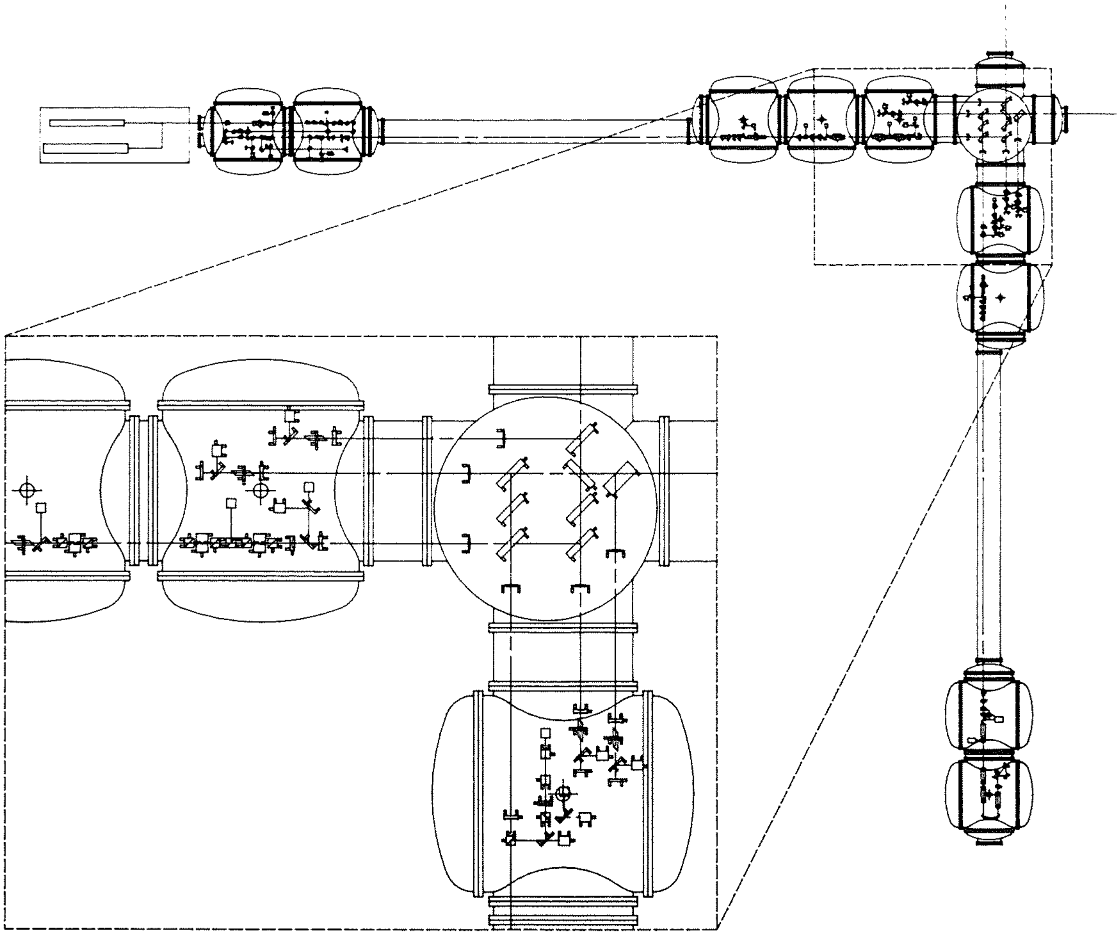


Figure IV–C–14 Layout of optical components in a resonant recycling interferometer. *Unmagnified view:* Most of the optical components in the input and output chains serve similar functions as in the broad-band recycling interferometer (see Figure IV–C–13). An important difference in this resonant-recycling system is that the interferometer's beam splitter is not at the intersection of the main-cavity optical beams. The input and output optics chains are offset from the positions in the broad-band recycling interferometer. The offset is made by shifting the locations of the mode-cleaner tubes and associated outer HAM chambers, using appropriate adapters. *Magnified view:* The beam splitter (lower left in the diagonal chamber) is at the intersection of the input and output light beams (lines coming from the left and going downwards). The cavity coupling mirror is at the intersection of the beams that couple to the main cavities (extending to the right and upwards).

b. End stations, mid stations. The end stations and mid stations at both sites (Figure IV–C–15) are relatively simple, containing only test-mass chambers and associated vertical gate valves, pumps, and beam-tube isolation valves. The end stations each house one Type 2 test-mass chamber. An end cap is isolated from the test-mass chamber by an expansion joint and anchored to the building foundation, thereby minimizing perturbations of the test-mass chamber from atmospheric pressure fluctuations.

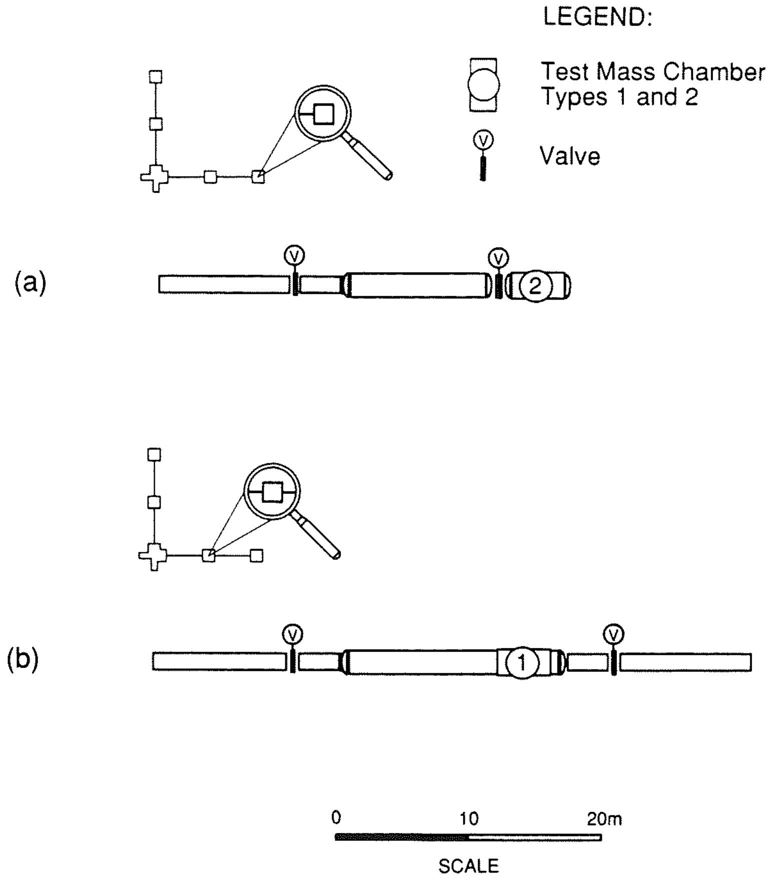


Figure IV–C–15 Phase-A vacuum-system layout in (a) the end stations and (b) the mid stations. Site 1 includes two end stations and two mid stations; Site 2 has two end stations and no mid stations. Each mid station houses a Type 1 test-mass chamber (see Figure IV–C–7) and each end station has a Type 2 test-mass chamber (see Figure IV–C–8). Vertical gate valves are placed in the beam tubes near their entry to the station enclosures. Inside the station a short beam-tube extension connects to a larger-diameter filler tube, to be replaced by additional test-mass chambers as part of the upgrades to Phases B and C.

The layout for the mid stations at Site 1 is essentially identical to that of the end stations except that (1) the beam tube extends from both ends of the mid station and (2) a Type 1 test-mass chamber is used to permit access to the test-mass assembly without interfering with the operation of the full-length interferometer.

At Site 2, where no mid station is planned, a gate valve, a roughing-pump set and an ion pump are incorporated at the midpoint of each arm. These simple features permit use of the same 2-km beam-tube module design at both sites.

D. Vacuum System: Vacuum Design

1. Vacuum design requirements

The LIGO vacuum-system design requirements are discussed in Section II-E. Table IV–D–1 repeats the pressure data from that section, shows the conversion to column density, and specifies the maximum leak rate.

TABLE IV–D–1
LIGO VACUUM SYSTEM REQUIREMENTS AND GOALS

GAS SPECIES	INITIAL REQUIREMENT	GOAL
	Allowable column density[1] (molecules · cm^{-2})	
H_2	1.3×10^{16}	1.4×10^{13}
H_2O	1.3×10^{15}	1.4×10^{12}
N_2	7.5×10^{14}	7.9×10^{11}
CO	5.8×10^{14}	6.1×10^{11}
CO_2	2.7×10^{14}	2.9×10^{11}
	Equivalent partial pressure (torr @ 300 K)	
H_2	1×10^{-6}	1×10^{-9}
H_2O	1×10^{-7}	1×10^{-10}
N_2	6×10^{-8}	6×10^{-11}
CO	5×10^{-8}	5×10^{-11}
CO_2	2×10^{-8}	2×10^{-11}
	Maximum pressure in chambers (torr @ 300 K)	
	1×10^{-6}	
	Maximum leak rate (atm · $\text{cm}^3 \cdot \text{s}^{-1}$ of He)	
Each beam-tube module or chamber	1×10^{-10}	
Entire LIGO		1×10^{-9}

[1] Column density is defined as the number of molecules contained in the optical path per unit cross-sectional area expressed in molecules · cm^{-2}. For convenience, the table also gives the specification in terms of the equivalent averaged partial pressure for the 4-km beam tubes.

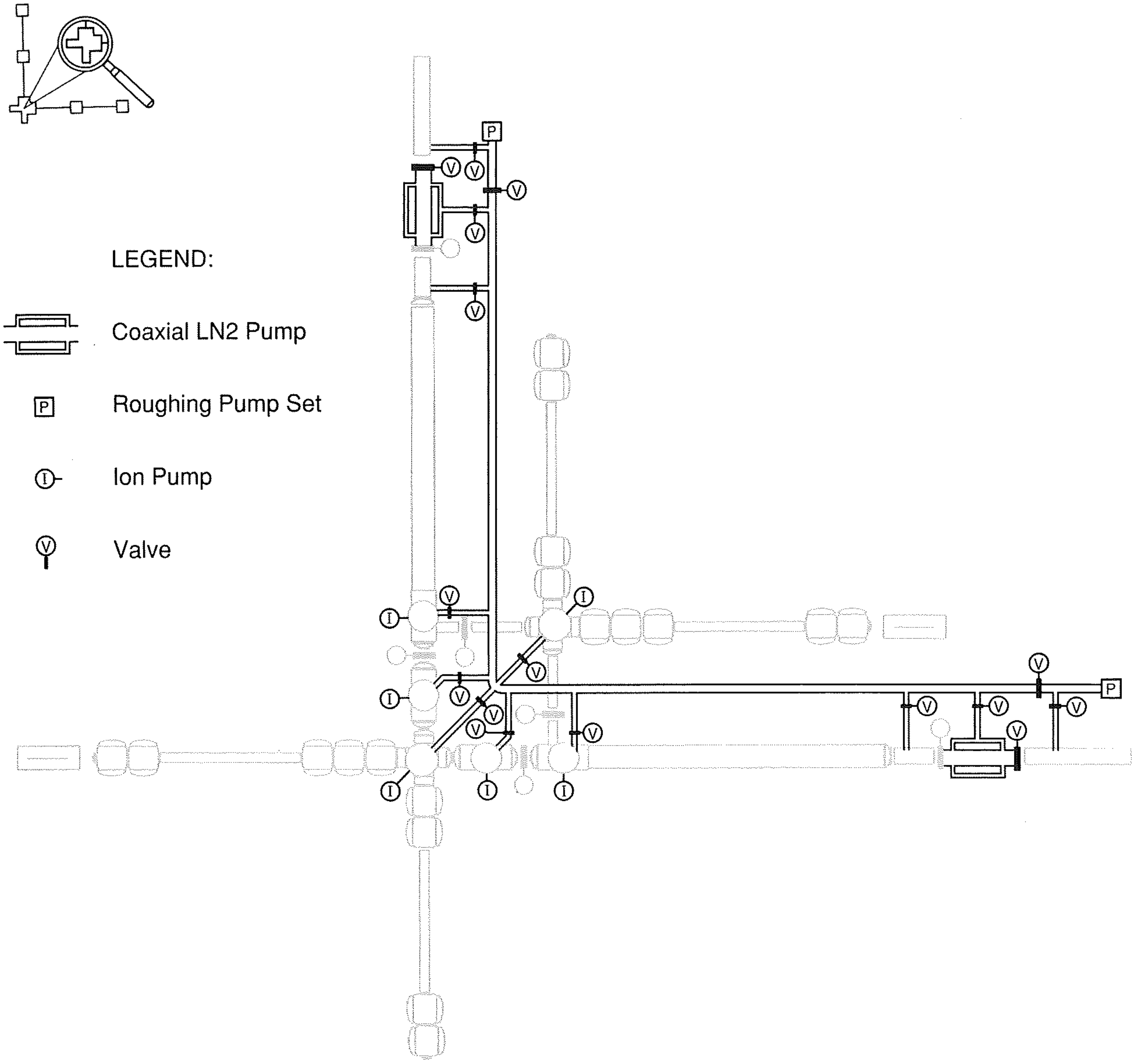
The vacuum requirements are most demanding in the phase-sensitive paths of the interferometer: the beam tubes, the diagonal chamber, the test-mass chambers, and the interconnecting vacuum tubes. The allowable residual gas pressures given in Table IV-D-1 are set to constrain statistical fluctuations in the refractive index of the residual gas column between the test masses. The less stringent requirement on chamber pressure is set so that residual gas does not degrade the mechanical performance of the test-mass suspensions.

2. Vacuum-system pumping configuration

High vacuum throughout the LIGO is achieved and maintained using ion pumps. All LIGO vacuum pumps and valves are contained in the stations, except for those ion pumps distributed along the beam tubes. Turbomolecular pumps, backed by mechanical pumps, are used for all rough-pumping operations. Quiet liquid-nitrogen-cooled surfaces assist in pumping the high condensible gas-load transients in the stations.

a. Corner-station configurations. The vacuum-pump configuration for the corner station at Site 1 is illustrated schematically in Figure IV–D–1; Site 2 is similarly arranged. The roughing-pump sets are located where the beam-tube modules enter the station enclosure. A 24-in.-diam roughing manifold threads its way through the corner station to each Type 1 test-mass chamber and each diagonal chamber. These chambers have ion pumps that are turned on after a few hours of rough-pumping. Coaxial liquid-nitrogen-cooled pumps adjacent to the beam tubes trap the condensible gas load of a newly pumped down test-mass chamber or diagonal chamber complex.

Figure IV–D–1 (facing page) Pumping configuration for the Phase-A corner-station vacuum system at Site 1. The pumping system and associated manifold and valves are overlaid on an image of Figure IV–C–6. A 24-in.-diam rough-pumping manifold runs adjacent to the arms, terminating at two roughing-pump sets. The same roughing pumps evacuate the main beam tubes and the chambers. Each chamber (except the HAM chambers) is connected to the manifold through a valve. After initial rough pumping the chambers are isolated from the roughing manifold by the valves and the vacuum is maintained by vibration-free ion pumps attached to all chambers but the HAMs. The HAM chambers are pumped through the adjoining diagonal chamber. A pair of coaxial liquid-nitrogen-cooled pumps (one on each arm, top and right) provides high pumping speed for water vapor. The Site 2 pumping configuration is similar.


LEGEND:
Coaxial LN2 Pump
P Roughing Pump Set
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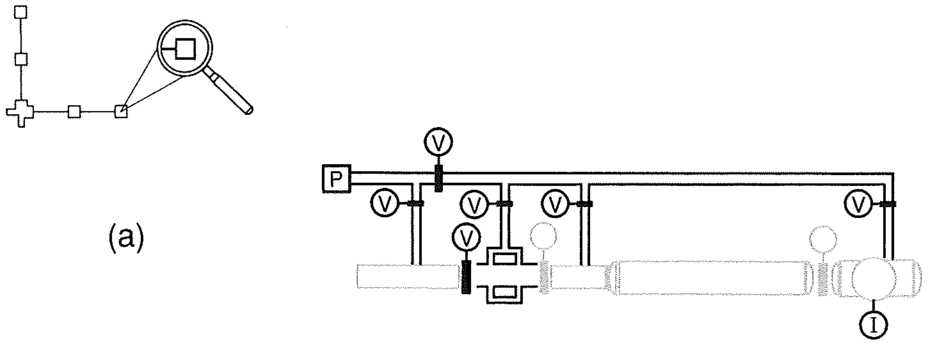
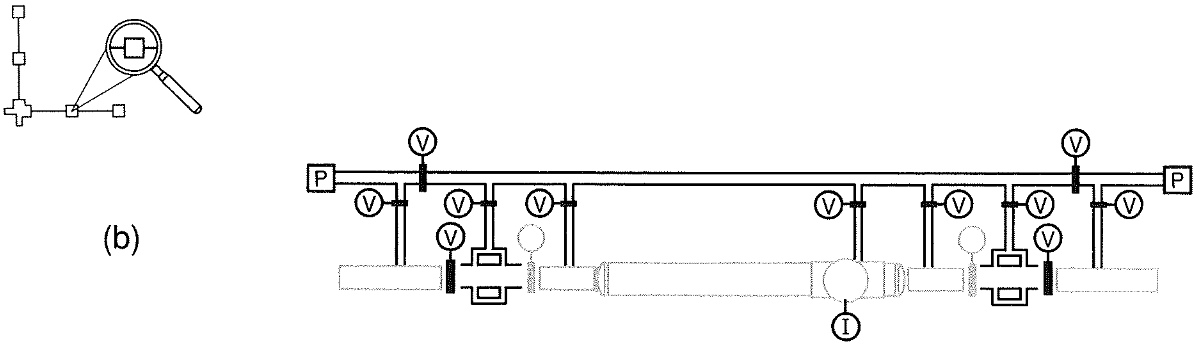


(a)



(b)

b. Mid stations and end stations. The vacuum-pumping configurations for the end stations and mid stations are shown in Figure IV–D–2. The configuration and operating strategy follow those employed in the corner station. Rough-pumping sets are mounted on the ends of the beam-tube modules, and ion pumps are installed on each test-mass chamber. Liquid-nitrogen pumps trap the transient condensible gas loads within the stations.

Figure IV–D–2 (facing page) Pumping configuration for Phase A vacuum systems in the (a) end stations (both sites) and (b) mid stations (Site 1 only) overlaid on an image of Figure IV–C–15. The pumping strategy is similar to that employed in the corner station (see Figure IV–D–1). Each station has a 24-in. pumping manifold that connects the chambers to roughing-pump sets located near the adjacent beam tubes. Each chamber includes an ion pump for steady-state pumping, and coaxial liquid-nitrogen-cooled pumps trap the condensible gases within the stations.

c. Beam tubes. Each beam-tube module has seven 2500 $L \cdot s^{-1}$ ion pumps (with getters) distributed at equal intervals along its length, as shown schematically in Figure IV–D–3. The ion pumps are installed directly on the beam tube without isolation valves. The pressure will vary along the tube axis, changing from a minimum at the pump locations to a maximum midway between. The pump size and distribution interval have been chosen to tolerate the failure of a pump or the development of a small leak; in such circumstances, the beam-tube module pumping will gradually degrade rather than catastrophically fail.

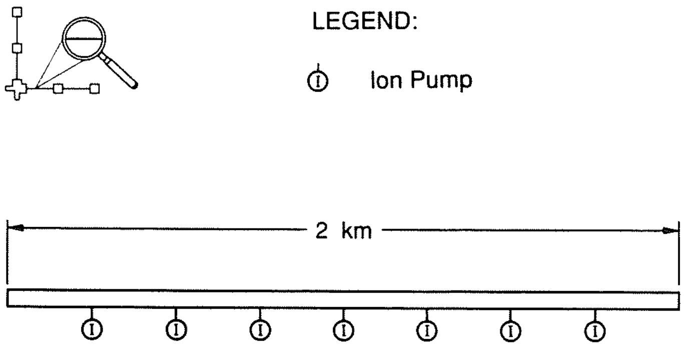


Figure IV–D–3 Distribution of seven ion pumps along a beam-tube module.

d. Roughing-pump sets. Each roughing-pump set consists of a 100 $L \cdot s^{-1}$ mechanical pump~~, a~~ 500 $L \cdot s^{-1}$ Roots pump ("blower"), and a 2200 $L \cdot s^{-1}$ turbomolecular pump, which effectively prevents backstreaming of hydrocarbons into the vacuum system. The turbomolecular pump is mounted through a short plenum and valve directly on top of the beam tube. Pumping speed at the ends of the beam tubes, in molecular flow, is about 1000 $L \cdot s^{-1}$. Pumping speed in molecular flow at the chambers, through the long roughing manifolds, is estimated to be 400 $L \cdot s^{-1}$. The roughing-pump sets are provided with valves to accommodate leak detectors for the beam tubes.

e. Chamber pumping. As described in Section IV.C.3, each Type 1 test-mass chamber has a 2500 $\mathrm{L \cdot s^{-1}}$ ion pump installed on the air-lock unit, above the air-lock cover. With currently estimated gas loads, the ion pump can be turned on, and the roughing pumps shut down, after 4 hours of rough-pumping, resulting in a pressure of less than 10^{-6} torr. After the pressure is low enough, the air lock may be opened.

Each diagonal chamber has two 2500 $\mathrm{L \cdot s^{-1}}$ ion pumps, and the two Type 2 test-mass chambers connected to the diagonal chamber at the vertex of the beam tubes have one 2500 $\mathrm{L \cdot s^{-1}}$ ion pump each. The operating strategy is similar to that of the Type 1 test-mass chamber. The diagonal-chamber pumps also evacuate the HAM chambers.

f. Condensible-gas pumping. Each liquid-nitrogen pump[1] in the corner station consists of a dewar, nominally 8 ft in diameter and 12 ft long, with a hold-time of about 3 months. The pumping surface is a section 12-ft long and 48 in. in diameter, aligned with the beam tube. The dewar can be isolated between two 48-in.-diam gate valves for regeneration. A length of 48-in.-diam tube connects the dewar vacuum vessel to the 6-ft-diam extension of the beam tube within the corner station. For gases such as water vapor that condense efficiently at liquid-nitrogen temperature, only 4% of the incident flux propagates into the beam tube. Smaller (4-ft-long) liquid-nitrogen pumps are used in end stations and mid stations.

3. Beam tube vacuum design concept

The beam-tube modules will be built from 304L stainless steel,[2] processed for low hydrogen content. Stainless-steel sheet will be obtained from the steel mill with a No. 1 hot-rolled finish, the least expensive finish available, and the most desirable for scattered light attenuation. The tube section will be spiral welded in 40-ft-long sections and individually leak tested to 1/10 the LIGO specification (see Table IV–D–1).

The vacuum surfaces of each section will be cleaned at the manufacturing plant before shipment to the site. The cleaning method has yet to be established; however, steam cleaning with a mild detergent solution produced the lowest level of contaminants among the methods tried by us, and resulted in an acceptable outgassing rate (see Appendix D). It is also a low cost method, suitable for high volume cleaning.

Beam tube parameters relevant to vacuum properties are summarized in Table IV–D–2.

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[1] The liquid-nitrogen pumps, together with the local ion pumps, provide a water vapor pumping speed of about 26,000 $\mathrm{L \cdot s^{-1}}$ at the Type 1 test-mass chambers. The speed at the diagonal chamber connected to the Type 1 test-mass chambers is about 14,000 $\mathrm{L \cdot s^{-1}}$, and the speed at the diagonal chamber at the beam tube intersection is about 32,000 $\mathrm{L \cdot s^{-1}}$.

[2] The L grade of 304 is selected to avoid carbon precipitation in the welds, which could eventually lead to leaks.

TABLE IV–D–2
BEAM-TUBE MODULE PARAMETERS

Beam-tube module diameter	48 in.	
Beam-tube module length	2 km	
Beam-tube module volume	2.3×10^{6} L	
Beam-tube surface area exposed to vacuum	7.7×10^{7} cm^{2}	
Outgassing rate for hydrogen ($t_0 = 1$ hr)	$1 \times 10^{-12}(t_0/t)^{\frac{1}{2}}$	torr$\cdot$L$\cdot$s$^{-1}\cdot$cm^{-2}
Outgassing rate for water vapor ($t_0 = 1$ hr)	$1.4 \times 10^{-7}(t_0/t)$	torr$\cdot$L$\cdot$s$^{-1}\cdot$cm^{-2}
Outgassing rate for water vapor (after mild bake)	1×10^{-14}	torr$\cdot$L$\cdot$s$^{-1}\cdot$cm^{-2}
Roughing-pump set, maximum speed in viscous flow	500 L$\cdot$s^{-1}	
Roughing-pump set, speed in molecular flow	1000 L$\cdot$s^{-1}	
Ion pump speed, nominal	2500 L$\cdot$s^{-1}	
Number of ion pumps per beam-tube module	7	
Distance between ion pumps	250 m	
Partial pressure, hydrogen ($t = 1000$ hr)	4×10^{-10} torr	
Partial pressure, water (unbaked, $t = 1$ yr)	9×10^{-8} torr	
Partial pressure, water (baked)	1×10^{-10} torr	

a. Gas load. Operating pressure in a vacuum vessel is determined by the ratio of gas load to pumping speed. The LIGO beam tubes have no internal components other than the stainless-steel baffles, and the gas load consists solely of material evaporating from or diffusing out of the tube walls and baffle surfaces. The initial gas load from unbaked, stainless-steel chamber walls is almost all water vapor. The conventional procedure to obtain high vacuum is to perform a mild bakeout (100–150 °C) of the system. This almost completely eliminates water vapor, so that the dominant residual gas is hydrogen, which slowly diffuses out of the bulk metal.

The initial hydrogen content of standard commercial stainless steel is in the range of 1 to 4 ppm by weight. The corresponding outgassing rates are 1.5×10^{-10} to 6×10^{-10} torr$\cdot$L$\cdot$s$^{-1}\cdot$cm^{-2} after 1 h under vacuum. These rates will decrease as the square root of time under vacuum [IV–D–1]. Reducing the hydrogen outgassing rate to an acceptable level would require bakeout-temperatures in excess of 500 °C. Such high temperatures, even over short segments of the tube, generate considerable mechanical stresses on the tube welds and supports, and would present a major risk. The alternative of increasing pump speed would introduce unacceptable costs.

The low-hydrogen steel we tested has a measured outgassing rate as low as 3×10^{-15} torr $\cdot$ L $\cdot$ s^{-1} $\cdot$ cm^{-2}. Four chamber samples were fabricated from this steel and subjected to long-term outgassing tests. Details of the experimental setup and measurements are described in Appendix D. As shown in Figure IV–D–4, the samples show considerable scatter; however a rate of 1×10^{-12} torr $\cdot$ L $\cdot$ s^{-1} $\cdot$ cm^{-2}

after 1 h under vacuum is a reasonable value to use for design purposes. For the LIGO beam tubes, with the pumps provided, this results in a hydrogen partial pressure of 4×10^{-10} torr after 1000 h under vacuum. This pressure is below the goal level of Table IV–D–1, and will continue to decrease with time.

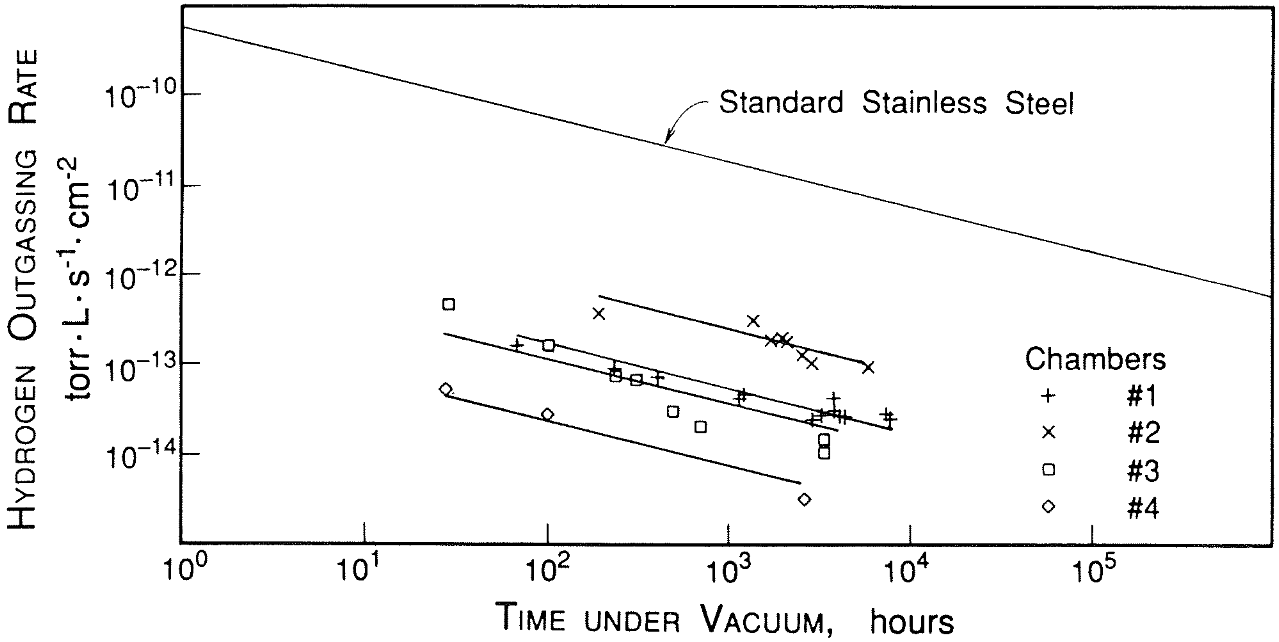

Figure IV–D–4 Hydrogen outgassing rate as a function of time under vacuum for four test vacuum chambers manufactured from low-hydrogen steel (obtained from J&L Specialty Products Corp.). These chambers were subjected to different cleaning procedures: (1) uncleaned, (2) hot water/detergent washed, (3) steam cleaned with detergent, and (4) cold water/detergent washed. The predicted outgassing rate for standard stainless steel is shown for comparison.

Hydrogen outgassing from welds must also be considered; any filler material will be degassed prior to welding, and an inert gas environment for the welding operations should exclude hydrogen from hot surfaces. Because the zone affected by welding constitutes less than 1% of the surface area of the finished tube, these precautions to control the outgassing of welds should be adequate.

Water outgassing from a stainless-steel vacuum vessel has a nominal rate of 1.4×10^{-7} $\mathrm{torr} \cdot \mathrm{L} \cdot \mathrm{s}^{-1}\mathrm{cm}^{-2}$ after 1 h under vacuum [IV–D–2], and decreases with time under vacuum. All four test chambers have outgassing rates lower than this, by a factor ranging from 2 to 5. The calculated partial pressure of water vapor in the LIGO beam tubes, corresponding to the model in [IV–D–2], meets the initial requirement in Table IV–D–1 after 8000 h under vacuum. As discussed in the next section, a mild bakeout to reduce water vapor outgassing is planned during this period. Reaching the partial-pressure goal of 10^{-10} torr requires reducing the water-vapor outgassing rate to 10^{-14} $\mathrm{torr} \cdot \mathrm{L} \cdot \mathrm{s}^{-1}\mathrm{cm}^{-2}$, a level that is routinely obtained by mild baking.

b. Implementation. After field assembly of a beam-tube module is completed, it will be pumped down; this will take less than 24 h, using the roughing-pump sets in the stations. After pump down, the module will be leak tested. A residual gas analyzer will be used in preliminary tests to establish the total air leak. A helium probe will be used to locate leaks.[3] Leaks in the beam-tube module will be found and repaired until the leak rate drops below 3×10^{-11} $\mathrm{torr} \cdot \mathrm{L} \cdot \mathrm{s}^{-1}$ of air (10^{-10} $\mathrm{atm} \cdot \mathrm{cm}^{-3} \cdot \mathrm{s}^{-1}$ of He) which is sufficient to ensure that weld quality is adequate for long term operation.

After leaks have been located and repaired, the partial pressure for air will be leak-rate limited and will be less than 2×10^{-14} torr. Partial pressures for nitrogen, hydrogen and water vapor will be confirmed against the calculated values. Bakeout of the tube to reduce water vapor outgassing will then proceed.

The installation of conventional, permanently-installed bakeout heaters and insulation along the entire LIGO beam tubes at both sites cannot be accommodated in our present budget. In addition, if heaters and insulation were to be installed, they would interfere with subsequent diagnostic leak checking. It is planned, instead, to use manually-installed portable insulated heater jackets which are moved from one tube section to the next. During the final pump down of a beam-tube module, heater jackets are installed on 200 ft of beam tube at a time, and heated to 200 °C for 24 h. During this time the equivalent of $\sim 7 \times 10^{7}$ hours of room-temperature water-vapor outgassing will be achieved. (This should result in an outgassing rate of 2×10^{-15} $\mathrm{torr} \cdot \mathrm{L} \cdot \mathrm{s}^{-1} \cdot \mathrm{cm}^{-2}$.) During this sequential bakeout operation, a purge flow of gaseous nitrogen is introduced at one end to prevent the water vapor released by baking from re-contaminating the previously baked surfaces. A flow speed of 40 cm/s at a pressure of 1 torr reduces the diffusion probability for water vapor to below 10^{-10} at 1 meter upstream from the point of release. The purge gas[4] thus "sweeps" the water vapor released by baking toward the pumped (and still unbaked) end of the tube.

The procedure outlined above is untried so far, and will be demonstrated on a model before implementing it in the LIGO. The unbaked LIGO beam-tubes will meet the needs of the initial interferometers; nevertheless, we consider it advisable to perform the sectional bakeout described above before startup of interferometer operations in order to expel undetected contaminants from the beam tubes and to advance our readiness for higher sensitivity interferometers. After the initial bakeout, we will operate the interferometers until it appears likely that sensitivity will be limited by gas pressure. At that stage, additional bakeouts will be performed, if necessary.

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[3] A helium pulse will take about 5 minutes to travel one km and reach 50% of its final value.

[4] A special requirement on the purge gas is that *its* partial pressure of water be of the order of 10^{-10} torr or less.

4. Chamber vacuum design concept

In this section, we present an analysis of the pumpdown transient behavior for selected chamber configurations.

The vacuum chambers will be made from the same low-hydrogen stainless steel used for the beam tubes,[5] and with the specified ion pumps should pump down to $\sim 1 \times 10^{-9}$ torr of hydrogen. The chambers and internal supporting members (vibration-isolation stacks, optical tables) can be vacuum baked as necessary.[6, 7] These steps will result in a gas load from the chamber that is small compared to the water outgassing from installed interferometer components. Good vacuum engineering of the interferometers will be necessary to achieve acceptable vacuum levels in reasonable times.

A pump-down-transient analysis of the chamber configurations has been done by numerically tracing gas fluxes. Table IV–D–3 summarizes the highlights of this analysis for two representative chamber configurations: (1) a vertex chamber assembly,[8] and (2) a mid-station Type 1 test-mass chamber. The table gives a "snapshot" of the water-vapor partial pressures at various points in the LIGO vacuum system at two times (4 h and 24 h) after the start of a pump down from atmospheric pressure.

The table shows that the pump-down transients for these cases present no problem for the initial interferometers (expressed as a fraction of the column density requirement; see Table IV–D–1). With the assumptions for the interferometer gas loads given in Table IV–D–3, it would take 18 days to achieve the column density goal desired for interferometers of advanced design. Should this delay become a problem in the future it will be solved by choosing interferometer components more compatible with high vacuum practice than that assumed in the model and possibly installing larger pumps at the chambers.

References

IV–D–1 R. Calder and G. Lewin, "Reduction of Stainless Steel Outgassing in Ultra-High Vacuum," *Brit. J. Appl. Phys.*, **18**, 1459 (1967).

IV–D–2 B. B. Dayton, "Outgassing Rate of Contaminated Metal Surfaces," *1961 Transactions of the Eighth National Vacuum Symposium,* **1**, 42 (Pergamon Press 1962).

IV–D–3 R. S. Barton and R. P. Govier, "The Effect of Cleaning Technique on the Outgassing Rate of 18/9/1 Stainless Steel," *Vacuum*, **20**, 1 (1970).

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[5] Standard stainless steel, baked at high temperature by the chamber manufacturer in order to reduce the hydrogen outgassing rate to $< 1 \times 10^{-12}$ torr · L · s^{-1} · cm^{-2} after 1 h under vacuum, is a practical alternative for the chambers.

[6] The vacuum seals in the chambers, gate valves, and air locks will be elastomer "O" rings (which limit the maximum bakeout temperature to about 200 °C).

[7] This processing results, for subsequent pump downs from atmospheric pressure, in a water vapor outgassing rate of 1×10^{-10} torr · L · s^{-1} · cm^{-2} after 10 h under vacuum [IV–D–3].

[8] A vertex chamber assembly consists of the diagonal chamber, HAM chambers, and two Type 2 test-mass chambers located at the intersection of the arms.

TABLE IV–D–3
CHAMBER PUMPDOWN TRANSIENTS[1]

	t=4 h	t=24 h	
CASE A: CORNER STATION VERTEX CHAMBER ASSEMBLY			
Gas load, interferometer components[2]	5.3×10^{-2}	8.8×10^{-3}	$\text{torr} \cdot \text{L} \cdot \text{s}^{-1}$
Pressure at beam splitter (ion pump OFF)[3]	1.4×10^{-4}		torr
Pressure at beam splitter (ion pump ON)	5.5×10^{-6}	9.2×10^{-7}	torr
Pressure at beam splitter (gate valve OPEN)		2.8×10^{-7}	torr
Pressure at LN_2 trap inlet		2.0×10^{-8}	torr
Pressure at beam tube inlet		9.0×10^{-10}	torr
Pressure at 250 m		5.7×10^{-10}	torr
Pressure at 2 km		2.6×10^{-11}	torr
Column density		2.5×10^{13}	$\text{molecules} \cdot \text{cm}^{-2}$
Fraction of allowable column density:			
initial requirement		0.019	
goal		18	
CASE B: MID STATION TEST MASS CHAMBER			
Gas load, interferometer components[2]	4.3×10^{-3}	7.1×10^{-4}	$\text{torr} \cdot \text{L} \cdot \text{s}^{-1}$
Pressure at test mass (ion pump OFF)[3]	1.2×10^{-5}		torr
Pressure at test mass (ion pump ON)	1.9×10^{-6}	3.6×10^{-7}	torr
Pressure at test mass (air lock OPEN)		9.6×10^{-9}	torr
Pressure at LN_2 trap inlet		2.3×10^{-9}	torr
Pressure at beam tube inlet		9.5×10^{-10}	torr
Pressure at 250 m		6.1×10^{-10}	torr
Pressure at 2 km		2.8×10^{-11}	torr
Column density		3.9×10^{12}	$\text{molecules} \cdot \text{cm}^{-2}$
Fraction of allowable column density:			
initial requirement		0.003	
goal		2.8	

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[1] Table entries assume that the roughing-pump set runs for 4 h, at which time the local ion pump(s) is turned on and the roughing valve is closed. Twenty hours later, the gate valves to the beam tubes are opened. The analyses assume that the water vapor gas load varies as $1/t$, and that the chamber being pumped down is the only source of gas flux in the system. The final results are expressed as column density along the full 4-km system length.

[2] The gas load from the empty vacuum vessels is typically at least an order of magnitude smaller than the gas load from the interferometer components.

[3] All pressure values are calculated for a temperature of 300 K.

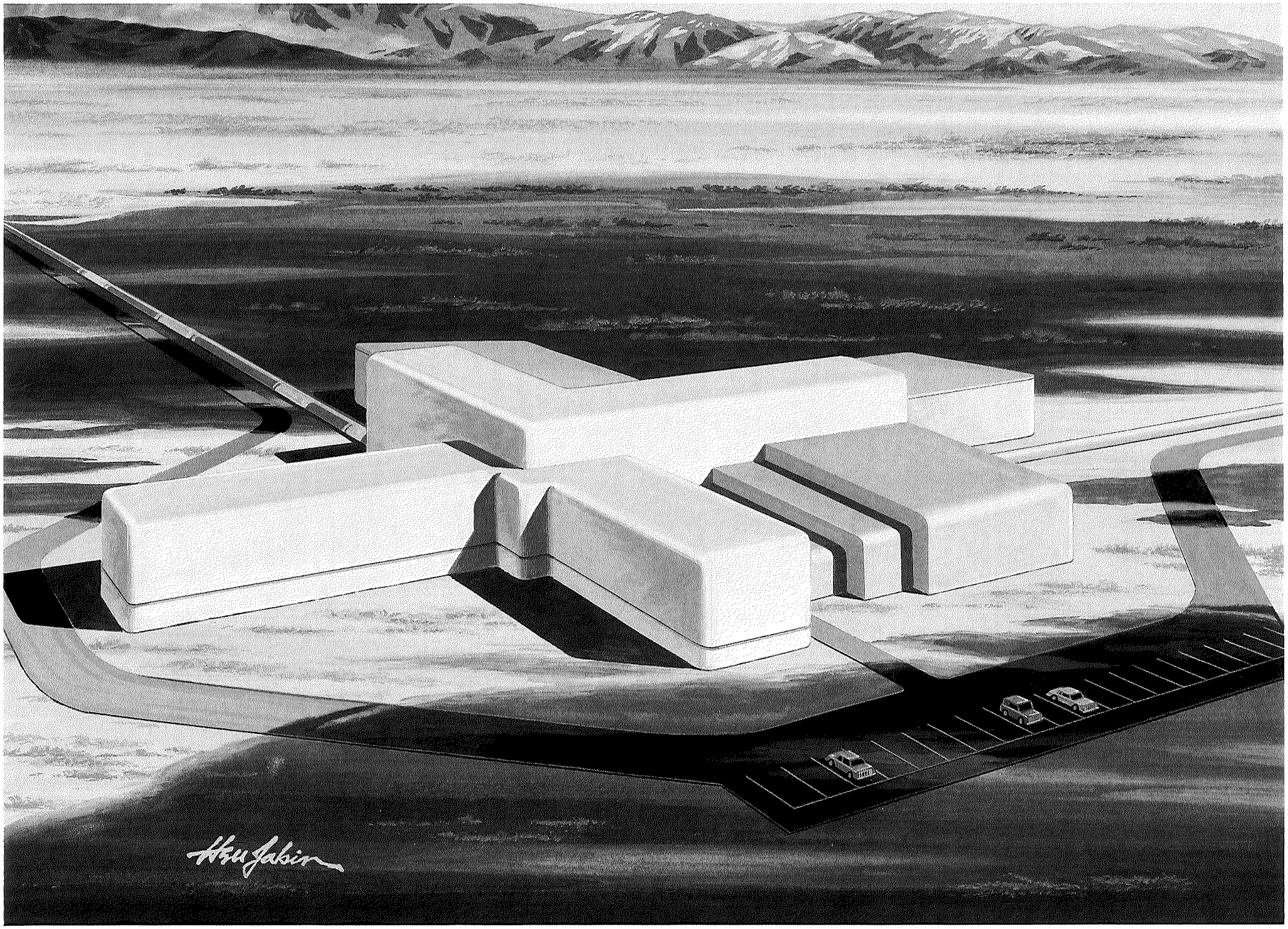


Figure IV–E–1 (facing page) Illustration of corner-station enclosure.

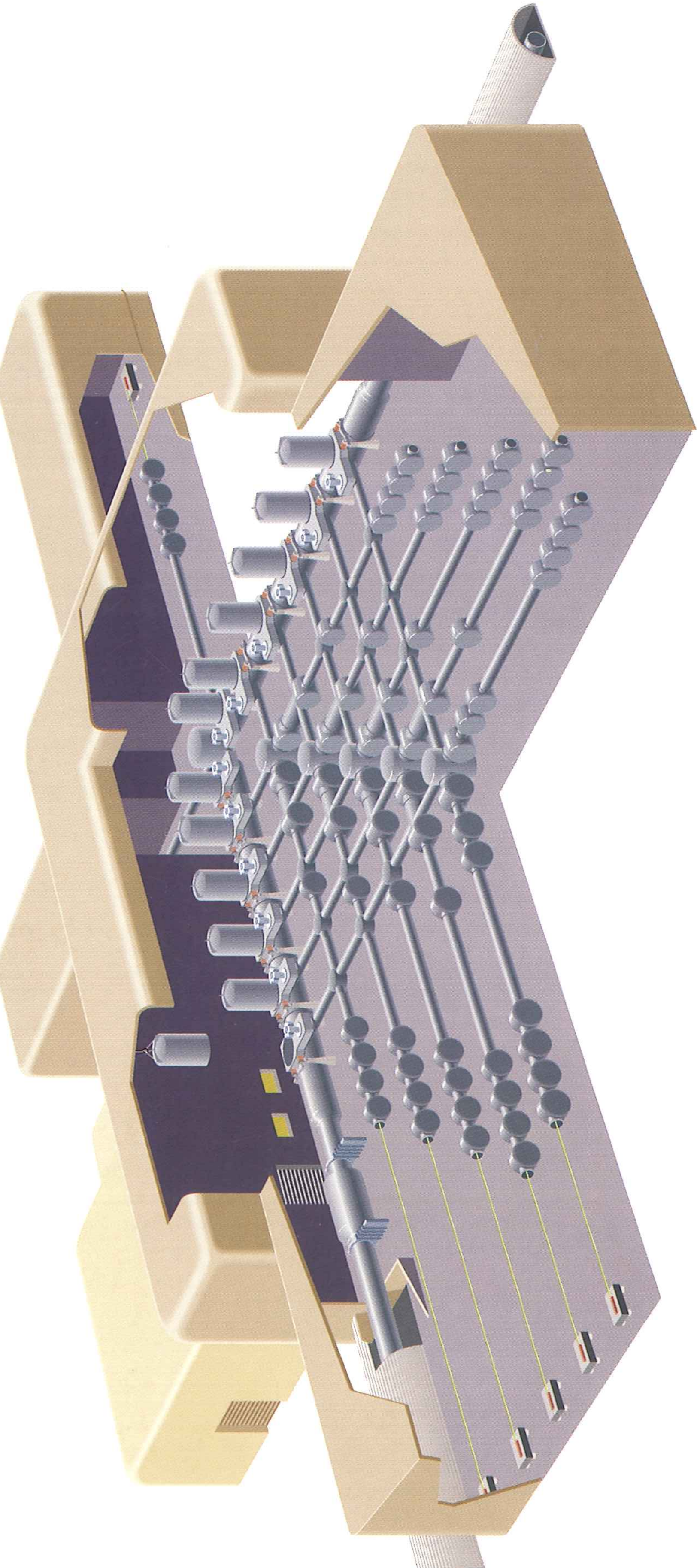
E. Enclosure Design

The enclosures for the stations and the beam tubes provide the operating environment for the LIGO vacuum system, equipment, and operations personnel. The buildings must provide a quiet, low-vibration environment for the interferometer components, and must provide a clean environment to minimize contamination of the vacuum system and optical components. The buildings will be sealed and pressurized to preclude entry of dust, pollen, vermin, and other sources of contamination. The most critical systems regarding acoustic and vibrational noise are those that run continuously, such as air-conditioning and laser-cooling equipment. The required ambient conditions in the vicinity of interferometer components are summarized in Table IV–E–1.

Figure IV–E–2 (facing page) Cut-away drawing of Site 1 corner-station enclosure. The vacuum chamber configuration is the mature Phase–C LIGO facility. The beam tubes and their enclosures emerge from the corner station at the far left and far right of the figure.

TABLE IV–E–1
AMBIENT CONDITIONS
FOR INTERFEROMETER COMPONENTS

Temperature	23 ±1.5 °C
Humidity (relative)	40 ± 5%
Vibration	$< 2 \times 10^{-9}$ m/$\sqrt{\mathrm{Hz}}$ (f < 10 Hz)
	$< 2{\times}10^{-7}$ (Hz/f)^2 m/$\sqrt{\mathrm{Hz}}$ (10 Hz < f < 10 kHz)*
Sound pressure	$< 10^{-4}$ Pa/$\sqrt{\mathrm{Hz}}$ (10 Hz < f < 10 kHz)*
	< 45 dB (A-weighted) rms
Air quality (dust)	
Vacuum chamber area	Fed. Std. 209 Class 50,000 (goal)
Exposed optics	Fed. Std. 209 Class 200
Clean room (work surface)	Fed. Std. 209 Class 100
Positive pressure	> 10 Pa (0.1 mbar)
Electromagnetic interference	
Electric fields	< 1 mV/m$\sqrt{\mathrm{Hz}}$ (f < 10 kHz)*
Magnetic fields	< 2 nT/$\sqrt{\mathrm{Hz}}$ (f < 10 kHz)*
	< 100 nT rms (f = n × 60 Hz)
*Narrow-band exceptions permitted	



Rendering by J. Nils Lindstrom © 1989 Caltech

1. Corner-station enclosure

The corner-station enclosure is illustrated in Figure IV–E–1. Its Phase-A floor plan at Site 1 is shown in Figure IV–E–3, and that for Site 2 in Figure IV–E–4. The floor plans are similar except that the area provided for vacuum chambers at Site 2 is somewhat smaller because it will accommodate fewer interferometers. The layout of the planned Phase-C expansion of the vacuum system is shown in Appendix A, and a representation of the Site-1, Phase-C, corner station is shown in Figure IV–E–2.

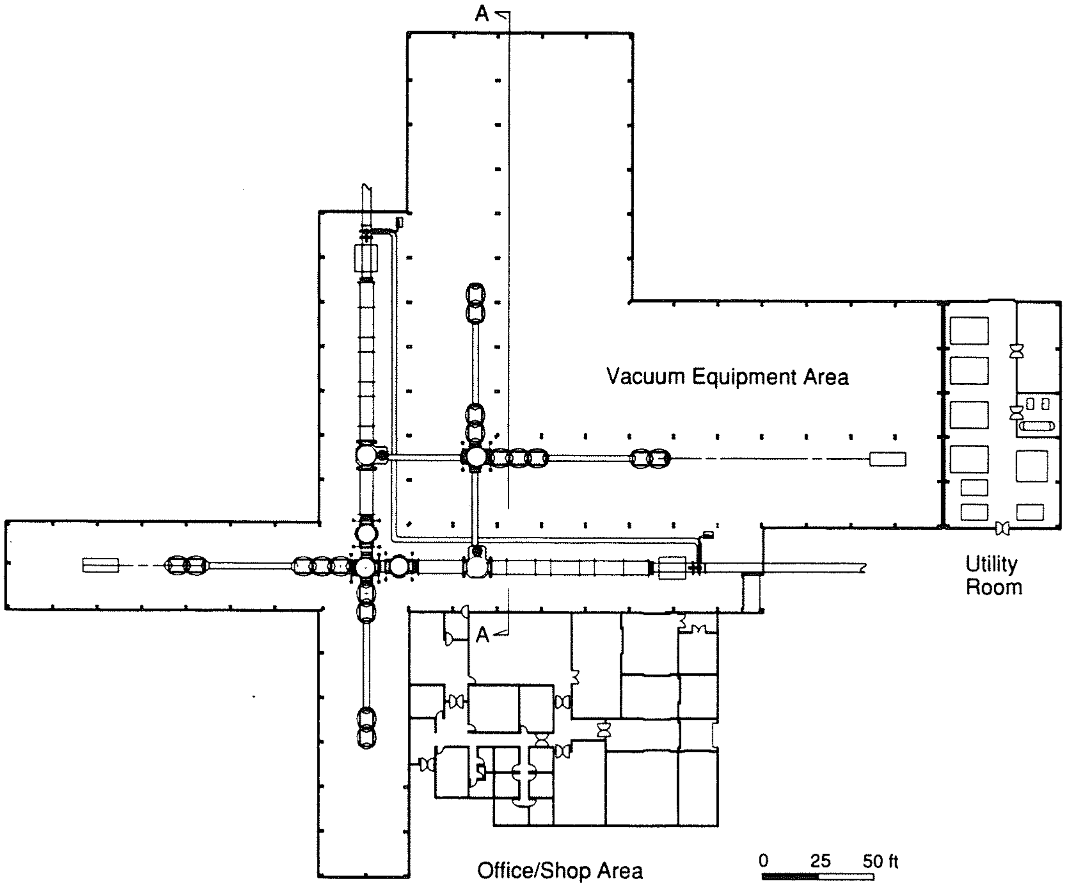


Figure IV–E–3 Floor plan for the Site 1 corner station in Phase A. Upgrades for Phases B and C will introduce more chambers and tubes into the "vacuum equipment area," but will not enlarge the building (see Appendix A, Figure A-4 for comparison). Section (A–A) is shown in Figure IV–E–5.

The buildings house vacuum equipment, lasers, and optical and electronic components necessary to operate the interferometers. A utility room contains the

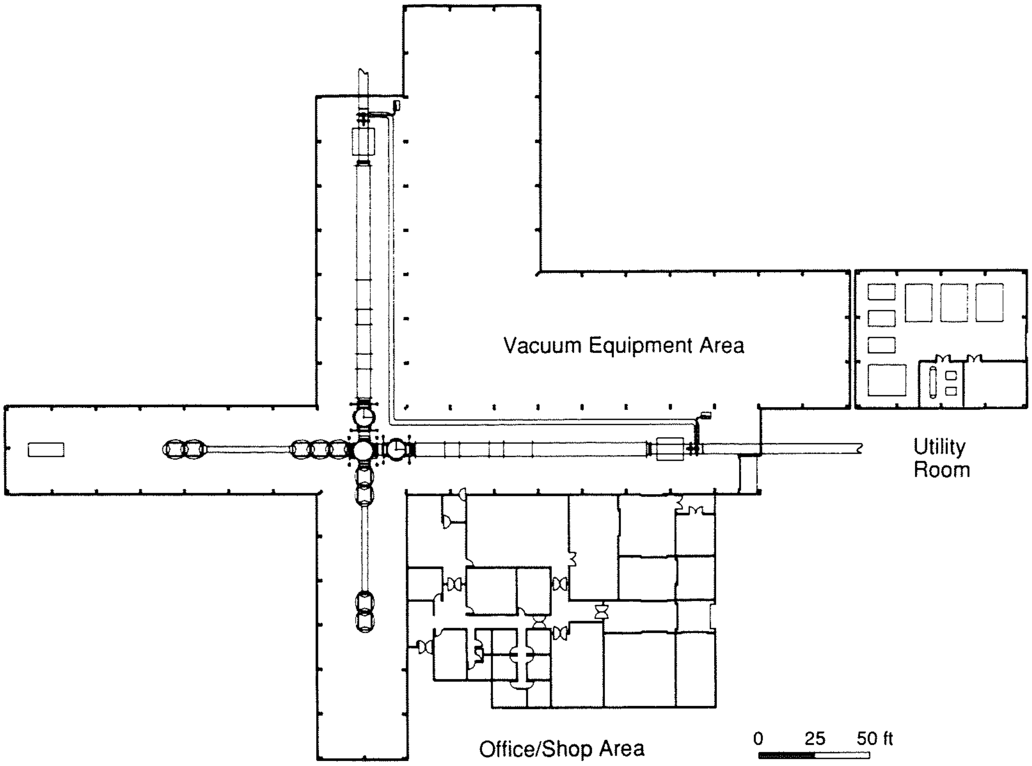


Figure IV–E–4 Floor plan for the Site 2 corner station in Phase A. This layout is identical to that at Site 1, except that the "Vacuum Equipment Area" and "Utility Room" occupy less area, commensurate with the smaller number of interferometers at this site.

building air-handling equipment and the pumps and heat exchangers for the local laser-cooling loops. A small, remotely-located chiller plant ($\sim$100 m distant) provides chilled water for building air conditioning and laser cooling. To reduce transmission of vibration from machinery or personnel to the interferometers, separate foundations are provided for the vacuum-equipment and laser area, the utility room, and the office and shop area.

a. Vacuum-chamber and laser area. The vacuum-chamber and laser area enclosure (labeled "Vacuum Equipment Area" in Figures IV–E–3 and IV–E–4) is a single-story structure of varying height with an area of about 60,000 ft^2 at Site 1, and about 48,000 ft^2 at Site 2. The building is of steel-frame construction with both interior and exterior walls to provide added resistance to dust penetration from the outside. The roof and exterior walls are metal double-skinned, insulated-foam-core panels with double-lock standing seam. The inside walls are covered by preformed panels with baked-enamel finish for sealing and cleanliness control. A dropped ceiling, finished with mylar-covered acoustic tiles, is provided to control acoustic reflections and to trap dust which may leak through the roof. The building interior, including the volume between the inner and outer walls, is pressurized slightly over atmospheric pressure as a further measure of dust protection. The buildings have no windows, eliminating a potential source of dust contamination, improving thermal control, and providing security.

Interior ceiling height is 50 ft in the region over the test mass chambers and 30 ft elsewhere. A section view of this area is shown in Figure IV–E–5. Eight underhung bridge cranes provide complete coverage of the vacuum equipment. The crane system consists of two 10-ton cranes over the test-mass chambers, and six 5-ton cranes for the remaining area. The cranes come with swing-out sections and interlocking crossovers to transfer equipment between the crane runways. All cranes include speed controls and soft-start devices.

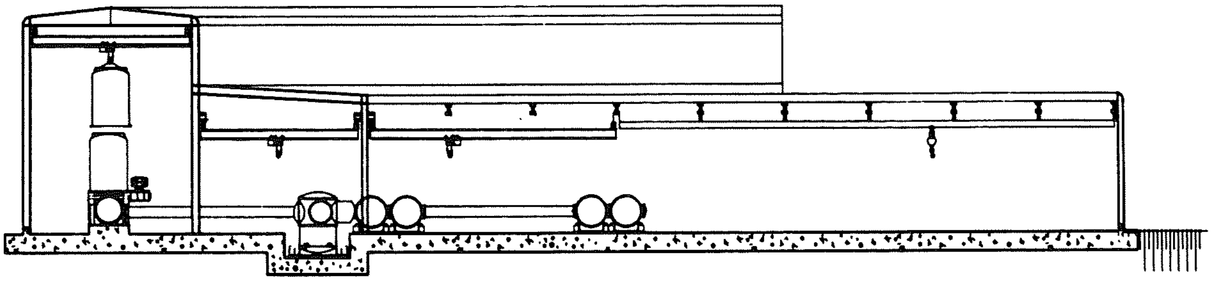


Figure IV–E–5 Section view of the Site 1 corner station, showing variation in interior ceiling height to accommodate Type 1 test-mass chambers and overhead cranes. The view corresponds to the Section (A–A) indicated in Figure IV–E–3.

The building is constructed on a reinforced-concrete mat foundation, finished with rubber flooring.

b. Utility room. Heating, ventilation, and air conditioning (HVAC), including humidity and dust control, are provided by air-handling equipment in the utility room and by a small chiller plant, which is remotely located. Cooling for the lasers is provided individually by closed-loop deionized-water cooling systems with heat exchangers coupled to the chilled-water lines; the laser-cooling systems are also located in the utility room.

c. Office and shop areas. The office and shop area layout, common to both sites, is shown in Figure IV–E–6. This area contains office space for resident and visiting personnel, rooms for monitoring and control equipment for the facility and interferometers, and space for testing and service operations. The general layout is planned to reduce the introduction of contaminants by having personnel and equipment move from outside to inside through increasingly clean regions.

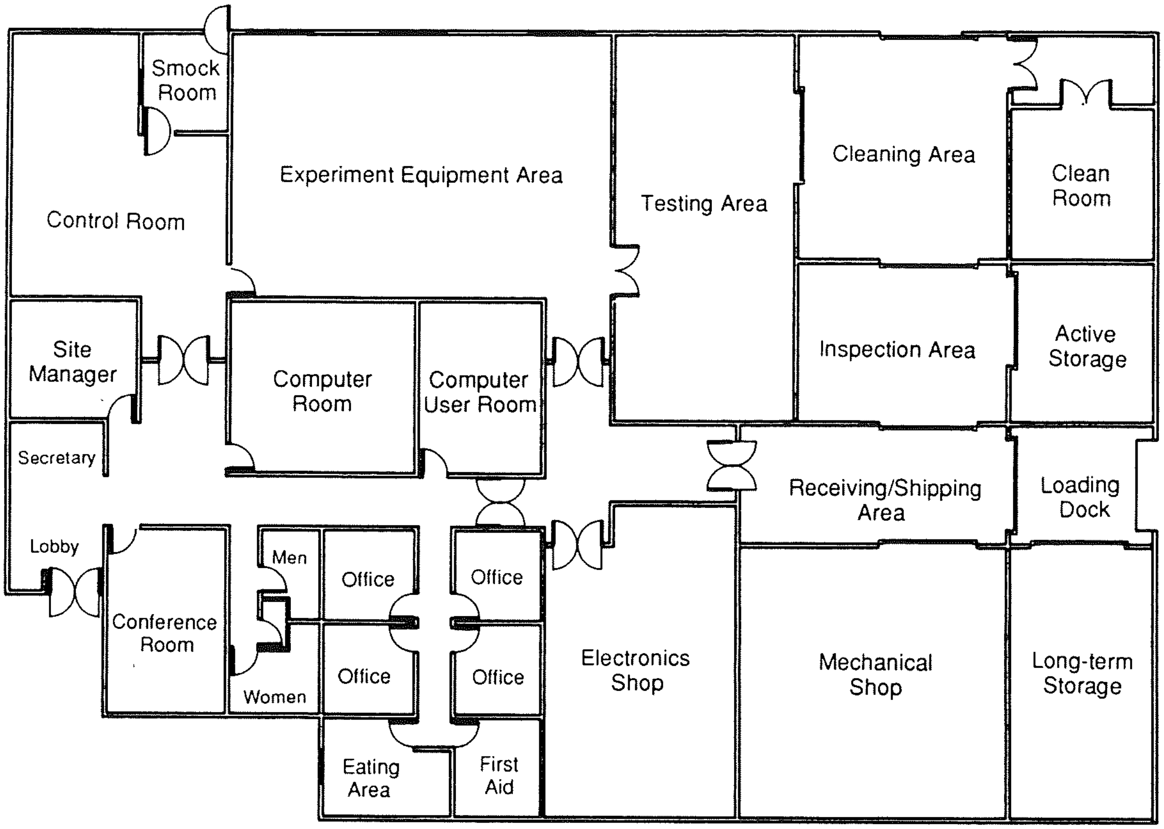


Figure IV–E–6 Floor plan of the office and shop area, common to the corner stations at both sites. The vacuum-equipment area is adjacent to the top wall in the figure.

The control room is the operational center of the facility. Manned 24 h/day, all systems-status and performance parameters are monitored and controlled from this location. Laser power and cooling will be activated from the control room. Vacuum-system pumps and valves will be controlled by the operator, although activation of the large roughing pumps and valves in the remote end stations and mid stations will require positive intervention by another person, local to the equipment. The tape drives for the data logging system are housed in the control room. Interferometer status and alarms will be monitored from here, and the operator will be able to perform some interferometer adjustments. Access to the laser area and vacuum chambers, including the end stations and mid stations, will be controlled by the operator. Physical security of the facility will be monitored by a system of low-light-level television cameras displayed in the control room.

The experimental equipment area will contain electronic equipment for centralized control of—and data acquisition from—the interferometers. This is the primary area for personnel who are working on the development or maintenance of interferometers when they are not installing or removing components in the vacuum chambers. All adjustments of the interferometers can be performed from this area. The experimental equipment area also contains the electronic equipment

for acquiring and processing data from auxiliary-physical-parameter measurements and facility-housekeeping measurements.

A testing area is provided for setup and checkout of interferometer components before installing them into the vacuum system. This room will contain a small laser, vacuum chambers for performance testing, and a vacuum bakeout chamber.

Equipment that arrives at the LIGO installation will be processed in a manner which ensures the integrity of the clean environments. Packages that arrive at the loading dock will be cleaned externally before being moved into the receiving/shipping area. There, they are unpacked from the outer shipping container and moved to the inspection area, where the inner packaging is removed and the contents are verified. Equipment destined for the vacuum equipment area is moved through the cleaning area for removal of dust or contamination. The doors connecting these areas will be opened one at a time, to prevent outside dust or particulate contamination attached to packaging from reaching the clean vacuum-chamber and laser areas. The processing areas and connecting doorways are large enough to handle optics assemblies, vibration-isolation stack components, and vacuum chambers.

A clean room is provided for working on interferometer optics and lasers. It is designed with vertical laminar air flow to provide a Class 1000 room environment; laminar-flow clean benches provide Class 100 working surfaces. Entry is through an air-shower anteroom, large enough to accommodate both the long argon-ion lasers and large test-mass assemblies.

Mechanical and electronics shops are provided for maintenance and repair of interferometer and facility equipment. The electronics shop contains electronic repair instruments and calibration equipment for vacuum instrumentation, auxiliary-physical-parameter instrumentation, computers, and interferometer electronics. The mechanical shop contains small machining and welding equipment for maintenance or modification of interferometer components and vacuum chambers.

Figure IV–E–7 (facing page) Artist's illustration of a right-arm mid-station enclosure. The beam-tube enclosure is shown entering the mid-station enclosure on the left and exiting on the right. The roof line is higher over the vacuum-equipment area and loading zones to allow clearance for test-mass chambers and overhead cranes. The enclosure for the left-arm mid station is a mirror image of the figure. The enclosure designs for the end stations are similar to the mid stations.

2. Mid stations and end stations

The enclosures for mid stations and end stations are all of identical design (see Figure IV–E–7), differing only in vacuum equipment layout. The floor plans for the right-arm end stations, and the mid stations at Site 1, are shown in Figure IV–E–8 and Figure IV–E–9 respectively. The design concept follows that of the corner station. The vacuum-equipment area is of double wall construction with covered floors, dropped acoustic tile ceiling, and an overhead bridge crane. The area contains test-mass chambers, roughing pumps, liquid-nitrogen pumps, and valves. It is sized for the planned Phase-C expansion of the vacuum equipment, which involves adding Type 1 test-mass chambers to each building (see Appendix A).

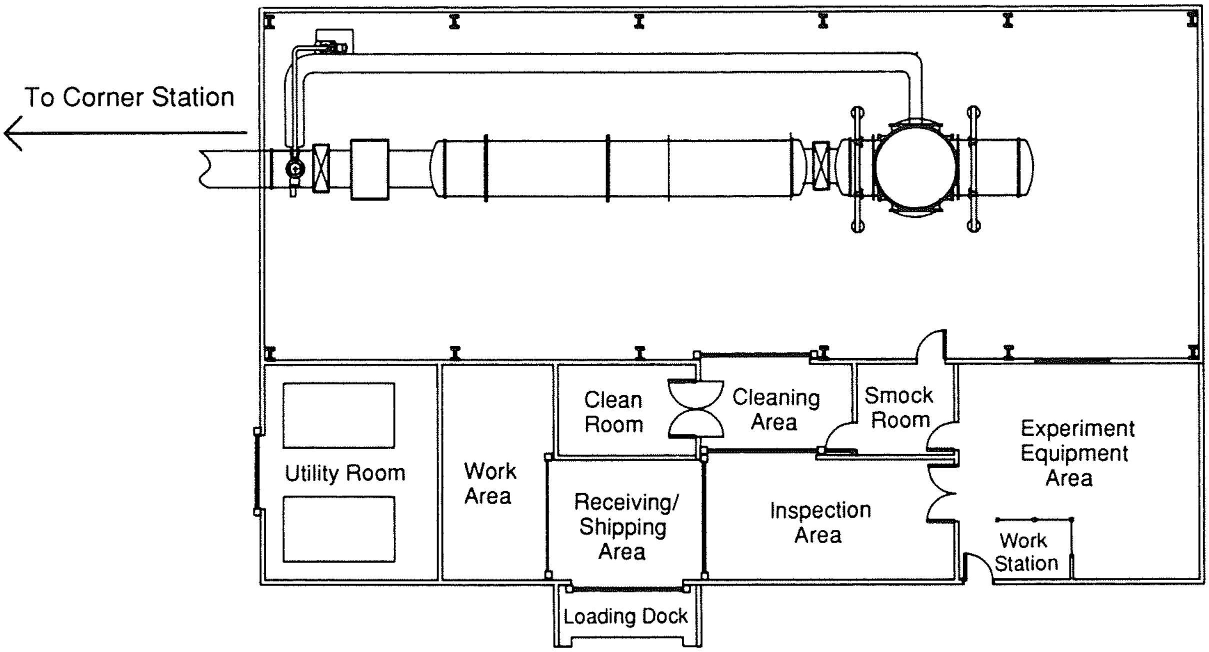


Figure IV–E–8 Floor plan of the right-arm end stations, common to both sites. The left-arm end stations have similar (mirror-imaged) floor plans.

The adjacent service area serves a function similar to the office and shop areas of the corner station. An attached utility room (with separate foundation for vibration control) contains HVAC equipment. A small chiller is remotely located.

Access to the service area and the vacuum-chamber area is controlled and monitored by the facility operator in the corner station.

3. Tube enclosure

The tube enclosure protects the LIGO beam-tube walls from vibration induced by wind. It also provides a degree of protection against vandalism or stray bullets from hunters. An underground tunnel has been ruled out for cost reasons.

A concrete-arch cover design was chosen which, when integrated with the continuous mat foundation,[1] provides a rigid, stable structure enclosing the beam tubes. An elevation section view of the covered tube is shown in Figure IV–E–10. The

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[1] The tube cover is built in place in 80-ft sections after field assembly and testing of the beam tubes is completed. An inflated air bag will be used as a form for the arch structure. A section of half-round corrugated-steel pipe is placed over the beam tube to support the air bag. The inflated

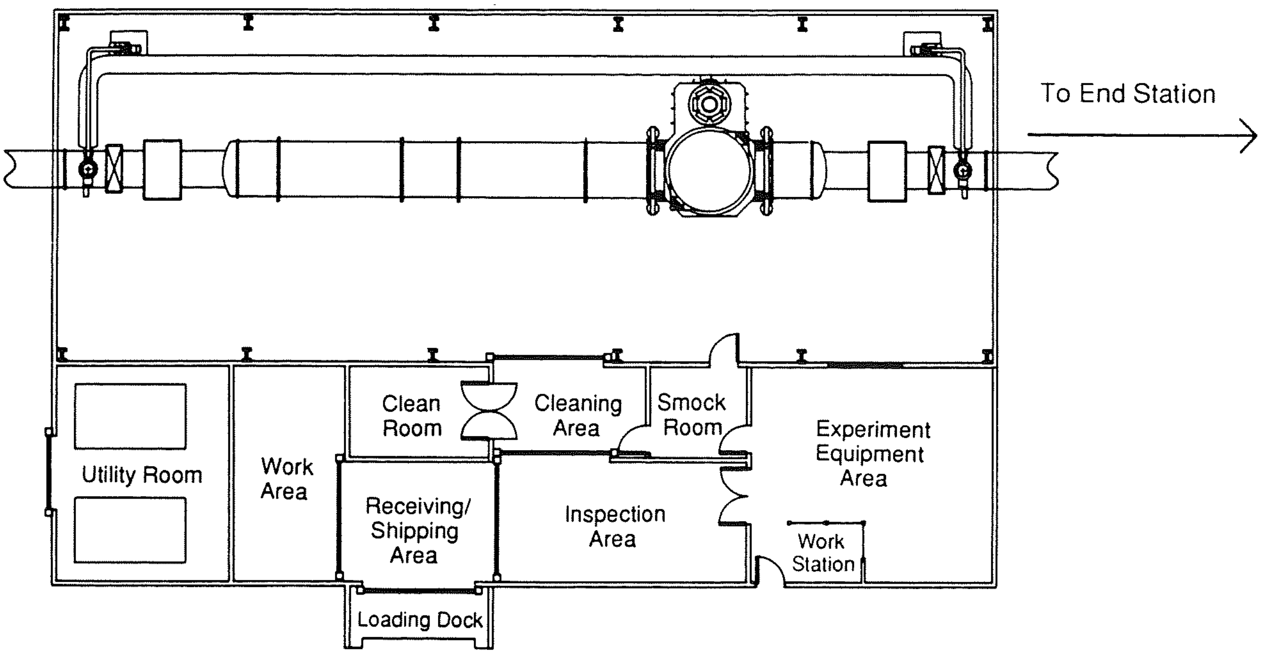

Figure IV–E–9 Floor plan of the right-arm mid station at Site 1. The left-arm mid station has a similar (mirror-imaged) floor plan. There are no mid stations at Site 2.

cover size is chosen to provide adequate room for access to repair leaks, adjust the alignment of the beam tubes, or conduct beam-tube bakeouts. The cover also protects electrical power distribution and communications lines.

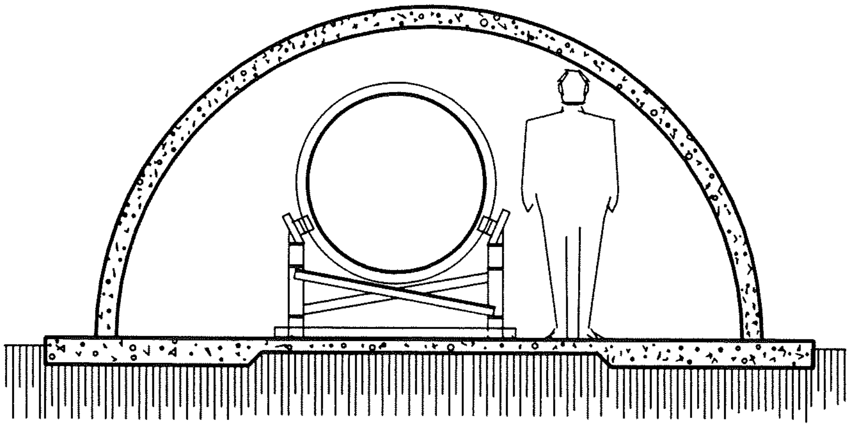

Figure IV–E–10 Elevation section view of the covered beam tube.

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air bag is restrained from above by flexible steel straps attached to the foundation slab. Preformed reinforcing bars are laid into place over the air bag form and wired together. High strength, low-slump "shotcrete" is then sprayed in place. In 2 to 4 hrs, the concrete gains sufficient strength to support itself. The air bag is deflated and moved with the half-round steel pipe to the next section.

F. Instrumentation, Control, and Data System

An initial concept for the instrumentation, control and data system for the LIGO is presented, based in part on the experience gained with prototype interferometers. The concept will be further refined during the course of the engineering design of the facilities and the interferometers.

The concept schematized in Figure IV–F–1 is a distributed system with centralized data archiving. The system consists of small computers and work stations interconnected by a standard communication link, enabling users at different locations on the site to monitor the state of the facilities and the interferometers. The system is readily implemented with current computer and instrumentation technology. The functions of the system are broadly classified into facility monitoring and control, interferometer monitoring and control (including environmental monitoring), data archiving, and on-line analysis.

1. Facility monitoring and control

One part of the distributed system will be dedicated to plant monitoring and control. The system acquires and displays the physical variables of the facilities (such as temperatures, power flow, and laser cooling) and state variables (such as building occupancy and fire monitors). It also provides control functions for safe operation of the facilities, such as interlocks on laser power.

Another dedicated system will monitor and control the vacuum system. This system will monitor data such as residual gas pressures, the spectra of residual gas analyzers, ion-pump currents, and the states of valves, mechanical pumps, and liquid nitrogen traps. It will also control the sequencing of changes of state of the vacuum system.

The data from the plant-monitoring and vacuum-data systems will be delivered to the archive and be accessible for trend and correlation studies in the scientific data analysis. The facilities will be controlled from the central station.

2. Interferometer monitoring and control

The facility instrumentation and data system will be connected by standard interfaces to computers that monitor and control the interferometers. The anticipated data rate is approximately 50 kbytes/s/interferometer. The large-bandwidth signals will have a direct data-bus connection to the facility-archiving system. The diagnostic instruments used in interferometer testing and development (such as dynamic signal analyzers, RF spectrum analyzers, and digital oscilloscopes) are controlled by the standard ethernet and IEEE-488 bus network.

Dedicated processors, tightly linked to the interferometers, will be used to control the suspension, automated alignment, and fringe-acquisition systems of the interferometers. The data rates associated with these functions are too high to be included (unprocessed) in the general facility control and monitoring system.

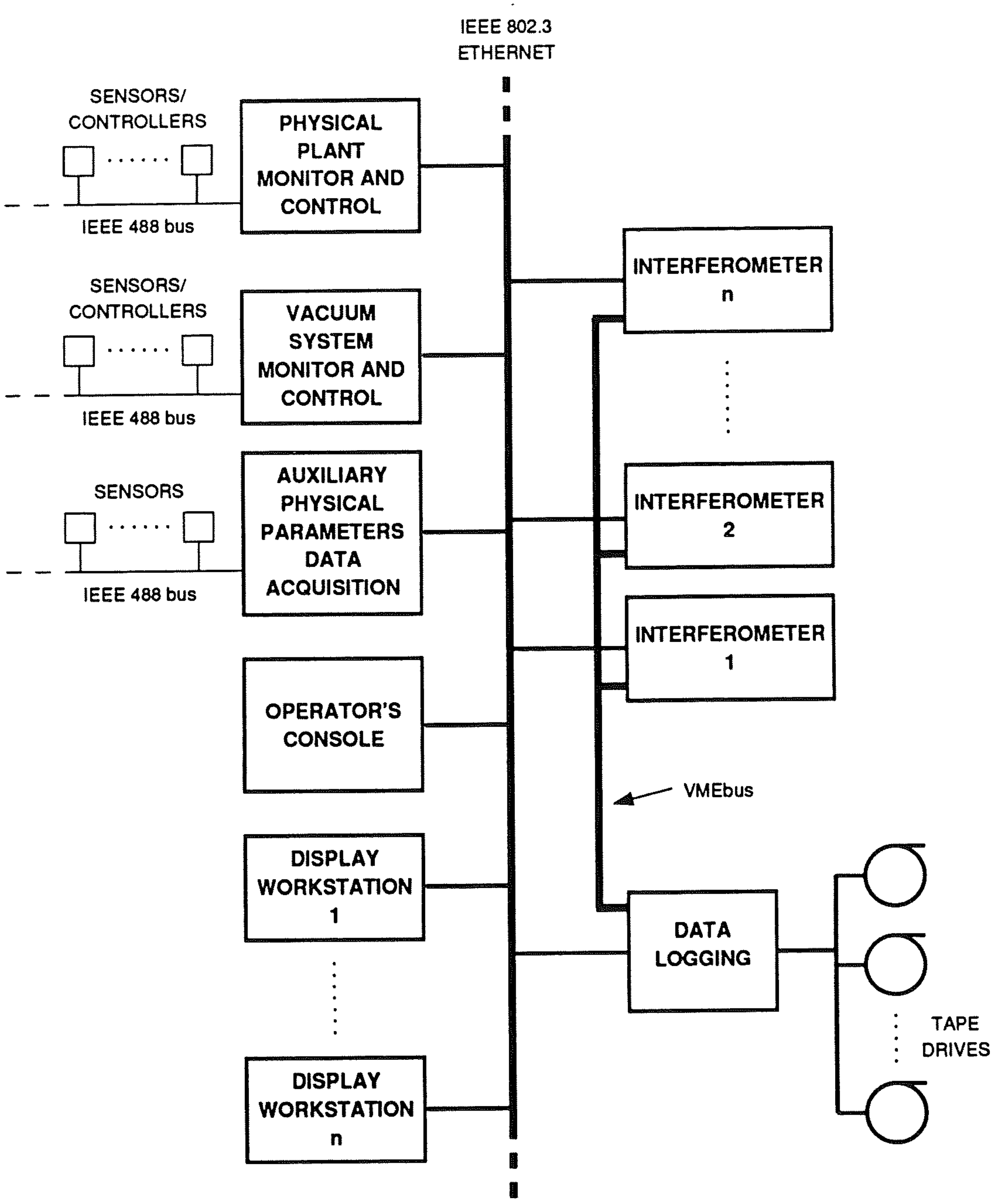

Figure IV–F–1 Diagram of the instrumentation, control, and data system for a LIGO site. A distributed architecture is used for all facility monitoring and control functions serviced by a standard (Ethernet) network. The interferometers are locally controlled by dedicated processors (not shown). The high bandwidth output data from the interferometers are transmitted to the facility archiving system by a dedicated (VME) data bus. The archiving system combines the interferometer output with facility and auxiliary monitoring signals. Display workstations throughout the facility can access data from anywhere in the system.

The interferometers develop a large number of signals involved with the control of lasers, beam positioning, mass positioning, and damping. These signals are needed during the interferometer development and some of them will be archived for subsequent use in the scientific data analysis.

A dedicated computer will monitor, process, and format for archiving the signals derived from auxiliary sensors (see Volume 1, Section VII).

3. Data archiving

A representative list of the signals developed by the monitoring systems and the interferometers is shown in Table IV–F–1. The total data rate is too high for economical storage with current technology, and we propose initially to completely archive only the most important data. As data storage technology advances we may record more fully a larger number of the available signals. The minimum storage requirements and the data-management plans are dominated by the data flow from the interferometers. The gravitational-wave output signal will be archived continuously; this sets the scale for the archiving load. A single interferometer will generate 5×10^9 bytes/day, which is manageable using high-density storage (such as 8-mm-tape video cassettes, which would be filled at the rate of two per day). The facilities will provide both archival high-density storage and disk storage for on-line analysis.

The data will be archived with time tags accurate to 1 μs to enable gravitational-waveform analysis and to maintain phase information for long integrations in a periodic-source search. The GPS satellite system will be used to maintain the required time accuracy.

4. On-line data analysis

We plan to carry out some on-line data analysis using work stations connected to the ethernet and with access to the disk archive. The work stations have the capability to search[1] for burst sources as described in Volume 1, Section VII. At Site 1 they would check the amplitude ratio between half- and full-length interferometer signals.

During interferometer development, the work stations will perform diagnostic data analyses, such as the cross-correlation of the interferometer output signals with ancillary interferometer signals and the auxiliary monitoring system.

The full-scale analysis of the archived data from both sites will take place on the university campuses. If required, supercomputer facilities available in national centers will be used.

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[1] One method is to use a dedicated work station for burst-template filtering and threshold detection. The machine would be directly coupled to the interferometer with access to the high-data-rate gravitational-wave output. When a threshold is exceeded, a signal is sent to other processors on the ethernet to request data that have been stored in short-term ring buffers. In this way signals that embrace the time of the threshold crossing and are relevant to the data analysis will be archived, without placing huge demands on data storage capacity.

TABLE IV–F–1
REPRESENTATIVE LIST OF SIGNALS[1]

SIGNAL	DESCRIPTION	NUMBER	BAND-WIDTH (kHz)	DATA RATE (kbytes/s)
	Interferometer Signals			
Interferometer output	Gravitational-wave signal	1	10	40
Symmetric port	Intensity monitor	1	10	(40)
Main cavity lock		2	10	(80)
Beam splitter lock		1	10	(40)
Recycling mirror lock		1	10	(40)
Main frequency lock		1	10	(40)
Trim frequency lock		1	10	(40)
Side arm lock		2	10	(80)
	Alignment Signals			
Main cavity angle	2 angles/mirror	8	1	(32)
Beam position	2 axes/mirror	8	1	(32)
Recycling mirror	2 angles, 2 positions	4	1	(16)
Mode cleaner	2 angles, 2 positions	4	1	(16)
	Suspension Signals			
Main cavity mirror	5 degrees of freedom	20	0.1	(8)
Deflection mirror	5 degrees of freedom	10	0.1	(4)
Beam splitter	5 degrees of freedom	5	0.1	(2)
Recycling mirror	5 degrees of freedom	5	0.1	(2)
Mode cleaner	5 degrees of freedom	10	0.1	(4)
	Auxiliary Monitor Signals			
Low freq. seismic	1/building	3	0.03	0.4
High freq. seismic	3/test-mass chamber	15	0.3	18
Acoustic pressure	1/test-mass chamber	5	2	(40)
Line power	1/building	3	0.1	1.2
Low freq. mag. field	3 axis magnetometer/building	9	0.03	1.1
High freq. mag. field	3 loops/test-mass chamber	15	0.01	0.6
RF interference	1/building	3	0.1	1.2
Cosmic ray showers	1/building	3	0.01	0.12
Housekeeping	Temperatures, voltages, states, etc.	100	0.001	0.4

[1] The table is included to illustrate the scale of the data flow. The signals with data rates in parentheses are not continuously archived. The data rates (kbytes/s) are based on a sampling rate of twice the bandwidth, and a sampling resolution of two bytes.

G. Electrical Power

The estimated electrical power consumption for the LIGO installations is presented here. Because the power consumption for the fully evolved (Phase-C) LIGO is only modestly larger than that for Phase A, the Phase-C estimates have been used for planning the installed power capacity. The average annual power consumption during Phase A is used for the purposes of estimating operating costs.

The estimates for capacity required and power consumption are summarized in Table IV–G–1 for Site 1. A total installed capacity of 2 MW is planned at each site.

TABLE IV–G–1
SITE 1 POWER CONSUMPTION

	Capacity[1] (kW)	Average[2] (kW)
1. Lighting	143	45
2. HVAC	640[3]	450[3]
3. Vacuum pumps:		
Beam tube roughing	200[4,5]	
Chamber roughing	33[4]	1
Ion pumps (first year of operation)	6	
Ion pumps (fully operational)		1
4. Electronic equipment	200[6]	100
5. Shop and service equipment	60	28
6. Chamber bakeout heaters	80[4]	
7. Lasers (including cooling)	320[4,6]	160
8. Reserve	631	
TOTAL	2000	785

[1] Short term peak transients excluded.
[2] Average power consumption after startup of operations.
[3] Site dependent.
[4] Will not operate simultaneously; only line 7 is included in total.
[5] 3.8×10^5 kW-h total.
[6] Phase-C maximum estimates.

The minimum lighting necessary for personnel and equipment is provided in the large vacuum-chamber and laser areas, supplemented by high-intensity, local lighting for work areas. Incandescent lighting will be used in these areas, for reduced radio-frequency interference.

Power requirements for HVAC equipment may be traded off against capital costs and are site dependent. Standard HVAC design practices, including the use of "economizers" and chilled-water plenums, have been assumed for the power and cost estimates.[1]

Vacuum-roughing pumps are operated at a low-duty cycle and contribute negligibly to the average power consumption. The beam tubes are pumped down only once, during startup operations. During beam-tube rough-pumping, none of the lasers will be operating; during chamber rough-pumping, at least one laser (associated with the interferometer(s) being evacuated) can be shut down temporarily. The power required for the roughing pumps may thus be "borrowed" from the laser power capacity, and need not be added into facility-power capacity requirements. Similar reasoning is used for the chamber bakeout heaters, which are operated only occasionally.[2]

Because of the low operating pressure of the LIGO, ion-pump power consumption is negligible. The maximum occurs during the first year of operation and is less than 6 kW.

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[1] It is impractical to use dissipated heat from the lasers to heat the corner building because of the low temperature (35 °C max.) of the coolant returned from the laser tubes.

[2] Power for beam-tube bakeout will be provided by rented portable generators.

V. SITES

A. Site Requirements

The scientific demands of the LIGO place a number of conditions on the selection of sites. These are summarized in Table V-1.

TABLE V-1
SITE SPECIFICATIONS

Number of sites	2
Distance between sites	
minimum	2500 km
maximum	4500 km
Arm length (nominal)	4 km
Angle between arms	
nominal	90 deg
tolerance	± 15 deg
Slope of arms	< 0.2 deg
Orientation, absolute	No requirement
Orientation, relative	Optimized for average of coincidence projection alignment and Virgo-optimized alignment[1]

[1] Refer to Volume 1, Section V.C for discussion.

The site requirements are met most economically by flat places that are large enough to accommodate the interferometer arms. The sites should be far enough from urban development to ensure that they are seismically and acoustically quiet, but still within convenient distance of housing for resident and visiting staff. Electrical power and road or rail access should be sufficiently close to allow economical construction. Soils and drainage characteristics must be suitable for LIGO construction, and environmental impact concerns must be addressable.

B. Site Investigation Process

An early survey of potential sites was conducted by Stone & Webster Engineering Corporation in 1983. The survey attempted to find flat areas in the continental U.S. owned or controlled by the Federal Government or state governments, and covered over 100 sites. One conclusion of this and other surveys is that the number of suitable sites drops off sharply if the arm lengths exceed 4–5 km. A subsequent JPL study conducted in 1984 identified more potential sites, and additional siting possibilities were brought to our attention by various interested parties. To illuminate some of the issues involved in site selection, we briefly summarize our findings for eight sample site candidates (Tables V–2 and V–3).[1] One site from Group I and one from Group II could form a site pair that meets the specifications in Table V–1.

TABLE V–2
EXAMPLES OF SITE CANDIDATES

	GROUP 1 ("Western" Sites)
EAFB	Edwards Air Force Base, California
INEL	Idaho National Engineering Laboratory, Idaho
OVRO	Owens Valley Radio Observatory, California
SV	Skull Valley, Utah
	GROUP II ("Eastern" Sites)
COL	Columbia Township, Maine
FD	Fort Dix, New Jersey
LP	Livingston Parish, Louisiana
NRAO	NRAO Greenbank, West Virginia

Site investigations require a succession of increasingly costly studies, summarized in Table V–3. Some studies have already been performed at certain sites, or will be carried out under our present grant. Most require access to the land, and therefore require landowners' approval. The intent is not to fill out the matrix of Table V–3, but to collect sufficient information to permit us to make a reasonable judgment of the suitability of sites. Final site selection will not begin before this proposal is approved by NSF. We will then undertake a site selection process, using procedures approved by NSF, which will weigh scientific merit, availability, construction suitability, and costs for each site. This process is meant to satisfy the highest standards of scientific and technical review, and will be rigorous and thorough in all respects. Upon approval by the NSF to proceed, the required additional characterization studies will be done for the selected sites. The results of the hydrology and geotechnical studies and the topographic survey data will be furnished to the engineering contractors for use in detailed design of the LIGO installations.

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[1] These eight sites are listed for illustration; no preference or final selection is implied.

TABLE V–3
LIGO SITE SELECTION TASKS

TASK	EAFB	INEL	OVRO	SV	COL	FD	LP	NRAO
1. Preliminary Layout	X	X	X	X	X	X	X	X
2. Vertical Profile/Earthwork Estimate	X		X		X	X	X	X
3. Ambient Ground Noise Survey	X				X		X	
4. Biological Survey	X							
5. Archeological Survey	I.P.				X			
6. Paleontological Survey	I.P.							
7. Hydrological Survey	X							
8. Preliminary Ground Survey	X				X			
9. Preliminary Geotechnical Survey	X				X			
10. Detailed Geotechnical Survey					X			
11. Topographical Survey								

NOTES:

X denotes task is completed.
I.P. denotes task in process.

Tasks 3–11 require landowners' approval.
Task 3 establishes ambient seismic vibration spectra before construction.
Tasks 4–6 provide data for environmental and cultural impact assessment.
Task 7 determines drainage and flood protection requirements.
Task 8 is a simple staking survey to locate alignment for items 9 & 10.
Tasks 9 & 10 determine excavation, fill compaction and foundation requirements.
Task 11 is aerial photogrammetric contour mapping, to determine earthwork profiles.

C. Site Development

Construction is initiated with surveying and earthwork for the beam-tube and building foundations. Roads that access the LIGO stations are needed both during and after construction.[2] Provisions for drainage and erosion control, connections to power, water, and sewage utilities, fire protection, site cleanup and landscaping, and fencing for site security and public safety are required. Although the details of these activities vary widely among the candidate sites, site development costs at all sites are dominated by the earthwork required to achieve a level layout of the interferometer arms.

After site preparation and earthwork are complete, the foundations and floor slabs for the stations and the foundation slabs for the beam-tube modules are laid. Reference monuments are installed on the beam-tube-module foundations at 250 m intervals (at the approximate locations of the pump stations). Each end station and mid station has one reference monument, and there are three in the corner station. The reference monuments are used to determine the final alignment of the beam tubes (see Section IV.C.2.c.i).

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[2] Roadways and parking areas will be paved over a suitable base after the main construction activities are completed, so that delicate equipment can be transported with minimum disturbance.

VI. IMPLEMENTATION PLAN

In this section, the organization of the LIGO work-breakdown structure is described and the schedule for design and construction tasks is presented. The organization and roles of the personnel who are responsible for implementing the LIGO are discussed, and a subcontracting plan is presented. The section ends with a discussion of the process for designing and fabricating the initial interferometers.

A. Work-Breakdown Structure

The work-breakdown structure (WBS) for the design and construction of LIGO facilities and equipment, including initial interferometers, is shown[1] in Figure VI–1. The WBS presents the organization of all construction-implementation activities and is used to generate schedule and cost baselines. It includes

(1) *Site development*: earthwork; roads; electrical utility connection, on-site substation, and electrical-power distribution among stations; water supply; sewer or septic tank; fire protection; site cleanup, landscaping, and fencing.

(2) *Enclosures*: corner-station buildings for the vacuum-equipment and laser area, office and shop areas, utility room, and chiller plant; end- and mid-station buildings; electrical distribution within buildings; HVAC equipment, primary-laser-cooling equipment, and cranes; beam-tube enclosures.

(3) *Vacuum equipment*: all vacuum vessels (including ports and feedthroughs) except the beam-tube modules; interferometer supports, intravacuum optical benches, and vibration-isolation stacks; integral air showers and backfill systems; all pumps and valves, except those along the beam tubes; LN_2 supply and distribution; adapters, caps, compensators and anchors; rough-pumping lines; installation, bakeout, leak check and performance testing.

(4) *Beam-tube modules*: beam-tube sections and supports, stiffeners, expansion joints, cleaning, leak checking, sealing and shipping; field assembly (including alignment), baffles; beam-tube pumps, pump tees, and instrumentation ports and valves; system cleaning, leak check and bakeout.

(5) *Support equipment*: lasers, laser-cooling heat exchangers and flow controllers, optics and electronics for laser addition, laser stabilization, and optical tables; vacuum-system monitoring and control equipment; auxiliary-physical-parameter instrumentation and data-acquisition equipment; data-logging and display equipment; intrasite communications equipment; test and diagnostic instrumentation and equipment; office and shop furnishings and equipment; and security monitoring and control equipment.

(6) *Initial interferometer(s)*: optics, mechanical assemblies, and electronics for input and output light conditioning; beam splitters and main cavity test-mass

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[1] The presentation of the WBS in Figure VI–1 is to Level 2, which will serve the purposes of the discussions in this section. Details of the WBS are presented in tabular form in Appendix C.

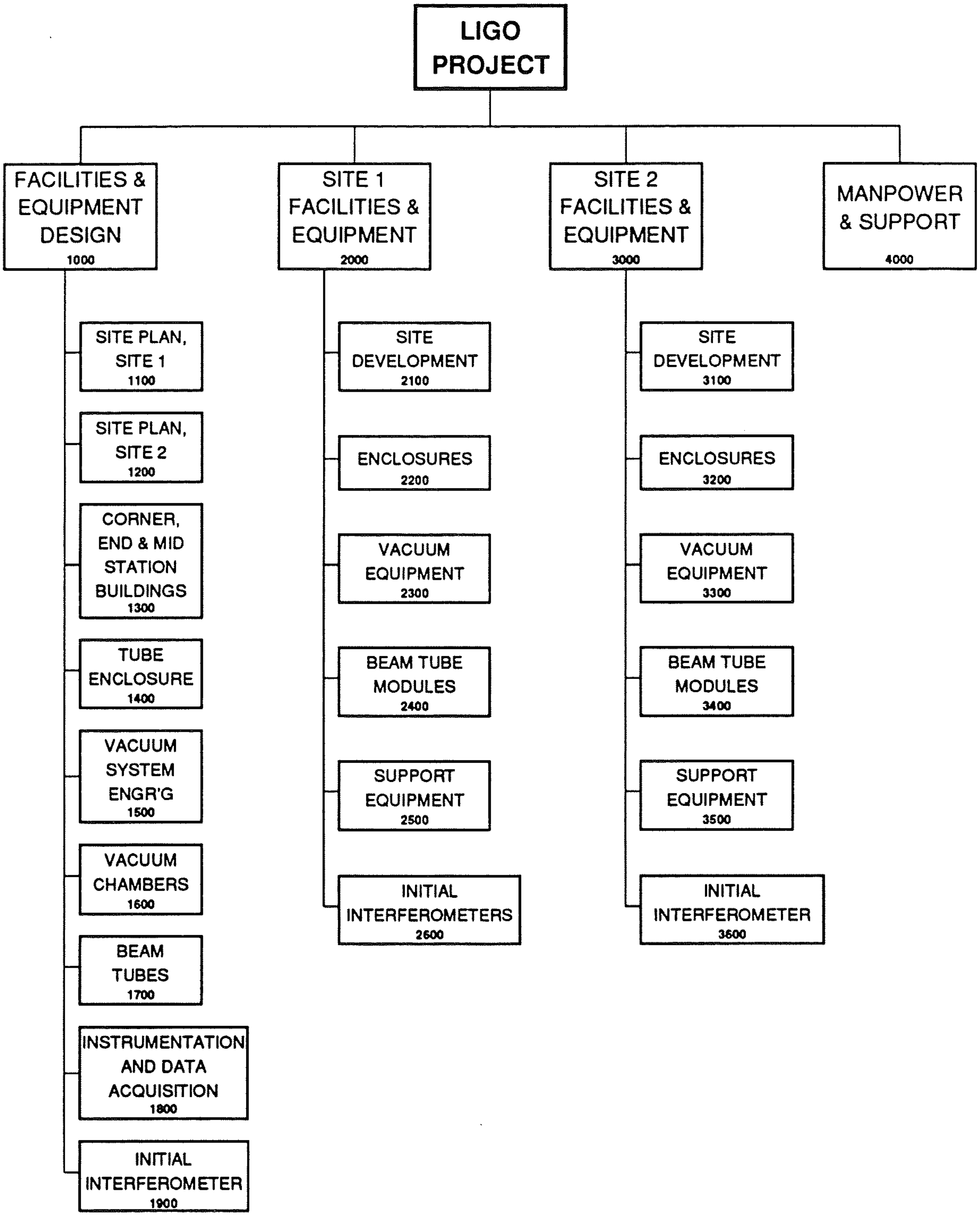

Figure VI–1 Work-breakdown structure (WBS) for the design and construction of the LIGO facilities and equipment.

assemblies; light phase/frequency stabilization servos; servos for pointing, positioning, and motion-damping of suspended components; automatic-alignment, beam-centering, and mode-matching systems; servos for phase locking of lasers between interferometers; and interferometer data acquisition, formatting, compression, and interfacing to the LIGO data-logging system.

B. Organization and Responsibilities

LIGO design and construction will be implemented by the LIGO Engineering Group, under the direction of the Chief Engineer.[2] The organization of the Engineering Group during the design and construction phases is shown in Figure VI–2.

The Director (and Principal Investigator) has overall responsibility for the LIGO Team effort in meeting project requirements and goals. The Director is accountable to the NSF and, being resident at Caltech, to the Caltech Administration, which accepts fiduciary responsibility for the LIGO Project. The Director shall appoint and convene from time to time a Design Review Board, composed of experts in relevant disciplines, to review and provide advice on the design and implementation plans of the LIGO Engineering Group.

The Chief Engineer reports to the Director. The Chief Engineer is responsible for management, control and accounting of LIGO configuration, schedule and cost. The Chief Engineer will draw upon the scientific expertise of the LIGO Team to provide guidance and evaluation of LIGO design and construction decisions. The Chief Engineer shall apprise the Director of progress and anticipated or actual deviations from planning baselines, and recommend corrective action where necessary.

The Facilities Manager is responsible for site planning, enclosure design, site development and enclosure construction at both sites. This person is also responsible for acquisition and installation of shop equipment, office furnishings, and security equipment. The Facilities Manager will be assisted by a Resident Engineer at each site; they will monitor construction progress and design compliance, and will engage the services of local testing laboratories as required to measure and document as-built quality.

The Vacuum Equipment Manager is responsible for vacuum-system design, and for the fabrication, installation, and testing of all vacuum equipment contained in the stations.

The Beam Tube Manager is responsible for the mechanical design, shop fabrication, field assembly, and testing of the beam-tube modules.

The Instrumentation and Data Systems Manager is responsible for the design, procurement, installation, integration, and testing of the vacuum-system monitoring and control equipment, auxiliary-physical-parameter instrumentation and data-acquisition equipment, intrasite-communication equipment, data logging and dis-

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[2] Support and review functions for all engineering efforts will be provided on a continuing basis by the science groups.

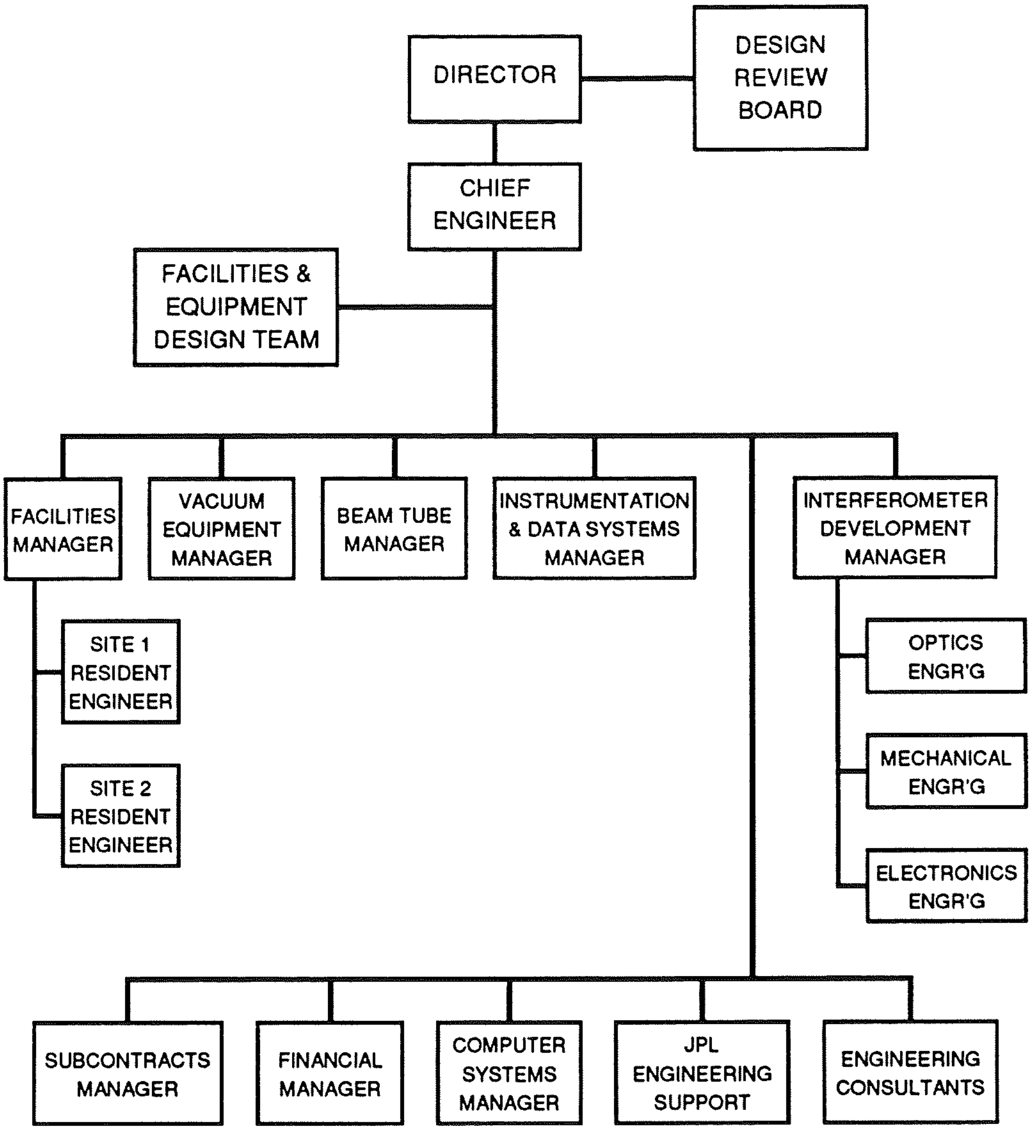

Figure VI–2 Organization chart for the LIGO Engineering Group during design and construction of the facilities.

play equipment, all software engineering and programming, and test and diagnostic equipment.

The Interferometer Development Manager is responsible for design, fabrication, installation, integration, and testing of lasers, optical components, and mechanical assemblies and electronics for the initial LIGO interferometers.

The Instrumentation and Data Systems Manager and the Interferometer Development Manager will interact on a continuing basis with the scientists and the research and development activities.

The Facilities and Equipment Design Team will be responsible for the coordinated design, development, construction, integration, testing and support of all LIGO systems. It will be composed of the Facilities Manager, Vacuum Equipment Manager, Beam Tube Manager, Instrumentation and Data Systems Manager, and the Interferometer Development Manager, and will be chaired by the Chief Engineer.

The LIGO Engineering Group will be supported by a Subcontracts Manager, who will oversee subcontract development, negotiations and performance monitoring;[3] a Financial Manager, who will monitor, correlate and report on cost and schedule performance; and a Computer Systems Manager, who will be responsible for LIGO computer systems planning and operations. The group will draw substantially upon Caltech's Jet Propulsion Laboratory for technical advice and assistance in such areas as site planning, soils engineering, Global Positioning System surveying, power engineering, HVAC engineering, structural analysis, and reliability, quality assurance, and safety engineering. Outside engineering consultants will be engaged to assist in certain areas, such as ambient seismic and vibration transmission measurements, vibration isolation of structures, geotechnical evaluation of sites, mitigation of environmental or cultural disturbances during construction, and other specialized problems outside the scope of major subcontractors' activities for which in-house expertise does not exist.

C. Design and Construction Schedule

The LIGO design and construction schedule for WBS Level 2 is shown in Figure VI–3. The schedule establishes a logical sequence of design and construction activities, accommodates the anticipated NSF funding profiles, and meets the requirements of the Level-1 schedule given in Volume 1, Section XII. A single field crew will be responsible for vacuum equipment installation and testing at both sites, and another single crew will be responsible for field assembly of the beam tubes at both sites. Sequencing the vacuum-system field construction as shown in Figure VI–3, using the same crews at both sites, will provide continuity, efficiency and enhanced quality.

The schedule provides long lead times for procurement of low-hydrogen-content steel. Fabrication of beam-tube sections will be matched to the field assembly process, so it will not be necessary to store large quantities of finished, cleaned, tested, and sealed beam-tube sections.

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[3] The Subcontracts Manager, a procurement professional who is a member of the LIGO engineering staff, technically provides only procurement liaison; fiduciary responsibility for all subcontracting remains with the Caltech Purchasing Department, with review and approval by the Office of General Counsel.

DESIGN/CONSTRUCTION SCHEDULE

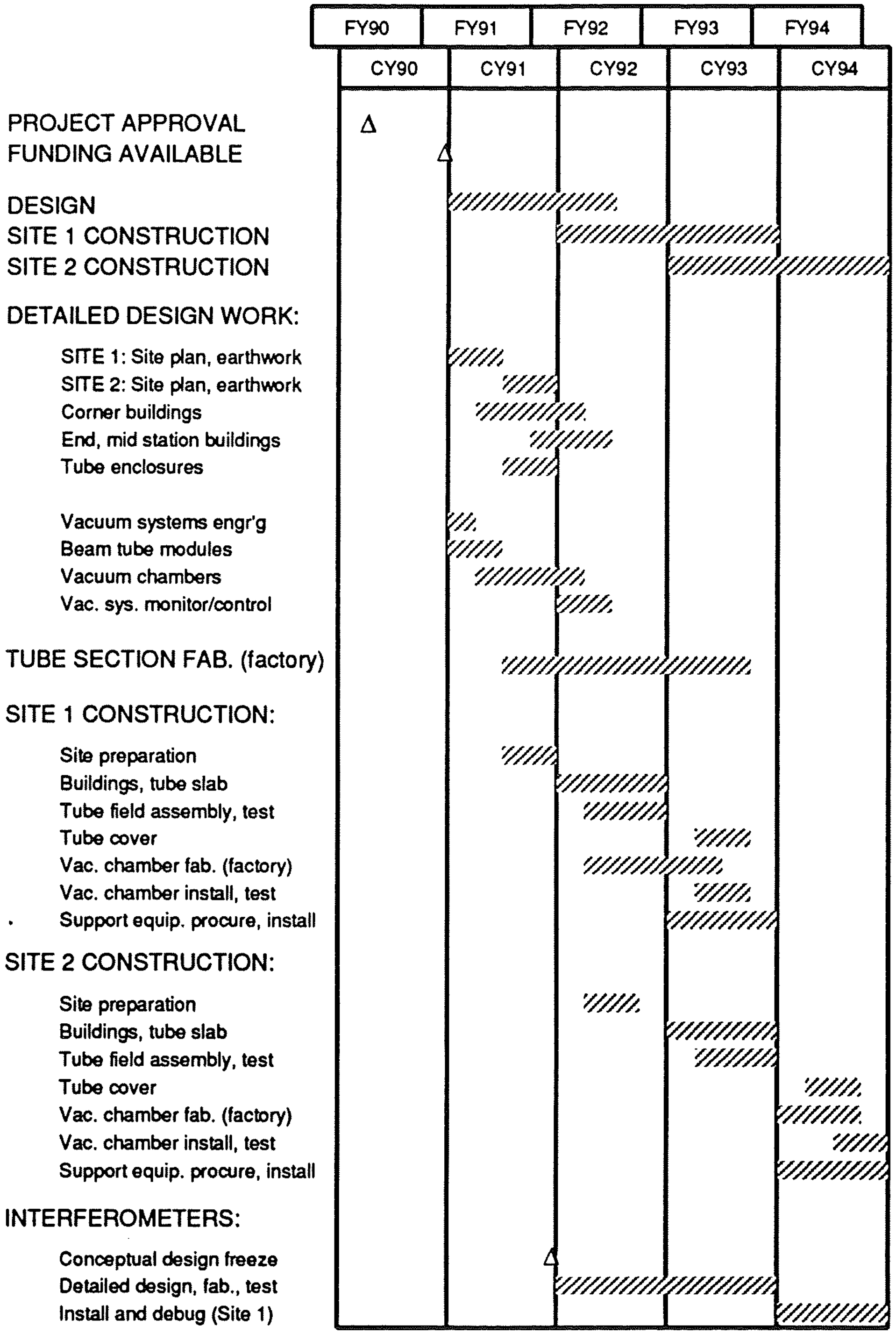

Figure VI–3 LIGO design and construction schedule.

D. Subcontracting Plan

1. Design phase

a. Facilities architectural and engineering design. The LIGO Project will employ the services of one or more architectural, engineering and construction (A&E) firms for detailed design and documentation covering site planning; corner-, end-, and mid-station buildings; and tube enclosures for both sites. The facilities design will be assigned to a single firm, or several firms forming a team, with appropriate expertise. The design-phase product will consist of construction documents (detailed drawings and specifications) suitable for obtaining fixed-price bids for construction. During the construction phase, the A&E firm will maintain control of documentation, generating new documentation as required by design changes, and participate in the review and resolution of nonconformances and claims. It will provide as-built documentation at the completion of construction. Management of the A&E design subcontract for the facilities will be the responsibility of the LIGO Facilities Manager.

b. Vacuum equipment design (and construction). A subcontract will be placed with a firm that has large-scale vacuum-system design and fabrication experience to design the LIGO vacuum system, to perform detailed design of all vacuum equipment except for the beam tubes, and to fabricate, install, and test this equipment. Given the novel features of the LIGO vacuum equipment, it is essential that a single subcontractor be responsible for design, fabrication, installation, and testing of an integrated system. Authority to proceed with fabrication, installation, and testing will be given after the design-phase work has been successfully completed and reviewed. Management of the vacuum-equipment subcontract will be the responsibility of the LIGO Vacuum Equipment Manager.

c. Beam tube design (and construction). A subcontract will be placed with a firm to provide detailed design engineering, fabrication, installation, and testing services for the beam-tube modules.[4] The design of the beam tubes has been separated from the rest of the vacuum system because it departs substantially from that of conventional vacuum systems and is more closely related to pipeline construction. This division of design tasks entails no significant risk; the interfaces between the beam-tube modules and the remainder of the vacuum system are few, readily identified and documented. Management and supervision of the beam-tube module subcontract will be the responsibility of the LIGO Beam Tube Manager.

Except for small subcontracts that may be placed for specific design tasks, all other LIGO subsystems will be designed in-house.

2. Construction phase

a. Facility construction. Site development, and construction of corner-,

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[4] Although this subcontract may be performed by the same contractor responsible for the vacuum equipment, this is not a requirement.

end-, and mid-station buildings, and tube enclosures for both sites will be subcontracted to a single construction firm. The design-phase A&E subcontractor will provide construction-phase configuration management, documentation maintenance and change control, and implementation advice. Management and supervisory responsibility for facility construction lies with the Facilities Manager, supported by a Resident Engineer at each site who provides on-site monitoring. Quality assurance services will be provided by local testing laboratories, through subcontracts arranged by the Resident Engineers.

b. Vacuum equipment fabrication. Installation and testing of vacuum equipment will be performed by the design subcontractor, as discussed above. The construction-phase subcontract will continue to be managed and supervised by the LIGO Vacuum Equipment Manager; on-site installation and testing will be monitored by the Resident Engineers.

c. Beam tube construction. Fabrication and field assembly of beam-tube modules will be performed by the beam-tube-design subcontractor. Management and supervision of the beam tube subcontract will be the responsibility of the LIGO Beam Tube Manager, assisted during field assembly by the Resident Engineers.

d. Other. A substantial number of small construction-phase subcontracts are anticipated for interferometer optics fabrication and testing, mechanical-assembly fabrication, and electronics fabrication and testing. These will be governed by detailed design drawings and specifications developed within the LIGO team, and will be supervised by the Interferometer Development Manager.

All subcontracts will be competitively solicited, negotiated procurements.

E. Interferometer Design and Fabrication

The initial interferometers will be designed in the future, and a detailed work-breakdown structure for fabrication and installation is therefore not available. The research program described in Volume 1, Section VIII.B will materially affect the final design, now still in a conceptual phase. The Interferometer Development Manager shall have responsibility for the efforts outlined below.

1. Interferometer design, fabrication and testing

The engineering design will begin by dividing the interferometer into a set of functional subsystems. For each subsystem, we will specify technical and performance specifications, a set of tasks that require detailed engineering definition and design, a procedure and schedule for procurement and fabrication, and a description of the test and qualification procedures. The initial interferometers will use common subsystems designs, except for scaling some of the optical and electronic parameters in the half-length interferometer. When practical, components or subsystems will be fabricated through industrial subcontracts. Subsystems will be assembled, inspected and tested[5] on campus prior to shipment to the sites for integration into

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[5] Although the campus facilities will be capable of assembly and testing of LIGO interferometer

the initial interferometers.

2. Installation and operation of the initial LIGO interferometers

After construction at the first site is completed and the facility is accepted from the contractors, LIGO engineering and scientific personnel will install the initial interferometers. The same group will perform these functions at the second site one year later (supported by a post-construction agreement), and will also train the operations and facilities-maintenance staff.

Once an interferometer is functioning, data runs will be initiated to uncover possible shortcomings in the performance of the interferometer or in the reliability of the supporting facilities. Experience gained during installation of the first interferometer should allow installation of the additional interferometers to proceed with few surprises. The operation of three interferometers in triple coincidence, constituting the initial LIGO detector, will complete the final shakedown of the LIGO facilities and equipment.

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subsystems, the first integration of all the subsystems of a LIGO interferometer will take place at the remote sites.

VII. COST SUMMARY

This proposal requests support for a 4-year program to design, build, and operate a Laser Interferometer Gravitational-Wave Observatory (LIGO) and to continue research and development of interferometric detectors. At the end of this period, construction and outfitting of the proposed facilities will be complete and we will be ready to begin operations as described in Volume 1, Section VI.C.1. (At that time, we expect to submit a proposal for the continued operation of the LIGO and for continued research and development (R&D) of detector technology as well as data analysis.[1]) In this section we present the total estimated cost and supporting details of the proposed R&D, design and construction program.

The cost presentation is organized into three parts. Tables VII–1, VII–2, and VII–3 give an overview of the complete program. The tables are followed by a presentation of budget details in the standard NSF format, with supporting data. Cost estimates for the LIGO design and construction project, with a few exceptions noted below, are organized in accordance with the work-breakdown structure (WBS) discussed in Section VI and presented in detail in Appendix C.

TABLE VII–1
LIGO PROJECT—TOTAL COST SUMMARY
FY89 $M

	1991	1992	1993	1994	TOTAL	Note:
Research and Development	3.0	3.0	3.0	3.0	12.0	1
LIGO Design and Construction	44.6	49.4	48.1	37.7	179.8	2
Remote Site Operations				2.0	2.0	3
TOTAL ESTIMATED COST, FY89 $M	47.6	52.4	51.1	42.7	193.8	
Inflation allowance @ 5%/yr, FY89 base	4.9	8.3	11.0	11.8	36.0	
TOTAL ESTIMATED COST, ESCALATED $M	52.5	60.7	62.1	54.5	229.8	

Note 1: Caltech/MIT on–campus research and development effort.

Note 2: Total cost of remote LIGO installations including initial interferometers, excluding ~$7.0M in local sales taxes pending decision on ownership of LIGO facilities (government or private).

Note 3: LIGO remote site operations cost for first year, Site 1.

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[1] Cost estimates for the full operations phase following design and construction are presented in Appendix B.

Table VII–1 presents a total cost summary for the proposed program. *Research and Development* provides for the activities described in Volume 1, Section VIII.B, including the related part of LIGO project salaries, supplies, expenses, and equipment. *LIGO Design and Construction* covers the total estimated cost of the LIGO facilities and initial interferometers, including the remainder of LIGO project scientific, engineering, administrative, and management support. *Remote Site Operations* covers the cost of on-site permanent staff (see discussion in Volume 1, Section VI), facility and equipment maintenance, and utilities for Site 1, where operations will begin in the fourth year. All costs are given in FY 1989 dollars. An inflation allowance, computed at a rate of 5% per year, is computed and added to the annual FY 1989 dollar amounts shown.

TABLE VII–2
LIGO PROJECT—ANNUAL LEVELS OF EFFORT FOR LIGO PROJECT STAFF DURING CONSTRUCTION PHASE[1]
FY89 $M

	Research and Development	**Design and Construction**	**Remote Site Operations[2] (Site 1)**
Manpower:			
Faculty (number involved)	Six (6) total faculty involved in all activities		
Staff Scientists (FTEs[3])	6	5	1
Engineers/Programmers (FTEs)	3	8	1
Technicians (FTEs)	5	3	9
Administrative/Clerical (FTEs)	3	4	1
Graduate Research Assistants (number)	10		
Undergraduate Research Ass't (number)	12		
Costs (FY89 $M):			
Salaries and benefits	1.3	1.4	0.6
JPL support (2 FTEs)		0.3	
Supplies, expenses, travel	0.2	0.3	
Plant maintenance			0.6
Electrical power			0.7
Equipment	0.6		
Overhead	0.9	1.0	0.1
TOTAL COST PER YEAR (FY89 $M)	3.0	3.0	2.0

[1] Columns correspond to cost categories listed in Table VII–1.
[2] On-site permanent staff, plant maintenance and electrical power costs, 1994 only.
[3] Full-time equivalents (each represents 12 man-months).

Table VII–2 displays the annual levels of effort for LIGO project staff associated with *each* of the three types of activity shown in Table VII–1. Manpower requirements are in "full-time-equivalents" (FTEs) or number of persons involved, as appropriate. The total costs of the R&D program and the LIGO site operations (Site 1 only) are included.

TABLE VII-3
LIGO PROJECT—DESIGN AND CONSTRUCTION COST SUMMARY
FY89 \$M

	1991	1992	1993	1994	TOTAL	Reference:[1]
1. LIGO team salaries, expenses, travel	3.0	3.0	3.0	3.0	12.0	Table VII-2
2. Facilities and equipment design[2]	10.0	1.8	1.6	1.0	14.4	WBS 1100-1700
3a. Site 1 facilities and equipment:						
Site development	6.3				6.3	WBS 2100
Buildings		12.5			12.5	WBS 2200-2250
Beam-tube enclosure			6.6		6.6	WBS 2260
Vacuum equipment (except tubes)		12.5	10.1		22.6	WBS 2300
Beam tubes	8.9	4.9			13.8	WBS 2400
Support equipment			4.1		4.1	WBS 2500
Initial interferometers		1.0	1.0	3.0	5.0	WBS 2600
3b. Site 2 facilities and equipment:						
Site development		5.5			5.5	WBS 3100
Buildings			8.8		8.8	WBS 3210-3250
Beam-tube enclosure				6.6	6.6	WBS 3260
Vacuum equipment (except tubes)				11.6	11.6	WBS 3300
Beam tubes	8.9		4.9		13.8	WBS 3400
Support equipment				3.7	3.7	WBS 3500
Initial interferometers				2.5	2.5	WBS 3600
3. Total, facilities and equipment (3a + 3b)	24.1	36.4	35.5	27.4	123.4	
SUBTOTAL, Lines 1–3	37.1	41.2	40.1	31.4	149.8	
4. Contingency @ 20%	7.5	8.2	8.0	6.3	30.0	
TOTAL, DESIGN AND CONSTRUCTION	44.6	49.4	48.1	37.7	179.8	

[1] WBS *nnnn* refers to the work-breakdown structure organization of cost in Appendix C, where further details may be found.
[2] Excluding instrumentation, data-acquisition system and interferometer design (performed in-house, included in Item 1).

Table VII–3 provides a further breakdown of the *Design and Construction* costs and serves as an index to the detailed breakdowns provided in Appendix C. The time phasing of costs reflects the schedule and subcontracting plan given in Section VI. The following notes apply to the cost data presented in this section.

Period covered: The proposed period covers the design and construction phase, a 4-year interval beginning December 1, 1990, and ending November 30, 1994. For simplicity, we have referred to the period from December 1, 1990 through November 30, 1991, as "1991," and subsequent year references have a corresponding meaning.

Ownership: We have assumed that title to LIGO facilities and equipment will be retained by the U.S. Government during the construction phase, and transferred to Caltech upon startup of regular operations. Consequently, local sales taxes have been omitted.

Sites: The candidate sites with lowest estimated construction costs have been used. The choice of different sites could substantially increase the estimated construction costs.

Subcontracts: The subcontracting plan of Section VI includes four major subcontracts with professional or industrial firms. The attached NSF budget forms (not tailored for a multi-year construction project) may convey the impression that these subcontracts can be broken into separate parts for each budget year. It is in the best interest of the LIGO Project and the Government to obligate these contractors for the full term and full scope of the planned work (but including a "Limitation of Obligation" clause to control the rate of funding). The cost estimates assume that such agreements will be negotiated. Once these subcontracting arrangements have been formally made, disruptions in funding will invariably lead to increased total cost.

Design: "Design cost" refers to all costs associated with products and services such as plans, drawings, specifications, studies, reports, investigations, shop drawing review, inspection, testing, construction liaison and management provided by the design subcontractors.

Contingency: Design and construction costs have been estimated based upon the best available information. The unprecedented nature of the LIGO project mandates a management reserve (to be held in the Director's Office) of at least 20%.

MIT subcontract: All MIT costs for personnel, equipment, supplies, expenses, and travel are merged with Caltech costs for the purposes of preparing this budget. A separate subcontract will be negotiated with MIT for work associated with this proposal.

Residual Funds Statement

We anticipate no residual funds at the end of the current grant funding period.

12/1/90 - 11/30/94

SUMMARY PROPOSAL BUDGET

CUMULATIVE BUDGET
(1989 dollars)

ORGANIZATION CALIFORNIA INSTITUTE OF TECHNOLOGY	FOR NSF USE ONLY PROPOSAL NO.	DURATION (MONTHS) Proposed / Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR R. E. VOGT	AWARD NO.	

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.6. show number in brackets)		NSF FUNDED PERSON-MOS CAL.	ACAD	SUMR	FUNDS REQUESTED BY PROPOSER	FUNDS GRANTED BY NSF (IF DIFFERENT)
1. R. E. VOGT	PI & PD, PROFESSOR OF PHYSICS				$	$
2. R. W. P. DREVER	PROFESSOR OF PHYSICS					
3. K. S. THORNE	PROFESSOR OF THEORETICAL PHYSICS					
4. R. WEISS	PROFESSOR OF PHYSICS, MIT					
5. (2) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)						
6. (6) TOTAL SENIOR PERSONNEL (1-5)					532,400	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. ( ) POST DOCTORAL ASSOCIATES						
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)		1716			7,402,200	
3. ( ) GRADUATE STUDENTS					480,000	
4. ( ) UNDERGRADUATE STUDENTS					240,000	
5. ( ) SECRETARIAL-CLERICAL					330,400	
6. ( ) OTHER						
TOTAL SALARIES AND WAGES (A+B)					8,985,000	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) 29.25% - excluding undergrads					2,557,915	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)					11,542,915	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $1,000:)						
TOTAL PERMANENT EQUIPMENT					17,673,600	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					762,400	
2. FOREIGN					50,400	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 2. TRAVEL 3. SUBSISTENCE 4. OTHER						
TOTAL PARTICIPANT COSTS						
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES					1,282,000	
2. PUBLICATION COSTS/PAGE CHARGES					22,800	
3. CONSULTANT SERVICES						
4. COMPUTER (ADPE) SERVICES						
5. SUBCONTRACTS					122,381,800	
6. OTHER					32,423,832	
TOTAL OTHER DIRECT COSTS					156,110,432	
H. TOTAL DIRECT COSTS (A THROUGH G)					186,139,747	
I. INDIRECT COSTS (SPECIFY)						
TOTAL INDIRECT COSTS					7,778,762	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)					193,918,509	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPM 252 AND 253)						
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)					$ 193,918,509	$

PI/PD TYPED NAME & SIGNATURE*	DATE	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
INST. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date of Rate Sheet	Initials - DGC Program

NSF Form 1030 (1-87) *Supersedes All Previous Editions*

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPM 233)

RESEARCH AND DEVELOPMENT,
LIGO DESIGN AND CONSTRUCTION
12/1/90 - 11/30/91

SUMMARY PROPOSAL BUDGET

FIRST YEAR - 1991
(1989 dollars)

ORGANIZATION CALIFORNIA INSTITUTE OF TECHNOLOGY	FOR NSF USE ONLY PROPOSAL NO.	DURATION (MONTHS) Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR R. E. VOGT	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)		NSF FUNDED PERSON-MOS. CAL.	ACAD	SUMR	FUNDS REQUESTED BY PROPOSER	FUNDS GRANTED BY NSF (IF DIFFERENT)
1. R. E. VOGT	PI & PD, PROFESSOR OF PHYSICS				$	$
2. R. W. P. DREVER	PROFESSOR OF PHYSICS					
3. K. S. THORNE	PROFESSOR OF THEORETICAL PHYSICS					
4. R. WEISS	PROFESSOR OF PHYSICS, MIT					
5. (2) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)						
6. (6) TOTAL SENIOR PERSONNEL (1-5)					133,100	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. ( ) POST DOCTORAL ASSOCIATES						
2. (33) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)		396			1,746,800	
3. (10) GRADUATE STUDENTS					120,000	
4. (12) UNDERGRADUATE STUDENTS					60,000	
5. (4) SECRETARIAL-CLERICAL					75,100	
6. ( ) OTHER						
TOTAL SALARIES AND WAGES (A+B)					2,135,000	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)	29.25% - excluding undergrads				606,938	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)					2,741,938	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $1,000:)						
TOTAL PERMANENT EQUIPMENT	See budget explanation page 2				626,250	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					190,000	
2. FOREIGN					12,600	
	See budget explanation page 3					
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 2. TRAVEL 3. SUBSISTENCE 4. OTHER						
TOTAL PARTICIPANT COSTS						
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES	See budget explanation page 4				320,500	
2. PUBLICATION COSTS/PAGE CHARGES					5,700	
3. CONSULTANT SERVICES						
4. COMPUTER (ADPE) SERVICES						
5. SUBCONTRACTS	See budget explanation pages 5 - 9				33,976,500	
6. OTHER	See budget explanation page 10				7,779,958	
TOTAL OTHER DIRECT COSTS					42,082,658	
H. TOTAL DIRECT COSTS (A THROUGH G)					45,653,446	
I. INDIRECT COSTS (SPECIFY)	58% of T.D.C. excluding equipment, subcontracted amounts beyond first $25,000 of each subcontract (5), JPL work order, and contingency					
TOTAL INDIRECT COSTS					1,969,528	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)					47,622,974	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPM 252 AND 253)						
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)					$ 47,622,974	$

PI/PD TYPED NAME & SIGNATURE*	DATE	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
INST. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date of Rate Sheet	Initials - OGC Program

NSF Form 1030 (1-87) *Supersedes All Previous Editions*

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPM 233)

RESEARCH AND DEVELOPMENT,
LIGO DESIGN AND CONSTRUCTION
12/1/91 - 11/30/92

SUMMARY PROPOSAL BUDGET

SECOND YEAR - 1992
(1989 dollars)

ORGANIZATION CALIFORNIA INSTITUTE OF TECHNOLOGY	FOR NSF USE ONLY PROPOSAL NO.	DURATION (MONTHS) Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR R. E. VOGT	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)		NSF FUNDED PERSON-MOS CAL.	ACAD	SUMR	FUNDS REQUESTED BY PROPOSER	FUNDS GRANTED BY NSF (IF DIFFERENT)
1. R. E. VOGT	PI & PD, PROFESSOR OF PHYSICS				$	$
2. R. W. P. DREVER	PROFESSOR OF PHYSICS					
3. K. S. THORNE	PROFESSOR OF THEORETICAL PHYSICS					
4. R. WEISS	PROFESSOR OF PHYSICS, MIT					
5. (2) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)						
6. (6) TOTAL SENIOR PERSONNEL (1-5)					133,100	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. ( ) POST DOCTORAL ASSOCIATES						
2. (33) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)		396			1,746,800	
3. (10) GRADUATE STUDENTS					120,000	
4. (12) UNDERGRADUATE STUDENTS					60,000	
5. (4) SECRETARIAL-CLERICAL					75,100	
6. ( ) OTHER						
TOTAL SALARIES AND WAGES (A+B)					2,135,000	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)	29.25% - excluding undergrads				606,938	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)					2,741,938	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $1,000.)						
TOTAL PERMANENT EQUIPMENT	See budget explanation page 2				1,537,250	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					191,600	
2. FOREIGN					12,600	
	See budget explanation page 3					
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 2. TRAVEL 3. SUBSISTENCE 4. OTHER						
TOTAL PARTICIPANT COSTS						
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES	See budget explanation page 4				320,500	
2. PUBLICATION COSTS/PAGE CHARGES					5,700	
3. CONSULTANT SERVICES						
4. COMPUTER (ADPE) SERVICES						
5. SUBCONTRACTS	See budget explanation pages 5 - 9				37,180,300	
6. OTHER	See budget explanation page 10				8,479,958	
TOTAL OTHER DIRECT COSTS					45,986,458	
H. TOTAL DIRECT COSTS (A THROUGH G)					50,469,846	
I. INDIRECT COSTS (SPECIFY) 58% of T.D.C. excluding equipment, subcontracted amounts (first $25,000 incurred during first year), JPL work order, and contingency						
TOTAL INDIRECT COSTS					1,897,956	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)					52,367,802	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPM 252 AND 253)						
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)					$ 52,367,802	$

PI/PD TYPED NAME & SIGNATURE*	DATE	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
INST. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date of Rate Sheet	Initials - DGC Program

NSF Form 1030 (1-87) *Supersedes All Previous Editions*

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPM 233)

RESEARCH AND DEVELOPMENT,
LIGO DESIGN AND CONSTRUCTION
12/1/92 - 11/30/93

SUMMARY PROPOSAL BUDGET

THIRD YEAR - 1993
(1989 dollars)

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (MONTHS)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION CALIFORNIA INSTITUTE OF TECHNOLOGY					
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR R. E. VOGT					
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	NSF FUNDED PERSON-MOS.			FUNDS REQUESTED BY PROPOSER	FUNDS GRANTED BY NSF (IF DIFFERENT)
	CAL.	ACAD	SUMR		
1. R. E. VOGT — PI & PD, PROFESSOR OF PHYSICS				$	$
2. R. W. P. DREVER — PROFESSOR OF PHYSICS					
3. K. S. THORNE — PROFESSOR OF THEORETICAL PHYSICS					
4. R. WEISS — PROFESSOR OF PHYSICS, MIT					
5. (2) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
6. (6) TOTAL SENIOR PERSONNEL (1-5)				133,100	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES					
2. (33) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	396			1,746,800	
3. (10) GRADUATE STUDENTS				120,000	
4. (12) UNDERGRADUATE STUDENTS				60,000	
5. (4) SECRETARIAL-CLERICAL				75,100	
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				2,135,000	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) 29.25% - excluding undergrads				606,938	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				2,741,938	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $1,000.)					
TOTAL PERMANENT EQUIPMENT See budget explanation page 2				5,733,450	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				192,400	
2. FOREIGN				12,600	
See budget explanation page 3					
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 2. TRAVEL 3. SUBSISTENCE 4. OTHER					
TOTAL PARTICIPANT COSTS					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES See budget explanation page 4				320,500	
2. PUBLICATION COSTS/PAGE CHARGES				5,700	
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS See budget explanation pages 5 - 9				31,997,600	
6. OTHER See budget explanation page 10				8,279,958	
TOTAL OTHER DIRECT COSTS				40,603,758	
H. TOTAL DIRECT COSTS (A THROUGH G)				49,284,146	
I. INDIRECT COSTS (SPECIFY) 58% of T.D.C. excluding equipment, subcontracted amounts (first $25,000 incurred during first year), JPL work order, and contingency					
TOTAL INDIRECT COSTS				1,898,420	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				51,182,566	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPM 252 AND 253)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 51,182,566	$

PI/PD TYPED NAME & SIGNATURE*	DATE	FOR NSF USE ONLY		
		INDIRECT COST RATE VERIFICATION		
INST. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date of Rate Sheet	Initials - DGC Program

NSF Form 1030 (1-87) *Supersedes All Previous Editions*

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPM 233)

RESEARCH AND DEVELOPMENT,
LIGO DESIGN AND CONSTRUCTION
12/1/93 - 11/30/94

SUMMARY PROPOSAL BUDGET

FOURTH YEAR - 1994
(1989 dollars)

ORGANIZATION CALIFORNIA INSTITUTE OF TECHNOLOGY	FOR NSF USE ONLY		
	PROPOSAL NO.	DURATION (MONTHS)	
		Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR R. E. VOGT	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)		NSF FUNDED PERSON-MOS. CAL.	ACAD	SUMR	FUNDS REQUESTED BY PROPOSER	FUNDS GRANTED BY NSF (IF DIFFERENT)
1. R. E. VOGT	PI & PD, PROFESSOR OF PHYSICS				$	$
2. R. W. P. DREVER	PROFESSOR OF PHYSICS					
3. K. S. THORNE	PROFESSOR OF THEORETICAL PHYSICS					
4. R. WEISS	PROFESSOR_OF PHYSICS, MIT					
5. (2) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)						
6. (6) TOTAL SENIOR PERSONNEL (1-5)					133,100	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. ( ) POST DOCTORAL ASSOCIATES						
2. (33) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)		396			1,746,800	
3. (10) GRADUATE STUDENTS					120,000	
4. (12) UNDERGRADUATE STUDENTS					60,000	
5. (4) SECRETARIAL-CLERICAL					75,100	
6. ( ) OTHER						
TOTAL SALARIES AND WAGES (A+B)					2,135,000	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) 29.25% - excluding undergrads					606,938	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)					2,741,938	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $1,000:)						
TOTAL PERMANENT EQUIPMENT	See budget explanation page 2				9,776,650	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					188,400	
2. FOREIGN					12,600	
	See budget explanation page 3					
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 2. TRAVEL 3. SUBSISTENCE 4. OTHER						
TOTAL PARTICIPANT COSTS						
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES	See budget explanation page 4				320,500	
2. PUBLICATION COSTS/PAGE CHARGES					5,700	
3. CONSULTANT SERVICES						
4. COMPUTER (ADPE) SERVICES						
5. SUBCONTRACTS	See budget explanation pages 5 - 9				19,227,400	
6. OTHER	See budget explanation page 10				6,579,958	
TOTAL OTHER DIRECT COSTS					26,133,558	
H. TOTAL DIRECT COSTS (A THROUGH G)					38,853,146	
I. INDIRECT COSTS (SPECIFY) 58% of T.D.C. excluding equipment, subcontracted amounts (first $25,000 incurred during first year), JPL work order, and contingency						
TOTAL INDIRECT COSTS					1,896,100	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)					40,749,246	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPM 252 AND 253)						
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)					$ 40,749,246	$

PI/PD TYPED NAME & SIGNATURE*	DATE	FOR NSF USE ONLY		
		INDIRECT COST RATE VERIFICATION		
INST. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date of Rate Sheet	Initials - DGC Program

NSF Form 1030 (1-87) *Supersedes All Previous Editions*

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPM 233)

REMOTE SITE OPERATIONS
(Site 1)
12/1/93 - 11/30/94

SUMMARY PROPOSAL BUDGET

FOURTH YEAR - 1994
(1989 dollars)

ORGANIZATION CALIFORNIA INSTITUTE OF TECHNOLOGY	FOR NSF USE ONLY PROPOSAL NO.	DURATION (MONTHS) Proposed / Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR R. E. VOGT	AWARD NO.	

	NSF FUNDED PERSON-MOS. CAL.	ACAD	SUMR	FUNDS REQUESTED BY PROPOSER	FUNDS GRANTED BY NSF (IF DIFFERENT)
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)					
1. R. E. VOGT PI & PD, PROFESSOR OF PHYSICS				$	$
2. R. W. P. DREVER PROFESSOR OF PHYSICS					
3. K. S. THORNE PROFESSOR OF THEORETICAL PHYSICS					
4. R. WEISS PROFESSOR OF PHYSICS, MIT					
5. (2) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
6. (6) TOTAL SENIOR PERSONNEL (1-5)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES					
2. (11) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	132			415,000	
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. (1) SECRETARIAL-CLERICAL				30,000	
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				445,000	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) 29.25%				130,163	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				575,163	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $1,000:)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					
2. FOREIGN					
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 2. TRAVEL 3. SUBSISTENCE 4. OTHER					
TOTAL PARTICIPANT COSTS					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES					
2. PUBLICATION COSTS/PAGE CHARGES					
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS					
6. OTHER See budget explanation page 10				1,304,000	
TOTAL OTHER DIRECT COSTS				1,304,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				1,879,163	
I. INDIRECT COSTS (SPECIFY) 20.3% of salaries and benefits					
TOTAL INDIRECT COSTS				116,758	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				1,995,921	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPM 252 AND 253)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 1,995,921	$

PI/PD TYPED NAME & SIGNATURE*	DATE	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION
INST. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked / Date of Rate Sheet / Initials - DGC / Program

NSF Form 1030 (1-87) *Supersedes All Previous Editions*

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPM 233)

LIGO BUDGET EXPLANATION PAGE 1 -- LINE A and B -- PERSONNEL

Line A3 -- Salary for Dr. Thorne is fully paid by Caltech and Thorne's separate NSF grant, and are not included here.

Line A4 -- Professor R. Weiss, MIT
All MIT costs, including salaries for professorial faculty, are integrated with Caltech costs for the purposes of preparing this budget. A separate subcontract will be negotiated with MIT for effort associated with this proposal following authorization by the NSF.

Line A5 -- Other Senior Personnel
F.J. Raab, Assistant Professor of Physics, Caltech

Assistant Professor, MIT
To be appointed; a search is currently in progress.

Line A6 -- Total Senior Personnel
In accordance with Caltech Policy, individual faculty man-month and salary data are furnished under separate cover to the NSF.

Line B2 -- Other Professionals:

Position	FTEs	Ave. Rate	1991	1992	1993	1994
R&D and LIGO Design & Construction:						
Scientist	11	$51.1	$562,100	$562,100	$562,100	$562,100
Engineer	11	$67.6	$743,600	$743,600	$743,600	$743,600
Technician	8	$35.0	$280,000	$280,000	$280,000	$280,000
Administrative Support	3	$53.7	$161,100	$161,100	$161,100	$161,100
Line B2 Total:			$1,746,800	$1,746,800	$1,746,800	$1,746,800
Remote Site Operations:						
Site Manager	1	$55.0				$55,000
Programmer	1	$45.0				$45,000
Technician	9	$35.0				$315,000
Line B2 Total:						$415,000

LIGO BUDGET EXPLANATION PAGE 2 -- LINE D -- EQUIPMENT

	Method	1991	1992	1993	1994
LINE D -- EQUIPMENT					
1. Equipment in support of research and development					
a. Computing and data acquisition equipment:					
Workstations	12 @ $10K ea	$30,000	$30,000	$30,000	$30,000
File Server		$65,000			
A/D Converters, VME	8 @ $2.5K ea	$20,000			
D/A Converters, VME	8 @ $2.5K ea	$20,000			
VME Bin + Controller	2 @ $27.5K ea	$55,000			
b. Upgrades to the 40 meter facility:					
End Tanks, 4' diameter	5 @ $60K ea		$180,000	$120,000	
Internal Supports/Vibration Isolation	5 sets @ $70K ea			$210,000	$140,000
Beam Tubes, 24" diameter	300 ft @ $300/ft	$90,000			
Pumps and Gauges			$78,000		
Tanks & Supports, 18" diameter	4 @ $15K ea				$60,000
Laser Tubes	4 @ $22K ea	$22,000	$22,000	$22,000	$22,000
c. Upgrades to the 5 meter facility:					
Ar+ Laser		$84,000			
Laser Cooling		$13,000			
d. Optics, mirrors, test masses:					
Mirror Substrates, Superpolished, 1.5" diameter	60 @ $300 ea	$4,500	$4,500	$4,500	$4,500
Mirror Substrates, Superpolished, 4" diameter	50 @ $4.3K ea	$53,750	$53,750	$53,750	$53,750
Mirrors/Test Masses, 8" diameter	20 @ $18K ea	$90,000	$90,000	$90,000	$90,000
Mirror Coating Runs	48 @ $4.5K ea	$54,000	$54,000	$54,000	$54,000
Small Optical Components	200 @ $500 ea	$25,000	$25,000	$25,000	$25,000
Wave Front Mapper					$65,000
2. Site 1 Support Equipment	Ref. WBS 2500			$4,124,200	
3. Site 2 Support Equipment	Ref. WBS 3500				$3,725,500
4. Initial Interferometers	Ref. WBS 2600 & 3600		$1,000,000	$1,000,000	$5,506,900
Line D Total:		$626,250	$1,537,250	$5,733,450	$9,776,650

LIGO BUDGET EXPLANATION PAGE 3 -- LINE E -- TRAVEL

	1991		1992		1993		1994	
	# trips	Amt	# trips	Amt	# trips	Amt	# trips	Amt
LINE E1 -- DOMESTIC TRAVEL								
1. Trips from L.A. to NSF 2 people, $2,100* ea	4	$16,800	2	$8,400	2	$8,400	2	$8,400
2. Travel between L.A. and Boston 2 people, $1,900* ea	16	$60,800	12	$45,600	12	$45,600	12	$45,600
3. Trips from L.A. to Contractors 4 people, $2,000* ea	10	$80,000	12	$96,000	3	$24,000		
4. Trips from L.A. to Site 1 4 people, $500* ea	7	$14,000	8	$16,000	12	$24,000	22	$44,000
5. Trips from L.A. to Site 2 4 people, $1,800* ea	2	$14,400	3	$21,600	12	$86,400	12	$86,400
6. Trips from L.A. to Scientific Conferences 2 people, $2,000* ea	1	$4,000	1	$4,000	1	$4,000	1	$4,000
Line E1 Total:		$190,000		$191,600		$192,400		$188,400
LINE E2 -- FOREIGN TRAVEL								
1. Trips from L.A. to potential LIGO Collaborators 2 people, $2,100* ea	2	$8,400	2	$8,400	2	$8,400	2	$8,400
2. Trips from L.A. to International Conferences 2 people, $2,100* ea	1	$4,200	1	$4,200	1	$4,200	1	$4,200
Line E2 Total:		$12,600		$12,600		$12,600		$12,600

* Trip base costs are estimated as follows:

Destination	LA/Boston	Chicago	Wash, DC	Site 1	Site 2	Munich
R/T Coach Airfare	$1,180	$1,050	$1,144		$1,144	$1,262
R/T Mileage @ $.20/mi				$100		
Hotel, 5 nites @ $50				$250	$250	
Hotel, 5 nites @ $100	$500	$500	$500			
Per Diem, 5 da @ $28	$140	$140	$140	$140	$140	
Per Diem, 5 da @ $150						$750
Car Rental, 5 da @ $40		$200	$200		$200	
Ground Trans, misc. exp.	$80	$110	$116	$10	$66	$88
Total 1-man trip:	$1,900	$2,000	$2,100	$500	$1,800	$2,100

LIGO BUDGET EXPLANATION PAGE 4 -- LINE G -- OTHER DIRECT COSTS

	1991	1992	1993	1994
LINE G1 -- MATERIALS AND SERVICES				
1. Office Supplies	$36,500	$36,500	$36,500	$36,500
2. Graphic Arts - copying, illustration and engineering reproduction services	$34,500	$34,500	$34,500	$34,500
3. Telephone & Postage	$37,300	$37,300	$37,300	$37,300
4. Computer Supplies - tapes, printer toner and paper, etc.	$41,500	$41,500	$41,500	$41,500
5. Equipment Maintenance - computer, copy and FAX machine maintenance; lab equipment maintenance	$40,900	$40,900	$40,900	$40,900
6. Miscellaneous Lab Supplies - electronic components, liquid nitrogen, shop materials, etc.	$38,600	$38,600	$38,600	$38,600
7. Small Equipment Purchases - (under $500) electronic and mechanical components, mirror mounts, etc.	$50,800	$50,800	$50,800	$50,800
8. Machine Shop Services - (@ $35/hr)	$40,400	$40,400	$40,400	$40,400
Line G1 Total:	$320,500	$320,500	$320,500	$320,500
LINE G2 -- PUBLICATIONS				
1. Page Charges - 100 pages @ $40/page	$4,000	$4,000	$4,000	$4,000
2. Reprints (100 copies) - 100 pages @ $17/page	$1,700	$1,700	$1,700	$1,700
Line G2 Total:	$5,700	$5,700	$5,700	$5,700

LIGO BUDGET EXPLANATION PAGE 5 -- LINE G -- OTHER DIRECT COSTS (CONTINUED)

	Note	1991	1992	1993	1994	TOTAL
LINE G5 -- SUBCONTRACTS						
1. MIT	(1)					
2. Facilities A&E Design, Construction Supervision & Inspection Subcontract	(2)	$2,366,200	$716,700	$613,900	$265,200	$3,962,000
3. Facilities Construction Subcontract	(2)	$6,279,800	$17,916,800	$15,377,100	$6,629,500	$46,203,200
4. Vacuum Equipment Subcontract	(2)	$4,877,100	$13,243,300	$10,703,100	$12,332,700	$41,156,200
5. Beam Tubes Subcontract	(2)	$20,453,400	$5,303,500	$5,303,500		$31,060,400
Line G5 Total:		$33,976,500	$37,180,300	$31,997,600	$19,227,400	$122,381,800

Note (1): All MIT costs are integrated with Caltech costs for the purpose of preparing this budget. A separate subcontract will be negotiated with MIT for effort associated with this proposal following authorization by the NSF.

Note (2): Detail for each Subcontract identified as Items 2-5 is contained in budget explanation pages 6-9, respectively.

LIGO BUDGET EXPLANATION PAGE 6 -- LINE G -- OTHER DIRECT COSTS (CONTINUED)

	WBS(1)	1991	1992	1993	1994	TOTAL
LINE G5 -- SUBCONTRACTS						
Facilities A&E Design,	1110	$401,900				
Construction Supervision	1120	$251,200				
& Inspection Subcontract:	1210	$349,400				
	1220		$218,400			
	1310	$965,900				
	1320		$498,300			
	1330			$348,700		
	1410	$397,800				
	1420			$265,200		
	1430				$265,200	
		$2,366,200	$716,700	$613,900	$265,200	$3,962,000

Note (1): Detail for each Work Breakdown Structure (WBS) element is contained in Appendix C.

LIGO BUDGET EXPLANATION PAGE 7 -- LINE G -- OTHER DIRECT COSTS (CONTINUED)

	WBS(1)	1991	1992	1993	1994	TOTAL
LINE G5 -- SUBCONTRACTS						
Facilities Construction Subcontract:	2100	$6,279,800				
	2210		$8,816,400			
	2220		$910,200			
	2230		$910,200			
	2240		$910,200			
	2250		$910,200			
	2260			$6,629,500		
	3100		$5,459,600			
	3210			$6,897,400		
	3220			$910,200		
	3230			$14,900		
	3240			$910,200		
	3250			$14,900		
	3260				$6,629,500	
		$6,279,800	$17,916,800	$15,377,100	$6,629,500	$46,203,200

Note (1): Detail for each Work Breakdown Structure (WBS) element is contained in Appendix C.

LIGO BUDGET EXPLANATION PAGE 8 -- LINE G -- OTHER DIRECT COSTS (CONTINUED)

	WBS(1)	1991	1992	1993	1994	TOTAL
LINE G5 -- SUBCONTRACTS						
Vacuum Equipment Subcontract:	1500	$1,339,500				
	1610	$3,537,600				
	1620(2)		$749,600	$605,800		
	1630				$698,100	
	2300(2)		$12,493,700	$10,097,300		
	3300				$11,634,600	
		$4,877,100	$13,243,300	$10,703,100	$12,332,700	$41,156,200

Note (1): Detail for each Work Breakdown Structure (WBS) element is contained in Appendix C.
Note (2): Vacuum equipment costs contained in WBS 1620 and 2300 are distributed between 1992 and 1993.

LIGO BUDGET EXPLANATION PAGE 9-- LINE G -- OTHER DIRECT COSTS (CONTINUED)

	WBS(1)	1991	1992	1993	1994	TOTAL
LINE G5 -- SUBCONTRACTS						
Beam Tubes Subcontract:	1710	$769,700				
	1720	$574,100				
	1730	$1,415,600				
	1740		$392,800			
	1750			$392,800		
	2410	$8,847,000				
	2420		$4,910,700			
	3410	$8,847,000				
	3420			$4,910,700		
		$20,453,400	$5,303,500	$5,303,500	$0	$31,060,400

Note (1): Detail for each Work Breakdown Structure (WBS) element is contained in Appendix C.

LIGO BUDGET EXPLANATION PAGE 10 -- LINE G -- OTHER DIRECT COSTS (CONTINUED)

LINE G6 -- OTHER DIRECT COSTS

	Rate	Base	1991	1992	1993	1994
JPL Support Work Order:						
Direct Labor Cost		2 FTEs	$145,500	$145,500	$145,500	$145,500
Paid Leave	17.0%	of Direct Labor	$24,735	$24,735	$24,735	$24,735
Staff Benefits	19.5%	of Direct Labor & Paid Leave	$33,196	$33,196	$33,196	$33,196
Labor Subtotal			$203,431	$203,431	$203,431	$203,431
Laboratory Burden	12.9%	of Labor Subtotal	$26,243	$26,243	$26,243	$26,243
Section Staff Burden	11.0%	of Labor Subtotal	$22,377	$22,377	$22,377	$22,377
Total Direct Cost			$252,051	$252,051	$252,051	$252,051
Support Burden	6.8%	of Total Direct Cost	$17,139	$17,139	$17,139	$17,139
General Burden	4.0%	of T.D.C. & Support Burden	$10,768	$10,768	$10,768	$10,768
Total, JPL Support:			$279,958	$279,958	$279,958	$279,958
Contingency:	20.0%	of Total Estimated Design & Construction Costs (see text, Table VII-3)	$7,500,000	$8,200,000	$8,000,000	$6,300,000
Line G6 Total, R&D and LIGO Design & Construction:			$7,779,958	$8,479,958	$8,279,958	$6,579,958
Remote Site Operations:						
Plant Maintenance (including computer instrumentation, vacuum system, buildings and lasers)						$603,200
Electrical Power						$700,800
Line G6 Total, Remote Site Operations:						$1,304,000

Current and Pending Support for Research and Education in Science and Engineering

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of the proposal.

I. **Name of Investigator** R. W. P. DREVER	Source of Support	Project Title	Award Amount (or Annual Rate)	Period Covered by Award	Person-Months or % of Effort Committed to the Project			Location of Research
					ACAD.	SUMM.	CAL. YR.	
A. *Current Support* List—if none, report none	NSF	CALTECH/MIT LIGO (Note 1)	3,954,564	12/1/88- 11/30/89			80%	CALTECH/MIT
B. *Proposals Pending* 1. List this proposal	NSF	CALTECH/MIT LIGO (Note 2)	193,918,509	12/1/90- 11/30/94			80%	CALTECH/MIT
2. Other pending proposals, including renewal applications. If none, report none.	NSF	CALTECH/MIT LIGO (Note 1)	3,999,994	12/1/89- 11/30/90			80%	CALTECH/MIT
3. Proposals planned to be submitted in near future. If none, report none.	NONE							
II. **Name of co-principal investigator and/or faculty associate** A. ____________ B. ____________								
III. **Transfer of Support** If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.								
IV. **Other agencies to which this proposal has been/will be submitted**								

USE ADDITIONAL SHEETS AS NECESSARY

Note 1: "Continued Prototype Research and Development and Planning for the Caltech/MIT Laser Gravitational Wave Detector (Physics)"

Note 2: "The Construction, Operation, and Supporting Research and Development of a Laser Interferometer Gravitational-Wave Observatory"

NSF FORM 1239 (1-87)

Current and Pending Support for Research and Education in Science and Engineering

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of the proposal.

I. **Name of Investigator** F. J. RAAB	Source of Support	Project Title	Award Amount (or Annual Rate)	Period Covered by Award	Person-Months or % of Effort Committed to the Project			Location of Research
					ACAD.	SUMM.	CAL. YR.	
A. *Current Support* List—if none, report none	NSF	CALTECH/MIT LIGO (Note 1)	3,954,564	12/1/88- 11/30/89			70%	CALTECH/MIT
B. *Proposals Pending* 1. List this proposal	NSF	CALTECH/MIT LIGO (Note 2)	193,918,509	12/1/90- 11/30/94			70%	CALTECH/MIT
2. Other pending proposals, including renewal applications. If none, report none.	NSF	CALTECH/MIT LIGO (Note 1)	3,999,994	12/1/89- 11/30/90			70%	CALTECH/MIT
3. Proposals planned to be submitted in near future. If none, report none.	NONE							
II. **Name of co-principal investigator and/or faculty associate** A. ______ B. ______								
III. **Transfer of Support** If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.								
IV. **Other agencies to which this proposal has been/will be submitted**								

USE ADDITIONAL SHEETS AS NECESSARY

Note 1: "Continued Prototype Research and Development and Planning for the Caltech/MIT Laser Gravitational Wave Detector (Physics)"

Note 2: "The Construction, Operation, and Supporting Research and Development of a Laser Interferometer Gravitational-Wave Observatory"

NSF FORM 1239 (1-87)

Current and Pending Support for Research and Education in Science and Engineering

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of the proposal.

I. **Name of Investigator** K. S. THORNE	Source of Support	Project Title	Award Amount (or Annual Rate)	Period Covered by Award	Person-Months or % of Effort Committed to the Project			Location of Research
					ACAD.	SUMM.	CAL. YR.	
A. *Current Support* List—if none, report none	SEE ATTACHED							
B. *Proposals Pending* 1. List this proposal	SEE ATTACHED							
2. Other pending proposals, including renewal applications. If none, report none.								
3. Proposals planned to be submitted in near future. If none, report none.								
II. **Name of co-principal investigator and/or faculty associate** A. ______ B. ______								
III. **Transfer of Support** If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.								
IV. **Other agencies to which this proposal has been/will be submitted**								

USE ADDITIONAL SHEETS AS NECESSARY

NSF FORM 1239 (1-87)

CURRENT AND PENDING SUPPORT FOR RESEARCH AND EDUCATION IN SCIENCE AND ENGINEERING

Name of Investigator: Kip S. Thorne

Source of Support	Project Title	Award Amount	Period	Calendar Year % of Effort	Location of Research
Current:					
NSF	Relativistic Astrophysics	$215,200	2/15/89 2/14/90	50	Caltech
NASA	Investigations of Stellar Oscillations	$224,000	2/1/88 1/31/90	7*	Caltech
NASA	Theoretical Studies of Active Galactic Nuclei	$420,493	1/1/88 12/31/89	8*	Caltech & other institutions
NSF	Continued Prototype Research & Development & Planning for the Caltech/MIT Laser Gravitational Wave Detector (Physics)	$3,954,564	12/1/88 11/30/89	15**	Caltech & MIT
Pending:					
NASA	Investigations of Stellar Oscillations	$114,000	2/1/90 1//31/91	7*	Caltech
NASA	Theoretical Studies of Active Galactic Nuclei	$226,119	1/1/90 12/31/90	8*	Caltech & other institutions
NSF	Relativistic Astrophysics	$160,000	11/1/90 10/31/91	50	Caltech
NSF	Continued Prototype Research & Development & Planning for the Caltech/MIT Laser Gravitational Wave Detector (Physics)	$3,999,994	12/1/89 11/30/90	15**	Caltech & MIT
NSF	The Construction, Operation, and Supporting Research and Development of a Laser Interferometer Gravitational-Wave Observatory	$193,918,509	12/1/90 11/30/94	15**	Caltech & MIT

*Thorne receives no salary from these grants (current or pending). The 7% and 8% included in 50% shown for Thorne's current and pending grants.

**15% included in 50% shown for Thorne's current NSF grant; 15% included in Thorne's 50% shown for pending NSF grant. Thorne receives no salary from this grant.

Current and Pending Support for Research and Education in Science and Engineering

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of the proposal.

I. **Name of Principal Investigator** R. E. VOGT	Source of Support	Project Title	Award Amount (or Annual Rate)	Period Covered by Award	Person-Months or % of Effort Committed to the Project			Location of Research
					ACAD.	SUMM.	CAL. YR.	
A. *Current Support* List—if none, report none	NSF	CALTECH/MIT LIGO (Note 1)	3,954,564	12/1/88– 11/30/89			100%	CALTECH/MIT
B. *Proposals Pending* 1. List this proposal	NSF	CALTECH/MIT LIGO (Note 2)	193,918,509	12/1/90– 11/30/94			100%	CALTECH/MIT
2. Other pending proposals, including renewal applications. If none, report none.	NSF	CALTECH/MIT LIGO (Note 1)	3,999,994	12/1/89– 11/30/90			100%	CALTECH/MIT
3. Proposals planned to be submitted in near future. If none, report none.	NONE							
II. **Name of co-principal investigator and/or faculty associate** A. ________ B. ________								
III. **Transfer of Support** If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.								
IV. **Other agencies to which this proposal has been/will be submitted**								

USE ADDITIONAL SHEETS AS NECESSARY

NSF FORM 1239 (1-87)

Note 1: "Continued Prototype Research and Development and Planning for the Caltech/MIT Laser Gravitational Wave Detector (Physics)"

Note 2: "The Construction, Operation, and Supporting Research and Development of a Laser Interferometer Gravitational-Wave Observatory"

Current and Pending Support for Research and Education in Science and Engineering

The following information should be provided for each investigator and other senior personnel. ***Failure to provide this information may delay consideration of the proposal.***

I. **Name of Investigator** R. WEISS	Source of Support	Project Title	Award Amount (or Annual Rate)	Period Covered by Award	Person-Months or % of Effort Committed to the Project			Location of Research
					ACAD.	SUMM.	CAL. YR.	
A. *Current Support* List—if none, report none	1. NSF	CALTECH/MIT LIGO (Note 1)	3,954,564	12/1/88-11/30/89			65%	CALTECH/MIT
	2. NASA	COBE SATELLITE MISSION	1,516,771	8/83-11/89			15%	GODDARD/MIT
B. *Proposals Pending* 1. List this proposal	NSF	CALTECH/MIT LIGO (Note 2)	193,918,509	12/1/90-11/30/94			65%	CALTECH/MIT
2. Other pending proposals, including renewal applications. If none, report none.	1. NSF	CALTECH/MIT LIGO (Note 1)	3,999,994	12/1/89-11/30/90			65%	CALTECH/MIT
	2. NASA	COBE SATELLITE MISSION	350,000	1/90-12/91			15%	GODDARD/MIT
3. Proposals planned to be submitted in near future. If none, report none.	NONE							
II. **Name of co-principal investigator and/or faculty associate** A. __________ B. __________								
III. **Transfer of Support** If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.								
IV. **Other agencies to which this proposal has been/will be submitted**								

USE ADDITIONAL SHEETS AS NECESSARY

NSF FORM 1239 (1-87)

Note 1: "Continued Prototype Research and Development and Planning for the Caltech/MIT Laser Gravitational Wave Detector (Physics)"

Note 2: "The Construction, Operation, and Supporting Research and Development of a Laser Interferometer Gravitational-Wave Observatory"

APPENDICES

of these beam crossings, refer to Figure II–2 in Section II.D; note that beams for pairs of test masses (e.g., 1-2, 3-4, 5-6) are at different heights. Test-mass pairs at the same height belong to full-length and half-length interferometers of the same detector. The height differences are sufficient to allow a vacuum wall to isolate the vacuum envelopes where the beams of different detectors intersect. The intersections shown in Figures A–1 and A–2 are actually small modules composed of intersecting tubes with an interior wall in the horizontal plane. Where interferometer beams cross at the same height, there can be no internal vacuum wall; thus the vacuum envelopes corresponding to pairs of interferometers of the same detector are connected. This arrangement satisfies the requirement of permitting service access to one detector without disturbing another detector.

The cost of expansion from the proposed Phase-A LIGO to a Phase-B configuration, using current estimates, is about $40M (FY89 dollars). This includes the manufacture, installation, and testing of the vacuum equipment (Site 1: eight Type 1 test-mass chambers plus two diagonal chambers with associated HAM chambers; Site 2: four Type 1 test mass chambers plus a diagonal chamber with associated HAM chambers) and the components and equipment for three additional interferometers. It does not include the cost of LIGO-team work force, expenses or travel associated with the planning and supervision of the expansion or the development, installation, or testing of the interferometers.

Expansion from a Phase-B configuration to a Phase-C configuration would cost a similar amount ($40M).

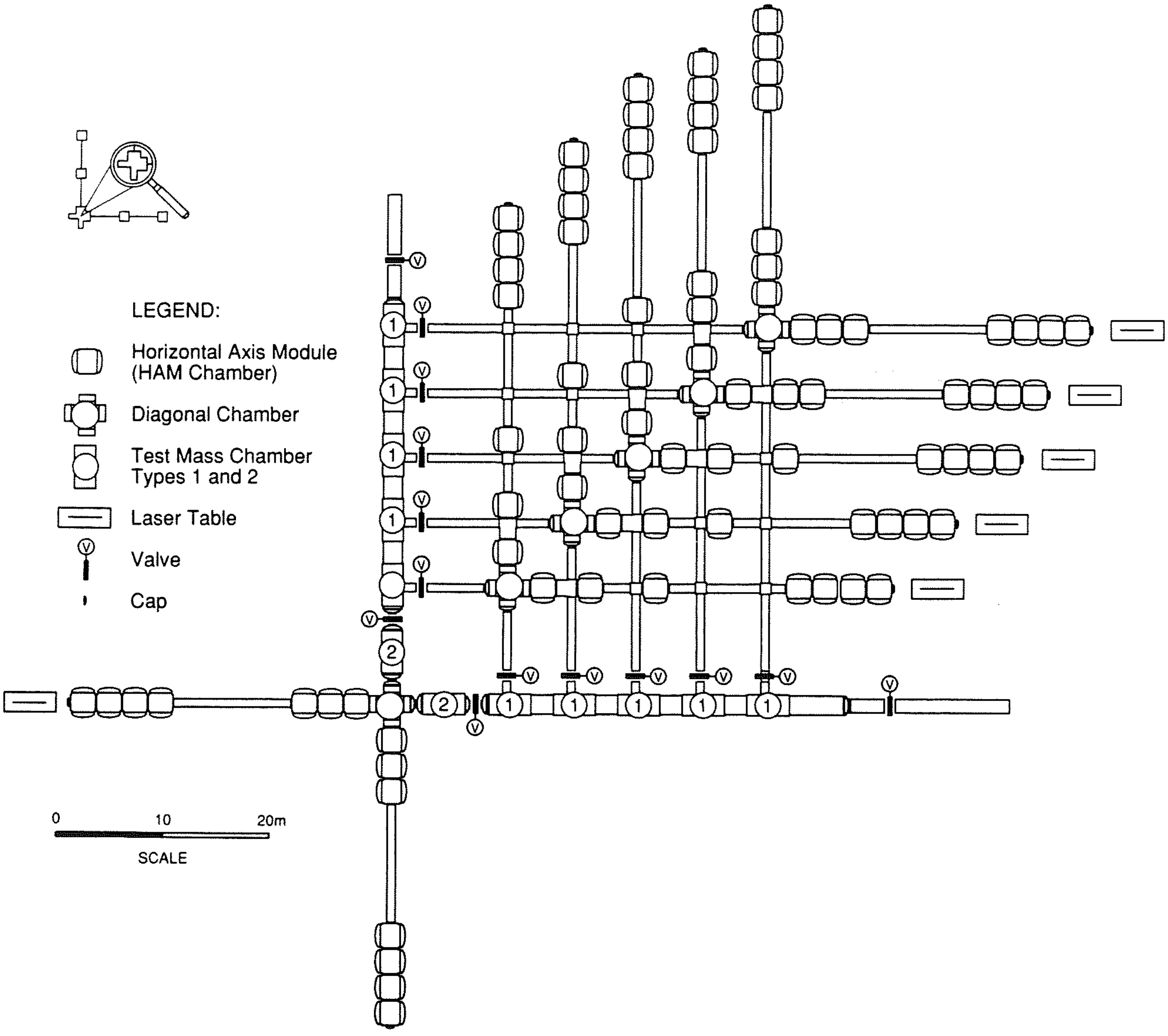

Figure A–1 Layout of corner-station vacuum chambers for Site 1, Phase C, to accommodate six independently operating interferometers. The configuration is an extension of the basic layout described in Figure IV–C–6 and shows how the modular chamber concept of the initial phase A design allows for the expansion of the facility's capabilities. New components, not needed in the initial phase, are the beam-crossing modules placed between the HAM chambers. The phase B configuration would include the chamber complexes for four interferometers.

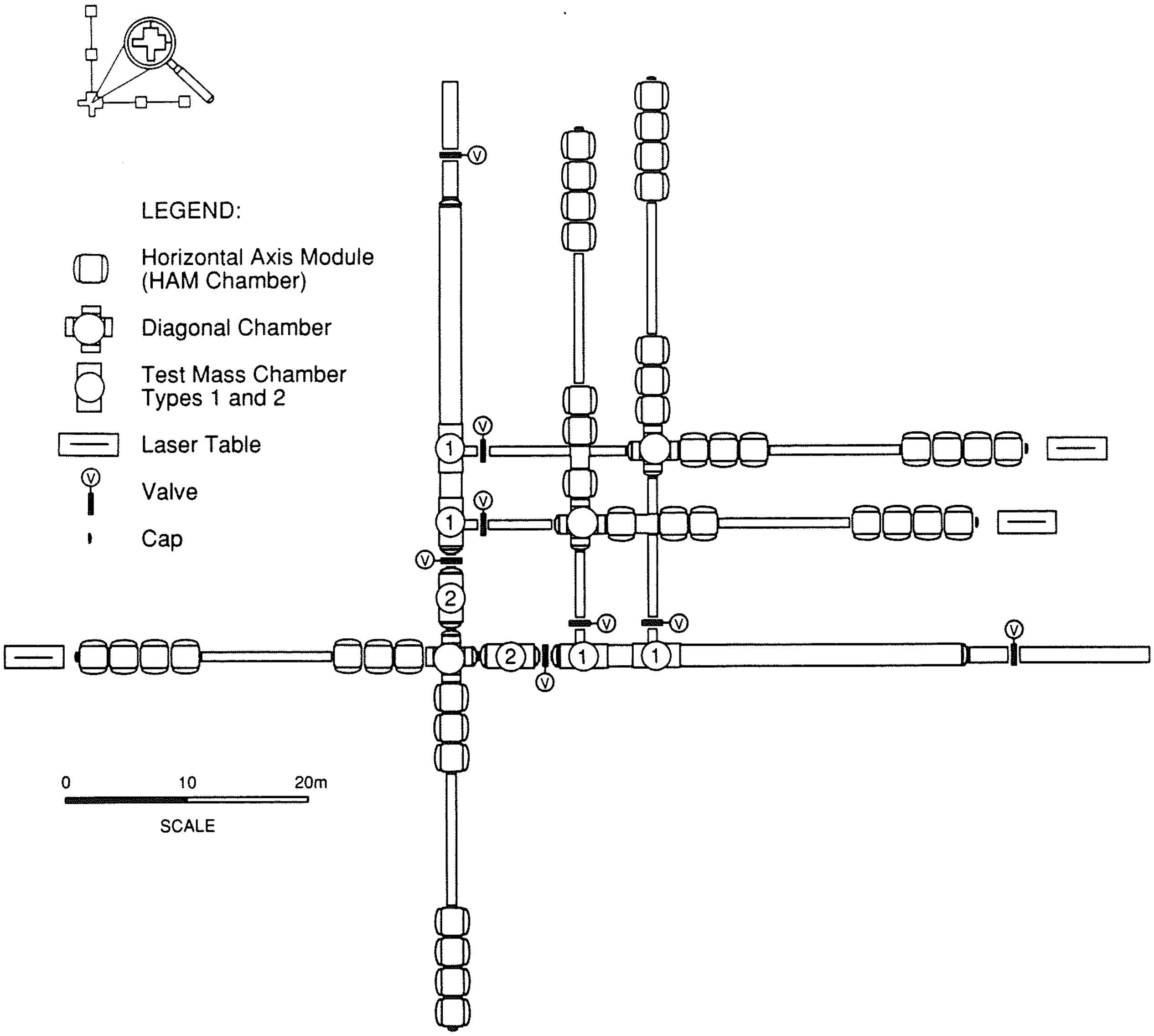

Figure A–2 Layout of corner-station vacuum chambers for Site 2, Phase C, to accomodate three independently operating interferometers. The Phase-B configuration would include the chamber complexes for two interferometers.

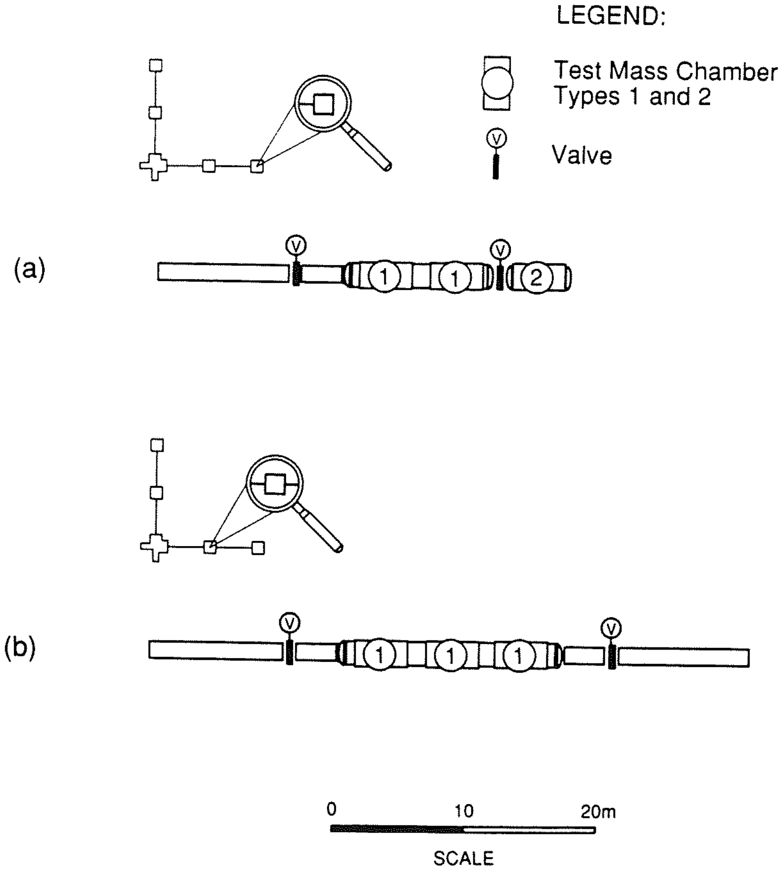

Figure A–3 Phase-C vacuum system layout in (a) the end stations (Site 1 and Site 2) and (b) the mid stations (Site 1 only). Two Type 1 test-mass chambers are added to each station in the positions reserved during the Phase-A construction (see Figure IV–C–15). The Phase-B configuration would include only one additional Type 1 test-mass chamber in each station.

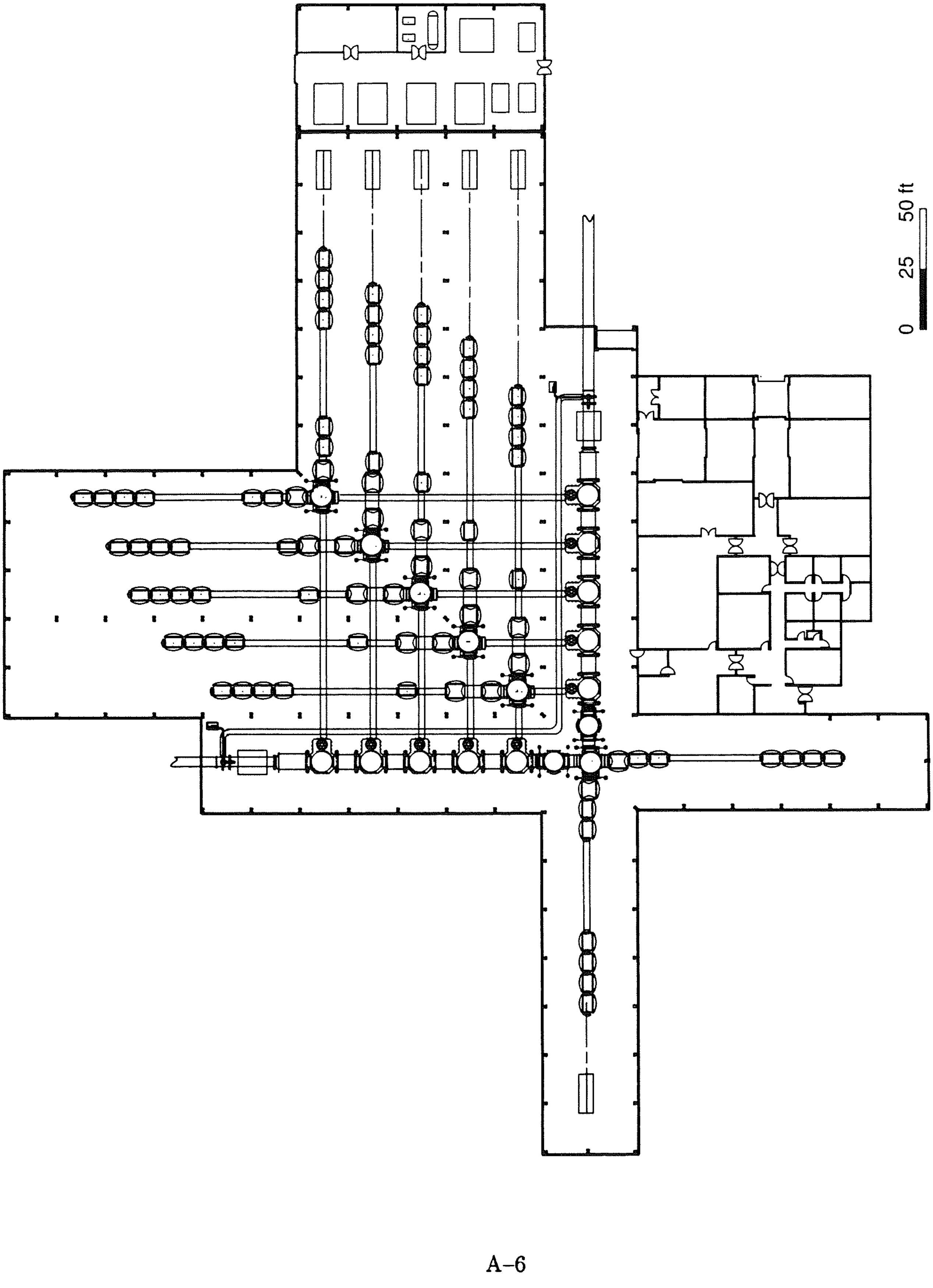

Figure A–4 Floor plan for the Site 1 corner station in Phase C.

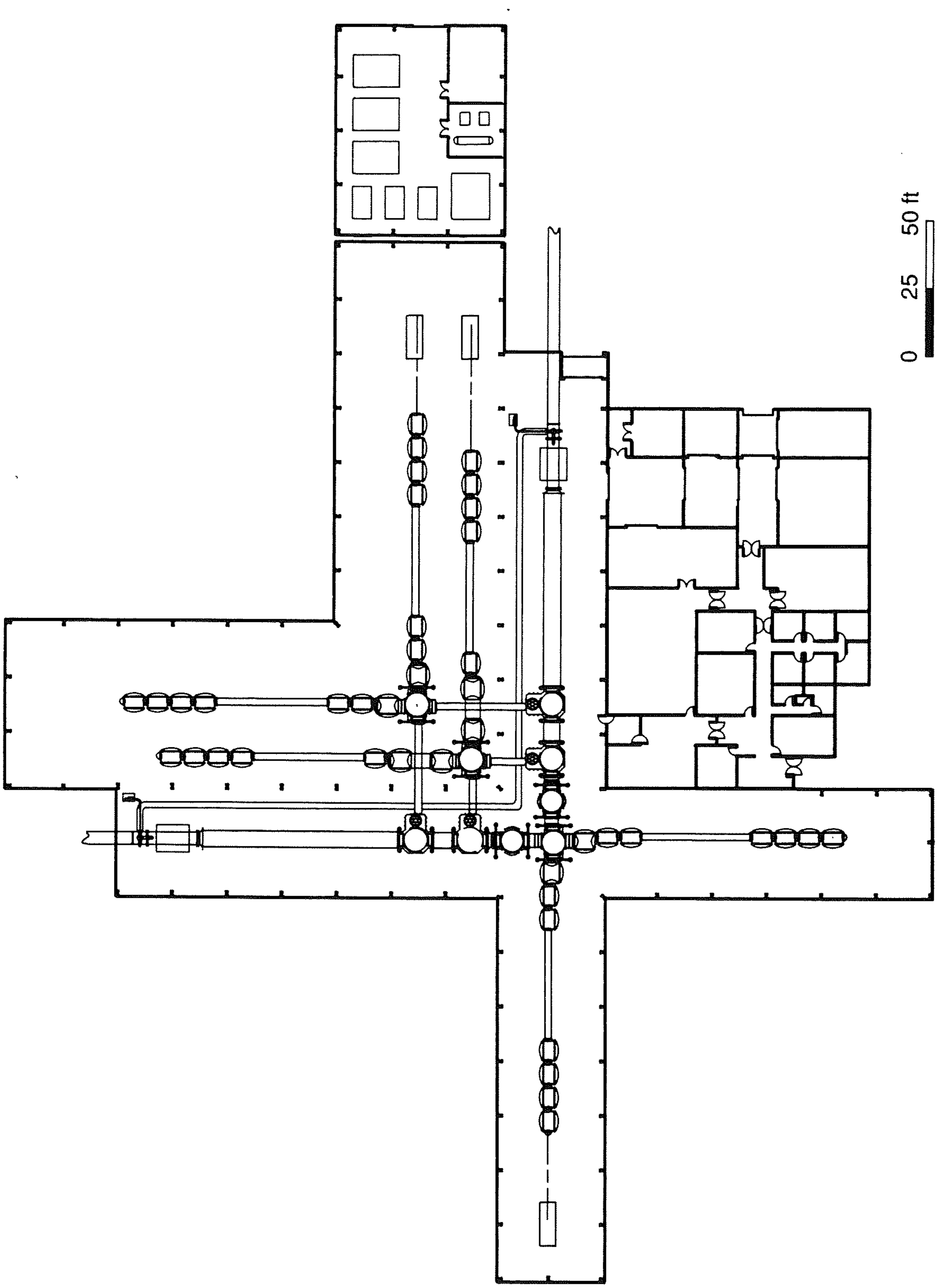

Figure A–5 Floor plan for the Site 2 corner station in Phase C.

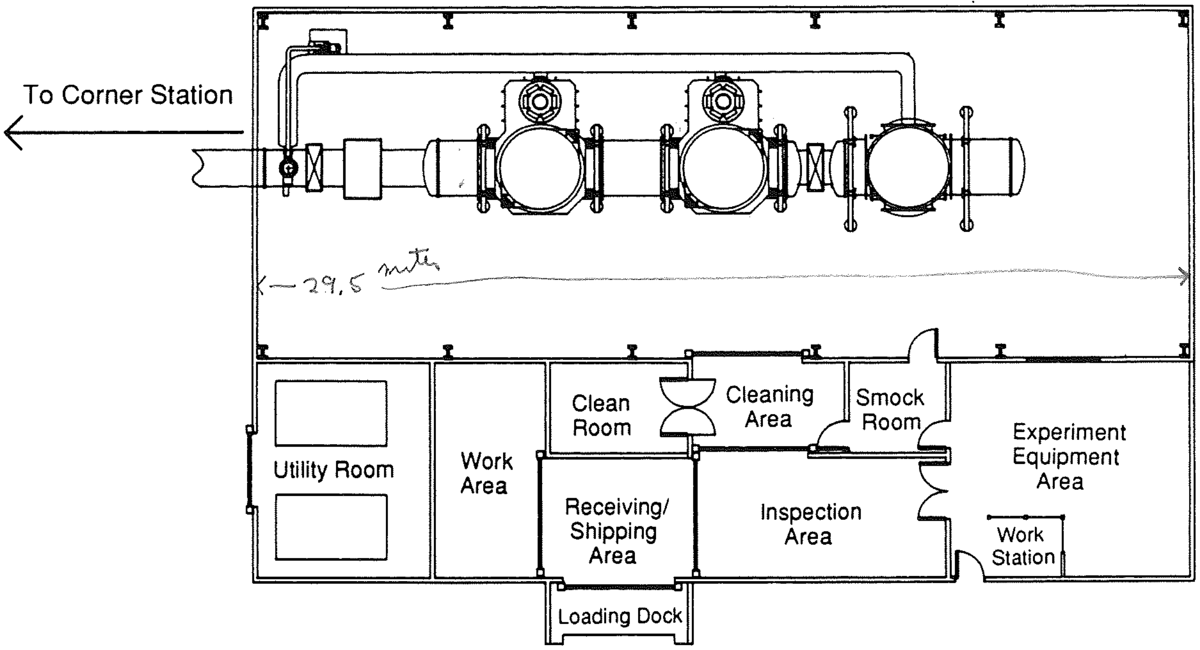

Figure A–6 Floor plan of the right-arm end stations for Phase C (common to both sites). The left-arm end stations have similar (mirror-imaged) floor plans.

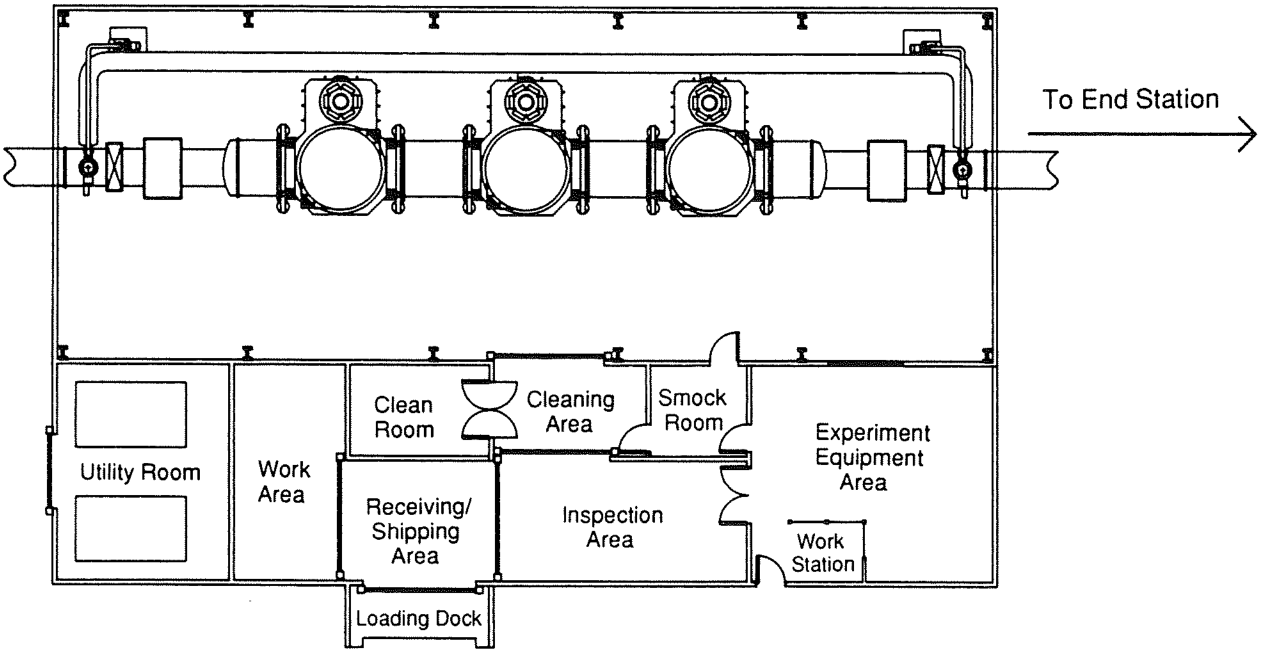

Figure A–7 Floor plan of the right-arm mid station at Site 1, Phase C.

APPENDIX B

POST-CONSTRUCTION OPERATIONS COST

We present an estimate of the costs of maintaining and operating the LIGO facilities. These activities are subsequent to design and construction and are beyond the scope of this proposal. Table B–1 illustrates our best guesses for manpower requirements and cost of steady-state (e.g., Phase B) LIGO operations.

TABLE B–1
OPERATIONS PHASE
LEVEL OF EFFORT AND ANNUAL COSTS
FY89 $M

	On-campus R&D, Operations Management, Data Analysis	**Remote Site Operations[1] (Site 1)**	**Remote Site Operations[1] (Site 2)**
Manpower:			
Faculty (number involved)	6		
Staff Scientists/Postdoctoral Associates (FTEs[2])	16	1	1
Engineers/Programmers (FTEs)	8	1	1
Technicians (FTEs)	8	9	9
Administrative/Clerical (FTEs)	5	1	1
Graduate Research Assistants (number)	12		
Undergraduate Research Ass't (number)	12		
Costs (FY89 $M):			
Salaries and benefits	2.7	0.6	0.6
Supplies, expenses, travel	0.4		
Plant maintenance		0.6	0.5
Electrical power		0.7	0.6
Equipment	1.0		
Overhead	1.9	0.1	0.1
TOTAL COST PER YEAR (FY89 $M)	6.0	2.0	1.8

[1] On-site permanent staff, plant maintenance and electrical power costs.
[2] Full-time equivalents (each represents 12 man-months).

Anticipated staffing requirements are discussed in Volume 1, Section VI. Stated briefly, the on-campus (Caltech and MIT) staff will: (1) pursue continuing research and development of advanced interferometer technologies; (2) develop, fabricate, install and test improvements to the LIGO remote site facilities and interferometers; (3) develop and install new interferometers; (4) provide planning and oversight of the operations of the remote sites; and (5) conduct gravitational-wave observations, interpretation, and data analysis. Personnel at the two remote sites will be responsible for direct operation and maintenance of the facilities, and will provide technical assistance to visiting scientific and engineering staff. The cost of operations at the reduced-capability Site 2 is expected to be slightly lower than that at Site 1. The total operating cost of the LIGO is estimated to be about $9.8M per year, in 1989 dollars.

This sum does not include capital costs for new interferometers. From time to time, installation of complete new interferometers is expected which are optimized for different scientific objectives, or which employ different principles from the existing interferometers. Based on estimates for the initial interferometers, each new interferometer would cost about $2.5M; a complete triple-coincidence detector would cost about $7.5M.

APPENDIX C

DESIGN AND CONSTRUCTION COST DETAIL

This appendix presents the estimated design and construction costs for the LIGO and the basis for individual cost items, organized according to the work-breakdown structure (WBS) discussed in Section VI (see Figure C–1). Note that WBS elements 1800, 1900, and 4000 are not analyzed here; these represent on-campus expenditures accounted for in Section VII, Table VII–3, line 1.

The cost presentation is organized into three parts. Part I presents a *Summary* of the Level 1 WBS elements, and Part II presents the *Supporting Detail.* In Part II, an entry in the column labeled "BOE" (Basis Of Estimate) provides a code letter that defines the estimating method or a page reference to Part III, *Unit Cost Detail,* which provides further breakdown and source information.

The BOE codes are defined as follows:

"A" = **Building and construction tables.** Building and construction cost estimates have been extracted from two sources: *Building Construction Cost Data,* 1989 [C–1], and *National Construction Estimator,* [C–2]. Where ranges are provided by the source, a judgment has been applied, accounting for known factors which may bias the relative cost. Where no relative weighing factors are known, the arithmetic mean of the range has been used.

"B" = **Published prices.** Prices have been obtained from current catalogs or price lists. Applicable discounts have been incorporated. This is the preferred method of estimating and has been used whenever possible.

"C" = **Vendor quotes.** Several vendors have been asked to provide budgetary estimates, and the average price within the competitive range has been used.

"D" = **In-house analyses.** A detailed study has been performed and a detailed cost-estimating document has been prepared.

"E" = **Engineering estimates.** Where no other means for determining price is available, LIGO engineers with experience in the relevant field have supplied estimates.

Contractor G&A and Fee: All cost estimates reflect direct costs, as delivered to the purchaser of the item or service. Where use of a general contractor is contemplated (WBS 2100–2400, 3100–3400; see Section VI.D), provision for the contractor's general and administrative (G&A) expenses and fee is included and separately stated. A rate of 23.8% is used, as recommended by Reference [C–2].

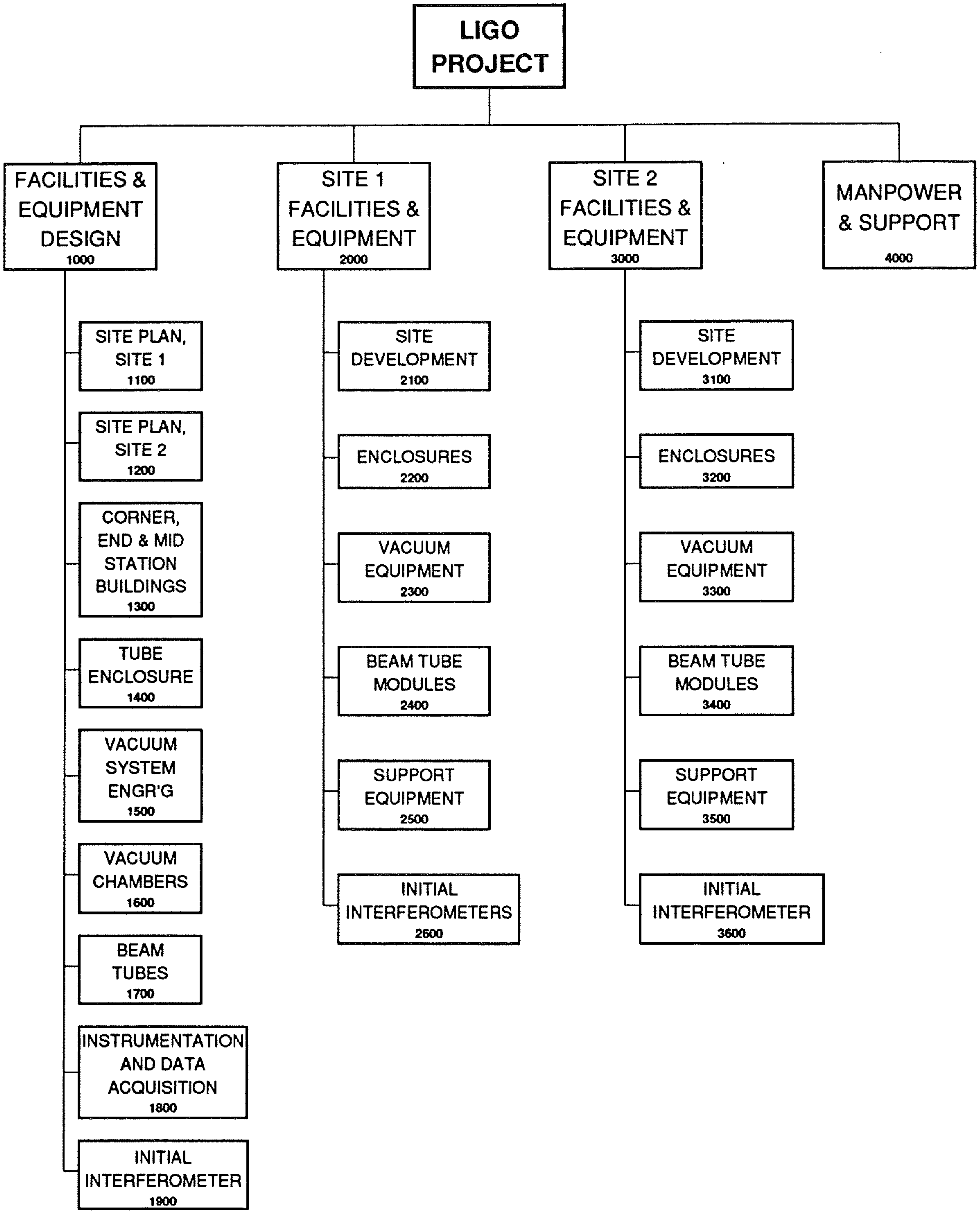
LIGO PROJECT
FACILITIES & EQUIPMENT DESIGN 1000
SITE 1 FACILITIES & EQUIPMENT 2000
SITE 2 FACILITIES & EQUIPMENT 3000
MANPOWER & SUPPORT 4000
SITE PLAN, SITE 1 1100
SITE PLAN, SITE 2 1200
CORNER, END & MID STATION BUILDINGS 1300
TUBE ENCLOSURE 1400
VACUUM SYSTEM ENGR'G 1500
VACUUM CHAMBERS 1600
BEAM TUBES 1700
INSTRUMENTATION AND DATA ACQUISITION 1800
INITIAL INTERFEROMETER 1900
SITE DEVELOPMENT 2100
ENCLOSURES 2200
VACUUM EQUIPMENT 2300
BEAM TUBE MODULES 2400
SUPPORT EQUIPMENT 2500
INITIAL INTERFEROMETERS 2600
SITE DEVELOPMENT 3100
ENCLOSURES 3200
VACUUM EQUIPMENT 3300
BEAM TUBE MODULES 3400
SUPPORT EQUIPMENT 3500
INITIAL INTERFEROMETER 3600

Figure C–1 (facing page) Work-breakdown structure (WBS) for the design and construction of the LIGO facilities and equipment. (The figure is identical to Figure VI–1 in the main text.)

REFERENCES

C–1. *Building and Construction Cost Data, 1989*, 47th Edition, W. D. Mahoney, ed. (R. S. Means Company, Inc.), 1989.

C–2. *1989 National Construction Estimator*, 37th Edition, M. D. Kiley and W. Moselle, eds. (Craftsman Book Company), 1989.

LIGO WORK BREAKDOWN STRUCTURE

PART I
Summary

LIGO WBS 1000 -- FACILITIES AND EQUIPMENT DESIGN -- SUMMARY

			Subtotal (000)	Total Cost (000)
1000		Facilities and Equipment Design, Reports, Supervision, Management & Inspection		$14,437.6
	1100	Site Plan, Site 1	$653.1	
	1200	Site Plan, Site 2	$567.8	
	1300	Corner, End, & Mid Station Buildings	$1,812.9	
	1400	Tube Enclosure	$928.2	
	1500	Vacuum Systems Engineering	$1,339.5	
	1600	Vacuum Chambers and Equipment	$5,591.1	
	1700	Beam Tubes	$3,545.0	

LIGO WBS 2000 -- SITE 1 FACILITIES AND EQUIPMENT -- SUMMARY

			Amount (000)	Subtotal (000)	Total Cost (000)
2000		Site 1 Facilities & Equipment			$70,844.0
	2100	Site Development		$6,279.8	
		2110 Earthwork	$2,811.6		
		2120 Access Road & Parking	$1,188.5		
		2130 Drainage & Erosion Control	$244.6		
		2140 Power	$1,076.2		
		2150 Water & Sewer	$181.5		
		2160 Fence	$222.8		
		2170 Landscaping & Lighting	$39.5		
		2180 Fire Protection	$448.9		
		2190 Dewatering	$66.2		
	2200	Enclosures		$19,086.7	
		2210 Corner Station	$8,816.4		
		2220 Left-Arm End Station	$910.2		
		2230 Left-Arm Mid Station	$910.2		
		2240 Right-Arm End Station	$910.2		
		2250 Right-Arm Mid Station	$910.2		
		2260 Tube Module Enclosures	$6,629.5		
	2300	Vacuum Equipment		$22,591.0	
		2310 Corner Station Equipment	$13,272.2		
		2320 Left-Arm End Station Equipment	$1,685.2		
		2330 Left-Arm Mid Station Equipment	$2,974.2		
		2340 Right-Arm End Station Equipment	$1,685.2		
		2350 Right-Arm Mid Station Equipment	$2,974.2		
	2400	Beam Tube Modules		$13,757.7	
		2410 Factory Fabrication	$8,847.0		
		2420 Field Installation	$4,910.7		
	2500	Support Equipment		$4,124.2	
		2510 Laser Equipment	$414.2		
		2520 Data Acquisition & Recording Equipment	$479.4		
		2530 Instrumentation	$2,264.8		
		2540 Office & Shop Equipment	$524.8		
		2550 Spares	$441.0		
	2600	Initial Interferometers		$5,004.6	
		2610 Optical Components	$1,294.8		
		2620 Mechanical Assemblies	$1,092.6		
		2630 Control Electronics	$2,112.0		
		2640 Data Acquisition Electronics	$505.2		

LIGO WBS 3000 -- SITE 2 FACILITIES AND EQUIPMENT -- SUMMARY

			Amount (000)	Subtotal (000)	Total Cost (000)
3000		Site 2 Facilities & Equipment			$52,456.8
	3100	Site Development		$5,459.6	
		3110 Earthwork	$2,426.5		
		3120 Access Road & Parking	$1,188.5		
		3130 Drainage & Erosion Control	$210.5		
		3140 Power	$983.3		
		3150 Water & Sewer	$91.7		
		3160 Fence	$86.7		
		3170 Landscaping & Lighting	$39.5		
		3180 Fire Protection	$366.7		
		3190 Dewatering	$66.2		
	3200	Enclosures		$15,377.1	
		3210 Corner Station	$6,897.4		
		3220 Left-Arm End Station	$910.2		
		3230 Left-Arm Mid-Point	$14.9		
		3240 Right-Arm End Station	$910.2		
		3250 Right-Arm Mid-Point	$14.9		
		3260 Tube Module Enclosures	$6,629.5		
	3300	Vacuum Equipment		$11,634.6	
		3310 Corner Station Equipment	$7,436.2		
		3320 Left-Arm End Station Equipment	$1,685.2		
		3330 Left-Arm Mid-Point Equipment	$414.0		
		3340 Right-Arm End Station Equipment	$1,685.2		
		3350 Right-Arm Mid-Point Equipment	$414.0		
	3400	Beam Tube Modules		$13,757.7	
		3410 Factory Fabrication	$8,847.0		
		3420 Field Installation	$4,910.7		
	3500	Support Equipment		$3,725.5	
		3510 Laser Equipment	$207.1		
		3520 Data Acquisition & Recording Equipment	$479.4		
		3530 Instrumentation	$2,087.7		
		3540 Office & Shop Equipment	$510.3		
		3550 Spares	$441.0		
	3600	Initial Interferometer		$2,502.3	
		3610 Optical Components	$647.4		
		3620 Mechanical Assemblies	$546.3		
		3630 Control Electronics	$1,056.0		
		3640 Data Acquisition Electronics	$252.6		

PART II
Supporting Detail

LIGO WBS 1000 -- FACILITIES AND EQUIPMENT DESIGN -- SUPPORTING DETAIL

		Amount (000)	Subtotal (000)	BOE
1000	Facilities and Equipment Design, Reports, Supervision, Management & Inspection		$14,437.6	
1100	Site Plan, Site 1		$653.1	D
	1110 A&E Design & Specifications	$401.9		
	1120 Construction Supervision & Quality Control	$251.2		
1200	Site Plan, Site 2		$567.8	D
	1210 A&E Design & Specifications	$349.4		
	1220 Construction Supervision & Quality Control	$218.4		
1300	Corner, End, and Mid Station Buildings		$1,812.9	D
	1310 A&E Design & Specifications	$965.9		
	1320 Construction Supervision & Quality Control, Site 1	$498.3		
	1330 Construction Supervision & Quality Control, Site 2	$348.7		
1400	Tube Enclosure		$928.2	D
	1410 A&E Design & Specifications	$397.8		
	1420 Construction Supervision & Quality Control, Site 1	$265.2		
	1430 Construction Supervision & Quality Control, Site 2	$265.2		
1500	Vacuum Systems Engineering		$1,339.5	D
1600	Vacuum Chambers and Equipment		$5,591.1	D
	1610 Design, Specifications & Procedures	$3,537.6		
	1620 Management, Supervision & Quality Assurance, Site 1	$1,355.4		
	1630 Management, Supervision & Quality Assurance, Site 2	$698.1		
1700	Beam Tubes		$3,545.0	D
	1710 Design, Specifications & Procedures	$769.7		
	1720 Process Engineering	$574.1		
	1730 Management, Supervision & Quality Assurance, Factory	$1,415.6		
	1740 Management, Supervision, Quality Assurance & Field Assembly, Site 1	$392.8		
	1750 Management, Supervision, Quality Assurance & Field Assembly, Site 2	$392.8		

LIGO WBS 2100 -- SITE 1 SITE DEVELOPMENT -- SUPPORTING DETAIL

		Method	Unit Cost (000)	Subtotal (000)	BOE
2000	Site 1 Facilities & Equipment				
2100	Site Development			$6,279.8	
2110	Earthwork			$2,811.6	
	2111 Cut	220,000 cu yd @ $4/cu yd	$880.0		A
	2112 Fill	175,000 cu yd @ $4/cu yd	$700.0		A
	2113 Site Grading-Beam Tubes		$215.3		C
	2114 Site Grading-Stations		$115.5		C
	2115 Mobilization		$360.3		D
	2116 Contractor Burdens & Fee	23.8% of direct costs	$540.5		A
2120	Access Road & Parking			$1,188.5	
	2121 Construction	80,000 sq yd @ $12/sq yd	$960.0		E
	2122 Contractor Burdens & Fee	23.8% of direct costs	$228.5		A
2130	Drainage & Erosion Control			$244.6	
	2131 Drainage		$57.6		E
	2132 Erosion Control		$140.0		E
	2133 Contractor Burdens & Fee	23.8 % of direct costs	$47.0		A
2140	Power			$1,076.2	
	2141 Transmission to Site		*		
	2142 Substation/Switchgear		$377.7		D
	2143 Distribution Along Arms		$491.6		D
	2144 Contractor Burdens & Fee	23.8% of direct costs	$206.9		A
2150	Water & Sewer			$181.5	
	2151 20 GPM Domestic Type Well		$14.2		A
	2152 Storage Tank		$10.7		A
	2153 Continuous Chlorination System		$1.7		A
	2154 Pipe, 3" PVC	10,000 ft @ $7/ft	$70.0		A
	2155 Corner Station Septic Tank		$15.0		A
	2156 End & Mid Station Septic Tanks	4 @ $8K ea	$32.0		E
	2157 Sewer Pipe, 6" PVC	200 ft @ $15/ft	$3.0		A
	2158 Contractor Burdens & Fee	23.8% of direct costs	$34.9		A
2160	Fence			$222.8	
	2161 Chain Link Fence, 48" high	36,000 ft @ $5/ft	$180.0		A
	2162 Contractor Burdens & Fee	23.8% of direct costs	$42.8		A
2170	Landscaping & Lighting			$39.5	
	2171 Landscaping	5,000 sq ft @ $4/sq ft	$20.0		A
	2172 Lighting	4 area lighting poles @ $2,980 ea	$11.9		A
	2173 Contractor Burdens & Fee	23.8% of direct costs	$7.6		A
2180	Fire Protection			$448.9	
	2181 Pumps & Housing		$50.0		D
	2182 Mains	1,000 ft @ $30/ft	$30.0		D
	2183 Hydrants		$3.0		D
	2184 Water Storage Tank		$50.0		D
	2185 Fire Suppression		$196.0		D
	2186 Fire Detection		$33.6		D
	2187 Contractor Burdens & Fee	23.8% of direct costs	$86.3		A
2190	Dewatering			$66.2	
	2191 First Month		$31.6		A
	2192 Additional Months	1 add'l month	$21.9		A
	2193 Contractor Burdens & Fee	23.8% of direct costs	$12.7		A

*Local electric company allocates power transmission installation costs on their monthly power bills.

LIGO WBS 2210 -- SITE 1 ENCLOSURES, CORNER STATION -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
2000	Site 1 Facilities & Equipment				
2200	Enclosures				
2210	Corner Station			$8,816.4	
2211	Vacuum Chamber Area (60,000 sq ft)			$5,660.3	
	2211.01 Foundation (36" slab)	6666.7 cu yd @ $150/cu yd	$1,000.0		A
	2211.02 Framing	400 ton @ $2,000/ton	$800.0		A
	2211.03 Girts & Purlins	165 ton @ $2,200/ton	$363.0		A
	2211.04 Siding	68,000 sq ft @ $9/sq ft	$612.0		A
	2211.05 Interior Liner	68,000 sq ft @ $3/sq ft	$204.0		A
	2211.06 Roof	63,000 sq ft @ $10/sq ft	$630.0		A
	2211.07 Ceiling	60,000 sq ft @ $5/sq ft	$300.0		A
	2211.08 Flooring	60,000 sq ft @ $5/sq ft	$300.0		A
	2211.09 Access Aids	60,000 sq ft @ $2/sq ft	$120.0		A
	2211.10 Electrical	60,000 sq ft @ $6/sq ft	$360.0		A
	2211.11 Bridge Crane System		$490.0		C
	2211.12 Heating, Ventilating, & Air Conditioning		$361.3		D
	2211.13 Embedded Steel	60,000 sq ft @ $2/sq ft	$120.0		A
2212	Shop & Service Area (13,500 sq ft)			$1,074.8	
	2212.01 Foundation (12" slab)	500 cu yd @ $140/cu yd	$70.0		A
	2212.02 Framing	85 ton @ $2,000/ton	$170.0		A
	2212.03 Girts & Purlins	25 ton @ $2,200/ton	$55.0		A
	2212.04 Siding & Roofing	22,000 sq ft @ $9/sq ft	$198.0		A
	2212.05 Interior Partitions	30,000 sq ft @ $5/sq ft	$150.0		A
	2212.06 Ceiling-Office & Shop	13,500 sq ft @ $4/sq ft	$54.0		A
	2212.07 Flooring	13,500 sq ft @ $2.5/sq ft	$33.8		A
	2212.08 Roll Doors	10 @ $4,600 ea	$46.0		C
	2212.09 Doors & Windows	36 doors; 6 large windows	$14.0		E
	2212.10 Plumbing	13,500 sq ft @ $2.5/sq ft	$33.8		A
	2212.11 Electrical	13,500 sq ft @ $5/sq ft	$67.5		A
	2212.12 Monorail System		$60.0		C
	2212.13 Heating, Ventilating, & Air Conditioning		$100.0		D
	2212.14 Clean Room Air Filtration & Ceiling	324 sq ft @ $70/sq ft	$22.7		A
2213	Utility Room (5,000 sq ft)			$120.8	
	2213.01 Equip. Foundation (8" slab)	123.5 cu yd @ $221/cu yd	$27.3		A
	2213.02 Prefab Building	5,000 sq ft @ $14/sq ft	$70.0		C
	2213.03 Mechanical & Electrical	5,000 sq ft @ $3.7/sq ft	$18.5		A
	2213.04 Partitions	1,000 sq ft @ $5/sq ft	$5.0		A
2214	Chiller Plant (2,025 sq ft)			$288.8	
	2214.01 Equip. Foundation (6" slab)	65 cu yd @ $221/cu yd	$14.4		A
	2214.02 Block Wall, 16' high	2,880 sq ft @ $5/sq ft	$14.4		A
	2214.03 Equipment: Chillers, Pumps, Tanks, etc.		$260.0		C
2215	Contractor Burdens & Fee	23.8% of direct costs		$1,671.7	A

LIGO WBS 2220 -- SITE 1 ENCLOSURES, LEFT-ARM END STATION -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
2000	Site 1 Facilities & Equipment				
2200	Enclosures				
2220	Left-Arm End Station			$910.2	
2221	Vacuum Chamber Area (4,000 sq ft)			$502.0	
	2221.01 Foundation (24" slab)	296.3 cu yd @ $145/cu yd	$43.0		A
	2221.02 Framing	25 ton @ $2,000/ton	$50.0		A
	2221.03 Girts & Purlins	20 ton @ $2,200/ton	$44.0		A
	2221.04 Siding	13,000 sq ft @ $8/sq ft	$104.0		A
	2221.05 Interior Lining	13,000 sq ft @ $3/sq ft	$39.0		A
	2221.06 Roof	4,000 sq ft @ $10/sq ft	$40.0		A
	2221.07 Ceiling	4,000 sq ft @ $5/sq ft	$20.0		A
	2221.08 Flooring	4,000 sq ft @ $5/sq ft	$20.0		A
	2221.09 Access Aids	4,000 sq ft @ $2/sq ft	$8.0		A
	2221.10 Electrical	4,000 sq ft @ $6/sq ft	$24.0		A
	2221.11 Bridge Crane System		$70.0		C
	2221.12 Heating, Ventilating, & Air Conditioning		$40.0		D
2222	Shop & Service Area (2,000 sq ft)			$189.6	
	2222.01 Foundation (8" slab)	50 cu yd @ $140/cu yd	$7.0		A
	2222.02 Framing	12 ton @ $2,000/ton	$24.0		A
	2222.03 Girts & Purlins	4 ton @ $2,200/ton	$8.8		A
	2222.04 Siding & Roofing	4,600 sq ft @ $8/sq ft	$36.8		A
	2222.05 Interior Partitions	2,000 sq ft @ $3/sq ft	$6.0		A
	2222.06 Ceiling	2,000 sq ft @ $4/sq ft	$8.0		A
	2222.07 Flooring	2,000 sq ft @ $2.5/sq ft	$5.0		A
	2222.08 Roll Doors	5 @ $4,600 ea	$23.0		A
	2222.09 Doors & Windows		$7.0		B
	2222.10 Plumbing	2,000 sq ft @ $2.5/sq ft	$5.0		A
	2222.11 Electrical	2,000 sq ft @ $7/sq ft	$14.0		A
	2222.12 Monorail System		$31.0		C
	2222.13 Heating, Ventilating, & Air Conditioning		$14.0		D
2223	Utility Room (500 sq ft)			$12.2	
	2223.01 Equip. Foundation (8" slab)	15 cu yd @ $221/cu yd	$3.3		A
	2223.02 Prefab Building	500 sq ft @ $14/sq ft	$7.0		C
	2223.03 Mechanical & Electrical	500 sq ft @ $3.7/sq ft	$1.9		A
2224	Chiller Plant (270 sq ft)			$31.4	
	2224.01 Equip. Foundation (8" slab)	8 cu yd @ $221/cu yd	$1.8		A
	2224.02 Block Wall, 16′ high	528 sq ft @ $5/sq ft	$2.6		A
	2224.03 Equipment: Chillers, Pumps, Tanks, etc.		$27.0		C
2225	Contractor Burdens & Fee	23.8% of direct costs		$175.0	A

LIGO WBS 2230 -- SITE 1 ENCLOSURES, LEFT-ARM MID STATION -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
2000	Site 1 Facilities & Equipment				
2200	Enclosures				
2230	Left-Arm Mid Station			$910.2	
2231	Vacuum Chamber Area (4,000 sq ft)			$502.0	
	2231.01 Foundation (24" slab)	296.3 cu yd @ $145/cu yd	$43.0		A
	2231.02 Framing	25 ton @ $2,000/ton	$50.0		A
	2231.03 Girts & Purlins	20 ton @ $2,200/ton	$44.0		A
	2231.04 Siding	13,000 sq ft @ $8/sq ft	$104.0		A
	2231.05 Interior Lining	13,000 sq ft @ $3/sq ft	$39.0		A
	2231.06 Roof	4,000 sq ft @ $10/sq ft	$40.0		A
	2231.07 Ceiling	4,000 sq ft @ $5/sq ft	$20.0		A
	2231.08 Flooring	4,000 sq ft @ $5/sq ft	$20.0		A
	2231.09 Access Aids	4,000 sq ft @ $2/sq ft	$8.0		A
	2231.10 Electrical	4,000 sq ft @ $6/sq ft	$24.0		A
	2231.11 Bridge Crane System		$70.0		C
	2231.12 Heating, Ventilating, & Air Conditioning		$40.0		D
2232	Shop & Service Area (2,000 sq ft)			$189.6	
	2232.01 Foundation (8" slab)	50 cu yd @ $140/cu yd	$7.0		A
	2232.02 Framing	12 ton @ $2,000/ton	$24.0		A
	2232.03 Girts & Purlins	4 ton @ $2,200/ton	$8.8		A
	2232.04 Siding & Roofing	4,600 sq ft @ $8/sq ft	$36.8		A
	2232.05 Interior Partitions	2,000 sq ft @ $3/sq ft	$6.0		A
	2232.06 Ceiling	2,000 sq ft @ $4/sq ft	$8.0		A
	2232.07 Flooring	2,000 sq ft @ $2.5/sq ft	$5.0		A
	2232.08 Roll Doors	5 @ $4,600 ea	$23.0		A
	2232.09 Doors & Windows		$7.0		B
	2232.10 Plumbing	2,000 sq ft @ $2.5/sq ft	$5.0		A
	2232.11 Electrical	2,000 sq ft @ $7/sq ft	$14.0		A
	2232.12 Monorail System		$31.0		C
	2232.13 Heating, Ventilating, & Air Conditioning		$14.0		D
2233	Utility Room (500 sq ft)			$12.2	
	2233.01 Equip. Foundation (8" slab)	15 cu yd @ $221/cu yd	$3.3		A
	2233.02 Prefab Building	500 sq ft @ $14/sq ft	$7.0		C
	2233.03 Mechanical & Electrical	500 sq ft @ $3.7/sq ft	$1.9		A
2234	Chiller Plant (270 sq ft)			$31.4	
	2234.01 Equip. Foundation (8" slab)	8 cu yd @ $221/cu yd	$1.8		A
	2234.02 Block Wall, 16' high	528 sq ft @ $5/sq ft	$2.6		A
	2234.03 Equipment: Chillers, Pumps, Tanks, etc.		$27.0		C
2235	Contractor Burdens & Fee	23.8% of direct costs		$175.0	A

LIGO WBS 2240 -- SITE 1 ENCLOSURES, RIGHT-ARM END STATION -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
2000	Site 1 Facilities & Equipment				
2200	Enclosures				
2240	Right-Arm End Station			$910.2	
2241	Vacuum Chamber Area (4,000 sq ft)			$502.0	
	2241.01 Foundation (24" slab)	296.3 cu yd @ $145/cu yd	$43.0		A
	2241.02 Framing	25 ton @ $2,000/ton	$50.0		A
	2241.03 Girts & Purlins	20 ton @ $2,200/ton	$44.0		A
	2241.04 Siding	13,000 sq ft @ $8/sq ft	$104.0		A
	2241.05 Interior Lining	13,000 sq ft @ $3/sq ft	$39.0		A
	2241.06 Roof	4,000 sq ft @ $10/sq ft	$40.0		A
	2241.07 Ceiling	4,000 sq ft @ $5/sq ft	$20.0		A
	2241.08 Flooring	4,000 sq ft @ $5/sq ft	$20.0		A
	2241.09 Access Aids	4,000 sq ft @ $2/sq ft	$8.0		A
	2241.10 Electrical	4,000 sq ft @ $6/sq ft	$24.0		A
	2241.11 Bridge Crane System		$70.0		C
	2241.12 Heating, Ventilating, & Air Conditioning		$40.0		D
2242	Shop & Service Area (2,000 sq ft)			$189.6	
	2242.01 Foundation (8" slab)	50 cu yd @ $140/cu yd	$7.0		A
	2242.02 Framing	12 ton @ $2,000/ton	$24.0		A
	2242.03 Girts & Purlins	4 ton @ $2,200/ton	$8.8		A
	2242.04 Siding & Roofing	4,600 sq ft @ $8/sq ft	$36.8		A
	2242.05 Interior Partitions	2,000 sq ft @ $3/sq ft	$6.0		A
	2242.06 Ceiling	2,000 sq ft @ $4/sq ft	$8.0		A
	2242.07 Flooring	2,000 sq ft @ $2.5/sq ft	$5.0		A
	2242.08 Roll Doors	5 @ $4,600 ea	$23.0		A
	2242.09 Doors & Windows		$7.0		B
	2242.10 Plumbing	2,000 sq ft @ $2.5/sq ft	$5.0		A
	2242.11 Electrical	2,000 sq ft @ $7/sq ft	$14.0		A
	2242.12 Monorail System		$31.0		C
	2242.13 Heating, Ventilating, & Air Conditioning		$14.0		D
2243	Utility Room (500 sq ft)			$12.2	
	2243.01 Equip. Foundation (8" slab)	15 cu yd @ $221/cu yd	$3.3		A
	2243.02 Prefab Building	500 sq ft @ $14/sq ft	$7.0		C
	2243.03 Mechanical & Electrical	500 sq ft @ $3.7/sq ft	$1.9		A
2244	Chiller Plant (270 sq ft)			$31.4	
	2244.01 Equip. Foundation (8" slab)	8 cu yd @ $221/cu yd	$1.8		A
	2244.02 Block Wall, 16' high	528 sq ft @ $5/sq ft	$2.6		A
	2244.03 Equipment: Chillers, Pumps, Tanks, etc.		$27.0		C
2245	Contractor Burdens & Fee	23.8% of direct costs		$175.0	A

LIGO WBS 2250 -- SITE 1 ENCLOSURES, RIGHT-ARM MID STATION -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
2000	Site 1 Facilities & Equipment				
2200	Enclosures				
2250	Right-Arm Mid Station			$910.2	
2251	Vacuum Chamber Area (4,000 sq ft)			$502.0	
	2251.01 Foundation (24" slab)	296.3 cu yd @ $145/cu yd	$43.0		A
	2251.02 Framing	25 ton @ $2,000/ton	$50.0		A
	2251.03 Girts & Purlins	20 ton @ $2,200/ton	$44.0		A
	2251.04 Siding	13,000 sq ft @ $8/sq ft	$104.0		A
	2251.05 Interior Lining	13,000 sq ft @ $3/sq ft	$39.0		A
	2251.06 Roof	4,000 sq ft @ $10/sq ft	$40.0		A
	2251.07 Ceiling	4,000 sq ft @ $5/sq ft	$20.0		A
	2251.08 Flooring	4,000 sq ft @ $5/sq ft	$20.0		A
	2251.09 Access Aids	4,000 sq ft @ $2/sq ft	$8.0		A
	2251.10 Electrical	4,000 sq ft @ $6/sq ft	$24.0		A
	2251.11 Bridge Crane System		$70.0		C
	2251.12 Heating, Ventilating, & Air Conditioning		$40.0		D
2252	Shop & Service Area (2,000 sq ft)			$189.6	
	2252.01 Foundation (8" slab)	50 cu yd @ $140/cu yd	$7.0		A
	2252.02 Framing	12 ton @ $2,000/ton	$24.0		A
	2252.03 Girts & Purlins	4 ton @ $2,200/ton	$8.8		A
	2252.04 Siding & Roofing	4,600 sq ft @ $8/sq ft	$36.8		A
	2252.05 Interior Partitions	2,000 sq ft @ $3/sq ft	$6.0		A
	2252.06 Ceiling	2,000 sq ft @ $4/sq ft	$8.0		A
	2252.07 Flooring	2,000 sq ft @ $2.5/sq ft	$5.0		A
	2252.08 Roll Doors	5 @ $4,600 ea	$23.0		A
	2252.09 Doors & Windows		$7.0		B
	2252.10 Plumbing	2,000 sq ft @ $2.5/sq ft	$5.0		A
	2252.11 Electrical	2,000 sq ft @ $7/sq ft	$14.0		A
	2252.12 Monorail System		$31.0		C
	2252.13 Heating, Ventilating, & Air Conditioning		$14.0		D
2253	Utility Room (500 sq ft)			$12.2	
	2253.01 Equip. Foundation (8" slab)	15 cu yd @ $221/cu yd	$3.3		A
	2253.02 Prefab Building	500 sq ft @ $14/sq ft	$7.0		C
	2253.03 Mechanical & Electrical	500 sq ft @ $3.7/sq ft	$1.9		A
2254	Chiller Plant (270 sq ft)			$31.4	
	2254.01 Equip. Foundation (8" slab)	8 cu yd @ $221/cu yd	$1.8		A
	2254.02 Block Wall, 16' high	528 sq ft @ $5/sq ft	$2.6		A
	2254.03 Equipment: Chillers, Pumps, Tanks, etc.		$27.0		C
2255	Contractor Burdens & Fee	23.8% of direct costs		$175.0	A

LIGO WBS 2260 -- SITE 1 ENCLOSURES, TUBE MODULE -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
2000	Site 1 Facilities & Equipment				
2200	Enclosures				
2260	Tube Module Enclosures			$6,629.5	
	2261 Slab	25,712 ft @ $75/ft	$1,928.4		A
	2262 Arch Enclosures	25,712 ft @ $130/ft	$3,342.6		A
	2263 Pump Access	28 @ $3K ea	$84.0		C
	2264 Contractor Burdens & Fee	23.8% of direct costs	$1,274.5		E

LIGO WBS 2310 -- SITE 1 VACUUM EQUIPMENT, CORNER STATION -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
2000	Site 1 Facilities & Equipment				
2300	Vacuum Equipment				
2310	Corner Station Equipment			$13,272.2	
2311	Beam Manifolds			$3,830.4	see page C-41
	2311.01 Test Mass Chamber, Type I	2 @ $1,013.1K ea	$2,026.2		
	2311.02 Tube Isolation Valve Assembly	2 @ $117K ea	$234.0		
	2311.03 LN2 Trap, Coaxial (Long)	2 @ $597.1K ea	$1,194.2		
	2311.04 Additional Components		$376.0		
2312	Offset Chamber Assembly			$2,689.3	see pages C-42, C-43
	2312.01 Reserved				
	2312.02 Diagonal Chamber		$533.5		
	2312.03 HAM Chamber	9 @ $188.3K ea	$1,694.7		
	2312.04 Tube, Mode Cleaner	2 @ $45.5K ea	$91.0		
	2312.05 Connector to Test Mass Chamber	2 @ $144.5K ea	$289.0		
	2312.06 Additional Components		$81.1		
2313	Vertex Chamber Assembly			$3,763.2	see page C-44
	2313.01 Test Mass Chamber, Type II	2 @ $483K ea	$966.0		
	2313.02 Diagonal Chamber		$533.5		
	2313.03 HAM Chamber	9 @ $188.3K ea	$1,694.7		
	2313.04 Tube, Mode Cleaner	2 @ $45.5K ea	$91.0		
	2313.05 Connector to 6′ Tube	2 @ $129.9K ea	$259.8		
	2313.06 Additional Components		$218.2		
2314	Roughing Pump System			$397.8	see page C-45
	2314.01 Roughing Pump Set	2 @ $138K ea	$276.0		
	2314.02 Roughing Line		$121.8		
2315	LN2 Supply & Distribution	2 @ $20K ea		$40.0	see page C-45
2316	Contractor Burdens & Fee	23.8% of direct costs		$2,551.5	A

LIGO WBS 2320 -- SITE 1 VACUUM EQUIPMENT, LEFT-ARM END STATION -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
2000	Site 1 Facilities & Equipment				
2300	Vacuum Equipment				
2320	Left-Arm End Station Equipment			$1,685.2	see page C-46
2321	Beam Manifold			$1,181.5	
	2321.01 Reserved				
	2321.02 Test Mass Chamber, Type II		$483.0		
	2321.03 Tube Isolation Valve Assembly		$117.0		
	2321.04 LN2 Trap, Coaxial (Short)		$353.6		
	2321.05 Connector to 6' Tube		$129.9		
	2321.06 Additional Components		$98.0		
2322	Roughing Pump System			$168.5	
	2322.01 Roughing Pump Set		$138.0		
	2322.02 Roughing Pump Line		$30.5		
2323	LN2 Supply & Distribution			$11.2	
	2323.01 Tubing (Jacketed)		$4.4		
	2323.02 Valves (Insulated)		$6.8		
2324	Contractor Burdens & Fee	23.8% of direct costs		$324.0	A

LIGO WBS 2330 -- SITE 1 VACUUM EQUIPMENT, LEFT-ARM MID STATION -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
2000	Site 1 Facilities & Equipment				
2300	Vacuum Equipment				
2330	Left-Arm Mid Station Equipment			$2,974.2	see page C-47
2331	Beam Manifold			$2,056.4	
	2331.01 Test Mass Chamber, Type I		$1,013.1		
	2331.02 Reserved		$0.0		
	2331.03 Tube Isolation Valve Assembly	2 @ $117K ea	$234.0		
	2331.04 LN2 Trap, Coaxial (Short)	2 @ $353.6K ea	$707.2		
	2331.05 Reserved				
	2331.06 Additional Components		$102.1		
2332	Roughing Pump System			$321.0	
	2332.01 Roughing Pump Set	2 @ $138K ea	$276.0		
	2332.02 Roughing Pump Line		$45.0		
2333	LN2 Supply & Distribution			$25.0	
	2333.01 Tubing (Jacketed)		$18.2		
	2333.02 Valves (Insulated)		$6.8		
2334	Contractor Burdens & Fee	23.8% of direct costs		$571.8	A

LIGO WBS 2400 -- SITE 1 BEAM TUBE MODULES -- SUPPORTING DETAIL

		Method	Qty	Unit Cost	Extension (000)	Subtotal (000)	BOE
2000	Site 1 Facilities & Equipment						
2400	Beam Tube Modules					$13,757.7	
2410	Factory Fabrication of Beam Tube Section					$8,847.0	
	2411 Wall Material Costs, T304L/low H2	2,830 lb @ $1.4895/lb	640	$4,215	$2,697.6		C
	2412 Fabricate Cylinder	40 ft @ $63.70/ft	640	$2,548	$1,630.7		C
	2413 Stiffeners	22/section @ $80 ea	640	$1,760	$1,126.4		C
	2414 Expansion Joint	1/section @ $833 ea	640	$833	$533.1		C,E
	2415 Precision Reform Ends	2/section @ $50 ea	640	$100	$64.0		C,E
	2416 Clean, Leak Check & Seal Ends		640	$1,160	$742.4		C
	2417 Transport to Field		640	$550	$352.0		C
	2418 Contractor Burdens & Fee	23.8% of direct costs			$1,700.8		A
2420	Field Installation, Including Related Equipment					$4,910.7	
	2421 Position, Fitup, & Weld Ends		672	$900	$604.8		C,E
	2422 Supports & Baffles		640	$900	$576.0		C,E
	2423 Ion Pumps w/ Accessories		28	$59,600	$1,668.8		C
	2424 Pump Tee: 2.5" Gate Valve & Flanges		28	$14,000	$392.0		B,C,E
	2425 System Cleaning		1	$100,000	$100.0		C,E
	2426 Bakeout Labor, Energy & Equipment		1	$350,000	$350.0		C,E
	2427 Leak Check & Repair		1	$275,000	$275.0		E
	2428 Contractor Burdens & Fee	23.8% of direct costs			$944.1		A

LIGO WBS 2500 -- SITE 1 SUPPORT EQUIPMENT -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
2000	Site 1 Facilities & Equipment				
2500	Support Equipment			$4,124.2	
2510	Laser Equipment			$414.2	see page C-48
	2511 Lasers	4 @ $79.3K ea	$317.2		
	2512 Laser Cooling Units	4 @ $7.5K ea	$30.0		
	2513 Laser Table & Mounts	2 @ $33.5K ea	$67.0		
2520	Data Acquisition & Recording Equipment			$479.4	see page C-49
	2521 Software		$15.0		
	2522 Hardware		$444.0		
	2523 Cabling & Installation		$20.4		
2530	Instrumentation			$2,264.8	
	2531 Vacuum System Monitoring & Control		$291.4		see page C-50
	2532 Vacuum Diagnostic Instrumentation		$396.0		see page C-50
	2533 Vacuum Test Equipment		$449.0		see page C-50
	2534 Physical Environment Monitoring		$622.6		see page C-51
	2535 Electronic Test Equipment		$505.8		see page C-52
2540	Office & Shop Equipment			$524.8	
	2541 Furniture		$67.4		D
	2542 Shipping & Receiving		$38.4		D
	2543 Shop Equipment		$276.7		D
	2544 Telephones & Intercom		$100.0		C
	2545 Security Equipment		$42.3		D
2550	Spares			$441.0	D
	2551 Mechanical Pump		$16.0		
	2552 Blower		$13.0		
	2553 Turbopump		$39.0		
	2554 Ion Pump Power Supply		$16.0		
	2555 Ion Gage Controller		$13.0		
	2556 Mass Spectrometer		$47.0		
	2557 Control Computer		$40.0		
	2558 Data Acquisition System		$30.0		
	2559 Valves & Other Parts		$227.0		

LIGO WBS 2600 -- SITE 1 INITIAL INTERFEROMETERS -- SUPPORTING DETAIL

		Method	Unit Cost (000)	Subtotal (000)	BOE
2000	Site 1 Facilities & Equipment				
2600	Initial Interferometers	2 @ $2,502.3K ea	$2,502.3	$5,004.6	
2610	Optical Component Groups				
	2611 Input Mode Cleaner to Test Masses		$279.0		D
	2612 Beamsplitter to Output Mode Cleaner		$52.2		D
	2613 Output Mode Cleaner to Final Photodiode		$44.9		D
	2614 Laser Input Window to Main Mode Cleaner Modematching		$79.6		D
	2615 Laser Tables (In-Air)		$129.4		D
	2616 Pointing Systems		$17.5		D
	2617 Laser Phase Locking (Between Interferometers)		$44.8		D
2620	Mechanical Assemblies				
	2621 Test Mass	4 @ $30.8K ea	$123.2		D
	2622 Splitter/Comp. Plate/Pickoff/Deflector	5 @ $25.8K ea	$129.0		D
	2623 Lenses	14 @ $5.5K ea	$77.0		D
	2624 Generic Suspended Components	52 @ $2.5K ea	$130.0		D
	2625 Rigid Mount Components, In-Vacuum		$51.6		
	2626 Extra-Vacuum Optical Mounts		$35.5		
2630	Control Electronics				
	2631 Lightphase/Frequency Servo	12 @ $27K ea	$324.0		D
	2632 Auto Alignment/Beam-Centering Unit	10 @ $18.5K ea	$185.0		D
	2633 Optical Levers	17 @ $8.5K ea	$144.5		D
	2634 Final Output PD		$19.5		D
	2635 Table Alignment	17 @ $16K ea	$272.0		D
	2636 Damping Electronics	74 @ $1.5K ea	$111.0		D
2640	Data Acquisition Electronics				
	2641 A/D Converter (Fast)	8 @ $3K ea	$24.0		B
	2642 A/D Converter (Slow)	8 @ $2K ea	$16.0		B
	2643 D/A Converter (Fast)	8 @ $2.5K ea	$20.0		B
	2644 D/A Converter (Slow)	8 @ $2.2K ea	$17.6		B
	2645 VME 147A CPU	4 @ $12.5K ea	$50.0		B
	2646 Sun 4/260 (Control Computer)		$65.0		B
	2647 Digital Servo Controller (VME)	4 @ $15K ea	$60.0		B

LIGO WBS 3100 -- SITE 2 SITE DEVELOPMENT -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
3000	Site 2 Facilities & Equipment				
3100	Site Development			$5,459.6	
3110	Earthwork			$2,426.5	
	3111 Stump Removal	100 Ac @ $1,600/Ac	$160.0		A
	3112 Fill	260,000 cu yd @ $5/cu yd	$1,300.0		A
	3113 Site Grading-Beam Tubes		$200.0		C
	3114 Site Grading-Stations		$100.0		C
	3115 Mobilization		$200.0		D
	3116 Contractor Burdens & Fee	23.8% of direct costs	$466.5		A
3120	Access Road & Parking			$1,188.5	
	3121 Construction	80,000 sq yd @ $12/sq yd	$960.0		E
	3122 Contractor Burdens & Fee	23.8% of direct costs	$228.5		A
3130	Drainage & Erosion Control			$210.5	
	3131 Drainage		$30.0		E
	3132 Erosion Control		$140.0		E
	3133 Contractor Burdens & Fee	23.8 % of direct costs	$40.5		A
3140	Power			$983.3	
	3141 Transmission to Site		*		
	3142 Substation/Switchgear		$302.7		D
	3143 Distribution Along Arms		$491.6		D
	3144 Contractor Burdens & Fee	23.8% of direct costs	$189.0		A
3150	Water & Sewer			$91.7	
	3151 Domestic Type Well	1 ea 20 GPM; 2 ea 5 GPM	$24.2		A
	3152 Storage Tank		$10.7		A
	3153 Continuous Chlorination System		$1.7		A
	3154 Pipe, 3" PVC	500 ft @ $7/ft	$3.5		A
	3155 Corner Station Septic Tank		$15.0		A
	3156 End Station Septic Tanks	2 @ $8K ea	$16.0		E
	3157 Sewer Pipe, 6" PVC	200 ft @ $15/ft	$3.0		A
	3158 Contractor Burdens & Fee	23.8% of direct costs	$17.6		A
3160	Fence			$86.7	
	3161 Chain Link Fence, 48" high	14,000 ft @ $5/ft	$70.0		A
	3162 Contractor Burdens & Fee	23.8% of direct costs	$16.7		A
3170	Landscaping & Lighting			$39.5	
	3171 Landscaping	5,000 sq ft @ $4/sq ft	$20.0		A
	3172 Lighting	4 area lighting poles @ $2,980 ea	$11.9		A
	3173 Contractor Burdens & Fee	23.8% of direct costs	$7.6		A
3180	Fire Protection			$366.7	
	3181 Pumps & Housing		$50.0		D
	3182 Mains	1,000 ft @ $30/ft	$30.0		D
	3183 Hydrants		$3.0		D
	3184 Water Storage Tank		$50.0		D
	3185 Fire Suppression		$139.2		D
	3186 Fire Detection		$24.0		D
	3187 Contractor Burdens & Fee	23.8% of direct costs	$70.5		A
3190	Dewatering			$66.2	
	3191 First Month		$31.6		A
	3192 Additional Months	1 add'l month	$21.9		A
	3193 Contractor Burdens & Fee	23.8% of direct costs	$12.7		A

INCLUDES

USED IN ESTIMATE OF SITE PREPARATION

*Local electric company allocates power transmission installation costs on their monthly power bills.

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LIGO WBS 3210 -- SITE 2 ENCLOSURES, CORNER STATION -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
3000	Site 2 Facilities & Equipment				
3200	Enclosures				
3210	Corner Station			$6,897.4	
3211	Vacuum Chamber Area (43,200 sq ft)			$4,087.0	
	3211.01 Foundation (36" slab)	4,800 cu yd @ $156.3/cu y	$750.0		A
	3211.02 Framing	300 ton @ $2,000/ton	$600.0		A
	3211.03 Girts & Purlins	130 ton @ $2,200/ton	$286.0		A
	3211.04 Siding	42,500 sq ft @ $9/sq ft	$382.5		A
	3211.05 Interior Liner	42,500 sq ft @ $3/sq ft	$127.5		A
	3211.06 Roof	43,200 sq ft @ $10/sq ft	$432.0		A
	3211.07 Ceiling	43,200 sq ft @ $5/sq ft	$216.0		A
	3211.08 Flooring	43,200 sq ft @ $5/sq ft	$216.0		A
	3211.09 Access Aids	43,200 sq ft @ $2/sq ft	$86.4		A
	3211.10 Electrical	43,200 sq ft @ $6/sq ft	$259.2		A
	3211.11 Bridge Crane System		$375.0		C
	3211.12 Heating, Ventilating, & Air Conditioning		$270.0		D
	3211.13 Embedded Steel	43,200 sq ft @ $2/sq ft	$86.4		A
3212	Shop & Service Area (13,500 sq ft)			$1,074.8	
	3212.01 Foundation (12" slab)	500 cu yd @ $140/cu yd	$70.0		A
	3212.02 Framing	85 ton @ $2,000/ton	$170.0		A
	3212.03 Girts & Purlins	25 ton @ $2,200/ton	$55.0		A
	3212.04 Siding & Roofing	22,000 sq ft @ $9/sq ft	$198.0		A
	3212.05 Interior Partitions	30,000 sq ft @ $5/sq ft	$150.0		A
	3212.06 Ceiling-Office & Shop	13,500 sq ft @ $4/sq ft	$54.0		A
	3212.07 Flooring	13,500 sq ft @ $2.5/sq ft	$33.8		A
	3212.08 Roll Doors	10 @ $4,600 ea	$46.0		C
	3212.09 Doors & Windows	36 doors; 6 large windows	$14.0		E
	3212.10 Plumbing	13,500 sq ft @ $2.5/sq ft	$33.8		A
	3212.11 Electrical	13,500 sq ft @ $5/sq ft	$67.5		A
	3212.12 Monorail System		$60.0		C
	3212.13 Heating, Ventilating, & Air Conditioning		$100.0		D
	3212.14 Clean Room Air Filtration & Ceiling	324 sq ft @ $70/sq ft	$22.7		A
3213	Utility Room (5,000 sq ft)			$120.8	
	3213.01 Equip. Foundation (8" slab)	123.5 cu yd @ $221/cu yd	$27.3		A
	3213.02 Prefab Building	5,000 sq ft @ $14/sq ft	$70.0		C
	3213.03 Mechanical & Electrical	5,000 sq ft @ $3.7/sq ft	$18.5		A
	3213.04 Partitions	1,000 sq ft @ $5/sq ft	$5.0		A
3214	Chiller Plant (2,025 sq ft)			$288.8	
	3214.01 Equip. Foundation (6" slab)	65 cu yd @ $221/cu yd	$14.4		A
	3214.02 Block Wall, 16' high	2,880 sq ft @ $5/sq ft	$14.4		A
	3214.03 Equipment: Chillers, Pumps, Tanks, etc.		$260.0		C
3215	Contractor Burdens & Fee	23.8% of direct costs		$1,326.0	A

LIGO WBS 3220 -- SITE 2 ENCLOSURES, LEFT-ARM END STATION -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
3000	Site 2 Facilities & Equipment				
3200	Enclosures				
3220	Left-Arm End Station			$910.2	
3221	Vacuum Chamber Area (4,000 sq ft)			$502.0	
	3221.01 Foundation (24" slab)	296.3 cu yd @ $145/cu yd	$43.0		A
	3221.02 Framing	25 ton @ $2,000/ton	$50.0		A
	3221.03 Girts & Purlins	20 ton @ $2,000/ton	$44.0		A
	3221.04 Siding	13,000 sq ft @ $8/sq ft	$104.0		A
	3221.05 Interior Lining	13,000 sq ft @ $3/sq ft	$39.0		A
	3221.06 Roof	4,000 sq ft @ $10/sq ft	$40.0		A
	3221.07 Ceiling	4,000 sq ft @ $5/sq ft	$20.0		A
	3221.08 Flooring	4,000 sq ft @ $5/sq ft	$20.0		A
	3221.09 Access Aids	4,000 sq ft @ $2/sq ft	$8.0		A
	3221.10 Electrical	4,000 sq ft @ $6/sq ft	$24.0		A
	3221.11 Bridge Crane System		$70.0		C
	3221.12 Heating, Ventilating, & Air Conditioning		$40.0		D
3222	Shop & Service Area (2,000 sq ft)			$189.6	
	3222.01 Foundation (8" slab)	50 cu yd @ $140/cu yd	$7.0		A
	3222.02 Framing	12 ton @ $2,000/ton	$24.0		A
	3222.03 Girts & Purlins	4 ton @ $2,200/ton	$8.8		A
	3222.04 Siding & Roofing	4,600 sq ft @ $8/sq ft	$36.8		A
	3222.05 Interior Partitions	2,000 sq ft @ $3/sq ft	$6.0		A
	3222.06 Ceiling	2,000 sq ft @ $4/sq ft	$8.0		A
	3222.07 Flooring	2,000 sq ft @ $2.5/sq ft	$5.0		A
	3222.08 Roll Doors	5 @ $4,600 ea	$23.0		A
	3222.09 Doors & Windows		$7.0		B
	3222.10 Plumbing	2,000 sq ft @ $2.5/sq ft	$5.0		A
	3222.11 Electrical	2,000 sq ft @ $7/sq ft	$14.0		A
	3222.12 Monorail System		$31.0		C
	3222.13 Heating, Ventilating, & Air Conditioning		$14.0		D
3223	Utility Room (500 sq ft)			$12.2	
	3223.01 Equip. Foundation (8" slab)	15 cu yd @ $221/cu yd	$3.3		A
	3223.02 Prefab Building	500 sq ft @ $14/sq ft	$7.0		C
	3223.03 Mechanical & Electrical	500 sq ft @ $3.7/sq ft	$1.9		A
3224	Chiller Plant (270 sq ft)			$31.4	
	3224.01 Equip. Foundation (8" slab)	8 cu yd @ $221/cu yd	$1.8		A
	3224.02 Block Wall, 16' high	528 sq ft @ $5/sq ft	$2.6		A
	3224.03 Equipment: Chillers, Pumps, Tanks, etc.		$27.0		C
3225	Contractor Burdens & Fee	23.8% of direct costs		$175.0	A

LIGO WBS 3230 -- SITE 2 ENCLOSURES, LEFT-ARM MID-POINT -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
3000	Site 2 Facilities & Equipment				
3200	Enclosures				
3230	Left-Arm Mid-Point			$14.9	
	3231 Equipment Foundation		$3.0		A
	3232 Prefab Building		$7.0		C
	3233 Mechanical & Electrical		$2.0		A
	3234 Contractor Burdens & Fee	23.8% of direct costs	$2.9		A

LIGO WBS 3240 -- SITE 2 ENCLOSURES, RIGHT-ARM END STATION -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
3000	Site 2 Facilities & Equipment				
3200	Enclosures				
3240	Right-Arm End Station	Ref. WBS 3220		$910.2	
3241	Vacuum Chamber Area (4,000 sq ft)			$502.0	
	3241.01 Foundation (24" slab)	296.3 cu yd @ $145/cu yd	$43.0		A
	3241.02 Framing	25 ton @ $2,000/ton	$50.0		A
	3241.03 Girts & Purlins	20 ton @ $2,200/ton	$44.0		A
	3241.04 Siding	13,000 sq ft @ $8/sq ft	$104.0		A
	3241.05 Interior Lining	13,000 sq ft @ $3/sq ft	$39.0		A
	3241.06 Roof	4,000 sq ft @ $10/sq ft	$40.0		A
	3241.07 Ceiling	4,000 sq ft @ $5/sq ft	$20.0		A
	3241.08 Flooring	4,000 sq ft @ $5/sq ft	$20.0		A
	3241.09 Access Aids	4,000 sq ft @ $2/sq ft	$8.0		A
	3241.10 Electrical	4,000 sq ft @ $6/sq ft	$24.0		A
	3241.11 Bridge Crane System		$70.0		C
	3241.12 Heating, Ventilating, & Air Conditioning		$40.0		D
3242	Shop & Service Area (2,000 sq ft)			$189.6	
	3242.01 Foundation (8" slab)	50 cu yd @ $140/cu yd	$7.0		A
	3242.02 Framing	12 ton @ $2,000/ton	$24.0		A
	3242.03 Girts & Purlins	4 ton @ $2,200/ton	$8.8		A
	3242.04 Siding & Roofing	4,600 sq ft @ $8/sq ft	$36.8		A
	3242.05 Interior Partitions	2,000 sq ft @ $3/sq ft	$6.0		A
	3242.06 Ceiling	2,000 sq ft @ $4/sq ft	$8.0		A
	3242.07 Flooring	2,000 sq ft @ $2.5/sq ft	$5.0		A
	3242.08 Roll Doors	5 @ $4,600 ea	$23.0		A
	3242.09 Doors & Windows		$7.0		B
	3242.10 Plumbing	2,000 sq ft @ $2.5/sq ft	$5.0		A
	3242.11 Electrical	2,000 sq ft @ $7/sq ft	$14.0		A
	3242.12 Monorail System		$31.0		C
	3242.13 Heating, Ventilating, & Air Conditioning		$14.0		D
3243	Utility Room (500 sq ft)			$12.2	
	3243.01 Equip. Foundation (8" slab)	15 cu yd @ $221/cu yd	$3.3		A
	3243.02 Prefab Building	500 sq ft @ $14/sq ft	$7.0		C
	3243.03 Mechanical & Electrical	500 sq ft @ $3.7/sq ft	$1.9		A
3244	Chiller Plant (270 sq ft)			$31.4	
	3244.01 Equip. Foundation (8" slab)	8 cu yd @ $221/cu yd	$1.8		A
	3244.02 Block Wall, 16' high	528 sq ft @ $5/sq ft	$2.6		A
	3244.03 Equipment: Chillers, Pumps, Tanks, etc.		$27.0		C
3245	Contractor Burdens & Fee	23.8% of direct costs		$175.0	A

LIGO WBS 3250 -- SITE 2 ENCLOSURES, RIGHT-ARM MID-POINT -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
3000	Site 2 Facilities & Equipment				
3200	Enclosures				
3250	Right-Arm Mid-Point	Ref. WBS 3230		$14.9	
	3251 Equipment Foundation		$3.0		A
	3252 Prefab Building		$7.0		C
	3253 Mechanical & Electrical		$2.0		A
	3254 Contractor Burdens & Fee	23.8% of direct costs	$2.9		A

LIGO WBS 3260 -- SITE 2 ENCLOSURES, TUBE MODULE -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
3200	Site 2 Facilities & Equipment				
3200	Enclosures				
3260	Tube Module Enclosures			$6,629.5	
	3261 Slab	25,712 ft @ $75/ft	$1,928.4		A
	3262 Arch Enclosures	25,712 ft @ $130/ft	$3,342.6		A
	3263 Pump Access	28 @ $3K ea	$84.0		C
	3264 Contractor Burdens & Fee	23.8% of direct costs	$1,274.5		A

LIGO WBS 3310 -- SITE 2 VACUUM EQUIPMENT, CORNER STATION -- SUPPORTING DETAIL

		Method	Amount (000)	Amount (000)	Subtotal (000)	BOE
3000	Site 2 Facilities & Equipment					
3300	Vacuum Equipment					
3310	Corner Station Equipment				$7,436.2	
3311	Beam Manifolds				$1,805.6	
	3311.01 Reserved					
	3311.02 Tube Isolation Valve Assembly	Ref. WBS 2311.02		$234.0		see page C-41
	3311.03 LN2 Trap, Coaxial (Long)	Ref. WBS 2311.03		$1,194.2		see page C-41
	3311.04 Additional Components			$377.4		
	3311.04.01 Tubing, 72" diameter	105 ft @ $1,000/ft	$210.0			E
	3311.04.02 Supports for 72" tubing		$11.6			E
	3311.04.03 Adapter, 72"/48"		$30.0			E
	3311.04.04 Expansion Joint, 72" diameter	2 @ $1.2K ea	$4.8			E
	3311.04.05 Expansion Joint, 48" diameter		$1.2			C
	3311.04.06 HEPA Filtered Air Supply Unit		$18.0			C
	3311.04.07 Heaters & Insulation		$49.4			E
	3311.04.08 Install, Bake, Leak Check & Checkout		$52.4			E
3312	Reserved					
3313	Vertex Chamber Assembly	Ref. WBS 2313			$3,763.2	see page C-44
	3313.01 Test Mass Chamber, Type II	2 @ $483K ea		$966.0		
	3313.02 Diagonal Chamber			$533.5		
	3313.03 HAM Chamber	9 @ $188.3K ea		$1,694.7		
	3313.04 Tube, Mode Cleaner	2 @ $45.5K ea		$91.0		
	3313.05 Connector to 6' Tube	2 @ $129.9K ea		$259.8		
	3313.06 Additional Components			$218.2		
3314	Roughing Pump System	Ref. WBS 2314			$397.8	see page C-45
3315	LN2 Supply & Distribution	Ref. WBS 2315			$40.0	see page C-45
3316	Contractor Burdens & Fee	23.8% of direct costs			$1,429.6	A

LIGO WBS 3320 -- SITE 2 VACUUM EQUIPMENT, LEFT-ARM END STATION -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
3000	Site 2 Facilities & Equipment				
3300	Vacuum Equipment				
3320	Left-Arm End Station Equipment			$1,685.2	
3321	Beam Manifold			$1,181.5	
	3321.01 Reserved				
	3321.02 Test Mass Chamber, Type II	Ref. WBS 2313.01	$483.0		see page C-44
	3321.03 Tube Isolation Valve Assembly	Ref. WBS 2311.02	$117.0		see page C-41
	3321.04 LN2 Trap, Coaxial (Short)	Ref. WBS 2321.04	$353.6		see page C-46
	3321.05 Connector to 6' Tube	Ref. WBS 2313.05	$129.9		see page C-44
	3321.06 Additional Components	Ref. WBS 2321.06	$98.0		see page C-46
3322	Roughing Pump System	Ref. WBS 2322		$168.5	see page C-46
3323	LN2 Supply & Distribution	Ref. WBS 2323		$11.2	see page C-46
3324	Contractor Burdens & Fee	23.8% of direct costs		$324.0	A

LIGO WBS 3330 -- SITE 2 VACUUM EQUIPMENT, LEFT-ARM MID-POINT -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
3000	Site 2 Facilities & Equipment				
3300	Vacuum Equipment				
3330	Left-Arm Mid-Point Equipment			$414.0	
3331	Connector			$193.1	
	3331.01 Tube Isolation Valve Assembly	Ref. WBS 2311.02	$117.0		see page C-41
	3331.02 Ion Pump w/Accessories		$59.6		C
	3331.03 Pump Tee, 2.5" Gate Valve, Flanges		$14.0		B,C,E
	3331.04 Install, Bake, Leak Check & Checkout		$2.5		E
3332	Roughing Pump System			$141.3	
	3332.01 Roughing Pump Set	Ref. WBS 2314.01	$138.0		see page C-45
	3332.02 Roughing Pump Line		$3.3		E
3333	Reserved				
3334	Contractor Burdens & Fee	23.8% of direct costs		$79.6	A

LIGO WBS 3340 -- SITE 2 VACUUM EQUIPMENT, RIGHT-ARM END STATION -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
3000	Site 2 Facilities & Equipment				
3300	Vacuum Equipment				
3340	Right-Arm End Station Equipment	Ref. WBS 3320		$1,685.2	
3341	Beam Manifold			$1,181.5	
	3341.01 Reserved				
	3341.02 Test Mass Chamber, Type II	Ref. WBS 2313.01	$483.0		see page C-44
	3341.03 Tube Isolation Valve Assembly	Ref. WBS 2311.02	$117.0		see page C-41
	3341.04 LN2 Trap, Coaxial (Short)	Ref. WBS 2321.04	$353.6		see page C-46
	3341.05 Connector to 6' Tube	Ref. WBS 2313.05	$129.9		see page C-44
	3341.06 Additional Components	Ref. WBS 2321.06	$98.0		see page C-46
3342	Roughing Pump System	Ref. WBS 2322		$168.5	see page C-46
3343	LN2 Supply & Distribution	Ref. WBS 2323		$11.2	see page C-46
3344	Contractor Burdens & Fee	23.8% of direct costs		$324.0	A

LIGO WBS 3350 -- SITE 2 VACUUM EQUIPMENT, RIGHT-ARM MID-POINT -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
3000	Site 2 Facilities & Equipment				
3300	Vacuum Equipment				
3350	Right-Arm Mid-Point Equipment	Ref. WBS 3330		$414.0	
3351	Connector			$193.1	
	3351.01 Tube Isolation Valve Assembly	Ref. WBS 2311.02	$117.0		see page C-41
	3351.02 Ion Pump w/Accessories		$59.6		C
	3351.03 Pump Tee, 2.5" Gate Valve, Flanges		$14.0		B,C,E
	3351.04 Install, Bake, Leak Check & Checkout		$2.5		E
3352	Roughing Pump System			$141.3	
	3352.01 Roughing Pump Set	Ref. WBS 2314.01	$138.0		see page C-45
	3352.02 Roughing Pump Line		$3.3		E
3353	Reserved				
3354	Contractor Burdens & Fee	23.8% of direct costs		$79.6	A

LIGO WBS 3400 -- SITE 2 BEAM TUBE MODULES -- SUPPORTING DETAIL

		Method	Qty	Unit Cost	Extension (000)	Subtotal (000)	BOE
3000	Site 2 Facilities & Equipment						
3400	Beam Tube Modules					$13,757.7	
3410	Factory Fabrication of Beam Tube Section					$8,847.0	
	3411 Wall Material Costs, T304L/low H2	2,830 lb @ $1.4895/lb	640	$4,215	$2,697.6		C
	3412 Fabricate Cylinder	40 ft @ $63.70/ft	640	$2,548	$1,630.7		C
	3413 Stiffeners	22/section @ $80 ea	640	$1,760	$1,126.4		C
	3414 Expansion Joint	1/section @ $833 ea	640	$833	$533.1		C,E
	3415 Precision Reform Ends	2/section @ $50 ea	640	$100	$64.0		C,E
	3416 Clean, Leak Check & Seal Ends		640	$1,160	$742.4		C
	3417 Transport to Field		640	$550	$352.0		C
	3418 Contractor Burdens & Fee	23.8% of direct costs			$1,700.8		A
3420	Field Installation, Including Related Equipment					$4,910.7	
	3421 Position, Fitup, & Weld Ends		672	$900	$604.8		C,E
	3422 Supports & Baffles		640	$900	$576.0		C,E
	3423 Ion Pumps w/ Accessories		28	$59,600	$1,668.8		C
	3424 Pump Tee: 2.5" Gate Valve & Flanges		28	$14,000	$392.0		B,C,E
	3425 System Cleaning		1	$100,000	$100.0		C,E
	3426 Bakeout Labor, Energy & Equipment		1	$350,000	$350.0		C,E
	3427 Leak Check		1	$275,000	$275.0		E
	3428 Contractor Burdens & Fee	23.8% of direct costs			$944.1		A

LIGO WBS 3500 -- SITE 2 SUPPORT EQUIPMENT -- SUPPORTING DETAIL

		Method	Amount (000)	Subtotal (000)	BOE
3000	Site 2 Facilities & Equipment				
3500	Support Equipment			$3,373.2	
3510	Laser Equipment	Ref. WBS 2510		$207.1	see page C-48
	3511 Lasers	2 @ $79.3K ea	$158.6		
	3512 Laser Cooling Units	2 @ $7.5K ea	$15.0		
	3513 Laser Table & Mounts	1 @ $33.5K ea	$33.5		
3520	Data Acquisition & Recording Equipment	Ref. WBS 2520		$479.4	see page C-49
	3521 Software		$15.0		
	3522 Hardware		$444.0		
	3523 Cabling & Installation		$20.4		
3530	Instrumentation			$1,735.4	
	3531 Vacuum System Monitoring & Control		$268.2		see page C-53
	3532 Vacuum Diagnostic Instrumentation		$298.0		see page C-53
	3533 Vacuum Test Equipment	Ref. WBS 2533	$449.0		see page C-50
	3534 Physical Environment Monitoring Instrumentation		$391.5		see page C-54
	3535 Electronic Test Equipment		$328.7		see page C-55
3540	Office & Shop Equipment			$510.3	D
	3541 Furniture		$63.9		
	3542 Shipping & Receiving		$34.2		
	3543 Shop Equipment		$276.7		
	3544 Telephones & Intercom		$100.0		
	3545 Security Equipment		$35.5		
3550	Spares			$441.0	D
	3551 Mechanical Pump		$16.0		
	3552 Blower		$13.0		
	3553 Turbopump		$39.0		
	3554 Ion Pump Power Supply		$16.0		
	3555 Ion Gage Controller		$13.0		
	3556 Mass Spectrometer		$47.0		
	3557 Control Computer		$40.0		
	3558 Data Acquisition System		$30.0		
	3559 Valves & Other Parts		$227.0		

LIGO WBS 3600 -- SITE 2 INITIAL INTERFEROMETER -- SUPPORTING DETAIL

		Method	Unit Cost (000)	Subtotal (000)	BOE
3000	Site 2 Facilities & Equipment				
3600	Initial Interferometer	1 @ $2,502.3K ea	$2,502.3	$2,502.3	
3610	Optical Component Groups				
	3611 Input Mode Cleaner to Test Masses		$279.0		D
	3612 Beamsplitter to Output Mode Cleaner		$52.2		D
	3613 Output Mode Cleaner to Final Photodiode		$44.9		D
	3614 Laser Input Window to Main Mode Cleaner Modematching		$79.6		D
	3615 Laser Tables (In-Air)		$129.4		D
	3616 Pointing Systems		$17.5		D
	3617 Laser Phase Locking (Between Interferometers)		$44.8		D
3620	Mechanical Assemblies				
	3621 Test Mass	4 @ $30.8K ea	$123.2		D
	3622 Splitter/Comp. Plate/Pickoff/Deflector	5 @ $25.8K ea	$129.0		D
	3623 Lenses	14 @ $5.5K ea	$77.0		D
	3624 Generic Suspended Components	52 @ $2.5K ea	$130.0		D
	3625 Rigid Mount Components, In-Vacuum		$51.6		D
	3626 Extra-Vacuum Optical Mounts		$35.5		D
3630	Control Electronics				
	3631 Lightphase/Frequency Servo	12 @ $27K ea	$324.0		D
	3632 Auto Alignment/Beam-Centering Unit	10 @ $18.5K ea	$185.0		D
	3633 Optical Levers	17 @ $8.5K ea	$144.5		D
	3634 Final Output PD		$19.5		D
	3635 Table Alignment	17 @ $16K ea	$272.0		D
	3636 Damping Electronics	74 @ $1.5K ea	$111.0		D
3640	Data Acquisition Electronics				
	3641 A/D Converter (Fast)	8 @ $3K ea	$24.0		B
	3642 A/D Converter (Slow)	8 @ $2K ea	$16.0		B
	3643 D/A Converter (Fast)	8 @ $2.5K ea	$20.0		B
	3644 D/A Converter (Slow)	8 @ $2.2K ea	$17.6		B
	3645 VME 147A CPU	4 @ $12.5K ea	$50.0		B
	3646 Sun 4/260 (Control Computer)		$65.0		B
	3647 Digital Servo Controller (VME)	4 @ $15K ea	$60.0		B

PART III
Unit Cost Detail

LIGO WBS 2311 -- SITE 1 CORNER STATION, BEAM MANIFOLDS -- UNIT COST DETAIL

	Method	Unit Cost (000)	Unit Cost (000)	Unit Cost (000)	BOE
2000 Site 1 Facilities & Equipment					
2300 Vacuum Equipment					
2310 Corner Station Equipment					
2311 Beam Manifolds					
2311.01 Test Mass Chamber, Type I				$1,013.1	
2311.01.01 Chamber Shell			$411.8		C
2311.01.02 Feedthroughs			(incl)*		
2311.01.03 Optics Supports			$206.8		
2311.01.03.01 Suspension Frame		$4.0			E
2311.01.03.02 Seismic Stack		$120.0			E
2311.01.03.03 Support Beams		$58.8			C
2311.01.03.04 Bellows		$10.0			C
2311.01.03.05 Air Mounts		$10.0			B
2311.01.03.06 Foundations		$4.0			E
2311.01.04 Air Shower Manifold & Vacuum Valve			$15.2		C,E
2311.01.05 Valves, 10"/2.5"			$17.6		B
2311.01.06 Ion Pump, w/ Accessories			$68.8		C
2311.01.07 Airlock Mechanism			$146.0		C
2311.01.08 Lift Cage & Mechanism			$100.0		E
2311.01.09 Heaters & Insulation			$12.0		E
2311.01.10 Install, Bake, Leak Check & Checkout			$34.9		E
2311.02 Tube Isolation Valve Assembly				$117.0	
2311.02.01 Valve, 48" w/ matching flanges & seals			$111.8		C
2311.02.02 Lateral Support for 48" valve			$1.1		E
2311.02.03 Expansion Joint, 48"			$0.6		C
2311.02.04 Heaters & Insulation			$0.5		E
2311.02.05 Install, Bake, Leak Check & Checkout			$3.0		E
2311.03 LN2 Trap, Coaxial (Long)				$597.1	
2311.03.01 Chamber, 10′ diameter x 14′	501 sq ft @ $400/sq ft		$200.4		C,E
2311.03.02 LN2 Vessel, 8′ diameter x 12′	488 sq ft @ $400/sq ft		$195.2		C,E
2311.03.03 Multilayer Insulation	501 sq ft @ $50/sq ft		$25.1		E
2311.03.04 Valve, 48" w/matching flanges & seals			$111.8		C
2311.03.05 Lateral Support for 48" valve			$1.1		E
2311.03.06 Tubing, 48" diameter	6 ft @ $667/ft		$4.0		E
2311.03.07 Expansion Joint, 48" diameter			$0.6		C
2311.03.08 External LN2 & Vacuum Plumbing, Gaging			$31.9		E
2311.03.09 Heaters & Insulation			$7.6		E
2311.03.10 Install, Bake, Leak Check & Checkout			$19.4		E
2311.04 Additional Components				$376.0	
2311.04.01 Tubing, 72" diameter	182.6 ft @ $1,000/ft		$182.6		E
2311.04.02 Supports for 72" tubing	2 @ $5K ea		$10.0		E
2311.04.03 Adapter, 72"/48"	2 @ $15K ea		$30.0		E
2311.04.04 Expansion Joint, 72"	4 @ $1.2K ea		$4.8		E
2311.04.05 Expansion Joint, 48"	6 @ $0.6K ea		$3.6		C
2311.04.06 Cap, 48"	2 @ $6.5K ea		$13.0		E
2311.04.07 Lateral Support for 48" cap	2 @ $1.1K ea		$2.2		E
2311.04.08 Adapter, 48"/30"	2 @ $8K ea		$16.0		E
2311.04.09 HEPA Filtered Air Supply Units	2 @ $9K ea		$18.0		C
2311.04.10 Heaters & Insulation			$44.8		E
2311.04.11 Install, Bake, Leak Check & Checkout			$51.0		E

*amount included in preceding item

LIGO WBS 2312 -- SITE 1 CORNER STATION, OFFSET CHAMBER ASSEMBLY -- UNIT COST DETAIL

	Qty	Unit Cost (000)	Unit Cost (000)	Unit Cost (000)	BOE
2000 Site 1 Facilities & Equipment					
2300 Vacuum Equipment					
2310 Corner Station Equipment					
2312 Offset Chamber Assembly					
2312.01 Reserved					
2312.02 Diagonal Chamber				$533.5	
2312.02.01 Chamber Shell			$154.6		C
2312.02.02 Feedthroughs			(incl)		
2312.02.03 Optics Support			$158.5		
2312.02.03.01 Table		$10.0			E
2312.02.03.02 Seismic Stack		$60.0			E
2312.02.03.03 Support Beams		$64.5			C,E
2312.02.03.04 Bellows		$10.0			C
2312.02.03.05 Air Mounts		$10.0			B
2312.02.03.06 Foundations		$4.0			E
2312.02.04 Air Shower Manifold & Vacuum Valve			$15.2		B,C,E
2312.02.05 Valves, 10"/2.5"			$17.6		B
2312.02.06 Ion Pump, w/Accessories	2	$68.8	$137.6		C
2312.02.07 Connector, 60" diameter x 24"	2	$14.0	$28.0		E
2312.02.08 Heaters & Insulation			$6.5		E
2312.02.09 Install, Bake, Leak Check & Checkout			$15.5		E
2312.03 HAM Chamber				$188.3	
2312.03.01 Chamber Shell			$104.3		C
2312.03.02 Feedthroughs			(incl)		
2312.03.03 Optics Support			$60.3		
2312.03.03.01 Table		$7.0			E
2312.03.03.02 Seismic Stack		$39.3			E
2312.03.03.03 Support Beams		$3.5			C,E
2312.03.03.04 Bellows		$2.0			C
2312.03.03.05 Air Mounts		$7.5			B
2312.03.03.06 Foundations		$1.0			E
2312.03.04 Air Shower Manifold & Vacuum Valve			$15.2		C,E
2312.03.05 Heaters & Insulation			2.4		E
2312.03.06 Install, Bake, Leak Check & Checkout			$6.1		E

LIGO WBS 2312 -- SITE 1 CORNER STATION, OFFSET CHAMBER ASSEMBLY (CONT.) -- UNIT COST DETAIL

WBS	Item	Method	Unit Cost (000)	Unit Cost (000)	BOE
2000	Site 1 Facilities & Equipment				
2300	Vacuum Equipment				
2310	Corner Station Equipment				
2312	Offset Chamber Assembly				
2312.04	Tube, Mode Cleaner			$45.5	
2312.04.01	Tubing, 30" diameter	37 ft @ $416/ft	$15.4		E
2312.04.02	Expansion Joint, 60" diameter		$1.0		E
2312.04.03	Adapter, 60"/30"	2 @ $10K ea	$20.0		E
2312.04.04	Heaters & Insulation		$4.2		E
2312.04.05	Install, Bake, Leak Check & Checkout		$4.9		E
2312.05	Connector to Test Mass Chamber			$144.5	
2312.05.01	Tubing, 30" diameter	31 ft @ $416/ft	$9.5		E
2312.05.02	Expansion Joint, 30" diameter		$0.5		E
2312.05.03	Valve, 30" w/ matching flanges & seals		$68.6		C
2312.05.04	Lateral Support for 30" valve		$0.7		E
2312.05.05	Adapter, 60"/30"		$10.0		E
2312.05.06	Connector, 60" diameter x 24"	2 @ $14K ea	$28.0		E
2312.05.07	Orifice Assembly for 30" tube		$15.0		E
2312.05.08	Heaters & Insulation		$5.0		E
2312.05.09	Install, Bake, Leak Check & Checkout		$7.2		E
2312.06	Additional Components			$81.1	
2312.06.01	Cap, 60"	2 @ $8K ea	$16.0		E
2312.06.02	Lateral Support for 60" cap	2 @ $1.5K ea	$3.0		E
2312.06.03	Tubing, 24" diameter	57 ft @ $333/ft	$19.0		E
2312.06.04	HEPA Filtered Air Supply Unit	4 @ $9K ea	$36.0		C
2312.06.05	Heaters & Insulation		$0.6		E
2312.06.06	Install, Bake, Leak Check & Checkout		$6.5		E

LIGO WBS 2313 -- SITE 1 CORNER STATION, VERTEX CHAMBER ASSEMBLY -- UNIT COST DETAIL

WBS	Item	Method	Unit Cost (000)	Unit Cost (000)	BOE
2000	Site 1 Facilities & Equipment				
2300	Vacuum Equipment				
2310	Corner Station Equipment				
2313	Vertex Chamber Assembly				
2313.01	Test Mass Chamber, Type II			$483.0	
2313.01.01	Chamber Shell		$154.6		C
2313.01.02	Feedthroughs		(incl)		
2313.01.03	Optics Support	Ref. WBS 2311.01.03	$206.8		B,C,E
2313.01.04	Air Shower Manifold & Vacuum Valve		$15.2		C,E
2313.01.05	Valves, 10"/2.5"		$17.6		C
2313.01.06	Ion Pump, w/Accessories		$68.8		C
2313.01.07	Heaters & Insulation		$5.7		E
2313.01.08	Install, Bake, Leak Check & Checkout		$14.3		E
2313.02	Diagonal Chamber	Ref. WBS 2312.02		$533.5	B,C,E
2313.03	HAM Chamber	Ref. WBS 2312.03		$188.3	B,C,E
2313.04	Tube, Mode Cleaner	Ref. WBS 2312.04		$45.5	E
2313.05	Connector to 6′ Tube			$129.9	
2313.05.01	Valve, 48" w/matching flanges & seals		$111.8		C
2313.05.02	Lateral Support for 48" valve		$1.1		E
2313.05.03	Adapter w/ Expansion Joint, 60"/48"		$13.0		C,E
2313.05.04	Heaters & Insulation		$0.7		E
2313.05.05	Install, Bake, Leak Check & Checkout		$3.3		E
2313.06	Additional Components			$218.2	
2313.06.01	Cap, 60"	6 @ $8K ea	$48.0		E
2313.06.02	Lateral Support for 60" cap	2 @ $1.5K ea	$3.0		E
2313.06.03	Adapter w/Expansion Joint, 60"/30"	4 @ $13K ea	$52.0		C,E
2313.06.04	Lateral Support for 60"/48" adapter	4 @ $0.9K ea	$3.6		E
2313.06.05	Connector, 48" diameter x 24"	2 @ $10K ea	$20.0		E
2313.06.06	Orifice Assembly for 48" tube	2 @ $16K ea	$32.0		E
2313.06.07	Tubing, 24" diameter	26 ft @ $333/ft	$8.7		E
2313.06.08	HEPA Filtered Air Supply Unit	4 @ $9K ea	$36.0		C
2313.06.09	Heaters & Insulation		$3.2		E
2313.06.10	Install, Bake, Leak Check & Checkout		$11.7		E

LIGO WBS 2314 & 2315 -- SITE 1 CORNER STATION, ROUGHING PUMP SYSTEM & LN2 SUPPLY AND DISTRIBUTION -- UNIT COST DETAIL

		Method	Unit Cost (000)	Unit Cost (000)	BOE
2000	Site 1 Facilities & Equipment				
2300	Vacuum Equipment				
2310	Corner Station Equipment				
2314	Roughing Pump System				
	2314.01 Roughing Pump Set			$138.0	
	2314.01.01 Turbomolecular Pump		$37.0		B
	2314.01.02 Rootes Blower		$17.0		B
	2314.01.03 Mechanical Pump		$19.0		B
	2314.01.04 Roughing Manifold & Valves		$50.0		E
	2314.01.05 Install, Leak Check & Checkout		$15.0		E
	2314.02 Roughing Line			$121.8	
	2314.02.01 Tube, 24" diameter	303 ft @ $333/ft	$100.9		E
	2314.02.02 Install, Leak Check & Checkout		$20.9		E
2315	LN2 Supply & Distribution			$20.0	
	2315.01 Tubing (Jacketed), 1" diameter	120 ft @ $110/ft	$13.2		C
	2315.02 Valves (Insulated), 1" diameter	4 @ $1.7K ea	$6.8		C

LIGO WBS 2320 -- SITE 1 VACUUM EQUIPMENT, LEFT-ARM END STATION -- UNIT COST DETAIL

		Method	Unit Cost (000)	Unit Cost (000)	BOE
2000	Site 1 Facilities & Equipment				
2300	Vacuum Equipment				
2320	Left-Arm End Station Equipment				
2321	Beam Manifold				
	2321.01 Reserved			$0.0	
	2321.02 Test Mass Chamber, Type II	Ref. WBS 2313.01		$483.0	B,C,E
	2321.03 Tube Isolation Valve Assembly	Ref. WBS 2311.02		$117.0	C,E
	2321.04 LN2 Trap, Coaxial (Short)			$353.6	
	2321.04.01 Chamber, 10' diameter x 6'	250 sq ft @ $400/sq ft	$100.0		C,E
	2321.04.02 LN2 Vessel, 8' diameter x 4'	186 sq ft @ $400/sq ft	$74.4		C,E
	2321.04.03 Multilayer Insulation	250 sq ft @ $50/sq ft	$12.5		E
	2321.04.04 Valve, 48" w/ matching flanges & seals		$111.8		C
	2321.04.05 Lateral Support for 48" valve		$0.7		E
	2321.04.06 Tubing, 48" diameter	6 ft @ $667/ft	$4.0		E
	2321.04.07 Expansion Joint, 48" diameter		$0.6		E
	2321.04.08 External LN2 & Vacuum Plumbing, Gaging		$31.9		E
	2321.04.09 Heaters & Insulation		$4.9		E
	2321.04.10 Install, Bake, Leak Check & Checkout		$12.8		E
	2321.05 Connector to 6' Tube	Ref. WBS 2313.05		$129.9	C,E
	2321.06 Additional Components			$98.0	
	2321.06.01 Cap, 60"		$8.0		E
	2321.06.02 Lateral Support for 60" cap		$1.5		E
	2321.06.03 Expansion Joint, 60" diameter		$1.0		C
	2321.06.04 Tubing, 72" diameter	37 ft @ $1,000/ft	$37.0		E
	2321.06.05 Supports for 72" diameter tubing		$2.0		E
	2321.06.06 Expansion Joint, 72"	2 @ $1.2 ea	$2.4		C
	2321.06.07 Adapter, 72"/48"		$15.0		E
	2321.06.08 HEPA Filtered Air Supply Unit		$9.0		C
	2321.06.09 Heaters & Insulation		$9.7		E
	2321.06.10 Install, Bake, Leak Check & Checkout		$12.4		E
2322	Roughing Pump System				
	2322.01 Roughing Pump Set	Ref. WBS 2314.01		$138.0	B,E
	2322.02 Roughing Line			$30.5	
	2322.02.01 Tubing, 24" diameter	76 ft @ $333/ft	$25.3		E
	2322.02.02 Install, Leak Check & Checkout		$5.2		E
2323	LN2 Supply & Distribution			$11.2	
	2323.01 Tubing (Jacketed), 1" diameter	40 ft @ $110/ft	$4.4		C
	2323.02 Valves (Insulated), 1" diameter	4 @ $1.7K ea	$6.8		C

LIGO WBS 2330 -- SITE 1 VACUUM EQUIPMENT, LEFT-ARM MID STATION -- UNIT COST DETAIL

		Method	Unit Cost (000)	Unit Cost (000)	BOE
2000	Site 1 Facilities & Equipment				
2300	Vacuum Equipment				
2330	Left-Arm Mid Station Equipment				
2331	Beam Manifold				
	2331.01 Test Mass Chamber, Type I	Ref. WBS 2311.01		$1,013.1	B,C,E
	2331.02 Reserved			$0.0	
	2331.03 Tube Isolation Valve Assembly	Ref. WBS 2311.02		$117.0	C,E
	2331.04 LN2 Trap, Coaxial (Short)	Ref. WBS 2321.04		$353.6	C,E
	2331.05 Additional Components			$102.1	
	2331.05.01 Tubing, 72" diameter	37 ft @ $1,000/ft	$37.0		E
	2331.05.02 Supports for 72" diameter tubing		$2.0		E
	2331.05.03 Expansion Joint, 48"		$0.6		C
	2331.05.04 Expansion Joint, 72"	2 @ $1.2K ea	$2.4		E
	2331.05.05 Adapter, 72"/48"	2 @ $15K ea	$30.0		E
	2331.05.06 HEPA Filtered Air Supply Unit		$9.0		C
	2331.05.07 Heaters & Insulation		$9.8		E
	2331.05.08 Install, Bake, Leak Check & Checkout		$11.3		E
2332	Roughing Pump System				
	2332.01 Roughing Pump Set	Ref. WBS 2314.01		$138.0	B,E
	2332.02 Roughing Line			$45.0	
	2332.02.01 Tubing, 24" diameter	112 ft @ $333/ft	$37.3		E
	2332.02.02 Install, Leak Check & Checkout		$7.7		
2333	LN2 Supply & Distribution			$25.0	
	2333.01 Tubing (Jacketed), 1" diameter	165 ft @ $110/ft	$18.2		C
	2333.02 Valves (Insulated), 1" diameter	4 @ $1.7K ea	$6.8		C

LIGO WBS 2510 -- SITE 1 SUPPORT EQUIPMENT, LASERS -- UNIT COST DETAIL

		Method	Unit Cost (000)	Unit Cost (000)	BOE
2000	Site 1 Facilities & Equipment				
2500	Support Equipment				
2510	Laser Equipment			$120.3	
2511	Lasers			$79.3	
	2511.01 Laser, Argon-Ion	COHERENT Model No. INNOVA 200-25	$77.5		B
	2511.02 Etalon Assembly	COHERENT Model No. 924	$1.8		B
2512	Laser Cooling Units	COHERENT Model No. CA60	$7.5	$7.5	B
2513	Laser Table & Mounts			$33.5	
	2513.01 Laser Table	NEWPORT Model No. RS-616-24 (special)	$26.0		C
	2513.02 Mounts	NEWPORT Model No. XMA STD	7.5		B

LIGO WBS 2520 -- SITE 1 SUPPORT EQUIPMENT, DATA ACQUISITION & RECORDING -- UNIT COST DETAIL

		Qty	Unit Cost (000)	Extension (000)	Subtotal (000)	Subtotal (000)	BOE
2000	Site 1 Facilities & Equipment						
2500	Support Equipment						
2520	Data Acquisition & Recording Equipment					$479.4	
2521	Software						
	2521.01 VX Works SW OS License	1	$15.0		$15.0		B
2522	Hardware				$444.0		
	2522.01 LAN Repeater	2	$1.5	$3.0			B
	2522.02 Laser Printer	2	$2.5	$5.0			B
	2522.03 Sun 4/110 (Spare)	1	$34.0	$34.0			B
	2522.04 Sun 4/110 (Housekeeping)	6	$34.0	$204.0			B
	2522.05 Sun 4/260 (Data Logging)	1	$65.0	$65.0			B
	2522.06 Helical Scan Tape Drive	8	$3.5	$28.0			B
	2522.07 Telebit T2500 Modems	2	$1.4	$2.8			B
	2522.08 Ethernet Tranceivers	11	$0.2	$2.2			B
	2522.09 Sun 4/60 (Display/Development)	10	$10.0	$100.0			B
2523	Cabling & Installation				$20.4		
	2523.01 2KM FO LAN Cables w/Connectors	8	$2.0	$16.0			B
	2523.02 LAN Cable Installation	32 hrs	$50/hr	$1.6			E
	2523.03 50' Drop Cables			$0.8			E
	2523.04 Misc. Cables, Connectors, etc.			$2.0			E

LIGO WBS 2531, 2532 and 2533 -- SITE 1 SUPPORT EQUIPMENT, VACUUM SYSTEM INSTRUMENTATION -- UNIT COST DETAIL

		Description	Qty	Unit Cost (000)	Extension (000)	Subtotal (000)	BOE
2000	Site 1 Facilities & Equipment						
2500	Support Equipment						
2530	Instrumentation						
2531	Vacuum System Monitoring & Control					$291.4	
	2531.01 Computer w/ Color Monitor	HP 98583G OPT 011, HP 370	2	$28.2	$56.4		B
	2531.02 Disks, 323 MBYTE	HP 7959S	2	$7.2	$14.4		C
	2531.03 Tape Drive		1	$4.0	$4.0		E
	2531.04 Laserjet Printer, 8PPM	HP 33440A	1	$2.7	$2.7		C
	2531.05 Software				$5.0		E
	2531.06 HP-IB Extenders, Single Ended	HP 37204A OPT 13	2	$1.5	$3.0		B
	2531.07 HP-IB Extenders, Double Ended	HP 37204A OPT 14	11	$1.9	$20.9		B
	2531.08 Fiber Optic Cable, 2 km, incl. connectors		4	$2.1	$8.4		C
	2531.09 Data Acquisition System	HP 3852 + options	6	$11.6	$69.6		B,E
	2531.10 Software for HP 3852	HP 44458A			$2.0		B
	2531.11 Short HP-IB Fiber Optic Cables				$8.0		E
	2531.12 Relay Racks		8	$1.5	$12.0		E
	2531.13 Graphic Display Panel				$10.0		E
	2531.14 Uninterruptible Power Supply				$5.0		E
	2531.15 Installation & Checkout	1,000 hrs @ $70/hr			$70.0		E
2532	Vacuum Diagnostic Instrumentation						
	2532.01 Ion & Pirani Gages					$100.0	B,E
	2532.01.01 Corner Station		16	$2.0	$32.0		
	2532.01.02 End Stations		10	$2.0	$20.0		
	2532.01.03 Mid Stations		12	$2.0	$24.0		
	2532.01.04 Beam Tube		12	$2.0	$24.0		
	2532.02 Mass Spectrometer Unit					$296.0	
	2532.02.01 Mass Spectrometer		8	$30.0	$240.0		E
	2532.02.02 Valves, all metal		8	$6.0	$48.0		B
	2532.02.03 Roughing Valve & Tee		8	$1.0	$8.0		E
2533	Vacuum Test Equipment						
	2533.01 Leak Detectors					$299.0	
	2533.01.01 Conventional, Turbopumped		3	$33.0	$99.0		E
	2533.01.02 Ultrasensitive		2	$100.0	$200.0		E
	2533.02 Vacuum Gage Calibration Stand					$150.0	
	2533.02.01 Spinning Rotor Gauge		3	$12.0	$36.0		E
	2533.02.02 Turbopump		1	$15.0	$15.0		E
	2533.02.03 Ion Pump		1	$15.0	$15.0		E
	2533.02.04 Design, Build & Checkout				$84.0		E

LIGO WBS 2534 -- SITE 1 SUPPORT EQUIPMENT, PHYSICAL ENVIRONMENT MONITORING INSTRUMENTATION -- UNIT COST DETAIL

	Qty	Unit Cost (000)	Extension (000)	Subtotal (000)	Subtotal (000)	BOE
2000 Site 1 Facilities & Equipment						
2500 Support Equipment						
2530 Instrumentation						
2534 Physical Environment Monitoring					$622.6	
2534.01 Seismic Vibration				$191.0		
2534.01.01 Translational Monitor	10	$7.9	$79.0			B,E
2534.01.02 Rotational Monitor	10	$7.9	$79.0			B,E
2534.01.03 Seismometer	5	$6.6	$33.0			D
2534.02 Acoustic Vibration Monitor	5	$5.7		$28.5		B
2534.03 Radiofrequency Interference Monitor	5	$9.5		$47.5		E
2534.04 Magnetic Pulse Interference Monitor	10	$8.2		$82.0		E
2534.05 Cosmic Ray Veto Detector	5	$18.9		$94.5		B,E
2534.06 Temperature & Humidity				$28.7		
2534.06.01 Temperature Monitor	60	$0.4	$24.0			B,E
2534.06.02 Humidity Monitor	5	$0.9	$4.5			B,E
2534.06.03 Calibration Set	1	$0.2	$0.2			B,E
2534.07 Mains Power				$10.0		D
2534.08 Housekeeping				$56.3		
2534.08.01 HVAC Monitor	1	$50.0	$50.0			D
2534.08.02 Weather Station	1	$6.3	$6.3			B
2534.09 Airborne Particle Counter	8	$3.3		$26.4		B
2534.10 Equipment Installation				$57.7		D

LIGO WBS 2535 -- SITE 1 SUPPORT EQUIPMENT, ELECTRONIC TEST EQUIPMENT -- UNIT COST DETAIL

		Qty	Unit Cost (000)	Extension (000)	Subtotal (000)	BOE
2000	Site 1 Facilities & Equipment					
2500	Support Equipment					
2530	Instrumentation					
2535	Electronic Test Equipment				$505.8	
	2535.01 Oscilloscope, Digital 500 MS/s	3	$11.5	$34.5		C
	2535.02 Oscilloscope, Digital 10 MS/s	6	$1.5	$9.0		C
	2535.03 Oscilloscope, Analog 150 MHz	14	$2.8	$39.2		C
	2535.04 Oscilloscope, Analog 20 MHz	12	$0.6	$7.2		C
	2535.05 RF Network/Spectrum Analyzer	5	$23.0	$115.0		C
	2535.06 Audio FFT Spectrum Analyzer	4	$13.0	$52.0		C
	2535.07 LCZ Meter	1	$7.3	$7.3		C
	2535.08 Function Generator	6	$8.4	$50.4		C
	2535.09 RF Synthesizer	3	$6.0	$18.0		C
	2535.10 Logic Analyzer	2	$3.2	$6.4		C
	2535.11 Frequency Counter	2	$1.6	$3.2		C
	2535.12 Low Noise Preamps	24	$2.8	$67.2		C
	2535.13 Lock-In Analyzer	6	$2.1	$12.6		C
	2535.14 HV Power Supply	4	$3.5	$14.0		C
	2535.15 LV Power Supply	8	$1.6	$12.8		C
	2535.16 NIM Bin/Power Supply	6	$1.3	$7.8		C
	2535.17 Special Purpose Probes			$3.5		C
	2535.18 Real Time Clock System	2	$15.0	$30.0		E
	2535.19 Miscellaneous			$15.7		E

LIGO WBS 3531, 3532 and 3533 -- SITE 2 SUPPORT EQUIPMENT, VACUUM INSTRUMENTATION -- UNIT COST DETAIL

		Description	Qty	Unit Cost (000)	Extension (000)	Subtotal (000)	BOE
3000	Site 2 Facilities & Equipment						
3500	Support Equipment						
3530	Instrumentation						
3531	Vacuum System Monitoring & Control					$268.2	
	3531.01 Computer w/ Color Monitor	HP 98583G OPT 011, HP 370	2	$28.2	$56.4		B
	3531.02 Disks, 323 MBYTE	HP 7959S	2	$7.2	$14.4		C
	3531.03 Tape Drive		1	$4.0	$4.0		E
	3531.04 Laserjet Printer, 8PPM	HP 33440A	1	$2.7	$2.7		C
	3531.05 Software				$5.0		E
	3531.06 HP-IB Extenders, Single Ended	HP 37204A OPT 13	2	$1.5	$3.0		B
	3531.07 HP-IB Extenders, Double Ended	HP 37204A OPT 14	11	$1.9	$20.9		B
	3531.08 Fiber Optic Cable, 2 km, incl. connectors		4	$2.1	$8.4		C
	3531.09 Data Acquisition System	HP 3852 + options	4	$11.6	$46.4		B,E
	3531.10 Software for HP 3852	HP 44458A			$2.0		B
	3531.11 Short HP-IB Fiber Optic Cables				$8.0		E
	3531.12 Relay Racks		8	$1.5	$12.0		E
	3531.13 Graphic Display Panel				$10.0		E
	3531.14 Uninterruptible Power Supply				$5.0		E
	3531.15 Installation & Checkout	1,000 hrs @ $70/hr			$70.0		E
3532	Vacuum Diagnostic Instrumentation						
	3532.01 Ion & Pirani Gages					$76.0	B,E
	3532.01.01 Corner Station		16	$2.0	$32.0		
	3532.01.02 End Stations		10	$2.0	$20.0		
	3532.01.03 Reserved				$0.0		
	3532.01.04 Beam Tube		12	$2.0	$24.0		
	3532.02 Mass Spectrometer Unit					$222.0	
	3532.02.01 Mass Spectrometer		6	$30.0	$180.0		E
	3532.02.02 Valves, all metal		6	$6.0	$36.0		B
	3532.02.03 Roughing Valve & Tee		6	$1.0	$6.0		E
3533	Vacuum Test Equipment						
	3533.01 Leak Detectors	Ref. WBS 2533.01				$299.0	E
	3533.02 Vacuum Gage Calibration Stand	Ref. WBS 2533.02				$150.0	E

LIGO WBS 3534 -- SITE 2 SUPPORT EQUIPMENT, PHYSICAL ENVIRONMENT MONITORING -- UNIT COST DETAIL

		Qty	Unit Cost (000)	Extension (000)	Subtotal (000)	Subtotal (000)	BOE
3000	Site 2 Facilities & Equipment						
3500	Support Equipment						
3530	Instrumentation						
3534	Physical Environment Monitoring					$391.5	
3534.01	Seismic Vibration				$98.8		
3534.01.01	Translational Monitor	5	$7.9	$39.5			B,E
3534.01.02	Rotational Monitor	5	$7.9	$39.5			B,E
3534.01.03	Seismometer	3	$6.6	$19.8			D
3534.02	Acoustic Vibration Monitor	3	$5.7		$17.1		B
3534.03	Radiofrequency Interference Monitor	3	$9.5		$28.5		E
3534.04	Magnetic Pulse Interference Monitor	5	$8.2		$41.0		E
3534.05	Cosmic Ray Veto Detector	3	$18.9	$56.7	$56.7		B,E
3534.06	Temperature & Humidity				$24.5		
3534.06.01	Temperature Monitor	54	$0.4	$21.6			B,E
3534.06.02	Humidity Monitor	3	$0.9	$2.7			B,E
3534.06.03	Calibration Set	1	$0.2	$0.2			B,E
3534.07	Mains Power				$10.0		D
3534.08	Housekeeping				$56.3		
3534.08.01	HVAC Monitor	1	$50.0	$50.0			D
3534.08.02	Weather Station	1	$6.3	$6.3			B
3534.09	Airborne Particle Counter	6	$3.3		$19.8		B
3534.10	Equipment Installation				$38.8		D

LIGO WBS 3535 -- SITE 2 SUPPORT EQUIPMENT, ELECTRONIC TEST EQUIPMENT -- UNIT COST DETAIL

		Qty	Unit Cost (000)	Extension (000)	Subtotal (000)	BOE
3000	Site 2 Facilities & Equipment					
3500	Support Equipment					
3530	Instrumentation					
3535	Electronic Test Equipment				$328.7	
	3535.01 Oscilloscope, Digital 500 MS/s	2	$11.5	$23.0		C
	3535.02 Oscilloscope, Digital 10 MS/s	3	$1.5	$4.5		C
	3535.03 Oscilloscope, Analog 150 MHz	8	$2.8	$22.4		C
	3535.04 Oscilloscope, Analog 20 MHz	6	$0.6	$3.6		C
	3535.05 RF Network/Spectrum Analyzer	3	$23.0	$69.0		C
	3535.06 Audio FFT Spectrum Analyzer	2	$13.0	$26.0		C
	3535.07 LCZ Meter	1	$7.3	$7.3		C
	3535.08 Function Generator	4	$8.4	$33.6		C
	3535.09 RF Synthesizer	3	$6.0	$18.0		C
	3535.10 Logic Analyzer	1	$3.2	$3.2		C
	3535.11 Frequency Counter	1	$1.6	$1.6		C
	3535.12 Low Noise Preamps	14	$2.8	$39.2		C
	3535.13 Lock-In Analyzer	3	$2.1	$6.3		C
	3535.14 HV Power Supply	2	$3.5	$7.0		C
	3535.15 LV Power Supply	6	$1.6	$9.6		C
	3535.16 NIM Bin/Power Supply	4	$1.3	$5.2		C
	3535.17 Special Purpose Probes			$3.5		C
	3535.18 Real Time Clock System	2	$15.0	$30.0		E
	3535.19 Miscellaneous			$15.7		E

APPENDIX D

MEASURED OUTGASSING PROPERTIES OF STAINLESS STEEL

Tests were conducted in a vacuum test facility (VTF) constructed as part of a study on the outgassing properties of stainless steel. This appendix describes these tests, which show that the LIGO vacuum system can be simplified in design and improved in performance by fabricating the beam tubes from a special low-hydrogen-content stainless steel.

1. Low-Hydrogen Stainless Steel

The vacuum obtainable in a stainless-steel vacuum vessel is typically limited by outgassing of water adsorbed on the metal surfaces and by diffusion of hydrogen from the bulk to the surface. A mild bakeout (at temperatures of about 100 °C) can reduce the water-outgassing to the extent that hydrogen gas is the principal constituent. In small vacuum systems the hydrogen-outgassing problem may be remedied either by a long high-temperature bakeout (800–950 °C is typical) or by a large increase in the pumping speed of the system. Neither technique is practical for the LIGO beam tubes.

An alternative is to reduce the hydrogen content of the stainless-steel stock prior to fabrication of the vacuum hardware. Vacuum-processing of the molten stainless steel ("vacuum melting") is effective, but would triple the cost of the stock material and could result in major procurement delays because of the limited facilities for such processing. Another approach is to subject coiled stainless-steel sheet to two special annealing steps in which the material is heated in a hydrogen-free purge gas for 24 hr. This annealed product is only nominally more expensive than standard stainless steel and is readily produced in large quantities.

A sample of type 304L stainless steel, processed for low hydrogen content by the annealing method, was developed and kindly provided to us by J&L Specialty Products Corporation, Pittsburgh, PA. Initial hydrogen content measurements by commercial laboratories on specimens cut from this sample proved inconclusive; their measurement sensitivity seemed to be below our requirements. For this reason we constructed the VTF (Figure D–1) to make direct measurements of outgassing rates in a carefully calibrated apparatus.

2. Sample Preparation

The procured sample was 50 inches wide and 0.155 inches thick, with a No. 1 hot-rolled finish (nominally 0.00015 inches rms, the roughest, least-costly finish available). Four cylindrical chambers, 30-cm diameter by 1.2-m long, were fabricated from this sample. Electron-beam welding (performed in an evacuated environment) was used to eliminate the possibility of dissolving additional hydrogen into the welds. A prebaked 2.75 inch conflat flange and half nipple was welded onto one end of each chamber. Prior to final assembly, a different cleaning procedure was used on the interior surfaces of each cylinder (see Table D–1).

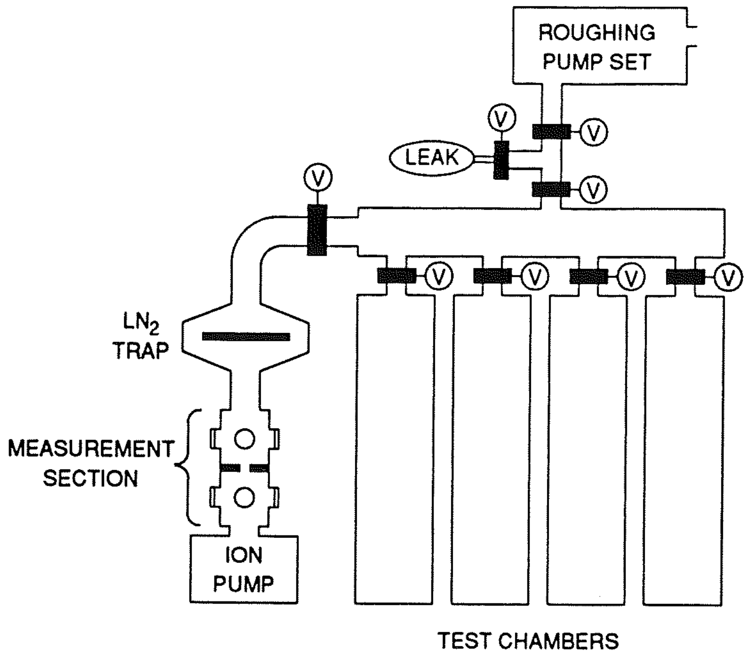


Figure D–1 Schematic diagram of the vacuum test facility (VTF) designed to measure gas flow from the test chambers. The VTF is an all-metal, bakeable vacuum system using a turbomolecular-pump backed by a mechanical pump to minimize hydrocarbon contamination. Chambers (and other components) to be tested for outgassing are connected to a manifold through all metal valves. After initial pumpdown of a chamber, the roughing pump is isolated from the system and the outgassing flux is determined in the measurement section on the left of the figure. The measurement section consists of two sections separated by a calibrated orifice evacuated by an ion pump. Each section is equipped with a residual gas analyzer (RGA), a spinning-rotor gauge (to provide an NIST-traceable calibration for the RGA) and an ionization gauge. The outgassing flow of a particular molecular species is determined by measuring the pressure difference between the two sections with the RGAs. The relation between the gas flow and the differential pressure is known by numerical modeling and confirmed by calibration with standard leaks of different gas species. A LN_2 trap is included in the measurement section to reduce the background of condensible gases (e.g., H_2O) when measuring the outgassing of a non-condensible gas (e.g., H_2). Controlled leaks are used periodically to maintain the calibration of the RGA's against the spinning-rotor gauges.

3. Test Apparatus and Procedure

Figure D–1 illustrates the apparatus used to measure outgassing from the test chambers. A single roughing-pump/turbomolecular-pump set is used to separately pump each of the test chambers through a manifold with appropriate valves. The ion pump, measurement section and liquid-nitrogen-trap ensemble is used to obtain independent measurements from each of the test chambers. Absolute gas flow measurements for any gas constituent are obtained by monitoring the pressure gradient across an orifice in the measurement section (see Figure D–1).

Outgassing of water vapor and hydrocarbons can be measured directly with

TABLE D–1
TEST CHAMBER CLEANING METHODS

Chamber Number	Process
1	Uncleaned, except obvious spots were wiped off.
2	Oakite 33 detergent, 20% solution in hot (136–143 °F) deionized water, brushed on, let stand for 30 minutes, then rinsed with hot deionized water.
3	Steam cleaned using Oakite 33 detergent, 20% solution, aspirated through steam equipment operating at 200 °F, let stand for 10 minutes, then rinsed with steam.
4	Oakite 33 detergent, 20% solution in cold (room temperature) deionized water, brushed on, let stand for 30 minutes, then rinsed with cold deionized water.

residual gas analyzers (RGA) while pumping on a particular chamber. An accumulation technique is used to measure hydrogen outgassing: hydrogen gas accumulates in an isolated vacuum chamber for some time, the valve to that chamber is opened, and the resulting gas flux transient through the orifice is measured with the RGAs. Numerical integration of the gas pulse gives the total hydrogen yield. Each chamber is measured in turn while the others accumulate hydrogen for subsequent measurements.

4. Test Results

Approximately one year's data on hydrogen outgassing from the four test chambers are shown in Figure D–2. For comparison, the estimated outgassing rate for a similar chamber constructed with standard stainless steel [D–1] is also shown in the figure. The test chambers show a large variance in initial hydrogen-outgassing rate which is not yet understood. The worst case hydrogen-outgassing rate is, however, approximately two orders of magnitude less than expected for standard commercial stainless steel.

Water-vapor outgassing from all four test chambers exhibited outgassing rates inversely proportional to time (for 6000 hours under vacuum). Water-vapor outgassing data for chamber number 1 (uncleaned) is presented in Figure D–3 along with the prediction of the standard theory [D–2]. Similar trends were observed in the other three chambers.

Hydrocarbon outgassing was lowest in the steam-cleaned chamber, approximately 100 times lower than in the uncleaned chamber.

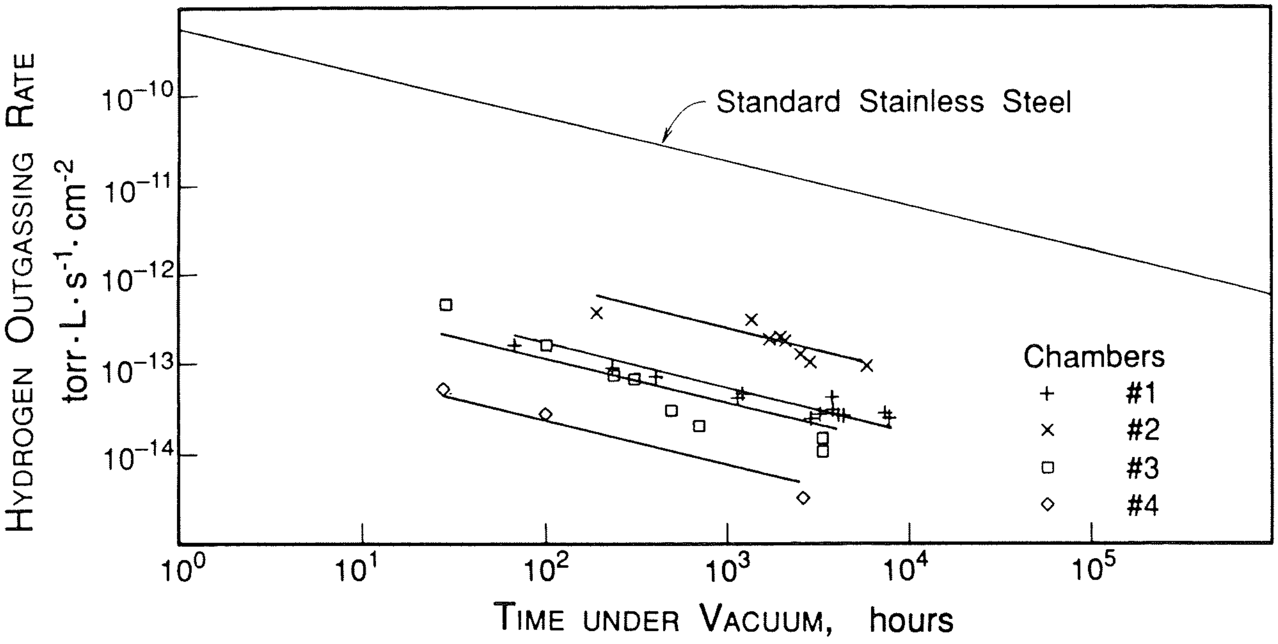


Figure D–2 Hydrogen-outgassing rate versus time under vacuum for four test vacuum chambers manufactured from low-hydrogen steel (obtained from J&L Specialty Products). These chambers were subjected to different cleaning procedures: uncleaned (1), hot water/detergent washed (2), steam cleaned with detergent (3), and cold water/detergent washed (4). The upper line is the expected degassing curve for standard stainless steel based on a diffusion model.

5. Conclusions

Fabricating vacuum chambers and beam-tube sections from stainless steel processed for low hydrogen content should result in acceptable outgassing rates for hydrocarbons and hydrogen. Unbaked chambers made from type 304L stainless steel processed for low hydrogen content have achieved hydrogen-outgassing rates as low as 3×10^{-15} torr · L · s^{-1} · cm^{-2}. With the pumping system described in Section IV.D, this would result in a partial pressure of hydrogen in the beam tubes of approximately 5×10^{-11} torr.

Test data confirm that water-vapor outgassing will not be a problem for initial interferometers; however, a mild bakeout is planned to reduce water-vapor pressure to the goal for advanced interferometer operation.

Steam cleaning (a practical and low-cost method of removing surface contamination) resulted in lower hydrocarbon outgassing than other cleaning methods tested, with no measurable effect on water-outgassing rates.

References

D–1 R. Calder and G. Lewin, "Reduction of Stainless Steel Outgassing in Ultra-High Vacuum," *Brit. J. Appl. Phys.*, **18**, 1459, (1967).

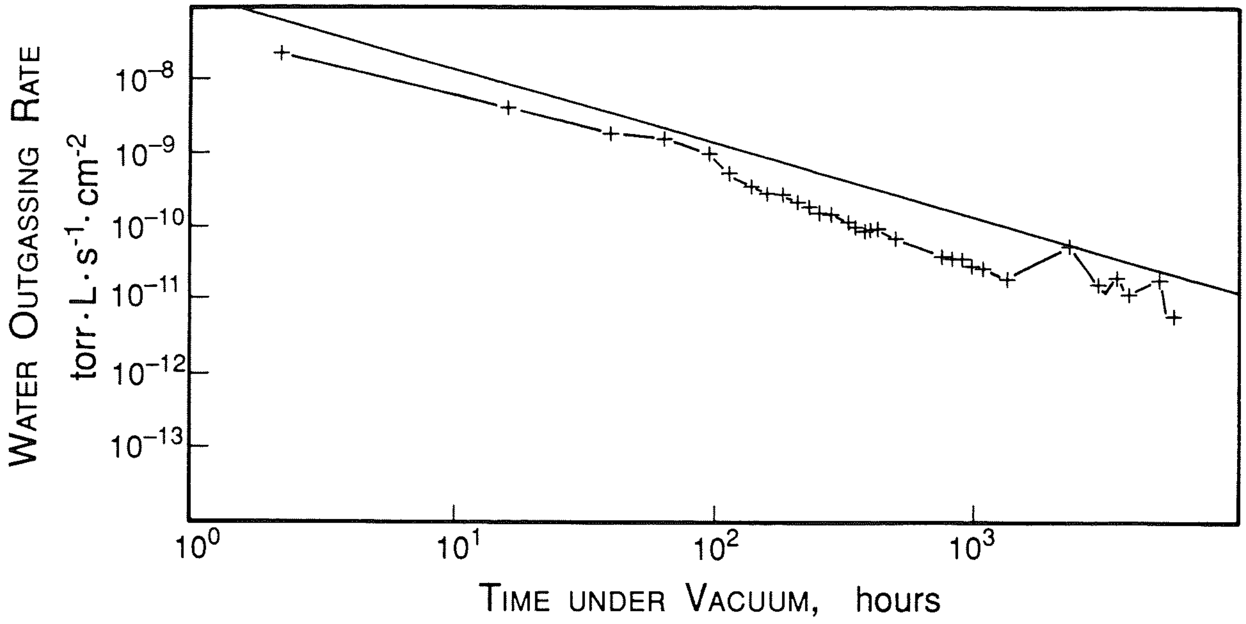
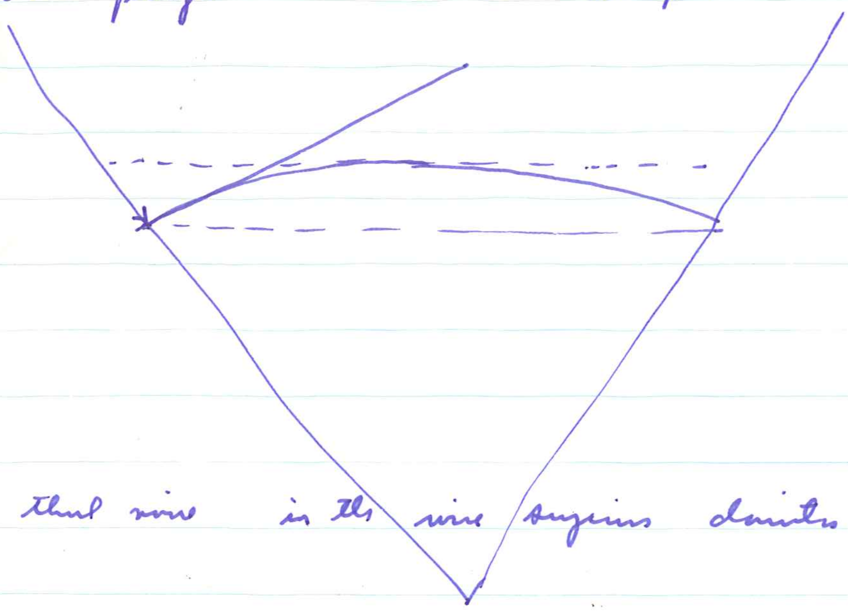


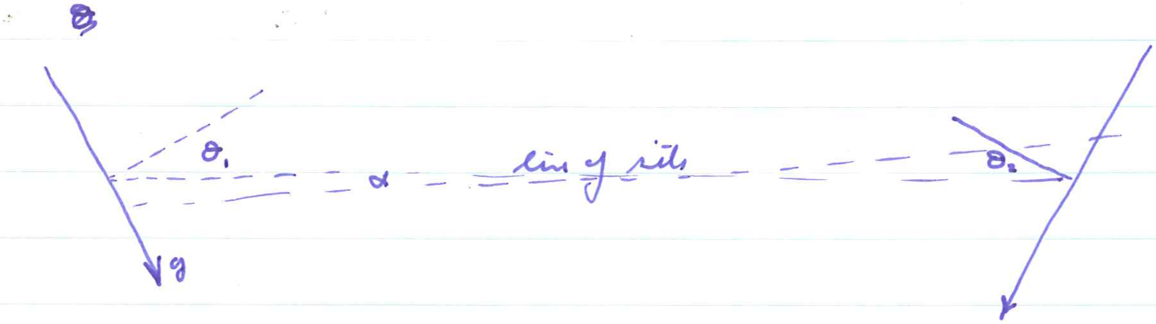
Figure D–3 Water-outgassing rate versus time under vacuum for a chamber fabricated from low-hydrogen-content stainless steel. The lower curve is the measured outgassing rate of an uncleaned chamber. The slope discontinuities are due to periods when the chamber was closed for accumulation measurements. All four test chambers have similar water-outgassing curves. The upper line is a prediction based on a standard model for unbaked stainless-steel systems showing a 1/t dependence where t is the time under vacuum.

D–2 B. B. Dayton, "Outgassing Rate of Contaminated Metal Surfaces," *Transactions of the Eighth National Vacuum Symposium*, **1**, 42 (Pergamon Press 1962).

Suppose the pointing method is via midpoint



assume that noise in the wire suspensions dominates



Component of the noise along line of sight

$$\varphi_{TH} = \left(\theta_1^2 + \theta_2^2\right)^{1/2}$$

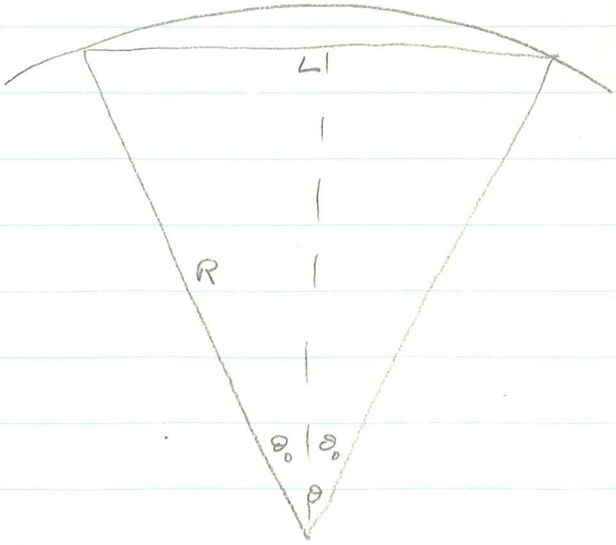
Now θ_1 and θ_2 are not independent

$\theta_1 = \theta_0 + \alpha$ $\qquad$ $\theta_2 = \theta_0 - \alpha$

$$\varphi_{TH} = \left((\theta_0+\alpha)^2 + (\theta_0-\alpha)^2\right)^{1/2}$$

$$= \left(\theta_0^2 + 2\alpha\theta_0 - 2\alpha\theta_0 + 2\alpha^2\right)^{1/2}$$

$$= \left(\theta_0^2 + 2\alpha^2\right)^{1/2}$$



$\theta_0 = \dfrac{L}{2R_\oplus} = 6.3 \times 10^{-4}$

ADDITIONAL THERMAL NOISE AMPLITUDE FROM VERTICAL SUSPENSION AS A FUNCTION OF DEVIATION OF LIGO PLANE FROM HORIZONTAL

$$\varphi = c\left(\theta_0^2 + 2\alpha^2\right)^{1/2}$$

$$\theta_0 = \frac{L}{2R_\oplus} = 6.3\times10^{-4} \text{ Rad}$$