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# Option/Specimen Contract/Phase II
# Exhibit IV
# Design Requirements for the In-Vacuum Mechanical Elements of the Advanced LIGO Seismic Isolation System for the BSC Chamber

## A. References (on enclosed CD, Exhibit II); note that in case of apparent conflict between a referenced document and this text, this text shall take precedence.

1. Actuator drawings: BEI Kimco, #LA18-32-006Z, #LA50-62-004Z
2. Chamber SolidWorks files: HAM-Chamber, HAM Support Rod, HAM Expansion Bellows Assembly, BSC Chamber Lower, BSC Chamber Upper, BSC Support Rod, BSC Expansion Bellows Assy.
3. D020525-00, Advanced Seismic Isolation Technology Demonstrator (309 files)
4. Displacement Sensor drawings: ADE #020536-A01 (10 mm sensor), ADE 20 mm sensor
5. External Support Parts: for BSC (9 files), for HAM (14 files)
6. Seismometer Lock files: STS-2 folder (28 files), GS-13 folder (63 files)
7. Seismometer drawings: Streckeisen STS-2, Mark Products L-4C, Geotech GS-13
8. D000241-C, LIGO II Stiff Active Seismic Isolation System
9. D010120-D, Cable Clamps, 40M
10. D030100-00, ADVLIGO SEI BSC Optical Table & Structure Limits
11. D030169-00, ADVLIGO SEI Corner Configuration
12. D961094-04, HAM Assembly
13. D970412-01, BSC Overall Assembly
14. D972001-B, BSC Top Assembly
15. D972121-F, BSC Support Tube Weldment
16. D972501-B, HAM Top Assembly
17. D972610-G, HAM Support Tube Weldment
18. E960022-07, LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures
19. E960050-A, LIGO Vacuum Compatible Materials List
20. E990452-L, SPP-080 Rev. O, Cleaning & Preserving LIGO BSC & HAM Aluminum Weldments and Machined Shims
21. E990453-N, SPP-081 Rev. O, Final Cleaning and Packaging of LIGO S.S. Support Tubes, Leg Elements and Balance Weights
22. E990456-B, SPP-093 Rev. C, FT-IR Test Procedure, BSC Downtube & Support Table Assembly, D972210

## B. General:

1. The structure's purpose is to provide a mounting surface for optical components that is isolated from the local floor vibration. The BSC structure will be mounted in a LIGO BSC chamber. The elements of a structure are shown schematically in plan view in D000241, LIGO II Stiff Active Seismic Isolation System; this

contract is limited to the in-vacuum portion of this schematic. The structure consists of three stages that are interconnected with springs. Stage 0 mounts on existing chamber support elements. It supports Stage 1 with three blade springs and flexures, and has actuators mounted that adjust the position of Stage 1. Stage 1 will have seismometers mounted to track its motion and displacement sensors to monitor its position with respect to Stage 0. Stage 1 supports Stage 2 with three blade springs and flexures, and has actuators mounted that adjust the position of Stage 2. Stage 2 has seismometers mounted to track its motion and displacement sensors to monitor its position with respect to Stage 1.

2. The Technology Demonstrator files D020525 depict a prior design that has much the same features as the subject of this task; it is included as reference only.
3. The structure shall be designed to be shipped as an assembled module (except for the pods, which are shipped separately). Custom crating shall be designed and provided, with adequate bracing and packaging to hold the units securely under severe shipping loads.

**C. Stage Structures:**

1. Major structure elements shall be made of aluminum to keep weight to a minimum, while minimizing material costs.
2. The BSC structure Stage 0 shall mount on the twenty bosses of each of the two Support Tubes (D972121) in the BSC Chamber (D972001).
3. The optical table of the BSC structure, shown in D030100, shall be of inverted configuration, as compared with the Technology Demonstrator structure. That is to say, optical components shall be clamped to the bottom of the Optical Table, rather than to the top.
4. As shown in D030100, mounted hardware on the BSC support tubes shall not protrude more than 1.90" (4.8 cm) beyond the inboard interface bosses of the Support Tubes. Tool access shall be within 2.88" (7.3 cm) beyond that point.
5. See drawing D030100; the portion of the BSC structure between the horizontal mounting interface with the Support Tubes and the structure's optical table plane shall be capable of a reduction in height of up to 10 cm, by a simple re-design, thus lowering the optical table. Note: the LIGO project shall commit to the height decision prior to the start of the Phase II contract.
6. The BSC structure assembly shall include a means for lifting with a crane hook, above its center of gravity, such that the dimension from the position of the axis of the support tube to the center of the hook pin shall not be greater than 60.87" (154.6 cm). No part of the BSC structure assembly shall extend more than 1.5" (3.8 cm) above the center of the hook pin (see D030100).
7. All portions of the structure shall fit within the BSC chamber with a minimum clearance of 0.5" (1.3 cm). Note that Chamber SolidWorks files are provided for convenience in solids modeling; however, information from drawing D970412 is to be used for confirming clearance with the BSC chamber. The three, separate stages of each structure shall fit together with inter-stage clearances of at least 0.2" (0.5 cm).

8. The structure shall be designed to survive shipping loads and earthquake shock loads of 1.0 g vertical and 0.5 g horizontal for an assembled module.
9. The structure must be suitably stiff to allow proper functioning of the servo control systems. The criteria stated below for the various structural elements or stages apply to the structure complete with mounted displacement sensors, dummy seismometers, actuators, and a mass equal to the structure payload, distributed over the optical table. Finite Element models of the complete design must be constructed to quantitatively predict and document compliance with these requirements. In addition to the structure being designed, the finite element model shall also include (on Stage 0) (see External Support Parts for the BSC): the support tubes, mounting caps and bases, crossbeams, crossbeam attachment plates and crossbeam feet (pointed at $45^o$, toward the chamber center). Assume that the crossbeam feet are freely supported for analysis purposes. The Finite Element model shall also include a dummy payload whose CG is clamped at an X, Y of 9.1”, 9.1” (23.1 cm, 23.1 cm); see H.2.

   Assume a sinusoidal excitation, that applies a force, $p(t) = p_0\cos(2*pi*f*t)$, where f = frequency and t = time, along the actuator's nominal force axis, exerted between the stage holding the seismometer or displacement sensor and the stage to which the other side of the actuator is mounted. On the seismometer/ displacement sensor's stage, this excitation will cause a sinusoidal displacement at the location of the actuator's center of gravity (CG), $x_a(t)$ and one at the CG of the seismometer or displacement sensor, $x_s(t)$. These displacements shall be measured along the seismometer’s, the displacement sensor’s and the actuator's nominal axes. The frequency-domain Fourier coefficient X(f) is defined by x(t) = Re{X(f)*cos(2*pi*f*t)}. X(f) is complex, i.e., X(f) = |X(f)| exp{i phase(X(f))}.

   - For common-corner seismometer/actuator and displacement sensor/actuator pairs that share an axis direction on stages 1 and 2: the phase of the transfer function $X_s/X_a$ shall be greater than -90 degrees for all frequencies below 500 Hz.
   - For all other pairs of seismometer and actuator, and displacement sensor and actuator on stages 1 and 2: the phase of $X_s/X_a$ shall be greater than -90 degrees for all frequencies below 150 Hz.
   - For all pairs of displacement sensor and actuator on stage 0: the phase of $X_s/X_a$ shall be greater than -90 degrees for all frequencies below 100 Hz. If a mode that causes a phase excursion has only minimal amplitude in the $| X_s/X_a |$ of all of the above pairs, and the phases return above -90 degrees above the resonance frequencies, and with Caltech's consensus, the modal frequency may not count against this requirement. (This sort of behavior may result from modes that primarily involve motion of the external structure.)

10. The minimum design resonant frequency for all parts of Stages 1 and 2 shall be 150 Hz.

11. Kinematic Locator devices (such as screws) are required between Stage 0 and Stage 1, and between Stage 1 and Stage 2 (see D030169) to serve the following functions. These shall be kinematic, accessible (including when the modules are in their respective chambers) and conveniently adjusted.
    - They shall place the stages at their proper relative (operational) orientations in all 6 degrees of freedom (DOFs) for a multitude of purposes: assembly, alignment, installation of displacement sensors, installation of actuators, adjustment of operational limit stops, etc.
    - Screws with spring-loaded tips shall be provided to aid in clamping stages together adequately in their kinematic locators.
    - For assembly, the stages will be locked in the location determined by the kinematic locators (see Lockdowns, next item). For installation of displacement sensors and actuators, the stages may be held against the kinematic locators by either the spring tip screws or the lockdown system. For adjustment, tuning, and testing the spring-tip screws shall be sufficient to hold the stages against the kinematic locators. While the isolation is operational, the kinematic locator devices (screws) shall be backed off or removed to prevent interfering with actuator motion. They shall be sufficiently hardened and procedures shall be such as to prevent their damage during transitions to and from a locked position.
12. Lockdown systems are required between Stage 0 and Stage 1, and between Stage 1 and Stage 2 (see D030169) to serve the following functions. These shall lock the stages in all 6 DOFs, and shall be accessible (including when the structures are in their respective chambers) and conveniently adjusted, and shall be designed to support the larger of: a) earthquake loads as described above, and b) 50% more than expected shipping and handling loads.
    - When set in the clamping mode, they shall hold the stages in their respective operating positions and prevent relative motion between stages when exposed to earthquakes or shipping loads.
    - When set in the operational mode, they shall provide “stops” to limit travel during an earthquake to an conveniently set, adjustable, pre-determined value. The range of this setting shall be variable from 0 to 0.08” (0.2 cm).
13. Heavy structure elements shall have lifting provisions to aid in assembly.
14. The radii of gyration of Stage 1 and Stage 2 shall be at least 50% of the stage’s maximum radius, with the preferred value being at approximately 80% of that radius.

**D. Actuators, Seismometers, Displacement Sensors, Springs & Flexures:**

1. Components shall be provided for as follows (refer to the in-vacuum portion of D000241 and also see D030169):
    a. between Stage 0 and Stage 1:
        i. magnetic actuators, BEI Kimko LA50-62-004Z (44 $lb_f$ continuous stall) (see drawing; modifications are being worked for vacuum compatibility and heat dissipation), 6 each, 2 at each of 3 “corners”, one vertical and one tangential. Note: for this document,

the term “tangential” refers to a component having its axis perpendicular to the line connecting the center of the structure with the displacement sensor’s axis at the sensor plane (or, in the case of actuators and seismometers, “…with the actuator’s/ seismometer’s axis at the center of the actuator/seismometer”), in plan view. The plane defined by the actuation centers of the 3 horizontal actuators shall be within 0.040” (1 mm) of the plane defined by the lower zero moment points (LZMPs; see definition in iii. below) of the 3 flexures at that interface. These 2 planes shall be parallel to within 1 mrad. Each horizontal actuator shall have its axis parallel to the plane defined by the LZMPs to within 1 mrad. The “bobbin” (wired) side of the actuators shall be attached to the ground side of each stage interface, for directed heat transfer; for instance, the bobbin side of the Stage 0-Stage 1 actuators shall be attached to Stage 0, which is closer to ground state.

ii. capacitive displacement sensors, ADE Technologies, 20 mm ceramic passive probes (see drawing), 6 each, 2 at each of 3 “corners”, one vertical and one tangential. Each pair shall be at least 39” (1 m) from the other two pair at this stage interface. Each position shall be made with added mounting holes and spacers to alternatively mount the 10 mm ADE sensors. The displacement sensor targets shall be made of 1100 aluminum, at least twice as wide as the 20 mm dia. sensors, with a surface flatness of 0.0004” (10 micrometer) and a surface finish of 0.000004” (0.1 micrometer). The tangential sensor axes shall coincide with the plane defined by the LZMPs of the flexures to within 1 mm. The sensors for vertical displacement shall be parallel to the plane defined by the LZMPs of the flexures to better than 1 mrad. The axis of the each vertical displacement sensor shall be placed (as closely as practical) near the axis of the vertical actuator that spans the same stages at that corner. The target standoff for the 20 mm dia. displacement sensors shall be 0.080” (2 mm) and the targets shall be adjusted to be parallel to the displacement sensors to within 1 mrad.

iii. spring and flexure sets, 3 each, 1 at each of 3 “corners”, of Maraging 300 steel; springs of trapezoidal pattern and cut by EDM, designed to be planar and horizontal when under operational loading; springs and flexures to be designed for a maximum stress of 35% of yield strength, with a goal of 30%, when operating at the working load and with the flexure laterally offset as much as 1 mm from its nominal location. Spring and flexure design shall follow the patterns shown in Technology Demonstrator drawings p00067-029 through –037, with the exception of –033, Flexure Fix; this was incorporated to salvage parts that were warped during age hardening. If other exceptions are desired, they must be proposed to the Technical Manager and approved prior to final design. The design shall call out the procurement of material from a single heat of Maraging 300 steel for each set of springs, as well as performing heat treat of each set of springs in a common batch, in order to minimize variation of spring constants within a set.

Springs:
Max stiffness: 4225 $lb_f$/in (7.4e5 N/m)
Max length: 19.7" (50 cm)
Max base width: ½ of length
The spring must lie flat at the working load of the system. The radial position of the spring tips and flexures shall fall at between 70% and 90% of the maximum structure radius.

The 12 coupled frequencies shall lie between 2 and 10 Hz. Within this range, lower stiffness is preferred.

The flexures shall be designed such that the upper zero moment point of each flexure shall lie on the neutral axis of its spring. The zero moment points are defined by the following length from the fillet tangent at each end:

$$z = (1/k) * \tanh(k*L/2)$$

where k = sqrt{P/(E*I)} and L = flexure length, P = flexure load, E = Young's modulus, and I = flexure area moment of inertia. The springs and flexures shall be located within the structure such that the flexures lie at the corners of an equilateral triangle, which is centered in the structure in the X-Y plane.

b. on Stage 1 (mounted in pods):
   i. seismometer, Mark Products L-4C (see drawing), 6 each, 2 within each of 3 instrument pods, one vertical and one tangential, all within 1 mrad.
   ii. broadband seismometer, 3-axis, Streckeisen STS-2 (see drawing), 3 each, 1 within each of 3 instrument pods; each seismometer's axes directed as follows: +z axis vertical (upward), +y axis tangential and +x axis radial (toward the center of the structure), all within 1 mrad. Each STS-2 will have 3 devices for remotely locking and unlocking each axis; see Seismometer Lock files.

c. between Stage 1 and Stage 2:
   i. magnetic actuators, BEI Kimko LA18-32-006Z (7 $lb_f$ continuous stall) (see drawing; modifications are being worked for vacuum compatibility and heat dissipation), 6 each, 2 at each of 3 "corners", one vertical and one tangential. Configuration, position and location tolerances are as in D.1.a.i above.
   ii. capacitive displacement sensors, ADE Technologies #020536-A01, 10 mm ceramic passive probes (see drawing), 6 each, 2 at each of 3 "corners", one vertical and one tangential. Each pair shall be at least 39" (1 m) from the other two pair at this stage interface.

Each position shall be made with added mounting holes to alternatively mount the 20 mm ADE sensors. The displacement sensor targets shall be made of 1100 aluminum, at least twice as wide as the 20 mm dia. sensors, with a surface flatness of 0.0004" (10 micrometer) and a surface finish of 0.000004" (0.1 micrometer). The tangential sensor axes shall coincide with the plane defined by the LZMPs of the flexures. The sensors for vertical displacement shall be parallel to the plane defined by the LZMPs of the flexures to better than 1 mrad. The axis of each vertical displacement sensor shall be placed (as closely as practical) near the axis of the vertical actuator that spans the same stages at that corner. The target standoff for the 10 mm dia. displacement sensors shall be 0.020" (0.5 mm) and the targets shall be adjusted to be parallel to the displacement sensors to within 1 mrad.

iii. spring and flexure sets: , 3 each, 1 at each of 3 "corners", of Maraging 300 steel; springs of trapezoidal pattern and cut by EDM, designed to be planar and horizontal when under operational loading; springs and flexures to be designed for a maximum stress of 35% of yield strength, with a goal of 30%, when operating at the working load and with the flexure laterally offset as much as 1 mm from its nominal location. Spring and flexure design shall follow the patterns shown in Technology Demonstrator drawings p00067-029 through –037, with the exception of –033, Flexure Fix; this was incorporated to salvage parts that were warped during age hardening. If other exceptions are desired, they must be proposed to the Technical Manager and approved prior to final design. The design shall call out the procurement of material from a single heat of Maraging 300 steel for each set of springs, as well as performing heat treat of each set of springs in a common batch, in order to minimize variation of spring constants within a set.

Springs:
Max stiffness: 2512 $lb_f$/in (4.4e5 N/m)
Max length: 19.7" (50 cm)
Max base width: ½ of length
The spring must lie flat at the working load of the system. The radial position of the spring tips and flexures shall fall at between 70% and 90% of the maximum structure radius.

The 12 coupled frequencies shall lie between 2 and 10 Hz. Within this range, lower stiffness is preferred.

The flexures shall be designed such that the upper zero moment point of each flexure shall lie on the neutral axis of its spring. The springs and flexures shall be located within the structure such that the flexures lie at the corners of an equilateral triangle, which is centered in the structure in the X-Y plane.

d. on Stage 2 (mounted in pods):
   i. Seismometer, Geotech GS-13, 6 each, 2 at each of three "corners", 1 vertical and 1 tangential, all within 1 mrad. See drawing for the general configuration: page 1 for as-purchased, horizontal axis mounting, without tie-downs, and page 2 for one design with custom tie-downs. Modify the custom tie-down design as required to provide a kinematic mount of the GS-13 in the pod, for both the tangential and the vertical axis configurations. Each GS-13 will have a device for remotely locking and unlocking the instrument (see Seismometer Lock files).

2. Access shall be provided for installation, adjusting and removal of all pods, actuators, sensors, springs and flexures (including when the structures are in their respective chambers).

**E. Instrument Pods:**

1. This task provides for the design of the instrument pods, which will include provisions for installing seismometers and lock/unlock devices. The actual seismometers and lock/unlock devices, however, are to be provided by others.
2. The instrument pods will be removable (including when the modules are in their respective chambers) for maintenance. They should be repositionable upon replacement with 0.1 mrad angular and 0.004" (0.1 mm) positional accuracy.
3. The seismometers with their lock/unlock devices will be contained within the pods.
4. All instruments will be mounted in the pods kinematically.
5. Each Stage 1 pod shall contain an STS-2 seismometer and two L-4C seismometers. The Stage 1 pod shall accommodate mounting of the three lock/unlock devices (one for each axis) for the STS-2 seismometer, as defined by drawings in the folder, STS-2 Lock. It is preferred that the Stage 1 pods be located (as closely as practical) on-axis with the vertical actuators between Stages 0 and 1.
6. Each Stage 2 pod shall contain a GS-13 seismometer. The Stage 2 pod shall accommodate mounting of the lock/unlock device for the GS-13 seismometer, as defined by drawings in the folder, GS-13 Lock. It is preferred that the vertical Stage 2 pods be located (as closely as practical) on-axis with the vertical actuators between Stages 1 and 2.
7. The pods shall be sealed with reliable, ultrahigh vacuum seals; one acceptable type would be Conflat[*](CF)-type knife-edge flanges with flat copper gaskets.
8. The pods shall be filled with a trace gas mixture of 10 +/-1% neon in air for identification of leakage. This requirement can be met by performing pod

[*] Conflat is a registered trademark of Varian Vacuum Products

assembly inside a glove box filled with 100% trace gas mixture at atmospheric pressure.

9. Each pod shall have a CF-type flange welded to provide electrical access as follows:
    i. The Stage 1 pods shall have a 4.50" OD CF-type flange
    ii. The Stage 2 pods shall have a 2.75" OD CF-type flange

   This flange shall be compatible with repeated matings to a stainless steel CF-type flange of the same diameter, using copper gaskets, and still pass the pod leak test.
10. The interface between the stage and the instrument pod will be three 1.0" (2.5 cm) diameter, mounting pads.
11. Each pod shall pass a 1 x $10^{-10}$ tl/sec leak test, using helium in a hood type test.

**F. Alignment:**

1. The axes of the displacement sensors shall be aligned to better than 1% (i.e., a tangential sensor shall be tangential to <0.01" (0.25 mm) over 1" (2.5 cm)).
2. Each displacement sensor/target set shall be adjusted to be parallel within 1 mrad.
3. An alignment jig shall be provided to align each actuator coil with respect to its magnet such that its close tolerance side gap is balanced, side-to-side, to within 0.004" (0.1 mm) and it is mid-range in the directions of stroke and large tolerance side gap, to within 0.040" (1.0 mm). Actuator mounting feature details shall accommodate this alignment, and the jig design and procedures shall be such that the spacing is maintained upon jig removal.
4. Misalignment of the flexures and spring attachments could cause the system to suffer horizontal misalignments when released from the 6 DOF kinematic locators. The misalignment of the flexures and spring attachments shall not cause the suspended location of the system to be misaligned by more than 0.1 mm at any location between stage 0 and stage 1, and (0.05 mm) between stage 1 and stage 2.
5. A procedure and fixturing shall be provided for installing the springs and flexures without damage to the spring, the flexure or any other part of the system. Note that the flexure is easily damaged.

**G. Optical Table:**

1. The BSC structure optical table portion of Stage 2 shall be a rectangular (with corners clipped; see D030100) plate of 6061-T6 aluminum, with outer dimensions of 59.0" (150 cm) x 66.0" (168 cm), with the 66" (168 cm) dimension parallel to the chamber's support tubes.
2. The optical table shall be centered in the BSC chamber's plan view.
3. The optical table shall contain a matrix of ¼-20 tapped holes with minimum depth of 0.5" (1.3 cm) at a spacing of 2.00" (5.08 cm) x 2.00" (5.08 cm), spread over the entire surface. The holes shall have an 82$^{o}$ countersink of 0.390" (0.99 cm) diameter. One axis of the matrix shall be parallel to the axes of the chamber support tubes.

4. The optical table shall be flat within 0.01” (0.25 mm), with a surface finish of 64 rms or better.
5. The bottom surface of the optical table shall be 18.49” (47.0 cm) above the structure upper interface with the BSC Chamber Support Tubes. No part of the BSC structure shall protrude into an imaginary vertical axis box of cross sectional dimensions the size of the optical table at the plane of the optical table and extending downward, and reducing to dimensions of 66.0” (168 cm) x 49.45” (125.6 cm) with the 66.0” (168 cm) dimension parallel to the chamber’s support tubes) from 6.0” (15.24 cm) below the optical table and below. See Drawing D030100 for optical table shape details, shape and size of the “stay clear” zone and fastening tool access limits.

**H. Masses:**

1. The following masses are defined as part of the BSC Structure; the total of these shall be limited to a maximum of 8236 $lb_m$ (3736 kg); less mass is much preferred.
    i. all Structure elements defined elsewhere in these requirements, except for the Payload described in H.2 below, including structural members, pods, seismometers, actuators, displacement sensors.
    ii. trim masses, which shall be bolted to Stages 1 and 2 in locations and in increments of mass to make each loaded spring flat (correcting the levelness of each stage for variations in spring stiffness) which will level the optical table (to within 0.2 mrad).
    iii. balance masses, which shall be bolted to Stages 1 and 2 in locations and in increments of mass to properly locate the center of gravity (CG) of Stages 1 and 2 in accordance with H.4, when a Payload (see H.2) is installed.
2. The following masses are defined as the Payload:
    i. the aggregate of masses of individual nonsuspended optical components mounted on the optical table in a chamber; use 1389 $lb_m$ (630 kg) for modeling purposes
    ii. the aggregate of masses of individual suspended optical components mounted on the optical table in a chamber; use 375 $lb_m$ (170 kg) for modeling purposes

    These payload components are the responsibility of the LIGO project. The contractor is only responsible to emulate the mass properties of the payload for the purpose of testing the assembly in accordance with the Statement of Work requirement c.7. The total of masses of optical components (both non-suspended and suspended masses) shall be 1764 $lb_m$ (800 kg) for a BSC system. The effective first mass moments of the ensemble of payload components shall be:

    - Mx = total Payload mass times the composite center-of-mass x-position (direction parallel to the support tubes, referenced to optical table center) = +/- 16,100 $lb_m$-in (+/-185 kg-m)

- My = total Payload mass times the composite center-of-mass y-position (direction perpendicular to the support tubes, referenced to table center) = +/- 16,100 $lb_m$-in (+/-185 kg-m)
- Mz = non-suspended mass times the composite center-of-mass z-position (vertical, referenced to optical table surface) = -39,800 to -38,100 $lb_m$-in (-459 to -439 kg-m)

3. Interpretation (not requirements): given the envelope restrictions, anticipated mass of Stage 2, anticipated position of Stage 2 (without balance or trim masses) CG and the anticipated position of the Stage 2 LZMPs, the above mass requirements imply a total addition of non-structural mass (payload plus balance and trim mass) on Stage 2 of approximately 2646 $lb_m$ (1200 kg) total. The above requirements also imply a requirement to provide balance masses which total approximately 882 $lb_m$ (400 kg) (i.e., 2646 $lb_m$ (1200 kg) less the optics table mounted elements totaling 1764 $lb_m$ (800 kg)) and the capability to place these masses at the top of the Stage 2 envelope for the purpose of leveling the table and setting the CG position within the prescribed tolerance of H.4.
4. The CG of Stage 2 of the BSC structure shall lie from 0-0.31” (0-8 mm) above the plane of the centers of the actuators at the Stage 1-2 interface.
5. The Stage 1 CG shall lie at +/- 0.16” (+/- 4 mm) vertically with regard to the Stage 2 CG.

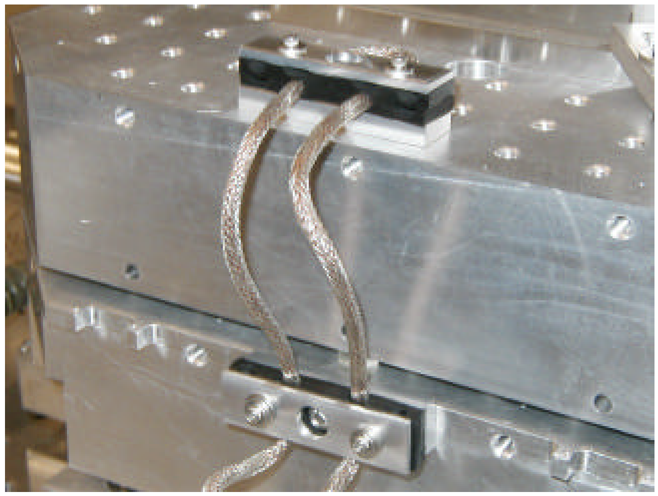
## I. Cabling:

1. Clamping and routing provisions shall be made for the following control system cables, at each of three equally spaced areas around each structure. These cables shall be clamped at each stage that they traverse in sequence of suspension hierarchy, with cables spaced and routed such that they do not touch each other, do not touch any other items between clamps and will not sag over time to a position that causes them to touch. Clamps to be used will be as shown on D010120-D, Cable Clamps, 40M; the assembly is as shown in this photo (following) of a smaller unit. This task provides the mounting provisions for the clamps and cables; clamps and cables are provided by others. The following list is for each of three positions around each structure.

   Stage 1 (cables clamped at Stage 0 and Stage 1):
   - STS-2 broadband seismometer, 1 ea, 9 twisted pair of 28 ga conductors per, with shield
   - L4-C seismometer, 2 ea, 3 twisted pair of 28 ga conductors per, with shield
   - capacitive displacement sensor, 2 ea, 1 coax of 28 ga (minimum) conductors per
   - BEI Kimco voice coil actuator, 2 ea, 1 twisted pair of 10 ga conductors per, with shield

   Stage 2 (cables clamped at Stage 0, Stage 1 and Stage 2):
   - GS-13 seismometer, 2 ea, 4 twisted pair of 28 ga conductors per, with shield

- capacitive displacement sensor, 2 ea, 1 coax of 28 ga (minimum) conductors per
- BEI Kimco voice coil actuator, 2 ea, 1 twisted pair of 16 ga conductors per, with shield
- Optical Suspension controls, 5 ea, 12 twisted pair of 28 ga conductors per, with shield



Cable clamp assemblies, 4 cable capacity

**J. Vacuum Compatibility:**

1. The structures shall be designed for an ultrahigh vacuum environment.
2. All materials exposed to the vacuum environment shall be in accordance with the approved materials list (E960022, E960050). Document E960050 shows two lists: Table 1 for approved materials, and Table 2 for materials that could possibly be provisionally approved, if required and conditions permit. Document E960022 shows the procedure LIGO uses to qualify materials and the cleaning methods used for small parts.
3. All welds shall be made as full penetration welds to eliminate trapped volumes caused by welding.
4. Other trapped volumes (except for pod interiors) shall be provided with holes for venting during pumpdown.
5. All tapped holes shall be made with 0.005" (0.13 mm) oversize taps for minimizing the potential for galling.
6. All nuts used external to the pods shall be retapped with 0.005" (0.13 cm) oversize taps for minimizing the potential for galling.
7. Stainless steel screws shall be used in aluminum tapped holes, and silver-plated stainless steel screws shall be used in stainless steel tapped holes, for minimizing the potential for galling. Silver plated screws shall be made undersize to account for plating thickness, and the plating thickness shall be controlled accordingly.

8. Lubricants (other than silver plating) are not acceptable in the assembled structures.
9. Processing: all parts shall be processed in a manner similar to that detailed in procedures listed in E990452, E990453 and E990456, which include the general processes listed below:
   - cleaning: after visual contamination is removed, brushes and wipes are used with lacquer thinner, acetone, alcohol, phosphoric acid, detergent and hot, deionized water for a thorough cleaning. A visual “water break” test is made to confirm the absence of a hydrocarbon film on the parts, and the parts are drained and blown dried with filtered $N_2$ or $C0_2$. Care is taken to not recontaminate by handling equipment or personnel throughout this and subsequent steps. Precautions are taken to assure safety in working with acid and combustible vapors.
   - sampling: the surfaces of each cleaned part are flushed with ultra high purity isopropyl alcohol (<1 ppm residue after evaporation), which is collected in a ultra clean bottle and shipped to the following laboratory for FTIR (Fourier Transform Infra Red) testing, a measurement of hydrocarbon content: Fitzsimmons & Associates, Inc., 1860 Arthur Drive, West Chicago, IL 60185 (telephone: 630 231-0680). Control samples of the alcohol are also taken and analyzed to confirm control of the sampling process. The results are reported to LIGO; if not approved, cleaning, sampling and baking are repeated until acceptable results are achieved.
   - bakeout: all parts are baked in a clean environment to temperatures of 120C for aluminum parts and 200C for stainless steel parts, with bake temperatures held for 48 hours.
   - assembly: once sampling results have been approved and the parts have been baked, the structure is assembled in a clean room, with cleanliness maintained. Pods are not part of the assembled module.
   - packaging: ultrahigh vacuum clean aluminum foil with fold lap seams and Class 100 “Strato-Gray” plastic sheeting (double bagged) with tie wire (inner bag) and heat sealed seams (outer bag) used to package the structure, following an explicit wrapping plan.
   - labeling: the outer bag is labeled to identify the assembly (part name, number/revision, serial number), date baked and the statement, “Cleaned and Baked for Ultrahigh Vacuum Service”
   - crating: the part is then crated with securing fixtures and pads, taking care to prevent puncturing the packaging. The crate is properly labeled and kept protected from precipitation.

**K. Drawing Notes:**

The following notes shall be added to all shop drawings, as appropriate:
1. All dimensions in inches
2. Dimensions and tolerancing per ASME Y14.5M-1994
3. Surface texture per ANSI/ASME B46.1-1985
4. Remove all burrs and break sharp edges to a maximum of 0.015”

5. All inside corners to be 0.015" radius max.
6. Countersink 82 degrees all tapped holes to major diameter
7. Countersink 82 degrees approximately 0.015 deep all drilled holes
8. Parts shall be thoroughly cleaned to remove all oil, grease, dirt and chips
9. All aluminum welding done by a GTAW process using 2% thoriated tungsten welding electrodes and ER4043 filler material
10. All stainless steel welding done by a GTAW process using 2% thoriated tungsten welding electrodes and ER308L filler material
11. All machining fluids shall be water soluble and free of sulfur, chlorine and silicone, such as Cincinnati Milacron's Cimtech 410 (stainless steel)
12. Etch or stamp the drawing part number on noted surface of the part and then a three digit serial number. Serial numbers start at 001 for the first part and proceed consecutively. Use 0.07" high characters. Example: D010165-A 001