CC: Linda Turner

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Gravitation and Cosmology Research Group
Cambridge, Massachusetts 02139

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TO: Beth Moore for Barish, Volt, Jones, Sandras, [illegible], [illegible], Whitcomb, Lazzarini **FAX#:** LIGO

ADDRESS: Caltech

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FROM: R. Weiss **OFFICE #:** (617)253-4824

Massachusetts Institute of Technology
Room 20B–145
Cambridge, Massachusetts 02139

NOTES: Also sent by e-mail

BEAM TUBE ENCLOSURE: FUNCTIONS AND REQUIREMENTS

A discussion document

Prepared by R. Weiss, February 27, 1995

1 FUNCTIONS OF THE BEAM TUBE ENCLOSURE

1.1 Reduce wind driven motion of the beamtube and baffles

1.2 Reduce temperature excursions and thermal gradients of the beam tube

1.3 Maintain a benign environment for the insulation and reduce corrosion

1.4 Provide protection against lightning and severe storms

1.5 Provide protection against vandalism

2 ACTIVITIES THAT WILL TAKE PLACE INSIDE THE ENCLOSURE

During installation and qualification:

2.1 Leak assay and localization

2.2 Leak repair

2.3 Installation of insulation and instrumentation for the bake

2.4 Final alignment after bake to establish clear aperture

2.5 Installation of environmental monitoring instrumentation: accelerometers, residual gas analysers, (microphones).

During operations:

2.6 Periodic realignment to make up for settlement of the slab

Contingencies:

2.7 Rebake of the tube if an accident occurs or if improved vacuum for higher sensitivity interferometers is required.

2.8 Leak localization and repair if pressure monitors indicate a leak has developed in the beam tube.

3 ENVIRONMENTAL EFFECTS MITIGATED BY THE ENCLOSURE

3.1 Reduction in temporal temperature variations: affecting primarily the hydrogen pressure but also the water and hydrocarbon partial pressures in the event that these are significant; the rate of gas bursts (if they should occur at all) driven by thermal expansion and contraction.

3.2 Reduction in the vertical temperature gradient on the tube: affecting the shape of the tube and temporal modulation of the clear aperture.

3.3 Reduction of the humidity leading to corrosion of the tube and supports and water logging of the insulation, primarily in Lousiana.

3.4 Reduction in the wind driven and acoustically driven motion of the baffles that would lead to increased phase noise from scattering.

4 WIRING AND INSTRUMENTATION INSIDE THE ENCLOSURE

NOTE: In addition to the wiring for facility health, safety and protection.

During installation, bake and qualification:

4.1 AC power for: residual gas analysers, conventional mass spectrometer leak detectors, liquid nitrogen sense and valve control, instrumentation data logging system, portable pump stations if additional pumping capacity is required in the initial installation steps, illumination, convenience power for test equipment.

4.2 Instrumentation wiring: residual gas analyser control and output (RS 232 or equivalent digital lines), thermometer analog lines to multiplexers, cold cathode and pirani gauge analog lines to multiplexers, liquid nitrogen sense and valve control lines, gate valve sense and control lines.

4.3 High current capacity wiring for the bake: distribution and return lines ≈ 2500 amperes insulated for ≤ 50 volts to ground for bake.

During operations:

4.4 AC power for: residual gas analyser, 3 axis accelerometers, illumination, convenience power for test equipment, *if distributed pumping is used:* ion or getter pump power, cold cathode and pirani gauge control, gate valve control.

4.5 Instrumentation wiring: *environmental monitoring system:* residual gas analyser control and output (RS 232 or equivalent digital lines), thermometer low bandwidth digital lines, 3 axis accelerometers mounted on beamtube medium bandwidth (≤ 500 Hz) digital lines; *vacuum system monitor and control:* pirani and cold cathode gauge low bandwidth digital lines, *if distributed pumping is used* ion or getter pump control and sense lines, gate valve sense and control lines.

Contingencies:

NOTE: Worst case is a rebake, a leak opening, unless very large $Q \geq 10^{-1}$ torr liters/sec, will most likely not require rebaking.

4.6 AC power (same as 4.1)

4.7 Instrumentation wiring (same as 4.2)

4.8 High current capacity wiring for a bake (same as 4.3)

DESCRIPTION OF THE BEAM TUBE INTERFACES TO THE ENCLOSURE

Initial assembly: The first steps are the positioning of the alignment benchmarks followed by the construction of the tube support slab and location of the tube supports. The initial assembly of the beam tube is to be carried out in the open under a temporary sun shield to reduce distortion of the tube due to solar heating. The longitudinal distortion of the assembled part of the tube with temperature will be restrained by temporary anchors that are moved as new sections are welded. The installation will use special purpose in-field clean room facilities for circumferential welding, baffle insertion, circumferential weld leak testing and final tube visual inspection. The tube will be maintained dust and bug free by its own pressurized air system which forces 60 ft^3/min of class 100 dry air through the tube throughout the assembly. The alignment of the tube is determined support by support using differential GPS. The initial alignment to achieve the minimum clear aperture of 107 cm (including the obstruction by the baffles) is set in this phase of the assembly.

In the current concept for the beamtube assembly, the installation of the beamtube enclosure follows closely after the welding of each new beam tube section. At the beam tube PDR, CBI informed us that the tube requires lightning protection by OSHA regulations from the beginning. The beam tube enclosure and an adequate grounding strategy are part of complying with the regulation. In the CBI plan personnel will enter the tube during the assembly to insert weld purge dams and the baffles and to carry out the final inspection of the welds. The enclosure will be needed to reduce the thermal excursions of the air in the tube to allow entry. As a consequence of both the lightning and thermal control, the tube enclosure becomes part of the process for the initial assembly.

Initial pump down: The initial pumpdown will take place after a 2km module has been assembled and anchored at both ends but with no insulation on the tube. The module will be pumped from the ends. It is during this phase of the operation that the few leaks that might have been missed in the component and individual circumferential weld tests will be found and be repaired in situ. Leaks large enough to find at this stage will have to be repaired by rewelding (most likely) with automatic welding equipment. In the current plan, these repairs would be made inside the enclosure. The leak hunting strategy is to first make an air signature assessment to the level of 10^{-5} torr liters/sec and if needed to make an air signature localization to within two tube sections by using residual gas analysers at all 9 ports on the module. The precision localization will be done by bagging and helium leak detection techniques. The most effective method of using helium leak detectors is to bring the helium mass spectrometer to the vacuum port nearest the suspected leak. This and the residual gas analysers will require power at each port.

The air signature localization methods require that the tube not wander more than about 5 degrees C (peak to peak) during a 5 hour period and for this reason will most likely have to be carried out at night. Helium leak detection will require that the helium leaking from bags be flushed out of the enclosure to prevent time consuming false indications if there are multiple leaks at places not being bagged. An air flow in the enclosure is needed to enable helium leak detection.

In this phase of the installation it would already be useful (I think essential) to have instrumentation wiring available running parallel to the tube. A centralized vacuum monitoring and control location seems like the only rational way to monitor the residual gas analysers and to observe and control the pumping. This does not require that CDS wiring be used since we can invest in a single set of redundant wiring that is carried from one 2km module to the next. Nevertheless, we should not make this decision lightly since an ordered installation of the permanent facility wiring, avoiding this redundancy, may be a less costly alternative overall.

Bake preparation and the bake: The insulation will be applied to the tube while in the enclosure since this step follows the initial leak hunt. Thermometers to monitor the bake and to control the bake power will be permanently attached to the tube at the same time as the insulation. These installations will require a modicum of lighting, ventilation and maneuvering room in the enclosure.

The bake power is applied directly to the tube using Joule heating in the resistance of the tubes. The power for the bake is planned to be generated by portable power supplies and is not carried as part of the facility power distribution system. To be effective in reducing the outgassing rate, the bake must be done simultaneously over the entire length of tubing not separated by valves. The minimum connected lengths are the 2km beam tube modules. In order to satisfy OSHA regulations for the maximum allowed potential of 40V relative to ground on exposed wiring, the present plan is to use separate power supplies for each 250 meter section of the beam tube module. The high current lines for the bake will be installed. during this phase of the construction. If there is already a bus line able to carry 2500 Amperes running parallel to the tube for reasons of grounding (discussed in other Parson's meetings), this could be used as a common current return line for all 250 meter sections.

During the bake we are planning to use turbo pump systems at the tube ends and liquid nitrogen pumping at all the ports to maintain sufficient pumping speed for condensable gases.

The placement of the thermometers is not yet decided but is bounded by a minimum of 3 per 250 meter section if only the average tube temperature is measured and a single control thermometer is used. The maximum would be 30 per 250 meters if it is required to monitor the temperature at each expansion joint and support. The need for such extensive instrumentation during the bake is a question of project policy. We can adopt the policy that once a 2km section has been characterized, the process has been established and the remaining modules will carry only the minimum instrumentation. The risk is that something can go wrong and we will be operating partially blind. Another consideration that should be folded into such a decision is the chance of an accident during operations which would require us to rebake the system. This again has impact on both the quality of the instrumentation and its permanence.

The control and monitor of the bake is an integrated function for the entire 2km module. A centralized location is needed to monitor the state of the traps, the pressures at the pumping stations, the partial pressures at the residual gas analysers (in place from the prior step) and the tube temperatures. The bake will generate noxious fumes emanating from the insulation, it is certain that if personnel are required to enter the enclosure during the bake some ventilation will be necessary or alternatively full face masks to protect eyes and provide air for breathing will be required.

Final qualification of the beam tube: The final leak assay and alignment of the tube takes place in this phase. Both activities will take place inside the enclosure.

The final acceptance of the tube module is contingent on establishing that the system is leak free to the level of 10^{-9} torr liters/sec and that it is possible to adjust the clear aperture (determined by inference with respect to the alignment monuments or by differential GPS to each tube support) to a minimum of 107 cm. The adjustment provided by the supports has a dynamic range of +- 7.5 cm in both vertical and horizontal. The final alignment (and the continuing alignment of the tube during operations to compensate for the settling of the slab) are still only in the conceptual stage. The concepts for the alignment once the enclosure is in place include:

1. Differential GPS through the enclosure with radoms placed over the tube supports (concept proposed by CBI).

2. Differential GPS directly through the enclosure providing it has sufficiently uniform dielectric properties. (If this is done will the enclosure still serve for adequate lightning protection?)

3. Differential GPS to reference locations outside the enclosure and sufficiently far removed to not suffer from scattering by the enclosure, followed by optical metrology to the supports.

4. Optical metrology from the monuments placed at 250 meter intervals outside the enclosure with access to the supports via the entries at each 250 meter entry to the enclosure (the original 1989 concept).

Irrespective of which of these concepts is adopted, the adjustments to bring the tube into alignment will most likely be made with the enclosure in place to account for the loading of the cover on the slab unless the slab is made substantially thicker than the planned 4 inches.

The final leak assay is planned to be carried out by the same methods as described in the section above on the initial pump down. The primary difference is the factor 10^4 increase in sensitivity required. The same conditions for thermal stability are needed to make the air signature leak localization. The reason is that the background residual gas should have been reduced by the bake by a factor of 10^4 except for hydrogen. Here it is critical that the dynamic range of the residual gas analysers be larger than 10^5 to avoid confusion by the temperature dependence of the hydrogen outgassing.

At this stage in the installation, the investment in the vacuum is sufficiently large that unless there are leaks greater than 10^{-5} torr liters/sec opened by the bake, we hope to make repairs by other methods than rewelding such as vacuum qualified epoxy or soldering. (As part of the qualification test, CBI will try some "spot" welding techniques to repair leaks without having to release the vacuum)

Operations:

The major activity involving personnel in the enclosure will be the realignment of the tube at the supports to maintain the clear aperture due to settling of the slab. The expectation is that the settling will be a logarithmic function of time with most of the amplitude in the first year. The amplitude depends on the soil mechanics and the construction techniques. For planning purposes it seems reasonable to assume that realignment will be needed in the first year after construction and with logarithmically decreasing frequency in ensuing years. (Need help from Parson's on how often)

The instrumentation that is planned to be operating in the enclosure as part of the environmental monitoring system consists of: residual gas analysers at intervals of 1 km, 3 axis accelerometers at selected baffle locations (four three axis accelerometers per 2km module were costed in the summer of 1994), a fraction of the thermometers used in monitoring the bake. The vacuum equipment will have: cold cathode and pirani gauge controllers. valve sense and control systems and if distributed pumping is used ion and/or getter pump controls and sensors.

The temperature excursions of the tube and the vertical temperature gradients of the tube must be considered.

The temperature of the tube affects the outgassing rate of all the residual gas components, the most important being hydrogen unless we have hydrocarbon contamination in the tube. The outgassing rate of hydrogen doubles with each increase of 8 degrees C in temperature around room temperature (water and most important hydrocarbons have doubling temperature increments between 6 to 10 degrees C).

If the tube is insulated with the parameters given in appendix 1, the thermal time constant of the tube is expected to be about 9 hours. The spectral filtering will be the equivalent of a single pole, so that a daily thermal cycle will be attenuated to ≈ 0.4 of the peak amplitude of the thermal excursion under the enclosure.

Suppose that the day to night variation of temperature in the passive and unregulated enclosure goes from a maximum of 55 C (in bright noon sun light but with wind) to 15 C (at night). The hydrogen pressure variation in the tube night to day would be about a factor of 4. If the residual gas induced phase noise is dominated by hydrocarbons with a doubling temperature increment of 6 degrees, the critical pressure would increase by a factor of approximately 7. These values are not alarming if we have enough margin in the pressure to begin with, which is most likely the case for the initial interferometer, but must be considered in operations of more sensitive interferometers. The possibility that temperature excursions of the tube will trigger gas bursts through expansion and contraction is unfortunately not estimable but will be one of the candidate hypotheses if it should turn out we have a day to night difference in non Gaussian noise.

Vertical (and to a lesser extent horizontal) temperature gradients in the enclosure will not be attenuated by the insulation much more than the average temperature excursions since the circumferential thermal resistance of the thin wall stainless steel tube is high. A reasonable model is to assume that the slab will remain at constant temperature while the air in the enclosure varies with a vertical thermal gradient proportional to the peak temperature at the top of the enclosed space. Using the same thermal excursions as in the example above and the properties of the insulation (with no convection in the enclosure), the vertical thermal gradient from top to bottom of the tube with a daily period could be as large as 0.1 degree C/cm. The standard thermoelastic calculations (again using parameters in appendix 1) give an arching of the tube between supports of about 2 cm. This is uncomfortably large especially if baffles are placed at other locations than the fixed supports.

Although these estimates must be carried out more carefully (as is proposed in suggested studies), there may well be reasons here to reduce the thermal excursions within the enclosure by using exterior low solar absorptivity/high infrared emissivity paints to reduce the insolation and to ventilate the enclosure during operations.

Contingencies:

The eventuality of having to fix leaks or to carry out a new bake are accomodated by the enclosure if it meets the requirements for the initial pumpdown and the initial bake.

SUGGESTED STUDIES

1. Alignment techniques and interaction with enclosure design

2. Thermal control of the beam tube during operations: improvement in thermal control of the enclosure, improvement in the insulation of the tube, relation to bake costs and enclosure costs.

3. Systems approach to facility and special purpose wiring: the relative advantages/difficulties of centralized wiring and control vs special purpose wiring and control only for the bakeout.

4. An analysis of the advantages/disadvantages of implementing distributed pumping from the start.

APPENDIX 1

Various Thermal Considerations for the LIGO Beam Tubes

Introduction: The estimates of various thermal characteristics of the LIGO beam tube and enclosure are discussed. The topics include:

1. A table of the assumed physical parameters
2. A table of the assumed structural parameters
3. Standard thermo-elastic formulations for the tube

1. Physical Parameters

Annealed 304L Stainless Steel

Y = Young's modulus = 1.9×10^{12} dynes/cm^2 = 2.8×10^4 kpsi

S = yield stress = 3.4×10^9 dynes/cm^2 = 5×10^1 kpsi

ρ_{SS} = density = 8 gm/cm^3

k_{SS} = thermal conductivity = 1.6×10^{-1} watts/cm K

c_{SS} = heat capacity = 4.8×10^{-1} joules/gm K

ϵ_{ir} SS = far − infrared emissivity oxidized = 2.6×10^{-1}

α_{solar} = solar absorptivity oxidized = 8×10^{-1}

α_{SS} = thermal expansion coefficient = $1.6 \times 10^{-5} + 1.6 \times 10^{-8}(T - 300K)$ 1/K

ρ_{SS} = electrical resistivity = $7.52 \times 10^{-5} + 8.65 \times 10^{-8}(T - 300K)$ ohm cm

Insulation (Knauf Duct Wrap)

k_{ins} = thermal conductivity = $4.0 \times 10^{-4} + 3.1 \times 10^{-6}(T - 300K)$ watts/cm K

ρ_{ins} = density = 1.6×10^{-2} gm/cm^3

c_{ins} = heat capacity $\approx 7.0 \times 10^{-1}$ joules/gm K

Air

ρ_{air} = density = $1.25 \times 10^{-3}(\frac{300}{T})$ gm/cm^3

η_{air} = viscosity = $1.8 \times 10^{-4}(\frac{T}{300})^{1/2}$ gm/cm sec

k_{air} = thermal conductivity = $2.2 \times 10^{-4}(\frac{T}{300})^{1/2}$ watts/cm K

c_{air} = heat capacity at constant pressure = 1.1 joules/gm K

P_{air} = Prandtl number = $\frac{\eta c}{k} = 1.1$

G_{air} = Grashof number = $\frac{g l^3 \Delta T \rho^2}{\eta^2 T}$ l = typical dimension of convection cell

k_{conv} = effective convective conductivity = $0.11\ k_{air}(G\ P)^{0.29}$

k_{wind} = thermal conductivity due to wind u = $(\rho_{air} k_{air} r c_{air} u)^{1/2}$ watts/cm K

Construction Materials

Concrete

ρ_{conc} = density = 2.2 gm/cm^3

k_{conc} = thermal conductivity = 1.8×10^{-2} watts/cm K

c_{conc} = heat capacity = 8×10^{-1} joules/gm K

ϵ_{conc} = total emissivity = 9×10^{-1}

Paints Zinc or Titanium Oxide

α_{solar} = solar absorptivity = 2.5×10^{-1}

ϵ_{ir} = far-infrared emissivity = 8.5×10^{-1}

Environment

J_{sun} = peak solar intensity at ground in June (WA.LA) = 1.2×10^{-1} watts/cm^2

u_{wind} = mean surface wind speeds in June (WA) = 2×10^2 cm/sec

u_{wind} = mean surface wind speeds in June (LA) = 1×10^2 cm/sec

T_{air} = mean air temperature in June (WA) = 21 C

T_{air} = mean air temperature in June (LA) = 26.6 C

2. Structural Parameters

Beam Tube

w = wall thickness = 3.23×10^{-1} cm

r = inside radius = 6.19×10^{1} cm

l_1 = long section length = 1.981×10^{3} cm

l_2 = short section length = 1.90×10^{3} cm

s = stiffening ring spacing = 7.6×10^{1} cm

t = stiffening ring width = 4.76×10^{-1} cm

h = stiffening ring height = 4.45 cm

ti = insulation thickness = 10.2 cm

Expansion joints Pathway Hydroformed

wb = wall thickness = 2.67×10^{-1} cm

lb = total length for 9 convolutions = 7.37×10^{1} cm

kb_{ax} = axial spring rate = 1.44×10^{9} dynes/cm = 8.24×10^{3} lbs/in

kb_{trans} = transverse spring rate = 1.75×10^{10} dynes/cm = 1.0×10^{5} lbs/in

Enclosure

rc = enclosure inner radius = 2.1×10^{2} cm

wc = enclosure wall thickness = 7.6 cm

3. Standard thermo-elastic formulations for the tube

Single supported tube end

Deflection at end

$$\delta = \alpha \frac{dT}{dz} \frac{l^2}{2}$$

δ = deflection in cm

α = thermal expansion coefficient in 1/K

$\frac{dT}{dz}$ = thermal gradient in K/cm

l = tube length in cm

Maximum thermal stress if restrained from bending by support

$$\sigma = \frac{3}{2} Y a \alpha \frac{dT}{dz}$$

σ = maximum stress in tube in dynes/cm^2

a = tube radius in cm

Y = Young's modulus of steel in dynes/cm^2

Restraining force required

$$F = \frac{3\pi Y a^3 w \alpha}{2l} \frac{dT}{dz}$$

F = force in dynes

w = thickness of tube wall in cm

Supported at both ends with fixed slope

Deflection in the middle of tube

$$\delta = \alpha \frac{dT}{dz} \frac{l^2}{8}$$

Maximum thermal stress if restrained from bending by additional support

$$\sigma = \frac{3}{2} Y a \alpha \frac{dT}{dz}$$

Restraining force required

$$F = \frac{6\pi Y a^3 w \alpha}{l} \frac{dT}{dz}$$