

## LIGO PROJECT

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Refer to: T960124-00-F  
Date: November 30, 1995

### **SUBJECT: ISSUES AND CONSIDERATIONS ON THE BEAM TUBE BAKE**

**Summary:** The bake out of the beam tube is no longer part of the CB&I contract and the question has been raised as to whether the bake out is really needed and if needed when is the best time to carry it out?

The overall cost of the bake was estimated by CB&I as approximately \$6M while the project estimate runs around \$4M. The bake incurs a consequential cost and in our fiscally constrained situation needs to be justified as an up-front cost if it is not delayed. A delay could be contemplated since the project schedule will allow about 1 1/2 years of pumping before the beam tube is needed for the initial interferometer.

The purpose of this note is to present the technical estimates to guide in assessing the risk of delaying the bake. The issues considered are:

- 1) The beam tube residual gas requirements for the initial interferometer and the goals for advanced detectors.
- 2) The relation between residual gas pressure and pumping strategy.
- 3) The best estimates for the outgassing rates before and after a bake
- 4) Performance of the initial interferometer vs time without a bake: water and hydrocarbon outgassing.
- 5) Contamination on mirrors and deposition on the liquid nitrogen isolation traps.
- 6) Leak detection limits without and with a bake
- 7) Several technical issues associated with working with a vacuum system having a large and temperature dependent gas load.

The conclusion that I draw from the estimates and analysis is that it would be ill advised to delay the bake. The reasons are:

- 1) The outgassing by water and the changes in the outgassing with daily changes in the beam tube temperature will impact the performance of the initial interferometer unless the beam tube is baked or more pumping capacity than that initially planned is provided.
- 2) The hydrocarbon outgassing could compromise the initial interferometer unless the beam tube is baked or additional pumping capacity is provided.
- 3) Even with increased pumping capacity, the slow reduction in the pressure with time,  $\frac{1}{t}$ , will most likely not keep up with the more rapid improvement in detector sensitivity with time so that early in the LIGO operations a bake will be needed.
- 4) The ultimate pressure for advanced detectors and the sensitivity to measure leaks at the level of  $10^{-9}$  torr liters/sec by residual gas analysis techniques cannot be attained without a bake. The complete qualification of the beam tube will be delayed without a bake.
- 5) The costs of the additional pumps and the difficulties of operating and diagnosing a vacuum system with as long a time constant and temperature dependence as the unbaked beam tube may offset the up-front savings from delaying the bake. A factor that must be considered is that pumps used to handle the pre bake gas load of water and possibly hydrocarbons are not the most effective pumps to deal with the post bake gas load which will be primarily hydrogen.

## RESIDUAL GAS IN THE BEAM TUBES : REQUIREMENTS AND GOALS

The allowed residual gas pressure in the beam tubes is set by the anticipated sensitivity of the detectors in the LIGO. The time varying optical electric fields due to fluctuations in the forward scattering by molecules traversing the light beams in the interferometer arms will cause phase fluctuations in the interferometer. The LIGO facilities design is intended to reduce the phase noise due to the residual gas in the beam tubes to a level below that of all other noise sources in the interferometer in the detection band. The phase noise due to the residual gas is **required** to be less than 1/2 of the shot noise contribution in the initial interferometer in the vicinity of the noise minimum,

$$h(f) < 5 \times 10^{-24}$$

The **goal** for the phase noise has been set at the level of 1/2 the phase noise associated with the quantum limit for a 1 ton test mass in a search for periodic waves at 100Hz.

$$h(f) < 1.5 \times 10^{-25}$$

The relationship between the equivalent strain noise and the residual gas parameters is given by

$$h(f) = \frac{2^{2.5} \pi^{1.25} \alpha \langle \rho \rangle^{0.5}}{\nu^{0.5} \lambda^{0.25} L^{0.75}} e^{-\frac{\sqrt{\pi \lambda L} f}{\nu}}$$

where:  $\alpha$  is the molecular polarizability ( $\text{cm}^3$ ) at the laser wavelength  $\lambda$ ,  $\langle \rho \rangle$  is the molecular number density averaged over the optical beam length  $L$  and  $\nu$  is the thermal speed of the molecule. (The expression is mildly sensitive to the dimensions of the optical mode in the arms, it is given for a geometry where the Gaussian waist occurs at one of the mirrors.) The expression is recast into an engineering formula for 300K as

$$h(f) = 4.8 \times 10^{-21} R \left( \frac{x}{H_2} \right) \sqrt{\langle P(\text{torr}) \rangle_L}$$

where  $R$  is a factor, specific to the gas species, proportional to the polarizability divided by the square root of the thermal speed relative to that of molecular hydrogen. The exponential cutoff of the phase noise for all significant molecules occurs at frequencies above the interesting gravitational wave band.

Table 1 gives the  $R$  factor and estimates for the average partial pressure of various constituents of

the residual gas for the initial and goal performance of the beam tube vacuum. The value of each entry in the table consumes the entire residual gas phase noise budget. Once a bake has been carried out, molecular hydrogen is the dominant residual gas species and it will most likely dominate the phase noise budget. The total phase noise is determined by summing the noise power from all residual gas species.

Hydrocarbons are particularly effective in producing phase noise. They have large polarizabilities and due to their mass move slowly spending relatively long periods traversing the optical beam.

**Table 1: Residual gas phase noise factor and average pressure**

<b>Gas Species</b>	<b>R(x/H<sub>2</sub>)</b>	<b>Requirement (torr)</b>	<b>Goal (torr)</b>
H <sub>2</sub>	1.0	1×10 <sup>-6</sup>	1×10 <sup>-9</sup>
H <sub>2</sub> O	3.3	1×10 <sup>-7</sup>	1×10 <sup>-10</sup>
N <sub>2</sub>	4.2	6×10 <sup>-8</sup>	6×10 <sup>-11</sup>
CO	4.6	5×10 <sup>-8</sup>	5×10 <sup>-11</sup>
CO <sub>2</sub>	7.1	2×10 <sup>-8</sup>	2×10 <sup>-11</sup>
CH <sub>4</sub>	5.4	3×10 <sup>-8</sup>	3×10 <sup>-11</sup>
AMU 100 hydrocarbon	38.4	7.3×10 <sup>-10</sup>	7×10 <sup>-13</sup>
AMU 200 hydrocarbon	88.8	1.4×10 <sup>-10</sup>	1.4×10 <sup>-13</sup>
AMU 300 hydrocarbon	146	5×10 <sup>-11</sup>	5×10 <sup>-14</sup>
AMU 400 hydrocarbon	208	2.5×10 <sup>-11</sup>	2.5×10 <sup>-14</sup>
AMU 500 hydrocarbon	277	1.4×10 <sup>-11</sup>	1.4×10 <sup>-14</sup>
AMU 600 hydrocarbon	345	9.0×10 <sup>-12</sup>	9.0×10 <sup>-15</sup>

## Relation between average pressure, outgassing rate and pumping :

For a uniform outgassing rate  $J$  the average pressure  $\langle p \rangle_L$  in the beam tube is given by

$$\langle p \rangle_L = J \left[ \frac{2\pi a L}{nF} + \frac{L^2}{4va^2(n-1)^2} \right]$$

where  $L$  is the length of the arm (module)  $a$  is the tube radius and  $v$  is the molecular velocity of the residual gas species.  $n$  is the number of pumps in the module each with pumping speed  $F$ .

The pumps are assumed to be distributed uniformly along the tube. The examples given use the

parameters:  $a = 62$  cm,  $L = 2 \times 10^5$  cm,  $v = \frac{2.2 \times 10^5}{\sqrt{\text{amu}}}$  cm/sec, the thermal velocity at 300K of

a molecule with mass amu. The first term in the expression is the pressure that would be attained without taking the tube impedance into consideration. The second term is due to the tube impedance and dominates for end pumping ( $n = 2$ ) and the pumping speed

$F = 2.5 \times 10^3$  liters/sec  $\Rightarrow 2.5 \times 10^6$  cc/sec when pumping gases with amu larger than 12.

The outgassing rates are given in terms of torr liters/sec cm<sup>2</sup> which need to be converted into torr cc/sec cm<sup>2</sup> to be compatible with the other quantities given. When considering distributed pumping in subsequent estimates, it is assumed that all pump ports on a module will be used,  $n = 9$

## Outgassing rates before and after bakeout:

The thermal release of gases adsorbed on the surface as well as the diffusion of gases out of the solid usually obey a Boltzmann exponential dependence with temperature  $T$

$$J(T) = ae^{-\frac{T_0}{T}}$$

where  $T_0$  is an activation temperature depending on the molecule and the type of surface. For water on the oxidized stainless steel  $T_0 = 1 \times 10^4$  K leading to a temperature increase of 6 K to double the outgassing rate at 300K. The activation temperature for CO, CO<sub>2</sub> are known to be similar while the activation temperatures for hydrocarbons are not known directly from our measurements but are expected to be comparable.

The situation with hydrogen is different, there are two processes involved in outgassing hydrogen. Hydrogen is stored in the steel as atomic hydrogen and diffuses to the surface with a diffusion constant that depends exponentially on the temperature. The atomic hydrogen is strongly bound to the surface and is only released when it combines into molecular hydrogen on the surface.

The rate limiting process, whether diffusion or recombination, depends on the prior history of the steel, the conditions on the surface and the temperature. One of the reasons for performing the qualification test was to establish the hydrogen outgassing rate which is not determinable from basic principles. The outgassing of hydrogen by the annealed beam tube steel with the oxide coated surface doubles with each increase of 7.5 K at 300K. We are not certain whether this outgassing is dominated by the coil steel itself or originates from the welds which become reloaded with hydrogen from the dissociation of water in the air during the welding process.

At fixed temperature the outgassing of adsorbed gases varies as  $\frac{1}{t}$ . This has been experimentally verified in the beam tube qualification test and other observations for H<sub>2</sub>O, CO<sub>2</sub>, CO and hydrocarbons that exhibit residual gas analyzer peaks at amu 41,43,55 and 57. The time dependence can be shown to be the result of a distribution of adsorption sites with different activation energies on the surface.

In the early days of LIGO vacuum research the logarithmic divergence of the total outgassing associated with such a time dependence was a much discussed topic and led to the mistaken notion that the water would eventually all be removed if one only waited long enough. To understand the outgassing, a detailed balance statistical mechanics model using the Langmuir theory of the surface was developed with a skewed Gaussian distribution of adsorption site activation temperatures. The model, which has been reasonably successful in fitting the outgassing data, indicates that the surfaces never loose all the water in the gentle bake we are giving but that the loosely bound water is pumped out while the tightly bound water, amounting to approximately a monolayer, remains on the surface. The ratio of the post to prebake water outgassing depends on the shape of the activation energy distribution function and the readsorption probability and is typically 10<sup>-3</sup> to 10<sup>-4</sup> when corrected for the time dependence.

The time dependence of the outgassing which depends on diffusion, such as hydrogen out of the interior of the steel or the water or hydrocarbons from the inside of elastomers, varies as  $\frac{1}{\sqrt{t}}$  or even more slowly.

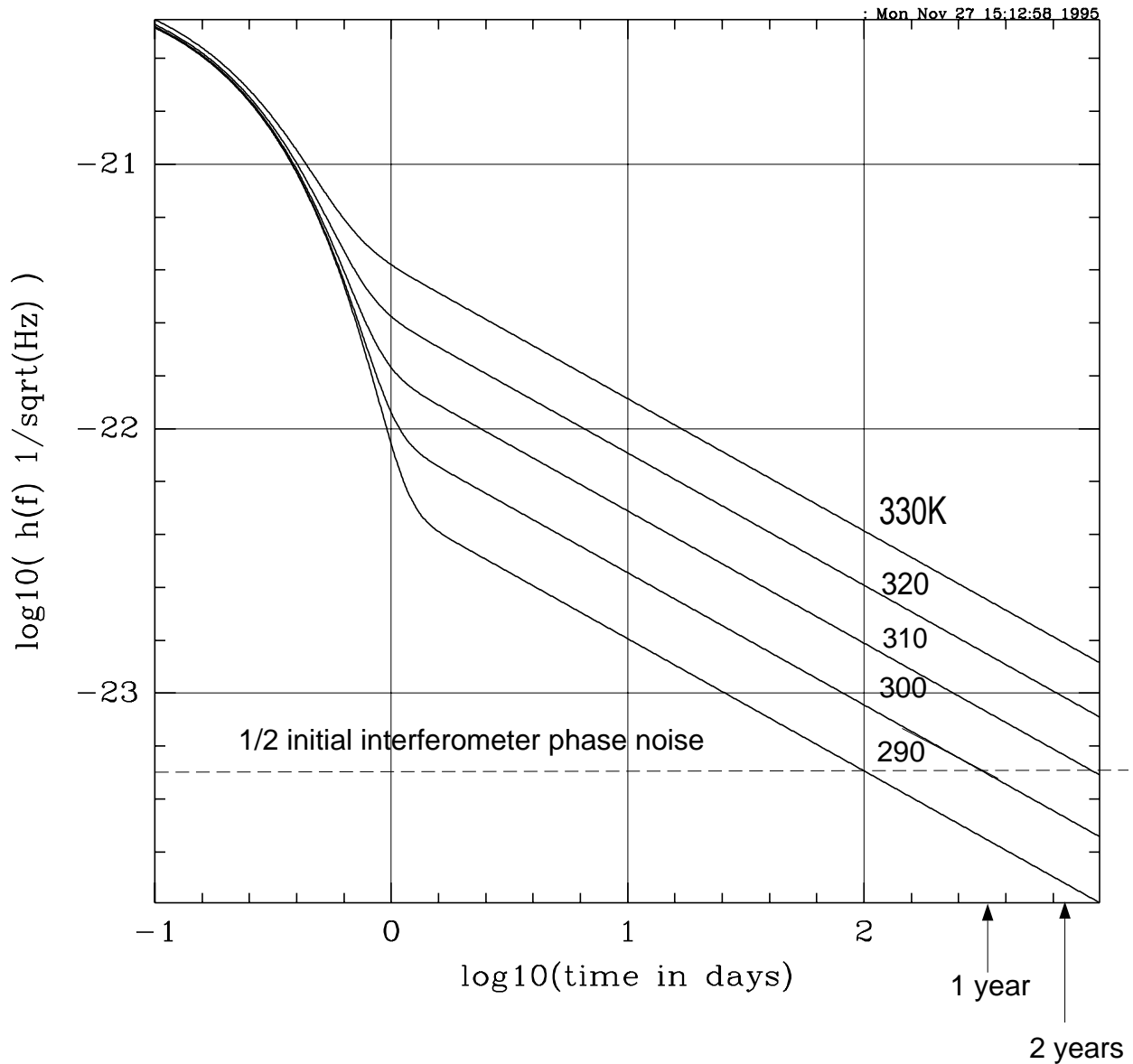
Table 2 gives the outgassing rates determined in the beam tube qualification tests before and after the bake. The observed time dependences come from 150 hours of operation prior to the 423K bake.

**Table 2: Outgassing rates before and after 423K bake**

gas	before bake	after 700 hr bake
	torr liters/sec cm <sup>2</sup>	torr liters/sec cm <sup>2</sup>
H <sub>2</sub> O	$J = \frac{1.2 \times 10^{-8}}{t(\text{hrs})}$	$J < 8.6 \times 10^{-18}$
CO	$J < \frac{5.8 \times 10^{-11}}{t(\text{hrs})}$	$J < 5 \times 10^{-16}$
CO <sub>2</sub>	$J < \frac{4.6 \times 10^{-11}}{t(\text{hrs})}$	$J < 1.6 \times 10^{-16}$
Hydrocarbon $\sum$ 41, 43, 55, 57	$J < \frac{2.2 \times 10^{-11}}{t(\text{hrs})}$	$J < 1.2 \times 10^{-17}$

**The phase noise from residual gas without a bakeout:**

Combining the data in Table 2 with the residual gas phase noise expressions and the average pressure relations, one arrives at several ways of evaluating the situation without a bake. Figure 1 shows the residual gas phase noise expressed as an equivalent gravitational wave strain amplitude spectral density due to water outgassing as a function of time with end pumping at 2500 liters/sec. This is the currently planned configuration. With the beam tube at 300K and starting with air having a -40C dew point, the water pressure crosses the requirement for the initial interferometer at about 1 year after the start of pumping. The day/night variations in tube temperature in the beam tube enclosure must also be considered. The other curves shown in the figure are the phase noise for 10K steps in temperature. These curves also follow a  $\frac{1}{t}$  dependence and show no significant reduction in the outgassing rates on heating and cooling until the beam tube has been raised to over 360K (this follows from the distribution of activation energies assumed in the surface model). My estimate is that during summer and clear skies the solar insolation will cause the beam tube to spend several hours per day at 330K so that most of the time the interferometer will be limited by residual gas phase noise if we do not take steps to reduce the water pressure by baking or increased pumping capacity (or temperature regulation of the beam tube).

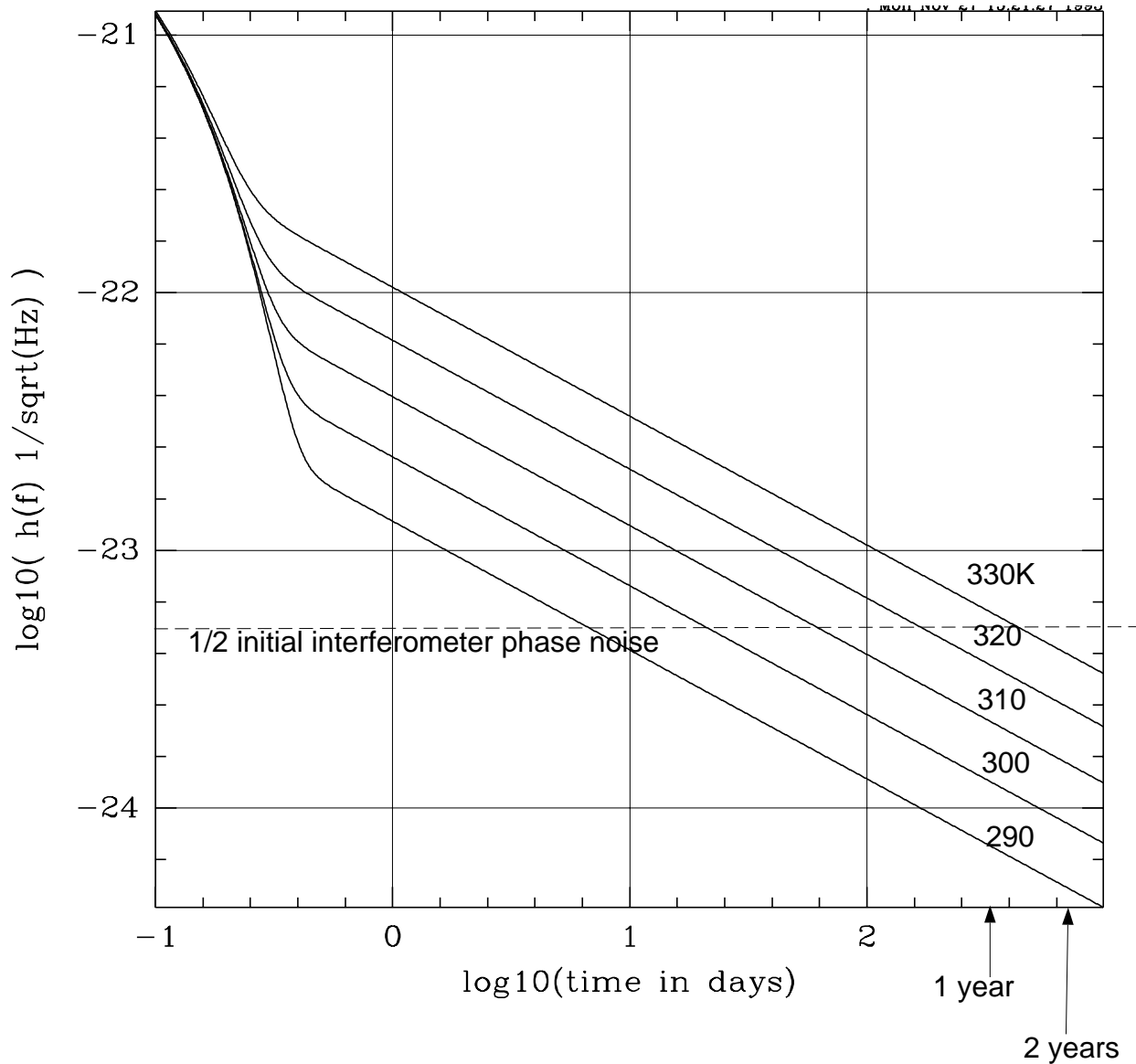


**Figure 1:** Gravitational wave strain amplitude density due to residual water in the beam tube vs time after pumpdown. The figure is drawn for a water outgassing rate of  $J = \frac{1.2 \times 10^{-8}}{t(\text{hrs})}$  torr liters/sec  $\text{cm}^2$ , end pumping ( $n=2$ ), a water pumping speed of  $2.5 \times 10^3$  liters/sec at each pump.

Figure 2 shows the phase noise from water of the unbaked system but with a full complement of 2500 liter/sec pumps at all nine ports of the 2 km beam tube module. The phase noise from the pressure at the temperature extremes meets the requirement for the initial detector at about 1.5 years after the pump down, but with no margin for detector development. The cost of the pumps is estimated at \$38K/ installed ion pump so a \$2.7M cost over the project. It is important to realize



that the pumps, which at this stage are needed to pump water (and as will be shown below also hydrocarbons), are not the best pumps to buy after a bakeout when the limiting gas species may be hydrogen.



**Figure 2:** Gravitational wave strain amplitude density due to residual water in the beam tube vs time after pumpdown. The figure is drawn for a water outgassing rate of  $J = \frac{1.2 \times 10^{-8}}{t(\text{hrs})}$  torr liters/sec  $\text{cm}^2$ , distributed pumping ( $n=9$ ), a water pumping speed of  $2.5 \times 10^3$  liters/sec in each pump.

The phase noise from CO and CO<sub>2</sub> is less than the water and can meet the initial requirement

without a bakeout and with enough margin to encompass the temperature fluctuations in the beam tube enclosure even with end pumping.

The phase noise from hydrocarbons, using the upper limit given in table 2, depends on the amu of the molecule, the temperature and the number of pumps. Table 3 gives the pump down time in days to meet the phase noise requirement at 300K for the initial detector without a bake as a function of the hydrocarbon mass. The pumping speed of the pumps is not critical since the tube pumping impedance will dominate. If the amu of the hydrocarbon is larger than 100, distributed pumping or a bake is required to meet the initial requirements. Hydrocarbons with amu larger than 700 are expected to have a vapor pressure low enough at 300K to not contribute to the phase noise budget even though they have a large polarizability. The exponential in the vapor pressure wins over the power law in the polarizability.

**Table 3: Maximum pumping time to reach phase noise requirement**

hydrocarbon	end pump	9 pumps
amu	days	days
100	144	2.2
200	$1.1 \times 10^3$	17.2
300	$3.6 \times 10^3$	57.0
400	$8.6 \times 10^3$	134.1
500	$1.7 \times 10^4$	262.5
600	$2.9 \times 10^4$	447.0

**Contamination on mirrors :**

The contamination deposited on the optics of the interferometer from outgassing by the beam tube and baffles is one of those concerns about which we wring our hands but do not now have any real facts. We therefore tend to be cautious. The current prejudice, based on some experience in mode cleaning cavities, is that the LIGO interferometer should operate with optical losses that increase at worst a few parts/million per year. The mirror heating associated with this absorption will require recollimation of the input beam and could, if significantly larger than this rate, become degenerative and destroy the coatings. The offending adsorbed layers are most likely hydrocarbons which are activated by the laser intensity to absorb the laser light. There is clear evidence of damage to optics in the region of high optical electric fields. The nature of the hydrocarbon that cause this damage is not known.

A rule of thumb we have used to avoid difficulties in the initial interferometer is that the deposition of hydrocarbons should be less than  $10^{-2}$  monolayers/ year ( $3 \times 10^{-7}$  torr liters/cm<sup>2</sup>/year)

The deposition of hydrocarbons on the test mass mirrors from outgassing by the beam tube and baffles can be determined from the outgassing rate of the materials and the assumption that the sticking (accommodation) coefficient of a hydrocarbon on the mirror will be close to unity. Hydrocarbons will most likely stick to the surface of the liquid nitrogen isolation traps placed at the beam tube ends. This combined with the fact that the pressure will be low enough so that molecular collisions can be neglected, allows the deposition on mirrors to be estimated by counting only the molecules that travel direct line paths from the baffles and beam tube to the mirror. The baffle height and spacing is chosen so that the mirror never “sees” the beam tube wall so the dominant contribution will come from baffle outgassing. A simple integration over the baffles, assuming a Lambertian distribution of the molecular emission at the baffle, leads to a molecular surface density,  $\sigma$ , deposition rate on the mirror given by

$$\frac{d\sigma}{dt} = \frac{Ja^2}{(L_1)^2}$$

where  $J$  is the total outgassing rate of the surface,  $a$  the beam tube radius and  $L_1$  the distance to the nearest baffle. Using  $8 \times 10^2$  cm as the distance to the nearest baffle, a beam tube radius of 62 cm and the deposition rate of  $10^{-2}$  monolayers in a year gives the upper limit of the allowed outgassing of hydrocarbons by the baffles as  $1.6 \times 10^{-12}$  torr liters/sec cm<sup>2</sup>. The contamination limits are not as stringent as the phase noise limits.

### Deposition on liquid nitrogen isolation trap surface

Another concern is the rate at which water from an unbaked beam tube will deposit on the liquid nitrogen isolation traps at the beam tube ends. The condensation of water on the trap surface leads to increased noise by boiling and eventually, when a thick enough layer has been deposited - approximately 0.2 micron or 2000 monolayers -, to an increase in the infrared emissivity of the surface above 0.05 accompanied by an increase in liquid nitrogen consumption due to radiative input from the 300K surfaces of the beam tube and vacuum equipment. For sake of these calculations I will assume that the trap will have to be recycled (closed off, warmed up and pumped out) every time the adsorbed layer exceeds 2000 monolayers.

The water surface density deposited on the trap is estimated by

$$\sigma = \frac{aLJt}{a_{\text{trap}}L_{\text{trap}}n}$$

where  $a$  is the beam tube radius,  $L$  is the beam tube length,  $a_{\text{trap}}$  and  $L_{\text{trap}}$  are the radius and length of the trap cryogenic surface,  $n$  the number of pumps along the beam tube length and

$J$  the water outgassing rate of the beam tube. After 1.5 years of pumping the outgassing rate for water of the unbaked system will be  $1 \times 10^{-12}$  torr liters/sec  $\text{cm}^2$  at 300K. Using equal trap and tube radii and a trap length of 2 meters, the time between trap recyclings would be longer than 4 years with end pumping only.

### **Leak detection with/without a bake**

The sensitivity of a leak assay and the precision of leak localization using air signature techniques depends on the residual gas spectrum and therefore the state of the outgassing in the beam tube. (Leak detection using bagging and helium as a tracer gas is not sensitive to the outgassing.)

The dominant contributions in the residual gas spectrum due to an air leak are from molecular nitrogen (amu 28) and oxygen (amu 32). The basis of the air signature leak detection method is to account for the residual gas analyzer measurements at amu 28 and 32. Several of the molecular species outgassed by the beam tube steel contribute at these amu values as well so that the method depends on separating these contributions from an air leak. The most troublesome gases are CO, CO<sub>2</sub> and hydrocarbons. Before the bake both amu 28 and 32 can be used to make the separation and an in-line liquid nitrogen trap is effective in reducing the hydrocarbon background without compromising the sensitivity to nitrogen or oxygen due to adsorption on the trap. After the bake the clean surfaces getter the oxygen so that the air signature methods must rely on amu 28 alone.

The experience in the beam tube qualification test indicates that it is possible to solve for an air signature at  $f \sim 10^{-2}$  of the residual gas peak at amu 28 before the bake and about  $5 \times 10^{-2}$  after the bake. A good estimator for the minimum detectable leak is then the CO outgassing of the beam tube. The minimum detectable leak is

$$F_{\min} \approx f J_{\text{CO}} \pi a L$$

which corresponds to a minimum detectable leak of  $10^{-7}$  torr liters/sec after 200 hours of pumping in the unbaked system and  $4 \times 10^{-10}$  torr liters/sec in the baked system

### **Difficulties in working with an unbaked system**

A practical consideration is the difficulty of working with and diagnosing a slow vacuum system with a large water gas load. The inconvenience alone is not adequate justification for arguing for the bake but adds further impetus. The bakeout reduces the gas load. With end pumping, the system time constant of a LIGO beam tube module will be approximately 1.5 hours for water and varies as  $\sqrt{\text{amu}}$  for other gases. The system will have a temperature dependence which causes the total pressure, primarily water, to vary by a factor of 2 with each 6K temperature change. The relatively high water pressure in the system will cause hydrogen to be generated by the dissociation of water in discharge and ionization gauges which confuse the residual gas measurements. None of these issues are fundamental but will cause us to spend more time and be more likely to make

errors in the initial shakedown of the beam tube vacuum system.

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