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Vacuum Hydrocarbon Outgassing Requirements

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1 Introduction

There are two basic reasons to limit the outgassing of materials and assemblies placed into the LIGO vacuum system:

- to limit the phase noise associated with scattering from the residual gas species in the long Fabry-Perot arms, and
- to limit mirror optical loss (scattering and absorption) due to condensed vacuum gas species.

The phase noise requirement must be satisfied by ensuring that the integrated outgassing from all of the LIGO in-vacuum components is within the pumping capacity of the system to keep the partial pressures of each gas species below requirements. A set of "goal" and "initial LIGO requirement" partial pressures, as a function of atomic mass number (AMU), has been established[1]. In this memorandum, a proposal is made for a set of "advanced LIGO required" partial pressures and an associated budget per subsystem. The required background outgassing rate in the vacuum bake ovens used for residual gas assay (RGA, or mass spectrometry) is also discussed.

Optical loss due to adsorption/condensation of (high molecular weight) gas species and subsequent interaction with the incident laser light is a material compatibility issue more than an allowable outgassing rate issue. LIGO Lab tests specific materials in optically resonant cavities with irradiance levels comparable to the highest levels in the observatory interferometers[2]. Discussion of the allowable limits for mirror optical loss (scattering and absorption) due to condensed vacuum gas species is not within the scope of this document.

2 Background

The LIGO vacuum system was designed and constructed to ensure that phase noise associated with scatter from residual gas species would allow strain sensitivities of order 10^{-25} 1/√Hz. To achieve this level of vacuum quality required great care in the control of air leaks and residual hydrocarbon contamination. To maintain the vacuum quality, all detector components placed into the vacuum system must be comprised only of approved ultra-high vacuum compatible materials (in acceptable quantities), carefully cleaned (per LIGO approved process specifications[3]) and assayed (RGA or FTIR) to assure compatibility.

The amplitude spectral density of the optical path length change, ΔL, as a function of frequency, f, for each residual gas species is given by[4]

$$\Delta L(f) = 4\pi \sqrt{\frac{2L_o}{kTw_o}} \left(\frac{\alpha}{\sqrt{v_o}} \right) \sqrt{p}\; e^{[-2\pi f w_o/(2v_o)]}$$

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[1] Rai Weiss, Larry Jones, Beam Tube Modules, 10/5/1995, G950082-00.

[2] "Optical screening of materials with a high-finesse Fabry-Perot cavity resonated continuously at 1.06-µm wavelength in vacuum", Applied Optics, Vol. 38, No. 25, 9/1/99 (LIGO-P990032-00)

[3] LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures, E960022

[4] M. Zucker, S. Whitcomb, Measurement of Optical Path Fluctuations due to Residual Gas, P940008-00.

where the arm length, L_o, is 4000 m; the temperature, T, is 298 K; the Gaussian beam radius, w_o, is 4 cm for initial LIGO and 6 cm for advanced LIGO, the Boltzman constant, k, is 1.04 x 10^{-25} m^3 torr/K; $v_o = \sqrt{\frac{2k_BT}{m}}$ is the most probable molecular velocity (m/s); k_B = 1.381 x 10^{-23} J/K; m is the molecular mass (kg); α is the molecular polarizability (m^3) and the partial pressure is p (torr). The molecular polarizability is best derived from measurements[5] of the refractive index of the gas, n, at wavelength, λ = 1064 nm:

$$\alpha(\lambda) = \frac{n(\lambda)-1}{2\pi\rho_\#}$$

where $\rho_\# = \frac{N_A p}{RT}$ is the number density of the gas (# molecules/m^3) with R = 0.06236 m^3-torr/mol/K and NA=6.022 x 10^{23} #/mol.

Expressed as the amplitude spectral density of the effective strain noise:

$$h(f) = R\sqrt{p}\; e^{[-2\pi f w_o/(2v_o)]}$$

$$R = 4\pi\sqrt{\frac{2}{kTw_oL_o}}\left(\frac{\alpha}{\sqrt{v_o}}\right) = 4.8\,x\,10^{-21}\left(R_x \big/ R_{H_2}\right)\quad\frac{1}{\sqrt{Hz\,torr}}$$

Values for the coefficient, R, are given in G950082-00[6] and repeated in Table 1 below. The Science Requirements Document (SRD)[7] sets optical phase noise due to fluctuations in the residual gas column density in the beam tubes and vacuum chambers at a level at or below an equivalent strain noise of 2 x 10^{-25} $1/\sqrt{Hz}$. The pressure limits in G950082 (and the "goal" column of Table 1) are set to achieve an equivalent strain noise of 1.5 x 10^{-25} $1/\sqrt{Hz}$ uniformly for all molecular species at low frequency.

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[5] R. Weiss, Scattering by Residual Gas, T890025-00.

[6] Rai Weiss, Larry Jones, Beam Tube Modules, 10/5/1995, G950082-00.

[7] A. Lazzarini, Science Requirements Document, E950018-02.

Table 1: Partial Pressure Limits from Residual Gas Scattering.

The coefficient R, the initial LIGO requirement and the goal are per G950082-00

Gas Species	$\left(R_x / R_{H_2}\right)$ $\left(m/\sqrt{Hz\ torr}\right)$	**Initial LIGO Requirement** (torr)	**Adv. LIGO Requirement** (torr)	**Goal** (torr)
H_2	1.0	1×10^{-6}	1×10^{-9}	1×10^{-9}
H_2O	3.3	1×10^{-7}	1×10^{-10}	1×10^{-10}
N_2	4.2	6×10^{-8}	6×10^{-11}	6×10^{-11}
CO	4.6	5×10^{-8}	5×10^{-11}	5×10^{-11}
CO_2	7.1	2×10^{-8}	2×10^{-11}	2×10^{-11}
CH_4	5.4	3×10^{-8}	3×10^{-11}	3×10^{-11}
AMU 100 Hydrocarbon	38.4	7×10^{-10}	2×10^{-12}	7×10^{-13}
AMU 300 Hydrocarbon	146	5×10^{-11}	2.2×10^{-13}	5×10^{-14}
AMU 500 Hydrocarbon	277	1×10^{-11}	9×10^{-14}	1×10^{-14}

3 Advanced LIGO Partial Pressure Requirements

It is difficult to achieve the partial pressure requirements for high Atomic Mass Unit (AMU) hydrocarbons associated with an equivalent strain noise of $1.5 \times 10^{-25}\ 1/\sqrt{Hz}$. The real goal is that the residual gas pressure is low enough that it does not limit performance. While this is readily achievable for a broadband instrument, it is difficult for a tuned response. The limiting sensitivity at the depth in the narrowband response of a tuned interferometer is basically the total internal noise (the root sum square of the following noise sources: substrate brownian noise, substrate thermoelastic noise, coating brownian noise and coating thermoelastic noise). The total internal noise decreases with frequency. There is a roll off in the frequency response of the optical path length noise due to the residual gas, defined by the transit time of the molecule across the Gaussian laser beam. Since the high AMU molecules are slower than the low AMU species, the low frequency asymptotic strain sensitivity associated with scattering from high AMU molecules can be higher than for low AMU molecules. By setting the partial pressures for the high AMU hydrocarbons (AMUs 100, 300 and 500) as indicated in Table 1, the strain sensitivities are matched at 400 Hz and equal to 1/5 of the total internal noise, as indicated in Figures 1 and 2.

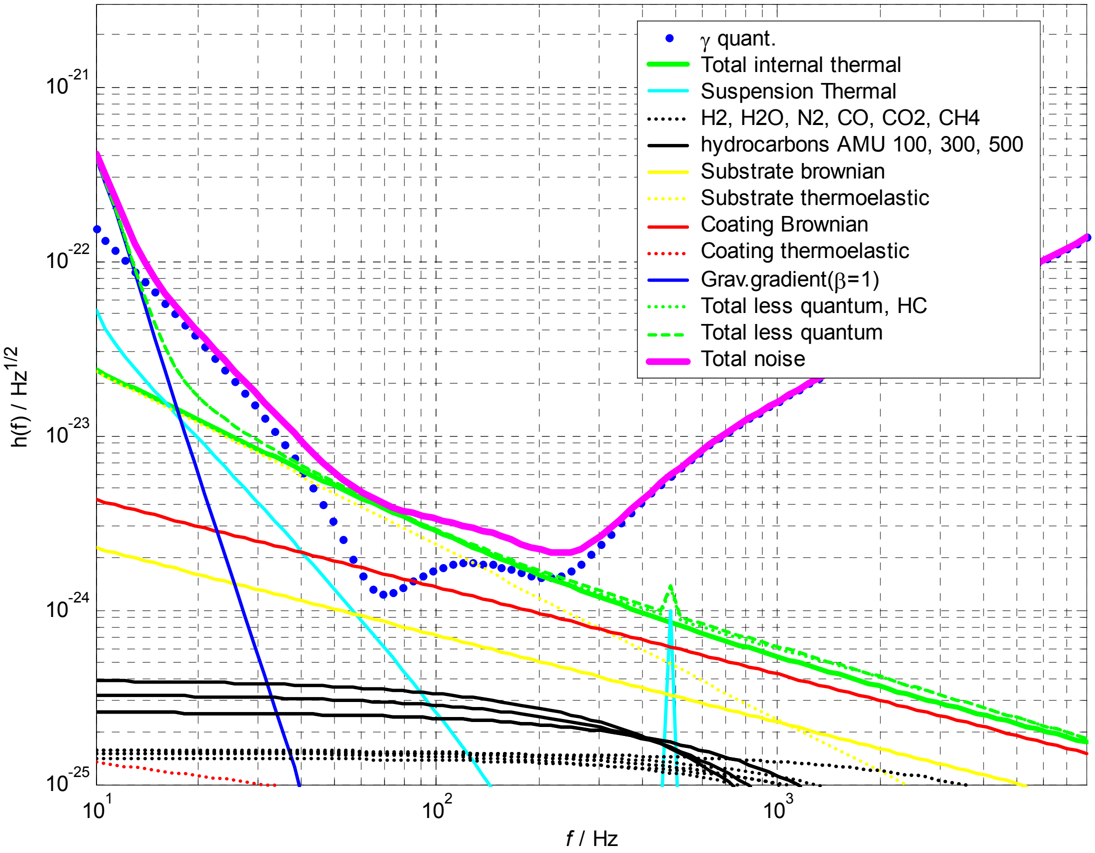

Figure 1. Effect of Optical Phase Noise Due to Residual Hydrocarbon Gas Pressure

Sapphire test masses with titania doped tantala/alumina coatings with the following parameters which effect the internal thermal noise:

Sapphire: Q = 200e6, E = 400 GPa, v = 0.23, a = 5.1e-6 1/K, Cp = 770 J/Kg/K, k = 33 W/m/K

titania doped tantala: E = 140 GPa, $\sigma = 0.23$, $C_v = 2.5e6$, $\alpha = 3.6e-6$, d =33, $\varphi = 2.1e-4$

alumina: E = 400 Gpa, $\sigma = 0.26$, $C_v = 3.09e6$, $\alpha = 5.4e-6$, d = 33, $\varphi = 0.1e-4$

Residual gas pressures are per the advanced LIGO requirements listed in Table 1.

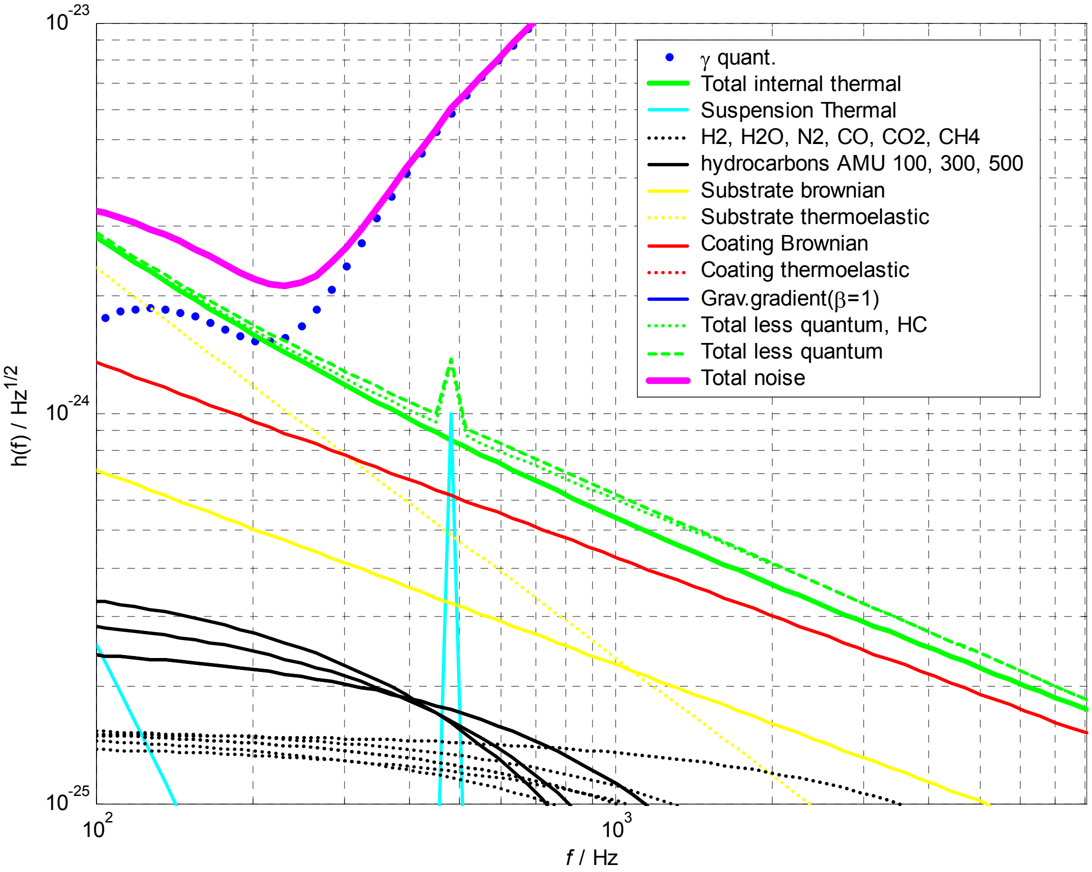

Figure 2. Effect of Optical Phase Noise Due to Residual Hydrocarbon Gas Pressure on the total non-quantum noise limit around 500 Hz. *The proposed partial pressure levels for the high AMU hydrocarbons results in a maximum 10% increase in the non-quantum noise at 420 Hz.*

4 Advanced LIGO Outgassing Budget

Outgassing of intrinsically vacuum compatible materials (metals, ceramics, glasses, …) is generally determined by the cleanliness of the surfaces (residual soaps and oils), desorption of water and air from their surfaces, and diffusion of hydrogen from the interior. Even for polymer materials water and air dominate their outgassing. Since the detector components represent a small increment in the surface area of intrinsically compatible materials (compared to the vacuum system) and the quantity of polymer materials will be very limited[D.C.1][8], there should be no issues with meeting the outgassing limits for H_2, H_2O, N_2, CO, CO_2, and CH_4[D.C.2]. Polymers represent essentially inexhaustible sources of hydrocarbon outgassing. Oil or soap films on the surface of (otherwise) vacuum compatible materials might eventually be pumped away over time, but are considered in

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[8] Water outgassing from the Flourel components of the seismic isolation system is a significant problem for initial LIGO. In advanced LIGO flouroelastomers (Flourel, Viton, Teflon, etc.) will be strictly limited. See for example: R. Weiss, Water Load on the Beam Tubes from Detector Components, 8/14/99.

this analysis to be infinite sources, on the time scales with which we are concerned (on the order of a year).

The sum of the partial pressures of the cracked by-products ("flags") of high AMU molecules, p_s, is approximately equal to the sum of the partial pressures of the high AMU molecules, i.e. there is approximately one cracked by-product per high AMU molecule:

$$p_s \equiv p_{41} + p_{43} + p_{53} + p_{55} + p_{57} \approx p_{100} + p_{300} + p_{500} + \ldots$$

We require that this HC sum mass partial pressure, p_s, be less than the requirement, p_{HC}:

$$p_s \le p_{HC} \equiv 2.3\, x\, 10^{-12}\ torr$$

where we take p_{HC} to be the sum of the proposed partial pressure limits for AMU 100, 300 and 500 in the table above. Of course, these chosen AMUs are somewhat arbitrary, but the contribution to the sum is dominated by AMU 100 and it is presumed to be unlikely that a particular material would contribute multiple AMU outgassing products. It should be noted that when evaluating and approving an RGA measurement (which generally spans to 100 AMU), any significant outgassing above the background at AMUs other than the sum mass components (i.e. AMU 41, 43, 53, 55 and 57) is cause for failing the bake load. Note also that we cannot distinguish whether a cracked component is from a very high (say 500 AMU) molecule or a lower AMU molecule (say 100 AMU). This results in a non-conservative limit since higher partial pressures are permitted for lower AMU molecules.

For a given unit (component or assembly), j, the hydrocarbon (HC) partial pressure summation, p_s, is directly proportional to the outgassing rate, J_{sj}, and the unit's area, A_j:

$$p_{sj} = \frac{J_{sj} A_j}{s}$$

$$p_s = \sum_j p_{sj} = \frac{1}{s} \sum_j J_{sj} A_j$$

where we assume that the HC outgassing rate, J_{sj}, is an intrinsic property of the material, component or assembly, j, and it's processing/handling and where s is the hydrocarbon pumping speed in the LIGO vacuum volume. The LIGO Vacuum Compatibility Document (LIGO-E960022-03) states a LIGO pumping speed of 3000 l/s. PSI design calculations[9] state that the pump rate (for gas species other than N_2, CO, CO_2, CH_4, H_2 and H_2O) is 1700 liters/sec for the end stations, 8500 liters/sec for the LHO corner station and 6800 liters/sec for the LLO corner station.

The hydrocarbon partial pressure summation is measured for the purpose of part/assembly quality assurance (QA; i.e. measurement on the components destined to go into the LIGO vacuum system) or part/material qualification (i.e. a sample to assure that the part/material is acceptable for design). If we designate this measurement as follows:

$$\hat{p}_s = \sum_j \hat{p}_{sj} = \frac{1}{\hat{s}} \sum_j J_{sj} \hat{A}_j$$

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[9] LIGO Vacuum Equipment Final Design Report, Volume II: Design, Attachment 4, Station Pumpdown and Ultimate Pressures, LIGO-C960964-00-V, PSI #V049-1-078, Rev.0

where $\hat{s}_j$ is the HC pump rate in the vacuum bake oven at the time of the mass spectrometer measurement of a measurement sample, or load, of component j with an area of $\hat{A}_j$. In order to compare the measured HC partial pressure summation to the criteria, p_{HC}, we must scale to the conditions in the LIGO vacuum system:

$$\sum_j \hat{p}_{sj}\left(\frac{\hat{s}_j}{s}\right)\left(\frac{A_j}{\hat{A}_j}\right) \le p_{HC}$$

Often the measured outgassing rate is limited by the vacuum oven background. Since we desire to qualify the load and not necessarily measure the outgassing rate, a background limited measurement can be acceptable if the background is low enough. This limit can be made smaller by using as much area as possible in the bake load or sample and/or using a low pump speed (when making the mass spectrometer measurement, not during the vacuum baking). However if the pumping speed is very low, then gettering to the chamber walls may dominate the measurement[10]. Current LIGO vacuum bake ovens (Table 2) have $\hat{s} \approx 30\, liters/\sec$ and $(\hat{s}/s) \approx 0.01$. The $\left({}^{A_j}\!\big/\!_{\hat{A}_j}\right)$ factor is very roughly on the order of 2 to 10 (though this depends on the component or assembly j) and applies only for the production QA bake loads (not the sample qualification bake load). This implies that $p_{sj} \approx \hat{p}_{sj}/10$. If one assumes about ~50 sources then the vacuum bake oven background should be comparable to $p_{HC}/5 \sim 10^{-12}$ torr. To date the background HC partial pressure summation in the LIGO bake ovens has generally been ~ 10^{-12} torr, as indicated in Table 2.

Table 2: Current Vacuum Bake Oven Parameters[D.C.3].

Location	Area (m^2)	all gas species			Hydrocarbon cracked ("flag") AMUs $\hat{p}_{HC,background} \equiv \sum(p_{41}+p_{43}+p_{53}+p_{55}+p_{57})$		
		(torr)	(torr-l/s)	(torr-l/s/m^2)	(torr)	(torr-l/s)	(torr-l/s/m^2)
Caltech[11]	0.26					2.5e-11 2e-12 (LN$_2$ cold trap during bake only)	
LHO	0.33					2e-11	
LLO	0.33						
Virgo (Pisa)[12]	0.25	7.5e-11	1.9e-9	7.5e-9	< 5e-12	< 4e-11	< 2e-10

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[10] In fact the methodology in E960022 advocates RGA measurement at multiple pump speeds to account for the virtual pumping to the chamber walls.

[11] Caltech bake oven hydrocarbon sum mass pressure background is taken as the best post-bake background with a clean load from a limited sample of bake load records. The background with a liquid N2 trap was reported in T970168-00. The LN2 trap was used during elevated temperature bake out of flourel or viton in order to keep the pump foreline clean.

A more careful accounting of the advanced LIGO vacuum load is estimated in Table 3. Ideally we would:

- subtract the outgassing, or partial pressure contribution, from the vacuum system infrastructure (beam tubes and vacuum chambers) and use the balance for the detector elements, and
- use actual areas and measured outgassing rates for the detector elements, to form an outgassing budget.

The beam tube installation (CBI's subcontract) succeeded in meeting the stringent outgassing requirements, indicated in Table 1. The requirements for the vacuum chambers (PSI's subcontract) was considerably more lenient; The vaccum installation was required[13] to achieve an ultimate pressure of 2 x 10^{-8} torr after 100 hrs after bakeout, of which 5 x 10^{-10} torr was allowed from species other than H_20, H_2, N_2, CO, CO_2, and CH_4. However, the mass spectrometer data in the acceptance test report[14] indicates that the partial pressure summation for HC flags is background limited to ~6 x 10^{-13} torr. Since this is a background limited measurement and the vacuum equipment is likely much cleaner (unless contaminated by the outgassing from the initial LIGO detector components[D.C.4]?), it is <u>not</u> included in the budget, i.e. assumed to be negligible.

Since much of the advanced LIGO design is uncertain at this time, rather than do a careful accounting by area, a budget has been established on the basis of a rough component list with approximate quantities, estimates of the quantity of components/assemblies per bake load and a HC outgassing weighting factor (Table 3). The HC outgassing weighting factor is intended to account for the likelihood of outgassing (either because of the polymer materials employed or because of the difficulty in cleaning the component or assembly). The weighting factor ranges from zero (no problem) to four (potentially high HC outgassing component). The breakdown in Table 3 is then used to project a budget for each subsystem, in terms of the allowed partial pressure summation for the HC flags (Table 4).

Table 4: Proposed Subsystem Outgassing Budget

	max partial pressure sum for HC Flags (torr)			
	end station	2k corner	4k corner	Notes
System	(torr)	(torr)	(torr)	
Seismic Isolation (SEI)	1.3E-12	1.4E-12	1.4E-12	
Vacuum (VAC)	0.0E+00	0.0E+00	0.0E+00	measured at < 6E-13 torr
Suspension (SUS)	6.5E-13	6.9E-13	6.3E-13	includes COC
Input Optics (IO)	0.0E+00	1.8E-14	2.1E-14	IO suspensions are under SUS
Auxiliary Optics (AOS)	1.5E-13	1.3E-13	1.4E-13	
Interferometer Sensing & Control (ISC)	7.2E-14	6.3E-14	7.4E-14	
System (SYS)	1.4E-13	1.8E-14	2.1E-14	
Total	2.3E-12	2.3E-12	2.3E-12	

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[12] The upper limits on the Virgo (Pisa) vacuum bake oven, hydrocarbon sum mass was taken by scaling and interpreting the results in T990072, which also reports the empty, clean oven total pressure and outgassing rate.

[13] Final Design Review Data Package, PSI #V049-1-103,5/8/96

[14] Left End Station Acceptance Test Report, PSI #V049-1-168, 5/28/98, pg. 36 and 40, LIGO-C981625-00-V

5 Vacuum Bake Oven Implications

In order to assure that the volume or quantity of components in each "production" bake load[15] does not exceed oven capacity, the RGA/oven background must be < 1.9 x 10^{-11} torr-liters/sec (as indicated in table 3). In general, the quantity per bake load for a particular item was defined, in Table 3, as a reasonable number, not as much as can fit into a chamber. However, this strategy still places a moderately severe constraint on the production logistics to have a bake load complement available before baking. Furthermore, when testing prototype units or materials one generally does not have sufficient quantity to fill a vacuum bake oven, and to do so can often be costly. Since the best empty/clean background rate achieved in the LIGO vacuum bake ovens (without a cold trap) is 2 x 10^{-11} torr-liters/sec, it seems clear that we should reduce the background outgassing rate. This conclusion and other implications for the vacuum bake ovens are summarized below:

- reduce the empty, clean oven background outgassing sum rate for the HC flags to ~2 x 10^{-12} torr-liters/sec (this may require additional pumping speed during baking and the capability to bake at higher temperatures)
- isolate the RGA head from the vacuum load during bake out (this is already the case on the LLO and LHO ovens, but not at Caltech)
- incorporate a variable orifice into the turbo-pump foreline to allow adjustment of the pumping speed (as indicated in the appendix to E960022, but not incorporated into any of the LIGO vacuum bake ovens)

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[15] i.e. bake loads which serve to demonstrate compliance with the outgassing requirement on the articles to be placed into the LIGO vacuum system

Table 3: Estimated Outgassing by Component

				Quantity					allocated max HC partical pressure					
System	Component or Assembly	Material	~ qty per bake load qualification	end sta. #	2k corner #	4k corner #	Area (ea.) (m^2)	Relative HC Outgas Rating	end station (torr)	2k corner (torr)	4k corner (torr)	max HC outgassing rate (torr-l/s/unit)	Min UHV oven Qty bake/RGA units	loads
SEI	Actuator, Large	epoxy	10	3	24	24		4	4.3E-14	4.3E-14	5.1E-14	7.6E-12	3	0.30
SEI	Actuator, Large	akadized aluminum	10	3	24	24		3	3.2E-14	3.2E-14	3.8E-14	5.7E-12	4	0.40
SEI	Actuator, Large	polyimide potting	10	3	24	24		2	2.2E-14	2.1E-14	2.5E-14	3.8E-12	5	0.50
SEI	Actuator, Small	epoxy	20	3	24	24		4	2.2E-14	2.1E-14	2.5E-14	3.8E-12	5	0.25
SEI	Actuator, Small	akadized aluminum	20	3	24	24		3	1.6E-14	1.6E-14	1.9E-14	2.9E-12	7	0.35
SEI	Actuator, Small	polyimide potting	20	3	24	24		2	1.1E-14	1.1E-14	1.3E-14	1.9E-12	10	0.50
SEI	Capacitive Sensor	PTFE wire & connectors	50	6	48	48		3	1.3E-14	1.3E-14	1.5E-14	1.1E-12	17	0.34
SEI	Capacitive Sensor	epoxy (2902, 2151)	50	6	48	48		4	1.7E-14	1.7E-14	2.0E-14	1.5E-12	13	0.26
SEI	Cabling	kapton, peek	3	22	197	168		4	1.1E-12	1.2E-12	1.2E-12	2.5E-11	1	0.33
SEI	pods, blades, hardware	aluminum, SS	3	1	8	8		1	1.2E-14	1.2E-14	1.4E-14	6.3E-12	3	1.00
SEI	structure	aluminum, air baked, FTIR	1	1	8	8		1	3.6E-14	3.6E-14	4.2E-14	1.9E-11	1	1.00
VAC	annulus seals	viton	10	9	55	47		0	0.0E+00	0.0E+00	0.0E+00			
VAC	envelope	stainless steel 304L	1	1	1	1		0	0.0E+00	0.0E+00	0.0E+00			
VAC	viewports	assembly (304 SS, Cu, FS, etc.)	20	1	1	1		0	0.0E+00	0.0E+00	0.0E+00			
SUS	OSEM, aluminum	Teflon PFA 440HP washers	50	48	384	288		3	1.0E-13	1.0E-13	9.1E-14	1.1E-12	17	0.34
SUS	OSEM, aluminum	kapton coil wire	50	12	96	72		2	1.7E-14	1.7E-14	1.5E-14	7.6E-13	25	0.50
SUS	OSEM, aluminum	assembly (alumina, ceramabond, solder, etc.)	50	12	96	72		2	1.7E-14	1.7E-14	1.5E-14	7.6E-13	25	0.50
SUS	OSEM, alumina	PFA 440HP washers	50	32	352	288		3	6.9E-14	9.5E-14	9.1E-14	1.1E-12	17	0.34
SUS	OSEM, alumina	kapton coil wire	50	8	88	72		2	1.2E-14	1.6E-14	1.5E-14	7.6E-13	25	0.50
SUS	OSEM, alumina	assembly (alumina, ceramabond, solder, etc.)	50	8	88	72		2	1.2E-14	1.6E-14	1.5E-14	7.6E-13	25	0.50
SUS	EQ Stops	viton	100	20	220	180	1.00E-04	4	2.9E-14	3.9E-14	3.8E-14	7.6E-13	25	0.25
SUS	Fiber damping goop	Teflon AF amorphous type 1601	100	4	20	20		4	5.8E-15	3.6E-15	4.2E-15	7.6E-13	25	0.25
SUS	OSEM cables	kapton, peek	50	20	152	112		4	5.8E-14	5.4E-14	4.7E-14	1.5E-12	13	0.26
SUS	magnet assy., upper	vacseal	10	12	96	72	7.85E-05	4	1.7E-13	1.7E-13	1.5E-13	7.6E-12	3	0.30
SUS	magnet assy., lower	vacseal	10	8	56	40	3.14E-06	4	1.2E-13	1.0E-13	8.4E-14	7.6E-12	3	0.30
SUS	structure/assy., quad	aluminum, UHV backed, RGA	1	1	5	3		1	3.6E-14	2.2E-14	1.6E-14	1.9E-11	1	1.00
SUS	structure/assy., triple	aluminum, UHV backed, RGA	1	0	6	6		1	0.0E+00	2.7E-14	3.2E-14	1.9E-11	1	1.00
SUS	structure/assy., single	aluminum, UHV backed, RGA	2	0	4	4		1	0.0E+00	9.0E-15	1.1E-14	9.5E-12	2	1.00
IO	Faraday Isolator	assembly (aluminum, stainless steel, etc.)	1	0	1	1		1	0.0E+00	4.5E-15	5.3E-15	1.9E-11	1	1.00
IO	relay mirrors & mounts	assembly (aluminum, stainless steel, etc.)	4	0	12	12		1	0.0E+00	1.3E-14	1.6E-14	4.8E-12	4	1.00
AOS	Pick-off mirror assy.	assembly	2	0	5	5		2	0.0E+00	2.2E-14	2.6E-14	1.9E-11	1	0.50
AOS	beam dump assy.	assembly	1	0	4	4		2	0.0E+00	3.6E-14	4.2E-14	3.8E-11	1	1.00
AOS	arm cavity baffle assy.	assembly	1	1	1	0		2	7.2E-14	9.0E-15	0.0E+00	3.8E-11	1	1.00
AOS	beam reducing telescope	assembly	1	1	4	4		2	7.2E-14	3.6E-14	4.2E-14	3.8E-11	1	1.00
AOS	active thermal compensator	assembly (nichrome wire, SS, Alu, kapton/peek)	1	0	2	2		2	0.0E+00	1.8E-14	2.1E-14	3.8E-11	1	1.00
AOS	relay mirrors & mounts	assembly (aluminum, stainless steel, etc.)	10	2	16	16		1	7.2E-15	7.2E-15	8.4E-15	1.9E-12	10	1.00
ISC	in-vacuum PD	assembly (kapton/peek, SS, Alu, ceramic, Si)	1	1	7	7		2	7.2E-14	6.3E-14	7.4E-14	3.8E-11	1	1.00
SYS	margin	20%	1	1	1	1		4	1.4E-13	1.8E-14	2.1E-14	7.6E-11	1	1.00
				63.72	513.49	437.2	HC partial press (torr):		2.3E-12	2.3E-12	2.3E-12	7.6E-13	min	OK
				Sum(Qty * HC Rating)			max HC press (torr):		2.3E-12			7.6E-11	max	
											oven pump rate (l/s)			3.7E+01
											oven RGA HC background (torr)			7.0E-10
											oven RGA HC background (torr-l/s)			1.9E-11

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[D.C.1]need to file Rai's report in the DCC & get a number

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[D.C.2]is this a correct assertion, or do we need to establish an outgassing budget for these molecules as well as the heavy hydrocarbons?

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[D.C.3]should complete the table with input from Lho & LLO

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[D.C.4]Do we have a recent RGA scan for the LIGO vacuum systems from which we can get the HC sum pressure? They don't appear in the LHO elogs.