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Outgassing from Aluminum Weld Samples

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1 Background

In recent suspension structural design work[1,2], we have had a number of issues with getting good quality welds in aluminum. As part of the welding process development for the suspension structure of the Output Mode Cleaner (OMC), some samples were available for outgassing evaluation. These samples are of varying weld quality. Since producing high quality aluminum welds may be important for Ultra-High Vacuum (UHV) service (cleanliness), but the cost increase for high quality welds can be significant, it was deemed prudent to make some measurements of the outgassing rate from the available samples of varying weld quality. The outgassing measurements made with a selected few of these weld samples is documented in this report. In addition, the justification of weld quality to be called out for LIGO weldments is given.

2 Weld Quality

The OMC weld samples were characterized as being either Class C, Class B or Class A according to Mil-Std-2219 ([3]),where Class A is the highest quality and Class the lowest. The Brookhaven LS project has selected class A of Mil-Std-2219 as the most appropriate weld qualification specification for their project. There is no known published standard for TIG welding of aluminum vacuum vessels. At the Argonne National Lab for the Advanced Photon Source (APS) production facility, MIL-STD-2219 for Class A welds was adopted (LS254, Quality Issues). This was the toughest specification against which APS aluminum welding performance could be judged.

Justification for specifying Class A welds for LIGO is given below.

2.1 Virtual Leaks

Small voids within the welds are possible, especially if the welding is performed in passes on both sides. Voids with channels to the surface represent virtual leaks. Rai Weiss has looked at this gas flow dynamics problem for the welded beam tube[4]. He found that under reasonable assumptions regarding the voids and channel geometries, there are no virtual leak concerns. I think that the same analysis applies to the detector components such as the suspension structure. Note that Rai looked at pumping nitrogen from the voids, but even if high AMUs are assumed (by calculating the associated molecular velocity for use in Rai's equations in LIGO-T940070-00) reasonable flaw dimensions do not represent a problem.

2.2 Uncleaned Surface Areas in Crevices, Cracks and Voids

The surfaces of the parts should be fairly clean before welding. If the welding is incomplete, has surface porosity or voids with channels to the surface, then cleaning subsequent to the welding will not be effective in these areas and these areas might wick in cleaning fluids and contaminants. Let's assume that the outgassing rate of these areas is about equal to an unbaked surface.

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[1] C. Torrie, Welding Expriences: Output Modecleaner and Recycling Mirror Designs, LIGO-G070656-00, 14 Oct 2007

[2] LIGO wiki page UHVWelding

[3] Fusion Welding for Aerospace Applications, Mil-Std-2219A, 18 Jul 2005

[4] R. Weiss, Notes on Virtual Leaks in the Beam Tube Spiral Welds, LIGO-T940070-00, Sep 24, 1994.

There is a fair amount of literature on the reduction of the total outgassing rate for aluminum after baking (at ~120C for ~48 hrs). However, what we really want to know if the reduction in the rate of hydrocarbon outgassing; We will re-expose our hardware to air/water after baking so the benefits of the bake for reducing H2O, O2, CO2, N2, etc. is not relevant.

Let's consider the beam tube bake (stainless steel at 150C). Beam Tube pre-bake hydrocarbon signature outgassing rate[5] (HnCpOq, Sum of AMUs 41, 43, 55, 57) is 2.2E-15 torr-liter/s/cm^2. Beam Tube post bake hydrocarbon signature outgassing rate is 5.3E-19 torr-liter/s/cm^2 (bake was 150C for ~20? days)[6]. So the hydrocarbon outgassing rate reduction due to the vacuum bake for the stainless steel of the beam tube is a factor of ~4000.

The post-bake aluminum hydrocarbon outgassing rate for a number of recent Caltech-LIGO vacuum bake loads, with aluminum parts, is ~ 3E-15 torr-liter/s/cm^2. (Note that this is likely a background noise limited value.)

The maximum HC outgassing allocation for the quad suspension structure[7] is ~4E-10 torr-liter/s/unit. Each quad structure has about 11.3 m^2 of surface area. So the available outgassing rate for weld flaws is

4E-10 - (3E-15 * 11.3 * 10^4) = 6E-11 torr-liter/s/unit. With an assumed factor of 4000 times greater outgassing per unit area, the allowable weld area is 6E-11/(4000*3E-15) = 5 cm^2/unit. This amounts to an effective increase in the overall surface area of the structure of (5*4000)/(11.3*1E4) = 18% (not very much at all).

The total length of welds in the quad structure is very roughly 8 m (the lower structure is not welded). If the weld width T = 0.6 cm, then Class A welds (per MIL-STD-2219A, Table V) allows 0.76 mm surface porosity flaw at a spacing of 6.08 mm, and a total of Minimum[8m/6.08E-3 = 1316 flaws, or (0.12*25.4/0.76)*8/(3*0.0254) = 421 flaws]. If the flaws are hemispherical, then the total area is 1050*Pi*0.076^2/2 = 3.8 cm^2 which approximately equals the allowed 5 cm^2. Similar amounts apply for subsurface porosity and inclusions. It seems Class A is reasonably well matched to our outgassing requirements.

3 Weld Samples

A single Class A and Class B weld sample was selected for testing (or these were the only available?). The samples are all comprised of 6061-T6 alloy. Photos of the available weld samples are shown in Figures 1 and 2. It is exceedingly unfortunate that these weld samples are so very small. One must take care in drawing conclusions from the outgassing measurements given the small sample sizes.

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[5] W. Althouse, Technical Board Meeting to Review Beam Tube HX2 Vacuum Test Results, LIGO-L970429-00, July 7, 1997.

[6] Rai Weiss, Residual Gas in the LIGO Beam Tubes: Science, Arts and Recipes, American Vacuum Society Baltimore November 5, 2003

[7] The Adv. LIGO requirements are defined in LIGO-T040001-00. However, the basis for this memo is incorrect; It needs to be revised. This memo advocates a HC outgassing level at least ~20 x better than needed. The table at the end of T040001-00 gives the allowed rate for the quad suspension structure as 1.9E-11 torr-liter/s/unit. So the allowed rate is ~20*1.9E-11 = ~4E-10 torr-liter/s/unit.

The surface areas of the Class B and Class A samples are 110 sq. cm and 2.33 sq. cm, respectively. The welds are both T-weld geometries, with weld passes taken on both sides. The weld lengths of the Class B and Class A samples are 12 cm and 3 cm, respectively (Including both sides of the T-weld separately as well as the ends of the welds). If we assume that the outgassing rate is dominated by contaminants in the porosity of the welds, then we are should normalize on the basis of the weld length.

Figure 1: Class A Weld Sample (for reference, the optics table hole spacing is 1 inch on centers)

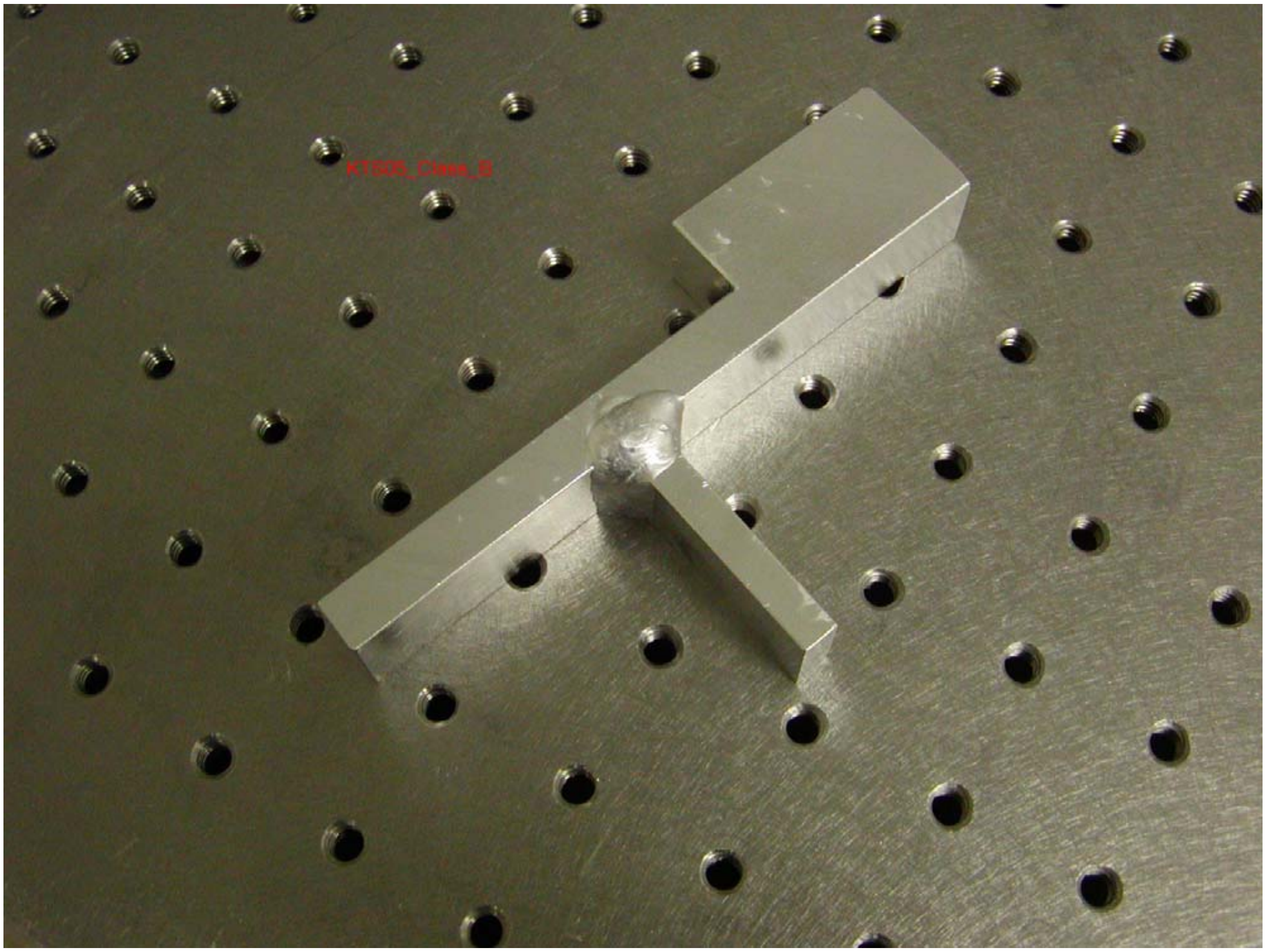
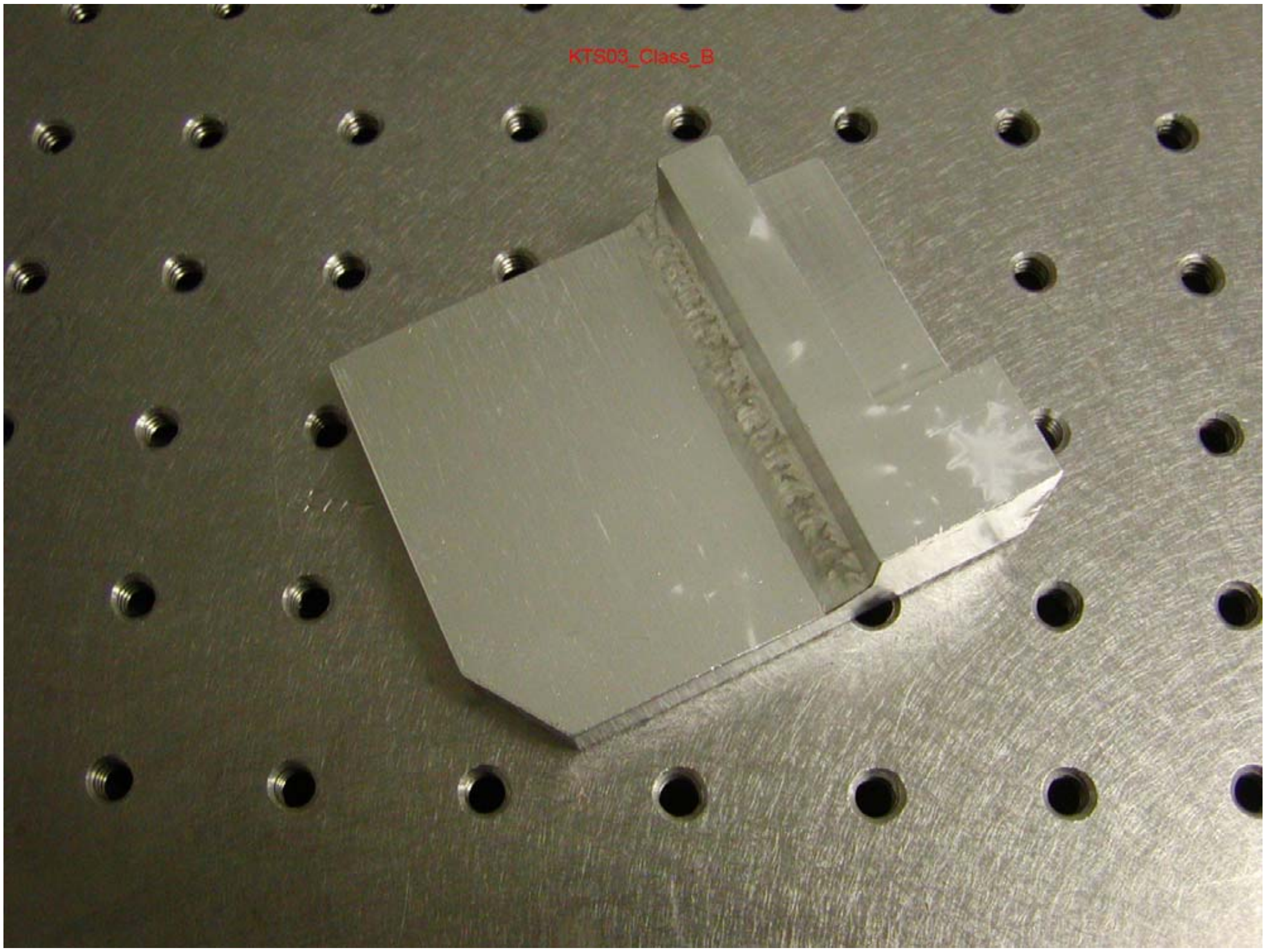


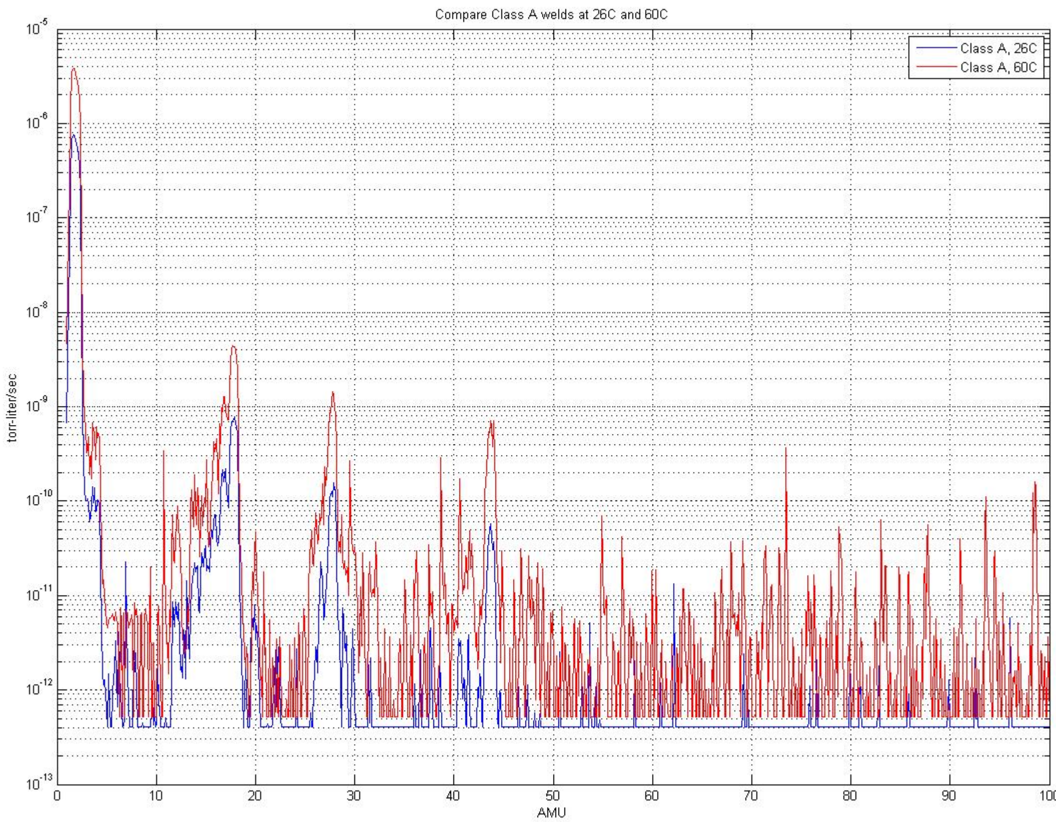
Figure 2: Class B Weld Sample (for reference, the optics table hole spacing is 1 inch on centers)



4 RGA Spectra

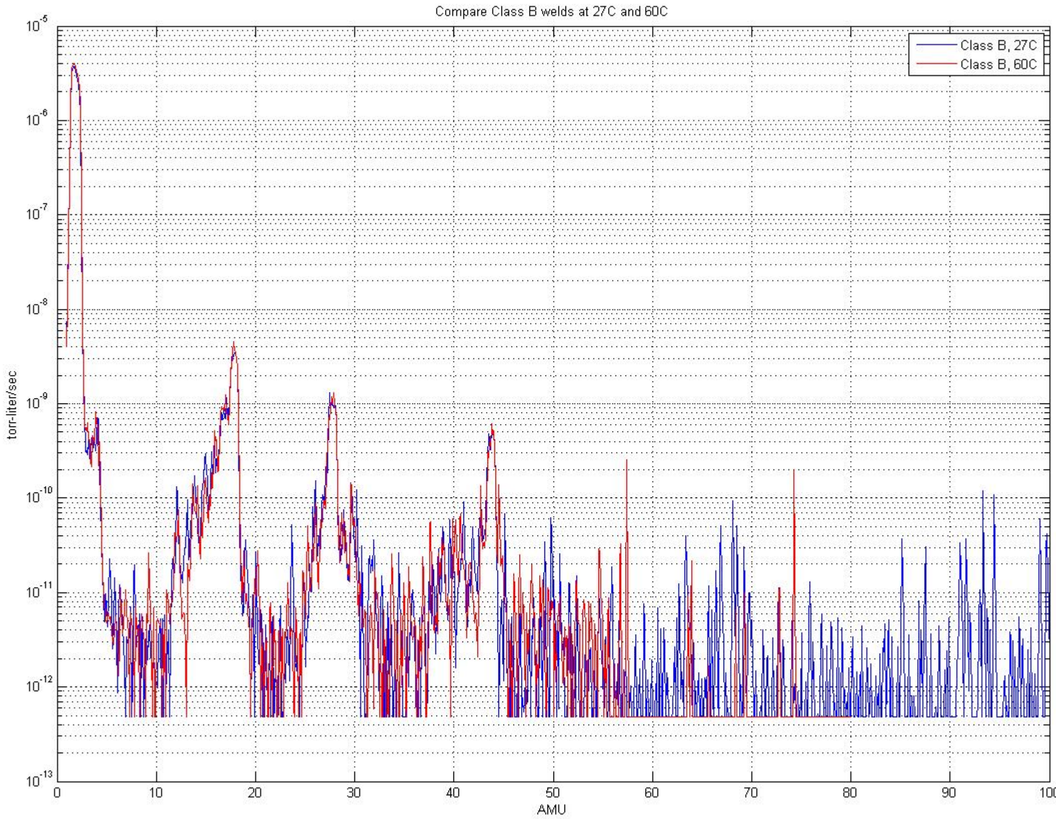
Residual Gas Assays (RGA) were performed at 60C and at room temperature, for both the Class A and Class B weld samples, after vacuum baking at 120C for 48 hrs for the LIGO vacuum preparation requirements, E960022. The Class A weld sample outgassing shows an increase in outgassing at 60C compared to room temperature (26C) as expected (Figure 3).

Figure 3: Class A Weld Sample outgassing at room temperature and elevated temperature



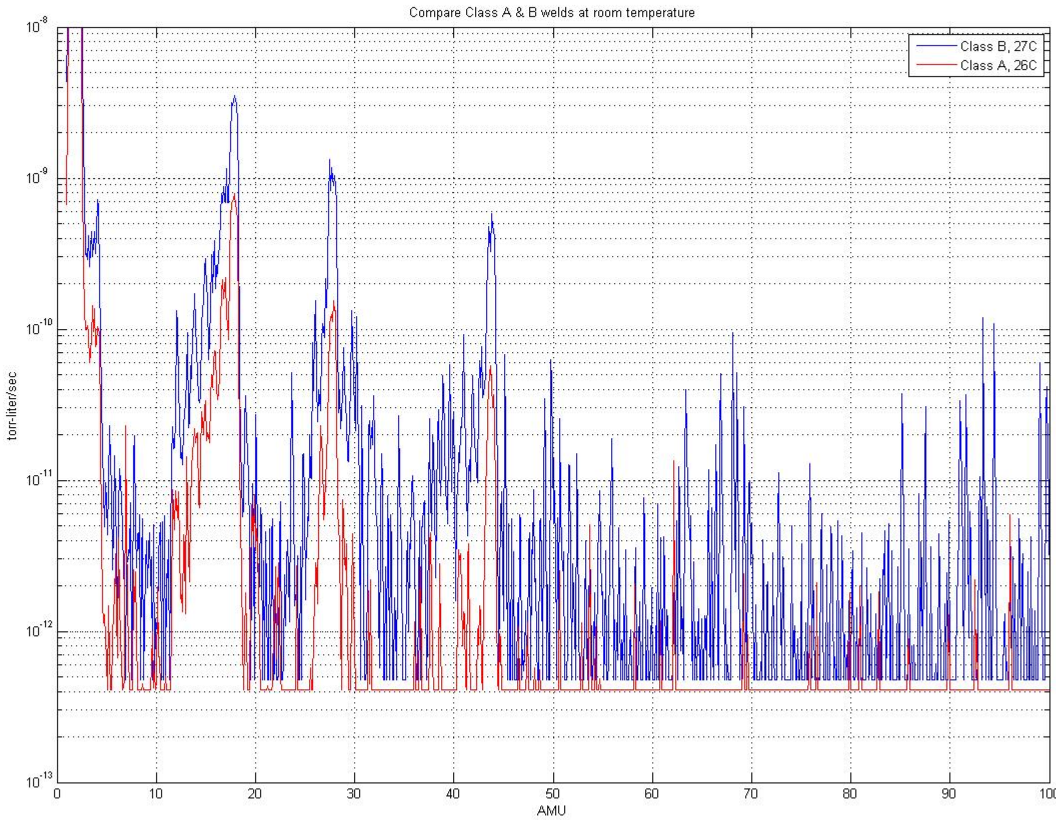
Unlike the Class A weld samples, the outgassing from the Class B weld samples do not show increased outgassing at elevated temperature (Figure 4). This is more than a little suspicious and points to a problem in the data or the vacuum baking.

Figure 4: Class B Weld Sample outgassing at room temperature and elevated temperature



We'll assume (for the time being) that the room temperature outgassing measurement for the Class B weld samples is valid. Comparing the room temperature measurements for the Class A and Class B welds (Figure 5) indicates significantly higher outgassing for Class B welds.

Figure 5: Comparison of room temperature outgassing for the Class A and Class B weld samples

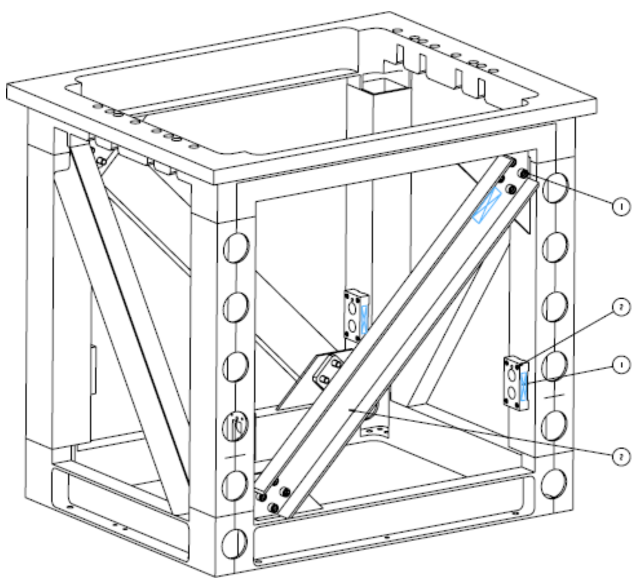
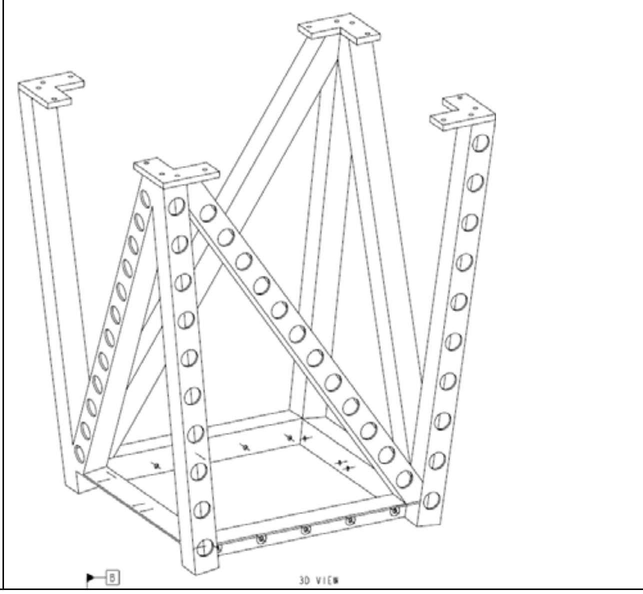


In accordance with E960022, we normally determine the hydrocarbon outgassing based on typical AMUs for cracking of high molecular weight hydrocarbons. These "flag" AMUs are 41, 43, 53, 55 and 57. The flag hydrocarbon outgassing rates are 6E-12 torr-liters/sec for Class A welds and 103E-12 torr-liters/sec for Class B welds at room temperature. The typical background level for the cracked flag hydrocarbon outgassing rate for our vacuum bake oven is ~2E-12 torr-liter/sec.

The flag HC outgassing rates normalized by weld length are then 2E-12 and 9E-12 torr-liter/sec/cm for Class A and B respectively. However, the Class A flag HC rate is background limited. As a consequence we can only say that Class B welds (based on this very small sample) have a flag HC outgassing rate > 5 times Class A welds.

The requirements (see footnote above) are for < 4E-10 torr-liter/sec for each SUS structure. The quad suspension structure has about 11.3 m^2 surface area. The length of weld in these structures depend upon the manufacturing approach, e.g. is the top and bottom rings of the upper quadruple pendulum structure are machined or welded from extruded sections. It is likely that these rings will be machined from plate minimizing the amount of weld length. An estimate of the weld length of the upper structure (Figure 6, from D060492) and the sleeve structure (Figure 6, D070552) is ~800 cm. With this weld length and even the Class A background limited rate, the apparent outgassing rate based on these sample measurements is ~4 times higher than required. Given uncertainties in the measurement, this is approximately comparable to equaling the requirement.

Figure 6: Quadruple Pendulum Suspension Structural Weldments

Upper Structure	Sleeve Structure
	

5 Conclusions

The Class B weld samples have measurably higher outgassing than Class A weld samples at room temperature. Based on this rather small sample test of weld samples, as well as other order of magnitude arguments on expected outgassing, we should require Class A welds for all LIGO aluminum weldments.