LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Document Type	**LIGO-T970053-00** -	**E**	01/15/97

Baffle Glaze Shedding

Rainer Weiss

Distribution of this draft:

xyz

This is an internal working note
of the LIGO Project..

California Institute of Technology
LIGO Project - MS 51-33
Pasadena CA 91125
Phone (818) 395-2129
Fax (818) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project - MS 20B-145
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

WWW: http://www.ligo.caltech.edu/

Baffle Glaze Shedding

Abstract

The shedding of glass by the baffles needs to be reduced to a level where accidental double coincidence between the Washington and Louisiana interferometers will be less than 0.1 events per year for events with 10msec duration. The glass shards may also cause failure in valves and turbo pumps. The shedding occurs in three regions: at the weld between the baffle cone and cylinder, the intersection of the baffle serrations with the baffle face and on the serrations themselves. The shedding is driven primarily by temperature change but is also influenced by vibration and state of baffle stress. A likely cause for the shedding is excess thickness of the glaze at the base of and on the serrations. Several techniques to reduce the shedding with the aim of salvaging the existing baffles have been tried in small scale laboratory experiments. The techniques need to be tested in full scale experiments which include all of the environmental drivers encountered in baffle installation and service in the field.

Introduction

We became aware of the problems with the glazed baffles in stages. The first indication was when the baffles were beginning to be installed in early November 1996. The CB&I workers noted that the baffles appeared dirty after being unpacked from their shipping boxes and removed from the Ameristat bags. It was quickly established that the dirt was not organic but rather glass shards and glass dust. Initially we thought that the larger shards came from the protruding part of the baffle at the weld between the cylinder and the cone (region 1 in Figure 1) abraded by the masonite packing separators in the shipping boxes. We also thought that the CO_2 jet cleaning at JPL had missed the frit overspray collected at the inner intersection of the cone and cylinder. To keep the installation schedule, we instituted a new cleaning step in the field consisting of a reagant grade 2-isopropanal wipe down with lint free tissues to the point where no more residue was collected by wiping the outer cylinder, the dirtiest part of the baffle. We also knew that the act of installing the baffle would dislodge more shards from the weld between the cylinder and cone and asked for two additional steps in the installation; a wire brushing of the weld edge after installation followed by a vacuum cleaning of the tube floor. The vacuum cleaning was found to be necessary as other debris (lint, bits of rubber, etc) was left due to the welding and leak hunting activities in the tube.

At the December CB&I/LIGO monthly meeting it was arranged that I enter the beam tube with CB&I personnel to make a first hand assessment of the conditions. I noticed black shards on the beam tube floor next to the most recently installed serrated baffle. The CB&I representative who was with me gave assurance that the area had been cleaned. I asked permission to look at other baffles in the beam tube and eventually walked to the gate valve. Each serrated baffle had left shards on the beam tube floor primarily on the side facing the mid station (front side of the baffle). Furthermore, the two baffles closest to the gate valve had much of the glaze removed on the outer

1/4 to 1/2 inch of the serrations due to abrasion by the slit Viton tube used as a guard during installation. The Viton was not used in the installation of subsequent baffles. The findings were reported at the meeting later that day but the understanding of the impact on the project came only slowly during the next week. Just to make sure that we were not fooling ourselves Rich Riesen was asked to maintain a visual and a photographic record of the shards as a function of time at a specific group of baffles.

The hazards associated with shedding

The possibility of non-Gaussian noise from dust falling through the interferometer beams has been a continuing concern throughout the design of the LIGO. The interferometers are remarkably sensitive to scattering by small particles. The optical phase shift associated with the forward scattering by a small particle in the beam is given by

$$\Delta\Phi = \frac{2\pi a^2}{\lambda r}$$

where Φ is the optical phase shift, approximately equal to the ratio of the scattered optical field to the main field, a is the radius of the particle , λ is the wavelength of the light and r is the distance between the scatterer and the place where the scattered and main fields are recombined. In the initial LIGO we are expecting to have an rms phase sensitivity in 10 msec of 10^{-9} radians so that with 1 μ light and a distance of 2 km, a 1 micron particle in the beam would cause a measurable event. Mie scattering becomes resonant when the particle size is comparable to the wavelength, so near 1 micron the estimated phase shift is an underestimate.

The length of the phase shift pulse depends on the residence time of the dust in the beam. If the dust is in free fall without a large initial velocity, the longest pulses would be those falling through ta diameter of the Gaussian beam

$$\tau = \frac{2\omega}{\sqrt{2gh}}$$

where τ is the pulse length, ω the Gaussian beam radius at the location of the particle, g the acceleration of gravity and h the distance through which the dust has fallen before entering the interferometer beam. Typical values are around 25 msec but there will be a broad spectrum of pulse lengths depending on where along the length of the beam the dust has entered as well as where it cuts across the beam cross section. The pulses will unfortunately have the bulk of their spectral power in the region where LIGO is most sensitive. They will also have a variety of pulse shapes depending on the geometry as well as their own dynamics (some will be rotating and as, we now know, many will have been derived from explosive events on the baffle with 100's of cm/sec initial velocities).

We have set 1 accidental coincidence every 10 years as a requirement on known non-Gaussian events for the LIGO operating as a self standing detector. The shedding by baffles, especially where driven by vibration and almost certainly when driven by explosive stress release in the baffles, will be strongly correlated in the 2 and 4 km interferometers at Washington. The safe criterion is to assume only the rejection provided by double coincidence between Washington and Louisiana. The accidental coincidence rate R_{12} is determined by the single site event rate $R_1 = R_2$ and the coincidence window width, τ_w, in time by

$$R_{12} = \tau_w R_1 R_2$$

The coincidence window width is determined by the length of the pulse, τ_p, and the uncertainty of the source location expressed as an arrival time uncertainty

$$\tau_w = \tau_p + \frac{2L}{c}$$

where L is the separation between the sites and c is the propagation velocity of gravitational waves. For 10 msec pulse lengths the **permitted event rate at each site is 1 event/hour.**

With 462 baffles in the Washington site and 360 at Louisiana and the assumption that all baffles are the same and shed isotropically, one can estimate the maximum overall shedding rate allowed per baffle. The ratio of the diameter of the optical beam to that of the baffle is 1/10 and assuming that only the upper half of the baffle will contribute, the allowed shedding rate/baffle of particles of all sizes larger than 0.5 microns is about 1/day. The initial visual data for many baffles exceeded this rate by one to two orders of magnitude, we had to take action.

An important question is the particle size distribution since with most dust distributions the number of small particles is vastly greater than the large ones. We are lucky here since it looks like the small particles are correlated with the large ones and a group of particles constitutes a single event. This is clearly the case in the explosive events from region 2 but seems also to be so for particles leaving regions 1 and 3. The best evidence comes from the electron microscope derived particle distributions shown in Figures 4 through 6. The data comes from baffle #18. Table 1 gives the total count of particles larger than 100 microns that were shed. These all came from a ring of about 100 cm^2 area of the baffle. The average surface density of visible particles is close to 5 per cm^2. The particle size distribution determined by bending a serration over a slide is shown in figure 4 along with standard dust particle size distributions which the glass seems to follow reasonably well. The ratio of the number of particles larger than 0.5 microns to those 100 microns or larger would be close to 10^4 if the shedding were uniform and isotropic. Looking at the surface particle distribution the slide left under the baffle in figure 5 and its reference in figure 6, one should have measured approximately 5 x 10^4 particles/cm^2 larger than 0.5 microns but only found under 100/cm^2. This still allows room for about a factor of 20 larger number of particles than those measured visually but it is unlikely given the shedding mechanisms. Clearly before one accepts a fix to the shedding problem this measurement should be done again.

Research to establish cause of the shedding

Particle distribution measurements were started on two serrated baffles that were at MIT for optical testing (Baffle #18 and #19) and a serrated baffle was placed in the beamtube mockup at

Caltech. From these measurements and further information from the field, it became evident that the shedding was highly variable. The data from the full scale baffle shedding measurements is summarized in Table 1. Serrated baffles shed more than unserrated ones. The baffles with thicker glaze at the serration base (region 2 in Figure 1) and on the serration teeth themselves (region 3) had higher shedding rates. Although limited by incomplete record keeping and small number statistics, it did seem that baffles that had been reworked (additional frit slurry placed on the serrations and at the base of the serrationns, then refired) were more prone to shedding than baffles that had not been reworked. Subsequent conversations with Chuck Layne at Ferro Corporation, the manufacturers of the frit, and Professors John Haggerty and Y. T. Chiang of the MIT Materials Processing Center indicated that the act of refiring is standard in the glaze and ceramics industry and that the likely cause of failure was the additional thickness of the glaze.

The largest source of the shedding in thick coated baffles has been found to be in region 2 where almost conical craters form with a base of 2 to 3 mm and a height (depth into the glaze) of close to the glaze thickness. The craters form explosively and can be detected with an accelerometer mounted on the baffle. The major part of the power in the acoustic spectrum of the explosion is between 1 to 10 kHz . The projectiles emerge normal to the surface, leave with velocities of approximately 100 cm/sec and spread debris into a full cone angle of about 30 degrees. The dynamics makes it likely that a burst of particles will enter both the 4 km and 2km beams at the Washington site, so that one would expect correlated events in the two interferometers from this source. There are 1084 region 2’s on each baffle resulting in a maximum of about 0.4 cc of shards with a 1/3 mm glaze coating. The volume of shards from the weld (region 1) is about 1.5 times larger assuming 1/4 mm glaze coating in this region. The in situ shedding by the glaze at the weld can be eliminated by removing the glass from this region prior to installation with a wire brush. The volume estimates more than account for the debris found in the Ameristat bags used to ship the baffles. The volume of shards in these bags ranges from 0.4 to 0.1 cc .

The remaining source of shedding is at the edges of the serrations and occasionally from the thick sections of glaze in the middle of the serration teeth (region 3). Estimate less than 5% of the shedding takes place at these locations.

Scanning electron microscope pictures were made of the polished edge of the region 2 for both a good baffle (non-shedding thin baffle) and a poor baffle (baffle #18). Figure 2 shows the good baffle. The stainless steel is at the bottom left while the glass (white) is at the top right. The oxide layer, necessary for good adhesion of the glaze to the metal, is the dark band running diagonally from top left to bottom right. Figure 3 shows the structure in baffle #18, the oxide layer is discontinuous and thinner. Adhesion of the glaze to the stainless steel is not the dominant problem at the moment, however, establishing that a good oxide layer is formed is a discriminant that will be useful in later tests to establish whether the shedding problem is under control.

By measuring the explosion rate in baffle #18 both at room temperature and outside (ΔT = 17C), it became clear that one of the strongest environmental drivers for shedding was cooling. Heating is less likely to cause shedding. Based on this observation a simple test was devised using cooling to -15C in a refrigerator freezer compartment. Sample pieces treated in various ways are placed in transparent sandwich bags to collect shards and allow particle counting while maintaining the history of their origin. All the research done on techniques to reduce shedding have used this testing method.

Methods tried to reduce the shedding

A summary of the results for various techniques used to reduce the shedding is given in Table 2 where the refrigerator cooling tests are tabulated. The primary idea has been to relieve the internal stress in the glass and to reduce the thickness of the glaze in the critical regions 2 and 3.

There is some theoretical work calculating the stress distribution in layered materials with different thermal expansion coefficients, elastic moduli and different thicknesses. Much of the work has been done in designing glass/metal hermetic seals. Refer to *Technology of Glass, Ceramic, or Glass-Ceramic to Metal Sealing* edt W. Moddeman, C. Merten, D. Kramer AMSE 1987 in particular the article by F.P. Gerstle and R.S. Chambers on “Analysis of End Stresses in Glass - Metal Bimaterial Strips”. The authors are at Sandia Labs in New Mexico.

Using the theory developed (which is non trivial) one can calculate the stresses in the glass as a function of the Young’s moduli of the steel and glass, the thermal expansion coefficients of the materials and, most relevant, the thickness ratio of the glass to stainless steel. The largest internal stress occurs for thickness ratios of 1/2 and tends to place the glass in tension rather than compression in region 2. The internal stresses vanish when the thickness ratio approaches zero or values much larger than 1. The breaking stress in compression is about 10 times larger than in tension. Although the calculations do not take the edge effects into account properly, they do serve as a guide and provide further evidence that the shedding is due to a thick glaze layer.

Annealing at 590C Annealing was done in an oven with a heating time of 6 hours, an annealing time of 8 hours and a cooling time of 8 hours. The glass took on a matt surface and there was a small increase in the backscattering brdf at 55 degrees angle of incidence. The annealing stopped the explosive stress release in region 2 but did not strongly reduce the shedding (contrary to instinct and the advice of most of the experts consulted)

HF etch at 48% concentration at 80F Etch rate of the glaze is close to 1 mil/min in flat sections and 2 to 3 mils/min in curved and strained sections. The etch does even out the surface. The process leaves a matt surface which needs to be washed off to eliminate a white powder most likely a flouride salt of one of the metal constituents in the frit. The matt surface increases the brdf but can be reduced to close to the original values by oven firing at 780C for several minutes. The shedding is reduced and this is a candidate method for larger scale tests.

Grinding followed by refiring at 800C The glaze is ground on both sides in region 2 and 3 to the thickness of the glaze in the baffle web. In the test, the grinding was done with the broad edge of a glass cutting wheel, one side at a time. In mass production the grinding would be done by abrasive wheels on both sides of the baffle in a centerless grinding configuration. The ground surface has a high brdf but refiring at 800C for a few minutes restores the low scattering. The shedding is again greatly reduced. This method may be the closest to techniques used in the glazing houses and is expected to be the most economical.

Refiring with a broad O_2 rich flame at 800C In this technique the regions 2 and 3 were heated on both sides with a “bushy” blue flame orange at the edge approximately 1 inch in diameter until the glaze reached 800C and was held there for 1 minute. On cooling the glaze at the serrations had a purple cast and the wetting of the glaze to the serration edges was smooth and covered the entire edge. The brdf was unchanged and there was no shedding. Do not understand why this worked. It did not change the thickness of the glaze in regions 2 and 3. This method would be the most economical of all those tried. Expect that we will finally have to talk with a chemist if there really is merit here.

Other technique that were tried were CO_2 laser machining and simple oven refiring at 780C. The laser machining is too costly and was not carried to a full test. The simple refiring was found not to reduce the shedding.

Next Steps

In addition to the steps being taken to procure shiny steel oxidized baffles, it is appropriate to try some of the more promising techniques to save the glazed baffles. The next stage will require full up tests where the baffle after being fixed is tested under mechanically stressed and temperature cycled conditions. To gain the needed sensitivity will require tests of 10 or so baffles simultaneously in a dedicated system for about a week. The large scale tests, if successful, should be followed by electron microscope scans of the cross-section in region 2 and 3 and a more comprehensive measurement of the particle size distribution.

It is critical to test the existing non-serrated baffles under realistic environmental conditions and to subject them to microscopic measurements if they pass the environmental tests. They offer one fall back position and, as practical concern, there are already many installed so we need to know if they also have to be removed from the beam tube.

Although I have not yet tried to find out which of the successful techniques is commercially available, expect that the grinding and refiring and the oxygen rich flame techniques are the most readily available.

Table 1: Full Scale Baffle Shedding Measurements

Description	exposure time	glaze thickness 2*t	min particle size	number of particles	number/ hour >100 mu	rate in LIGO beam
	days	mils	microns			number/hr
#18 (0.3g) s	3	18 (31)	100	500	6.9	160
#19(0.3g) s	2	14(17)	100	18	0.37	9
CIT 1 s	16	17(27)	100	360	0.94	22
WA 1 s	21		500	500	3.0	69
WA2 s	21		500	60	0.36	10
WA3 s	16		500	40	0.31	7
WA4 s	16		500	20	0.16	4
WA5 ns	20		500	2 - 5	0.01 - 0.03	0.2 - 0.6
CIT2 ns	4	4 - 8	100	< 21	<0.22 - 0.44	<5 - 10 **

NOTES:
** Unserrated baffle installed in Caltech mockup may be shedding primarily from region 1. This baffle needs to be wire brushed and cleaned.

Factor of 3 is used in projecting counts at minimum size of 500 microns in the field to 100 microns made in the labs.

s indicates serrated baffle, ns non serrated baffle

First number under glaze thickness is measured at the baffle web, the second number in () is on the serrations (region 3). The values in region 2 are close to the average.

Projection to the LIGO (last column) uses 462 baffles (WA), a beam to baffle diameter ratio of 1/10 and a factor of 1/2 to account for half the baffle below the beam.

(0.3g) indicates that the baffle was being shaken by 0.3g at 30 Hz, about 8 x 10^{-3} cm. Later measurements indicated little effect from the shaking.

Table 2: Small sample (5 inch section) shedding on cooling to -15C, *sandwich bag test*

Description and process	Backscatter BRDF	glaze thickness 2*t	number > 100 mu	number > 100 mu
	1 x 10^{-3} sr^{-1}	mils	FIRST COOLING	SECOND COOLING
baffle #18 s	1.0	18(31)	20	4
baffle #18 annealed 590C s	1.2	18(31)	12	3
uniform tooth annealed 590C s	1.8	15(20)	9	2
baffle #19 s	2.2	14(17)	1	0
old sample MIT 1 s	2.5	8(8)	0	0
old sample MIT 2 s	2	15(20)	9	2
old sample CIT 1 s		14(18)	2	0
old sample CIT 2 s		20(27)	5	0
old sample CIT 3 s		4(4)	0	0
old sampl CIT 4 ns		7	0	0
old sampl CIT 5 ns		6	0	0
# 18 HF etch 5 min, matt s	3 - 4	13 (22)	1	0
# 18 HF etch 5 min, oven refire 780C s	1.1	13(22)	0	0
# 18 oven refire 780C s	1.0	18(31)	7	2
# 18 ground s	3.2	18(22)		
# 18 ground, refired 800C, 1 min s	1.2	18(22)	0	0
# 18 fired in O_2 rich flame 800C, 1 min s	1.1	18(31)	0	0

Notes:
Particle counts made at serration end of the baffle. The other edges at the sides and the back of the samples are taped. Earlier measurements reported total particle counts which are not indicative of the shedding in the full baffle.

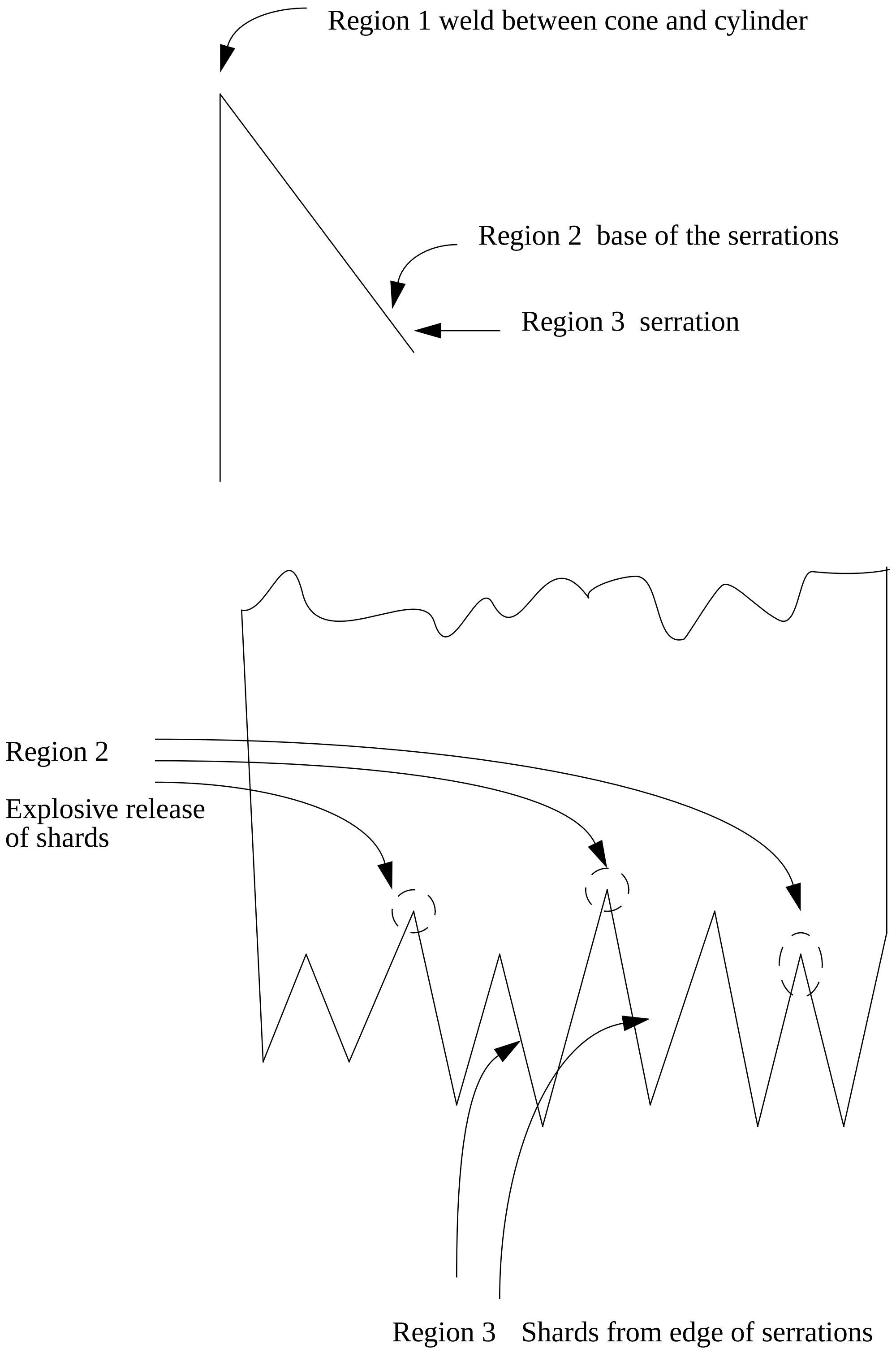

Figure 1. Schematic of baffle and locations of shard release

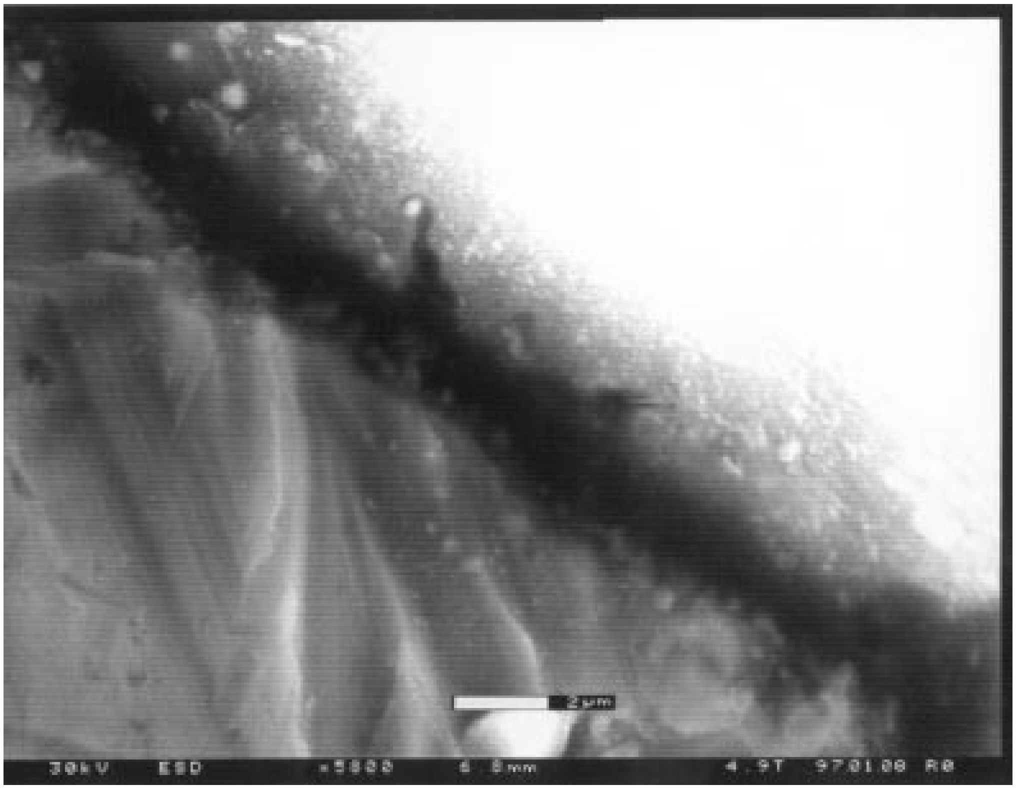

Figure 2 Scanning Electron Microscope picture of cross-section of thin non-shedding baffle.

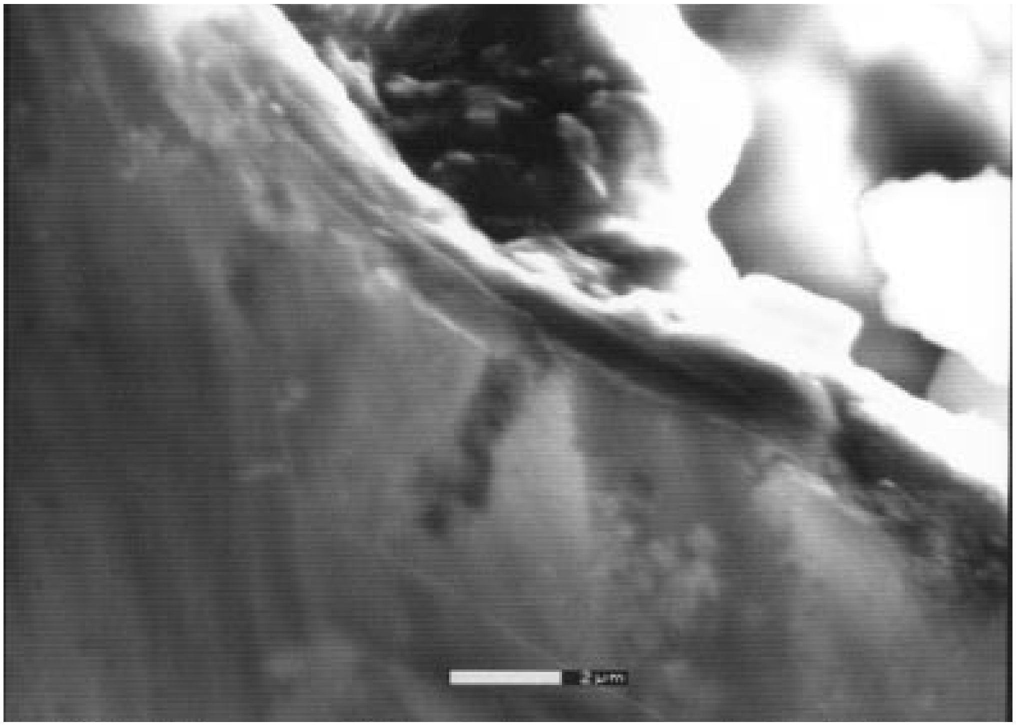

Figure 3 Scanning Electron Microscope picture of cross-section of Baffle #18.

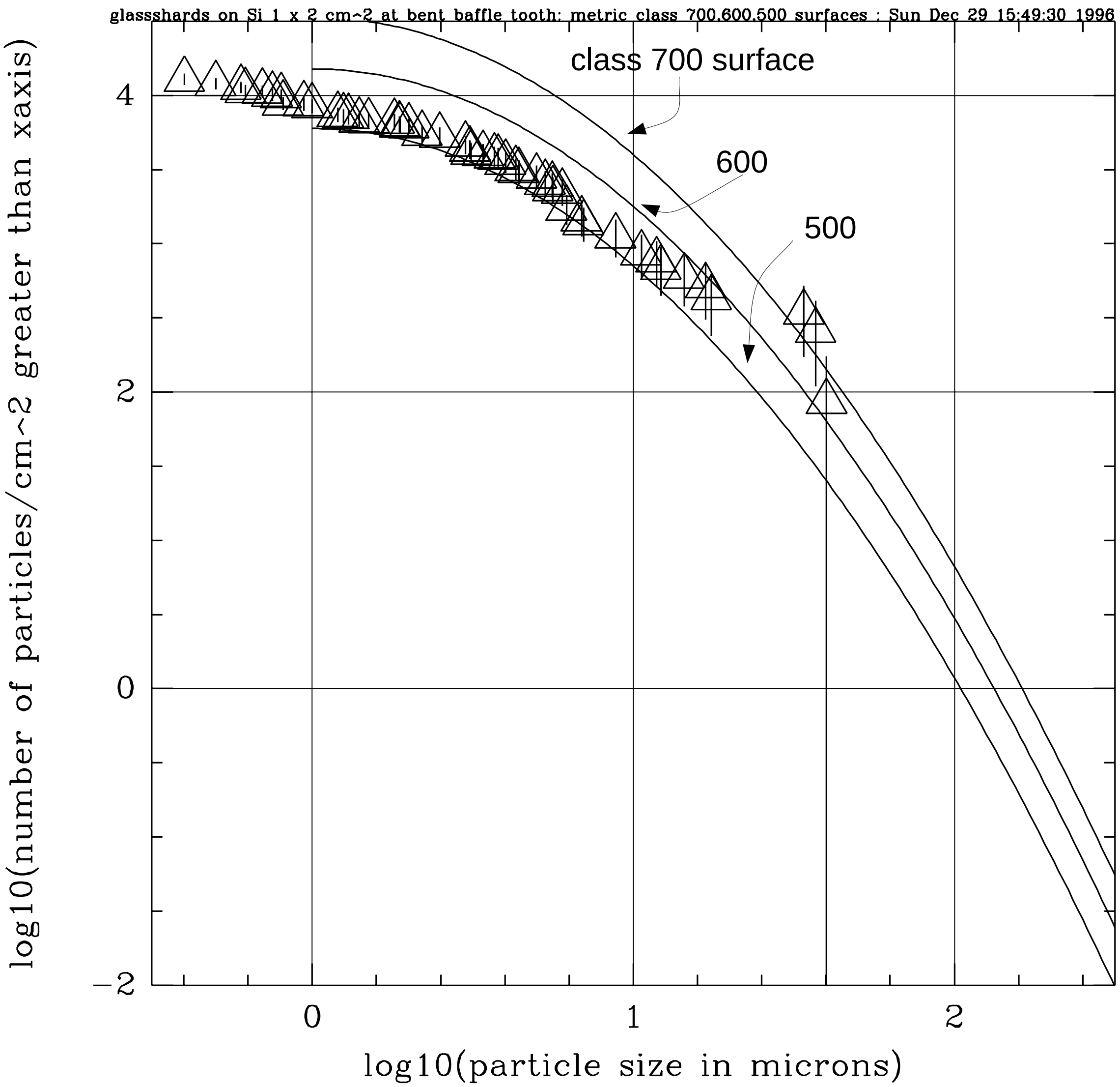

Figure 4 : Size distribution by collecting a sample onto a silicon wafer after bending a baffle tooth. The distribution is determined from a set of scanning electron microscope pictures. The solid lines indicate MIL SPEC surface distributions associated with class 700,600 and 500 surfaces with a particle distribution centered at 1 micron.

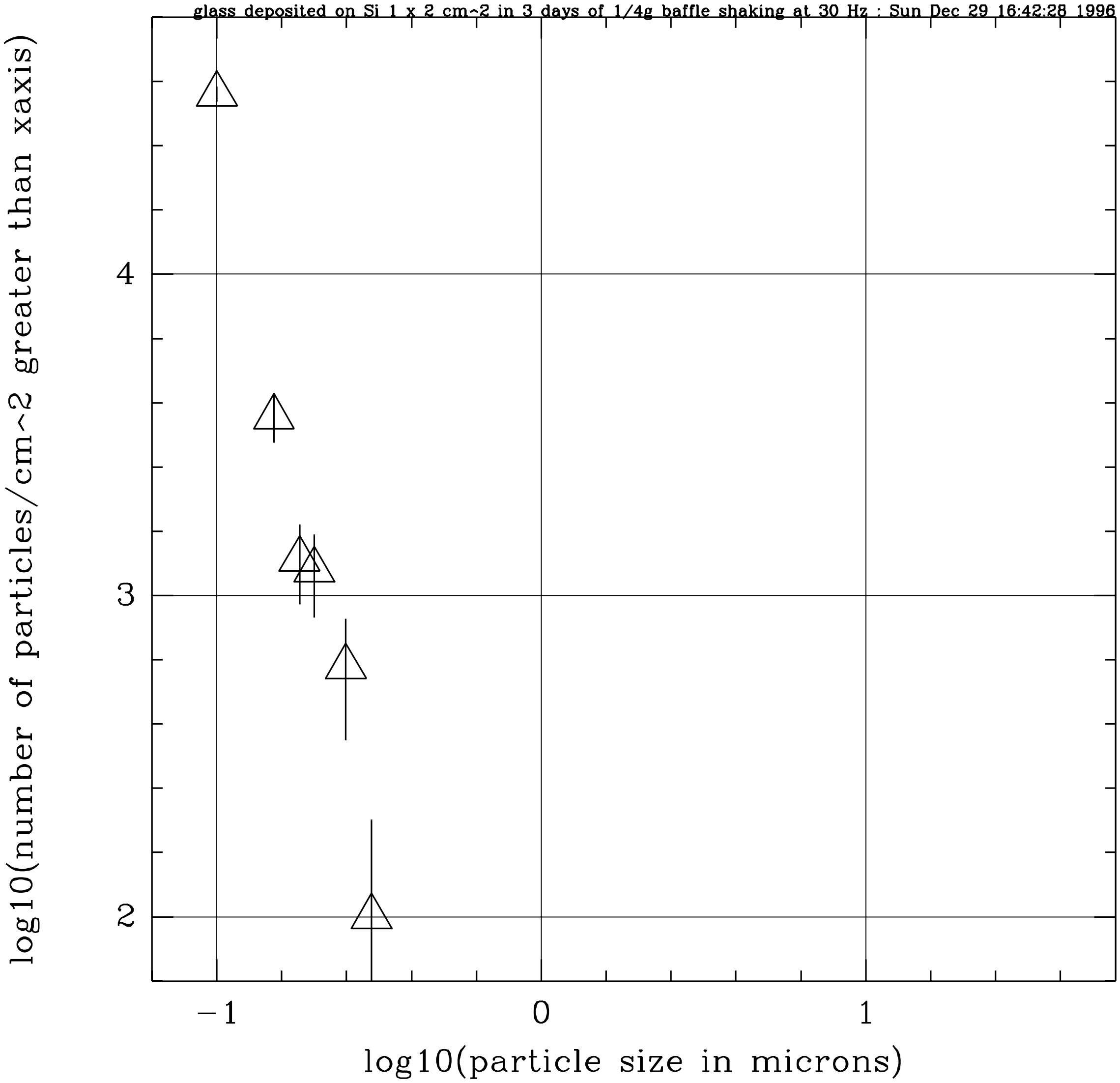

Figure 5 Particle size distribution collected on a silicon slide under baffle #18 exposed for 3 days. The disitribution shown in figure 6 is the dust background on the slide and from the room during the measurement.

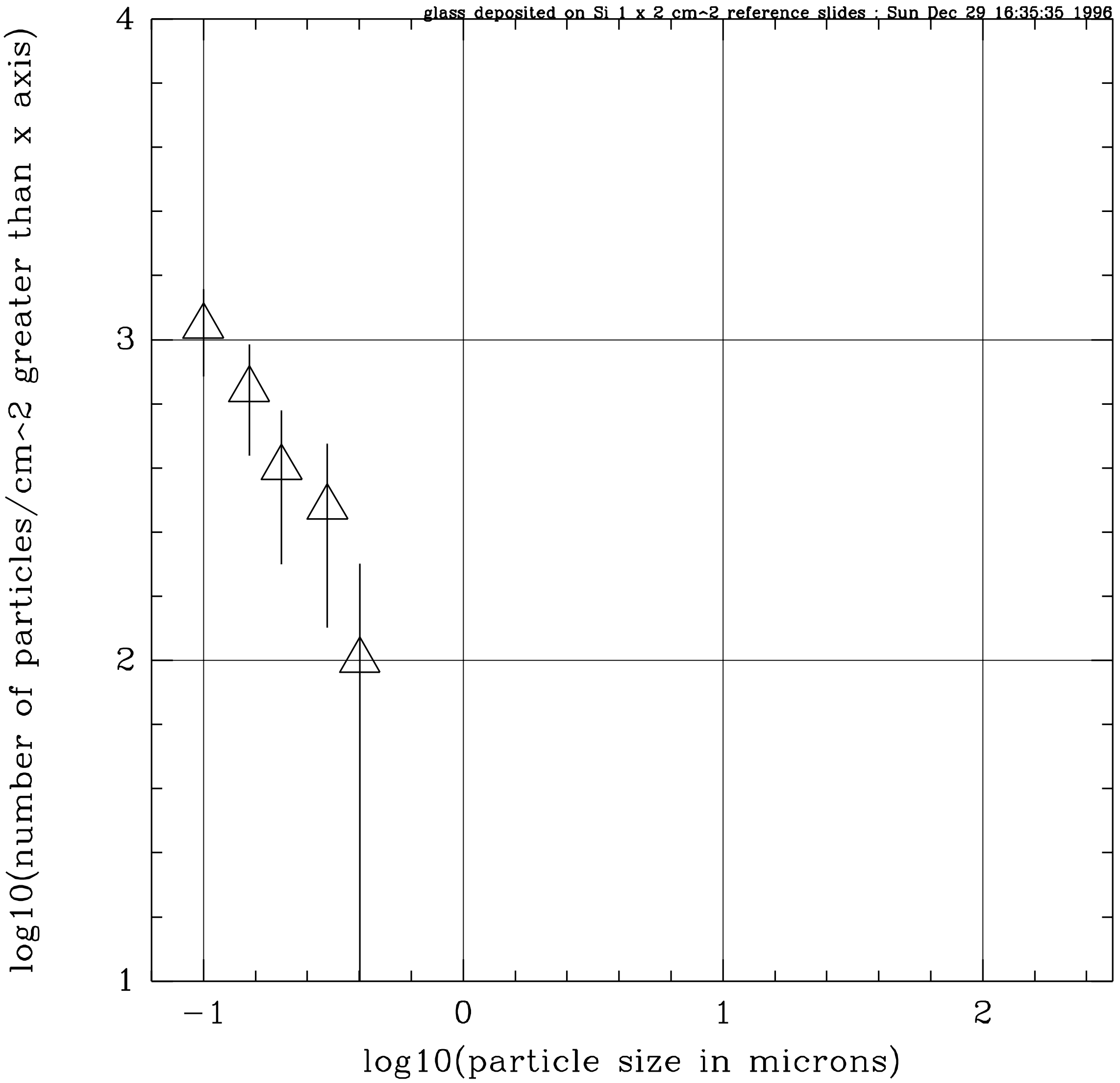

Figure 6 Reference sample for figure 5. Dust on silicon slide collected from the room including the dust initially on the slide.