MEMO:dust.tex

FROM: RW (December 9,1988)

TO: Althouse

CONCERNING: Dust accumulation on optics, scattering and requirements on clean area for the LIGO

REFERENCES

1) Federal Standards No. 209B April 24, 1973

Federal Standard Clean Room and Work Station Requirements, Controlled Environment

2) Military Standard 1246A August 18, 1967

Military Standard Product Cleanliness Levels and Contamination Control Program

3) *Air Pollution Control Engineering* Licht,W, Marcel Dekker, Inc., New York, 1980 (TD884.5.L52)

4) *The Particle Atlas* McCrone,W.C.,Delly,J.G., Ann Arbor Science Publishers, Inc.,1973 (TD883.M132)

5) *Particulate Fallout Predictions for Clean Rooms* Hamberg,O., Journal of Environmental Sciences, 25, 15, 1982.

6) *Impact of the STS Ground/Launch Particle Contamination Environment on an Optical Sensor* Bareiss,L.E. and Jarossy,F.J. in Progress in Astronautics and Aeronautics Vol 91 1984 AIAA.

Dust size distribution functions

There are several standards one must know to be able to interact with manufacturers and to connect with the literature.

The first is the estimated particle distribution stored in air as a function of air quality class. This is given in reference 1. The semi empirical graphical integral distribution of particle number density vs particle size for ordinary air can be expressed algebraically as

$$\rho(r > a) = \frac{7.6 \times 10^{-6} C(eng)}{a(\mu)^{2.21}}$$

where $\rho(r > a)$ is the number of dust particles per cc of air larger than radius a in microns. $C(eng)$ is the class environment which determines the dust loading of the air in units of the number of dust particles greater than 0.5 μ stored in a cubic foot of air. For example, a class 100 environment will on the average have 100 particles with radius greater than 0.5 μ per cubic foot. This represents a good clean room. The very best I know is class 10. To give a feeling for the classification, here are some other examples: the cleanest part of our lab was measured as a class 15000 area, the high bay area in the NASA shuttle assembly building at Cape Canaveral might be class 100000, an air controlled (not specifically dirty) industrial environment could be class 1000000, The second standard is a cleanliness criterion on parts themselves. Reference 2 gives the military standard, based on a semi empirical log normal probability distribution centered around 1 micron particle size, as

$$ln(n(r > x)) = .402(ln^2(x_1) - ln^2(x))$$

where $n(r > x)$ is the number of particles per sq ft greater than size x in microns stored on the surface, x_1 is the cleanliness level of the part. The cleanliness level is equal numerically to the largest particle in microns for which there is typically one particle of that size on the surface per sq ft. Examples: visibly clean surfaces have cleanliness levels less than 1500, clean optical surfaces have cleanliness levels less than 300 and what are considered very low scatter surfaces (for closest angular approach to sun or earth limb for survellience satellites) have cleanliness levels below 50.

In subsequent calculations with these "standard" surfaces it is useful to calculate the differential particle distribution on the surface. To simplify the algebra, define

$$y(x) = .402(ln(x))$$

The integral distribution can then be rewritten as

$$n(r > x) = \frac{{x_1}^{y(x_1)}}{x^{y(x)}}$$

and the derived differential distribution becomes

$$\frac{dn}{dx} = \frac{.804 ln(x) x_1^{y(x_1)}}{x^{y(x)+1}}$$

The differential distribution is given in mixed units; dn/dx is in units of particles per sq ft per particle size x measured in microns, x and x_1 have the same definitions as before.

A useful representation of the surface dust contamination for these "standard" surfaces is the fraction of the surface covered with dust. The differential fractional coverage, *df* in a particle size range $dx(\mu)$ is

$$df = (\frac{\mu}{ft})^2 \pi x^2 (\frac{dn}{dx}) dx$$

The total fractional coverage is

$$f = 2.73 \times 10^{-11} x_1^{y(x_1)} \int_{x(min)}^{x(max)} \frac{ln(x)}{x^{y(x)-1}} dx$$

I have done the integral numerically getting the value 83.7 for a particle size range of .01 to 1000 μ. The integral is only sensitive in the .2 to 50 μ range. A plot of log_{10} of the fractional coverage vs log_{10} of the surface cleanliness classification is shown in the figure. The figure shows that we should keep surfaces to a cleanliness level of better than 100 if we want the loss on the surfaces to be less than 10 parts per million. The conditions needed to keep the near forward dust scattering in the LIGO smaller than the intrinsic mirror scattering are both more stringent and more difficult to estimate since they depend on the particle size distribution in a more complicated way. Particles larger than λ of the light will Lambert scatter with a cross section proportional to the x^2,(the fractional coverage argument should apply to these), those comparable with the wavelength will resonantly scatter with a cross section inversely proportional to their internal losses, while those smaller than the wavelength will Rayleigh scatter with a cross section proportional to $\frac{x^6}{\lambda^4}$. I am still in the process of evaluating the relative importance of these different scattering mechanisms, an analysis of this will be included in a later memo.

The remaining question, for the moment, is to relate the air cleanliness class to the surface cleanliness. This is probably the least well defined part of the problem and subject to the largest uncertainty. The physics of the dust deposition process on the surface is not easy to predict from first principles (appendix) and one has to resort to the poor data in the literature. The best I have found is in reference 5.

Reference 5 gives a compilation of data on dust deposition on horizontal surfaces (vertical surfaces are expected to be a factor of ≈ 10 cleaner) in various clean rooms. The data is collected for deposited particle sizes larger than 5 μ and the room air conditions are given in terms of particle counts with size greater than 5 μ per cubic foot. An empirical relation is given for the deposition in one day. I have played with this relation assuming that the particle size distribution both on the surfaces and in the gas are the ones given above. The semi empirical relation between x_1, the surface cleanliness level, $C(eng)$ the air class environment, and $t(hr)$ the exposure time in hours is given by

$$x_1^{y(x_1)} = 2.06t(hr)C(eng)$$

The fraction of the surface covered becomes

$$f = 4.7 \times 10^{-9} t(hr)C(eng)$$

Examples: 1 day exposure in a class 100 environment gives a class 100 surface, the fraction of the surface covered with dust is 1.12×10^{-5}; a 1 day exposure in the cleanest part of our lab (class 15000) yields a surface dust coverage of 1.7×10^{-3}.

The 68% confidence limits give a factor of 3 on either side of the calculation based on the data in reference 5. The calculation seems reasonable based on my experience (amazing).

Some conclusions: It does look like we will have to be very clean, surfaces better than class 50, and it will not be easy in the large highbay to keep the overall air quality good enough, say C(eng) 20 or less for a day (a typical time to leave things open). We will have to prepackage optics or make the tanks good clean rooms.

Things still to be done:

1) Finish the forward scattering calculations, reduction in scattering will only make the contamination levels lower and do not effect the conclusions.

2) Determine the cost and operational tradeoffs between prepackaging vs in situ cleaning. HP now processes and transports Silicon wafers entirely by prepackaging in clean small

containers which remain around the wafers during processing. These mini super clean "rooms" are part of the product until final packaging. This is similar to the idea you had for the mirrors surrounded by containers opened only in the vacuum. It might be worthwhile to visit HP to see how they actual do it.

Appendix on Physical Processes Invoplved in Deposition

The processes are:

1) Gravitational settling. For particles larger than 10μ the dominant mechanism is preciptation at terminal velocity of the particles driven by gravity against the viscosity of the air (Stokes flow as in the Millikan Oil Drop experiment). The deposition density, σ in particles per cm^2 varies as

$$\sigma(x) \approx t\rho(x)\frac{2\rho g x^2}{9\eta}$$

where t is the exposure time, $\rho(x)$ is the particle density in the air for particles of size x, ρ is the specific gravity of the dust, assumed ≈ 2, g is earth's gravity and η is the viscosity of the air, 1.8×10^{-4} gm/sec cm. The enclosed figure from reference 3 shows the terminal velocities and Reynolds numbers for this process.

2) Diffusion out of the air. This process is important for particles 1μ and smaller. The diffusion constant for particles larger than a mean free path in air at STP ($\approx 3\mu$) is approximately given by

$$D = \frac{kT}{6\pi\eta x}$$

while the diffusion constant for particles smaller than a mean free path is

$$D \approx \frac{3}{8\pi x^2 \rho_g} v_{th}$$

where D is the diffusion constant in units of $\frac{cm^2}{sec}$,k is Boltzmann's constant, T the temperature, η the viscosity of the air, ρ_g the number density of the gas, and v_{th} the thermal velocity of the gas. The typical diffusion distance of the particles varies as

$$X^2_{avg} \approx 2(Dt)$$

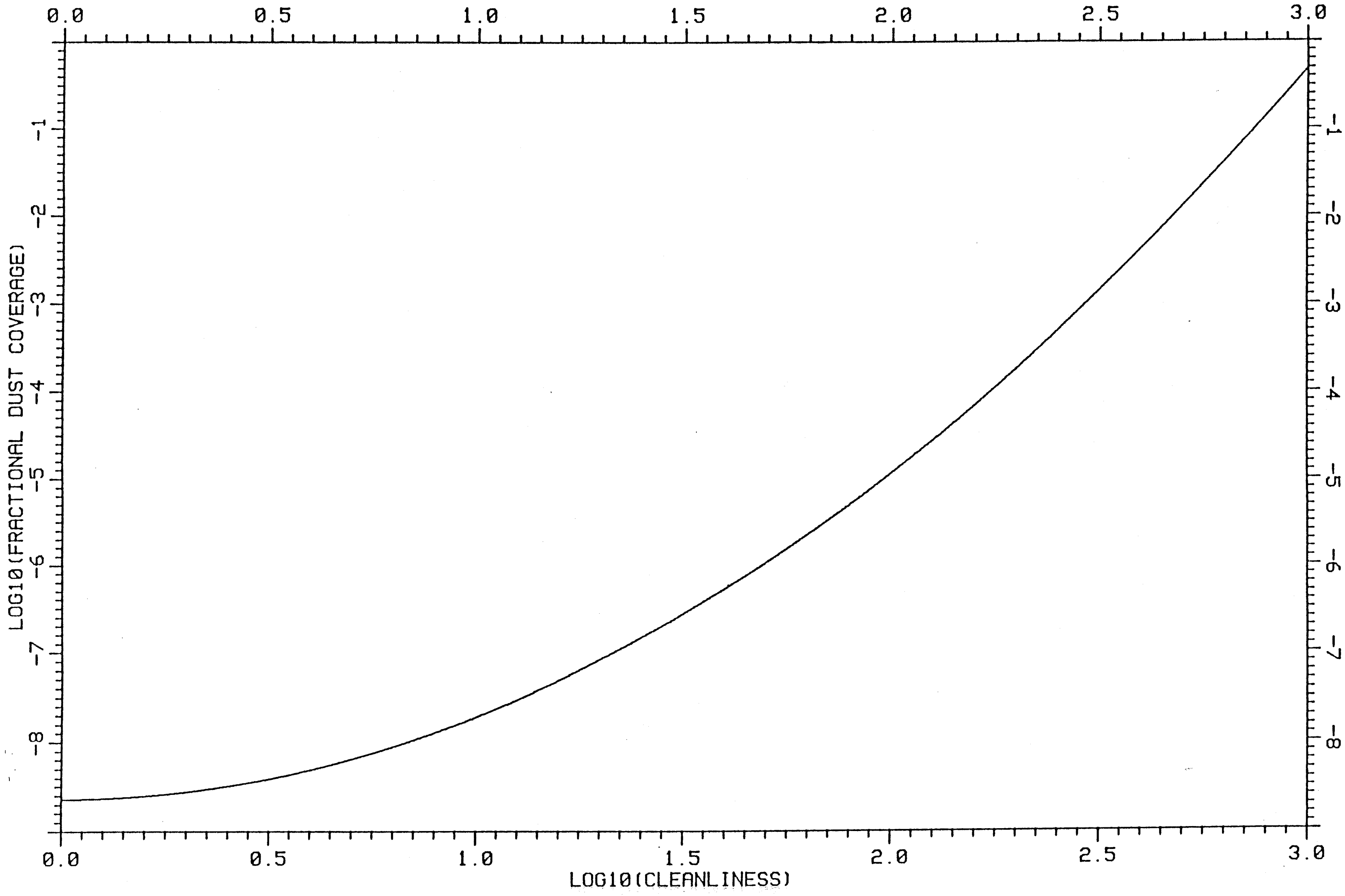
where t is the exposure time.

The figure from reference 3 relates diffusion constants in air at STP to particle size.

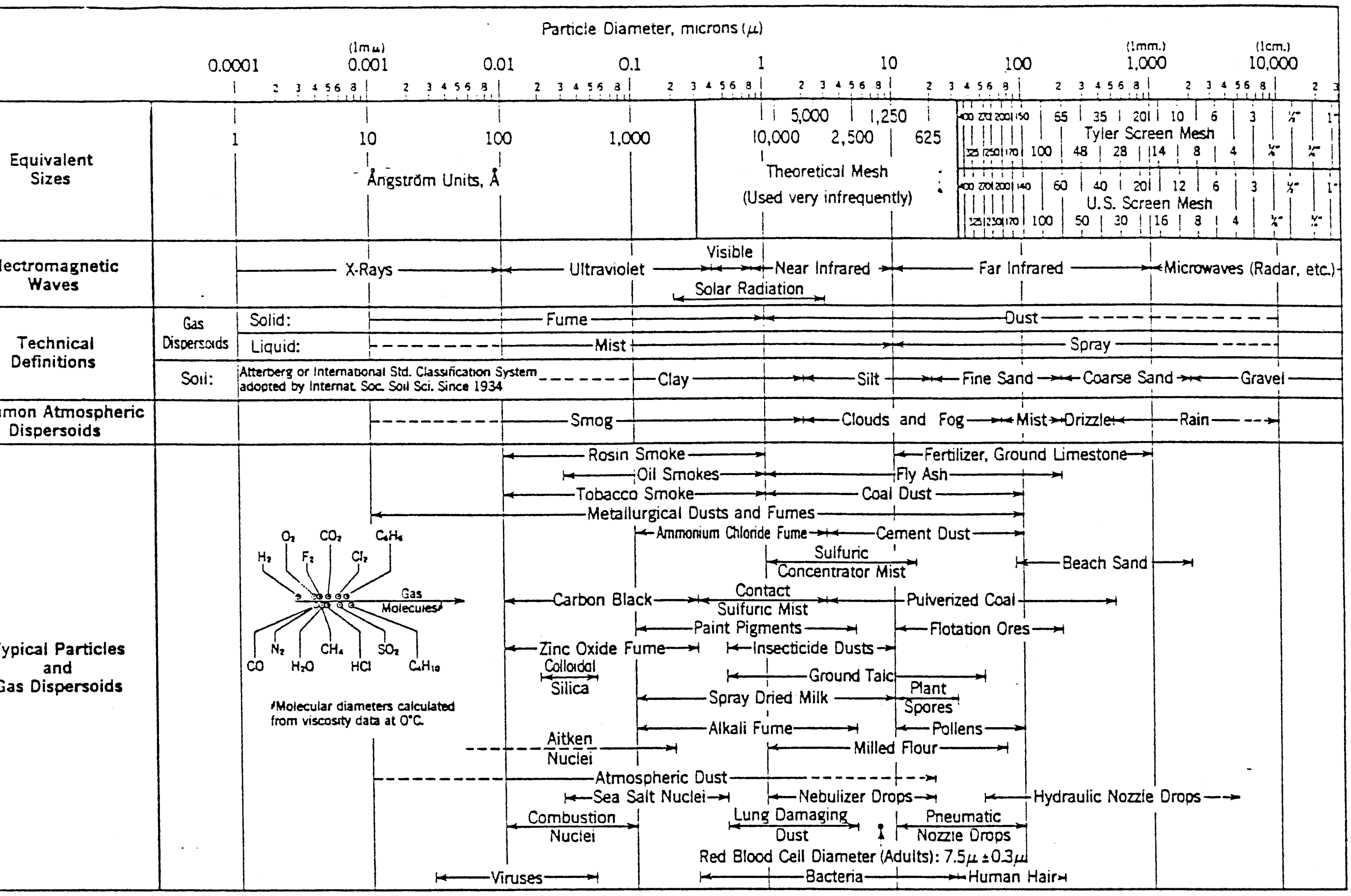
3) Electrostatic attraction. Long range electrostatic forces (both monopole and dipole) radically alter the deposition rates and sticking probability of the particles (as anyone who has played around high voltage terminals knows). If the dust particles are charged they see an attractive image in the surface for both dielectric or conducting surfaces. Dielectric surfaces usually have stored charge and by induced dipole/charge interactions with the dust become dirtier than metal surfaces.

4) Thermal convection. The flow around a surface and therefore the dust deposition rate is altered by the temperature gradient between the surface and the ambient air. A familiar example is the convective flow at radiators.

Processes 1 and 2 are easy to calculate once one knows the air classification and typical room air velocities, 3 and 4 are tough.



DUST SURFACE COVERAGE VS CLEANLINESS CATEGORY



FROM: AIR POLLUTION CONTROL ENGINEERING, LICHT, W. M. DEKKER INC. – 1980 (TD884.5.L52)

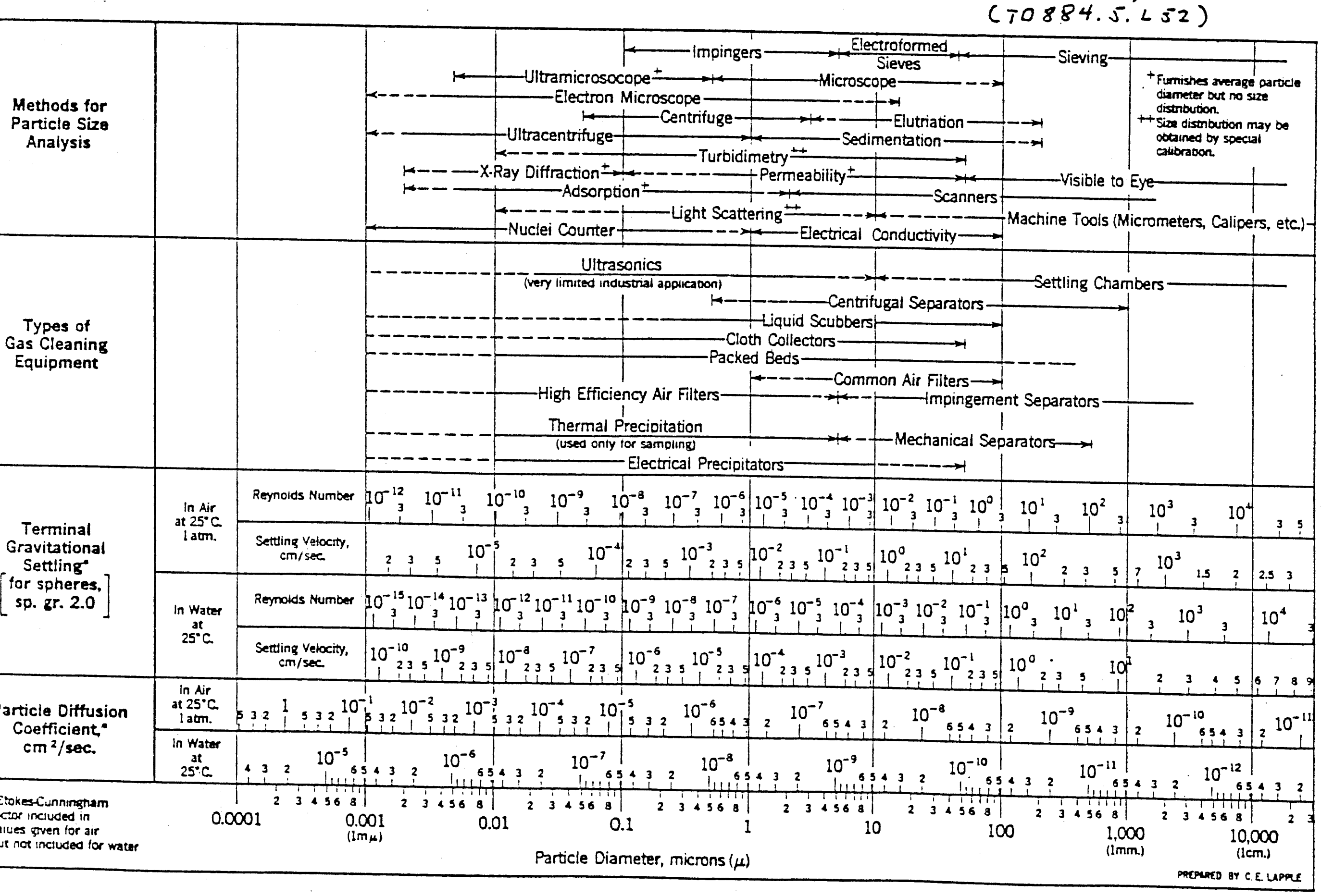
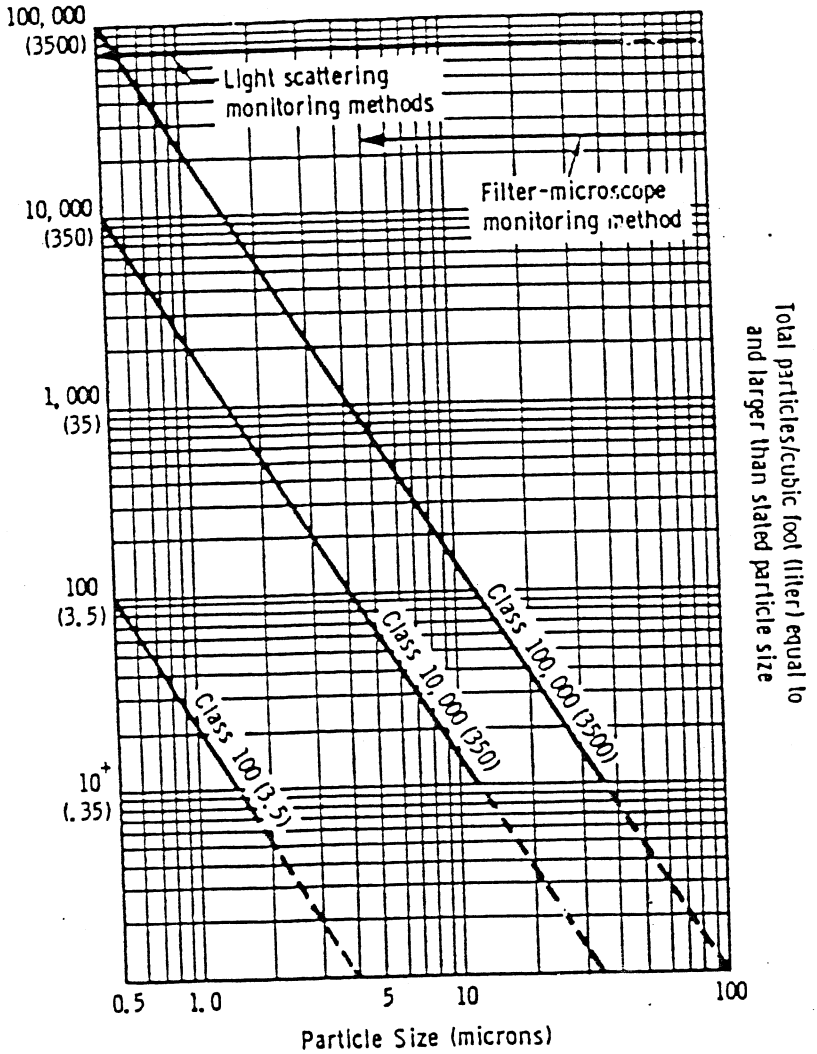


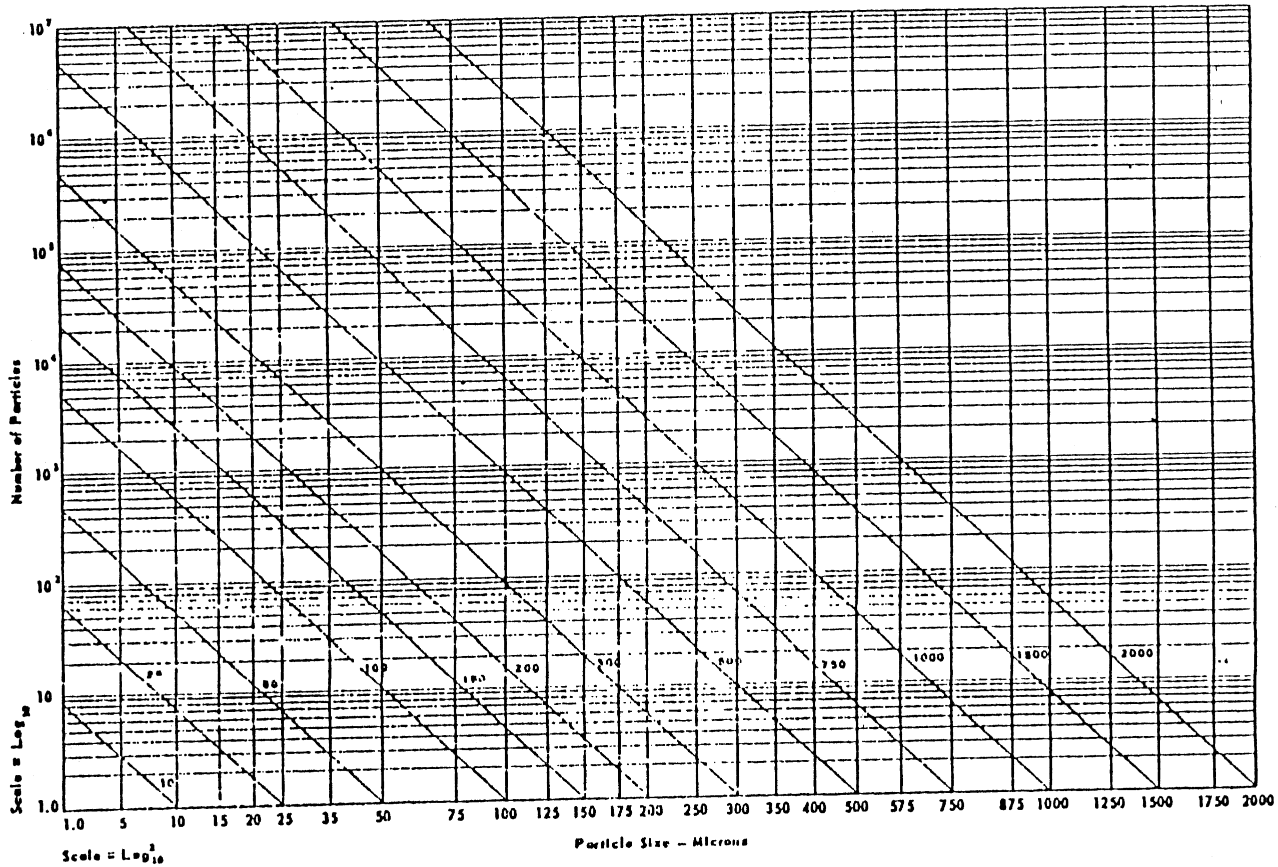
TABLE II. Particle size distribution curves



+Counts below 10 (0.35) particles per cubic foot (liter) are unreliable except when a large number of samplings is taken.

0993

CHART I
PRODUCT CLEANLINESS LEVELS



Research shows that naturally occurring particulate contamination follows a log-normal distribution with a geometric mean of near one (1) micron particle. This distribution follows a straight line when plotted on a log x log^2 scale graph. The grid is derived from the log-normal Gaussian distribution function which provides a close fit to real contamination data. The lines on the chart represent the maximum contamination permitted for each level and the plot point is the number of particles above given size versus particle size. The curves can be expressed as $\log n = 0.9260 (Log^2 X_1 - Log^2 X)$, where n is the number of particles, 0.9260 is the tangent of the angle, X is the particle size, and X_1 is the cleanliness level.

Review of the memo:

Dust accumulation on optics, scattering and requirements on clean area for the LIGO

by

Rai Weiss

I find this work a very useful guide for the cleanliness requirements at the LIGO facility. It appears that the author has done a thorough literature search, so that the emerging definition of cleanliness is sound and useful together with examples of cleanliness class of different environments. The mechanisms of dust deposition from the air are discussed and I believe all the most important mechanisms have been considered. However, as Rai Weiss points out, only the gravitational settling and the diffusion out of the air are calculable at present. It is comforting to know that calculations and experimental measurement of dust deposition on horizontal surfaces can be reconciled (third paragraph on p. 3), but it is not clear if such an agreement can be obtained for vertical surfaces which is presumably how one is going to handle mirrors in LIGO.

This memo has touched a very important subject in building the LIGO facility and has also given guidance for the handling of the problem. I happen to agree with the conclusions of the memo and I would like to suggest that the monitoring of cleanliness be implemented in LIGO labs as soon as this becomes feasible.

Andrej Čadež

Pasadena, January 5, 1989

FROM: Robert Spero 6 January 1989

SUBJECT: Comments on Memo dust.tex—"Dust accumulation ...", by R. Weiss

TO: Ernie Franzgrote

The conclusion of the memo

> We will have to prepackage optics or make the tanks good clean rooms

may be modified by the possibility of in situ cleaning, pointed out in the "Things still to be done" list.

We have had surprisingly few problems with dust at Caltech, considering that the lab is extremely dusty and no measures have been taken to make the vacuum system free of dust. The procedure for handling mirrors is to supply the coaters with custom-made O-ring sealed containers, so they can package the mirrors in the production clean room. Inspection of mirrors and final assembly of mirror–test masses is done on a laminar flow clean bench in the Caltech lab. A final drag-wipe cleaning is performed on the suspended, vertically-oriented mirrors before the vacuum system is sealed. This procedure results in no noticeable degradation of mirrors (total loss on the order of 50 ppm) when they are exposed to the air in the vacuum chamber for up to a few days between cleaning and pumpdown.

I suggest that the recommendations of super mirror manufacturers such as Litton be sought before decisions are made on the cleanliness requirements of the buildings or vacuum chambers. The cleanliness requirements and the operating procedures will be influenced by answers to the following questions:

- Is there any experimental data on how long a vertically-oriented mirror can remain exposed to the air in a not-so-clean room before the surface is degraded?
- What is the best method for cleaning the mirrors on the bench? in situ?
- Can the coating process be optimized for mirrors that will be exposed to fairly unclean environments for short durations?