Establishing a Cleanliness Program and Specifications for the Sudbury Neutrino Observatory

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I. INTRODUCTION

Given the need for ultra-low backgrounds at the centre of the SNO detector, requirements for heavy water purity (10^{-15} g/g Th) and the acrylic vessel materials ($2x10^{-12}$ g/g Th) have been set. The amount of mine dust (typically $3x10^{-6}$ g/g Th) either incorporated into acrylic bond joints or adhering to the photomultiplier tubes (PMT's), the support structure (PSUP), cables or the acrylic vessel must be strictly limited, so that no significant additional background results. It has been estimated by D. Sinclair[1)], that a total dust loads of 0.2 g on the interior of the acrylic vessel, 10 g on the exterior of the vessel, and 50 g on the PMT's and PSUP can be tolerated without changing the background significantly.

This document outlines a cleanliness program, provides specifications for parts of the program, and provides a framework for future work related to cleanliness. Previous work and reports are reviewed, and a new calculation of dust deposition rates is presented in the appendix.

The cleanliness program can be factored into five components

1. Establish clean conditions in the cavity before start of installation.

    specifications
    cleaning procedures
    certification

2. Deliver clean components at entrance of cavity.

    specifications and certification
    packaging
    transportation from surface to cavity

3. Maintain cleanliness in the cavity during installation.

    air quality
    components
    installation equipment
    personnel
    air and surface monitoring
    cleaning procedures during installation (janitorial)

4. Clean up and certification before closing and filling cavity

5. Maintenance and monitoring of cleanliness during operation

Each of these five areas includes design of equipment and facilities needed to accomplish the task, as well as operational procedures for personnel once equipment and facilities are in hand.

This report will deal primarily with item 3 - what is needed to maintain adequate cleanliness during the installation period. The other items will be covered in additional reports.

II. PREVIOUS WORK

The cleanliness requirements for SNO were first outlined in the report "Evaluation of Dust in Air Requirements", by H. Lee, E.D. Hallman and H.C. Evans[2]. The results of the mine dust measurements were shown to follow a number/size distribution law $dn(D)/dD = 211\ D^{-2.9}$, where n is the particle number/cm^3/μm, and D is the particle aerodynamic diameter in microns. (That particular example of unfiltered mine air corresponded to a "CLASS" of 10^7, i.e., a total of 10^7 particles of diameter 0.5 μm and larger per cubic foot. of air. See figure 1 for the definition of the air CLASS). Settling rates were estimated for filtered air and the importance of removing the larger dust particles (≥ 0.2 microns) was emphasized.

The dust levels present in typical mine air on the 6800 ft level of the Creighton mine have been measured on three separate occasions using a six-stage cascade impactor. Results show that dust loadings of 0.6 ± 0.2 mg/m^3 (or 0.6 ng/cm^3) are normally present, with the mean aerodynamic particle diameter close to 2.0 μm. During nearby drilling operations, levels can reach 5.5 mg/m^3, while measurements made during a mine shut down showed levels about one-third of the normal values. These measurements are summarized in ref. 3.

A general plan of an air circulation system for the cavity was presented in the document[4] "Cleanliness Considerations for Construction of the SNO Detector" by H.C. Evans & H.W. Lee and outlined in the Mk II Engineering Proposal (PSD-TM-12) edited by K. McFarlane.[5] It was planned that ducts would carry air through

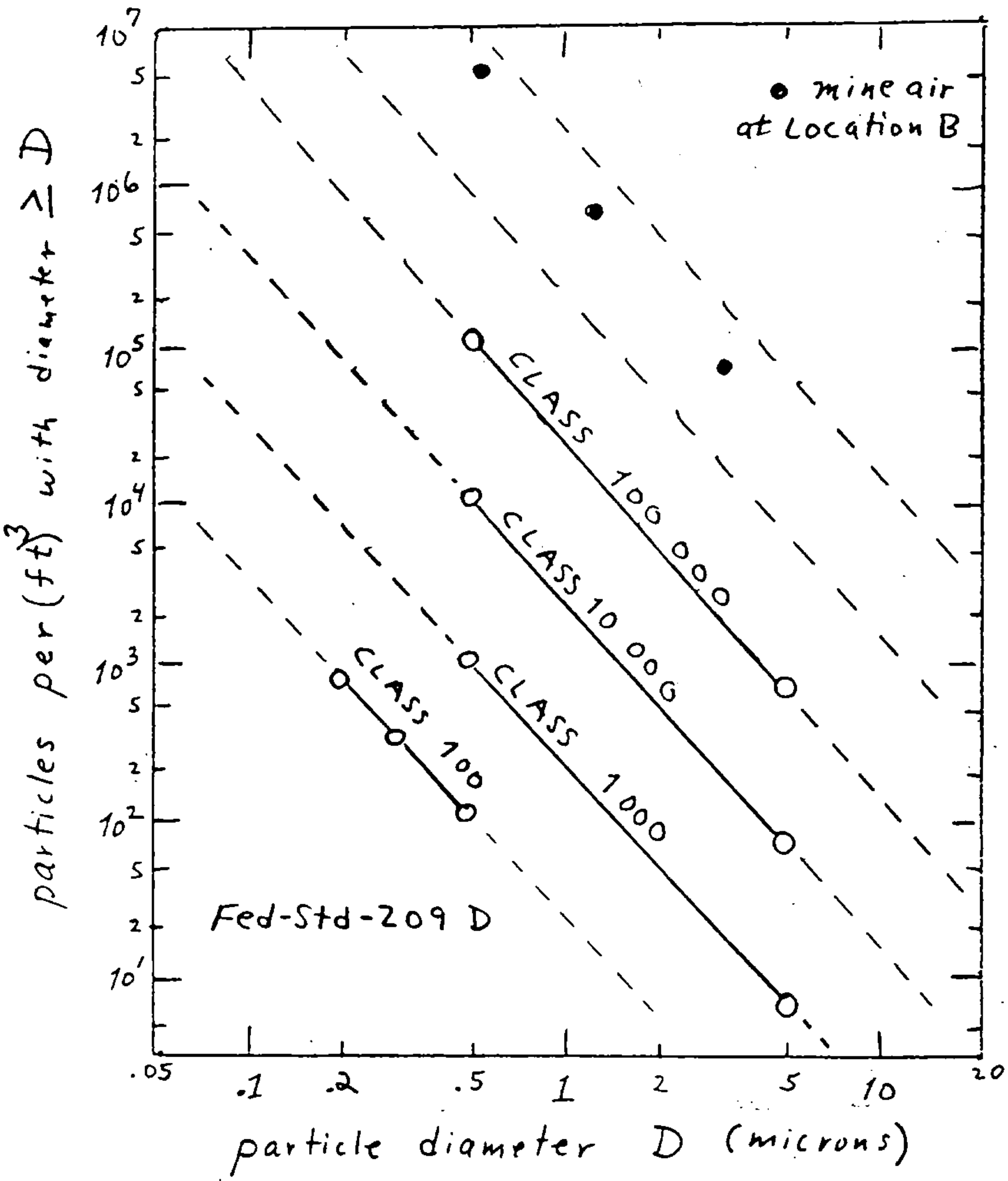

Figure 1. The definition of the CLASS of air in a clean room, from Federal Standard-209D. Note that the number of particles per ft^3 is an integral quantity, i.e., having diameters equal to or greater than the value D. The open circles denote diameters at which measurements are to be made in establishing the CLASS of the air according to the Federal Standard. The solid circles are integral values for mine air based on differential measurements made in the mine drift at location B (figure 3 in ref. 2 and figure A1 in the present appendix).

roughing (bag) filters in the access drifts, and HEPA filters at the top of the cavity, with return air ducts running from the cavity base to exhaust the air out the electronics corridor, and/or recirculate it through an additional HEPA filter at the cavity top. Assuming a filtering system consisting of:

(a) A bag filter assembly - 80% removal of particles with D>1 μm
- 99% removal of particles with D>10 μm

(b) A HEPA (high efficiency particulate) filter assembly - 99.97% removal of particles with D>0.3 μm

it was estimated for the Temple Review (October '89) that air of quality CLASS 1000 to 10,000 could theoretically be *supplied* with this filter system.[6] The draft Cavity Installation Plan (MONENCO CP 17-300-01) outlined a ventilation system for the cavity during the clean construction period.[7] (Both this and the Mk II ventilation system may need modification because of revised requirements for filtered-air capacity and cleaning procedures for the bonding of acrylic joints.)

Some dust may be removed by cleaning (i.e., rinsing) surfaces at the end of the installation period and by filtration from the light and heavy water as a part of normal operation. These methods represent the last resort for cleaning. The PSUP structure and signal cables, however, are complicated surfaces that will not admit to easy cleaning. The water purification system will remove in 37 days 1/e of the dust that is loosened and suspended in the light water, but this costs data-acquisition time. For these reasons it appears advisable to concentrate on keeping the dust deposition during installation within the prescribed limit. That is the subject of the next section.

III. ESTIMATE OF AIR CLEANLINESS AND DEPOSITION RATES

The amount of dust in the cavity at the time installation is completed will depend on the amount of dust present at the start of installation and on the amounts of dust introduced and removed during installation. Leaving aside the amount of dust present at the start of installation and the special problem of dust trapped in the bonded acrylic joints, we are left with the general requirement that the amount of dust introduced exceed the amount removed by no more than 50 grams. Sources of dust include personnel, equipment, components - basically anything brought into the cavity - and the particles present in the filtered mine air that were not removed by the filtration system. Dust is removed from the cavity by the exhausted air and by the manual cleaning of surfaces.

It is difficult to estimate or model all the factors that will influence the amount of dust remaining in the cavity before filling with water begins. However, it is possible to make a limited model for the cavity that will help in setting the parameters for the ventilation system, and which will illustrate the nature of the problem. In this model, which is described in detail in the appendix, the dust introduced into the cavity on equipment, etc., is assumed to enter the air and to leave the air by being exhausted via the ventilation system or by settling in the cavity. It is the latter mechanism, the settling of dust from the air, that is the net source of contamination in this model. The condition at equilibrium is that the amount of dust entering the air (on equipment and through filters) and the amount of dust leaving the air (through exhaust and settling) must be equal. This equilibrium condition determines the air cleanliness during installation and the amount of dust deposited.

Crude estimates suggest that the order of a gram of dust per day might be brought into the cavity. Since this is obviously a parameter that is not well determined, and one gram/day may be an underestimate, calculations have been made for a variety of input rates. The results are shown in figure 2 in the form of the time needed for 50 grams to deposit in the cavity (on 1000 m^2 of horizontal surface area). The installation period, about 18 months, is indicated by the horizontal dashed line. For example, if the dust input to the cavity were between 1 and 2 grams/day, then air exchanges of 6 and 14 per hour, respectively, would be required to keep the deposition rate below 50 grams in 18 months. (The most stringent White-Book value[2)] corresponds to a maximum of 7 grams in 18 months.) Just for reference, the quality of the air associated with the various deposition rates, as indicated by the CLASS value, is shown by the curved dashed lines.

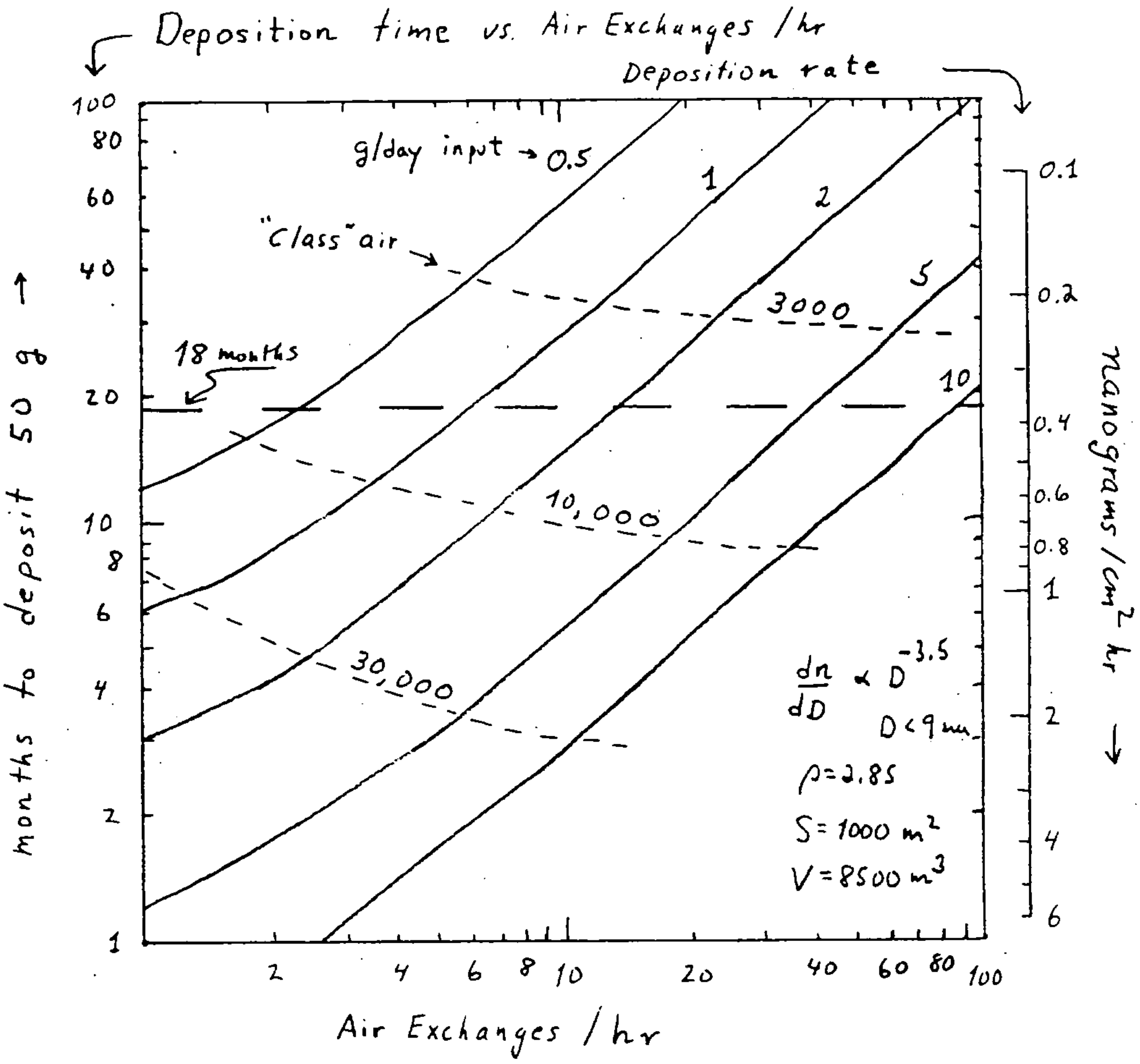

Figure 2. Settling times and deposition rates versus air exchanges per hour calculated with an equilibrium model for the air in the cavity. (See the appendix for a detailed description of the model). Results are given for different amounts of mine dust entering the cavity per day. If the calculated time to deposit 50g exceeds 18 months (the installation period, horizontal dashed line) the cleanliness requirement is considered met. The corresponding deposition rate in nanograms/cm^2/hr can be obtained from the right ordinate. The CLASS of the air (particles per ft^3 with $D \geq 0.5$ micron) at equilibrium in the cavity is indicated by the curved dashed lines.

The results in figure 2 give a quantitative indication of the importance of maximizing the number of air exchanges per hour as well as minimizing the amount of contamination introduced via personnel and equipment. The draft Cavity Installation Plan [7] calls for 4000 cfm of filtered "fresh" mine air and 16,000 cfm of recirculated filtered air for a total of 4 air exchanges per hour. **We recommend increasing the rate of air exchange to at least 10 air exchanges per hour.** This might be achieved through a combination of increasing the ducted air and adding stand-alone, portable fan/filter units. If engineering and cost considerations enable more than 10 exchanges per hour, that is clearly desirable and beneficial.

There are two model-independent numbers that can provide an additional perspective on this recommendation for air exchange: a typical office building or laboratory has 4-7 air exchanges per hour, and typical CLASS 10,000 to CLASS 100,000 conventional, i.e., turbulent flow cleanrooms have 20 air exchanges per hour.[8,9]

The relative humidity of the air is also an important factor in the deposition of dust. If the air is too dry, large static electric charges will accumulate on insulating surfaces and attract particulate from the air, significantly enhancing the deposition on such surfaces. (This effect is difficult to estimate and treat quantitatively: it has perforce not been included in the model described above. Unfortunately, most of the surface area in the cavity is electrically insulating.) If the air is too wet, particles cling to damp surfaces. A relative humidity in the range of 40±5% is recommended for industrial clean rooms[8]. We recommend that the cooling capacity of the air handling units located underground should be designed to provide a relative humidity of not more than 45%.

IV. MAINTENANCE OF CLEANLINESS DURING INSTALLATION

IV.1. Monitoring

A program to monitor the cleanliness of the air and surfaces during installation is required. Two types of air monitoring are needed, both of which are based on the scattering of laser light by particles. A fast response monitor located in the air supply following the bag filters will trigger a shutdown of the fans in the event of a leak or major failure of these filters. The HEPA filtered air in the cavity can be monitored by a single system with a manifold that enables sequential measurements at up to thirty or so separate locations. The air is brought to the monitor in plastic tubes, and a single measurement takes about 1.5 minutes, including the time needed to purge the counter for the next location. Particle number versus size can also be measured. The results are then logged by a small computer.

The deposition of dust on surfaces can be monitored by placing "witness plates" at locations throughout the cavity and corridors. Dust deposited on relatively smooth surfaces can be collected by a "tape lift" procedure or by wiping with a clean cloth or tissue. These probes can be read out in several ways: optically, by counting the particles in a microscope, or analytically by a variety of techniques, the most promising of which appears to be x-ray fluorescence. This latter method offers high sensitivity (about 0.5 microgram per cm^2) , and is relatively fast - 20 minutes to obtain a spectrum covering the elements from Ca through Sr. (X-ray fluorescence can also be used to monitor air by passing a sample of air through a small filter, which is then analyzed like any other sample. This method provides complementary information in the form of a mass measurement for mine dust and an elemental analysis.)

The sensitivity of commercially available airborne particle monitors is quite adequate for the present purposes, since this technique has been well developed for the semiconductor industry. Further developmental work needs to be done for surface monitoring, particularly the tape lift and wipe tests. Surface monitoring will be particularly important for the acrylic vessel, both as a measure of deposition rate and for the efficacy of cleaning procedures.

Provision for a small cleanliness "laboratory" should be made somewhere in the underground clean area. Space for the airborne monitor, an optical microscope, and an x-ray fluorescence spectrometer is needed. Each of these would require an area about the size of an office desk (4' x 6').

Rapid access to this equipment is required in order to make decisions about the level of cleanliness of equipment or components entering the clean area. Hence the need for the location of this equipment at the SNO site underground.

IV.2. Personnel

Development of standard cleanliness procedures to be followed by personnel, from equipment operators to installers to visitors, will be essential to minimize the introduction and dispersal of contamination. A training program for employees working underground should include cleanliness along with mine safety.

IV.3. Installation Equipment

Equipment brought into the clean area to be used for installation will need to satisfy the same requirements for cleanliness as the components that are brought in. Equipment that is used in the construction or installation phase, or which is brought in before the cavity is cleaned prior to installation, will have to undergo a thorough cleaning before the cavity as a whole is declared clean and ready for the installation phase. Monitoring of the cleanliness of equipment and, in general, all components entering the cavity must be planned.

IV.4. Cleaning Procedures During Installation

Cleaning of the areas where contamination collects should be done on a regular basis. The areas where this will be needed daily are the corridors with heavy personnel and equipment traffic and floor surfaces in the cavity. The appropriate combination of HEPA-filtered vacuum cleaning and wet-mopping will have to be determined through experience. Standard cleanroom methods such as the use of tacky floor mats and roll mops can also be applied. Where possible, surfaces of the detector that will accumulate dust and be difficult to wipe clean at the conclusion of installation should be covered. A fire-retardent plastic sheet with a tacky surface to impound the settled dust would serve well for this.

V. FURTHER CLEANLINESS CONSIDERATIONS

A review of clean room literature and experience indicates that sources of room dust (including working personnel) are important contributions to dust loading, and high rates of air circulation (20 air changes per hour) are needed to establish CLASS 100,000 under conditions of turbulent flow (the conventional cleanroom). Best results are achieved by keeping room construction processes as clean as possible, and surrounding the clean room with adjacent hallways or rooms of significant cleanliness.

The following recommendations refer to areas as denoted in the revised (8/91) underground layout:

1. Cleanable surfaces (shotcrete with an epoxy coating) should be specified for all areas in the underground laboratory. The degree of smoothness of the shotcrete and the thickness (build) of the epoxy coating may vary from one area to another depending on specific cleanliness requirements. The detailed specifications for these surfaces will be given in a separate document (Hallman and Evans, 1991).

2. After the liner is completed and installation ready to begin, the areas in which maximum cleanliness should be maintained are the cavity (including the lower ramp area), the deck area, and the control-room corridor to the cavity. Ducted, conditioned air supplied through HEPA filters at 35,000 cfm is recommended. A supplementary cavity air circulation system including prefilters and HEPA filters should be designed to recirculate cavity air at a rate of 15,000 cfm during the acrylic vessel/PSUP installation sequence. This could be accomplished with portable fan/filter units (1000 cfm each) mounted on the assembly deck as needed. The goal is to provide a total of 10 air changes per hour in the cavity. In general, a flexible installation to permit additional recirculation if needed, is desirable. More frequent air changes per hour in smaller volumes (such as the cavity dome above the deck and the control-room corridor) should be possible and are advisable. (After installation and during normal operation, the highest level of cleanliness will be maintained in the room (on the deck) enclosing the acrylic vessel chimney and cavity-access glove boxes. This area, called *the* "clean room" should have HEPA filtered air in a ceiling-to-floor flow pattern and at least 20 air changes per hour.)

A lower level of cleanliness during installation is tolerable in the other areas of the laboratory - the utilities room, wash station, change rooms, and electronics repair area. This lower level of cleanliness might be reflected in the choice of the wall finishes and the intensity of janitorial service, for example. However, these areas should also be supplied with HEPA filtered air and have at least 10 air changes per hour in order that they not become sources of contamination for the cleaner areas. Flexibility for additional filters and increased quantity of air recirculation should be allowed for.

3. The ventilation system for the cavity should include HEPA filter outlets under the deck near the top of the cavity, and return air ducts at the cavity floor, to establish an average downward air flow pattern.

4. At least a portion of the return air out of the cavity (possibly equal to the makeup air fraction) be directed through the control-room corridor and wash station areas to establish a primary air flow pattern outward, from the cleanest to the less clean areas in the laboratory. Thus, the pressure differentials in the various areas of the laboratory should be adjusted to provide a net flow of air from the remote parts of the laboratory toward the entrance to the laboratory.

5. Appropriate cleanliness procedures for the bonding of the seams in the acrylic vessel should be developed recognizing that a high level of cleanliness is required only at the location of the seam and only at the time of the final cleaning and insertion of the bonding agent. Thus, the large tent (described in ref. 5) containing its own supply of filtered air and the acrylic vessel as it is assembled is not envisioned here. Removal of fumes associated with the bonding process must also be considered.

6. Recirculation/filtering rates and the frequency of cleaning of laboratory areas should be established by tests and particle count analysis as installation operations are begun. The equipment and personnel required for this monitoring and cleaning are outlined elsewhere in this document.

While the ratio of fresh air to recirculated air undergoing HEPA filtration does not have a significant effect on the cleanliness of the air (and is not specified in this report), the amount of fresh air supplied is important for the quality of the working environment during installation, the cooling capacity needed, loading of filters, etc. It remains an important engineering question to be resolved.

VI. FURTHER RESEARCH AND DEVELOPMENT (a partial list)

1. Measurement of longer-term mine air dust levels (E.D. Hallman, throughout 1991).

2. Dust settling rates vs ventilation in the low level counting lab (4600 ft level, Creighton Mine) (E.D. Hallman, September 1991).

3. Coatings and cleanability tests for shotcrete and concrete surfaces (E.D. Hallman, late 1991).

4. Cleanliness of acrylic bonding underground (by Reynolds Polymer personnel (4600 ft lab) (late 1991).

5. Development of methods for measuring surface contamination (R. Stokstad, early 1992, in progress).

6. Establishing of dust in air and dust deposition monitoring protocol, costs, personnel and equipment (R. Stokstad, D. Hallman, late 1991, in progress).

7. Detailed design and specifications for air circulation and filters in the laboratory (MONENCO in progress).

8. Review of dust level and deposition estimates, ventilation and filtration design (SNO, MONENCO, consultant).

9. Cleaning methods, cleaning sequence and protection of cleaned surfaces for:
    liner, PSUP/PMT's, floors (including false floor in cavity).
    acrylic panels and assembled vessel.
    hoists, carts, lighting fixtures.
    personnel (clothing, etc.).
    Tests of cleaning efficiency on typical acrylic panels, PMTs and PSUP sections to be carried out as feasible.

Appendix

An Equilibrium Model for the Air in the Cavity

R. Stokstad

Equation:

The rate of increase of particulate in the air in the cavity = source rate - loss rate.

Source rate = particulate brought in on personnel and equipment during installation, and particulate from raw mine air that passes through the bag and HEPA filters. (The particulate left on the cavity surface at start of installation is not considered a source here).

Loss rate = room air exchange through HEPA filters and particulate settling out on surfaces.

$V*dn/dt = V*R_{in} - V*n*AE - S*n*v$

where:

V = cavity volume = 8500 m^3
$n = dn(D)/dD$ particles/vol/micron diameter
D= diameter of particle in microns
$R_{in} = R_{in}(D)$ = particles introduced /vol/time/micron
AE = cavity air exchanges per hour
S = cavity plus detector surface area projected onto horizontal
S = 1000 m^2
$v = v(D)$ = Stokes settling velocity = $3.6*10^{-3}$ *rho*D^2 cm/sec. (ref 10)
rho = density of norite = 2.85 g/cm^3

Solution:

$n(t) = [R_{in}/(AE+v*S/V)]*(1-\exp-(AE+v*S/V)t) + n(0)*\exp-(AE+v*S/V)t$

At equilibrium, after many room air exchanges, dn/dt=0:

$n(D) = R_{in}(D)/(AE + v(D)\cdot S/V)$

and the mass settling rate, mass(D) = $n(D)*pi/6*D^3*rho*v$.

The total mass settling rate and other quantities of interest are obtained by integrating the equilibrium solution over the particle diameter.

Input:

The average settling rate of an airborne particle in the vertical direction is given by the Stokes' velocity, which is proportional to the density and the square of the aerodynamic diameter. The assumption is that, even in turbulent conditions, this average vertical component of a particle's velocity is meaningful, at least for the larger particles that account for most of the deposited mass. (Until measurements can be made of settling rates under actual conditions during installation, this is the best one can do.) Of course, static electric forces and other mechanisms that would likely increase the settling rate are not included in this model.

The 1000 m^2 horizontal surface area on which the dust settles out consists of the upper outside and lower inside of the PSUP, and the same for the Acrylic Vessel plus the horizontally projected area of the cavity.

The input distribution (particle number versus size) of particulate is determined with the air-loading measurements reported by Lee, Hallman, and Evans[2)] and by Hallman and Cluff.[3)] The measured number-size (fig. A1) and mass-size distributions (fig. A2) are fit with a function of the form $dn(D)/dD = k*D^m$ particles/cm^3/micron for diameters up to a maximum size, D_{max}, above which there are no larger particles. The fits for m=-3.5 and D_{max} = 9 microns are shown in figures A1 and A2.

The fresh, raw mine air fed into the bag and HEPA filters has the same distribution as above, but the distribution of the particles that exit the filter is modified by the diameter-dependent transmission of the filters. The bag filter transmission is taken as unity for particles smaller than 0.3 micron and decreases proportional to $D^{-1.3}$ for larger particles, being 0.01 at 10 microns. The transmission of the HEPA filter is taken as $3*10^{-4}$ for all diameters. For air exchanges of 1 per hour and less, all the air is fresh. For larger values, a portion of the air is fresh and a portion is recirculated. The fresh air portion is taken as $1/AE^{(1/2)}$, which corresponds to 11200 cfm of fresh air at 5 exchanges per hour and

15,800 cfm of fresh air at 10 exchanges per hour. Recirculated air does not make any contribution to the

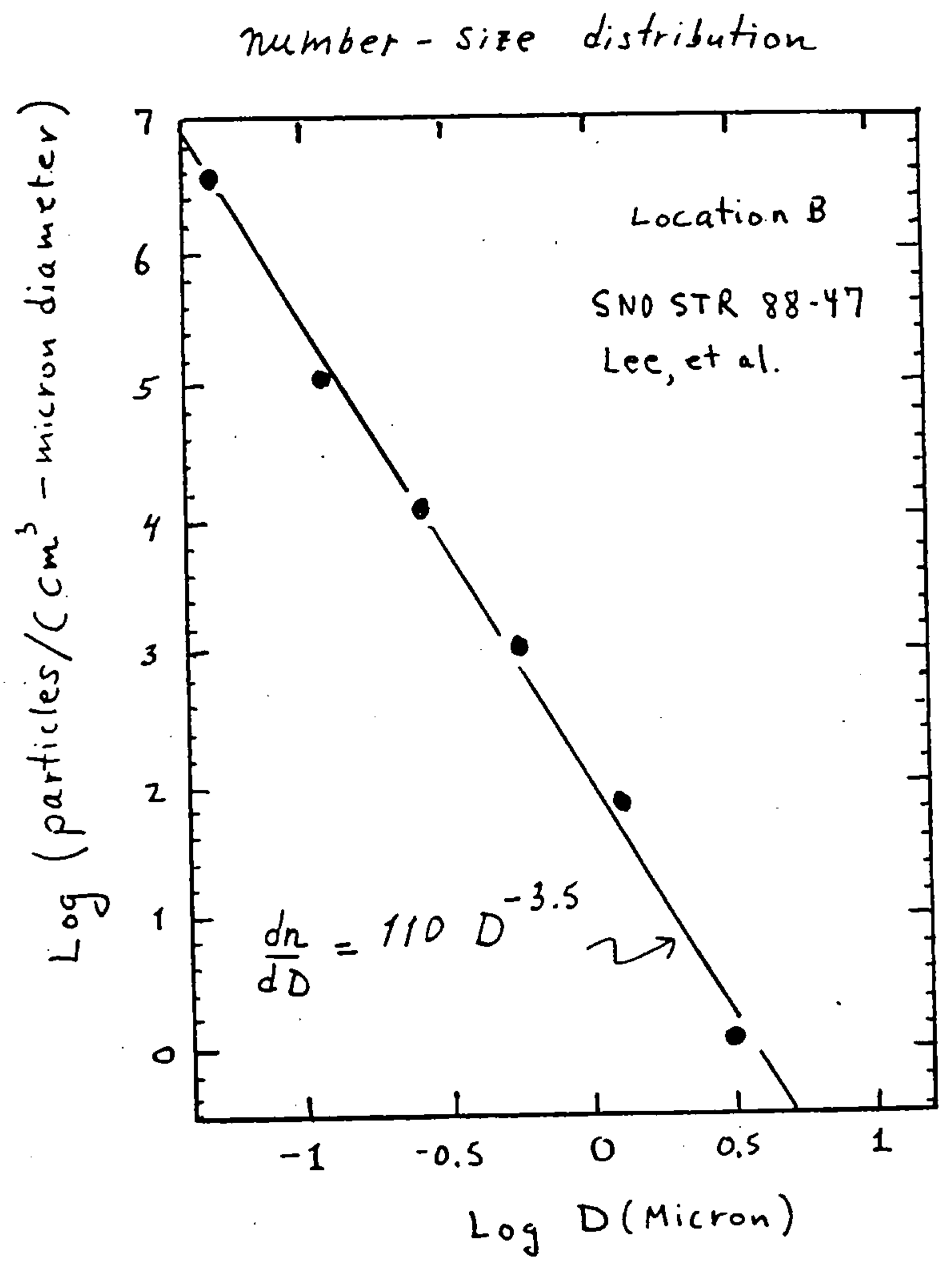

Figure A.1. The number-size distribution inferred from mass-size measurements made with a six stage cascade impactor. Taken from Ref. 2. The straight line corresponds to a power law distribution with an exponent of -3.5.

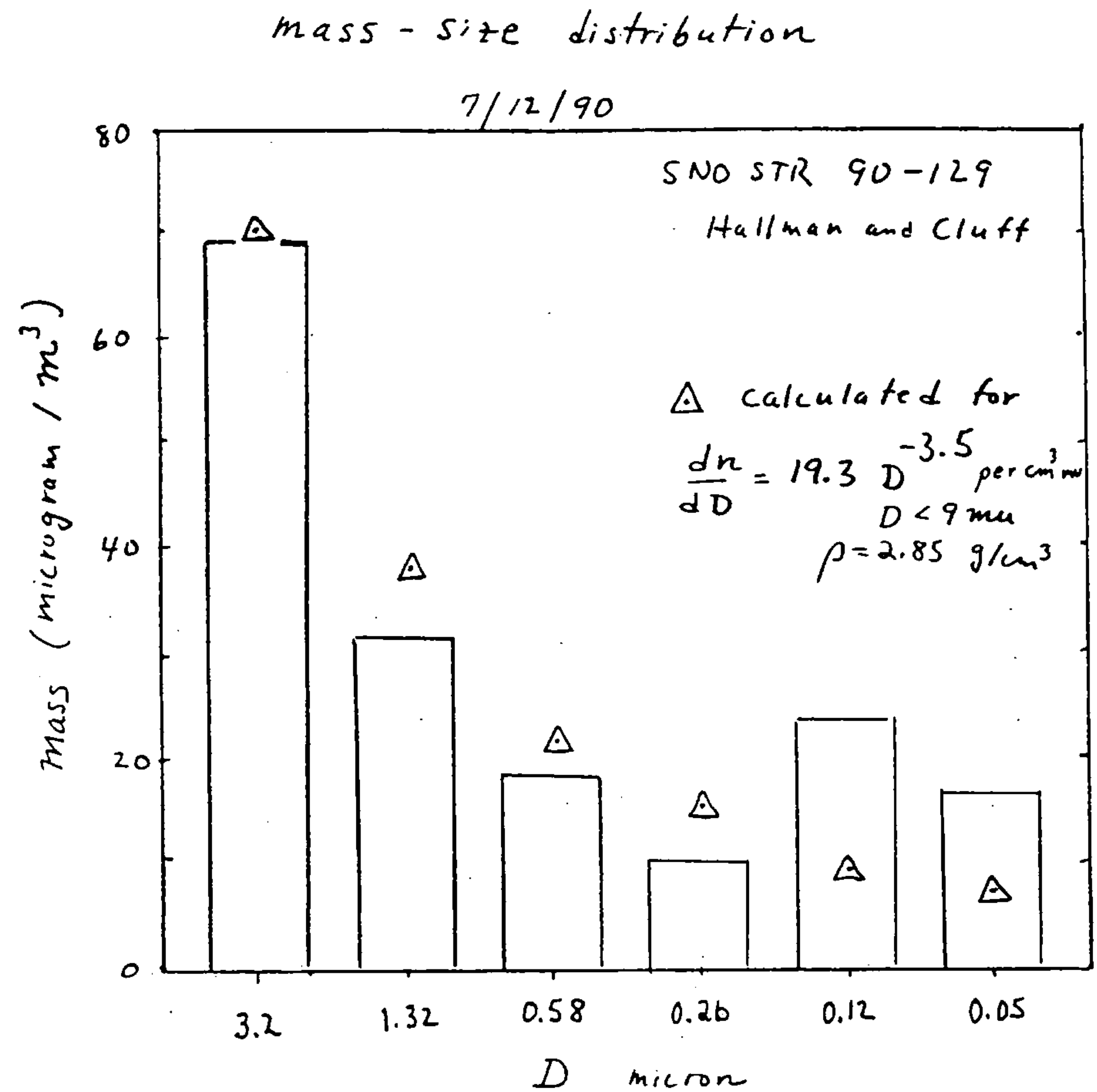

Figure A.2. Mass-size measurements made with the cascade impactor. Taken from ref. 3. The triangles are a fit to the data for the exponent -3.5 (from fig. A.1.) and the maximum diameter, D_{max} =9 microns.

particulate input. The fresh air is assumed to have a mass loading of 1 mg/m^3, which corresponds to normal mine operation and has the distribution $dn(D)/dD = 112*D^{-3.5}$ particles/cm^3/micron, D_{max} =9 microns.

The particulate carried in on personnel and equipment also has the same number-size distribution as the raw mine air, but the quantity is specified in units of grams of particulate per day (24 hours, 2 shifts.) A rough idea of the amount of particulate that might enter the cavity can be obtained from by the following argument: The smallest level of mine dust that can be measured in a quick wipe test is probably about 1 microgram per cm^2. We assume that this level of dust is present on the surfaces that enter the cavity and that half of it will get into the air and half will stay on the surface and exit the cavity. One person = 1.5 m^2. Ten people/shift and two shifts/day implies 150 mg entering via personnel in 24 hours. For the equipment, estimate a car's outer cover has 12 m^2 and after washing has 1 microgram/cm^2 on it. Half of this ends up in the cavity. Four cars/day implies 240 mg. Assume an equal amount of contamination from the material inside the car, and an equal amount from the tools and equipment and any packaging brought into the cavity. An additional 130 mg a day from misc., unspecified sources brings the total to 1 g/day.

For perspective, a person on a tour walking from the main shaft to the cavity can accumulate about 8 micrograms per cm^2 at 2 meters above the ground and about three times this amount at 30 cm above ground. A pile of mine dust weighing one gram is a cone about 5 mm high and 10 mm radius at the base.

It is clear that estimating the introduction of contamination is fraught with uncertainty. Correspondingly, accidents in the form of the introduction of bulk amounts of dust via equipment, personnel, or filter-failure have the potential to wreak havoc with a cleanliness program.

Results:

For a given mass input (grams/day) and air exchanges per hour, the settling rate at equilibrium is shown in figure 2 in terms of the time it takes for 50 grams to deposit or in terms of nanograms/cm^2/hr.

A more detailed picture of the situation is given in the following table, for the case of 1 gram per day input (41.7 mg/hr), plus the mass that enters via the filters, and 1 and 10 air exchanges per hour.

quantity	1/hr	10/hr
equilib. mass in the air (mg)	29.5	4.0
mass introduced by filters (mg/hr)	0.65	2.0
mass removed by air exchange (mg/hr)	29.5	40.
mass removed/hr by settling (mg/hr)	11.4	2.5
CLASS of air in cavity (N/ft^3, $D > 0.5$)	35,000	3,750
months to deposit 50 g on 1000 m^2	6	28

The deposition rate varies linearly with the input mass rate, approximately linearly with the surface-to-volume ratio S/V, and approximately inversely with the number of air exchanges per hour for AE>1. Calculations done with and without the filter contribution to the source of particulate indicate relatively small differences in the mass settling rates. This is because the bag filter preferentially removes the larger mass particles that contribute to the deposition of mass. The smaller particles that come through the filter system and which contribute little to the mass deposition, also settle more slowly and therefore are exhausted more efficiently by the exchange of air.

We have also done the same calculations with a different distribution function, viz., $dn(D)/dD=k*D^{-3.0}$ and $D_{max} = 5.6$ µm, which gives a reasonable, though not quite as good, fit to the distributions shown in figures A1 and A2. The settling rates are from 10 to 40 percent lower than with the distribution used above.

Comparison with previous estimates:

The SNO Overhead Presentations to the DOE/NSERC Review Committee included an estimate of the settling rates to be expected when the cavity is filled with HEPA-filtered air and there are no other sources of particulate[6)]. A settling rate of $7*10^{-16}$ g/cm^2/sec was estimated for filtered air having a CLASS of about 5000. Since we might expect that the ratio of the mass settling rate to the CLASS of the air should be roughly independent of the source of the contamination, this value of $1.4 *10^{-19}$ g/cm^2/sec/CLASS ought to be comparable to the corresponding values of $0.9*10^{-17}$ (for 1 exchange/hr) and $1.8*10^{-17}$ (10/hr). We see that, relative to the

CLASS of the air, the settling rates in the present calculation are larger by factors of 65 and 130, respectively.

There are a number of reasons for these apparently large differences. They have to do with using (in the Temple Review) a lower density for norite (2.2 instead of 2.85), a particular experimental mass distribution that is different from the one in fig. A2, filter factors that strongly attenuate the larger masses, linear approximations in integrating exponential functions and, in the present work, using analytical distributions that have been fit to experiment. While each approximation (or different way of making the estimate) by itself may be reasonable, they go in the same direction and their cumulative effect thus results in a significant difference. Part of the problem is the general feature that the value of CLASS (for our definition, N/ft^3, $D > 0.5$ micron) depends sensitively on the number of small particles, whereas the mass settling rate depends more on the number of large particles. Since the distribution functions are steep exponentials, this fact can lead to substantial swings in the ratio if different distributions are used.

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