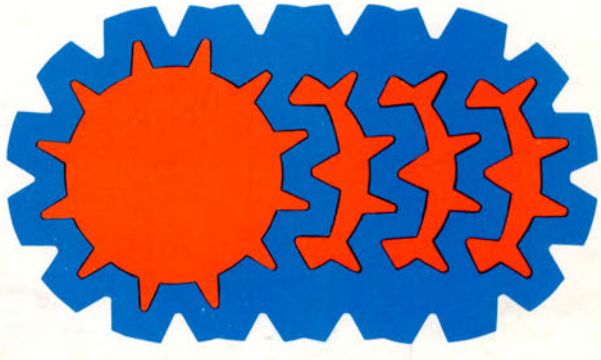
NIOSH

TECHNICAL INFORMATION

A THEORETICAL AND LABORATORY EVALUATION OF A PORTABLE DIRECT-READING PARTICULATE MASS CONCENTRATION INSTRUMENT



A THEORETICAL AND LABORATORY EVALUATION OF A PORTABLE DIRECT-READING PARTICULATE MASS CONCENTRATION INSTRUMENT

Bruce Almich

Marshall Solomon

George A. Carson, Ph.D.

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE

Public Health Service

Center for Disease Control

National Institute for Occupational Safety and Health

Division of Laboratories and Criteria Development

Cincinnati, Ohio

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402

July 1975

ACKNOWLEDGEMENTS

Acknowledgement is made to Don Murdock and Mary Geimeier whose assistance in the preparation of this paper are deeply appreciated.

HEW Publication No. (NIOSH) 76-114

CONTENTS

ABSTRACT

The design and construction of a prototype instantaneous dust mass concentration monitor was funded by the National Institute for Occupational Safety and Health in a competitively bid contract with the GCA Corporation of Bedford, Massachusetts. The contract performance specifications called for a portable, direct reading instrument, capable of providing accurate readings of total and respirable dust mass concentrations over the range of 1 to 50 mg/cu m. "Accuracy" of the instrument was defined in the specifications as "within ±25 percent of the measurements obtained from a companion simultaneous gravimetric respirable mass sample for 95 percent of the samples." "Respirable mass" readings were specified to be facilitated by a removable size selective device which conforms to the criteria of either the AEC or BMRC curves. A further specification required that the instrument be designed, tested, and approved for intrinsic safety per the U.S. Bureau of Mines, since a major utilization was intended to be in coal mines. The contract was satisfactorily completed. Three units of the model RDM 101 (the production version of this instrument) were subsequently purchased by NIOSH for testing and evaluation.

This paper documents the results of a study of the design, construction, performance, and theory of operation of the RDM 101. The electronic and mechanical designs of the three NIOSH owned units were analyzed from the standpoints of quality, durability, reliability, and completeness. Laboratory performance was judged from the results of coal dust measurements and comparisons in the NIOSH dust chambers. Simulated field performance results are presented from tests involving exposure of the instruments to extremes in temperature, humidity, vibration and dusty environments. During the entire study, the short and long term drifts of the calibration and operational parameters were noted and attempts were made to trace these drifts to their sources. The operational theory of the beta ray absorption principle by which these instruments operate was explored in detail.

The results and limitations of the theory together with the laboratory data and observations are discussed. Some implications of the laboratory results in relation to the general philosophy of personal sampling are made. Finally, an attempt is made to realistically estimate the overall usefulness and applicability of the RDM 101 to the characterization of particulate inhalation hazards in the industrial environment.

A THEORETICAL AND LABORATORY EVALUATION OF A PORTABLE DIRECT-READING PARTICULATE MASS CONCENTRATION INSTRUMENT

INTRODUCTION

The health hazards associated with the inhalation and pulmonary retention of airborne particulate matter are strongly dependent on the physical properties of the particulate. *(1-2)*[1] Accurate knowledge of these properties in the breathing zone facilitates the estimation of pulmonary deposition and consequently, the extent of the respiratory hazard. *(3)* This information also contributes to the successful implementation and evaluation of airborne particulate control strategies and systems. With the health of over five million U.S. workers being substantially impaired by airborne particulate matter in the industrial workplace, the necessity of adequate hazard evaluation and control cannot be overstressed. *(4)*

The requirements for particulate air sampling in the determination of compliance under the Occupational Health and Safety Act are based on an eight hour time weighted average (TWA) system. The statistical methods for the determination of noncompliance have been documented elsewhere. *(5)* However, a need has been demonstrated for instruments and methods to be used in more timely hazard determinations than may be statistically implied by the TWA concept. Such instruments and methods were designed to be used in the immediate identification of hazardous areas in the workplace in the context of such techniques as the walk through survey. While data obtained in this fashion may not represent a particularly sound indication of noncompliance, it does assist in the location, characterization, and ranking of problem areas for further consideration. The economics of these techniques become more favorable as the semi-fixed levels of an industrial hygienist's labor and sampling equipment are spread over greater and more diverse plant areas.

Under the Occupational Safety and Health Act, the National Institute for Occupational Safety and Health (NIOSH) is charged with the responsibility of conducting research in the production of recommendations for new and improved occupational health and safety standards. One aspect of this responsibility lies in the area of particulate sampling instrumentation and methods development. The methods and instruments under present consideration in this program are of a personal type in that they are portable and sample in the breathing zone of the individual worker. These instruments are designed to estimate individual exposures to particulates with the greatest practicable degree of certainty.

In the interest of meeting the need for instantaneous mass concentration monitors alluded to above, NIOSH funded the development of a direct reading instantaneous mass monitor in a competitively bid contract in 1971. The GCA Corporation of Bedford, Massachusetts was the contractor and the resulting instrument is the RDM 101 respirable dust monitor, shown in Figure 1. The contract performance specifications required the fabrication of a direct reading portable instrument, capable of providing accurate readings of total and respirable dust mass concentrations over the range of 1 to 50 mg/cu m. "Accuracy" of the instrument was defined in the specifications as "within ±25 percent of the measurements obtained from a companion simultaneous gravimetric respirable (or total) mass sample for 95 percent of the samples". "Respirable mass" readings were specified to be facilitated by a removable

[1] Italic numbers in parentheses refer to items in the list of references.

size selective device which conforms to the criteria of either the AEC or BMRC curves. A further specification required that the instrument be designed, tested, and approved for intrinsic safety per the U.S. Bureau of Mines, since a major utilization is intended to be in coal mines. The contract was satisfactorily completed. NIOSH has subsequently purchased three finished units from the first production run for testing and evaluation.

THEORY OF OPERATION

In order to fully understand the operational advantages and limitations of the GCA RDM 101, an independent investigation of its operating theory and the more general principles of beta absorption was carried out as part of this study. This section concerns itself with a discussion of the results of this investigation.

Measurements of mass concentration by the RDM 101-X are accomplished by the collection of dust from a known volume of air and the subsequent measurement of the mass of the collected sample. The dust is collected in a fixed time period (which normally depends on the "X" suffix of the model number) by a two stage aerosol sampling system at a nominal flowrate of two liters per minute. The time period is determined by the mass concentration and resolution ranges in which the instrument is to be operated. A removable 10-mm nylon cyclone precollector comprises the first stage. It removes the non-respirable fraction of dust, passing to the second stage all particles smaller than 2 μm in diameter (unit density spheres) and retaining all of those greater than 10 μm. *(6-7)* Referring to Figure 2, the second stage is a converging circular nozzle inertial impactor which collects the respirable (or total, if the cyclone is removed) dust on a thin mylar film substrate in a circular area of well defined diameter. Above the sample, incorporated into the impactor nozzle, is a radioactive ^{14}C source of beta radiation and below the sample and mylar film is a geiger tube detector. During the initial and final twenty seconds of collection (four seconds and sixty seconds for the RDM 101-0.2 and RDM 101-8 respectively), two counts are made to determine the attenuation of the radiation caused by the sample.

This process results in the determination of the mass per unit area, δ, of the sample. Since the diameter of the circular impaction spot, D, is known, the mass, M, of the sample may be calculated as follows:

$$M = \frac{\pi}{4} D^2 \delta. \qquad (1)$$

The mass concentration, C, is found by dividing equation (1) by the product of the flow rate, Q, and the effective sampling time, t_e

$$C = \frac{M}{\text{volume of air sampled}} = \pi \frac{D^2 \delta}{4Qt_e} \qquad (2)$$

In the calculation of C by the RDM 101, only δ is measured with all other quantities in Equation (2) lumped together as a calibration constant. The value of the effective sampling time, t_e will be derived later. The diameter of the impaction spot, D, varies randomly to only a small degree but tends to increase with concentration, leading to errors in the high end of the design range. Measurement of the area density, δ, carries a random error due to the nature of radioactive decay which is the most significant source of error, at least in the low end of the mass concentration range.

The theoretical foundations on which the operation of the RDM 101 is based include the statistics of radioactive decay, several empirical relationships involving the particle collection characteristics of the impactor stage and the interaction of beta radiation with matter, as well as the optimization of the operating cycle. It is our purpose here to examine the validity with which this theory has been applied to the design of the instrument.

In the collection of dust by inertial impaction, there is a cutoff in particle size below which deposition on the mylar substrate does not occur. Lilienfeld and Dulchinos *(6-7)* have calculated the diameters at which there is 50 percent collection efficiency for unit density, coal dust, and rock dust spheres. They are 0.36 μm, 0.3 μm, and 0.21 μm respectively. This portion of the sample contributes negligibly to the total mass. Experimental confirmation of these particle cutoff sizes has not yet been attempted. Determination of the diameter of the dust collection area on the mylar substrate has only been treated experimentally.

Beta radiation consists of high speed electrons emitted by atomic nuclei undergoing a transmutation process. In one type of beta decay a neutron in the nucleus of an atom disappears and a proton, electron and antineutrino are simultaneously created and accompanied by the release of energy. The magnitude of this released energy is a char-

acteristic of the nuclide. The electron and the neutrino are emitted from the nucleus and, along with the decayed atom, share the released energy. Since the angles at which the particles are emitted can vary, the energy imparted to the beta ray (electron) can also vary. Unlike the case of alpha decay which gives rise to monoenergetic radiation, beta radiation has a continuous energy spectrum ranging from zero to a characteristic maximum energy.

When beta rays pass through matter they lose their energy through elastic and inelastic collisions with atomic electrons and nuclei. A discussion of the principal characteristics of each of the four types of interaction and their relative importance in the energy range of ^{14}C betas follows. *(8)*

Inelastic collisions of beta rays with atomic electrons result in the excitation of electrons or ionization. The cross section per atom for fractional energy loss is proportional to the atomic number, Z, of the atoms in the absorbing medium. Thus losses per unit path length of the beta ray are proportional to nZ, the electron density, where n is the number of atoms per unit volume. The electron density can be expressed as

$$\rho_e = nZ = \rho_m L \frac{Z}{A}, \qquad (3)$$

where

ρ_e = electron density,

ρ_m = mass density,

L = Avogadro's number,

A = Atomic weight.

Since the energy loss per unit path length is proportional to nZ, the loss per unit area density along the path of the beta, $(1/\rho_m)$ (dT/ds), where T is kinetic energy and s is path length, is proportional to nz/ρ_m. The ratio, Z/A, is nearly equal for all elements (except hydrogen which contributes negligibly to the mass of particulates), falling only slightly with Z. So, from Equation (3), the ratio nZ/ρ_m is also nearly constant. An increase in the average ionization potential with Z contributes, along with the ratio nZ/ρ_m, to the slight decrease in $(1/\rho_m)$ (dT/ds) with increasing Z. These effects are partially compensated for when looking at the absorber thickness traversed instead of the actual path length of the beta because the ratio of path length to absorber thickness penetrated increases with Z. Therefore, when measured in terms of absorber thickness, the energy loss of beta rays in inelastic collisions with atomic electrons is almost independent of the composition of the absorbing material and proportional to its area density.

An inelastic collision of a beta ray with a nucleus is a radiative process in which X-rays are produced. This type of interaction has a cross section per atom proportional to Z^2 and therefore the losses per unit area density depend on the composition of the absorbing material. However, the response of the RDM 101 to this X-radiation is negligible.

Elastic collisions between beta rays and nuclei produce no radiation but rather energy is lost only to conserve momentum in the interaction. The cross section per atom is proportional to Z^2 and again $(1/\rho_m)$ (dT/ds) depends on the absorbing medium.

Elastic collisions of beta rays with atomic electrons result in the deflection of the beta rays without any electronic excitation. This process is significant only for very low energy betas (less than 100 eV) which do not concern us here.

The relative importance of ionizing and nuclear elastic collisions depends on both the beta energy and the atomic number of the absorbing material. For the beta radiation energy spectrum of ^{14}C, around 100 keV, ionization losses predominate in the light elements and in the heavy elements ($Z \simeq 80$), the two interactions are of comparable importance. The relative importance of ionizing and radiative collisions also depends on both the beta energy and Z. Ionization losses are largest at lower energies and radiative losses are greatest at higher energies. The two are about equal for 10 (MeV) betas in *Pb* ($Z = 82$) and 100 MeV betas in air ($Z = 7.22$). For ^{14}C, whose maximum beta energy is 156 keV *(9)*, and absorbing materials of interest in particulate air sampling, only ionization losses are significant. Thus, measurement of the area density of the impaction collected sample by the RDM 101 will be relatively insensitive to the chemical composition of the sample (except for radio-

active samples, of course!), varying about as much as Z/A. The error due strictly to Z/A variation is tabulated, for many of the elements, in Table 1.

Having shown that the absorption of ^{14}C beta radiation is dependent on the area density of the absorber, the next step is to describe how the two are related. Dealing with this problem theoretically is extremely difficult for two reasons, the effects of multiple scattering and straggling. Because of the low mass of beta rays, they can be scattered through large angles in their collisions. Also, the number of collisions each beta ray experiences before reaching the detector is very large. As a result, the ratio of path length to range varies from 1.2 to 4. Straggling is an effect due to the statistical distribution of energy losses in collisions of beta rays with absorbing atoms. Some betas may have many collisions with large energy losses in each, while others may have fewer and smaller losses in the absorber. An initially monoenergetic beam of beta rays will have a distribution of energies, after interacting with matter, which becomes broader with increasing absorber thickness.

Because of this complexity, we must rely on an empirically derived relationship for the absorption of beta rays. It has been found that the transmission curve is a nearly exponential attenuation *(8, 10)* and can be written as follows:

$$N = N_o e^{-\mu_m \delta}, \qquad (4)$$

where

N_o = initial number of betas,

N = number of betas passing through δ,

δ = mass per unit area of the absorber,

μ_m = mass absorption coefficient.

This relationship is the consequence of the combined effects of scattering, straggling, and the energy spectrum of beta radiation. Two conditions, that the energy spectrum and angular distribution remain nearly constant during absorption, result in exponential attenuation. They have been shown by Brownell *(11))* to be essentially correct. The first condition guarantees that the fraction of energy absorbed per unit path length is independent of s, the absorber thickness already traversed. The second guarantees that the total path length per unit of absorber thickness is independent of s. Together they imply that the fraction of energy absorbed per unit absorber thickness is independent of s, implying exponential attenuation. The transmission curve is only approximately exponential because these conditions are not rigorously valid and also, the shape of the transmission curve is somewhat dependent on geometry. Lilienfeld *(12)* has compared equation (4) to experiment, with δ in the range of zero to 3.5 mg/sq cm, using an arrangement similar to that of the current RDM 101 model with good results, i.e., exponential behavior.

The mass absorption coefficient, μ_m, is found experimentally to be related to the maximum energy, E_{max}, of the radiating nuclide and is given approximately by the formula (1):

$$\mu_m = 22.0\, E_{max}^{-1.33}, \qquad (5)$$

where E_{max} is in MeV and μ_m is in square centimeters per milligram. For ^{14}C, μ_m is 0.262 cm^2/mg. *(12)*

After exponential attenuation to very low transmission, beta radiation is reduced completely to zero. An empirical relationship between maximum range, R_{max}, and maximum beta energy, valid for 0.01 MeV $< E_{max} <$ MeV, is *(8)*

$$R_{max} = 412\, E_{max} (1.265 - 0.0954 \ln E_{max}), \qquad (6)$$

where E_{max} is in MeV and R_{max} is in milligrams per square centimeter. For ^{14}C, R_{max} is 28.26 mg/sq cm. At the top of the RDM 101-1's design range for example, (a mass concentration of 50 mg/cu m) the area density of the impaction spot reaches 24.7 mg/sq cm. This figure, along with the air, mylar substrate, vaseline coating, and geiger tube window, is just within the maximum range of the betas. For absorber thickness close to the maximum range, deviations from the exponential law of equation (4) occur. *(12)* The above impaction spot area density is based on an average measured spot diameter of 0.0718 cm obtained with the mass concentration at 2.0 $\pm$0.5 mg/cu m.

A useful property of the exponential decay represented by equation (4) is the dependence

of the ratio of two counts only on the difference in absorber area density and not on the value of N_0 or the actual magnitude of δ during either count. *(6)* For the RDM 101, this means that the ratio of its initial and final counts depend only on changes in area density and source activity which occur in the fixed measurement cycle and the collection of dust is the only significant change in this period. Changes in the density of air, mylar substrate thickness, or source activity between measurements do not require recalibration of the instrument. The validity of this argument is limited only by the degree to which exponential attenuations of beta rays is an approximation.

We can solve for the area density, δ, of the impaction collected sample in terms of the first and second beta counts, N_1 and N_2, taken by the RDM 101-1. Henceforth, reference will be made only to the most appropriate submodel, e.g. the instrument whose running time is one minute per sample, unless otherwise noted. The general equations and conclusions are the same for all instruments of the RDM 101-X series. Tabulations of specific numerical results for the other versions are left to the interested reader. Using equation (4)

$$\delta = \frac{-1}{\mu_m} \ln \frac{N_2}{N_1} = \frac{1}{\mu_m} (\ln N_1 - \ln N_2). \tag{7}$$

One of the sources of uncertainty in the measurement of δ is the statistical nature of radioactive decay. The number of counts in a given time interval has a Poisson probability distribution and thus a standard deviation equal to the square root of the mean number of counts. That is

$$\sigma_{N_1} = \sqrt{N_1} \tag{8}$$

and

$$\sigma_{N_2} = \sqrt{N_2} \tag{9}$$

Since δ is a function of N_1 and N_2, its variance is given by (13):

$$\sigma^2 \delta = \left(\frac{\vartheta \delta}{\vartheta N_1}\right)^2 \sigma^2_{N_1} + \left(\frac{\vartheta \delta}{\vartheta N_2}\right)^2 \sigma^2_{N_2} \tag{10}$$

Using equation (7) to evaluate the partial derivatives and substituting equations (8) and (9) into equation (10)

$$\sigma^2 \delta = \frac{1}{\mu_m^2} \left(\frac{1}{N_1} + \frac{1}{N_2}\right). \tag{11}$$

The uncertainty in mass concentration, C, due to $\sigma\delta$ follows from equations (2) and (11). The variance of C is

$$\sigma^2 C = \left(\frac{\vartheta C}{\vartheta \delta}\right)^2 \sigma^2 \delta = \left(\frac{\pi D^2}{4Qt_e}\right)^2 \frac{1}{\mu^2_m} \left(\frac{1}{N_1} + \frac{1}{N_2}\right), \tag{12}$$

and its standard deviation is

$$\sigma_C = \frac{\pi D^2}{4Qt_e \mu_m} \left(\frac{1}{N_1} + \frac{1}{N_2}\right)^{1/2}. \tag{13}$$

From equation (13) it can be seen that σ_C increases with decreasing N_1 and N_2. The counts, N_1 and N_2, decrease with increasing mass concentration since at higher dust levels the collected sample is larger and more beta rays are absorbed. Therefore the uncertainty in C increases with C. An estimate of σ_C can be obtained by evaluating N_1 and N_2 in the following manner:

$$N_1 = \int_0^{20} f_o \, e^{-\mu_m a t} \, dt = \frac{f_o}{\mu_m a} (1 - e^{-20 \mu_m a}), \tag{14}$$

$$N_2 = \int_{40}^{60} f_o \, e^{-\mu_m a t} \, dt = \frac{f_o}{\mu_m a} (e^{-40 \mu_m a} - e^{-60 \mu_m a}), \tag{15}$$

where

f_o = count rate before any dust is collected, and

a = dust collection rate in mg/cm² — sec.

In the latest model of the RDM 101, fo is approximately 1,500 counts per second. Assuming the mass concentration is constant during the 60-second sampling interval and the impaction spot diameter is 0.0718 cm (an experimental result of this study), the collection rate, a (which is related to δ by the equation, $\delta = at$) is a constant and given by

$$a = 0.00823C \text{ mg/cm}^2\text{-sec} \tag{16}$$

for C in mg/cu m. Using equations (13-16), the uncertainty in C at the 2σ level of confidence

for several mass concentrations is shown in Table 2. Sources of error other than the statistical nature of radioactive decay will lead to slightly greater uncertainty in C than that given in Table 2.

The choice of ^{14}C for the beta radiation source in the RDM 101 is a good one for several reasons *(14)*. From equation (6) we see that R_{max} increases with E_{max}. In order for the RDM 101 to measure concentrations up to 50 mg/cu m, the beta rays must have an E_{max} high enough to penetrate the sample collected at this concentration. From equations (5) and (11), we see that the uncertainty in the measurement of δ decreases with decreasing E_{max} so that, from this standpoint, the lowest possible E_{max} is desirable. A compromise between the above two requirements is achieved with ^{14}C. Other desirable properties of ^{14}C include its long half life, its decay to a stable nuclide, and the absence of gamma radiation. Due to the production of Compton electrons, gamma radiation would interfere with the detection of beta rays.

In calculating the mass concentration using equation (2), one must be careful to use the effective sampling time, t_e, which corresponds to the area density determined in equation (7). Because of the particular operating cycle of the RDM 101, in which the counts, N_1 and N_2, are made during the first and last 20 seconds of the one minute sampling interval, some of the mass is collected before the first count is complete and some after the second count begins. This means that not all of the mass collected in the one minute sampling interval is "seen" in the area density measurement. One can imagine a situation where counts are made before and after dust collection and in which the counts match those of the RDM 101. The time required to collect the dust in this hypothetical process, if done at the same flow rate and with the same impaction apparatus as the RDM 101, is the effective sampling time. Its value may be found by equating the ratios of the first and second counts obtained in the two ways. Dividing equation (15) by equation (14) gives the ratio for the RDM 101

$$\frac{N_2}{N_1} = \frac{e^{-40\mu_m a} - e^{-60\mu_m a}}{1 - e^{-20\mu_m a}} = e^{-40\mu_m a}. \tag{17}$$

The ratio for the hypothetical case follows from equation (4) and the relation, $\delta = at_e$

$$\frac{N_2}{N_1} = e^{-\mu_m a t_e} \tag{18}$$

Equating equations (17) and (18) it is found that $t_e = 40$ seconds.

The design specification for the original RDM 101 required that measurements of mass concentration be made in a 60-second period. A choice of operating cycle which makes optimal use of this allowed time can be arrived at by finding the counting times and effective sampling time which minimize the uncertainty in C given by equation (13). From equations (17) and (18), it can be seen that, unless the counting times for the two counts are equal, the effective sampling time will vary with the collection rate, a, and therefore, with the dust concentration. Such a condition would lead to systematic error in C because t_e is taken as a constant in equation (4). Therefore, we seek to minimize σ_C under the condition that the two counting times are equal. Representing each counting time by τ the relationship between the effective sampling time and τ follows from a generalization of equations (17) and (18) and is given by

$$t_e = 60 - \tau, \text{ seconds.} \tag{19}$$

Substituting equation (19) into equation (13), the resulting expression for σ_C as a function of τ is

$$\sigma_C = \frac{\pi D^2}{4 Q \mu_m (60 - \tau)} \left(N_1^{-1}(\tau) + N_2^{-1}(\tau)\right)^{1/2}, \tag{20}$$

where

$$N_1(\tau) = \int_0^{\tau} f_o e^{-\mu_m a t}\, dt = \frac{f_o}{\mu_m a}\left(1 - e^{-\tau\mu_m a}\right), \tag{21}$$

and

$$N_2(\tau) = \int_{60-\tau}^{60} f_o e^{-\mu_m a t}\, dt = \frac{f_o}{\mu_m a} e^{-60\mu_m a}\left(e^{\tau\mu_m a} - 1\right). \tag{22}$$

To find the minimum of equation (20), the derivative with respect to τ is set equal to zero and the expression is solved for τ^*. The de-

rivative is

$$\frac{d\sigma_C}{d\tau} = \frac{\pi D^2}{4Q\mu_m}\left(\frac{(N_1^{-1}(\tau) + N_2^{-1}(\tau))^{1/2}}{(60-\tau)^2} - \frac{N_1^{-1}(\tau)\left(\frac{dN_1}{d\tau}\right) + N_2^{-1}(\tau)\left(\frac{dN_2}{d\tau}\right)}{2(60-\tau)(N_1^{-1}(\tau) + N_2^{-1}(\tau))^{1/2}}\right) \quad (23)$$

$$= 0 \text{ at } \sigma_C \text{ min.}$$

where

$$\frac{dN_1(\tau)}{d\tau} = f_o e^{-\mu_m a};$$

$$\frac{dN_2(\tau)}{d\tau} = f_o e^{-60\mu_m a} e^{\mu_m a}. \quad (24)$$

After setting equation (23) equal to zero and some algebraic manipulation, the following expression is obtained:

$$0 = -1 + e^{\tau\mu_m a} - \frac{(60-\tau)\mu_m a}{2} + e^{60\mu_m a}\left(1 - e^{-\tau\mu_m a} - \frac{(60-\tau)\mu_m a}{2}\right). \quad (25)$$

With the aid of the high speed digital computer, equation (25) has been solved here for τ^* for several values of the collection rate, a. For mass concentrations in the range of one to eight mg/cu m, the numerical solutions yielded an optimal counting time of between 20 and 21 seconds. Thus, the RDM 101 has an optimal operating cycle in this range. For higher mass concentrations, the optimal counting time increases with concentration. Since the relative error σ_C/C is the most serious at low concentrations (see Table 2), optimizing the operating cycle at low concentrations is a good design choice.

The sources of error in the measurement of mass concentrations by the RDM 101 lie in the parameters of equation (2). The effective sampling time is constant and does not contribute to error. The flow rate varies very little and can be adjusted easily using the rotameter supplied with the unit for this purpose.

Errors in the measurement of δ are of two kinds. The first is due to deviations from the exponential transmission law of equation (4). The second is due to the statistical fluctuations in the number of beta decays over time. Deviations from exponential attenuation can be expected near "high end" concentrations for each instrument submodel since the absorber thickness is approaching the maximum range of the betas at this point. Uncertainty due to counting statistics lies within the accuracy specifications over the entire design range. The question of consistency in particle collection area has been approached experimentally. Variation in the impaction spot diameter with concentration will lead to systematic error and appears to be a serious problem for high ambient dust levels. A new coating for the mylar collection substrate has been recently developed by GCA to help alleviate this problem.

The ability of the RDM 101 to measure mass concentration of airborne particulates is strongly supported by theory over most of its design mass concentration range. Problems are indicated only for high concentrations which, in the case of the RDM 101-1, are those that approach 50 mg/cu m. Differences in response due to varying particulate composition are nominal from the standpoint of beta absorption theory. Differences in response due to varying particulate composition in the light of impactor and cyclone collection characteristics occur. These are handled on a case-by-case basis in a consultation process between the manufacturer and its customers, as we shall describe later.

MECHANICAL AND ELECTRONIC DESIGN PHILOSOPHY AND REALIZATION

Since the completion of the prototype version of the RDM 101 under NIOSH contract in 1971, each production run of the instrument incorporates significant improvements in an ongoing effort to refine the state of the art in direct reading dust concentration monitors. In this effort, the GCA Corporation accepts input for design improvements from customers and prospective customers, including the U.S. Bureau of Mines and NIOSH, and maintains a substantial in-house testing, development, and product improvement activity. This section is devoted to a critical evaluation of the mechanical and electronic design of the RDM 101, as they are embodied in the units available as of January 1, 1974, and represent improvements over previous designs. The remaining sections will be concerned with an evaluation of the degree to which the physical instrument reliably implements the theory previously presented, thus giving accurate mass concentration readings.

The mechanical design of any portable field instrument is a critical factor which determines the field reliability and ultimate usefulness of the instrument. This aspect of the design must necessarily be an evolving one which can only improve beyond a given point after the results of field use become known. Our analysis of the mechanical aspect of the RDM 101 design consisted of the following steps:

1.) A cursory examination of the three NIOSH owned units, which came from early production runs. The units were examined from the standpoints of quality, completeness, ruggedness, compactness, ease of operation and maintenance, and apparent quality control.

2.) The recording of mechanical pros and cons as the instruments progressed through an 18 month period of laboratory, simulated field use and actual field use at NIOSH. These notes were compared and merged with those of other RDM 101 owners, the majority of whom used the instruments extensively in the field.

3.) Transmitting the results of 1 and 2 above to the GCA Corporation for consideration in design changes. A majority of these results were already under consideration or had already become design changes in subsequent production units.

4.) Conducting special simulated field tests, involving accelerated levels of stress on the mechanical aspects of the units. These tests and results will be reported in the Laboratory Sections of this paper.

The analysis of the electronic design of the RDM 101 proceeded in much the same manner as the mechanical design analysis. However, the circuit design philosophy and realization as well as component quality and placement were more carefully investigated than any other aspect of the physical instrument. A brief discussion of the electronics follows.

The purpose of the electronic circuitry in the RDM 101 is to provide timing, control, power supply, and signal processing functions to implement the theory previously discussed. Combining equations (2), (5), and (7) above, we have

$$C = \frac{\pi D^2}{4\mu_m Q t_e} (\ln N_1 - \ln N_2) \quad (26)$$

where $\frac{\pi D^2}{4\mu_m Q t_e}$ is the system constant (about 9.8 for the RDM 101-1). Replacing the actual parameters, we obtain

$$C = 9.8 (\ln N_1 - \ln N_2) \quad (27)$$

where N_1 and N_2 are the initial and final beta counts respectively and C is in mg/cu m. The signal processing subsystem implements equation (27) in providing direct readings of C. Referring to the block diagram in Figure 3, output pulses from the G.M. beta detector tube are passed through two pulse shaping circuits, the threshold circuit and the monostable multivibrator. The result is a pulse train that is of normalized duration, t_d, and amplitude with a minimum of response to background noise generated in the G.M. tube. Each output pulse from the monostable causes the gating of a fixed reference voltage, $-E_{ref}$, to the input of integrator A3, via closure of switch S1, during each of the beta counting intervals. During

the noncounting interval, the integrator is disabled by the closure of switch S2 which discharges integrating capacitor, C1. During this interval, the exponentially decreasing integrator voltage E1, enables the output of comparator A4, as long as E1 exceeds reference voltage E_L. The output of comparator A4, gates the output of an oscillator count of a sample of F_{os} to the up-down counter, CN1. During the first beta count of a sample period, the assertion of the "Fwd" input to the gates causes upward counting to an accumulated count of X_1, given by equation (28):

$$X_1 = f_{os} R_2 C_1 \ln \left(\frac{N_1 E_{ref} t_d}{R_1 C_1 E_L}\right). \quad (28)$$

where N_1 is the initial number of counts passed by the threshold circuit. During the final beta count of each sample period, the "Rev" input to the gates is enabled, causing the downward counting by a quantity X_2, given by (28):

$$X_2 = f_{os} R_2 C_1 \ln \left(\frac{N_2 E_{ref} t_d}{R_1 C_1 E_L}\right), \quad (29)$$

where N_2 is the final number of counts passed by the threshold circuit. The resulting counter reading at the end of each sample period is $X_T = X_1 - X_2$ or

$$X_T = f_{os} R_2 C_1 (\ln N_1 - \ln N_2). \quad (30)$$

Thus, X_T is the result displayed on the digital readout, *D1*. Equations (28) and (29) indicate that the system constant can be adjusted by varying oscillator frequency, f_{os}, the primary calibration adjustment of the RDM 101.

To meet the requirements of varying ranges of mass concentrations encountered in practice as well as the theoretical bounds on concentration and resolution, the RDM 101-X is provided in four standard submodels, as indicated by the suffix, "X". Table 3 shows the different features of these submodels. The differences among the submodels lies in the electronic circuits which control measurement timing and the system constant. Submodel changes involve the replacement of plug-in "cards" and a factory recalibration. One of the two operating modes of the instrument allows semi-manual operation by which sampling time can be extended beyond the nominal period. Readings must be multiplied by a correction factor given in Table 1 of the operating manual, however.

To meet the requirements of intrinsic safety in coal mines, a number of features are incorporated into the RDM 101 design. The Unico Micronair pump was chosen to meet this requirement, and a number of current limiting and short circuit protection features are included. The RDM 101 units bear the U.S. Bureau of Mines intrinsic safety approval number 2G-2415. Integrity of the physical construction of the RDM 101 is maintained throughout, with the use of high quality components.

To summarize our investigation of the design aspects of the RDM 101, we conclude that the instruments are of high quality and reliability. The theory of beta absorption has been well implemented in the design and realization of this instrument. While the positive aspects of performance and reliability will be detailed under Laboratory Results and Discussion, we now list the following significant problems we have noted on our units during the study:

1.) Dusty environments, especially those involving coal dust, can cause fouling of the switch contacts and improper operation.

2.) Unused inputs of some of the digital logic integrated circuits are not treated as noted by the design handbook of their manufacturer, Texas Instruments. The possibility (though unrecorded to date) of computation errors exists in this situation.

3.) The impaction disk advance mechanism does not always operate properly.

4.) Reentrainment of dust in the nozzle in the absence of an impaction disk can result in deposition of dust on the G.M. tube window, necessitating a delicate and lengthy cleaning procedure.

5.) The instruments require frequent (secondary) recalibration of the "system constant" during the early months of their lives. Daily calibration checks in this period are desirable with weekly system constant adjustment being necessary during periods of heavy field use.

6.) The packing container is conducive to instrument damage during shipment.

7.) The batteries can be overcharged and damaged by leaving the charging unit connected too long in "full charge" mode.

8.) Adjusting flowrates (nominally set for 2.0 lpm) to 1.7 lpm necessary for some respirable mass sampling (requiring factory system constant recalibration) is difficult for some units.

9.) Jarring an instrument during a sample period results in battery contact slippage which causes premature stoppage of the instrument.

It is our understanding that the above problems and all other outstanding design problems found in the earlier versions of the RDM 101 are being corrected in the latest production run, as part of the interactive development procedure described at the beginning of this section. The manufacturer appears to exhibit a high level of competence in maintaining quality and reliability.

LABORATORY METHODS

The laboratory portion of this study was concerned with three primary areas. First, the intrinsic aspects of the RDM 101-1's performance were assessed in a study of the nature and short term variation of the important calibration parameters. Second, the ability of the instruments to sample polydisperse coal dust aerosols in a laboratory environment was judged, utilizing comparisons with gravimetric methods, correlations among instruments, and various additional measurements. Finally, simulations of environmental extremes were utilized to observe the effects of real world conditions on the performance of the instruments.

The calibration parameters of the RDM 101 are air flow rate, measurement cycle timing, system constant, and readout zeroing. In the course of this study, air flow rate was monitored and adjusted with the use of a soap bubble flowmeter, a thermocouple mass flowmeter and the rotameter supplied with each of the instruments. When calibrated, the rotameter enables one to maintain the flow rate of the instruments to better than ±2.5 percent of the 2.0 lpm nominal value. Flow rates were measured and maintained to this tolerance throughout the study. Readjustment was very seldom necessary. Measurement cycle timing is determined by a low frequency oscillator in the electronics section of the RDM 101. Since this oscillator drives an all-digital state determination circuit, proper timing relationships can normally be assured by measuring only the pump operating time during a cycle with the aid of a stopwatch.

More detailed timing measurements should not be attempted in the field and should be referred to the manufacturer. For this study, the one minute operating cycle times of the RDM 101-1's were measured regularly. Adjustment was never required and all measurements were within ±2.5 percent (1.5 seconds) of the 60 second nominal figure.

Assuming verification of the highly stable parameters of flowrate and timing as cited above, proper calibration of the remaining parameters of system constant and readout zeroing are normally the necessary and sufficient conditions for the assurance of correct RDM 101 operation. The system constant of each individual instrument is determined at the factory in a primary calibration process. At that time, a calibration impaction disk (unique to each instrument) is stamped with the average value produced by the digital readout of the instrument. This value results from the simulation of a known dust concentration by positioning the calibration disk in the path of the beta radiation between the first and final beta sampling intervals of a measurement cycle. During the period of this study frequent checks and recalibrations of the system constant were made in the laboratory, following the procedure recommended by the manufacturer. This procedure recommends taking an average of ten readings and readjusting if the result is more than ±10 percent away from the value stamped on the calibration disk. The adjustments were performed by changing the frequency of the oscillator (f_{os}, see Mechanical and Electronic Design, above) via a potentiometer provided for this purpose.

Readout zeroing is also a procedure described in the manufacturer's manual. This involves the averaging of ten readings when sampling particulate free air with the impaction disk in place throughout the opera tion cycle. The desired result is 0.0 ±0.1 mg/cu m. This procedure was followed frequently during this study, but the necessity of adjustment (changing a fixed resistor value) occurred only once with one instrument. The overall results of the calibration parameters area of this study will be presented later.

The ability of the RDM 101-1 to sample and characterize particulates in the laboratory environment was assessed utilizing the results from a number of experiments. For all of these experiments, polydisperse coal dust was used as the challenge aerosol. This dust consisted solely of Los Alamos standard test dust, with a mass mean aerodynamic diameter of 3.65 ±0.25 micrometers and a sigma-g of 2.2 ±0.1. Statistically sound correlations of mass concentration data were attempted only in the TLV concentration range for coal dust due to our limited laboratory resources. Except for very high dust concentrations, causing beta absorption and impaction problems, our confidence

in the reliability of the implemented theory replaced the need for varying mass concentrations. Actual RDM 101 performance in reasonable concentrations ranges other than those tested here should be within the specifications. All of this work involved the use of a Wright Dust Feed mechanism in conjunction with the small, high performance dust chamber pictured in Figures 4 and 5. The performance of this chamber is documented elsewhere *(15)*. It should be noted here however, that it is capable of generating and maintaining highly stable coal dust concentrations, especially in the 2.0 mg/cu m concentration range. Coefficients of variation considerably less than 5 percent are routinely produced for three hour runs involving four gravimetric personal samplers operated at 1.7 lpm.

The first series of experiments involving the system described above utilized single RDM 101-1's operated concurrently with three 37 mm (5.0 micrometer pore size type VM-1) total mass filters. Since an evaluation of size selective precollectors is not intended in this study, all runs were conducted in the absence of 10 mm nylon cyclones, unless otherwise noted. Flow rates of all sampling devices were maintained at 2.0 lpm. Means of the three total mass filter concentration data were compared to the means of 90 RDM 101-1 readings for each three hour run. Each of the three instruments was subjected to about a dozen runs. The dust concentration was maintained at 2.5 to 3.5 mg/cu m for every run. The schematic diagram shown in Figure 6 depicts the experimental setup used.

The second laboratory dust sampling experiment involved the simultaneous operation of all three RDM 101-1's as shown schematically in Figure 7 and pictorially in Figure 5. Each of the two 90 minute runs resulted in 60 data points for each instrument, representing a time series of correlation data. During both runs, the dust chamber mass concentration level was held as constant as possible in the 2.5 mg/cu m range.

The third experimental area involving actual dust sampling was comprised of correlating the diameter of impaction spots with the measured levels of dust concentration provided by the RDM 101-1. This experiment was considered important since constant impaction spot diameter is a prerequisite for proper RDM 101 operation throughout its intended concentration range. A filar micrometer was attached to a microscope to facilitate direct measurement of impaction spot sizes. Various combinations of impaction disk advance strategies, impaction disk petroleum jelly mixtures and dust chamber mass concentration levels were used, in an effort to establish agreement with the manufacturer's specification for mass concentration ranges. Rapid transitions between high and zero mass concentration levels were made in order to estimate the delays and perceived inaccuracies in measurements presumably due to re-entrainment of particles lodged in the impaction nozzle mechanism. These re-entrainment tests were made with the instrument in both a stationary and portable (e.g., being carried around the laboratory by the shoulder strap during the zero concentration measurement) operating modes.

The portable mode was intended to simulate a real world situation in which an instrument was carried from a highly dusty area to a much less contaminated location while making measurements.

An effort was also made to correlate the RDM 101-1 mass concentration readings with the actual mass of the impaction spot, in the 10 mg/cu m mass concentration range. In this range, each impaction spot should weigh in at about 20 micrograms. Weighing error was minimized by tare weighing a 10 mm VM-1 filter (after a small quantity of vaseline was applied), using the filter to collect a single spot in an instrument, and immediately performing the final weighing. The weighing error for this procedure was estimated using blank filters as a check, and found to be on the order of ± 2 micrograms. Although the filters could have interfered slightly with the beta absorption process, the data obtained appeared to be both relevant and useful.

A series of laboratory tests were performed on our three RDM 101-1's which consisted of in-depth real world simulations and the observation of long term (e.g. 6 to 14 months) drifts in calibration and performance. The charging units were not included in the simulations. These tests were extensive and varied, so only

a summary will be presented here. Low temperature operation was simulated in refrigerators at temperatures ranging from 0° to 50° F. Since the pumps quickly freeze up at ambient temperatures less than 32° F, two of the instruments were maintained at 35° F ±2° F for over two months during which measurements of all calibration parameters were made weekly. The same two instruments were alternately placed in an oven maintained at 100° ±5° F for over a month during which calibration parameter checks were again made weekly. Although no efforts were made to establish an upper bound for operating temperature it seems that 100° F is a reasonable figure for this maximum. No efforts were made to control relative humidity levels but they ranged from 10 to 85 percent. Rough field treatment and accelerated aging were simulated by subjecting two of the RDM 101-1's to several vibration table treatments.

These treatments were of ½ hour duration each and involved peak accelerations of from 1 to 5 g's. Fundamental frequencies were swept (at 1 minute repetition rates) from 1 to 200 Hz with both sinusoidal and triangular waveforms. The instruments were rigidly fastened to the table throughout these runs. Calibration parameters were checked and the instruments were inspected for damage after each run.

Measurements of the short and long term drifts associated with the two oscillators in the RDM 101's were included in most calibration parameter checks, especially during the vibration tests. The low frequency oscillator determines operating cycle timing and exhibited very little drift throughout the study. Since drift in the high frequency oscillator strongly determines drift in the system constant calibration parameter, this frequency was measured quite often in all three instruments with an electronic frequency counter.

Flowrate pulsation was measured at various intervals during the study in an effort to compare RDM 101 pump pulsation with pulsation levels encountered in personal sampler pump systems. Since a pressure transducer was used in the air line between the respective pumps and their 10 mm nylon cyclones, it was only possible to arrive at relative readings. Bendix and MSA pumps with and without approved pulsation dampeners were used for this comparison.

LABORATORY RESULTS AND DISCUSSION

The results of the dust chamber comparisons involving individual RDM 101's and three total mass filters (Figure 6) are shown in Table 4. The statistical t-test of means assumes that instrument resolution to ±0.2 mg/cu m at the 2.5 mg/cu m level is desired. Note that one instrument read quite high, one was quite low, and the third was very close to the means of the total mass filters. All of these results indicate operation within the manufacturer's specifications for accuracy, for coal dust at least.

The results of the calibration parameter study, conducted throughout the entire evaluation program, are presented in Table 5. The table presents a recommended minimum schedule of calibration checks for RDM 101's in decreasing order of frequency, as implied by the results of this study. The schedule assumes that the instrument will be in operation on a "full" schedule of 20 hours per week (about 14 hours are required per charge and the instruments can sample normally for about 3 hours on a charge) throughout their lifetimes. The "First Year" column should be used during the first calendar year after a new instrument is purchased, regardless of its intended use, to account for the effects of rapid initial drifts in some of the calibration parameters. "Laboratory" use means that the instrument will remain indoors, in a "room" environment, with little or no rough treatment. "Light" field use is subjectively differentiated from "heavy" field use by such examples as indoor machine shop or cotton mill operations ("light") as opposed to indoor-outdoor heavy construction, rock/coal mining operations and steel mills ("heavy"). These uses can also be differentiated by total ambient dust and dirt levels. Percentages contained in parentheses in the table indicate the requisite tolerance level for a given parameter. The other figures in parentheses are the number of readings that should be averaged together per calibration check or readjustment cycle. Of course, it is always wise to season a rigid calibration schedule with frequent spot checks and common sense, especially if the instruments are subjected to prolonged rough treatment. If the instruments are used only occasionally (especially during the first year of their lifetimes), e.g., less than two groups of three consecutive hours per month, calibration checks should be made on the system constant, and flow rate (with the rotameter) before each period of continuous operation. In addition, the impaction nozzle mechanism should be cleaned with compressed air or an alcohol solution at appropriate intervals, depending on dust loading conditions. Table 5 should hold reasonably well for all production runs of the RDM 101; at least until the manufacturer indicates a substantial improvement in first year calibration parameter drift, with the more frequent checks taking precedence between the "First Year" and "Heavy Field" columns.

Although the reader can make his own inferences from the data in Table 5, with regard to calibration parameter drift, special note is made with respect to the case of the system constant. During the first year in the lifetime of an RDM 101, significant drifts in this parameter, observed in both the three NIOSH instruments and the two Los Alamos (Group H-5) instruments result in the need for frequent checks and readjustments of the high frequency oscillator. Drifts in the system constant appear to be caused by drifts in the oscillator frequency, itself, during this period, since 100 Hz of oscillator drift corresponds to a noticeable change in the mean of ten system constant readings. Although the entire instrument is virtually immune to extremes in temperature and vibration of the type used in this study, an unexplainable drift is present in this oscillator, regardless of environmental conditions, in the first year or so of instrument life. After this period, subsequent drifts in the system constant are quite small and it is usually necessary to change the frequency of the oscillator from the factory-set value to maintain proper system constant calibration. This implies that major drifts arise from the oscillator circuit only in the infancy of the instrument, whereas longer term drifts of much lesser magnitude originate elsewhere. The prime intention of subsequent checks of the system constant would be to combat inaccuracies arising from dust that may have been deposited

directly on the geiger tube window during sampling, especially if the impaction disk is accidentally left out of the instrument.

The results of the direct comparisons made among the three RDM 101's with the coal dust tests are summarized in Table 6. The means, standard deviations, and 95 percent confidence intervals for the means are presented for the 60 time series readings of each instrument (and the three readings at each point in time averaged together) for the two runs. The chamber concentrations were maintained to a state-of-the-art level of constant mass concentration, and the sampling inlets in the chamber were no further than one foot from each other in the first run and one inch in the second. Still, the instrument readings ranged from 0.9 to 3.5 mg/cu m. while the means were judged to be very close to each other in the first run but somewhat separated in the second. Although sufficient information for a sound comparison of instrument versus chamber variance did not exist, a graph of the time series data for each run convincingly indicated that the instruments were "tracking" short term concentration variations in the best polydisperse dust chamber available. Linear correlation coefficients in the data were quite low (from 0.2 to 0.5) but these coefficients do not take account of the differences in phase of the time series data which appeared quite prominent in a visual analysis of the data graphs.

In search of a means to extract additional information from this data, the BMD computer time series data analysis programs were utilized. These programs utilize Fourier transform and Tukey filtering techniques *(16)* to extract frequency spectrum, phase, autocorrelation and cross correlation data from sets of time series data. As shown in Table 6, peaks and minima in the spectra resulting from this processing were very closely related in these data. Overlaying the spectral plots produced by the computer resulted in overall similarities among the individual instruments that were surprisingly close, especially at the chamber frequency components of 0.15 and 0.45 cycles per minute. Although phase relationships among the data were found to be a sensitive and indefinite function of position in the chamber, the results would tend to indicate agreement with the lack of linear time dependent correlation of the data caused mostly by time and spatial chamber ("phase") variations. Thus the contention that the instruments were "tracking" the variabilities within the chamber is strongly supported. The differences in overall means between instruments in the second run were not fully accounted for in this analysis, but could stem from two sources. First, the system constant of instruments 1 and 2 required slight adjustment when checked two weeks after the conclusion of run 2. Secondly, the time series graph of the data for run 2 indicated the possibility of somewhat erratic chamber performance towards the end of the run.

The coal dust deposits on an impaction disk (coated with regular petroleum jelly) resulting from the first phase of the impaction spot size study are shown in Figure 8. This disk was obtained from a three hour (constant chamber dust concentration) run and used for the impaction spot size measurements. The sixty spots on the disk have a mean diameter of 0.718 mm with a standard deviation of 0.0296, resulting in a 95 percent confidence interval of $\pm$0.006. This means that, for coal dust in the TLV concentration range, variations in the diameter of the impaction spot are negligible and make virtually no contribution to the error of the instrument. The mean of the 60 RDM readings was 2.01 mg/cu m and the 3 total mass filters indicated concentrations of 2.35, 2.37, and 2.38 mg/cu m, for this particular run.

Figure 9 illustrates an impaction disk prepared during a special coal dust chamber run in which the conditions were the same as described in the above section except that a different instrument was operated in manual mode for various periods of time to simulate higher dust concentrations. Table 7 shows the relations between various effective mass concentrations and impaction spot sizes. The linear correlation coefficient for the data is 0.96, with a coefficient of variation in spot size of 22 percent. These results strongly indicate an increasing contribution to the error of the instrument arising from variability in impaction spot diameter, as mass concentrations increases. It would be expected, however, that total error percentages (as cited in the instrument speci-

fications would not increase above the ±25 percent level, at least for coal dust, until extremely high dust mass concentration levels were reached. Also, the measurement of variations in impaction spot size using respirable dust sampling techniques would result in considerably less variation in these types of results.

Responding to reports from the U.S. Bureau of Mines that the inaccuracies in impaction spot sizes cause the RDM 101 to be unusable above 20 mg/cu m for coal dust, the GCA Corporation has developed a near-optimal mixture of vaseline and paraffin oil which is now supplied as the standard impaction disk coating medium. This medium exhibits no significant difference in performance over regular petroleum jelly for dry dust concentrations below 10 mg/cu m for the RDM 101-1. However, Figures 9 and 10 illustrate two disks (with the improved preparation) which have deposits corresponding to very high dust levels. Again, we expect respirable dust impaction spots to be more constrained than these pictured. Referring to the top of the disk pictured in Figure 10, and working clockwise around the disk, the first ten spots were obtained by taking one minute samples (with an RDM 101-1) of "real" coal dust concentrations, averaging 32.2 ±3.0 mg/cu m, as determined by the RDM readout. The next six spots resulted from re-entrainment of particles within the instrument, since the sampled air was dust free for these measurements. The re-entrainment readings varied from 1.5 mg/cu m (5 percent of the last true dust reading) when the instrument was not disturbed during a sample interval to 28.4 mg/cu m (87 percent of the last true dust reading) when the instrument was carried around the laboratory via the shoulder strap and placed on a table (lightly) during a sample interval. Six "clean air" sample intervals were required to obtain a reading below 1.0 mg/cu m (3 percent of the last true dust reading) when the instrument was being carried and handled in a simulated "light field use" fashion. The same sequence was repeated further along the disk pictured in Figure 9 at a "real" concentration level of 22.8 mg/cu m. This time, six clean air samples were required to obtain a reading below 1.0 mg/cu m (4.4 percent of the last true dust reading). The highest re-entrainment reading obtained was 15.8 mg/cu m (69.3 percent of true reading) when the instrument was carried and set down during a cycle.

The entire sequence was repeated for a third time at an average "real" concentration of 13.9 mg/cu m. This time, the high re-entrainment reading was 3.7 mg/cu m (26.6 percent of true) and six clean air measurements were needed to get the readings below 1 mg/cu m (7.1 percent of true). The remaining dozen spots on the disk show a relatively small coefficient of variation in diameter (12 percent, using approximately the same effective concentration range measurements as reported in Table 7. These results clearly indicate the superiority of the new impaction medium over regular petroleum jelly, especially for high concentrations. The unhappy result that significant errors in readings due to particle re-entrainment in the sampling apparatus is also definitely present. Again, one would expect somewhat reduced re-entrainment effects when the 10 mm nylon cyclone is attached and only respirable dust is passed on to the impaction stage.

In Figure 11, the disk shown represents results of extremely high coal dust concentration levels. Working clockwise from the top of the disk, the first third of the circumference contains impaction spots resulting from measurements of concentrations of approximately 50 ±5 mg/cu m. The first seven spots result from readings of the test cloud of 23.5 mg/cu m to 41.9 mg/cu m, whose coefficient of variation (CoV) is 22 percent. The apparent overlap of impaction spots and the rather strange results in data produced resulted in the advancement of the impaction wheel two spaces for each of the next five readings. These averaged 49.1 mg/cu m with a CoV of 9.7 percent, a much more believable answer. The average of the next three readings was 49.4 mg/cu m with a CoV of 2.5 percent. The remaining spots shown, together with an analysis of other data indicate the necessity of advancing the impaction wheel two spaces when sampling coal dust concentrations of greater than about 35.5 mg/cu m, even when using the optimum disk coating medium, with the RDM 101-1. This is probably true to varying degrees, regardless of the composition of the dust and the presence

of the cyclone. Measurements above 10 to 15 mg/cu m should not be attempted with impaction media other than the optimum coating mixture. Note the equivalency of the mass concentration figures presented here for the RDM 101-1 with other concentration levels given by the RDM 101-0.2, 4, and 8, a subject which will be treated subsequently in the conclusions section.

The results of the exercise in which impaction spots deposited directly on 10 mm VM-1 filters were weighed were quite encouraging and provided further verification of proper RDM 101 operation. With estimated weighing errors of ± 10 percent (for 20 micrograms), the average difference of 18 percent between RDM 101 readings and spot weights was a pleasant surprise. In no case of the 25 filters weighed, did the difference exceed 25 percent.

Comparison of the pulsation caused by the air moving system of the RDM 101 vis a vis the federal regulations contained in 30 CFR 74 is virtually impossible. With the 10 mm nylon cylcone attached, however, comparative pressure transducer readings place the performance of the RDM 101 somewhere between a completely undamped (MSA or Bendix) personal sampler pump and the same pumps equipped with approved pulsation dampeners. Although the impaction chamber of the RDM 101 is highly favorable to minimizing pulsation, further consideration may be warranted in further RDM designs, especially as instruments which may become candidates for compliance determination enter the field.

A final note on the environmental simulation results is included in this section. Within reasonable limits, it was impossible to damage the RDM 101 units or substantially accelerate the drift in calibration parameters by rough treatment. This feature is an admirable one in such a complex instrument.

The environmental condition causing a significant effect on the performance of the instrument was that of extremely high ambient dust concentrations. The areas of concern for this problem are the electrical switch contacts (which are to be subsequently improved by the use of sealed switches) and the deposition of dust on the geiger tube window and elsewhere within the instrument. These latter difficulties quickly appear in the form of drift in system constant, readout zeroing, and flowrate, all of which can easily be corrected. Adherence to a rigorous calibration schedule such as in Table 5, again, cannot be overstressed.

A field study utilizing one of the three NIOSH RDM 101's was conducted by NIOSH in a number of Vermont granite sheds for the characterization of respirable dust levels. The report resulting from this study indicates some correlation of RDM 101 results with those produced by stationary gravimetric personal sampler units. Difficulties with the mechanical and electrical shortcomings of the instrument (which were all corrected in subsequent design improvements) together with the inappropriateness of using a 1-minute sampling time for 0.3 mg/cu m dust levels prevented a rigorous and fair comparison. Plans to include appropriate models of RDM 101's in future field studies, including characterization of oil mists, silica dust, and hair sprays, among others, are currently in progress at NIOSH and elsewhere.

CONCLUSIONS

The RDM 101 represents a significant and, to date, unique advance in portable, direct reading particulate air sampling instrumentation. The theoretical and observed practical limitations of the beta absorption, impaction, and electronic principles utilized in this instrument appear to be relatively inconsequential if the instrument is used in a manner consistent with the operating manual and the results presented here. Although the particulates utilized in our studies have been necessarily limited as to composition and mass concentration ranges, we feel that the instrument can perform within the manufacturer's specifications when sampling particulates in the workplace, in general. Special cases with regard to composition do exist, mostly from the standpoint of impactor performance rather than beta absorption. However, the necessary precautions will be made known to the customer, before purchase, as part of the consulting services offered by the manufacturer. Since the same RDM 101-X submodel can hardly be expected to accurately sample all conceivable compositions, size distributions, and mass concentrations of particulates, the burden is clearly on the prospective customer to make his intended uses of the instrument fully known to the GCA consultant before committing himself to a purchase.

The first and most important step in selecting the proper instrument submodel and/or need for special system constant adjustment is the determination of the desired particulate compositions and concentrations to be sampled. The customer will presumably want to maximize the sensitivity of the instrument in the TLV concentration range of the contaminant to be sampled or alternatively, optimize or suboptimize the sensitivity over several TLV ranges, corresponding to several different particulate characteristics and compositions. Note that, in extending the 1 to 50 mg/cu m concentration range of the RDM 101-1 to the other submodels by multiplication by the conversion factor of running times (5.0, 0.25, 0.125 respectively) for the submodels 0.2, 4, and 8, it is apparent that the ranges for the submodels 0.2, 4, and 8 are more conservative than for submodel 1. Also, as a general rule of thumb, it is reasonable to assume that respirable dust readings will run from 40 to 60 percent of total dust readings in the same environment.

With this information in mind, the customer should make a thoughtful selection of the proper RDM 101 submodel to use in his particular situation, with the realization that factory readjustment at nominal cost is required for submodel, system constant, and flow rate changes.

When using the instrument in the workplace, the industrial hygienist should be aware of the possibility of inaccurate readings due to particle re-entrainment (when the instrument is taken from areas of heavy to light dust concentrations) and calibration drift. Virtually all other operational difficulties have been eliminated in the presently available units, however. It is also noteworthy that seemingly large variations in the instantaneous readings that may be obtained from the RDM 101 are, most likely, truly representative of the environment. After observing the variations in our best laboratory coal dust chamber while attempting to maintain the most constant concentrations possible, it is no surprise to hear reports of real world data that exhibit a high degree of reading-to-reading variability. The user of this instrument will necessarily develop both a statistical and a "gut" feel for the number of measurements required for his needs.

The industrial hygienist who has found that the acquisition of RDM 101 units is desirable for his particular application from technical and operational standpoints may also be asked to justify the relatively high acquisition costs of the equipment. The content of such a justification should include estimates of the cost and time savings resulting either directly or indirectly from the instantaneous information provided by the instrument. Estimates of increases in plant areas to be covered by each active member of the industrial hygiene measurements team should also be provided as part of a full explanation of the walk-through survey concept. One should also mention the process of utilizing direct reading instruments as a means of allocating

compliance sampling equipment and hazard control resources to plant areas that indicate this type of need. In some applications, such as coal mines, equipment of this type can be legally depreciated on the company's financial records over short periods of time, using accelerated schedules, as provided in the Internal Revenue Service regulations. The income tax savings realized by these depreciation methods, together with the operational cost effectiveness of this equipment should be fully described in a financial justification of its purchase.

Although actual field testing of the RDM 101 was not conducted firsthand by the members of this study team, we are maintaining an effort to collect and distribute this type of information. We feel quite strongly that this instrument has a high degree of applicability in the support of walk-through survey and hazard evaluation activities in an exceptionally wide variety of field situations. The fact that the RDM 101 is not a personal sampling device per se and the fact that its instantaneous readings cannot be directly compared with eight hour time weighted average standards are the two reasons why this type of instrument cannot be used in the actual determination of compliance. Since the usefulness of direct, instantaneous readings has been so well demonstrated in field hazard evaluation and control efforts, we hope that these two barriers do not deter the utilization of this type of instrumentation. Hopefully, further technical innovations in direct reading air sampling instrumentation will be encouraged in the future, at least by the existence and recognition of viable markets for this type of equipment.

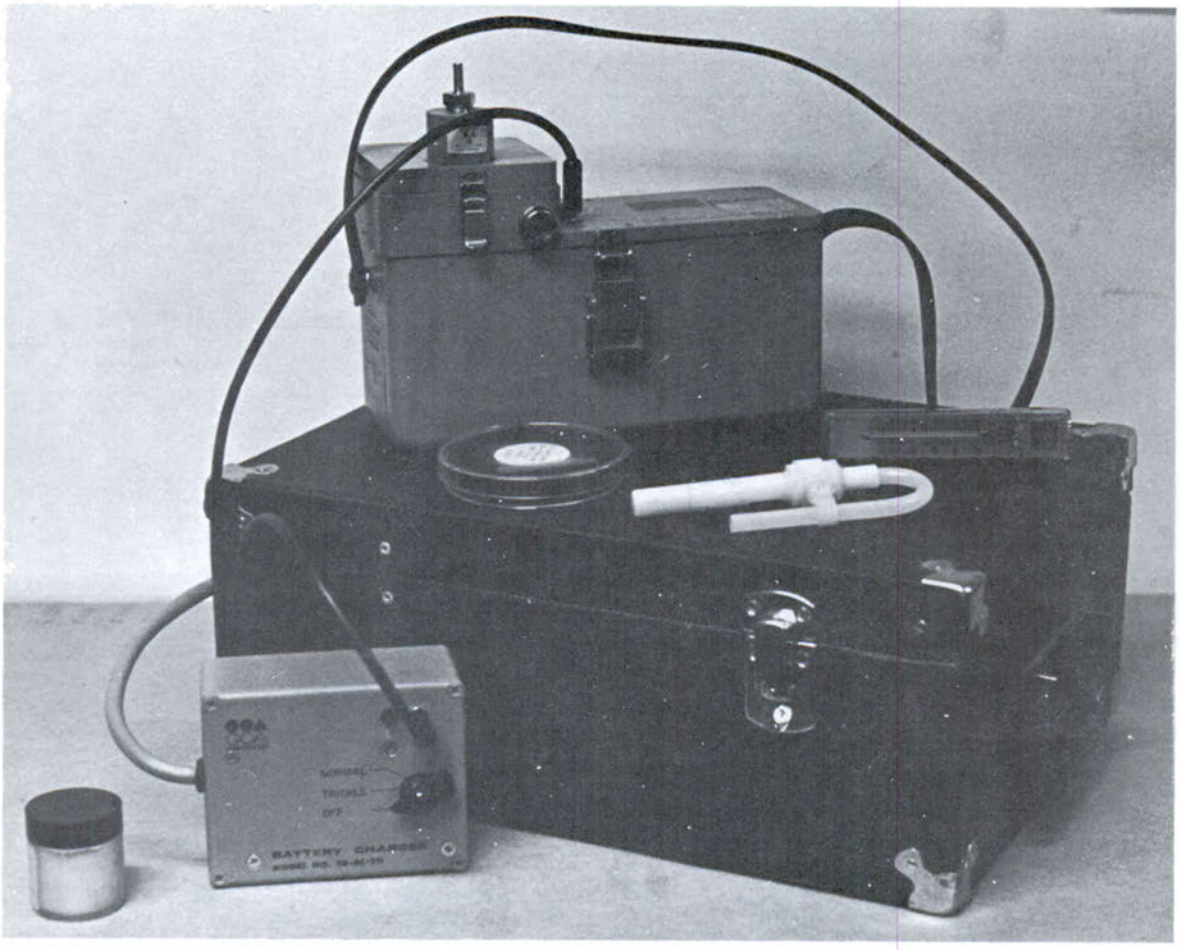


FIGURE 1. GCA Corporation's RDM 101 respirable dust monitor.

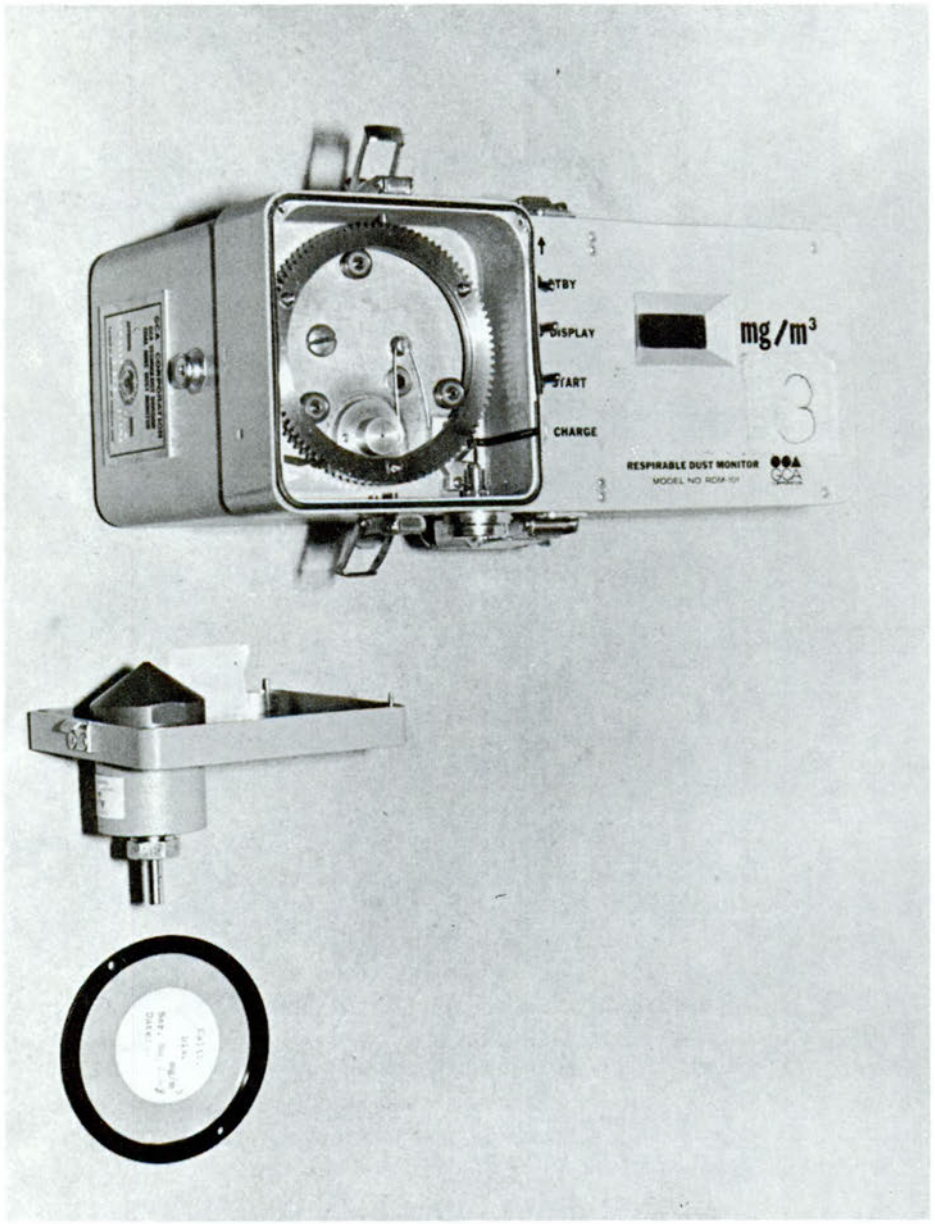


FIGURE 2. Component parts of impacting nozzle assembly.

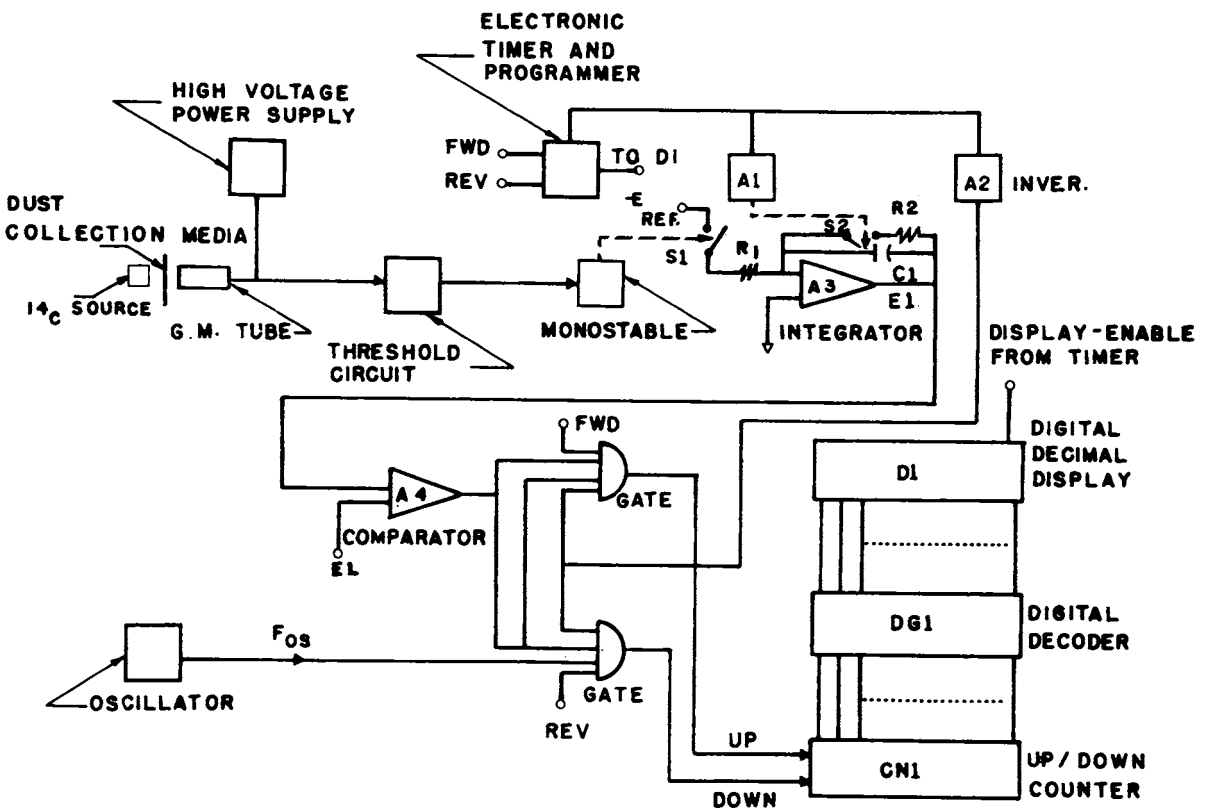
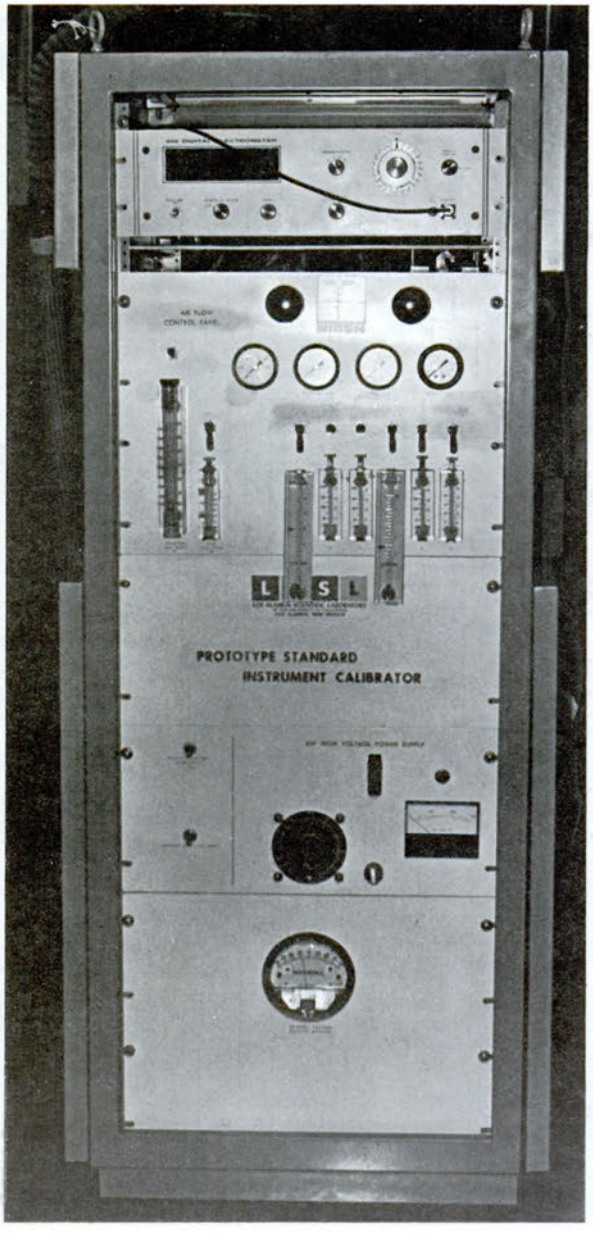


FIGURE 3. Electronic computing and timing block diagram of [illegible].



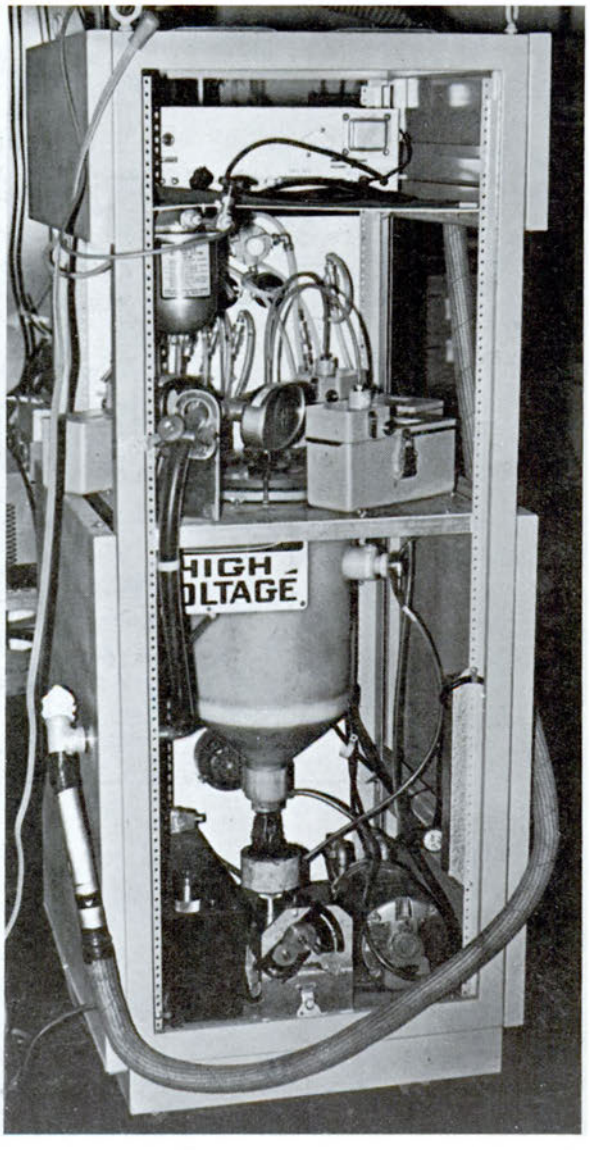


FIGURE 4. LASL built dust dispersion chamber.

FIGURE 5. Component parts of dust chamber.

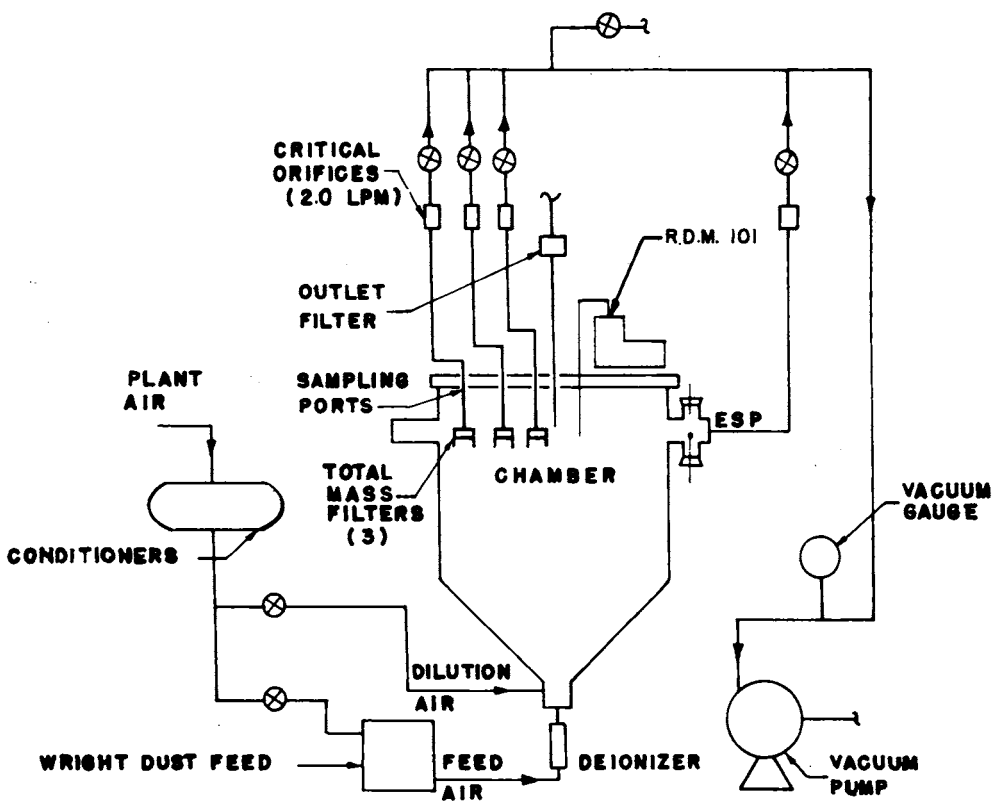


FIGURE 6. Apparatus for RDM-gravimetric comparisons.

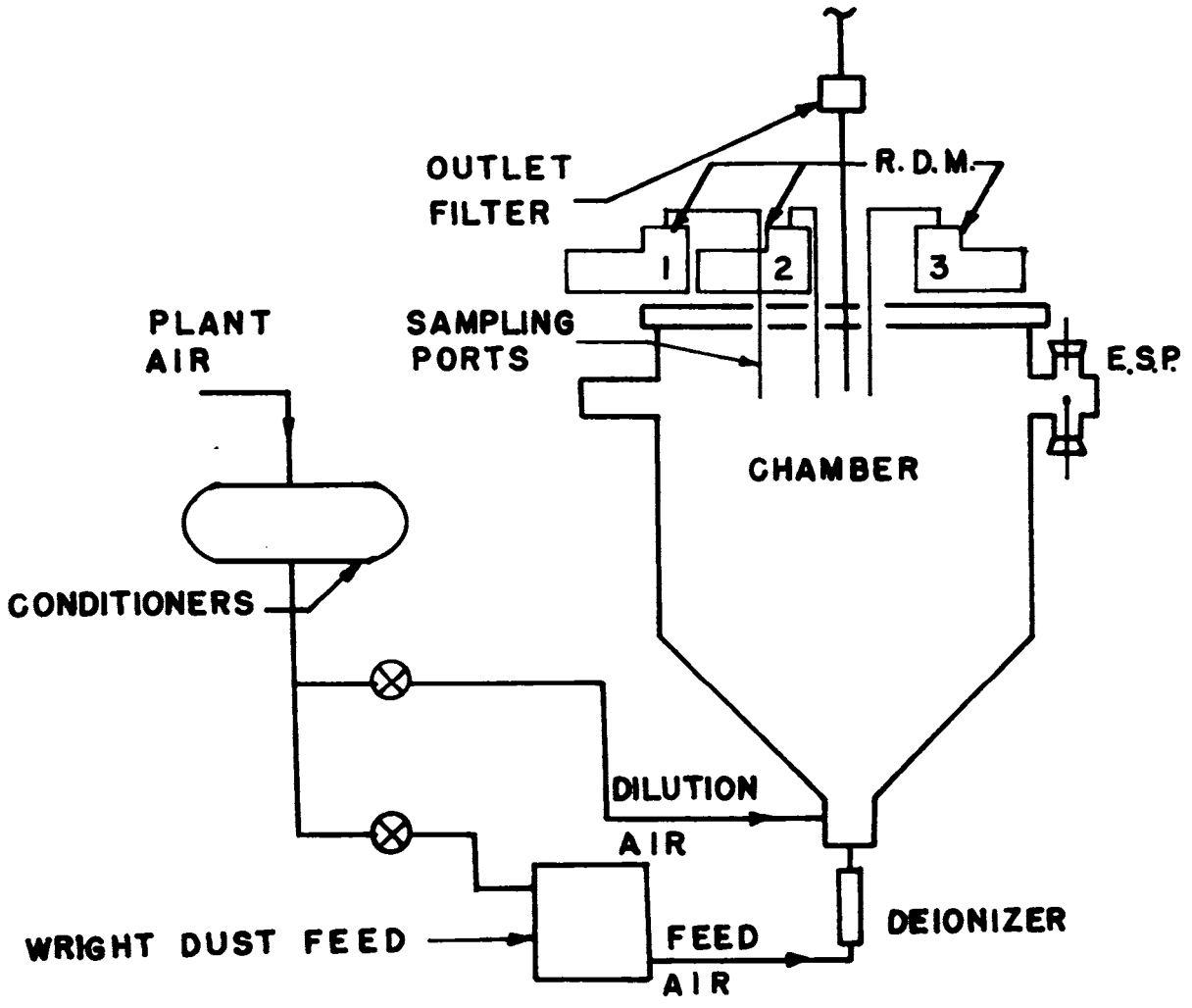


FIGURE 7. Apparatus for RDM-RDM correlations.

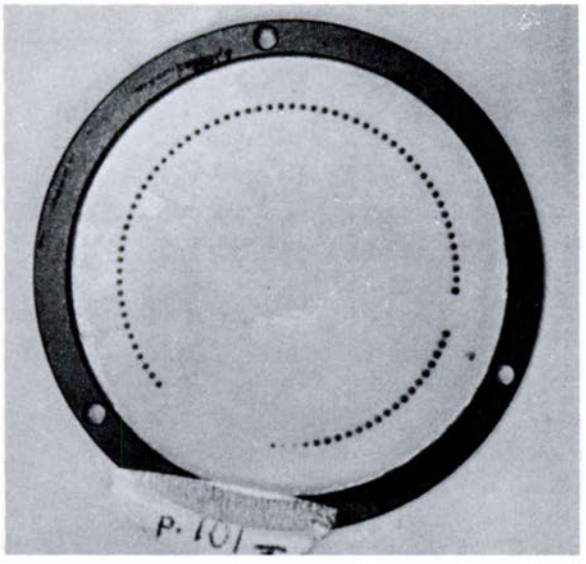


FIGURE 8. RDM impactor disk in normal operating mode.

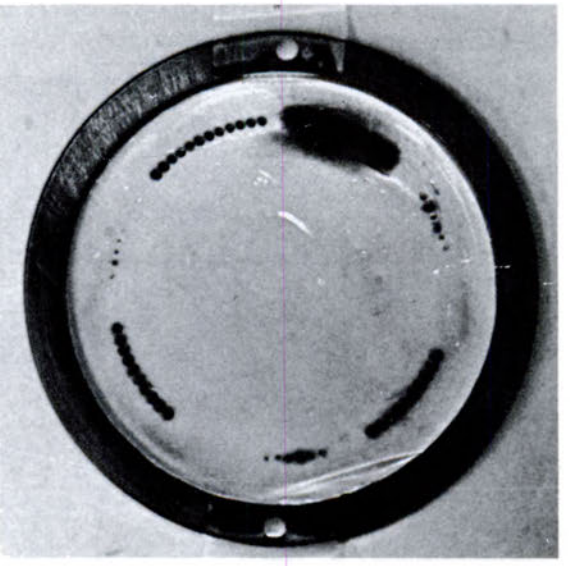


FIGURE 10. RDM impactor disk pattern with various concentration changes.

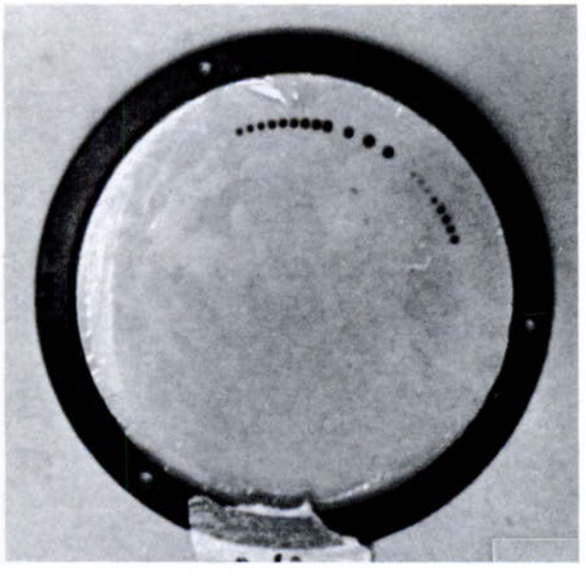


FIGURE 9. RDM impactor disk sampling higher dust concentrations.

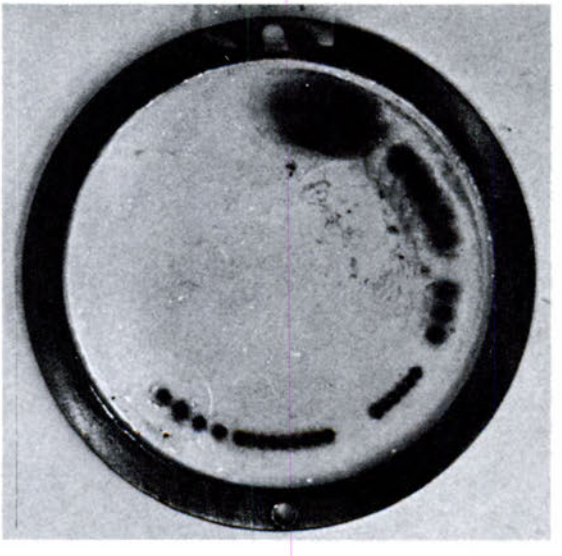


FIGURE 11. RDM impactor disk pattern with extremely high concentrations.

TABLES

TABLE 1. — Z/A errors for some elements.

These figures assume that the instrument system constant has been adjusted for the 0.500 Z/A ratio found in Carbon. Factory adjustment for other Z/A ratios is available.

Radioactive isotopes and elements above emitting radiation that effects geiger tubes are disqualified from consideration for this table.

Element	Atomic Number	Z/A Ratio	Z/A Error, percent
Actinium	89	0.392	−21.6
Aluminum	13	.482	−3.6
Antimony	51	.419	−16.2
Arsenic	33	.441	−11.8
Astatine	85	.403	−19.4
Barium	56	.408	−18.4
Beryllium	4	.444	−11.2
Bismuth	83	.397	−20.6
Boron	5	.462	−7.6
Bromine	35	.438	−12.4
Cadmium	48	.427	−14.6
Calcium	20	.499	−.2
Carbon	6	.500	.0
Cerium	58	.414	−17.2
Cesium	55	.414	−17.2
Chlorine	17	.479	−4.2
Chromium	24	.461	−7.8
Cobalt	27	.458	−8.4
Copper	29	.456	−8.8
Dysprosium	66	.406	−18.8
Erbium	68	.407	−18.6
Europium	63	.414	−17.2
Fluorine	9	.474	−5.2
Francium	87	.390	−22.0
Gadolinium	64	.408	−18.4
Gallium	31	.445	−11.0
Germanium	32	.441	−11.8
Gold	79	.401	−19.8
Hafnium	72	.403	−19.4
Holmium	67	.406	−18.8
Hydrogen	1	1.000	+200.0
Indium	49	.427	−14.6
Iodine	53	.418	−16.4
Iridium	77	.399	−20.2
Iron	26	.466	−6.8
Lanthanum	57	.410	−18.0
Lead	82	.396	−20.8
Lithium	3	.432	−13.6
Lutetium	71	.406	−18.8
Magnesium	12	.493	−1.4

TABLE 1. — Z/A errors for some elements — Continued.

Element	Atomic Number	Z/A Ratio	Z/A Error, percent
Manganese	25	.455	−9.0
Mercury	80	.399	−20.2
Molybdenum	42	.438	−12.4
Neodymium	60	.416	−16.8
Nickel	28	.477	−4.6
Niobium	41	.441	−11.8
Nitrogen	7	0.500	0.00
Osmium	76	.400	−20.0
Oxygen	8	.500	.0
Palladium	46	.431	−13.8
Phosphorus	15	.484	−3.2
Platinum	78	.400	−20.0
Polonium	84	.400	−20.0
Potassium	19	.486	−2.8
Praseodymium	59	.419	−16.2
Promethium	61	.415	−17.0
Protactinium	91	.394	−21.2
Radium	88	.389	−22.2
Radon	86	.387	−22.6
Rhenium	75	.403	−19.4
Rhodium	45	.437	−12.6
Rubidium	37	.433	−13.4
Ruthenium	44	.433	−13.4
Samarium	62	.412	−17.6
Scandium	21	.467	−6.6
Selenium	34	.431	−13.8
Silicon	14	.498	−0.4
Silver	47	.436	−12.8
Sodium	11	.478	−4.4
Strontium	38	.434	−13.2
Sulfur	16	.499	−0.2
Tantalum	73	.404	−19.2
Technetium	43	.439	−12.2
Tellurium	52	.407	−18.6
Terbium	65	.408	−18.4
Thalium	81	.396	−20.8
Thorium	90	.388	−22.4
Thulium	69	.407	−18.6
Tin	50	.421	−15.8
Titanium	22	.459	−8.2
Tungsten	74	.402	−19.6
Vanadium	23	.451	−9.8
Ytterbium	70	.405	−19.0
Yttrium	39	.439	−12.2
Zinc	30	.459	−8.2
Zirconium	40	.439	−12.2

TABLE 2. — Uncertainty in C due to statistical nature of radioactive decay, RDM 101—1.

C (mg/cu m)	$2\sigma_C$ (mg/cu m)	$2\sigma_C / C \times 100$ = percentage error
1.00	0.196	19.5
2.00	.202	10.1
40.00	1.105	2.75
50.00	1.817	3.64

TABLE 3. — RDM 101 submodel characteristics.

Characteristic	Submodel (RDM 101-X)			
	0.2	1	4	8
Mass concentration range in automatic mode (mg/cu m)	10 to 200	1 to 50	0.2 to 8.0	0.06 to 5.0
Last significant digit of display (mg/cu m)	1	0.1	0.01	0.01
Total time for one measurement	12 sec.	1 min.	4 min.	8 min.
Durations of initial and final beta count period	4 sec.	20 sec.	20 sec.	1 min.
Effective dust sampling time	8 sec.	40 sec.	220 sec.	7 min.
Minimum number of measurements per battery charge	350	200	60	30
Average number of measurements per impaction disk	95	95	95	95
Average number of measurements per impaction disk (very dusty environment — 2 advances/ measurement)	45	45	45	45
Duration of automatic readout activation	10 sec.	10 sec.	10 sec.	10 sec.

TABLE 4. — Results of RDM — gravimetric comparisons.

RDM unit no.	3 hour runs, number	Difference percent	T = statistics
1	11	RDM 19.0, High	$U = U_0$ to 0.01
2	13	RDM 2.4, High	$U = U_0$ to 0.01
3	11	RDM 20.3, Low	$U = U_0$ to 0.01

TABLE 5. — Recommended minimum calibration check / adjustment schedule for RDM 101.

Parameter	First year	Intended Use		
		Laboratory	Light Field	Heavy Field
System Constant (±5%) (10)	2/wk.	6/yr.	1/mo.	2/wk.+
Flow Rate (±2.5%):				
Rotameter (supplied)	2/mo.	4/yr.	6/yr.	1/wk.+
Bubblemeter (lab) (3)	4/yr.	1/yr.	2/yr.	4/yr.
Readout Zeroing (1) (10)	2/mo.	2/yr.	4/yr.	1/mo.
Cycle Timing (±2.5%) (3)	4/yr.	1/yr.	2/yr.	3/yr.

[1] Ten readings should average to within ±1 least significant digit of the readout about zero.

TABLE 6. — Results of RDM 101 vs. RDM 101 comparisons.

Run Number	N	X ± 95% CI (mg/m³)	Standard Deviation	Frequency Spectra of Data	
				Maxima (cycles/min.)	Minima (cycles/min.)
Run 1:					
RDM 1	60	2.25 ±0.09	±0.421	0.45, 0.15, 0.00	0.35, 0.05
RDM 2	60	2.24 ±0.11	± .521	.45, .15, .00	.37, .25
RDM 3	60	2.28 ±0.11	± .528	.45, .19, .00	.30, .10
Mean	60	2.26 ±0.07	± .326	.45, .15, .00	.35, .10
Run 2:					
RDM 1	60	2.26 ±0.10	± .483	.40, .15, .00	.35, .10
RDM 2	60	1.90 ±0.09	± .425	.45, .15, .00	.33, .05
RDM 3	60	2.09 ±0.14	± .636	.40, .25, .00	.35, .10
Mean	60	2.08 ±0.08	± .395	.40, .25, .00	.35, .12

TABLE 7. — Effective mass concentration vs. impaction spot size.

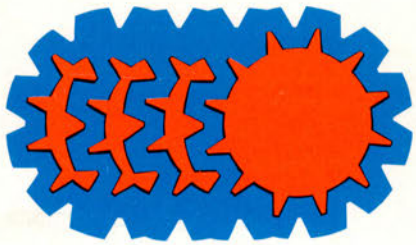
Spot No.	Effective Concentration Mg/cu m	Spot Diameter, mm
1	2.0	0.595
2	2.1	.614
3	1.9	.601
4	3.8	.693
5	3.3	.683
6	4.0	.698
7	6.0	.790
8	8.2	.841
9	9.6	.914
10	9.1	.884
11	22.4	1.102
12	19.9	1.029

REFERENCES

1. Hatch, T. F., and P. Gross: *Pulmonary Deposition and Retention of Inhaled Aerosols.* Academic Press. New York, (1964).
2. Davies, C. N.: "Dust Sampling and Lung Disease". *British Journal of Industrial Medicine.* 9:120, (1952).
3. Lippmann, M.: "Aerosol Sampling for Inhaled Hazard Evaluations". In *Assessment of Airborne Particulates.* T. T. Mercer, Morrow, and Stoeber, ed. Charles Thomas. Springfield, Ill., (1964).
4. *The President's Report on Occupational Safety and Health — December, 1973.* U.S. Government Printing Office Stock Number 4000-00288 (1973).
5. Leidel, Nelson A., and K. A. Busch: "Statistical Methods for the Determination of Noncompliance". U.S. Department of Health, Education, and Welfare, PHS/CDC/NIOSH Technical Report no. 76. Cincinnati, Ohio, (1973).
6. Lilienfeld, P., and J. Duchinos: "Coal Mine Dust Instantaneous Mass Monitor". Final Report, NIOSH contract no. CPE-R-70-0037. GCA Corporation, Bedford, Mass., (April, 1971).
7. Lilienfeld, P., and J. Dulchinos: "Portable Instantaneous Mass Monitor for Coal Mine Dust". *AIHAJ.* , 136, (1972).
8. Evans, R. D.: *The Atomic Nucleus.* McGraw Hill. New York, (1955).
9. Cook, C. S., L. M. Langer, and H. C. Price, Jr.: "Study of the Beta Spectra of Carbon-14 and Sulfur-35". *Physical Review. 74,* 548 (1948).
10. Shumilovski, N. N., and L. V. Mel'ttser: *Radioactive Isotopes in Instrumentation and Control.* The MacMillan Co. New York., (1964).
11. Brownell, G. L.: "Interaction of Phosphorus-32 Beta Rays With Matter". *Nucleonics. 10(6),* 30, (1952).
12. Lilienfeld, P.: "Beta Absorption-Impactor Aerosol Mass Monitor". *AIHAJ. 31,* 722, (1970).
13. Bowker, A. H., and G. J. Lieberman: *Engineering Statistics.* Prentice-Hall. Englewood Cliffs, NJ, (1959).
14. Lilienfeld, P.: "Beta Absorption Mass Monitoring of Particulates — A Review". AIHA Paper no. 71-1031, Joint Conf. on Sensing Environmental Pollutants. Palo Alto, California (1971).
15. Fairchild, C. I., et al: "The Standard Instrument Calibration Aerosol Test System". Los Alamos Informal Report no. LA-5405-MS, Los Alamos, New Mexico, (1973). LASL
16. Dixon, W. J. (ed.): *Biomedical Computer Programs No. 2.* University of California Press, (1971). pp 435-482.

☆ U. S. GOVERNMENT PRINTING OFFICE : 1975-657-696/5509 Region No. 5-11

HEW Publication No. (NIOSH) 76—114



U.S. DEPARTMENT OF
HEALTH, EDUCATION, AND WELFARE
Public Health Service
Center for Disease Control
National Institute for Occupational
Safety and Health

TECHNICAL INFORMATION