NBS TECHNICAL NOTE 973

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Smoke Detector Design and Smoke Properties

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Smoke Detector Design and Smoke Properties

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Errata sheet to accompany National Bureau of Standards Technical Note 973, Smoke Detector Design and Smoke Properties, by Richard W. Bukowski and George W. Mulholland.

The page number 8 has been inadvertently omitted.

On page 41, the third line from the bottom now reads:

≤ 0.16 m diameter;

it should read:

≤ 0.16 μm diameter.

November 1978

U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, Secretary
Dr. Sidney Harman, Under Secretary
Jordan J. Baruch, Assistant Secretary for Science and Technology
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

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SMOKE DETECTOR DESIGN AND SMOKE PROPERTIES[1]

Richard W. Bukowski and George W. Mulholland

The importance of a reference photometer and reference ionization detector in improving the reliability of smoke detectors is discussed. Recent developments in smoke detector technology are highlighted and theoretical as well as practical experience in regard to detector performance is summarized. Comparison of the theoretically predicted response of smoke detectors as a function of particle size with measured values is given. A monodisperse aerosol generator, an electrical aerosol analyzer with a size sensitivity from 0.01 to 1 μm, and an optical particle counter are described. The size distribution, mass and number concentration, optical density, and coagulation frequency for smoke from burning heptane and smoldering cotton lamp wick are presented. It is shown that a Junge type size distribution provides a good fit to the measured size distribution for both fresh and aged smoke.

Key words: Aerosol generators; detector testers; fire detectors; ionization detectors; light-scattering detectors; particle size distribution; smoke; smoke detectors.

1. INTRODUCTION

This paper consists of two parts. The first part concentrates on smoke detector design (sections 1-8) and the second part consists of recent research on smoke aerosol properties pertinent to smoke detection (sections 9-14).

Smoke detectors, particularly the residential variety, have undergone an extremely rapid growth in sales to where they are currently being compared with digital watches, pocket calculators, and citizens band radios in popularity. In the last five years, residential smoke detectors have grown from annual sales in the U.S. of less than a few hundred thousand to a market level of twelve to fourteen million in the calendar year 1977. You will note in figure 1 (which gives actual sales estimates prior to 1977 and our projections for 1977 and beyond) that the 1977 sales were two million units ahead of our projection made in May of 1977.

Because NFPA records indicate that approximately 75% of the U.S. fire deaths occur in residences and because studies [1][2] have indicated that almost half of these residential fire deaths could be prevented by the widespread use of residential smoke detectors, it is obvious that the impact of these sales on the reduction of U.S. fire losses can be great.

The vastly increased sales volume as well as technical developments in electronics have resulted in greatly decreased prices in the marketplace. For example, in 1971 residential smoke detectors cost an average of $125 per unit. Currently, a number of detectors are available for under $20 per unit retail

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[1] This paper was presented at the Third Joint Panel Meeting of the United States and Japan Natural Resources (U.J.N.R.) Panel on Fire Research and Safety, March 1978.

[2] Numbers in brackets refer to the literature references listed at the end of this paper.

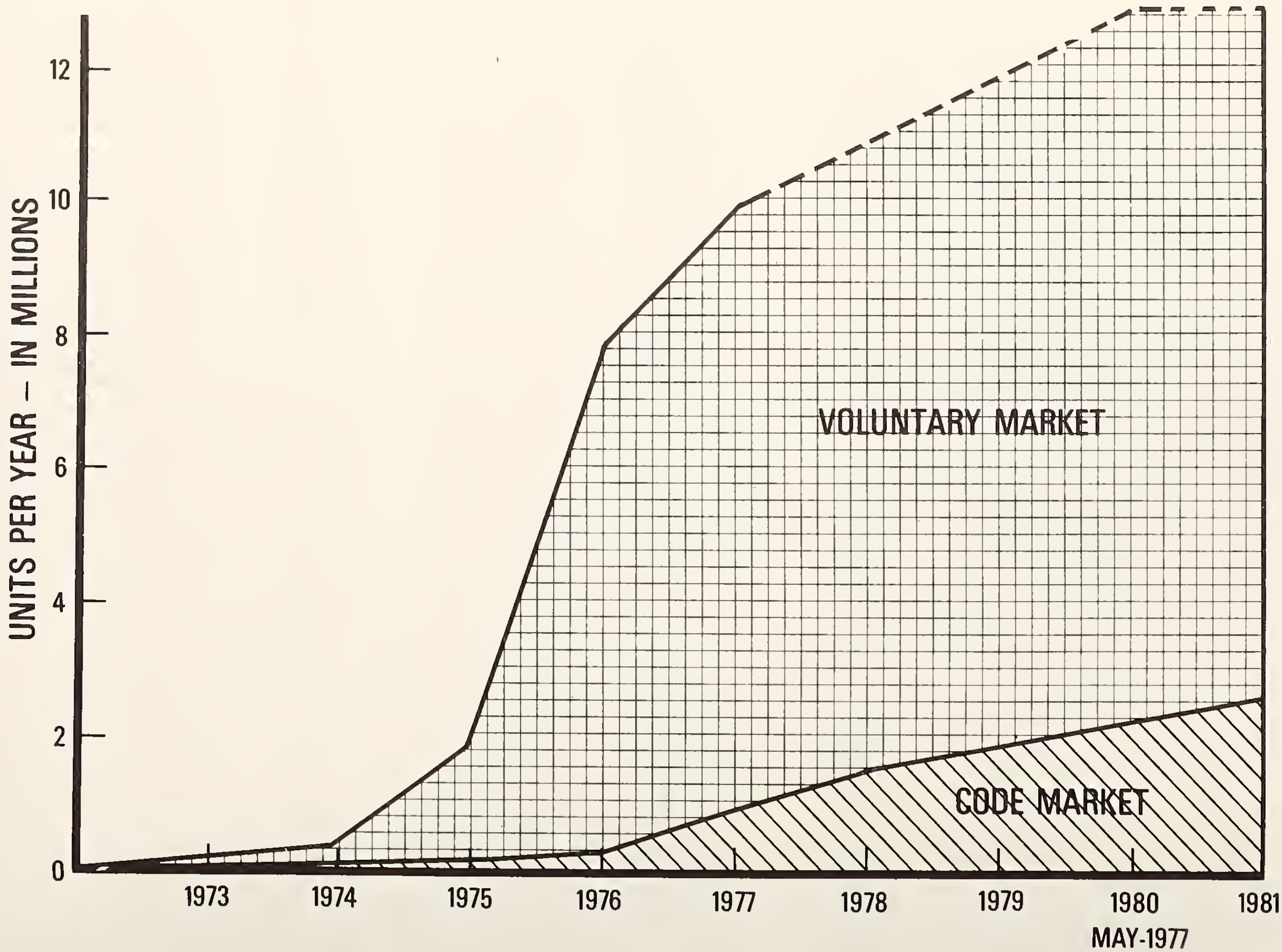

Figure 1. Smoke alarm market predictions.

($25 average - figure 2). While decreased cost, extensive consumer interest, and large-scale national advertising have all contributed to this increased sales volume it can also be readily understood that the performance and quality of the devices is critical in achieving the projected impact on fire losses. For this reason, the National Bureau of Standards, Center for Fire Research is deeply involved and committed to work which will provide a better understanding of the design, performance, and proper use of smoke detectors.

	1971	1977
NO. UNITS SOLD	50,000	12-14 MILLION
UNIT PRICE	$ 125	$ 25

Figure 2. Comparison of smoke detector sales and average retail cost -- 1971 and 1977.

2. POTENTIAL PROBLEM AREAS

Identified problem areas with residential smoke detectors can be divided into three broad categories. These are false alarms, performance and design, and reliability.

The primary cause of false alarms in residential applications is cooking. Technically, this is a difficult problem to overcome since the cooking process produces particulates of similar size ranges and concentrations to those seen in hostile fires. Our feeling is that, for most applications, optimum choice of type of detector and placement within the dwelling can preclude most false alarm problems from cooking. Also, a recent survey [2] has indicated that the false alarm problem with residential detectors may not be as large as was originally thought. Survey data indicate that, of the people contacted who own residential detectors, 96% rarely or never experienced a false alarm. Also, 97% of those people contacted indicated that they were completely satisfied with the device purchased.

With regard to design and performance, the problems are more complex. As the market has grown, many companies have begun manufacturing residential detectors. Some of these companies have invested little in research and have designed detectors strictly by trial and error. This has led to marginal designs and marginal performance. More recently, a number of semi-conductor manufacturers [3] have begun marketing smoke detector integrated circuits containing all necessary electronics except for the sensing chamber, power source, and sounding device (figure 3). Two manufacturers are producing ionization chambers which can be connected to these smoke detector integrated circuits, which essentially eliminates the need for any research and development on the part of the final manufacturer. Thus, more and more dependence

manufacturer [a]	model	ION	PHOTO
SILICONIX	SM 110	X	X
GENERAL INSTRUMENT	MEM 4962	X	
	MEM 4963	X	X
MOTOROLA	MC14461P/14462P	X	
SUPERTEX	SDIA	X	
	SD2A	X	X
NATIONAL SEMICONDUCTOR	LM1801	X	

a) RCA has also introduced an integrated circuit for smoke detectors. (model CA3097).

Figure 3. Current smoke detector integrated circuits [3].

is being placed on the role of the approving laboratory for assurance that marginal or poorly performing units are not marketed. Thus, the need for strict approval standards which assure a fairly high minimum level of performance has become increasingly important.

Another complicating factor in the poor design and performance area has been the cost competition in the marketplace. Price erosion has resulted in a great deal of "value engineering" being used in smoke detector designs. Minimizing production cost and very large production volumes have increased the impact of performance problems which do not show up until the detector is in the field. This situation has led to three major smoke detector recalls in this country in the last two years and the possibility that additional recalls may involve millions of units instead of the hundred thousand or less involved in the first three product recalls.

The third problem area of reliability is again a complex factor. Based on current failure rate predictions, the average residential smoke detector is expected to last on the order of 15 to 20 years before it has to be replaced. It would be desirable to design a detector such that any failure which would prevent its detection of a fire would be indicated to the homeowner by some type of trouble signal. Taken to the extreme, this would result in an extremely expensive unit. Thus, the approach taken has been to try to maximize the reliability of the device without significantly impacting its retail cost. Attempts are being made to devise a realistic method by which the failure rate of a given smoke detector design can be predicted mathematically. While this project is still in its initial stages, we hope to have some answers to this question by the end of 1978. Figure 4 shows a general curve of the variation of failure rate with time, valid for most electronic products [4]. Our goal is to have point A when the unit leaves the factory and point B at 25 to 30 years after sale.

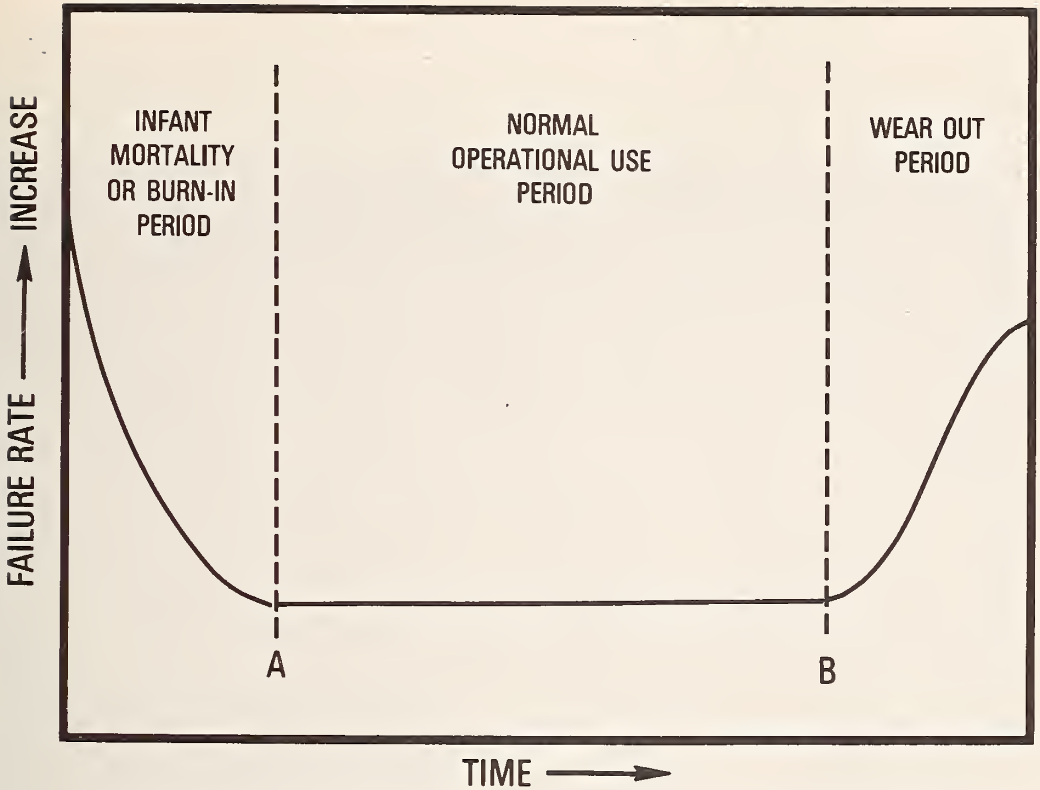

Figure 4. Typical variation of failure rate with time [4].

3. PHILOSOPHY OF APPROVAL STANDARDS

As was mentioned earlier, the product approval standards for residential smoke detectors are becoming increasingly important due to the large numbers of units and designs available. In the past, the philosophy of the U.S. approval standards has been essentially to try to duplicate the conditions of a few specific fires to which the detector might be exposed. While this philosophy has worked fairly well in the past, we feel that the philosophy used by the European approval standards would be better. This philosophy is not to duplicate a few specific fires at random but to design tests which exaggerate the differences between the units tested and which expose the detector to a bracketing range of conditions that might be expected but not necessarily any specific "real life" fire type. With regard to the detection performance testing of smoke detectors, for example, one would design a set of full-scale tests which expose the detector to a range of particle sizes, number concentrations, and refractive indices so that the reaction of the device to any particular combination of these variables within the extremes tested could be estimated.

4. REFERENCE INSTRUMENTATION

Both the increasing popularity of the use of smoke detectors and the increasing desire for additional knowledge about their performance has resulted in a large amount of testing being conducted by various organizations. More and more data are being generated which can be highly useful in expanding our knowledge of the subject. But, the increase in the numbers of people conducting tests has demonstrated the problems in comparability of the data obtained from different sources.

Basically, the comparability problems arise from the large variety of instrumentation being used to take smoke measurements in the tests. For example, the lamp color temperature and receiver spectral sensitivity of most photometers is not consistent or even specified. Therefore, we have developed a specification for a reference photometer (figure 5) which we are proposing as one such instrument. This photometer consists of a tungsten filament light source (figure 6) of a specified color temperature transmitting a collimated beam of light through a one-meter path length to a receiving element (figure 7) with a spectral response matching that of the human eye. By using the human eye response we hope not only to have a reference instrument by which to relate smoke detector response but also to be able to take measurements which relate to human visibility through smoke. While these measurements would not take into account the irritability of the smoke, we feel that the measurements will be meaningful in estimating the amount of time available to people in a fire area for escape or rescue.

In addition to the reference photometer, we are evaluating a reference measuring ionization chamber developed by a Swiss firm (figure 8). Since the photometer is not responsive to particles smaller than about 0.3 micrometers in diameter, the photometer will not correlate well with the output signal from an ionization chamber. Thus, where such correlations are necessary, some type of reference ionization chamber is necessary. This Swiss design is being evaluated by us and others in this country and in Europe and it appears to be the best design thus far proposed.

Another instrumentation problem that we are working on is that of reference test aerosols. Many people in fire research agree that the combustion generated aerosols now used for small-scale test purposes are too variable. Such parameters as material, density, moisture content, thermal history, ambient conditions, and others, have a great effect on the characteristics of the aerosol generated. Thus we feel that a mechanically generated aerosol is the only practical solution to eliminating or minimizing these variables. To this end, we are developing two types of aerosol generators. One will be a highly precise generator for laboratory use in small-scale test compartments; the other will be a less precise, but easy to use, portable unit for testing installed smoke detectors in the field. The field unit could be used to determine the sensitivity of an installed detector instead of just determining whether or not it is operating as is now done. A description of these aerosol generators is given in sections 11 and 14 of this paper.

5. TECHNICAL DEVELOPMENTS

Many technical developments have been made over the last few years in smoke detector design. Battery operated residential detectors which initially used special batteries which were expensive and hard to obtain are being replaced by designs using common batteries which are more available and inexpensive. Also, new concepts in the circuitry that monitor the battery condition have been made. Several detectors now on the market monitor the battery for both terminal voltage and internal resistance build-up which could prevent the operation of the sounding device in a fire situation.

Detector enclosure and chamber designs are making more use of basic theoretical parameters with great improvements in detection performance being seen. New types of sounding devices are being investigated which have better frequency characteristics for audibility, higher reliability, and lower power consumption.

Ionization detectors are being produced with less radioactive material and a new detector using a beta source is now being marketed for commercial applications. Designs of some newer ionization detectors exhibit increased sensitivity to larger particles. The lack of this capability has been a performance drawback in the past.

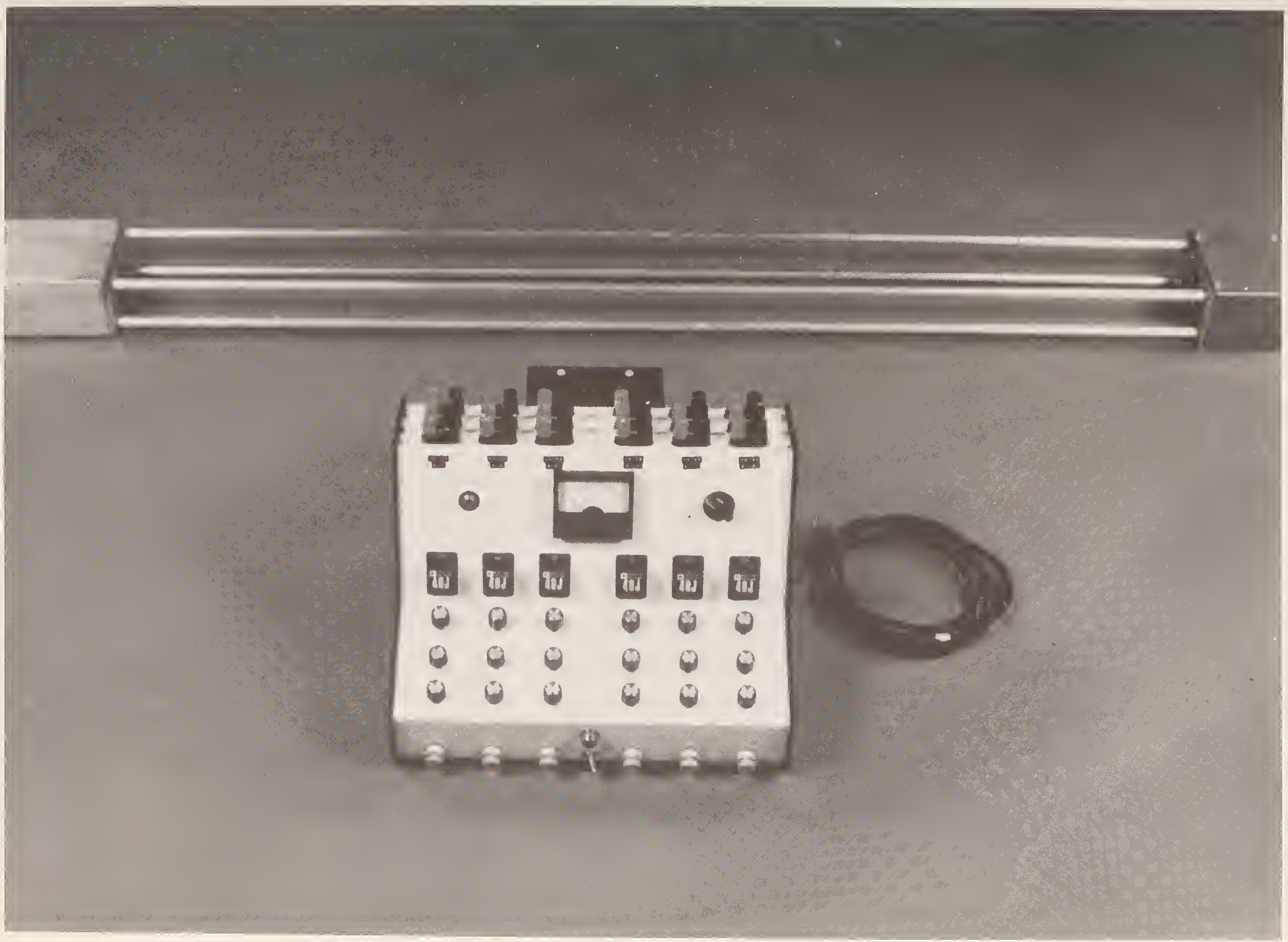

Figure 5. NBS reference photometer.

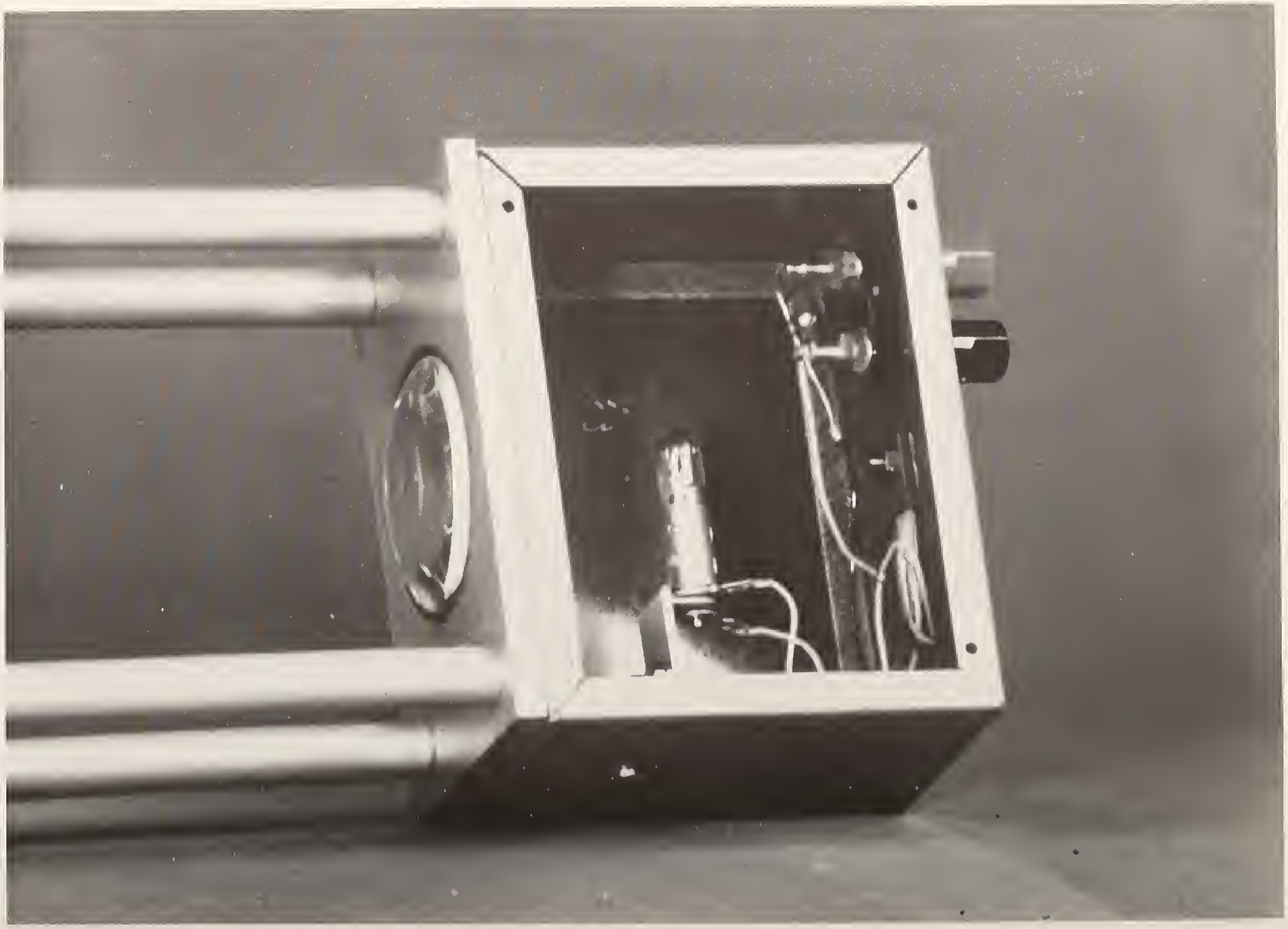

Figure 6. Photometer light source.

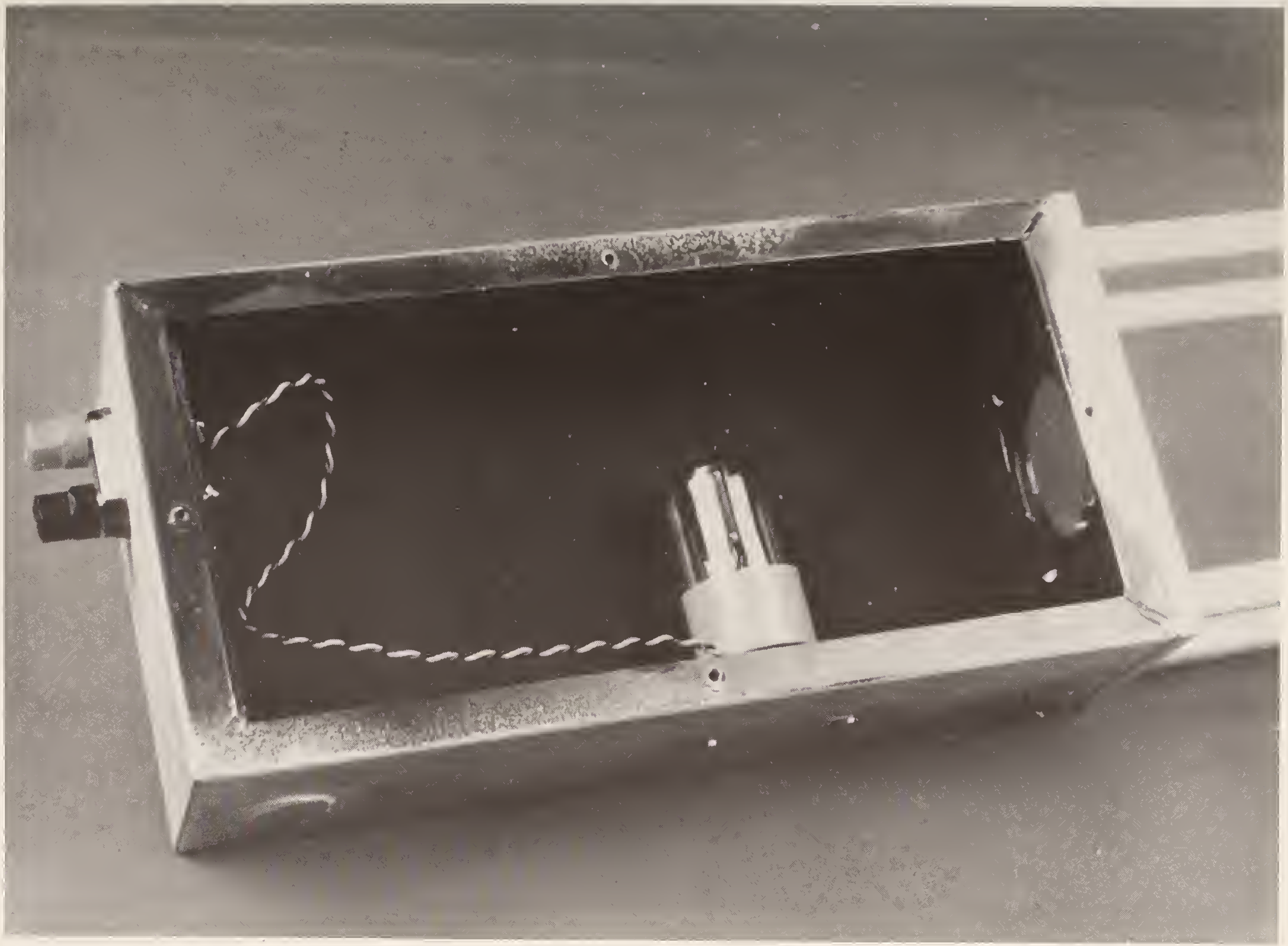

Figure 7. Photometer receiver.

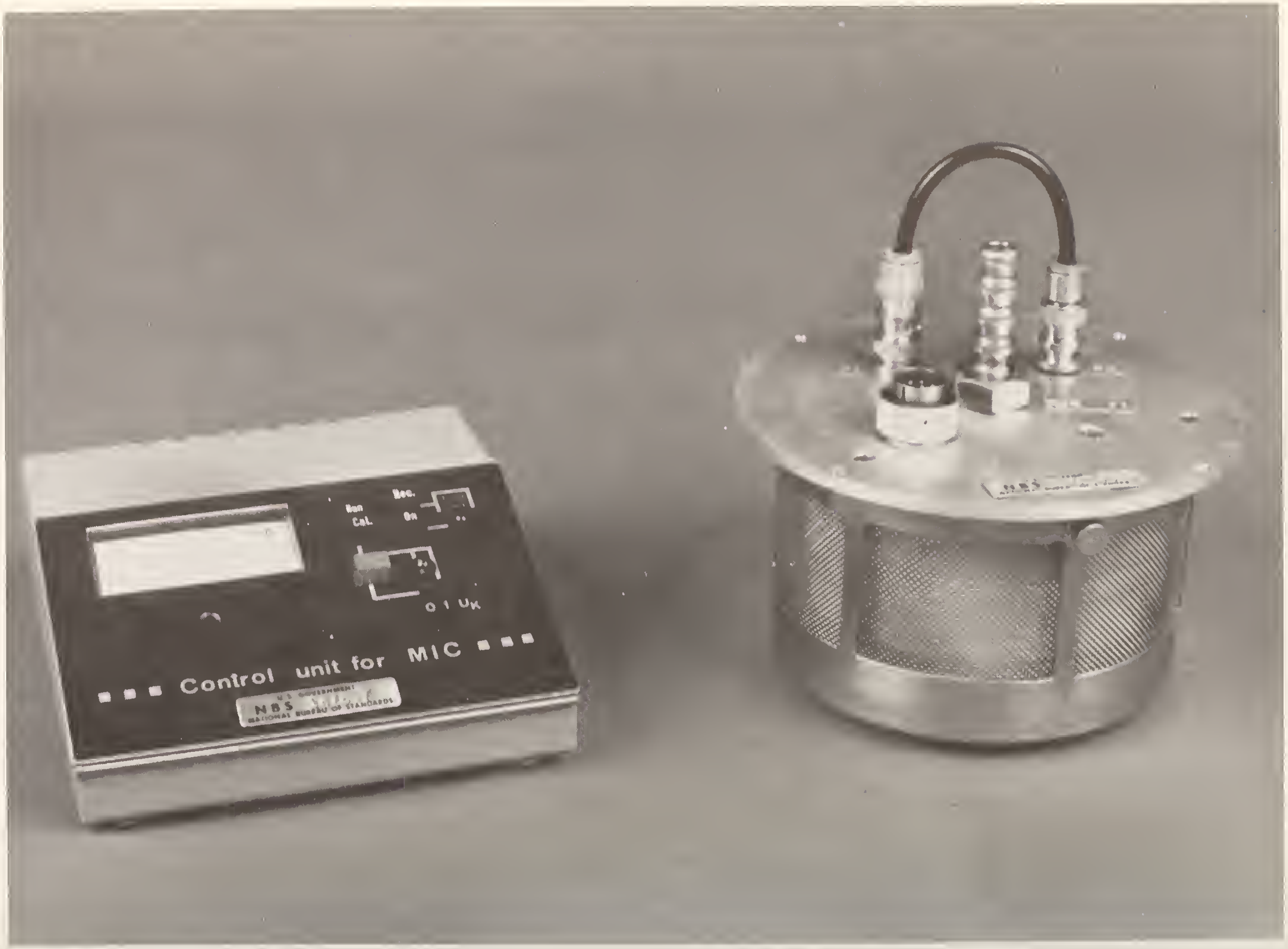

Figure 8. Measuring ionization chamber.

Photoelectric detectors are almost exclusively using long life light-emitting diode (LED) light sources, more efficient scattering angles, and light receivers and circuit designs which minimize time constant problems which had been encountered in earlier LED designs. More photoelectric detectors are using electronic ambient light rejection which eliminates the need for restrictive light-tight chambers which slow their response to fire produced aerosols. Photoelectric detectors in particular are also making better use of mechanical or electrical test features which allow testing of the entire detector circuit (including basic smoke sensitivity) simply by pushing an external button. This has come a long way from the original test buttons which did nothing more than connect the horn to the battery.

6. THEORETICAL WORK

Considerable emphasis in the Center for Fire Research (CFR) has centered on obtaining a better theoretical understanding of aerosol properties and design parameters which can affect the response of smoke detectors. To this end, the following summary of such theoretical considerations has been assembled from open literature reference sources, from results of tests conducted by CFR staff and others, and in some cases from observations by the authors.

7. IONIZATION DETECTORS

The general operation of an ionization chamber can be described in the following way. The chamber consists of a source of ionizing radiation positioned between two electrodes across which an electric potential is maintained (figure 9). The radiation source emits alpha particles (helium nuclei) or beta particles (electrons) at relatively high energies (e.g. 5.48 Mev for americium 241 alpha particles), creating positive ions by removing electrons from gas molecules along their path. The low energy electron released rapidly attaches to a neutral gas molecule which becomes a negative ion.

These ions are then drawn to the electrodes (positive ions to the negative electrodes and vice versa) where they give up their charge. This charge transfer represents a small ($\sim 10^{-11}$ A) current flow through the air space between the electrodes.

There are two ways in which an ion can be prevented from reaching the electrode and give up its charge. These are by recombination (random collision with an oppositely charged ion) or by being carried out of the chamber by convective airflow before reaching the electrode.

Some amount of recombination takes place in most ion chambers but is self-limiting. That is, the recombination rate is related to the ion density; the greater the density the greater the chance of a random collision. Thus, any chamber will have an equilibrium condition where the recombination rate and ion density will be constant.

Normally, the ion velocities are high enough and the convective flow rate low enough so that most ions reach the electrodes. When smoke particles enter the chamber, these particles capture ions, reducing their velocity by several orders of magnitude due to the increased mass of the particle-ion pair (figure 10). This reduced velocity allows the pair to be carried from the chamber before reaching the electrode, reducing the charge transfer and thereby the chamber current. It is this reduction in current which is used to trigger the alarm.

An alpha particle leaving the surface of americium 241 (Am) will create an equal number of positive and negative ions for a distance of about 4 cm (the mean range of an alpha particle of this energy in air at STP) [5]. If the electrode spacing in the chamber is 4 cm or less, a bipolar chamber results

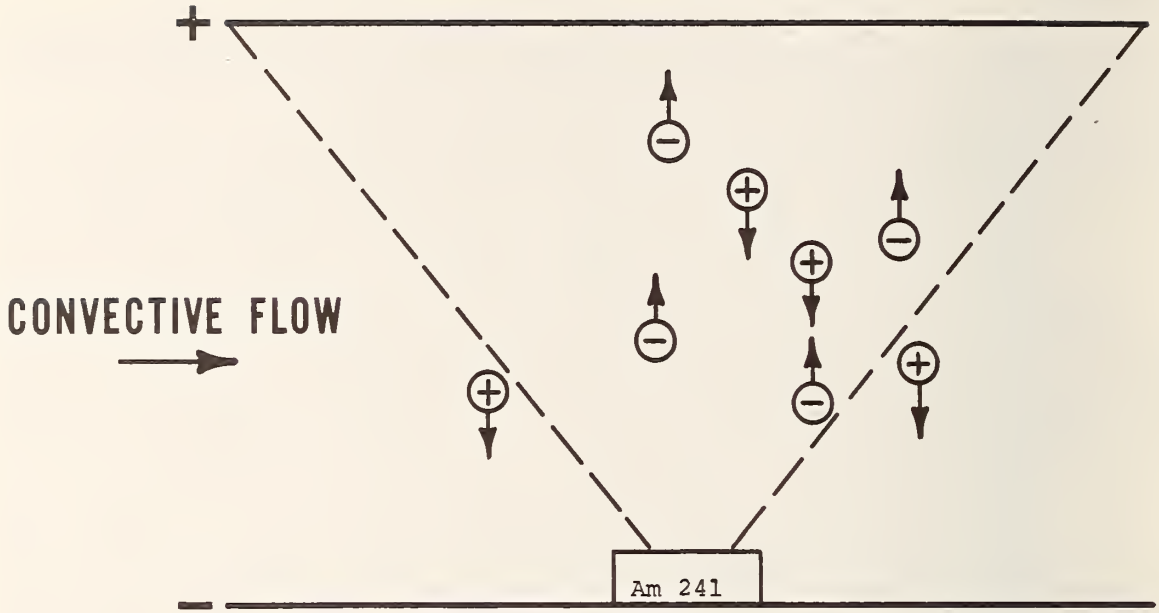

Figure 9. Ionization chamber operation - no smoke.

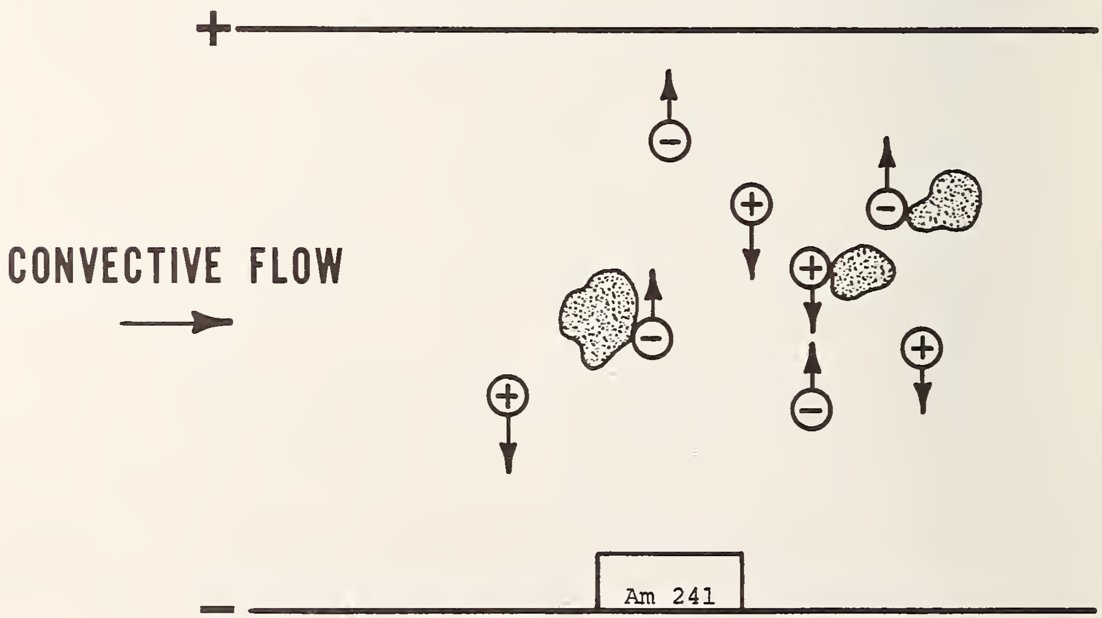

Figure 10. Ionization chamber operation - with smoke.

(figure 11). That is, ions of both polarities exist in the entire chamber. If, however, the electrode spacing is greater than 4 cm, a unipolar chamber is created (figure 12). The unipolar chamber has one region where both ion polarities are present (in this case in the first 4 cm from the source) and a region where ions of only one polarity are present. These two regions are separated by a space charge region which acts to stabilize the ion concentration in the unipolar region.

Another way of producing a unipolar chamber is to reduce the travel distance of the alpha particles to less than 4 cm by increasing the thickness of the outer gold plating on the americium. A gold thickness of 6.6 μm will reduce the alpha particles range to 0.45 cm in air [5].

7.1 Particle Size

Hosemann [6] derived a semi-empirical equation for the relative chamber signal of a bipolar ionization chamber. Scheidweiler [7] expressed this equation as follows:

$$S = \frac{Nd_p}{2\eta} + 1 - \sqrt{\left(\frac{Nd_p}{2\eta}\right)^2 + 1} \qquad (1)$$

and $$\eta = \frac{3\sqrt{\alpha q}}{C} = \text{chamber constant} \qquad (2)$$

where S = relative chamber signal = $\frac{\Delta I}{I_o}$

N = number of particles of size d_p

d_p = particle diameter

α = recombination coefficient

q = ion generation rate

C = Bricard capture coefficient

Litton has developed a detailed mathematical model for an ionization chamber [8] and finds that Hosemann's semi-empirical equation agrees within a few percent with his model results for all values of the quantity Nd_p/η. For low concentrations of a smoke aerosol equation (1) reduces to:

$$S \propto Nd_p \qquad (3)$$

That is, the output signal is proportional to the number of particles times the particle diameter. In this relation, the proportionality constant is a function of the chamber design parameters and would thus be slightly different for different chamber designs.

Equations (1) and (3) are for monodisperse aerosols. For polydisperse aerosols, equation (3) is simply summed over the particle size distribution as follows:

$$S \propto \sum_i N_i d_{p_i} \qquad (4)$$

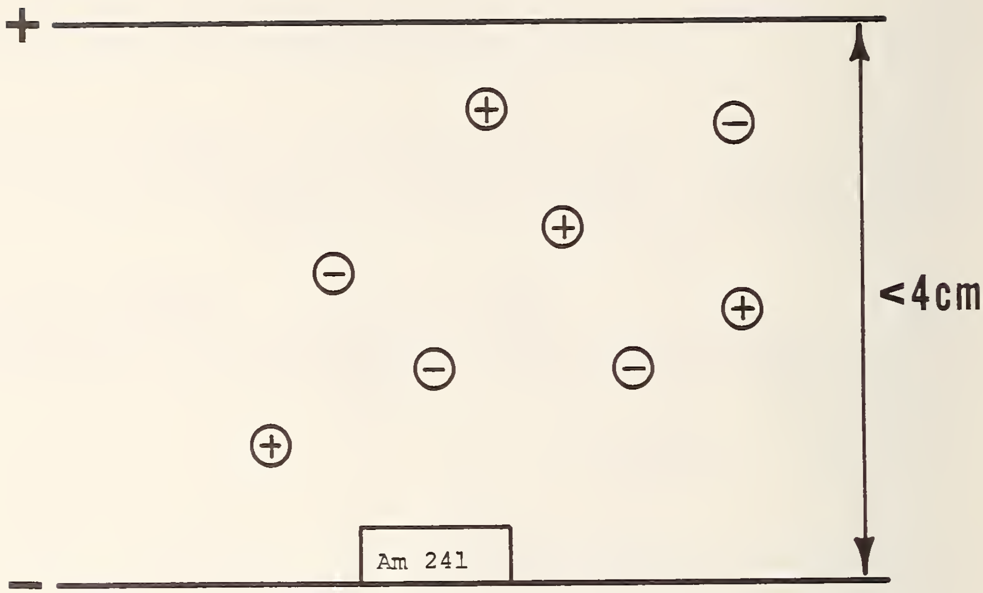

Figure 11. Bipolar ionization chamber.

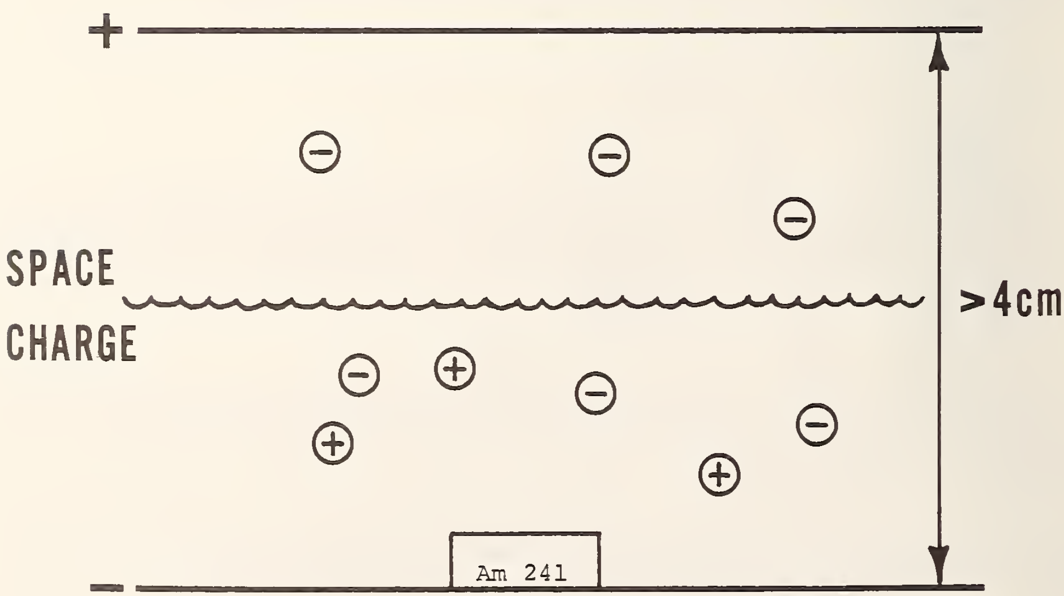

Figure 12. Unipolar ionization chamber.

When using this general relation, one must keep in mind that an aerosol particle size distribution is dynamic, varying with time and distance from the generation source. The particle diameter will tend to increase due to coagulation effects which are related principally to time and concentration. Also, particularly in combustion aerosols, the particle size distribution being generated can change as a function of temperature of combustion, material and its density, moisture content, and other factors.

When one looks at coagulation of liquid aerosol droplets or aerosols composed of solid nuclei with condensed liquid exteriors it can be seen that the number concentration for a fixed mass concentration is inversely proportional to the diameter cubed. Thus, if the aerosol diameter doubles, the number concentration would be reduced by 1/8 so that the overall effect would be the reduction of the relative chamber signal by a factor of 4. The effect of coagulation will be discussed in more detail in section 13.

7.2 High Air Velocities

Since the basic principle of operation of the ionization detector involves a small flow of current created by the transfer of charge across the chamber, any factor which interferes with this charge transfer will affect the chamber current and therefore the response. The effect of high air velocities is to blow the charged ions from the chamber before they can reach the electrodes and give up their charge. Since, under these conditions the charge transfer would be reduced, the chamber current would also be reduced, moving it toward alarm. This would have the effect of enhancing the sensitivity but can also cause a false alarm if the velocity is sufficient to remove enough ions. In his convective model, Litton [8] derived the following relation for the limits of convective flow in the chamber:

$$\left| Z_p \vec{E} \right| < \vec{V}_C < \left| \mu \vec{E} \right| \tag{5}$$

where Z_p = mobility of charged smoke particle

$\vec{E}$ = average electric field

$\vec{V}_C$ = convective velocity in the chamber

μ = mobility of an ion.

Design factors which can compensate for this effect would be velocity shielding by mechanical means, increasing the ionic velocity (and therefore, the ionic momentum) through the use of higher electrode collection potentials or the use of the unipolar type chamber design. Since the unipolar chamber contains a space charge region, this region tends to act as a buffer, releasing more ions into the unipolar region when the ion concentration falls below equilibrium. This essentially stabilizes the chamber performance over a much broader range of air velocities than with a bipolar chamber design. A comparison of the change in chamber current with increasing air velocity was given by Scheidweiler [7] and is shown in figure 13.

7.3 Low Air Velocities

Equation 5 also shows that the effects of low air velocities are almost a converse of the high velocity effects. That is, low velocities can allow charged smoke particles to reach the electrodes and discharge before the convective flow through the chamber can move them out of the chamber. This

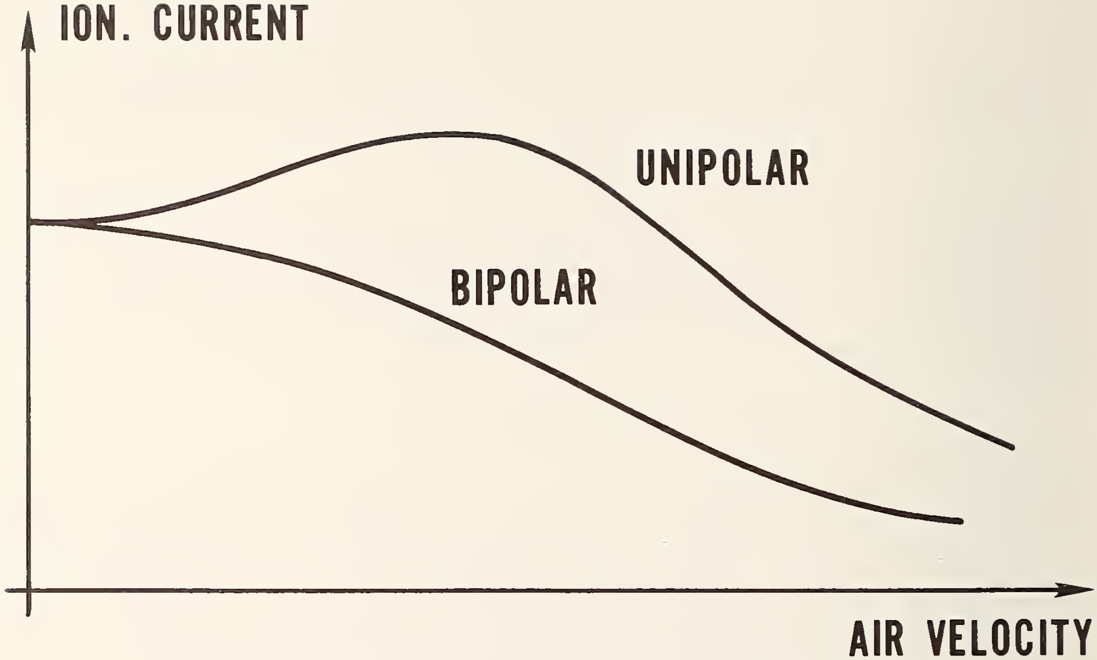

Figure 13. Influence of wind on a unipolar and a bipolar ionization chamber.

condition can result in an increase in chamber current and a corresponding loss of sensitivity. This effect may be a partial explanation (along with increased particle diameters and decreased number concentrations) of the apparent loss in sensitivity of ionization detectors to smoldering fires.

7.4 Chamber Design

7.4.1 Source Strength

The chamber constant (eq. 2) is a function of the volumetric ion generation rate, q (which is established by the source strength), the recombination coefficient, α, and Bricard's capture coefficient, C. The ion generation rate (q) is the only parameter which is affected by the detector design, the other parameters (α and C) being determined by the properties of the aerosol and ions.

From equations (1) and (2) in the limit of low particle concentrations it is seen that the detector sensitivity is inversely proportional to the square root of the ion generation rate and thus the source strength. In practice the advantage of the increased sensitivity with decreased source strength must be balanced against the reduction in the signal to noise ratio as the source strength is reduced. This effect can be seen in the new β source detectors which operate at very low source strength and chamber currents (several orders of magnitude below typical α source detectors). The β detector will detect the extremely small particulates from burning alcohol to which most α detectors will not respond. The β detector, however, has had to incorporate extensive RF shielding and, in addition to the normal sensing and reference chambers a third (balance) chamber is used to obtain acceptable stability.

7.4.2 Electrode Spacing

If the chamber electrodes are closer than the alpha particle path length, the alpha particles will not produce the maximum number of ion pairs possible.

If the electrode spacing is greater than the alpha particle path length, a unipolar chamber results. When determining proper electrode spacing, one must keep in mind that the thickness of gold outer foil plating of the ionization source greatly affects the alpha particle path length. As was explained earlier, an unplated source will have an alpha particle path length of 4.04 cm in air (at STP). Addition of a 6.6 μm thickness gold foil reduces the alpha particle path length to 0.45 cm. From this it can be seen that the plating thickness is extremely critical and that very small nonuniformities in the plating thickness can have great effects on the uniformity of chamber ionization.

Simon and Axmark [9] investigated the effect of electrode spacing on the ion chamber response both experimentally and theoretically for a parallel plate electrode design. The detector sensitivity, $\Delta I/I_o$, was measured as a function of electrode spacing, D, for a fixed value of the ratio of potential difference ϕ, to electrode spacing, ϕ/D = constant. As the plate separation was increased from 3 cm to 5 cm, the sensitivity increased by approximately 100%. For this experiment the range of the α particle was 3 cm so in one case the chamber is bipolar while in the other, there is a unipolar region in the chamber. The model calculation, which includes the effect of space charge in the field equation, was found to agree with the experimental results.

7.4.3 Electrode Bias Voltage

As shown in equation (5), if the bias voltage on the chamber electrodes is low, the ion velocity is low and there is more chance of recombination with opposite ions before the electrode is reached. Also due to lower ion momentum, the velocity at which captured ions can be blown from the chamber is reduced.

If the electrode bias voltage is high, there is less chance of recombination and less chance that captured ions can be blown from the chamber; but the radioactive source strength must be increased to maintain proper ion densities. This can be a problem in countries where maximum source strength specifications are set by law.

In the first case, the effect is an ion chamber inordinately sensitive to air movement. In the second case, the effect is to reduce the sensitivity of the chamber (unless the source strength is increased).

Litton [5] has studied the effect of the electrode bias voltage on the chamber performance. He finds that equation (2) is valid provided the chamber current is low compared to the saturation current ($I/I_s < 0.4$). As the current increases above this ratio, the chamber response depends on the electrode bias voltage as well as the source strength. For a given source strength and electrode geometry Litton found that there exists an optimum bias voltage for which the current difference is a maximum. He also found that an increase in the source strength S_α will shift the electrode bias ϕ_m at which ΔI is a maximum approximately as the square root of S_α.

7.4.4 Outer Shell Design

The design of the outer chamber shell relates to the high and low aerosol velocity effects. If the shell is too open, the higher aerosol velocity problem is enhanced and if too restricted, the low air velocity problem is enhanced or the aerosol stream may take the path of least resistance and by-pass the chamber completely.

7.5 Detector Enclosure Design

The outer enclosure of the detector can also be critical. If too open, the unit may be susceptible to false alarm at high airflows and if too restricted, the unit may alarm slowly due to delayed smoke entry. This effect was demonstrated in an experiment conducted by NBS a few years ago. Two detectors (A and B), identical except for their enclosures, were tested for sensitivity to smoke at varying air velocities. One unit (A) would not alarm for any smoke concentration at a flow of 0.076 m/s (15 fpm), while the other (B) showed only a small decrease in alarm point at this velocity. Conversely, one unit (B) would give a false alarm at a flow of only 1.5 m/s (300 fpm) while the other (A) was stable to much higher velocities.

In addition to velocity effects, the following factors should also be taken into account in a proper enclosure design.

1. The electric fields generated in the peripheral detector circuitry can affect the chamber operation.

2. Current leakage paths on high impedence components or on insulators in the sensing chamber can cause false alarms or non-operation.

3. Adhesion of charged aerosol particles to external plastic parts that have acquired a static charge can reduce the number of the small particles reaching the sensing chamber.

8. PHOTOELECTRIC DETECTORS

Most photoelectric detectors in common use operate on the light-scattering principle. The sensing chamber contains a source of light and a light receiver at some angle to the light beam arranged so that the receiver does not normally receive any of the transmitted light (see figure 14). When smoke particles enter the scattering volume (the volume of space which intersects both the light beam and viewing region of the receiver), light is scattered onto the receiver. This increase in luminous flux on the receiver is proportional to the concentration of smoke particles and is used to trigger the alarm.

Early light-scattering detectors used short lived incandescent lamps (1-5 year average life) and photoresistive receivers. Newer designs use light-emitting diodes as the light source (30 year or more life) and silicon receivers (photodiodes, phototransistors, and silicon cells). Newer designs have also eliminated the need for a darkened sensing chamber (to eliminate effects of ambient light) by using pulsed LED's and electronic circuits which reject the ambient signal. Elimination of this chamber has greatly improved the performance by allowing much freer entry of smoke to the sensing optics.

8.1 Particle Size

The output signal from a scattering type detector optical assembly is affected by particle diameter, complex refractive index, scattering angle, scattering volume, light wavelength, and particle shape. In general, the basic theory of light scattering is only well defined for spherical particles. Some limited calculations are available for a few other shapes such as cylinders and ellipsoids.

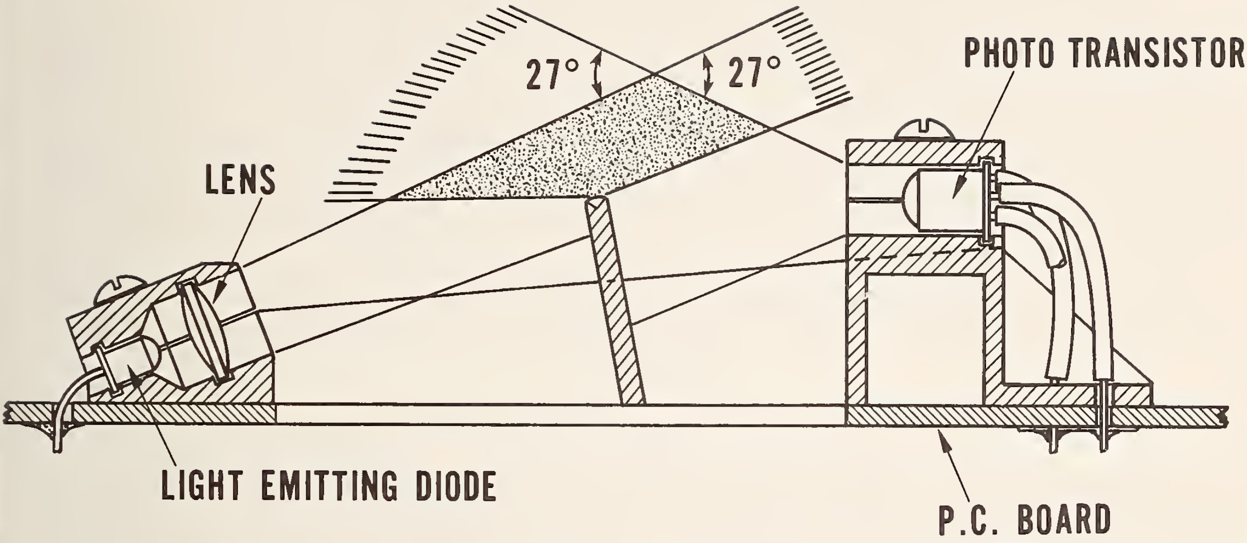

Figure 14. Light-scattering detector optics.

The effect of particle size falls into three regions defined essentially by the ratio of particle size to light wavelength [10]. These three regions are given below:

Rayleigh Region $d_p < 0.1$

Mie Region $0.1\lambda < d_p < 4\lambda^*$

Bricard Region $d_p > 4\lambda^*$

* Limit varies with refractive index.

In the Rayleigh scattering region, the output signal is essentially proportional to the 6th power of the particle diameter.

The upper limit of the Mie region is not clearly defined as it varies as a function of particle refractive index. At the Mie-Rayleigh boundary, the chamber output signal is proportional to the particle diameter to the 6th power and can oscillate in a damped sinusoidal manner until at the Mie-Bricard boundary it is proportional to d_p squared. The frequency of oscillation is a function of the refractive index of the particle.

For particles larger than about 4λ the theories of geometric optics (Bricard, Fraunhoffer diffraction) predominate. In this region the signal is essentially proportional to the particle diameter squared.

8.2 Scattering Angle

The angular intensity distribution of light scattered by particles varies with particle size (d_p), shape, and refractive index (M). An example of such an angular distribution is given in figure 15 [10]. This is for Mie scattering (particle diameter greater than one tenth of the wavelength) for a narrow band polydisperse aerosol with M = 1.33 (water vapor). While the distribution will vary with the above mentioned parameters for other size ranges, the same general characteristics are observed. That is, the greatest intensity is in the forward direction, decreasing to a minimum around 90°-100° and increasing again to a final value less than the initial value in the back scatter area. Only in the case of perfectly reflecting spheres is back scatter intensity greater than forward scatter.

From this characteristic one can deduce that a small, forward angle exhibits the best signal levels for most aerosols while angles around 90° would generally give the lowest signal levels.

8.3 Particle Shape

The effects of complex aerosol shapes are largely unknown. One can empirically determine the effective scattering cross section of a complex shaped particle but this parameter can change continuously as the particle tumbles randomly in an aerosol stream. If the aerosol concentration is high enough, it is valid in many cases to assume a random distribution of particle orientations.

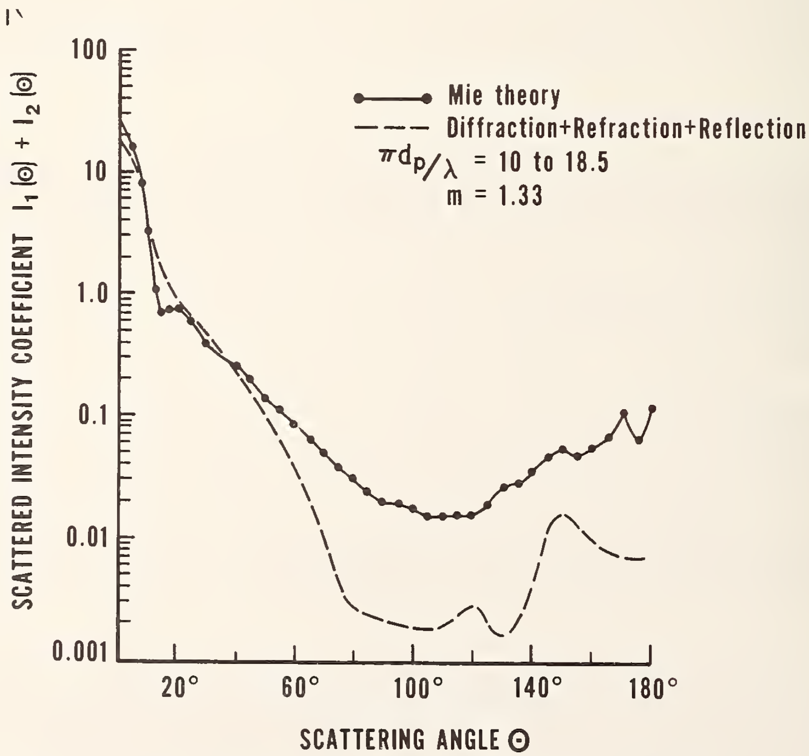

Figure 15. Mie scattering by polydisperse spheres, refractive index 1.33, compared with diffraction, refraction and reflection.

8.4 Refractive Index

Particle refractive index is a complex variable of the form:

$$M = M_o (1 - iK) \quad (6)$$

where M_o is the real part of refractive index

K is the absorption coefficient.

One should note that absorption is the imaginary portion of the term and the particle refractive index is only real where absorption is 0.

8.5 Wavelength

The principle effect of wavelength is to define the boundaries of the three scattering regions. Since the signal produced by an aerosol is strongest in the Mie and Bricard regions, wavelengths should be as short as possible so that a majority of the aerosol sizes to be measured are in these regions. This was not as much a problem when incandescent light sources were used since they are polychromatic and produce light over most of the visible spectrum, especially if driven at a relatively high color temperature. With the change to light-emitting diodes, however, red and infrared wavelengths became more common due to decreasing quantum efficiency of LED's at shorter wavelengths [11]. More recently, some improvement in yellow and green LED efficiencies have been made but new combinations of base materials may be necessary before these devices are usable at these shorter wavelengths.

8.6 Design Parameters

8.6.1 Entry

Ease of smoke entry into photoelectric detectors has improved greatly in the last few years. Careful study of low velocity flow dynamics and the more recent elimination of light-tight labyrinths by means of electronic ambient light rejection have been the principle causes of this improvement. It is now possible to actually scatter light from an aerosol outside of the detector enclosure. This obviously eliminates entry completely.

8.6.2 Circuit Time Constants

The change to light-emitting diode sources in photoelectric detectors also created time constant problems. This is because the total luminous flux from light-emitting diodes is only about 10% of that with incandescent sources. Thus, more sensitive photoresistive (Cd S or Cd Se) cells were necessary as light receivers. But the time constant of these photoresistive cells (to a step input) is inversely proportional to its luminous flux sensitivity. At normal LED light levels, time constants on the order of 5 minutes are common.

These time constant problems can and have been eliminated by the use of silicon devices such as photovoltaic cells, photodiodes or phototransistors. These devices, however, require more circuitry since they have no inherent gain and can increase the cost of a detector by as much as 30% over those using the photoresistive receivers. Hopefully, the cost savings associated with the newer large-scale integrated circuits now being designed for photoelectric (and ionization) detectors may offset the additional costs and result in better operating detectors with higher reliability.

9. SMOKE RESEARCH GOALS

Above we have discussed the general behavior of smoke detectors. From this point on we focus on properties of the smoke. In the United States there is interest in smoke properties for several applications in the field of fire protection:

1. Early detection of smoke to alert occupants.

2. The blockage of vision caused by smoke produced by the combustion of building materials.

3. The radiative heat transfer from smoke in the development of a fire up to flashover.

The major emphasis in smoke research at the National Bureau of Standards has been on the first application, which will be the focus of our discussion. The general goal of our research is to provide some of the basic data necessary for the development of improved smoke detectors and improved detector test methods. The first half of our presentation on smoke research will be concerned with the application of recently developed aerosol measurement techniques and aerosol generation methods to the determination of the sensitivity of smoke detectors as a function of particle size. The second half will be concerned with the properties of smoke aerosols used in testing detector performance. These properties will include size distribution, optical density, and the aging of smoke.

10. AEROSOL INSTRUMENTATION

The measurement of the size distribution of smoke aerosols is a difficult experimental problem. Smoke aerosols encompass a broad size range from on the order of 0.005 μm for particulate from a propane torch to as large as 5 μm for well aged smoke generated from a smoldering source such as urethane foam. The three orders of magnitude in this size range are equivalent to the change in size extending from the diameter of a pin to the diameter of a beach ball. The order of magnitude range in particle concentration is even greater. The particle concentration of smoke drawn through a cigarette may be as high as 10^{10} particles/cm^3 while the concentration of an aged smoke may be as low as 10^4 to 10^5 particles/cm^3. In addition to the difficulty of measuring such wide ranges in particle size and concentration, there is also the problem that an aerosol is a dynamic, unstable suspension. As an illustration of the dynamic nature of smoke, the number concentration of smoke will drop by a factor of ten from an initial concentration of 10^8 particles/cm^3 in two minutes as a result of coagulation.

No single instrument is capable of handling the range of concentrations and particle sizes encountered in smoke analysis. We shall describe two instruments that we have found to be quite useful for smoke characterization at low concentrations, 10^3-10^6 particles/cm^3. Special emphasis will be placed on the calibration of these instruments. In our work we find that perhaps half of our time is devoted to instrument calibration. Even with this effort, it was found that a measurement accuracy of ± 30% is about the best that can be obtained.

The principal instrument used in our study is the electrical aerosol analyzer developed by Liu, Whitby, Pui and Clarke [12,13] to measure the size distribution and concentration of aerosols in the size range 0.01 μm to 1 μm. This instrument is similar in principle of operation to the ion mobility counter described by Watanabe at the 1976 UJNR panel meeting. As shown in figure 16 it consists of three major parts: aerosol charger, mobility analyzer, and electrometer current sensor. During a measurement, the aerosol

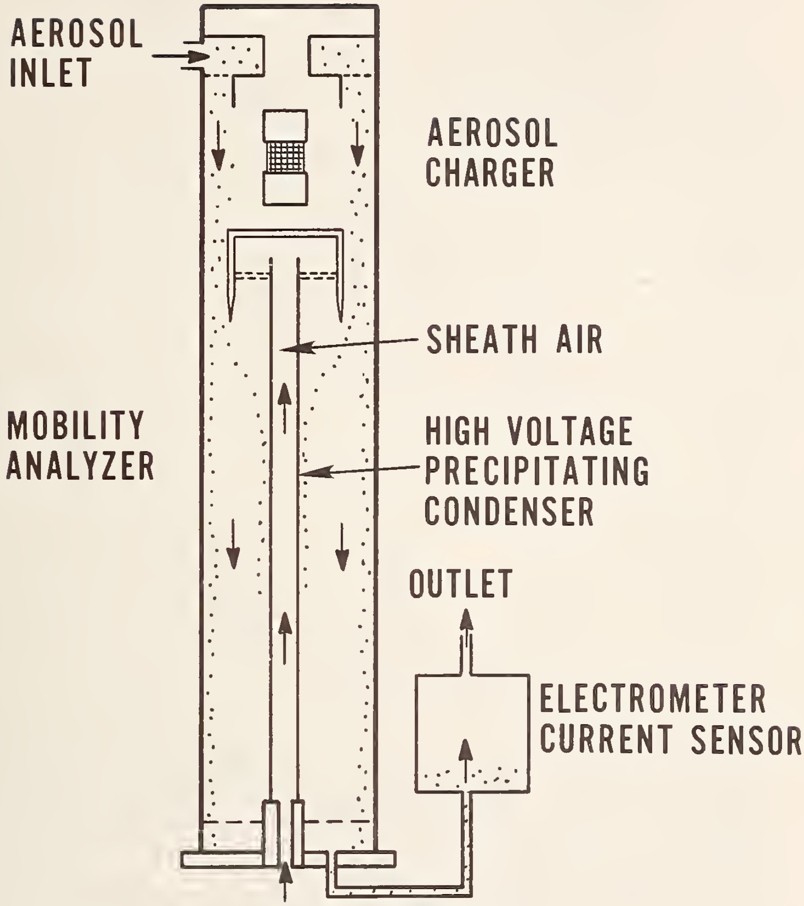

Figure 16. Electric aerosol analyzer.

is first sampled into the aerosol charger to expose the particles to unipolar positive ions produced by a corona discharge. The charged particles then enter a mobility analyzer where they are deflected through a laminar air stream in a cylindrical condenser. For a given voltage on the center rod, particles above a certain critical mobility (smaller than a certain critical size) are precipitated, while those with lower mobility (larger particles) escape and are sensed by the electrometer sensor. By changing the voltage on the center rod and measuring the corresponding electrometer current, the mobility and thus the size distribution of the aerosol can be determined.

A series of experiments was performed at the University of Minnesota and at the National Bureau of Standards [14] to determine the accuracy of the electrical aerosol analyzer (EAA) for the measurements of aerosol number concentration and volume concentration by comparison with a condensation nuclei counter (CNC) and a filter gravimetric method, respectively. A comparison of the total number concentration as determined by the two methods is shown in figure 17 for a polydisperse sucrose aerosol generated by an atomizer. It is seen that there is approximately a linear relationship between the number concentration determined by the two methods over the

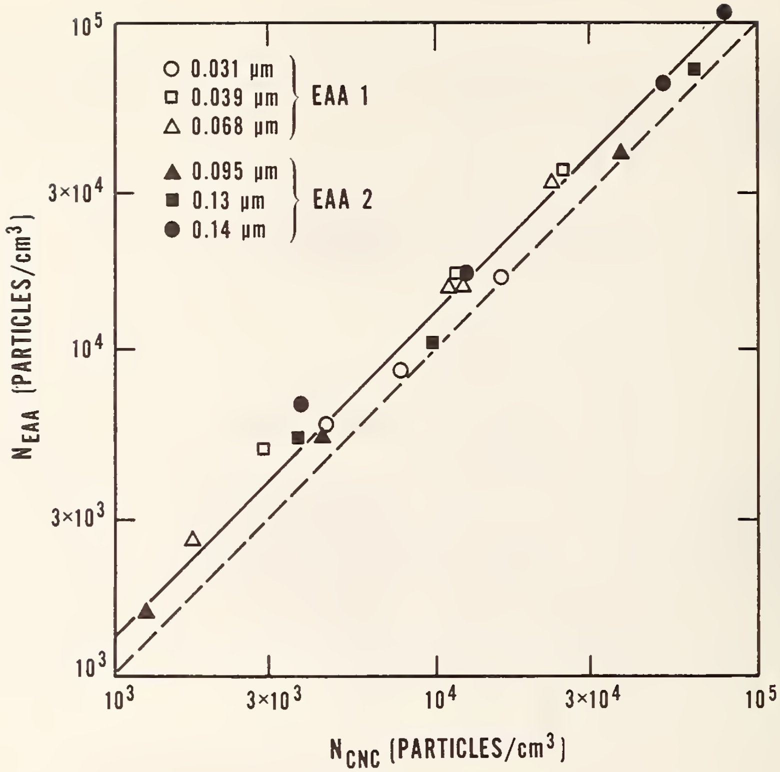

Figure 17. Comparison of the number concentration as determined by the electrical aerosol analyzer and the condensation nuclei counter for sucrose aerosols with various geometric mean number diameters [14]. (Two nominally identical electrical aerosol analyzers (EAA 1 and EAA 2) were used for the measurements. The dashed line corresponds to perfect agreement between the two instruments, while the solid line represents a least square fit of the data.)

concentration range 10^3 to 10^5 particles/cm^3. The data can be conveniently fitted to the following functional form:

$$\text{Log } N_{EAA} = \text{Log (const)} + \text{Log } N_{CNC} \tag{7}$$

From a least square fit of the data to equation (7) it is found that the constant equals 1.3, which means that the EAA overestimates the number concentration by about 30%.

The size dependence of the volume measurement by the electrical aerosol analyzer is presented in figure 18 for dioctyl phthalate aerosols generated by a nebulizer. The most significant feature about the data is the rapid decrease in the ratio V_{EAA}/V_{FILTER} for particle sizes larger than 0.4 μm. There are two likely reasons for this discrepancy. First, particles larger than 1.0 μm will contribute to the aerosol volume collected on the filter, but will not contribute significantly to the aerosol volume measured by the electrical aerosol analyzer. Secondly, the mobility versus particle size characteristic of the aerosol analyzer is rather flat in the 0.4 to 1.0 μm diameter size range, precluding the possibility of making accurate size distribution measurements in this range.

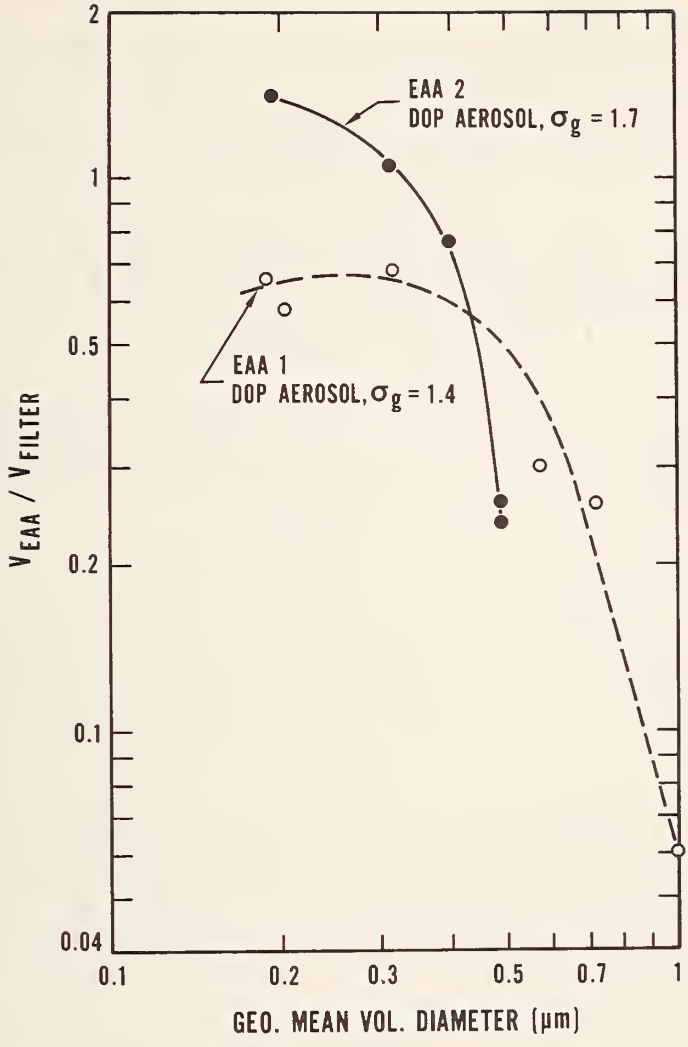

Figure 18. The effect of particle size on the ratio of the aerosol volume as determined by the EAA and filter collection method [14].

Particles with diameters in the size range 0.5 to 5 μm were measured by an optical particle counter that counts individual particles. In this instrument, a beam of light is focused into a small viewing volume through which the airborne particles pass one at a time. The amount of light scattered from each individual particle is measured by a photodiode detector. The detector signals (pulse height), which are related to the size of each particle, are then sorted and stored in channels of the multichannel analyzer of the instrument.

The conventional method of calibrating optical particle counters is with an aerosol formed by nebulizing a suspension of latex spheres of known particle size. This method was used in calibrating the optical particle counter. Later in this paper a new method for calibrating optical particle counters involving the laser doppler shift spectrometer will be described.

11. DETECTOR SENSITIVITY TO MONODISPERSE AEROSOLS

As was mentioned earlier, the particle size is an important parameter in determining the sensitivity of a smoke detector. In order to obtain accurate data on the size sensitivity of ionization and light-scattering type detectors, a joint National Bureau of Standards University of Minnesota study was initiated making use of the excellent capabilities at Minnesota for the measurement and generation of aerosols [15].

A major concern in the selection of an aerosol generation system was that it provide a stable, steady-state output to allow time for the smoke concentration in the detector to reach a steady-state and to allow time for the measurement of the concentration and size distribution of the aerosols. The aerosol generation system that was finally developed for the detector sensitivity measurements is illustrated in figure 19.

An atomizer was used to generate a polydisperse dioctyl phthalate aerosol, which was then made monodisperse by passage through an evaporation - condensation column. Next, the aerosol passes through conditioning equipment which controls the aerosol concentration, humidity, and charge, after which it enters the smoke detector chamber.

The resulting aerosol was quite monodisperse with a geometric standard deviation, σ_g, about 1.25. By varying the concentration of dioctyl phthalate in solution with isopropanol, it was possible to generate monodisperse aerosols over the size range 0.05 μm to 1.3 μm. The concentration range was about two orders of magnitude (2×10^4 to 3×10^6 particles/cm^3) for the generator. The concentration and particle size output of the generator were determined by the electrical aerosol analyzer, the optical counter, and by a filter gravimetric method.

The concentration dependence of the analog detector output is shown in figure 20 for particle sizes ranging from 0.15 μm to 0.57 μm. The detector is a light-scattering type with a nominal scattering angle of 21° and an infrared light-emitting diode with spectral peak around 940 nm. Over the concentration range studied, the analog signal was proportional to particle concentration and the sensitivity increased rapidly with increasing particle size. This detector did not respond to a particle size of 0.10 μm or less at concentrations as high as 3×10^6 particles/cm^3. The alarm voltage labeled in figure 20 corresponds to the detector signal produced by a polydisperse smoke aerosol with an optical density of 0.056 m^{-1} as measured in the Underwriters' Laboratories test chamber, which will be described in the next section. This value corresponds to the maximum threshold standard set by the Underwriters' Laboratories.

The detector sensitivity for the light-scattering type detector (S-2) and for an ionization type detector (R-2) are plotted versus particle size in figure 21. The detector sensitivity is defined as the detector output minus the background reading divided by the particle concentration and is expressed in the units μV-cm^3. The uncertainty in the determination of sensitivity is estimated to be ± 30% and is primarily attributed to the uncertainty in the measurement of the number concentration.

It is of interest to compare the experimental sensitivities with theoretical predictions. For the light-scattering type detector, the sensitivity is found to have approximately a six power dependence on particle size for the smaller sizes. This is in agreement with the theory of Rayleigh scattering, which is valid for particle sizes small compared to the wavelength of light. Qualitative agreement over the entire size range was obtained between the experimental sensitivity and the scattered intensity as calculated by Mie theory [15].

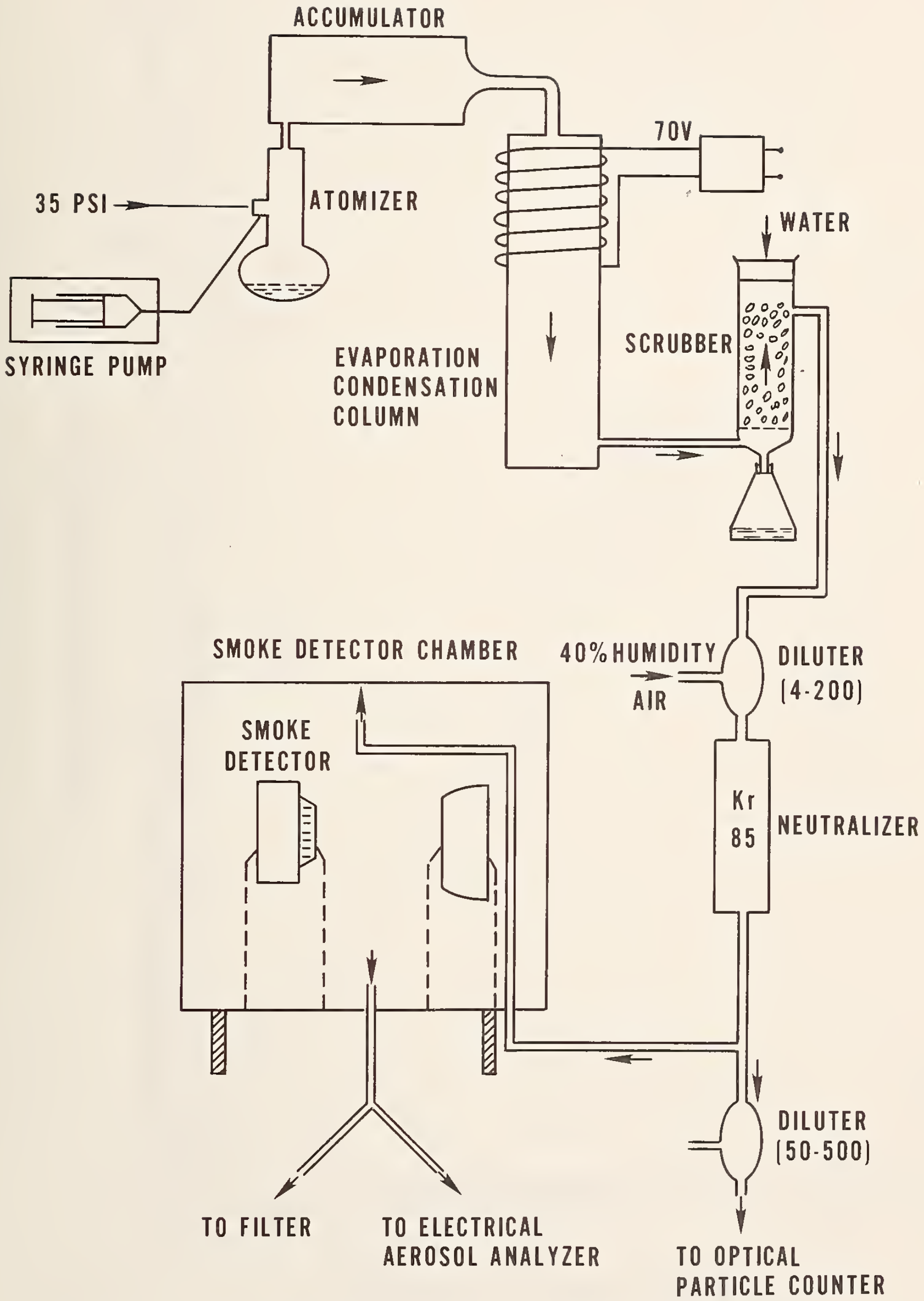

Figure 19. Monodisperse aerosol generation system [15].

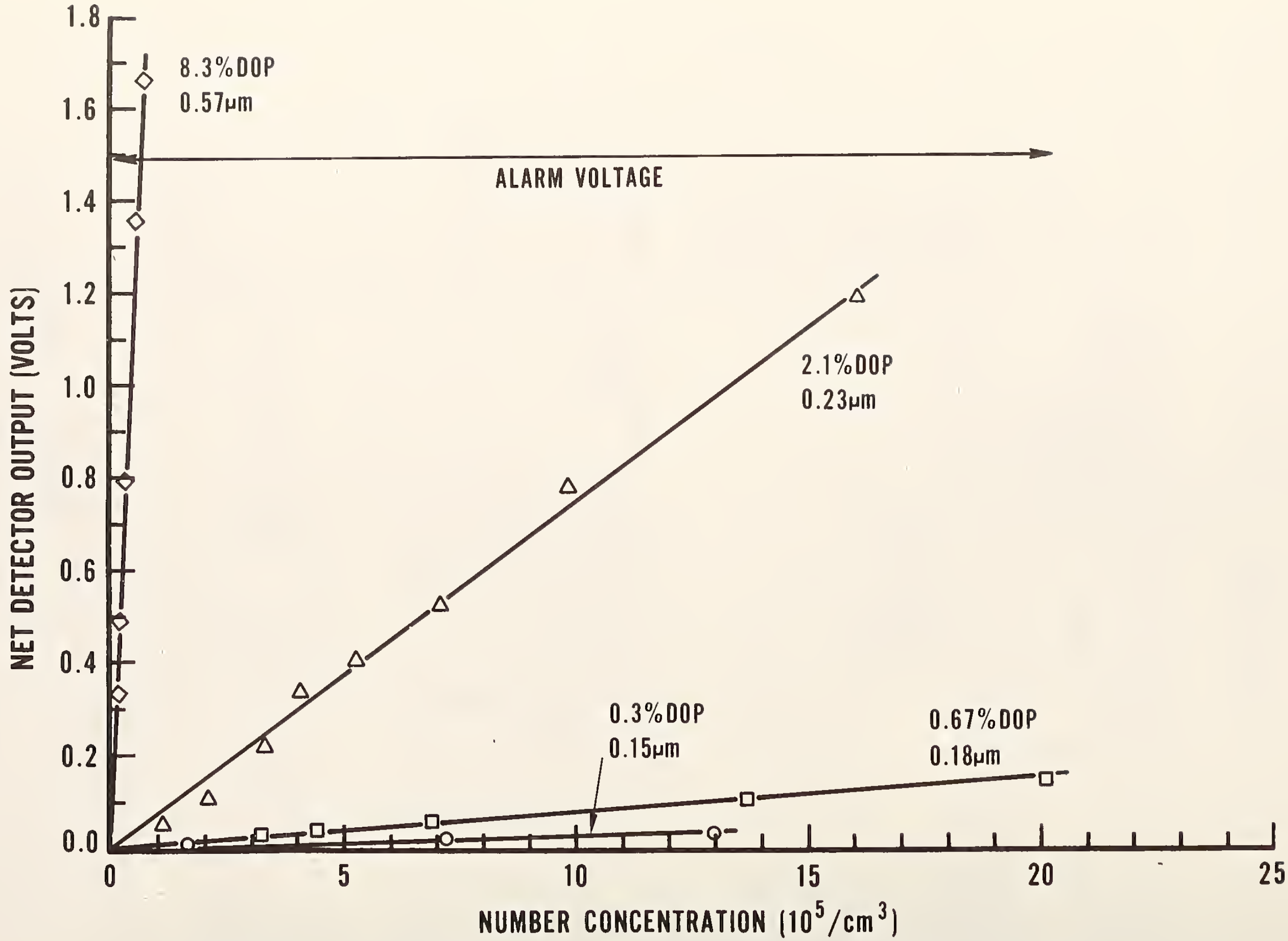

Figure 20. Response of a light-scattering type detector versus number concentration for monodisperse aerosol [15]. (The alarm voltage corresponds to the detector signal when exposed to a polydisperse smoke with an optical density of 0.056 m^{-1}.)

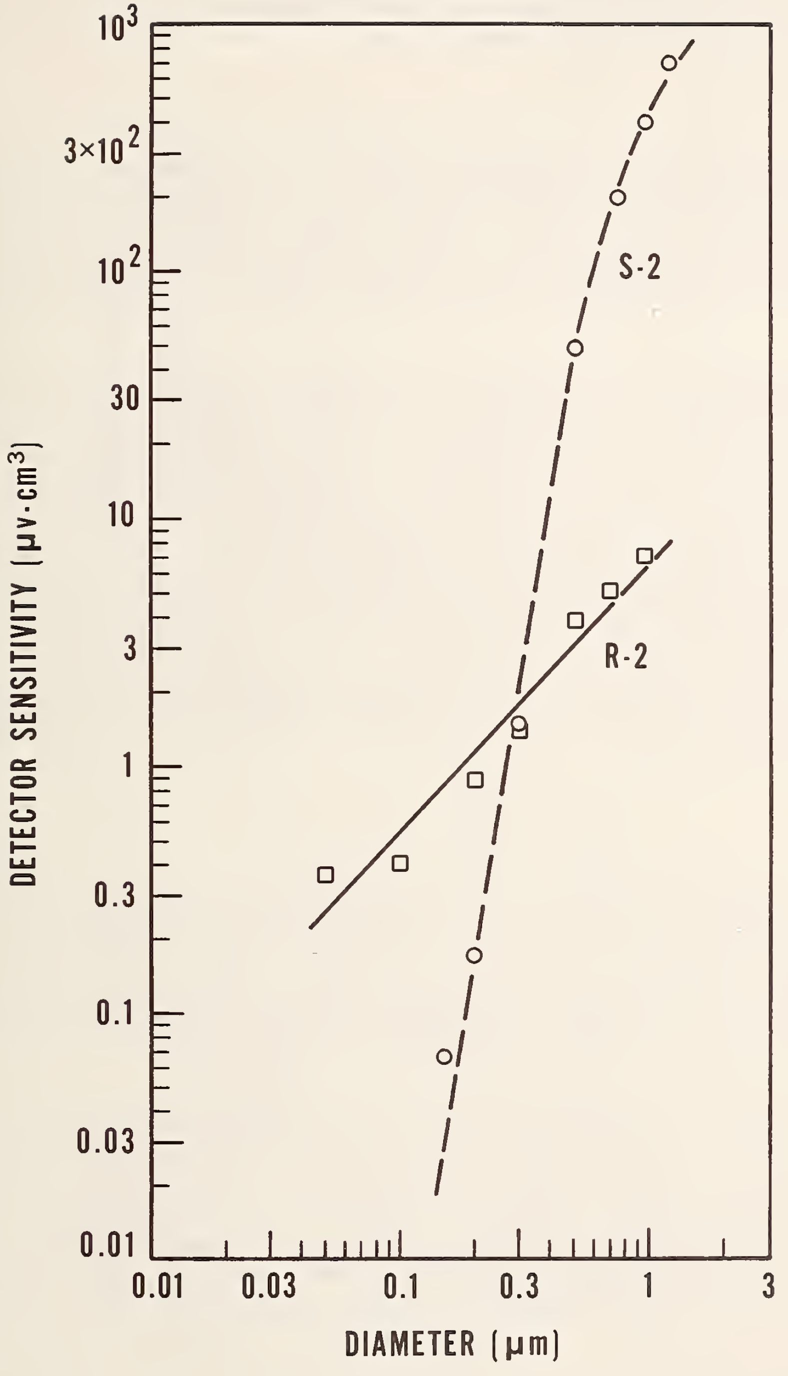

Figure 21. Detector sensitivity versus particle size for a light-scattering type detector (S-2) and for an ionization type detector (R-2) [15].

The ionization detector sensitivity data can be correlated with particle diameter by using a linear fit to a log-log plot as shown in figure 21. This indicates a power law relationship between detector sensitivity and particle size with the empirical relationship being:

$$S = 6.7\,\bar{D}_g^{\,1.1} \tag{8}$$

where S is the sensitivity and $\bar{D}_g$ the geometric mean number diameter. Thus it is seen that the detector sensitivity is nearly a linear function of particle size rather than being linearly related to the surface area of the particle or to the volume of the particle. This result is in qualitative agreement with Hosemann's theory [16], which predicts a linear relationship between sensitivity and particle size for low particle concentrations (see equation (3)).

It is seen in figure 21 that the ionization type detector is the more sensitive for particle sizes smaller than about 0.3 μm, while for larger particle sizes the light-scattering detector is the more sensitive. This difference in sensitivity has important practical implications. There is evidence from work at Georgia Institute of Technology by Bankston et al. [17] that smoke generated in the flaming mode of combustion for Douglas fir, polyvinylchloride, and rigid urethane foam is generally smaller than 0.3 μm while the same materials undergoing combustion or pyrolysis in the non-flaming mode produce particles larger than 0.3 μm. Thus one would expect that the ionization detector would be more sensitive to smoke generated from flaming materials and that the light-scattering detector would be more sensitive to smoke generated by non-flaming materials. This expectation has, in fact, been demonstrated in the testing of smoke detector response to various small-scale fires by Consumer's Union [18] and to large-scale fires by IIT Research Institute and Underwriters' Laboratories under contract to the National Bureau of Standards [19].

12. SMOKE PROPERTIES

In this section we shall concentrate on the properties of those smokes used in smoke detector testing: smokes generated from smoldering lamp wick and punk (imported from the orient as incense sticks) and the black soot smoke generated from the diffusion burning of heptane. The properties of interest will be the number concentration, mass concentration, optical density, and size distribution. The aging properties of smoke will be discussed in the next section. A more extensive discussion of the properties of these smokes can be found in a report by Lee and Mulholland [20].

The measurement of smoke properties was made in the Underwriters' Laboratories (UL 217 standard) smoke detector evaluation chamber which is used for the testing of residential smoke detectors for approval. The detector evaluation chamber is essentially a 50 x 50 x 170 cm closed horizontal box in which the smoke detector is mounted on the center of the top surface as shown in figure 22. The chamber is partitioned into a top and bottom - half sections by a platform extending almost the full length of the chamber. Smoke generated in the lower section is circulated through the box in the direction indicated by the arrows in figure 22. A constant circulation velocity of 0.18 m/s is maintained.

A photometer which measures the optical density of the circulating smoke has a path length of 152 cm and a beam width of 5 cm. It consists of an incandescent lamp (GE-4515) source operating on 2.4 V (2370K ± 50K color temperature) and a photovoltaic cell (Weston 594 RR) detector.

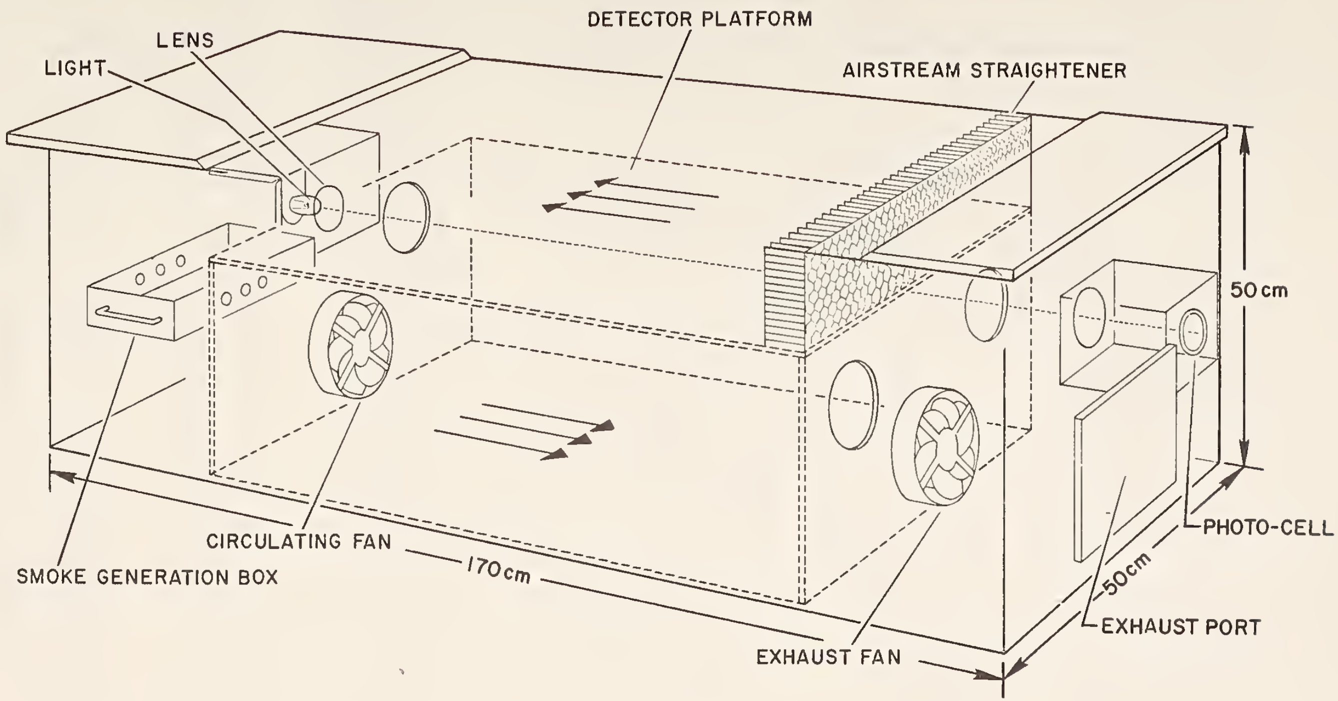

Figure 22. Smoke detector evaluation chamber.

In these measurements, a smoldering lamp wick or a heptane diffusion burner was placed in the burner end of the chamber and was withdrawn when the smoke reached a desired optical density level, ranging from 0.005 m^{-1} to 0.08 m^{-1}. After allowing about thirty seconds to insure uniform mixing, the aerosol was sampled by the analyzers.

The dependence of the optical density on mass concentration is shown in figure 23 for both smokes. The mass concentration for the lamp wick smoke and heptane smoke were determined by using the quartz crystal mass monitor [21] and the filter gravimetric method, respectively. The mass monitor was not effective in measuring the mass concentration of the sooty heptane smoke. The vertical bars in figure 23 represent the shift in optical density during the three- to four-minute sampling period required for collecting sufficient heptane smoke for precise filter weighing. Only a 20-30 second period was required for the mass monitor for the lamp wick smoke. The ratio of optical density per meter to mass concentration, termed the particulate optical density (POD), is an intensive property independent of concentration, at least over a certain range of concentrations. The POD for heptane smoke is 3.4 m^2/g and for cotton lamp wick smoke the value is 1.5 m^2/g. In an extensive paper reported at the Sixteenth Symposium on Combustion [22], Seader reports the dependence of optical density as measured in the NBS-AMINCO smoke density chamber [23] on mass concentration for high concentrations of smoke generated from the following materials for both flaming and non-flaming combustion: rigid polyvinylchloride, red oak, polystyrene, α-cellulose, Douglas fir, rigid urethane, and polyacrylonitrile-butadiene-styrene (ABS). All of the flaming combustion data can be approximately correlated by a linear plot with a POD of 3.3 m^2/g and the non-flaming combustion data, which appears to have somewhat more scatter, can be correlated by a linear plot with a POD of 1.9 x $10^{-3} m^2/g$. Thus, both from our study of low concentration smokes and the work of Seader at high concentrations, the light-obscuring property of many smokes to white light can be placed in two categories depending on the mode of smoke generation - flaming or non-flaming. It should be stressed that the measurements were made under specific flaming conditions and specific non-flaming conditions; for example, the non-flaming combustion data reported by Seader are based on exposing a given size sample to a flux of 2.5 W/cm^2. It is not known whether the POD is independent of changes in exposure conditions such as radiant flux, sample size and ambient temperature.

The size distributions for the lamp wick smoke and the heptane smoke as determined with the electrical aerosol analyzer are presented in figure 24. The quantity ΔN represents the number of smoke particles in the particle diameter size range log D_p to log D_p + Δ log D_p. The Δ presentation was used because data obtained from the measuring instruments were based on the average within each discrete range.

Two convenient parameters for characterizing the size distribution are the geometric mean number diameter, $\bar{D}_g$, as a measure of the average particle size and the geometric standard deviation, σ_g, as a measure of the breadth of the distribution.

$$\log \bar{D}_g = \sum_{i=1}^{n} \frac{\Delta N_i \log D_i}{N} \tag{9}$$

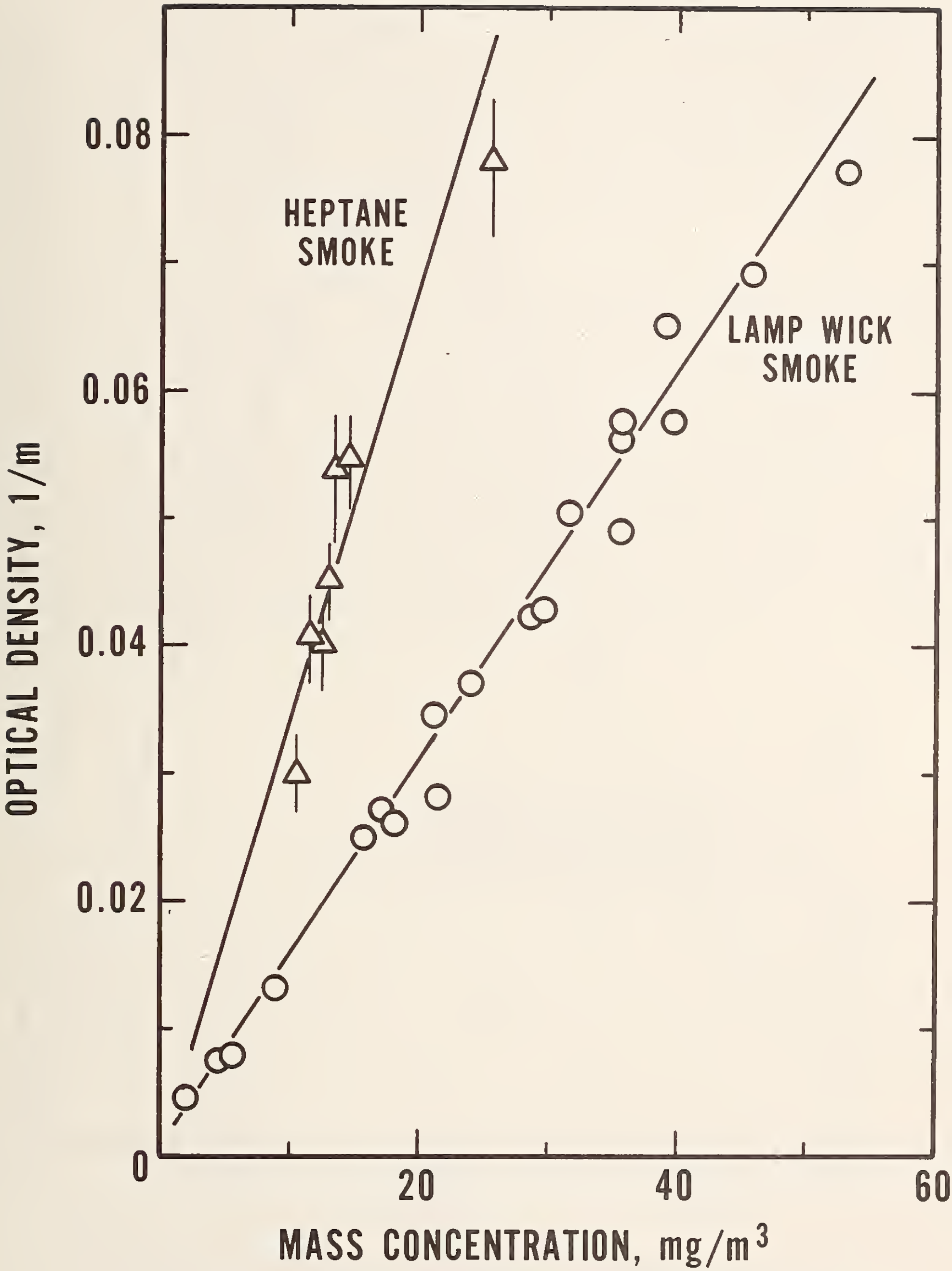

Figure 23. Optical density per meter versus mass concentration for lamp wick smoke and heptane smoke [20].

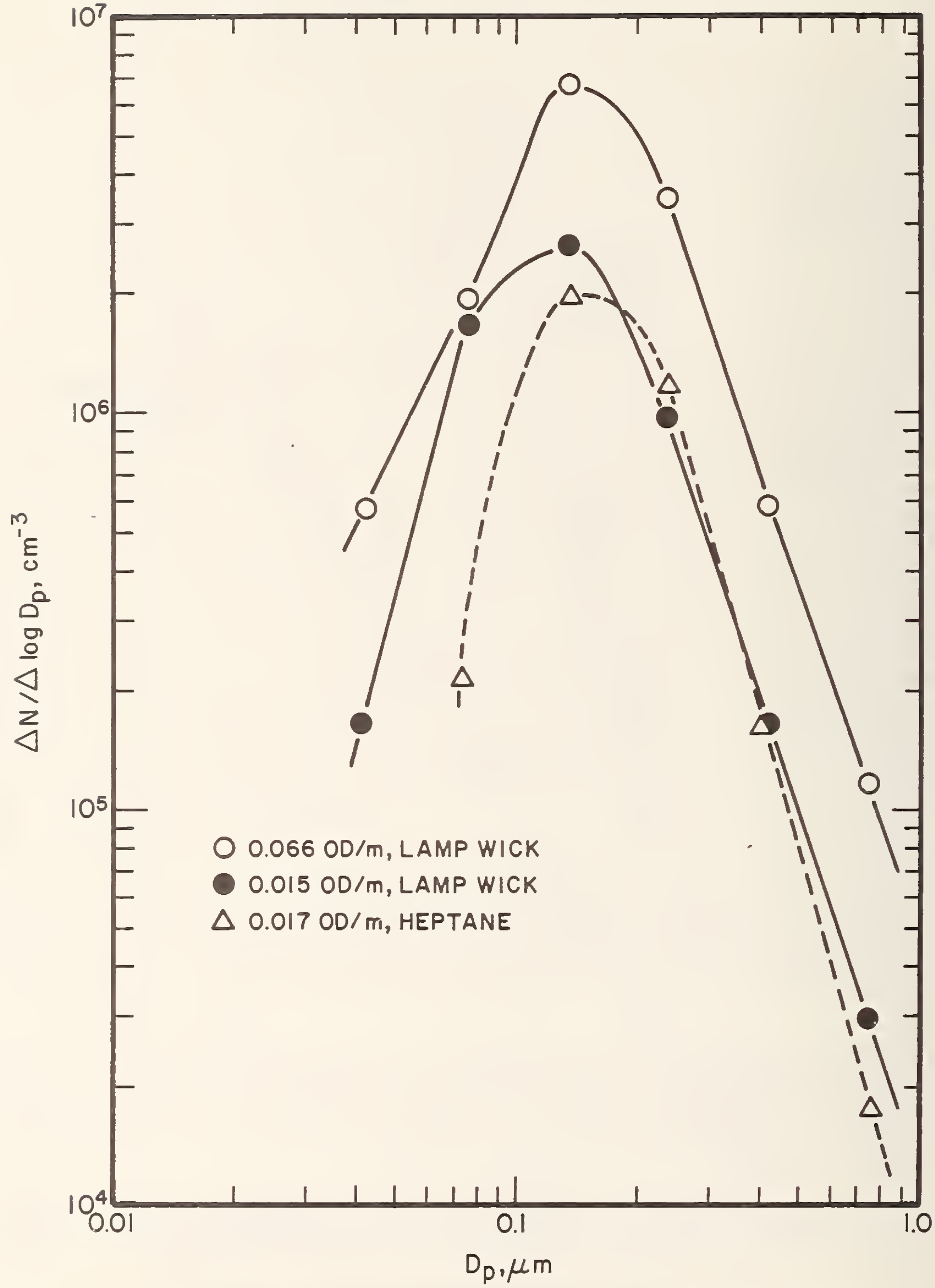

Figure 24. Particle size distribution for lamp wick and heptane smokes [20].

$$\log \sigma_g = \left[\sum_{i=1}^{n} \frac{\left(\log D_i - \log \overline{D}_g\right)^2 \Delta N_i}{N} \right]^{1/2} \tag{10}$$

where N represents the total number of particles and n represents the number of size classes. Both smokes have a $\overline{D}_g$ between 0.1 and 0.2 μm; however, the heptane smoke seems to have a somewhat narrower size distribution than lamp wick smoke. A summary of all of the smoke data is presented in table 1. The values of σ_g found in our work for smoldering lamp wick smoke are significantly larger than those reported by Watanabe at the 1976 UJNR panel meeting (1.6 and 1.7 versus 1.4). It is known that the size sensitivity of the instrument used in measuring the size distribution, the electrical aerosol analyzer, decreases for particle sizes over a few tenths of a micrometer [24] and this may be responsible for the difference in the values of σ_g.

As discussed in a previous section, the electrical aerosol analyzer has been evaluated for the measurement of the number concentration and volume concentration. Its sensitivity to monodisperse aerosols has also been examined [24]; however, there is no comprehensive study regarding its performance for polydisperse aerosols such as smokes. While we cannot be certain of the size distribution in absolute terms, the instrument is very useful in detecting relative changes in size distributions. For example, the effect of exposure condition on the size distribution of smoke generated from the combustion of α-cellulose is shown in figure 25. In one case a small α-cellulose disc was ignited by a premixed flame while in the other it was in contact with a metal surface maintained at 500°C. The particle size distribution peaked at less than 0.01 μm for the flaming mode compared to 0.075 μm for the smoldering mode. The effect of time on the size distribution of the smoke, which is termed smoke aging, is another process that can be studied with the electrical aerosol analyzer and will be the subject of the next section.

Table 1. Measured and derived parameters of smokes in the UL 217 chamber test

Instrument	UL 217 Optical density m^{-1}	PMM[a/] Mass concentration mg/m^3	EAA[b/] Mass concentration mg/m^3	EAA Number conc. 10^6 cm^{-3}	CNM[c/] Number conc. 10^6 cm^{-3}	$\overline{D}_g$ μm	σ_g
Lamp wick	0.066	42	21	3.4	2.5	0.14	1.7
Lamp wick	0.015	10	6	1.4	1.0	0.12	1.6
Heptane	0.017	5[d/]	5	0.9	0.3	0.16	1.5

a/ Piezoelectric mass monitor
b/ Electrical aerosol analyzer, unit density assumed
c/ Condensation nucleus monitor
d/ Filter gravimetric measurement

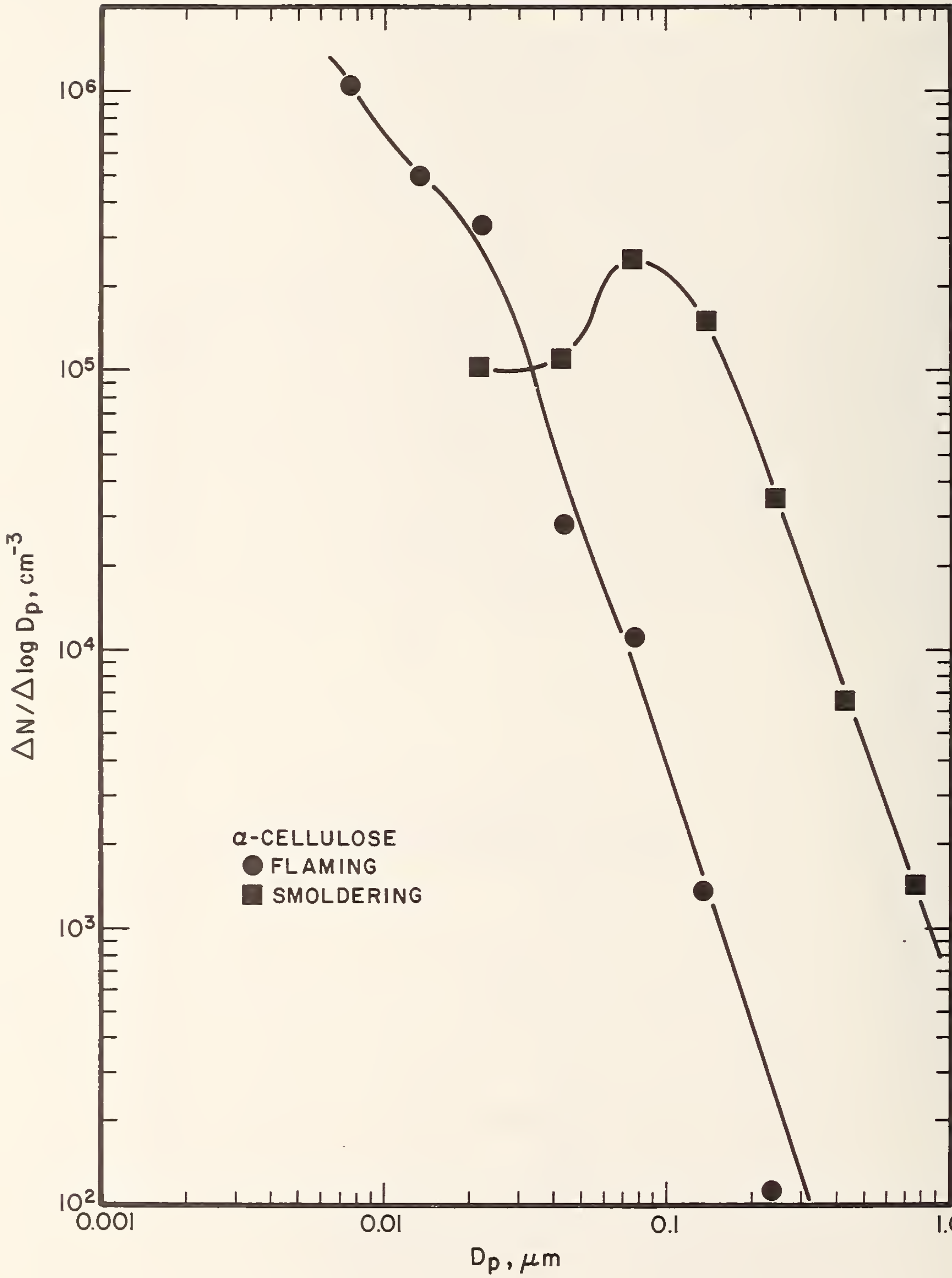

Figure 25. Smoke from α-cellulose under flaming and non-flaming exposure conditions [20].

13. SMOKE AGING

The behavior of smoke particles is dynamic from their formation to their transport to the walls or their dilution in the atmosphere. An experiment performed by K. Mniszewski at IIT Research Institute demonstrates the effect of aging of smoke detectors in the Underwriters' Laboratories test chamber. His data on the responses of a light-scattering type detector with a near forward scattering angle and of an ionization detector are plotted versus time in figure 26. The optical density of the light beam decreased about 5% during the eight-minute aging period. During this same time, the ionization detector response decreased by about 25% while the light-scattering detector increased by about 10%.

In a series of similar experiments at the National Bureau of Standards during which the number concentration and optical density were monitored versus time, a rapid decrease in number concentration occurred in a few minutes while the optical density remained essentially constant. This rapid drop in number concentration can be explained by the phenomenon of coagulation, which is simply the coalesence or attachment of aerosol particles as a result of collisions. The basic equation describing the rate of change of number concentration with respect to time is given by:

$$\frac{dN}{dt} = -\Gamma N^2 \tag{11}$$

Integration yields

$$N/N_o = 1/(1 + \Gamma N_o t), \tag{12}$$

where N_o is the initial concentration. For smoldering punk smoke, the coagulation frequency Γ equals 4.0×10^{-10} cm^3/s. Substituting this Γ into equation (12) one finds that an initial concentration of 3×10^6 particles/cm^3 decreases by a factor of two in 14 minutes.

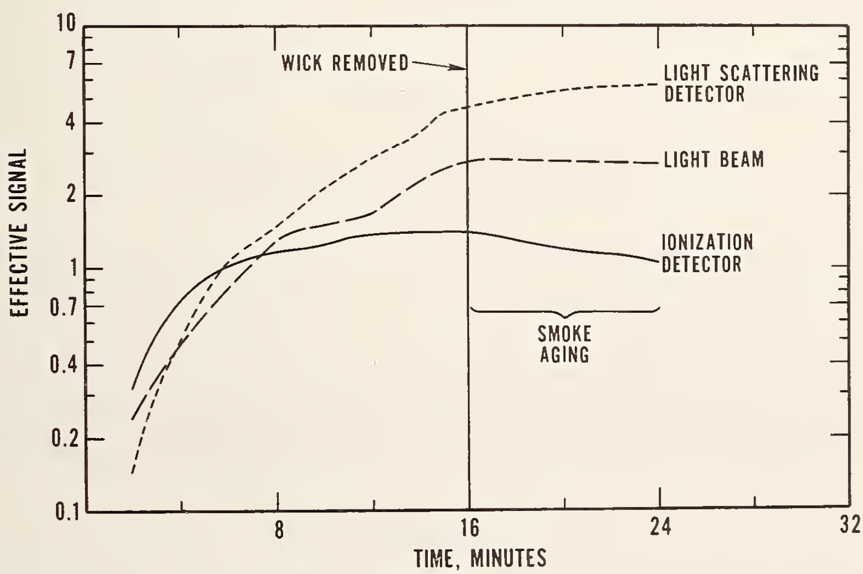

Figure 26. The effect of aging on smoke detector response.

The coagulation phenomenon creates two opposing effects on detector response. The decrease in the number concentration tends to decrease the detector output while the increase in particle size accompanying particle coalescence tends to increase the detector response. Which effect will predominate is determined by the size sensitivity characteristic for the detector.

The effect of aging on the size distribution of punk smoke is shown in figure 27. The smoke was generated in a 1.25 m cubical chamber and was allowed to age for up to 16 hours. The peak in the number distribution decreases by over two orders of magnitude while the particle size increases by about a factor of two. Coagulation is the dominant mechanism during the initial aging, but the mechanism of wall loss becomes the dominant process for the well aged, low concentration smoke.

All of the size distribution data in the previous figures plus the size distribution of punk smoke exposed to an air stream moving at a velocity of 2 m/s have been plotted in terms of Friedlander's self-preserving variables [25] ψ and η in figure 28. The number distribution is reduced by the total number of particles in the size distribution N(t), and the diameter is reduced by a quantity related to the average diameter for the size distribution, $(V/N)^{1/3}$, for that particular smoke. Thus

$$\psi = \frac{N}{\Delta \log N(t)} \tag{13}$$

$$\eta = D\ N(t)/V^{1/3}. \tag{14}$$

The data includes fresh smoke as well as aged smoke, smoke generated in both the flaming and smoldering modes, whitish smoke and black sooty heptane smoke, and smoke generated under different airflow conditions. There is qualitative agreement in the shape of the size distribution curves for all the data, especially for larger values of η. From the data for small η, it appears that the heptane smoke has a narrower distribution than the others.

Also shown in figure 28 are a reduced Junge like size distribution and a reduced log-normal size distribution.

$$\psi = 1.38\ \eta^3\ (\eta^3 + 0.2)^{-2}, \text{ Junge like} \tag{15}$$

$$\psi = 1.73 \exp - \left[\frac{\ln\ (1.23\ \eta)}{0.744}\right]^2, \text{ log-normal with } \sigma\text{=1.7.} \tag{16}$$

Equation (15) is a reduced version of the number distribution equation given in the 1976 UJNR panel meeting (p. 262). It appears that both the Junge like distribution and the σ_g = 1.7 log-normal distribution fit the data. It has been shown by Mulholland, et al. [26] in a coagulation calculation that the reduced algebraic distribution is only weakly affected by aging due to coagulation as is the case experimentally (see aging data in figure 28). This means that the algebraic distribution could be used as a model size distribution not only for a variety of smokes but also for smokes at various stages of aging. It is not known whether the log-normal size distribution also has this property.

14. LOOKING AHEAD

In our previous studies of smoke aging, we considered the highly idealized case of a perfectly mixed smoke. Our current theoretical work is concerned with the dynamics of smoke in a buoyant plume. To date our theory includes the effects of coagulation and of air entrainment in the plume and enables

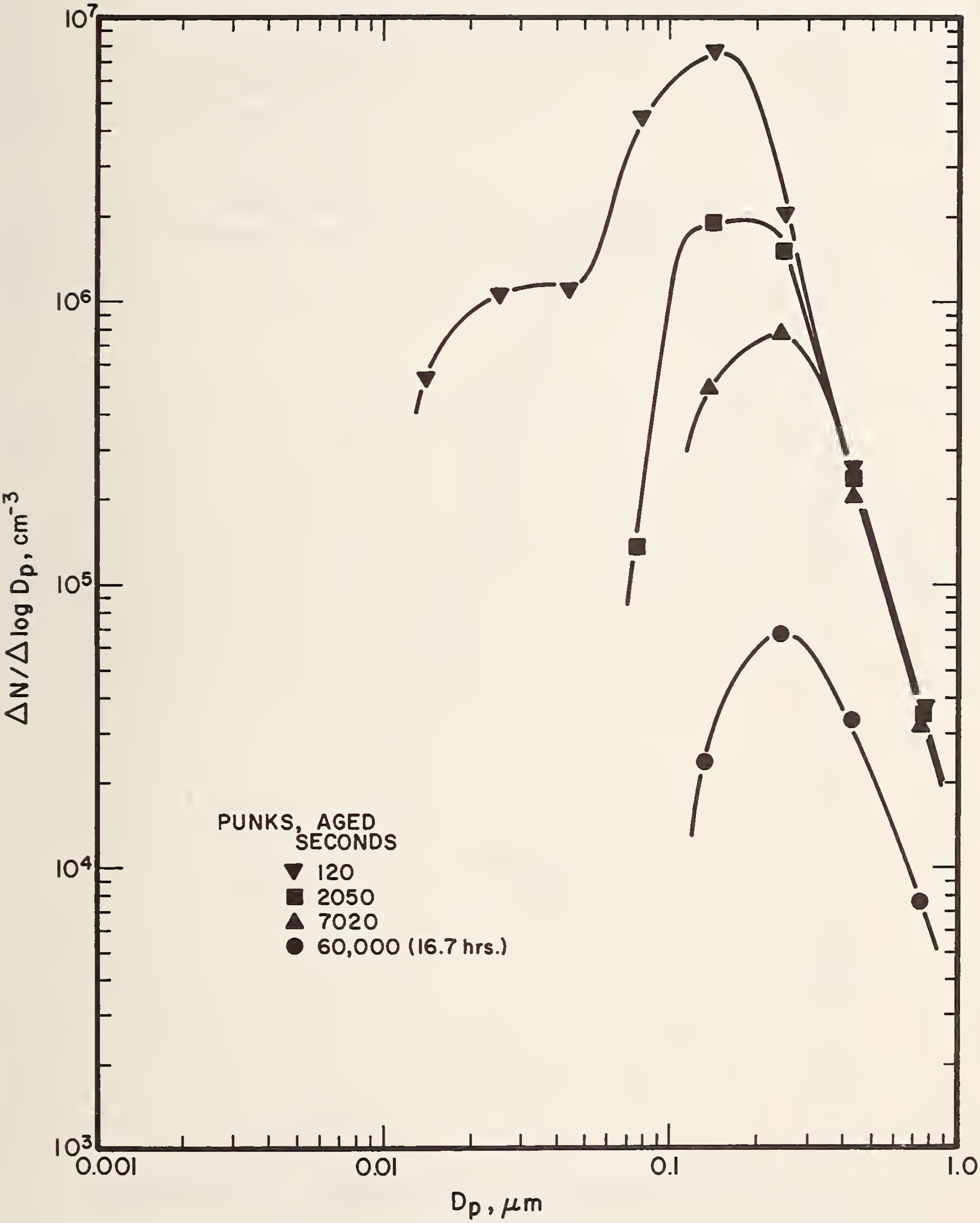

Figure 27. Aging of the punk smoke for up to 16 hours [20].

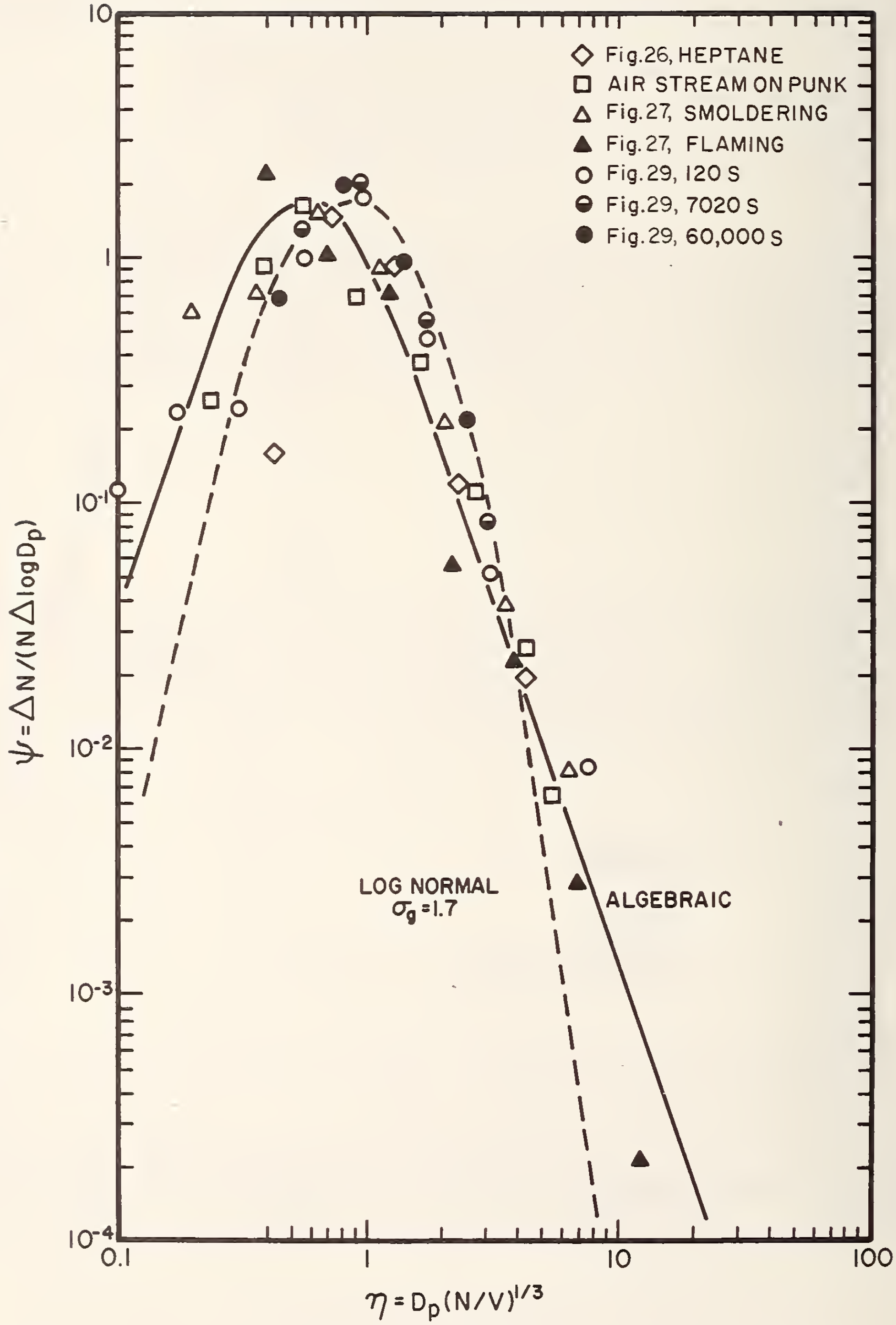

Figure 28. Size distribution in terms of reduced variables [20].

the calculation of the number concentration, mass concentration, and size distribution of the smoke particulate as a function of height. The relative significance of coagulation versus air entrainment on the particulate number flux is determined by a single dimensionless constant which we term the plume constant, A. Besides depending on the total rate of heat release and the rate of mass release, A also depends on the coagulation frequency, height and the number concentration at this reference height. For values of A greater than or equal to 0.1, coagulation becomes an important effect. In the future, we plan to include the mechanism of aerosol formation including nucleation and condensation in our study and to initiate an experimental study.

A second project of high priority is the development of a simplified version of the monodisperse aerosol generator for testing the sensitivity of installed smoke detectors. A prototype version of the tester is shown in figure 29 [27]. Some of the major design features are a repeatable, steady-state aerosol source; adjustable aerosol concentration over a range from 10 to 60 mg/m^3; mass median diameter of about 0.5 μm; and formation of the aerosol from the atomization of the pure liquid dioctyl phthalate.

A third project in progress is the absolute calibration of our optical particle counter using a laser Doppler size spectrometer developed by Chabay in the NBS Analytical Chemistry Division [28]. The principal of operation for the instrument is illustrated in figure 30. Light scattered out of a horizontally propagating laser beam by falling particles is collected at one angle in the vertical scattering plane. Beat frequencies in the photocurrent of the detector due to the Dopper shift of the radiation scattered by the settling aerosol are analyzed to determine particle velocities. The slip - corrected Stokes law settling velocity gives the particles size for a known particle density, while the amplitude of the beat frequency contains information on the number of particles of that size. The technique has a sizing accuracy of $\leq$0.16 m diameter for measuring particle sizes over the range 2 to 20 μm. The Berglund-Liu vibrating orifice generator [29] is being used for generating monodisperse ($\sigma_g \sim 1.05$) dioctyl phthalate particles for the calibration.

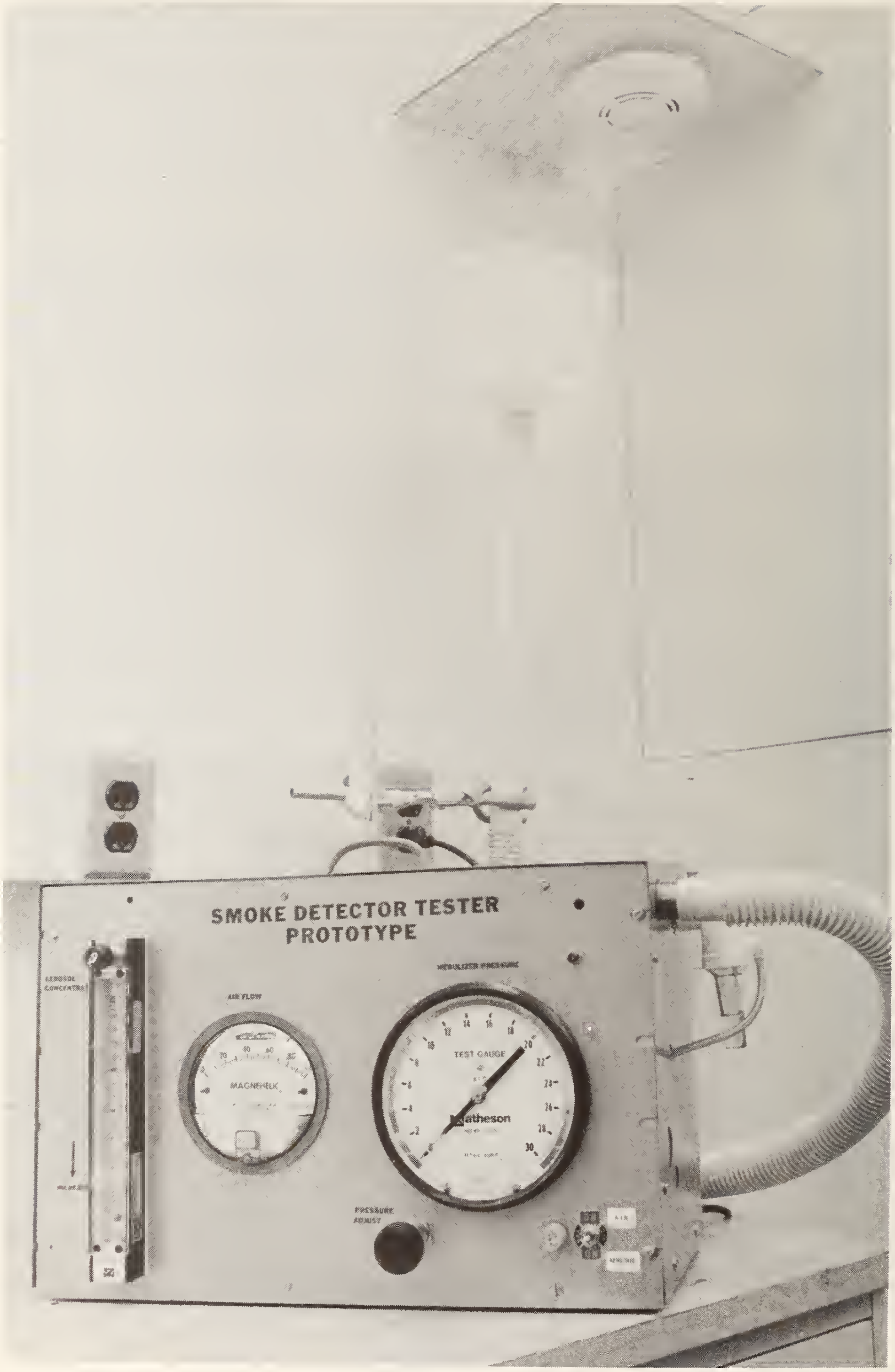

Figure 29. Smoke detector tester [27].

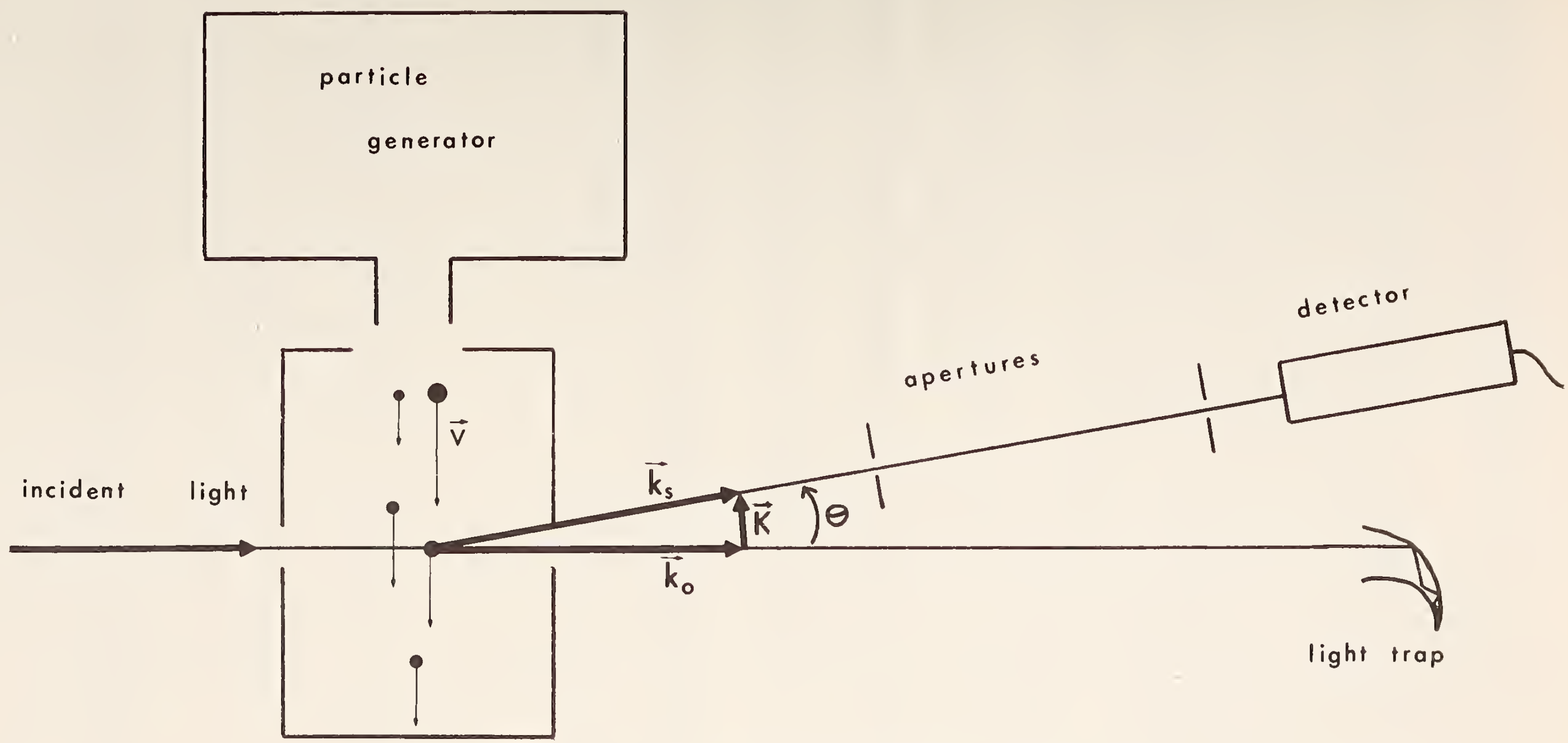

Figure 30. Laser doppler size spectrometer [28].

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The importance of a reference photometer and reference ionization detector in improving the reliability of smoke detectors is discussed. Recent developments in smoke detector technology are highlighted and theoretical as well as practical experience in regard to detector performance is summarized. Comparison of the theoretically predicted response of smoke detectors as a function of particle size with measured values is given. A monodisperse aerosol generator, an electrical aerosol analyzer with a size sensitivity from 0.01 to 1 μm, and an optical particle counter are described. The size distribution, mass and number concentration, optical density, and coagulation frequency for smoke from burning heptane and smoldering cotton lamp wick are presented. It is shown that a Junge type size distribution provides a good fit to the measured size distribution for both fresh and aged smoke.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Aerosol generators; detector testers; fire detectors; ionization detectors; light-scattering detectors; particle size distribution; smoke; smoke detectors.

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