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On A Scattered-Light Measuring Device for Use in Testing Types of Smoke Detectors

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Translated for:

Center for Fire Research
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Final Report

U. S. DEPARTMENT OF COMMERCE

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U.S. DEPARTMENT OF COMMERCE, Elliot L. Richardson, ***Secretary***

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Dr. Betsy Ancker-Johnson, ***Assistant Secretary for Science and Technology***

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Acting Director***

PREFACE

This report is a translation of a paper prepared by M. Pistor and presented by him at the Seventh International Seminar on Problems in Automatic Fire Detection held in Aachen, Germany, on March 5-6, 1975. The Seminar was presented by the Institute for Electronic Communication Technology of the Rheinish-Westfalian Technical College, Aachen, in conjunction with the Gesamthochschule in Duisburg.

This translation has been prepared to disseminate useful information to interested fire research personnel on a need-to-know basis and is not an original work of the Center for Fire Research.

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ON A SCATTERED-LIGHT MEASURING DEVICE FOR THE USE IN TESTING TYPES OF SMOKE DETECTORS

M. Pistor

Abstract

Generally, the response threshold value of fire detectors is tested with measuring instruments which operate on the same physical principle as the detectors to be tested. For example, this means that the response threshold value of an ionization chamber smoke detector is checked with an ionization measuring chamber and the response threshold value of an optical-type smoke detector operating on a light extinction principle is checked using an extinction measuring instrument. However, optical-type smoke detectors operating on a light-scatter principle (photoelectric in U.S. parlance) have also been checked using an extinction measuring instrument.

Since the light-scatter type of smoke detector is by far the most commonly used of the optical type of smoke detector it seems appropriate to use a light-scatter measuring instrument to check the response threshold value of these detectors. In addition, the need for such a measuring instrument is emphasized by the fact that both the parameters of the smoke aerosol and the design features of the measuring instrument are affected in different ways by light scatter and light extinction.

The author describes the technical features and design details of a newly-developed, light-scatter measuring instrument along with some experiments to determine its response to artificially-generated aerosols.

Key words: Fire detection; light extinction; light scatter; light-scatter measurements; photoelectric smoke detectors; smoke detectors.

1. INTRODUCTION

For early detection of damaging fires more and more use is being made of those detectors which react to the fire parameter, "smoke." Here, the optical or electrical properties of the smoke particles are used to trigger an alarm from the detectors.

At the present time, the smoke detectors on the market can be divided in two groups on the basis of their operating principles:

1. Detectors using the ionization chamber principle (so-called I-chamber detectors); and

2. Detectors having an optical detection principle. These include the so-called "light attenuation or light extinction" and "scattered-light" detectors.

Despite their physically-differing modes of operation, all three types of detectors have the common characteristic that their response threshold depends simultaneously upon particle size and smoke concentration. Thus, in dealing with these detectors we have to deal with complicated smoke (aerosol) detection devices whose initial signal depends, in various ways, upon the parameters of the smoke aerosol. Before licensing such devices for use as fire detectors one must test their reliability and response sensitivity under well-defined, reproducible, environmental conditions.

2. DIFFERENT SMOKE DETECTORS REQUIRE DIFFERENT TEST DEVICES

The two most important parameters of a smoke detector, namely the response threshold and its modification by environmental influences such as, e.g., temperature, humidity, corrosion, etc., can only be suitably tested using standard measurement devices which operate on the same physical principle as that of the detectors themselves.

If one wishes to determine how the response threshold varies as a result of environmental influences one subjects the detector to the basic test in the smoke test tunnel. The magnitude of the detector's response threshold is checked by proof-testing with test fires in the fire chamber. For example, it is conventional in the various test laboratories to test so-called I-chamber detectors for suitability by using a standard ionization chamber [1][1]. So-called optical detectors — for technical reasons the models on the market are mainly scattered-light detectors — have hitherto been tested using an extinction measurement device. This device measures the light attenuation resulting along a smoke-filled path from absorption and scattering of the incident light [2,3].

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[1] Bracketed numbers refer to references listed at the end of this paper.

2.1. Comparison of Scattered-Light Measurement and Light Attenuation Measurement

Figure 1 shows the measurement principle of scattered-light measurement in comparison with light attenuation measurement. In the latter, one is dealing with a two-beam process in which one light beam is attenuated by the smoke along the measurement stretch x_o. The other light beam emerging from the same source is unattenuated by smoke and enters the same photoreceptor as the measurement beam. By means of the thus derived comparison quantity it is possible to compensate for errors resulting from changes in the light source and in the receptor. To this measurement procedure, the Lambert-Beer law generally applies:

$$S = S_o \cdot \exp(-\bar{C}_e \cdot z \cdot x_o) \tag{1}$$

Here S_o and S are the power densities occurring at the source or at the receptor; z is the number of particles per unit volume, and x_o is the measurement path length. $\bar{C}_e$ is the so-called mean extinction cross section of a polydispersed aerosol. It depends upon the parameters of the particle size distribution, upon the optical refractive index of the particles, and upon the wavelength λ of the light source. The effect of forward scatter upon this sort of transmission measurement may be neglected here [4].

In scattered-light measurements, the axis of the photoreceptor is placed at a scattering angle θ relative to the axis of the incident light beam. Only the light scattered by the aerosol particles in the scattering volume V_{st} at the angle θ is received by the receptor. For this measurement principle, under certain assumptions, one can derive the following formula with the aid of the Mie theory:

$$\frac{I_s}{I_o} = \frac{\lambda^2 \cdot z \cdot V_{st}}{8\lambda^2 \, l^2} (i_1 + i_2) \; . \tag{2}$$

I_s is the radiation intensity measurable at the receptor at a distance l as scattered by the scattering volume at the angle θ. I_o is the radiation intensity incident upon the particles in the scattering volume V_{st}. The wavelength of light source is denoted by λ; z is, as in the light attenuation measurement, the particle concentration, and i_1, i_2 are the so-called Mie intensity functions. These are complicated functions of the scattering angle θ, of the complex refractive index $\bar{m}$, of the particle size d and of the wavelength λ.

cheaply than a light attenuation measuring device of corresponding quality.

5. A more punctiform measurement of the aerosol can be carried out. This permits determining the extent to which the concentration in the smoke test tunnel varies over the cross section.

6. Together with the light attenuation measuring device, changes in the aerosol parameters can be observed during measurements in the smoke test tunnel.

2.3. Requirements Affecting the Scattered-Light Measuring Device

The essential requirements which can be imposed upon a scattered-light measuring device for the type-testing of smoke detectors may be easily determined on the basis of testing practice up to the present:

1. The device must be so compactly constructed that it fits into the already existing smoke channel and at the same time does not substantially constrict the cross section of 38 x 38 cm^2.

2. The design should be as open as possible so that the smoke particles can flow undisturbed through the measurement volume (called scattering volume). The flow in the vicinity of the device likewise should be disturbed as little as possible.

3. The distance l_o, l already shown in figure 1, should be as small as possible and the light source must be as intense as possible in order to obtain an adequate measurement effect even for small smoke particles or low concentrations.

4. The device should be easy to build on the basis of design drawings without the necessity of precision adjustment.

5. The electronics for amplification and evaluation of the scattered-light measurement should be constructible with commercially-conventional, construction elements.

6. The device should react only to smoke particles, while being as independent as possible of environmental effects such as, foreign light, temperature, pressure, humidity, vibration, etc.

In the following the technical details of the structural groups will be explained.

3.1. Technical Details

The laser diode, of type LD 23, because of the limited heat conduction at room temperature, can only work in pulse operation. For this application this is no disadvantage. On the contrary it is even desirable to acquire scattered-light pulses in order to suppress interfering effects from daylight or from the 100-Hz radiation of artificial room illumination. This sort of light pulse generation has the further advantage that expensive, mechanical choppers can be omitted. The laser diode, at a pulse-peak-power at the input of 110 W and an efficiency of 11 percent, supplies a peak output power of 12 W. The pulse breadth amounts to 130 ns at a repetition frequency of 1 kHz. The power supply for the laser diode is furnished by a traditional d-c main supply over a special d-c converter LC 23 which can yield, at a 300-v output d-c voltage, peak currents of more than 40 amps. The LP 23 pulse generator generates pulses lasting 130 ns required by the laser diode. This pulse generator is controlled from the central pulse generator.

3.2. Various Considerations Affecting Selection of the Photodiode

1. The diode must also still yield a sufficiently measureable signal at very low intensities, i.e., 10-100 $\mu W/cm^2$.

2. The pulse rise time must be as low as possible so that the height of the light pulses, which is in fact a measure of the particle concentration, is converted into a proportional voltage pulse.

3. The maximum of the spectral sensitivity should lie as much as possible in the range of the wavelength of the light source.

4. The angle-dependent receiver characteristic should be as narrow as possible so that here, too, as in the case of the light source, special lenses can be dispensed with.

The silicon-PIN diode of type MD 2 used here meets all these requirements.

Diode and preamplifier are installed in a common brass housing, because of the required shielding. The preamplifier has a voltage amplification of 6,000 ($\hat{=}$ 76 dB) in the range 1 kHz to 1 mHz. The spectrum of the approximately saw-toothed electrical pulses at the amplifier input suffices nevertheless theoretically from the frequency of 1 kHz to infinity, as can be shown by the Fourier-series development. The individual lines of the spectrum have a spacing of 1 kHz. There is also present a dc-component. But in order to eliminate interference from daylight or, for example, from the 100-Hz artificial, room illumination the amplifier was decoupled with respect to d-c voltage and its 3-dB bandwidth fixed in the range 1 kHz to 1 mHz. This band width suffices for approximately errorless linear amplification of the electrical pulses since the essential part of its spectrum is limited to the range from 1 kHz to 1 mHz. By means of the alternating-current coupling of the two amplifiers V_1 and V_2, it is also possible to omit expensive offset compensation of the operation amplifiers employed. From the output of the amplifier V_2, the pulses arrive at the scanning holding circuit AHS. This circuit consists essentially of a capacitor having a low-loss factor, two electronic switches and an impedance converter. The capacitor is periodically charged up to a voltage which is proportional to the height of the scattered-light pulse and is again discharged before arrival of the next pulse. The setup is controlled by the central pulse generator which secures that the laser pulser and the evaluation circuit operate synchronously.

Since it can be assumed that the pulses at the output of V_2 are all of equal breadth, a short-time integrator suffices as a scanning holding circuit; this integrator is likewise constructed with an operation amplifier. The output voltage of such a circuit is proportional to the scattered-light pulse area divided by the pulse repetition time of 1 ms. Because of the small scanning ratio of the pulses (1/1,000), however, the output voltage would vanish in the noise and could no longer be measured. Hence, the integrator is controlled in such a way that it maintains the capacitor voltage for a duration of 900 μs and is set back only for a duration of about 100 μs. In this way the output pulse height is magnified by a factor of 900 as compared with normal integration.

The thus modified pulse train is delivered to a low-pass filter having a limiting frequency of $f_g = 1$ Hz. The limiting frequency is obtained as follows: the total scattered-light measuring setup can be conceived as though the laser light source were working continuously and as though there were a periodic scanning of the scattered-light signal which rises with particle concentration. According to Shannon's scanning theorem one obtains for the scanning rate T = 1 ms the condition:

$$T \leq 1/2\ f_g \qquad (3)$$

where f_g is the maximum frequency existing in the useful signal. This condition is certainly met since the particle concentration and hence the scattered-light signal varies only slowly when other aerosol parameters are kept constant. In order to exactly recover the useful signal the limiting frequency of the low-pass filter must be equal to f_g.

Control of the integrator is accomplished by means of so-called monostable multivibrators. These yield a pulse of a specific length for each trigger pulse coming from the pulse generator TG. All the structural components for control and evaluation which have been mentioned are, with the exception of the preamplifier V_1, constructed in integrated circuitry technique and mounted in a single housing.

3.3. Discussion of the Design

We will now make a few remarks regarding determination of the scattering angle and the space arrangement of the structural component. As has already been mentioned, in the apparatus the effect of the refractive index of the aerosol particles upon the output measured value should be as low as possible.

Many authors have already calculated the intensity functions i_1, i_2 according to the Mie theory, treating them as functions of the particle size, of the refractive index, and of the scattering angle [7,9-12,14]. The results of the complicated and time-consuming calculations show that the dependence of the intensity functions upon the refractive index at small scattering angles is least in the forward direction. Further, the scattering intensity, as a function of the scattering angle, is greater in the forward direction by a factor of from 100 to 1,000 and, therefore, also oscillates much less than at a scattering angle of, for example, 90° [11,14].

Figure 3 shows, for example, the intensity function i_2 as a function of the size parameter $\alpha = \Pi \cdot d/\lambda$ with the scattering angle θ as a parameter. Here d is the particle diameter and λ the wavelength of the light source. These calculations have been carried out by Pruessmann for the refractive index of soot particles [14]. For particles having a different refractive index, and for the intensity function i_1, one obtains similar typical curve profiles.

Figure 3 also shows that the intensity function oscillates very sharply as a function of the diameter in the scattering angle range of 90°, while in the forward scatter region it rises continuously with particle diameter d.

The marked dependence of the scattering power upon refractive index at a scattering angle of 90° seems to explain why some scattered-light smoke detectors now on the market react so differently to different types of smoke. These detectors usually cover the light scattered at a mean scattering angle of 90°.

All results mentioned above imply the desirability of a measurement setup which operates below an angle of forward scatter which is as small as possible.

Figure 4 shows to scale the arrangement of light source and receptor. The radiation of the GaAs laser diode is not as sharply collimated as, e.g., that of gas lasers. About 90 percent of the power radiates in a cone having an aperture angle of 23 percent [sic]. In order to avoid expensive optics for focusing the radiation, while at the same time limiting the scattering volume, an apertured diaphragm has been placed in front of the source. This then yields a radiation cone having the aperture angle $\gamma = 3.8°$. The power radiated into this solid angle can be estimated, with the aid of the radiation diagram of the laser diode, to be about 2 W. The intensity in the middle of the scattering volume thus amounts to about 20 W/cm^2 as a pulse peak value.

Since because of diffraction of the light rays at the circular diaphragms a part of the radiation reaches the photoreceptor, so-called Fresnel diffraction, it was also impossible to choose a scattering angle substantially less than 15°. This represents a compromise between attainment of a scattered-light measuring effect which is as great as possible and suppression of this undesirable diffraction, which moreover cannot be completely eliminated by additional smaller apertured diaphragms in front of the light source. In order to spatially limit the scattering volume and to provide a field against interfering light sources, the same apertured diaphragm was placed in front of the photoreceptor.

Limitation of the scattering volume is necessary in order to keep as low as possible the noise voltage of the photodiode, which is produced inter alia by scattering by air molecules. The size of the scattering volume, together with the particle concentration, has an influence upon the measurement effect.

The output voltage is proportional to the product $V_{st} \cdot z$. These facts should be taken into consideration whenever the measurement range of the equipment is determined.

The size of the scattering volume may be computed from the intersection of two cones. It amounts to about 0.5 cm^3. The scattered intensity arriving at the receptor may now be derived in accordance with equation (2) if the refractive index, the particle diameter and the concentration of the test aerosol are given. For a polydispersed aerosol the intensity functions should be evaluated as a function of particle diameter by using the distribution density function of the particle size and from this the mean value $i_1 + i_2$ should be formed.

In addition, the output voltage of the device can be calculated whenever the sensitivity of the photodiode and the pulse transmission function of the device are known.

3.4. Characteristic Equation of the Device

The relationship between particle concentration and output d-c voltage may be expressed in a formula as:

$$U_a = K_1 \cdot (i_1 + i_2) \cdot z + U_o \tag{4}$$

Here: z is the particle concentration; U_o the component arising from diffraction at diaphragms; and i_1, i_2 are the intensity functions which, as has already been mentioned, are dependent upon the wavelength λ, the mean scattering angle, upon the particle size, and upon the refractive index. The constant K_1 contains the design parameters of the arrangement and the transmission function of the amplifier.

Thus for an aerosol of constant refractive index and particle diameter the output voltage of the measuring device is directly proportional to the particle concentration.

3.5. Calibration of the Device

If finally a test aerosol is reproducible in the parameters of refractive index and particle diameter then it is possible to calibrate the device in a simple manner. The factor $K_1 (i_1 + i_2)$ appearing in equation (4) can be derived by measurement whenever at the same time measurements are made, using the above-mentioned particle counter, of the particle concentration z and the voltage U_a of the scattered-light measuring device. For this purpose, in principle, one measurement point suffices to obtain the calibration curve $U_a = f(z)$ since U_a is proportional to z. The voltage U_o is derived from measurement of U_a in a smoke-free measurement volume.

If the device is calibrated in this way, i.e., the test aerosol defined by U_a (z), then at all times it will be possible in conjunction with the particle counter to easily test whether the aerosol is constant in its properties.

3.6. Errors in the Measurement of Scattered-Light

Equation (4) still does not take into account the possible errors from scattering by air molecules and from extinction of the light beam on the path from the laser diode to the photodiode. Scattering by air molecules can be neglected in comparison with scattering by aerosol particles for the particle concentrations existing here which are from 10^3 to 10^6 particles per cm^3. This scattering also has no influence upon the measurement effect since it is practically already contained in the voltage U_o in equation (4). The extinction of the light beam in the case of a smoke-filled measurement length may be estimated as follows:

The decadic extinction modulus is defined as:

$$m_\lambda = \frac{10}{x_o} \cdot lg_{10} \frac{P_s}{P_e} \text{ in } \frac{dB}{m} \quad (5)$$

P_s is the radiation power emitted by the transmitter and P_e is that arriving at the receiver. The measurement path length is denoted by x_o. Together with the Lambert-Beer law (equation (1)) we obtain from this:

$$m_\lambda = 4.34 \cdot \bar{C}_e \cdot z \text{ in } \frac{dB}{m} \quad (6)$$

The mean extinction cross section of the test aerosol used here has been calculated by Kraus to be 0.175 μm^2.

For $z = 10^3\ cm^{-3}$ we obtain $m_\lambda = 0.8 \cdot 10^{-3}$ dB/m and

For $z = 10^6\ cm^{-3}$ we obtain $m_\lambda = 0.8$ dB/m.

For the last-mentioned value we obtain from this for P_s/P_e:

$$P_s/P_e = 10^{0.01} = 1.023$$

if one uses as the measurement path length the distances between the scattering volume and the transmitter or between the scattering volume and the receiver.

This means that for this relatively high aerosol concentration, with which traditional smoke detectors will long before have reached the alarm threshold, there is an error of only 2.3 percent in the output voltage of the measuring device. Thus this error can be neglected up to concentrations of about 10^6 cm^{-3}. If it is desired to compensate for the error, then, using a simultaneous light attenuation measurement, one can determine the ratio P_s/P_e and continually multiply the reduced output voltage of the scattered-light measuring device by this factor.

One can also compensate for the error automatically by building a control circuit. For this, one requires a light attenuation measurement in which the laser serves as a light source. A second photoreceptor at the distance $l_o + l$ converts the radiation, which has been attenuated by the smoke, into a proportionate d-c voltage. This voltage serves as a control quantity in a simple control cycle. A constant voltage serves as the reference value. The difference between the two voltages is the control deviation, which through an amplifier increases the supply voltage of the laser so that the latter yields a higher power and hence compensates for the light attenuation in the scattered-light measurement.

If this control circuit is also designed to be temperature independent then in addition one can compensate for the effect of environmental temperature upon the output power of the laser light source. This effect is not negligible if the scattered-light measuring device is also to be used in the proof test in the fire chamber.

Figure 5 shows the scattered-light device together with the evaluating circuit. Because of the required mechanical stability, light source and photoreceptor are firmly screwed to a 5-mm-thick steel plate.

4. MEASUREMENTS WITH TEST AEROSOLS

Figure 6 shows the arrangement of the scattered-light device in the smoke tunnel of the IENT. This closed test chamber serves for testing smoke detectors in the basic test. The aerosol is introduced at the point A through a pipe and circulated and then uniformly distributed by a ventilator, continually having a mean flow velocity of 0.2 m/s.

D is the light attenuation measurement length, I is the standard ionization chamber. The three measuring devices must as far as possible be so placed in the tunnel that equal particle concentrations exist in their measurement volume, but on the other hand this must be done in such a way that the devices do not interfere with one another.

The test aerosol is a paraffin-oil mist. The paraffin-oil, which is fluid at room temperature, is atomized under well-defined conditions and after having been diluted with filtered air is conducted into the smoke tunnel; here the particle concentration rises stepwise.

If measurements of an aerosol are carried out simultaneously with the three measuring devices then the following measured values are obtained:

1. Light attenuation measurement

   From equations (5) and (6):

$$m = 10/x_o \cdot lg_{10}\, P_s/P_e = 4.34 \cdot \overline{C}_e \cdot z$$

2. Scattered-light measurement

   From equation (4):

$$\Delta U_s = U_a - U_o = K_1 \cdot \frac{\quad}{(i_1 + i_2)} \cdot z$$

3. Ionization chamber [1]

$$y = K_2 \cdot \overline{d} \cdot z$$

$$\text{with } y = x\,\frac{2-x}{1-x};\quad x = \frac{\Delta i}{i_o} \qquad (7)$$

x is the relative different current when smoke enters into the measurement chamber.

All three measurements are proportional to the particle concentration z so that between m, ΔU_s and y there must also exist linear relationships. Diagrams can now be drawn with $m = f(\Delta U_s)$; $y = f(\Delta U_s)$ and $m = f(y)$, where the individual measurement points denote different concentrations.

In the diagram of figure 7, m is plotted as a function of ΔU_s, using the particle size as a parameter.

Curve 1 resulted from two measurements with an aerosol produced by the process described above. The aerosol is polydispersed, i.e., the particles have various sizes. Curve 2 was derived with an aerosol which was produced with a second generator of the same type at the same atomizing pressure. The curves 3 and 4 resulted from measurements with an approximately monodispersed aerosol, i.e., the particles all have about the same size. The aerosol is likewise paraffin-oil mist, produced with a generator in accordance with the "Lassen" principle.

Curve 3 resulted when the particle diameter was set at 0.4 μm; curve 4 at 0.3 μm. This diagram clearly confirms the above-mentioned, theoretically established, linear relationship between m and ΔU_s.

In the same way it was possible to establish by measurements a linear relationship between y and ΔU_s, as shown by figure 8.

Also, at higher flow velocities in the smoke tunnel of up to 2.4 m/s, it was possible, under otherwise identical measurement conditions, to show that the measurements m and ΔU_s remain proportional to one another. This is also true in the case when the concentration does not increase stepwise but linearly.

The deviations of individual measurement points in the diagrams of figures 7, 8 and 9 from the sketched ideal line arise on the one hand from measurement errors in the three devices but probably also from the fact that the particle concentration can vary locally, e.g., from vortex formation.

The differing sensitivities of the three devices to particles of different sizes or to particle size distributions can also be clearly shown.

Curve 4 "particle diameter 0.3 μm" is clearly steeper than curve 3 "d = 0.4 μm."

While in the light attenuation measurement the measurement $m(C_e, z)$ increases approximately as the square of the particle diameter, the scattered-light measurement for particles smaller than 1 μm in diameter is proportional to d^3 up to d^6. As is also apparent in figure 3, the scattered-light effect decreases very sharply for smaller particles. This tendency manifests itself still more clearly in the measurement results in figure 8. Curve 4 (d = 0.3 μm) is almost twice as steep as curve 3 (d = 0.4 μm). This is explainable by the fact that the measurement $y = K_2 \cdot z \cdot \bar{d}$ in the ionization chamber is only proportional the particle diameter.

The curves in figure 9 were drawn in order to be able to check the adjustment of the aerosol generators in comparison with earlier measurements. The tendency for the light attenuation measurement at larger particle diameters to yield a greater measurement effect in comparison with the I-chamber measurement can also be seen here.

In comparison with earlier measurements it was finally possible to establish that, although within a single measurement there exists a linear relationship between ΔU_S and m or y, nevertheless in different measurement series, clearly differing slopes of the lines $m(\Delta U_S)$, $y(\Delta U_S)$ occurred and this was under what were evidently the same adjustment conditions of the same aerosol generator. If one excludes measurement errors and equipment errors, then the differences cited can arise as a consequence of differing aerosol parameters.

It is known that for an atomizer at higher pressure the mean diameter of the generated particles is smaller. Some experiments with two aerosol generators of the same type at different pressure adjustments have confirmed this fact.

Thus in the testing of smoke detectors in the basic test, one must make sure that, in measuring the response threshold before and after stressing by environmental influence, the parameters of the test aerosol are reproduced with a certain tolerable deviation. For this purpose, use should be made of the measurements m, y and ΔU_S at increasing concentration.

Finally, it must also be mentioned that in the diagrams of figure 7 the light attentuation between source and receptor in the scattered-light measurement has still not been taken into account. For the test aerosol employed here the extinction cross section was assumed to be 0.18 μm^2. From this one obtains, depending upon the particle concentration, the following measurement errors:

z/cm^{-3}	m/dB/m	Error/%
10^6	0.8	2.5
$2 \cdot 10^6$	1.6	5.0
$4 \cdot 10^6$	3.2	10.0

4.1. Sensitivity of the Device

The smallest measurement with the scattered-light device, expressed in terms of the light extinction produced by paraffin-oil mist, amounted to 0.06 dB/m. In this way the measurement range is maintained which was required for the testing of smoke detectors in accordance with previous test guidelines.

The sensitivity of the device with respect to particle size and concentration depends upon various quantities which can in part be further varied. With the present device, fixed values are preassigned to the wavelength λ of the light source, the sensitivity of the photodiode and, within certain limits, to the scattering angle and the scattering volume.

The output power of the laser can be varied by changing the supply voltage. The size of the scattering volume depends upon the mean scattering angle and upon the diaphragm apertures. In contrast to the particle counter, with which individual particles are analyzed with respect to their size in a temporal sequence one after the other, here we are dealing with an integral measurement. This means that the output measurement is simultaneously a function of the particle diameter and of the mean particle concentration in the scattering volume. Hence, to estimate the largest and smallest measurable particle diameter it is necessary in each case also to specify the concentration, and conversely. According to the calculation process described by Kraus for determining the particle size parameters, with the present device it is possible to measure particles in the size range 0.2-5 μm. Since the scattered-light intensity at these limits depends very sharply upon particle diameter, it is possible here to give only an approximate measurement range from $z = 10^3$ to $10^6\ cm^{-3}$. These data apply in each case to the paraffin-oil test aerosol.

By modifying the structural elements in the amplifier the sensitivity of the device to concentration can be further reduced by a factor ranging from 10^2 to 10^3. If the scattering angle is enlarged then the sensitivity can also be reduced, depending upon particle size, by the factor 10-100. However, this has the disadvantage that then the measurement again depends more upon the refractive index of the particles.

For the main application of the device in the basic test the existing adjustment of the device parameters has shown itself to be good.

4.2. Use in the Proof Test

We are planning future testing of the device with aerosols from actual test fires. From the results, we will know whether for unfavorable refractive indices of these types of smoke or for low concentrations it will become necessary to further increase the sensitivity of the measuring equipment. This could be accomplished, for example, by increasing the laser power or by changing the amplifier data.

For use of the device in the proof test it is recommended that the temperature dependence of the laser be automatically compensated, as above-described, and that the measuring equipment, together with a more compactly-designed evaluating circuit, should be assembled on a common base plate. The power supply and the output signal can then be brought in or conducted out over relatively long cables.

The above-described scattered-light measuring device for the type-testing of smoke detectors has shown, through the measurement results, that the basic design is usable for the stated application and satisfies all requirements which need to be imposed upon such a device for the purpose of measurement, particularly in the basic test.

No claim is made that the existing design should be proposed as a standard measuring device since this first laboratory model was also intended for studying the problem of measuring light scattered by artificial aerosols in the smoke tunnel. This purpose has been achieved. In addition to this, the device is suited, together with the light attenuation device and the ionization chamber, to determining the parameters of the size distribution of test aerosols at a prescribed refractive index.

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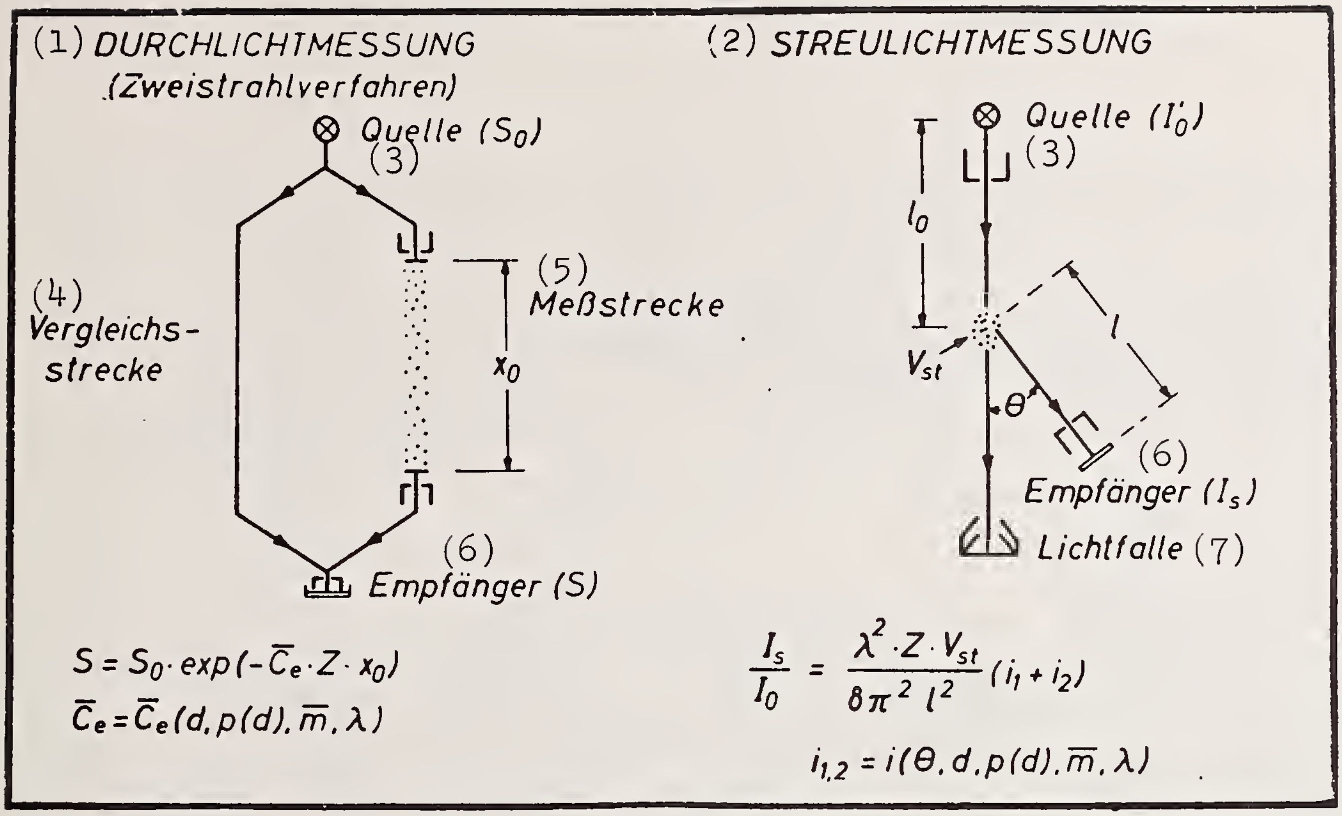


Key:
1. Transillumination measurement (double beam process)
2. Scattered-light measurement
3. Source
4. Comparison stretch
5. Measurement stretch
6. Receptor
7. Light trap

Figure 1. The Principle of Scattered-Light Measurement and Transillumination Measurement (see table 1)

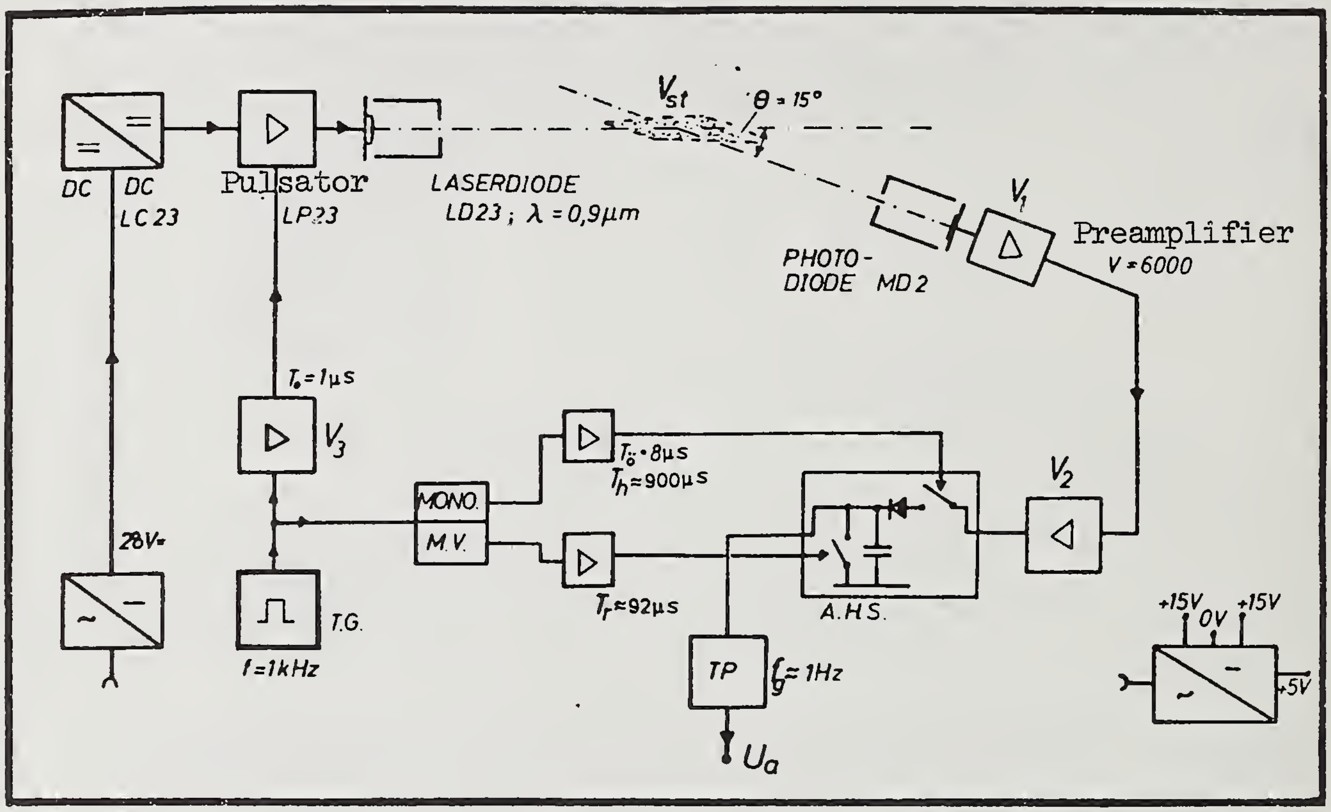


Figure 2. Block Schematic of the Laser Scattered-Light Measuring Device

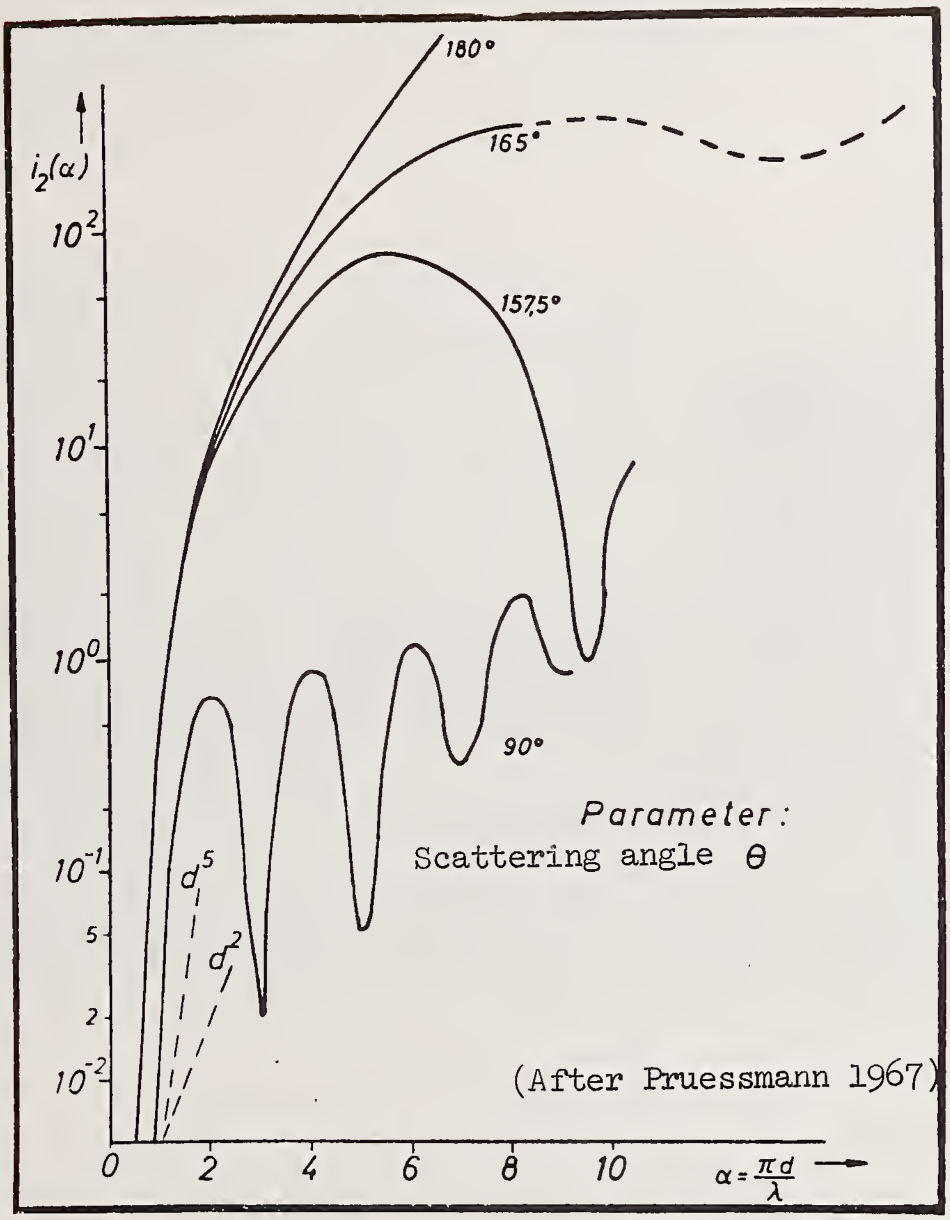
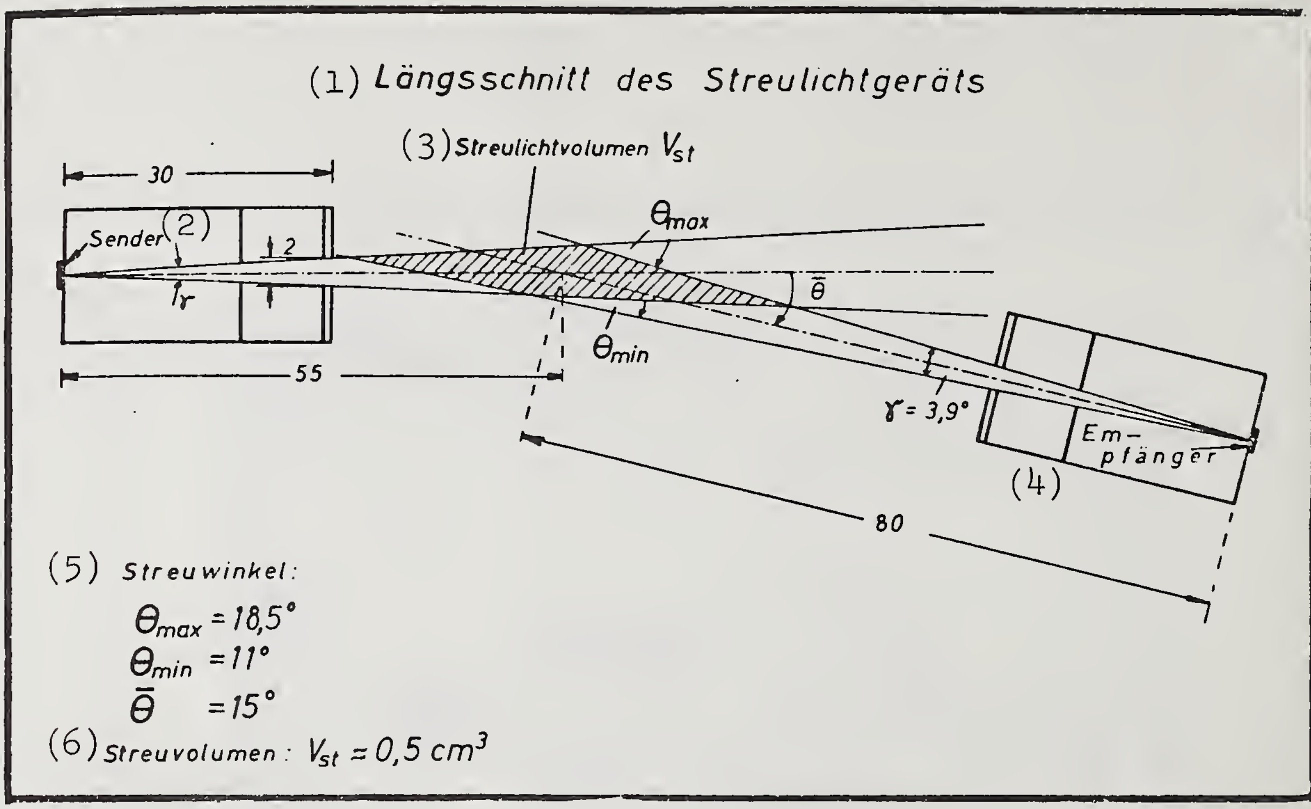


Figure 3. Intensity Function for Soot Particles



Key:
1. Longitudinal section of the scattered-light device
2. Transmitter
3. Scattered-light volume
4. Receiver
5. Scattering angle

Figure 4. Laser Scattered-Light Device; Geometry

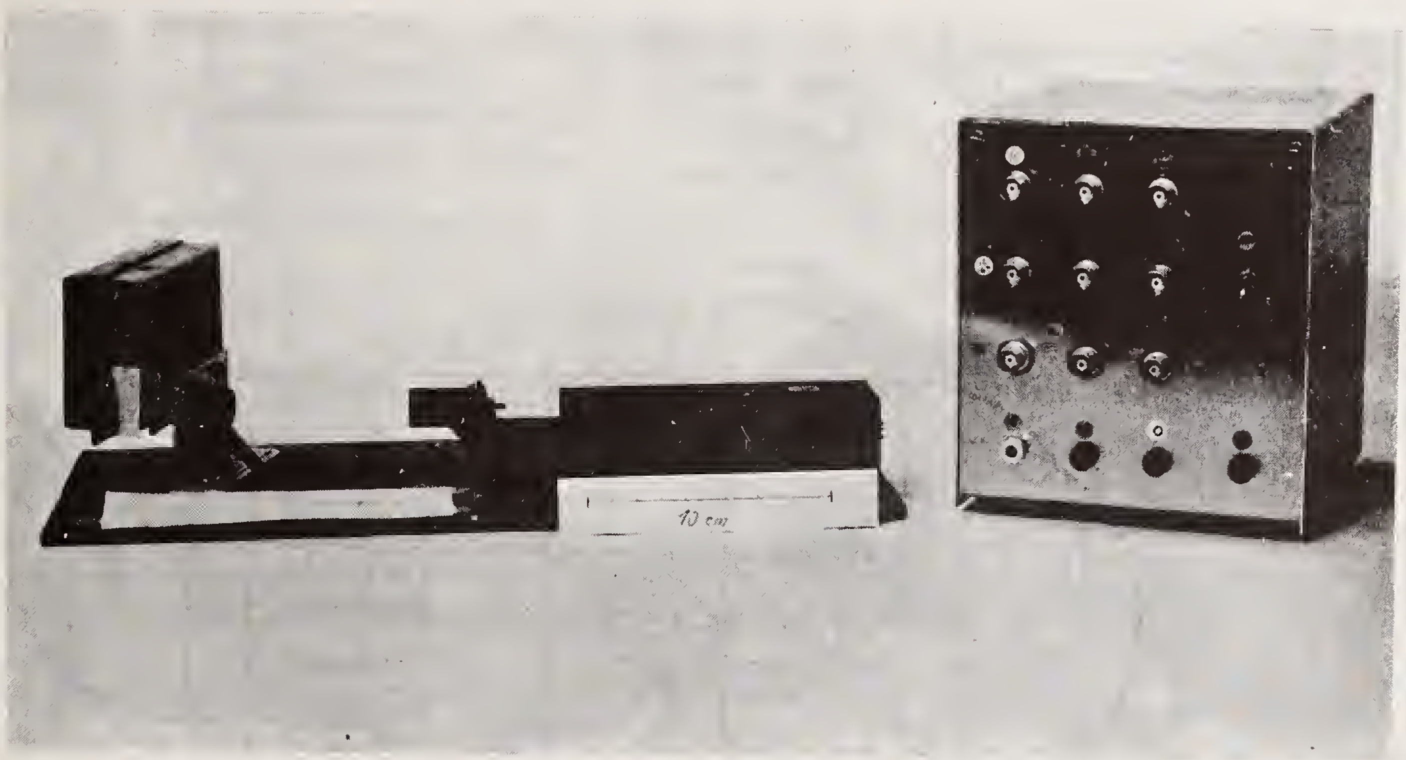
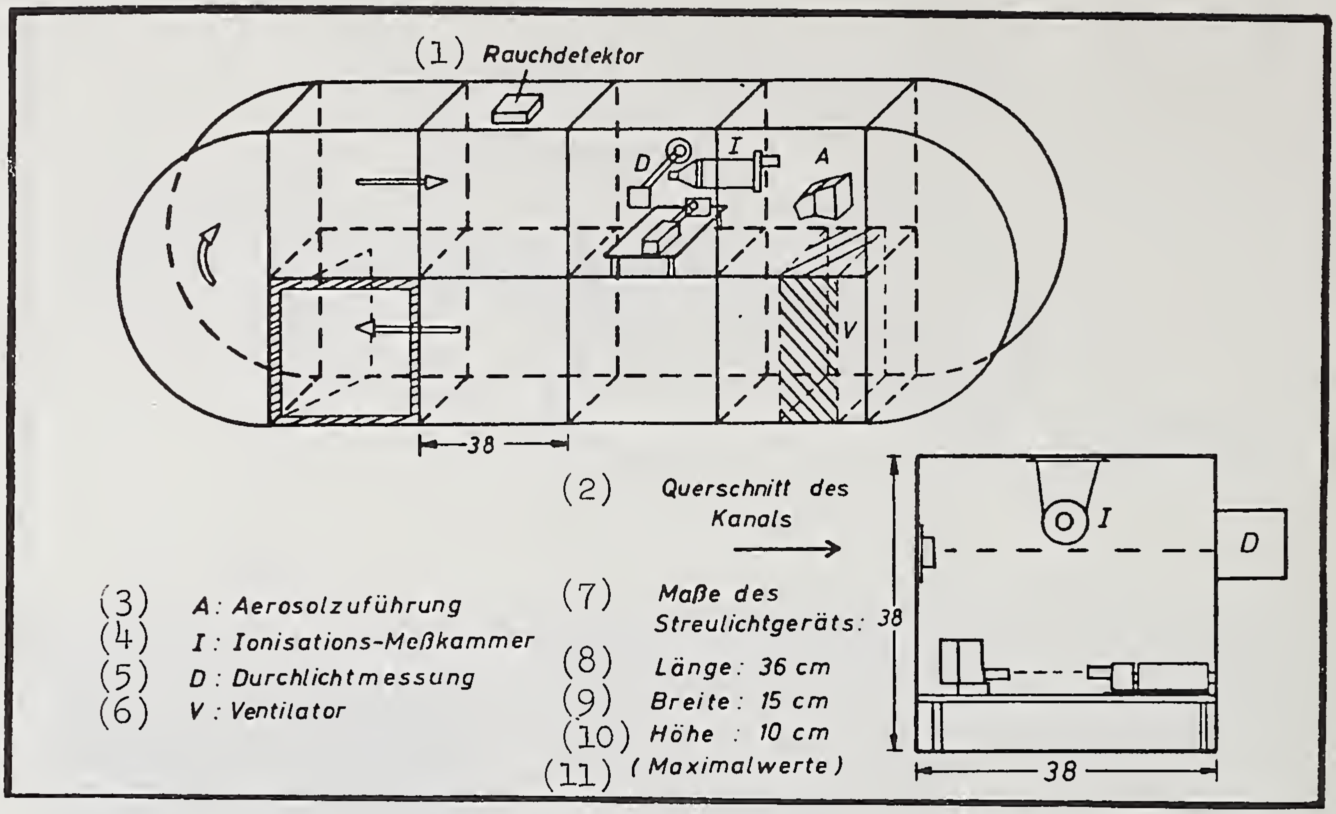


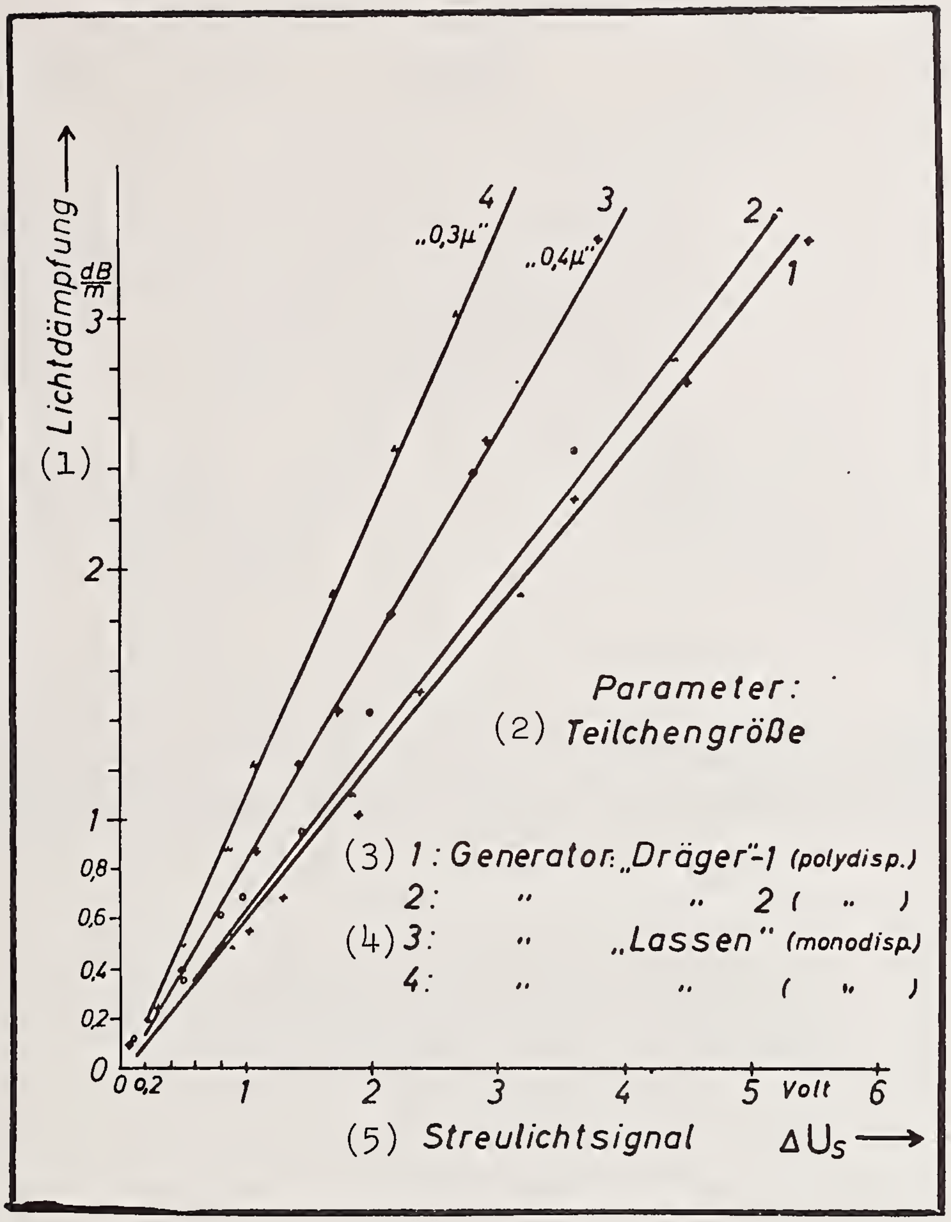
Figure 5. Scattered-Light Measuring Device with Evaluating Circuit



Key:

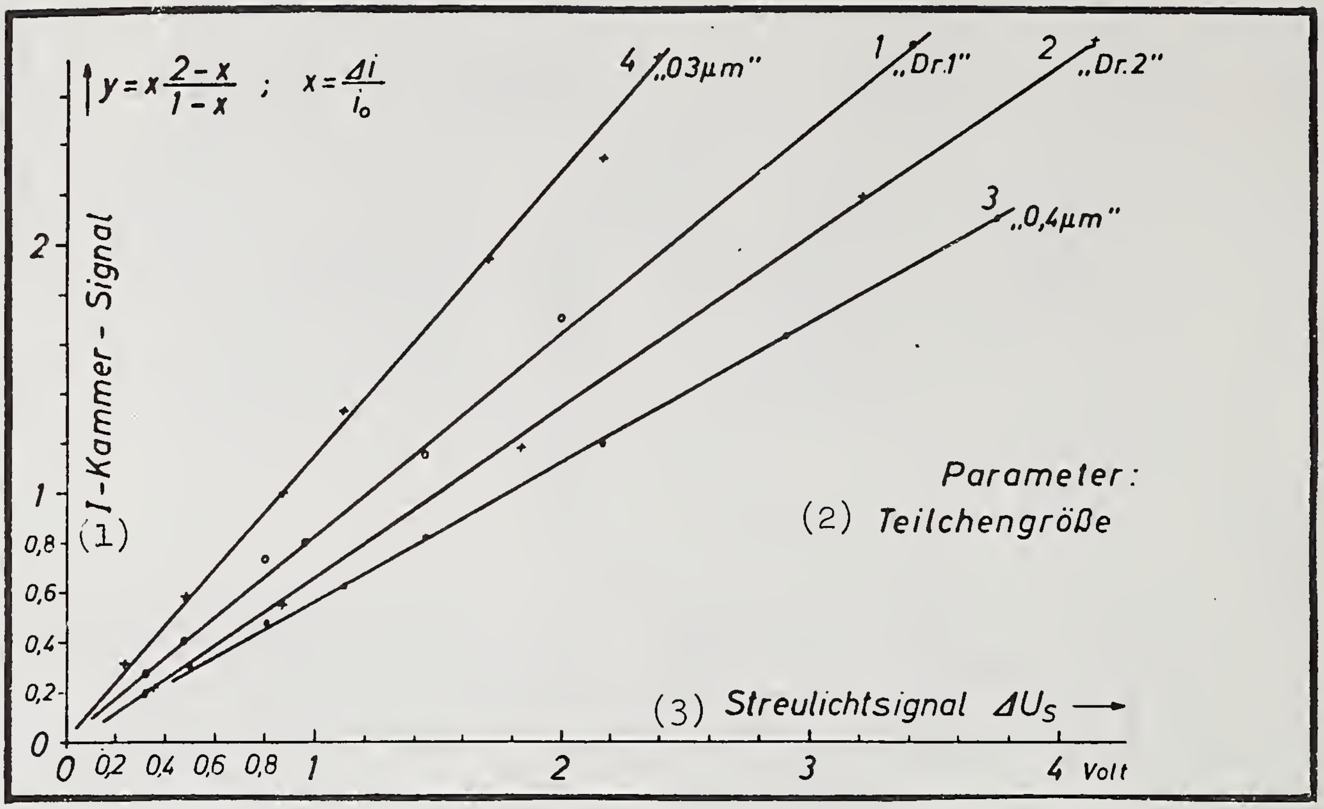
1. Smoke detector
2. Cross section of the channel
3. Aerosol intake
4. Ionization measuring chamber
5. Transillumination measurement
6. Ventilator
7. Dimensions of the scattered-light device:
8. Length
9. Width
10. Height
11. (Maximum values)

Figure 6. Arrangement of the Scattered-Light Device in the Smoke Channel



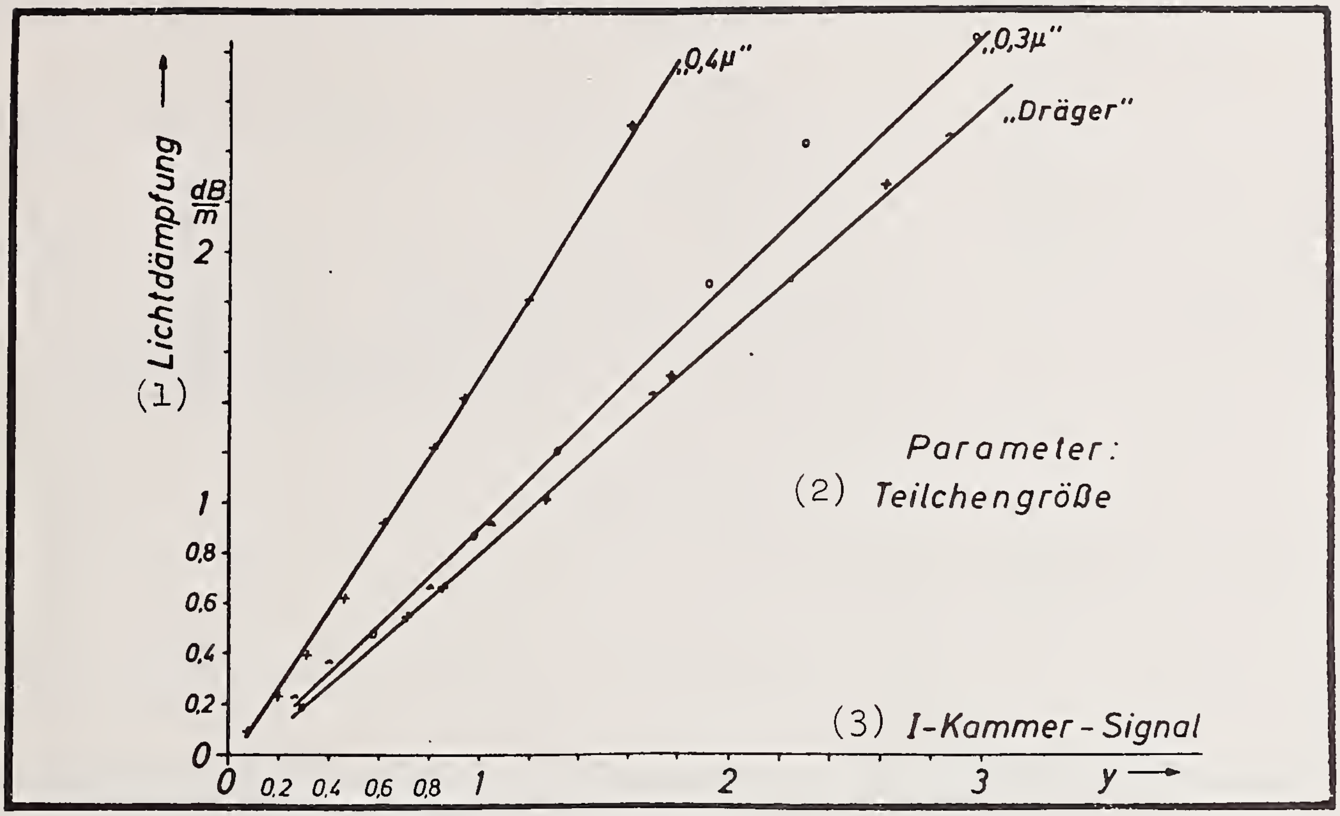
Key:
1. Light attenuation
2. Parameter: particle size
3. Generator: "Draeger" — (polydispersed)
4. Generator: "Lassen" (monodispersed)
5. Scattered-light signal

Figure 7. Light Attenuation as a Function of the Scattered-Light Signal



Key: 1. I-chamber signal
2. Parameter: particle size
3. Scattered-light signal

Figure 8. I-Chamber Signal as a Function of the Scattered-Light Signal



Key:
1. Light attenuation
2. Parameter: particle size
3. I-chamber signal

Figure 9. Light Attenuation as a Function of the I-Chamber Signal

Table 1. Technical Data for the Scattered-Light Device

1. Dimensions

Length: 36 cm; maximum width 15 cm; maximum height 10 cm

Scattering angle: $\theta_{max} = 18.5°$; $\theta_{min} = 11°$; $\bar{\theta} = 15°$

Scattering volume: = 0.4 cm^3

Distance between center of scattering volume and light source: 5.5 cm

Distance between center of scattering volume and receptor: 8.0 cm

Aperture angle of the radiation cone of the transmitter and receiver: 3.8°

Diaphragm aperture: 2 mm diameter

2. Electrical Data

a) Light source: GaAs laser diode, type LD 23
Manufactured by Laser Diode Laboratories, New Jersey, USA or the
E. Sommer Company, Frankfurt

Wavelength: λ = 0.9 μm

Mode of operation: pulse operation, pulse breadth: 130 ns, pulse repetition frequency: 1 kHz

Peak output power: 12 W at T_u = 25 °C

Peak output power: 9 W at T_u = 55 °C of which 90 percent is radiated in a cone having a 23° aperture angle

Power supply: 28 V = $\pm$ 3V, 250 mamps

Control using pulse generator, f = 1 kHz

Pulse width 1 μs, TTL (expansion unknown) — level

b) Photoreceptor: Silicon PIN diode, type MD 2
Manufactured by Monsanto or A. Neye, Hamburg-Quickborn

Sensitivity: 4 μamps per mW/cm^2

Dark current: 2.5 namps (H_d 1 $\mu W/cm^2$)

Pulse rise time: 3 ns

Maximum power loss: 300 mW

Maximum spectral sensitivity at λ = 0.9 μ

c) Pulse amplifier:

Voltage amplification V_n = 6,000 $\hat{=}$ 76 dB within the 3 dB limiting frequencies from 1 kHz to 1 mHz; V_n (100 Hz) = 58 dB
Push-pull coupling

3. Sensitivity of the Arrangement

$U_{a\,max}$ corresponds to a value > 6 dB/m = 86%/m light attenuation in the light attenuation measurement

$U_{a\,min}$ corresponds to 0.06 dB/m = 1.4%/m light attenuation in the light attenuation measurement

$\hat{=}$x = 0.03; y = 0.05 in the ionization chamber measurement (test aerosol: paraffin-oil mist)

4. Observation Error Resulting from Light Attenuation (Extinction) Between Light Source and Receptor

Error $\leq$ 2.5 percent for particle concentration of z $\leq$ 10^6 cm^{-3} (applicable for paraffin-oil mist with $\bar{C}_e$ = 0.18 μm^2).

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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.)*

Generally, the response threshold value of fire detectors is tested with measuring instruments which operate on the same physical principle as the detectors to be tested. For example, this means that the response threshold value of an ionization measuring chamber and the response threshold value of an optical-type smoke detector operating on a light extinction principle is checked using an extinction measuring instrument. However, optical-type smoke detectors operating on a light-scatter principle (photoelectric in U.S. parlance) have also been checked using an extinction measuring instrument.

Since the light-scatter type of smoke detector is by far the most commonly used of the optical type of smoke detector it seems appropriate to use a light-scatter measuring instrument to check the response threshold value of these detectors. In addition, the need for such a measuring instrument is emphasized by the fact that both the parameters of the smoke aerosol and the design features of the measuring instrument are affected in different ways by light scatter and light extinction.

The author describes the technical features and design details of a newly-developed, light-scatter measuring instrument along with some experiments to determine its response to artificially-generated aerosols.

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)* Fire detection; light extinction; light scatter; light-scatter measurements; photoelectric smoke detectors; smoke detectors.

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