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Integral Measurement Procedures for Determining Particle Size in Aerosols

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Institute for Electronic Communication
Technology of the Rheinisch-Westfalian
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Aachen, West Germany

Translated for:

Center for Fire Research
Institute for Applied Technology
National Bureau of Standards
Washington, D. C. 20234

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Final Report

U S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

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U.S. DEPARTMENT OF COMMERCE, Elliot L. Richardson, *Secretary*
James A. Baker, III, *Under Secretary*
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 Mr. F. J. Kraus and presented by him at the Colloquium on Aerosol Measurement Techniques held March 4, 1975, in Aachen, West Germany. The Colloquium 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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Richard G. Bright
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and Control Systems
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INTEGRAL MEASUREMENT PROCEDURES FOR DETERMINING PARTICLE SIZE IN AEROSOLS

F. J. Kraus

Abstract

In assessing the performance of smoke detectors in the laboratory, it is necessary to have standardized smoke measurement devices which function according to the same principles as the smoke detectors under test. In developing these measurement devices, a need exists to determine, as precisely as possible, the effects of the smoke characteristics on the measurement devices. This paper presents the correlation between smoke characteristics and comparative measuring devices important in smoke detector test work and how these measuring devices can also be used as aerosol measuring devices.

Key words: Aerosols; ionization chambers; light attenuation; scattered light; smoke detectors; test methods.

1. INTRODUCTION

In the USA in 1972, property valued in the amount of 2.7 billion dollars was destroyed by fire. About 12,000 persons yearly die in the USA by fire, most of them from the effects of smoke and noxious gases [1][1]. The problems of automatic fire detection increase in significance more and more. What is required for automatic fire detection is a measuring device which reacts to a definite fire characteristic and initiates an alarm signal when this characteristic exceeds a prescribed threshold. A frequently used fire characteristic is smoke which, as a rule, results from fires.

There already exists a number of automatic smoke detectors, working according to different functional principles. The common characteristic of all smoke detectors is the transformation of certain characteristics of smoke into an electrical quantity, which makes possible comparisons with a threshold value. Smoke detectors are, as a rule, subjected to technical tests, which are supposed to investigate whether

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

the detector is (1) sufficiently sensitive for the planned application, (2) already able to detect a fire at an early stage, and (3) whether the smoke detector retains this property unchanged over a sufficiently long period of time. These tests are, in practice, performed with artificial aerosols and with smoke from real test fires. It has turned out that smoke detectors react quite differently to different types of smoke. To obtain a norm for the sensitivity of a smoke detector, standardized smoke measurement devices have been developed, which work according to different functional principles, just like the smoke detectors themselves. The objective is always to compare a smoke detector under test with a standard measurement device which works according to the same functional principle as the smoke detector under test itself.

In developing these standard measuring devices, the task consisted in determining as accurately as possible the transformation properties between the smoke characteristics and the electrical quantity of measurement. In this paper it will be shown how the connection between smoke characteristics and the electrical quantity of measurement was determined for comparative measuring devices important in testing smoke detectors and what opportunities resulted therefrom for using these comparative measuring devices as aerosol measuring devices.

2. SMOKE MEASUREMENT DEVICES

In the following three sections, the three smoke measurement devices used in testing smoke detectors are described, and a theoretical hypothesis is derived for the connection between the electrical quantities of measurement and the parameters of the aerosol. To simplify the mathematical description, we first start with the measurements of monodisperse aerosols with spherical particles.

2.1. Extinction Measurement Device

With the extinction measurement device, attenuation of a parallel monochromatic light beam by aerosol particles is measured. In the practical design of the measurement device, it was found appropriate to use a so-called double-beam process. With this double-beam process, a light ray penetrates the measurement distance, homogeneously filled with aerosol, while a second light ray is directed through a mirror system directly on an optical receiver, without traversing the measuring distance. Both light rays are generated from the same light source and are focused on the same

receiver. By differentially modulating the two light rays, the associated signals can be separated electrically, and the degree of transmission of the measuring distance filled with aerosol can be directly measured by forming a quotient. When the adjustment is correct, the following is valid for the output signal (u) of the measuring device:

$$u = \tau \tag{1}$$

Here, τ is the degree of transmission of the aerosol.

According to the law of Bouguer and Lambert [2,3], the following is valid for this degree of transmission:

$$\tau = \exp\,[-\,\sigma \cdot l] \tag{2}$$

Here σ is the extinction modulus of the aerosol and l is the length of the measurement path. The extinction modulus σ can now be expressed according to Beer's law in terms of the particle concentration z (number concentration) and the extinction cross section C_{Ext} of an aerosol particle:

$$\sigma = z \cdot C_{Ext}$$

$$C_{Ext} = C_{Ext}\,(\lambda_E,\ d,\ \underline{m}) \tag{3}$$

The extinction cross section C_{Ext} is a function of the wavelength λ_E of the measured light, of the particle diameter d, and of the complex index of refraction $\underline{m}$ of the aerosol particle.

From equations (1), (2), and (3), there follows:

$$u = \exp\,[-\,z \cdot C_{Ext} \cdot l] \tag{4}$$

Simple solution of this equation leads to:

$$m = z \cdot C_{Ext} = \frac{0.434}{l} \log \frac{1}{u} \tag{5}$$

Here and below, m designates the measured value of the extinction measurement device. The extinction device used

in measurements to be described later works with monochromatic light of wavelength $\lambda_E = 0.8\ \mu m$. The effective length of the measuring path is $l = 76$ cm. The measured value m has the dimension [1/length]. The connection between the measured value m and the parameters of the aerosol are described by the assumption

$$m = z \cdot C_{Ext} \tag{6}$$

2.2. Scattered-Light Measurement Device

The scattered-light measurement device used in testing smoke detectors measures a collectivity of aerosol particles, just like the extinction measurement device. The boundary condition existing in its development was the practical design of a scattering volume open on all sides. This was to ensure that the aerosol should, as much as possible, not be influenced by the measurement process. The developed measuring device operates with a pulsed semiconductor laser at a wavelength of 0.905 μm and a mean scattering angle of 15° with respect to the forward direction. The limiting values for the scattering angle lie at 12° and 18°. The following assumption was made for the connection between the aerosol parameters influencing the measurement and the electrical output signal u of the scattered light measurement device:

$$u = K_2 \cdot z \cdot i$$

$$i = i(\Theta_o, \lambda_s, d, \underline{m}) \tag{7}$$

Here, i is the sum of the Mie intensity functions, and it depends on the scattering angle, the wavelength of the measured light, the particle diameter, and the complex index of refraction. The term z is the number concentration of the aerosol particles and K_2 is a device constant. The integration of the intensity function over the solid angle was taken into account in the device constant K_2 because of the small effective angular range.

2.3. Measurement Device According to the Small Ion Accumulation Effect

The measurement device according to the small ion accumulation effect, hereafter called the I-chamber for short, is in principle embodied in a cylindrical electric condenser arrangement, in which flows an ion stream. When there are smoke particles in the I-chamber, small ions accumulate at these smoke particles, which are larger by orders of magnitude, and thereby effect a measurable reduction of the ion current [4,5]. The I-chamber is continuously traversed by the aerosol contained in the surrounding air so that a continuous measurement of the collectivity of aerosol particles is possible. The following assumption is valid for the connection between the relevant aerosol parameters and the electrical output signal y of the measurement device:

$$y = K_1 \cdot z \cdot d \tag{8}$$

To justify this assumption, see references [6] and [7].

All three measurement devices described measure a collectivity of aerosol particles. The measurement volumes are all constructed as open as possible, so that the aerosol reaches the individual measurement zones uninfluenced. A close grouping of the measurement devices during measurement can achieve simultaneous measurement of the same particle concentration z by all three measurement devices. The measurement process is continuous in time. The connections cited for the individual measurement devices, between the aerosol parameters and the electrical output quantities of the measurement devices (equations 6-8), are to be understood as hypotheses, which require experimental verification.

3. EXPERIMENTAL TEST

To test the characteristic equations (6-8) of the measurement devices experimentally, all three measurement devices were installed in an aerosol channel and were exposed to a temporal rise in aerosol concentration. The measured values m (extinction measurement device), u (scattered-light measurement device) and y (I-chamber) are continuously recorded with time. Monodisperse paraffin oil mist was used as a test aerosol and it was produced by a La-Mer generator. The particle size of the test aerosol was determined by means of an "owl" (Tyndall colors). Computed results from the Mie theory were used to connect the position of the Tyndall colors and the geometric particle diameter d. The index of refraction of

the oil droplets was $\underline{m} = 1.41 - i0.15$. For evaluation, the always-simultaneously measured values, m and u, were plotted as functions of y. Figures 1 and 2 show that directly proportional relationships between m and y and between u and y always result. From the hypothetical assumptions (equations 6-8) there follows:

$$m = \underbrace{\frac{z \cdot C_E}{K_1 z \cdot d}}_{A'} \cdot y \tag{9}$$

$$u = \underbrace{\frac{K_2 z \cdot i}{K_1 z \cdot d}}_{B'} \cdot y \tag{10}$$

Since the aerosol itself was constant during the entire time of the experiment, as could be confirmed by checking with the Tyndall colors, all the measuring devices must have measured the same particle concentrations. If this were not the case, the proportionality factors A' and B' from equations (9) and (10) could not be constant, and no directly proportional relationship between the individual measured quantities could have resulted from the experiments. Information concerning the particle size of the aerosol is contained in the proportionality factors A' and B'.

$$A' = \frac{m}{y} = \frac{1}{K_1} \cdot \frac{C_E}{d} \tag{11}$$

$$B' = \frac{u}{y} = \frac{K_2}{K_1} \cdot \frac{i}{d} \tag{12}$$

It will now be shown that the interpretation of factors A' and B' given in equations (11) and (12), can be confirmed experimentally. For this purpose, experiments were performed in the manner described above, using several monodisperse aerosols, and the characteristic quantities A' and B' were determined each time. The experimental result obtained is the characteristic quantities A' and B' as functions of the

particle diameter d. These experimentally determined relationships A' (d) and B' (d) are then compared with C_E/d as a function of d and with i/d as a function of d, the dependences of both fractions being calculated from Mie theory. These theoretically calculated relationships are shown in figures 3 and 4. The drawn points (x) are measured values for the relationships A' and B' respectively. By fitting the ordinate scales for the measured functions A' (d) and B' (d) to the calculated functions C_E/d and i/d as functions of d, the device constants K_1 and K_2 could be determined.

$$K_1 = \left.\frac{C_E/d}{A'}\right|_{d_i} \quad i = 1 \cdots 13 \tag{13}$$

$$\frac{K_1}{K_2} = \left.\frac{i/d}{B'}\right|_{d_i} \quad i = 1 \cdots 9 \tag{14}$$

Here, i designates the individual measurements with monodisperse aerosols of different particle diameters. From these measurements, the following values result for the device constants:

$$K_1 = (2.6 \pm 0.1) \cdot 10^{-2}\ \mathrm{cm}^2 \tag{15}$$

$$\frac{K_1}{K_2} = (8.9 \pm 0.5)\ \frac{1}{\mathrm{V}\mu\mathrm{m}} \tag{16}$$

Actual constants resulted from the experimentally found data, that is the values K_1 and K_1/K_2, could be determined with an accuracy of 4% and 6% respectively — independent of the particle diameter d. Consequently, the relations cited in equations (6)-(8) can be reqarded as experimentally confirmed. The following relations are therefore valid for the connection between the relevant aerosol parameters and the electrical output quantities of the three integral measurement procedures which have been mentioned:

Extinction measurement: $m = z \cdot C_E$ (17)

I-chamber measurement: $y = 2.6 \cdot 10^{-2} \cdot z \cdot d \cdot \mathrm{cm}^2$ (18)

Scattered-light measurement: $u = 0.3 \cdot z \cdot i\ \mu\mathrm{Vcm}^3$ (19)

In the form in which they are given, equations (17)-(19) are valid for monodisperse aerosols, i.e. for aerosols whose particles all have the same diameter d. On passing to polydisperse aerosols, all quantities in equations (17)-(19), which depend on the random variable d (particle diameter), are to be replaced by their expectation values.

This means:

$$C_E \rightarrow \overline{C_E} = \int_0^\infty C_E(d) \cdot p(d)\, dd \tag{20}$$

$$i \rightarrow \overline{i} = \int_0^\infty i(d) \cdot p(d)\, dd \tag{21}$$

$$d \rightarrow \overline{d} = \int_0^\infty d \cdot p(d)\, dd \tag{22}$$

Here, p (d) is the probability density function for the particle diameter d of a polydisperse aerosol.

The equations for the measuring device, which form the starting point for the discussion below, take into account the relations given in equations (20)-(22), and are as follows:

$$m = z \cdot \overline{C_E} \tag{23}$$

$$y = K_1 \cdot z \cdot \overline{d} \tag{24}$$

with $K_1 = 2.6 \cdot 10^{-2}\ cm^2$

$$u = K_2 \cdot z \cdot \overline{i} \tag{25}$$

with $K_2 = 0.3\ \mu Vcm^3$

These equations are now generally valid for polydisperse aerosols. The specified device constants K_1 and K_2 are valid specifically for the measurement devices described above.

3.1. Remarks Concerning the Logarithmic Normal Distribution

Mutually divergent relationships are frequently cited for the probability density function of a logarithmic normal distribution. For this reason, some derivations and conceptual clarifications will be given at this point. The difference between the logarithm to base ten and the natural logarithm is frequently disregarded in the literature.

The following holds:

Logarithm to base 10: $\log a$

Natural logarithm (base e): $\ln a$

$$\log a = M \cdot \ln a; \quad M = \log e \simeq 0.43429$$

If x is a random variable, then

$$\psi(x) = \frac{1}{\sqrt{2\pi}\,\sigma} \cdot \exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\}; \int_{-\infty}^{+\infty} \psi(x)\,dx = 1$$

describes the probability density function of a Gaussian or normal distribution. The equation for the normalized Gaussian or normal distribution is as follows:

$$\psi(u) = \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{u^2}{2}\right\}; \quad u = \frac{x-\mu}{\sigma}$$

The following holds for the cumulative probability distribution:

$$\phi(x) = \int_{-\infty}^{x} \psi(s)\,ds; \quad d\phi(x) = \psi(x)\,dx$$

The distributions to be investigated later refer to the random variable particle diameter d (d = x). It has turned out that, with most condensation aerosols, the particle diameters themselves are not distributed normally, but only the logarithms of the particle diameters follow a normal distribution. The base according to which the logarithms are determined is here in the first instance unimportant. But if the normal distribution is to be described

by definite characteristic values (mean value, deviation), precise attention must be paid to which random variable is being considered.

The following holds:

Let x be a random variable

Let $u = f(x)$ be a transformed random variable with a normal distribution.

The probability density function $p(x)$ of the random variable x is sought.

Since the random variable u is distributed normally, the following assumption can be made for the cumulative probability function:

$$\phi(u) = \phi(f(x)) = P(x)$$

$$dP(x) = p(x)dx = \psi(f(x))\, df(x)$$

From this follows:

$$p(x) = \psi(f(x)) \cdot \frac{df(x)}{dx}$$

$$p(x) = \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{f(x)^2}{2}\right\} \frac{df(x)}{dx}$$

In many practical cases, a transformation of the following type can be assumed for the transformation $f(x)$:

$$f(x) = \frac{g(x) - g(\xi)}{\sigma}$$

Here, $g(x)$ is a new random variable, which is normally distributed about the constant mean value $g(\xi)$, with a standard deviation σ.

A random variable has a logarithmic normal distribution, when the logarithm of the random variables is distributed normally.

There thus results the following possibilities for describing a logarithmic normal distribution: $(x > 0)$

1. $g(x) = \log x; \qquad \frac{df(x)}{dx} = \frac{M}{\sigma x}$

2. $g(x) = M \cdot \ln x; \qquad \frac{df(x)}{dx} = \frac{M}{\sigma x}$

3. $g(x) = \ln x; \qquad \frac{df(x)}{dx} = \frac{1}{\sigma x}$

4. $g(x) = \frac{1}{M} \log x; \qquad \frac{df(x)}{dx} = \frac{1}{\sigma x}$

The associated probability density functions are:

1. $p(x) = \frac{M}{\sqrt{2\pi}\ \sigma x} \cdot \exp\left\{- \frac{\log x - \log \xi)^2}{2\sigma^2}\right\}$

2. $p(x) = \frac{M}{\sqrt{2\pi}\ \sigma x} \cdot \exp\left\{- \frac{(\ln x - \ln\xi)^2\ M^2}{2\sigma^2}\right\}$

3. $p(x) = \frac{1}{\sqrt{2\pi}\ \sigma x} \cdot \exp\left\{- \frac{(\ln x - \ln\xi)^2}{2\sigma^2}\right\}$

4. $p(x) = \frac{1}{\sqrt{2\pi}\ \sigma x} \cdot \exp\left\{- \frac{(\log x - \log\xi)^2}{2\sigma^2\ M^2}\right\}$

Now since all four probability density functions describe the same physical state of affairs, all four functions must also yield the same values. This is only possible with the consideration that the deviation σ is not numerically the same in all cases. In case 1 and 2, σ^2 gives the variance of log x (logarithm to base ten), while in case 3 and 4, σ^2 gives the variance of ln x (natural logarithm). The relationship between the deviation σ is given by

$$\sigma \left\{\log x\right\} = M \cdot \sigma \left\{\ln x\right\}; \qquad M = \log e = 0.43429$$

The subsequent discussion is always based on the transformation for the logarithmic normal distribution specified in case 3. There thus results for the probability density function:

$$p(d) = \frac{1}{\sqrt{2\pi}\ \sigma d} \exp' \left\{ - \frac{\ln \frac{d}{\varepsilon}^{2}}{2\sigma^2} \right\} \tag{26}$$

As already mentioned, σ^2 is here the variance of ln d, and ξ is the median value of the random variables d.

The width Λ is used as another parameter in describing the log-normal distribution:

$$\Lambda = \frac{\xi}{\text{Modus (d)}} = \exp' \left\{\sigma^2\right\} \tag{27}$$

The expectation value of d can be described in terms of ξ and Λ. The following holds:

$$\bar{d} = \int_0^\infty d \cdot p(d)dd = \xi \cdot \exp' \left\{ \frac{\sigma^2}{2} \right\} \xi\sqrt{\Lambda} \tag{28}$$

3.2. Determination of the Distribution Parameters of a Polydisperse Aerosol

In determining the particle size distribution of a polydisperse aerosol of an arbitrary type, determination of an unlimited number of parameters is required. This is experimentally impossible. A customary approximation in the solution of the problem consists in dividing the particle size distribution into a limited number of intervals based on the particle diameter. Each interval is here described by a parameter to be determined by technical measurement (histogram).

In the case treated here, only three integral measurement procedures are available, and thus, at most, three unknown parameters can be determined. Consequently, another approximation must be made in order to determine the particle size distribution of a polydisperse aerosol. The starting point must be that the type of particle size distribution is known in advance, and can be analytically represented by two free parameters.

To elucidate the measuring process, the discussion below takes as its starting point that the particle diameters of the aerosol under analysis have a logarithmic normal distribution. This assumption is always fulfilled with sufficient accuracy for aerosols of interest within the framework of automatic fire detection. This is true because condensation aerosols are considered exclusively.

To analyze a polydisperse aerosol, for example, such as that generated by the mist generators used in testing smoke detectors, the following relationships are available:

$$m = z \cdot \overline{C}_E \tag{29a}$$

$$u = K_2 \cdot z \cdot \overline{i} \tag{29b}$$

$$y = K_1 \cdot z \cdot \overline{d} \tag{29c}$$

$$\overline{C_E} = \overline{C_E}\ (\xi,\ \Lambda,\ \underline{m},\ \lambda_E) \tag{29d}$$

$$\overline{i} = \overline{i}\ (u,\ \Lambda,\ \underline{m},\ \lambda_s,\ \psi_o) \tag{29e}$$

$$\overline{d} = \overline{d}\ (\xi,\ \Lambda) \tag{29f}$$

The first three equations here refer to the measurement technique, while equations (29d) and (29e) are given by Mie theory. The following initial conditions are required to solve this system of equations:

1. The type of particle distribution must be known a priori (here e.g., log-normal distribution), and must be describable by two free parameters.

2. The aerosol particles must have a shape which is accessible to the theoretical calculations of Mie theory (e.g., homogeneous spheres, concentric spherical shells, rods, etc.)

3. The complex index of refraction $\underline{m}$ of the aerosol particles must be known a priori.

When the three initial conditions are fulfilled, and when the properties of the measuring devices described further above are taken into consideration, the following quantities in the system of equations (29) are known:

Device constants: K_1, K_2, λ_E, λ_s, ψ_o

Aerosol parameters: $\underline{m}$ (complex index of refraction)

The following can be determined by technical measurement:

$$m,\ u,\ y$$

The following remain as unknown quantities in the system of equations:

$$z,\ \overline{C_E},\ \bar{i},\ \bar{d},\ \xi,\ \Lambda$$

There thus remains the task of solving six equations with six unknowns. Now unfortunately, equations (29d) and (29e) cannot be represented analytically, and there thus exists no possibility for a closed analytic solution of the system of equations. To solve the problem, the following procedure was used:

From (29a), (29b), and (29c), there follows:

$$\frac{m}{y} = \frac{1}{K_1} \cdot \frac{\overline{C_E}}{\bar{d}} \rightarrow A = K_1 \cdot \frac{m}{y} = \frac{\overline{C_E}}{\bar{d}} \qquad (30)$$

$$\frac{u}{y} = \frac{K_2}{K_1} \cdot \frac{\bar{i}}{\bar{d}} \rightarrow B = \frac{K_1}{K_2} \cdot \frac{u}{y} = \frac{\bar{i}}{\bar{d}} \qquad (31)$$

The quantities A and B, defined by equations (30) and (31), can be determined by technical measurement.

With equations (29d) through (29f), and equation (28), it can be shown that A and B depend only on the two parameters ξ and Λ:

$$A = \frac{\overline{C_E}(\xi, \Lambda)}{\xi \cdot \sqrt{\Lambda}} \tag{32}$$

$$B = \frac{\overline{i}\ (\xi, \Lambda)}{\xi \cdot \sqrt{\Lambda}} \tag{33}$$

The two equations (32) and (33) can be solved numerically or graphically. The quantities A and B respectively, corresponding to equations (32) and (33) are shown in figures 5 and 6, in the range $0.1 \leq \xi \leq 0.7$, and for several special Λ-values. These figures serve to make clear the quantities A and B, which are derived from measured data when aerosol parameters ξ and Λ are prescribed. The original task, however, consists in determining the distribution parameters ξ and Λ from the measured data A and B. For this a further step is still necessary. If the lines A = constant and B = constant are drawn respectively in figures 5 and 6, the (ξ, Λ) combinations possible for constant parameters A and B are found.

From figure 5 follows: $\xi = \xi(\Lambda) \,\Big|\, A = \text{constant}$

From figure 6 follows: $\xi = \xi(\Lambda) \,\Big|\, B = \text{constant}$

These two functions are shown in figure 7. If the diagram shown in figure 7 has once been calculated, the desired distribution parameters ξ and Λ are found with the two measured values A and B, at the intersection of the associated curves A = constant and B = constant. If ξ and Λ are now known, equation (28) yields the mean particle diameter $\overline{d}$, and thus equation (24) yields the number concentration z of the aerosol particles. Since the measured quantities m, y, and u are continuously measured as functions of time, temporal changes in the particle concentration and in the particle size distribution can also be determined by technical measurement in the manner cited.

3.3. Application of the Procedure to Determine the Distribution of a Paraffin Oil Mist

As an example of the application of the described measurement process, the particle size distribution of a paraffin oil mist will be determined. The paraffin oil mist was generated with an aerosol generator of the Draeger firm. This mist generator is, in practice, used to test automatic smoke detectors and to test filter materials. With respect to the functional principle of the generator it need only be said that the aerosol is generated by a combined atomization and condensation process. Further particulars are found in the literature references [8-10]. Paraffin oil of the Merck firm (Darmstadt), with specification number 7162, was used as the basic substance. The aerosol generator was operated at an atomizing pressure 2 kPa/cm^2, and a mixing air throughflow of 50 l/min. The aerosol was led into an aerosol channel, and the measured values m, y, and u were continuously determined as functions of time.

At an arbitrarily-chosen point in time, the following measured values occurred:

$$m = 0.2 \text{ meter}^{-1}$$

$$v = 1$$

$$u = 1.39 \text{ volt}$$

From these measured values the quantities A and B were determined:

$$A = K_1 \cdot \frac{m}{y} = 2.6 \cdot 10^{-2} \cdot \frac{0.2}{1} \cdot \frac{\text{cm}^2}{\text{meter}} = 0.52\ \mu\text{m}$$

$$B = \frac{K_1}{K_2} \cdot \frac{u}{y} = 8.9 \cdot \frac{1.39}{1}\ \mu\text{m}^{-1} = 12.4\ \mu\text{m}^{-1}$$

Using the quantities A = 0.52 μm and B = 12.4 μm^{-1}, the associated distribution parameters ξ and Λ are found from the diagram shown in figure 7:

$$\xi = 0.3\ \mu\text{m}$$

$$\Lambda = 1.25$$

With these distribution parameters, the probability density function for the geometric particle diameters is determined. It is shown in figure 8.

A mean diameter of $\bar{d} = 0.336$ μm results from $\bar{d} = \xi \cdot \sqrt{\Lambda}$. The number concentration of the aerosol particles results from

$$z = \frac{y}{K_1 \bar{d}}$$

During the experiment described here, a concentration range of

$$0 \leq z \leq 2.86 \cdot 10^6 \text{cm}^{-3}$$

was traversed. At the time the particle sizes were determined, the concentration was:

$$z = 1.14 \cdot 10^6 \text{cm}^{-3}$$

Since factors A and B were constant at all times of the experiment, the aerosol distribution functions given in figure 8 did not change as the above-cited concentration range was traversed.

In the Institute for Dust Research at Bonn, the particle size was determined for aerosols of paraffin oil particles generated with the same aerosol generator as described previously [11]. In these experiments, measurements were made with an Andersen cascade impactor, and the median value of the number distribution was calculated from the measured mass distribution. The value thus calculated turned out to be 0.36 μm, which agrees quite well with the value determined here.

4. LIMITS OF THE MEASURING RANGE

In this section, the limits of the concentration range, which can be attained with the described measuring devices, will be investigated. It should be particularly stressed that the following considerations refer to the described measurement devices, as these are used to test automatic smoke detectors, and therefore should not be regarded as absolute limits for the associated measurement principle.

This limitation is particularly valid for the "upper limits" (high particle concentration and large particle diameters).

First of all, the limits of the measuring range for measuring monodisperse aerosols will be determined. The starting point is the previously-described constants of the measuring device, and the value $\underline{m} = 1.41 - i0.15$ (e.g. paraffin oil) is assumed as index of refraction. For the three starting quantities m, u, and y, of the three measurement devices, the measuring range limits specified in table 1 are valid.

Table 1. Limits of Measuring Range

		Minimum	Maximum
Extinction Measuring Device	m	$2.5 \cdot 10^{-8}\ \mu m^{-1}$	$5.2 \cdot 10^{-6}\ \mu m^{-1}$
Scattered-Light Measuring Device	u	0.08 V	10 V
I-chamber	y	0.025	2.5

Using the relations given in equations (17)-(19), and the values from table 1, the following determining equations result for the maximum or minimum obtainable particle concentration as a function of particle diameter:

Extinction Measuring Device

$$z_{max} = \frac{5.2 \cdot 10^6}{[C_E(d)/\mu m^2]}\ cm^{-3}$$

$$z_{min} = \frac{2.5 \cdot 10^4}{[C_E(d)/\mu m^2]}\ cm^{-3}$$

Scattered-Light Measuring Device

$$z_{max} = \frac{3.33 \cdot 10^7}{i(d)}\ cm^{-3}$$

$$z_{min} = \frac{2.7 \cdot 10^5}{i(d)}\ cm^{-3}$$

I-chamber:

$$z_{max} = \frac{9.6 \cdot 10^5}{[d/\mu m]} \ cm^{-3}$$

$$z_{min} = \frac{9.6 \cdot 10^3}{[d/\mu m]} \ cm^{-3}$$

The cited relationships are shown graphically in figure 9. The range in which all three measuring devices can be utilized simultaneously is severely bounded. The lower particle size limit lies at about 0.3 μm. The concentration range lies between 10^4 cm^{-3} and 10^6 cm^{-3}.

In the case of polydispersions, this measuring range broadens primarily towards smaller particles. With polydispersions, integral mean values are measured with respect to the extinction cross section and the intensity function. Consequently, the only point is that these mean values lie in the common measuring range of the three measuring devices. To make this clear, we stress that the mean value with respect to the three parameters C_E, i, and d, is not formed in the measuring devices themselves but, from a physical point of view, takes place in the aerosol-filled measurement volume. It thus becomes clear that, when the distributions are sufficiently broad, mean values less than 0.1 μm can certainly still be attained, although the lower measurement lies at about 0.3 μm for monodisperse aerosols. The measuring range limits for polydisperse aerosols are plotted in figures 10 and 11. The boundary lines were determined as in the case of monodisperse aerosols, only that now there occurs an additional dependence of the width of the distribution function (Λ). The range of mean values between 0.1 μm and 1 μm, which is of particular interest within the framework of automatic fire detection is covered quite well.

5. FINAL REMARKS

The described procedure to determine distribution parameters of aerosols permits measurements that occur continuously in time, without influencing the aerosol in its natural diffusion behavior by the extraction of samples. The measuring devices have relatively simple construction, so that they can be produced in larger numbers to achieve a practical "grid of measuring points"; thus, changes of an aerosol can be sensed while it is spreading out.

The measuring range of the individual measuring devices is tailored to problems posed in the area of automatic fire detection. However, the large number of parameters of the measurement devices easily permits practical design of substantial changes in the measuring range. Prior knowledge of the type of particle size distribution of the aerosol under analysis is required, but is not a very significant limitation. If no prior information is available concerning the type of particle distribution, preliminary analyses can be performed with other measuring devices, which as a rule "operate statically."

A limitation of the measuring process exists which, in the first instance, is significant: Only particles can be analyzed whose shape can be processed with the aid of Mie theory. This means that the particles of the aerosol under analysis must be spherical, prescinding from a few numerically-difficult exceptions.

With reference to real fire aerosols (i.e. smoke), this requirement for spherical aerosol particles is not fulfilled with certainty; nevertheless, the procedure is to be applied precisely to such aerosols: Interpretation of measured results (distribution parameters) found in this way, must take in account that the distribution parameters determined by technical measurement do not characterize the particle size distribution of the real fire aerosol, but the particle size distribution of a theoretical "equivalent aerosol" with spherical particles. This "equivalent aerosol," determined in this way, affects the three physical measurement principles, used during measurement, in the same manner as the real fire aerosol itself. Since these measurement principles generally agree with the measurement principles of automatic fire detectors, the effects of a fire aerosol on automatic fire detectors can likewise be described with the parameters of the associated "equivalent aerosol."

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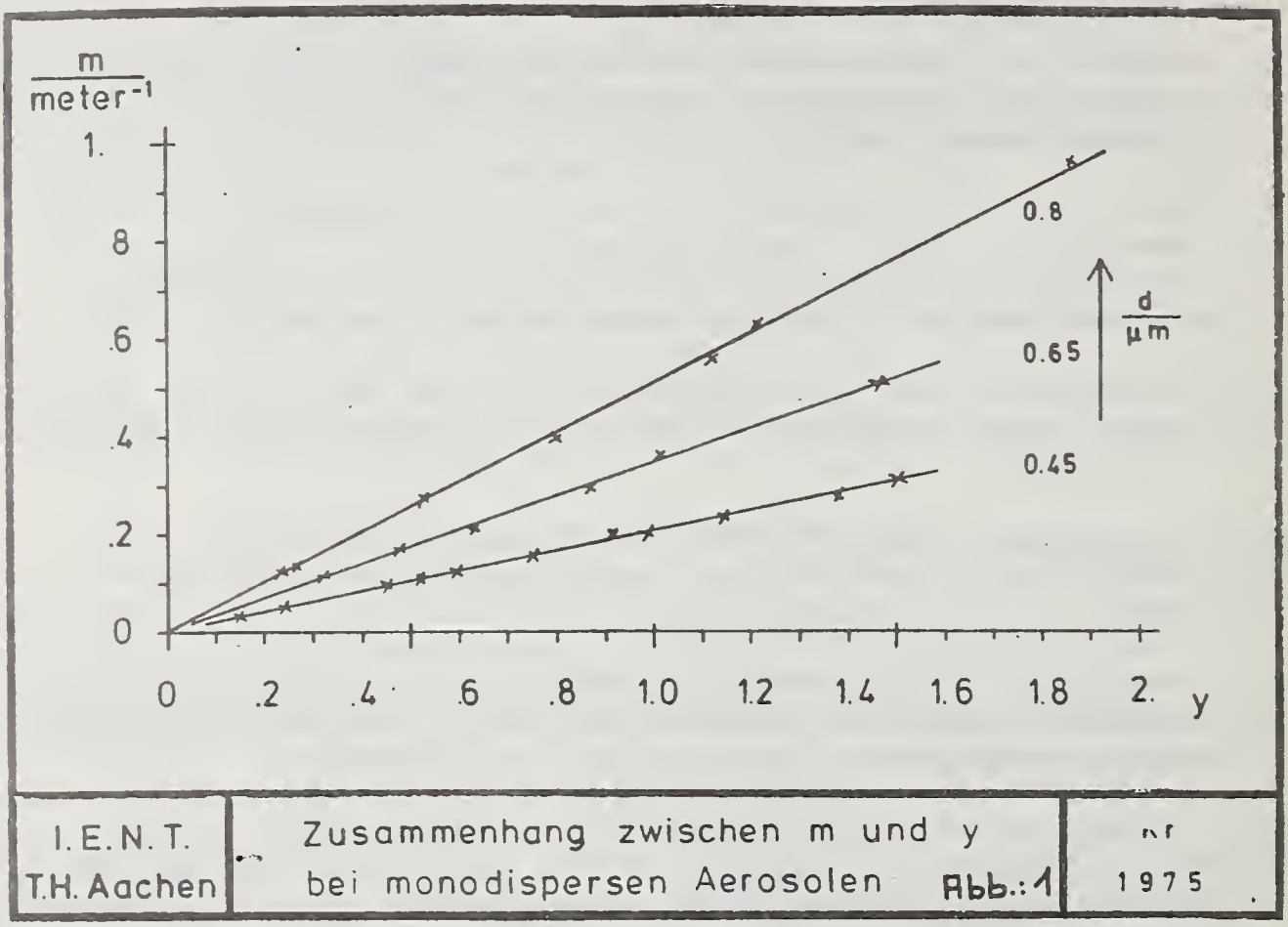

Figure 1. Relation between m and y for monodisperse aerosols

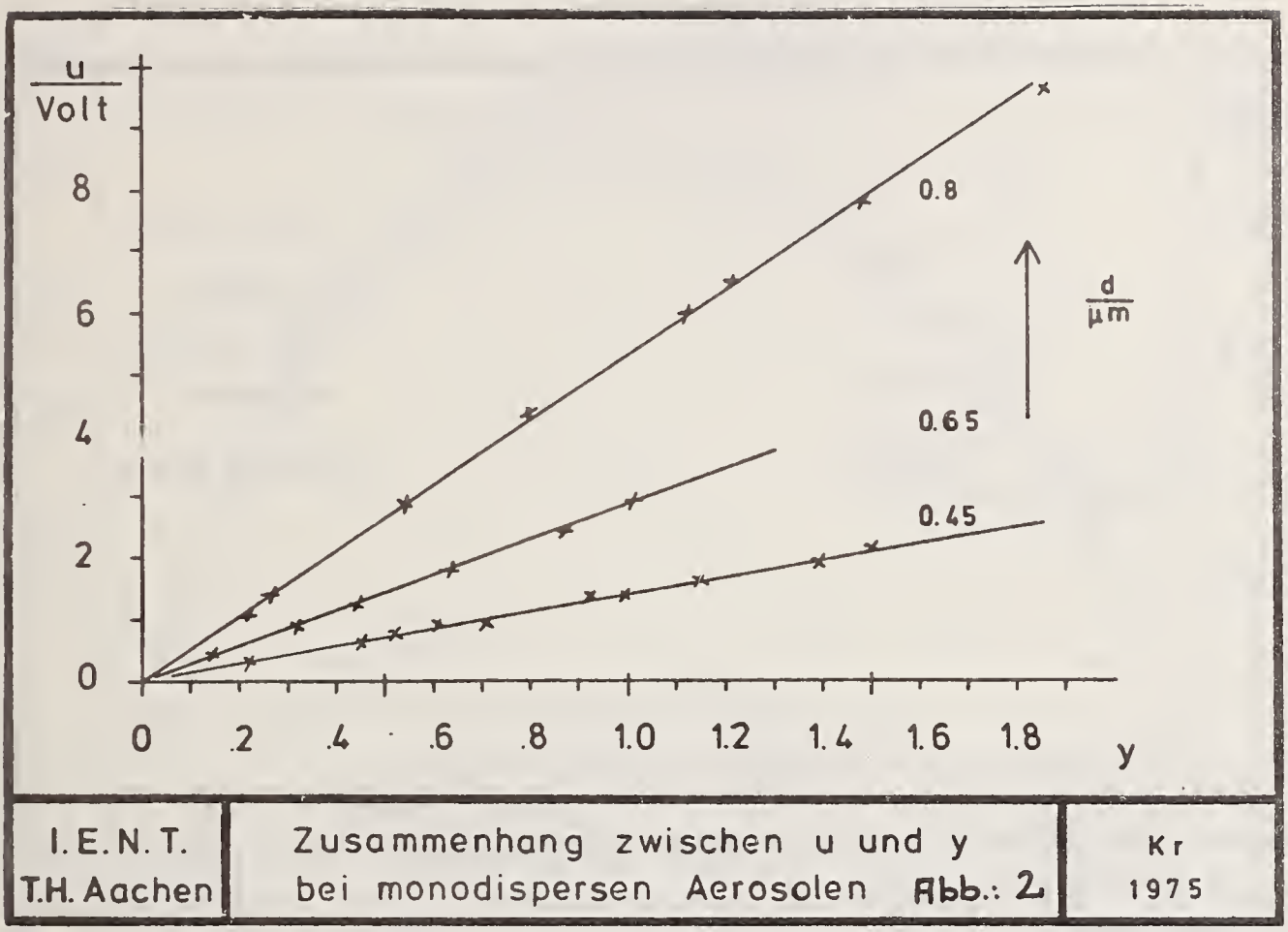

Figure 2. Relation between u and y for monodisperse aerosols

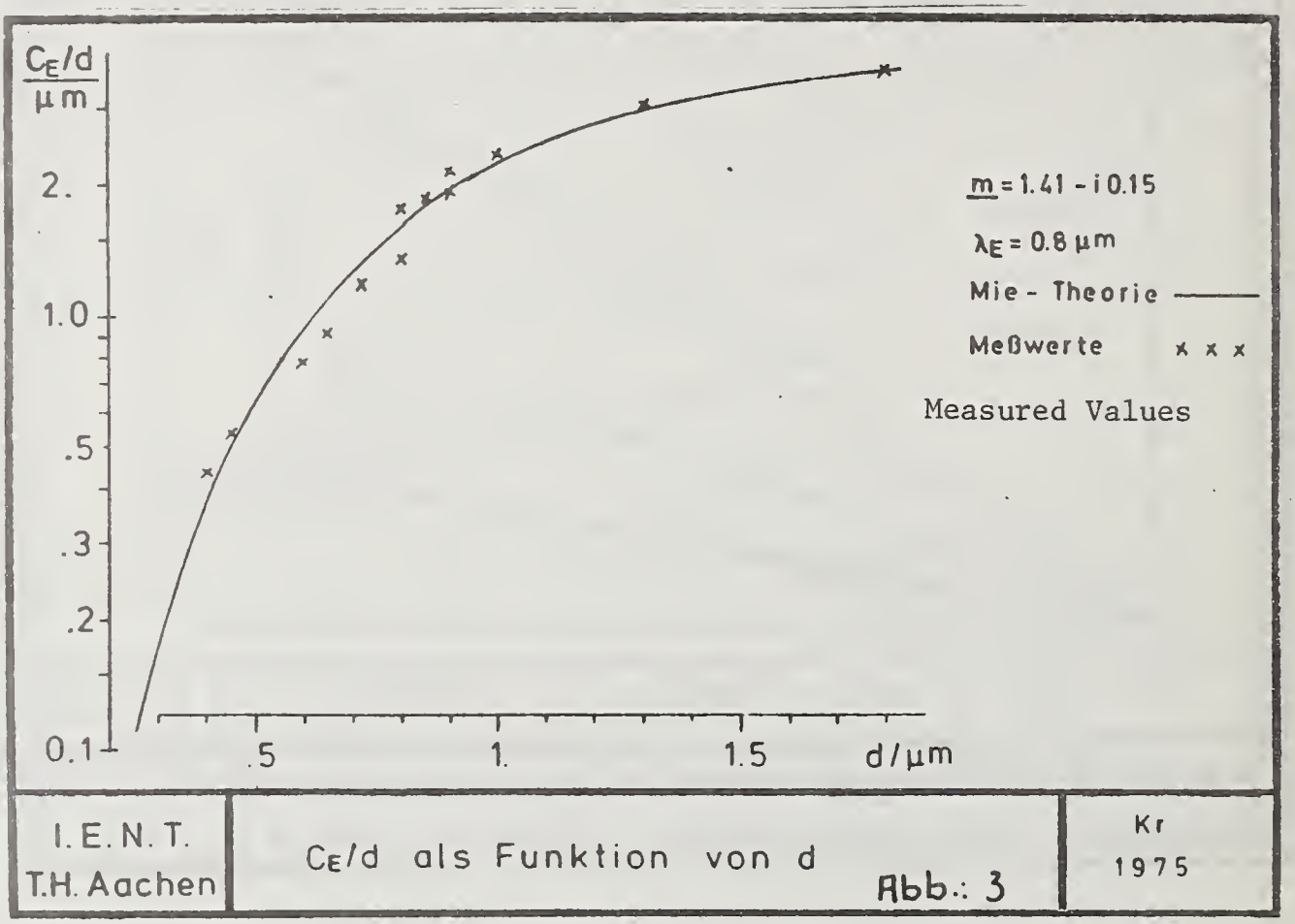

Figure 3. C_E/d as function of d

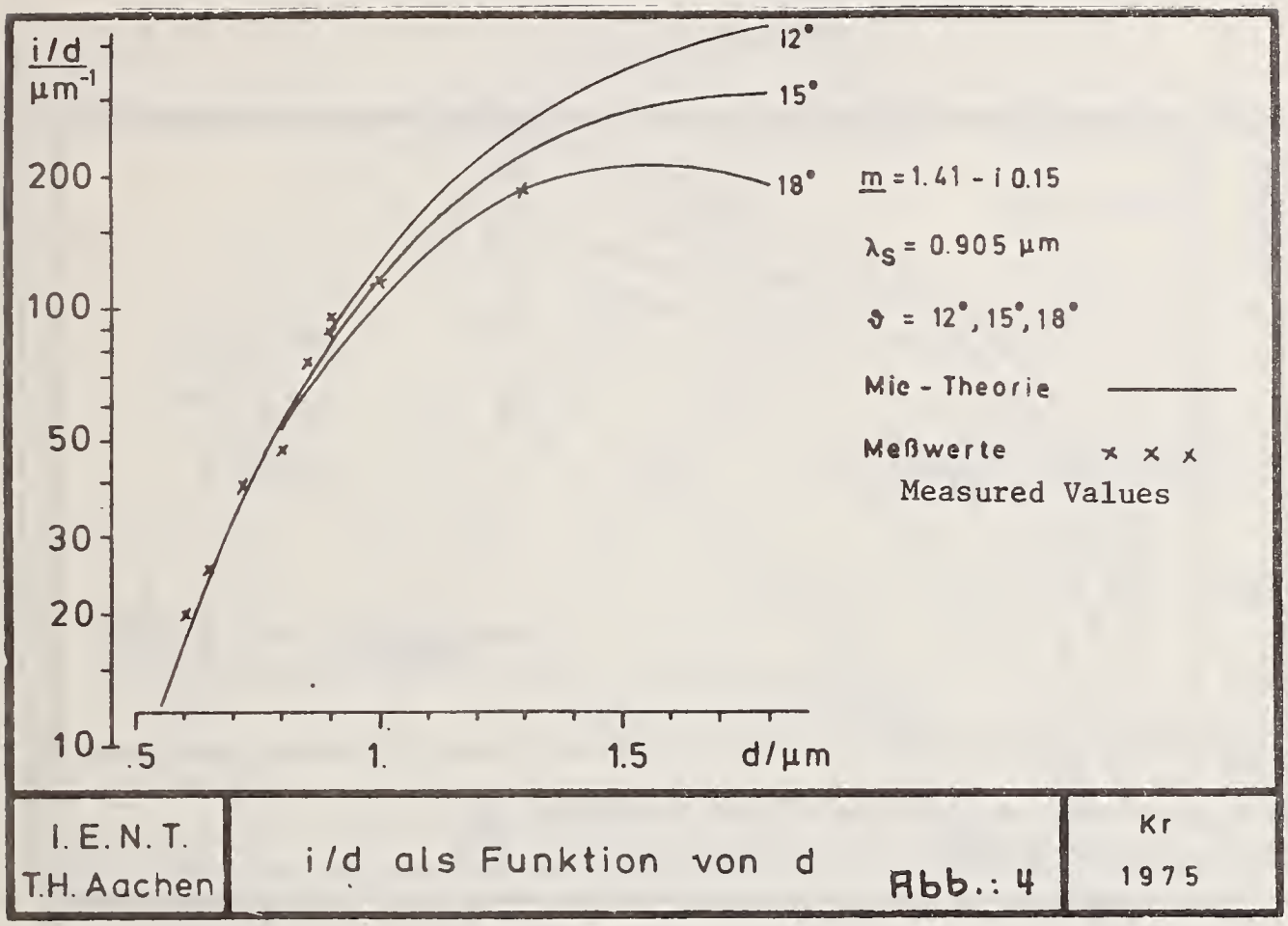

Figure 4. i/d as function of d

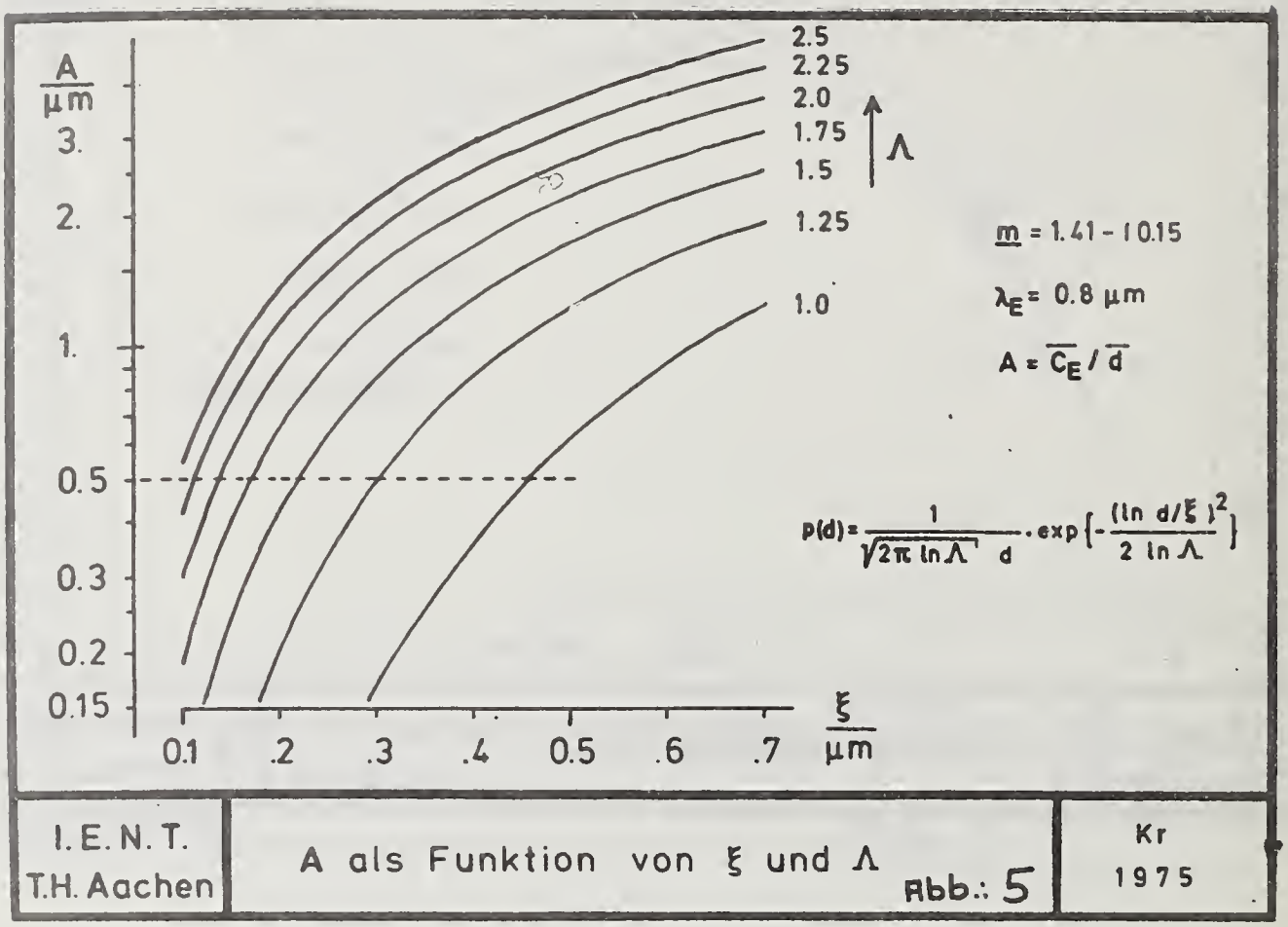

Figure 5. A as function of ξ and Λ

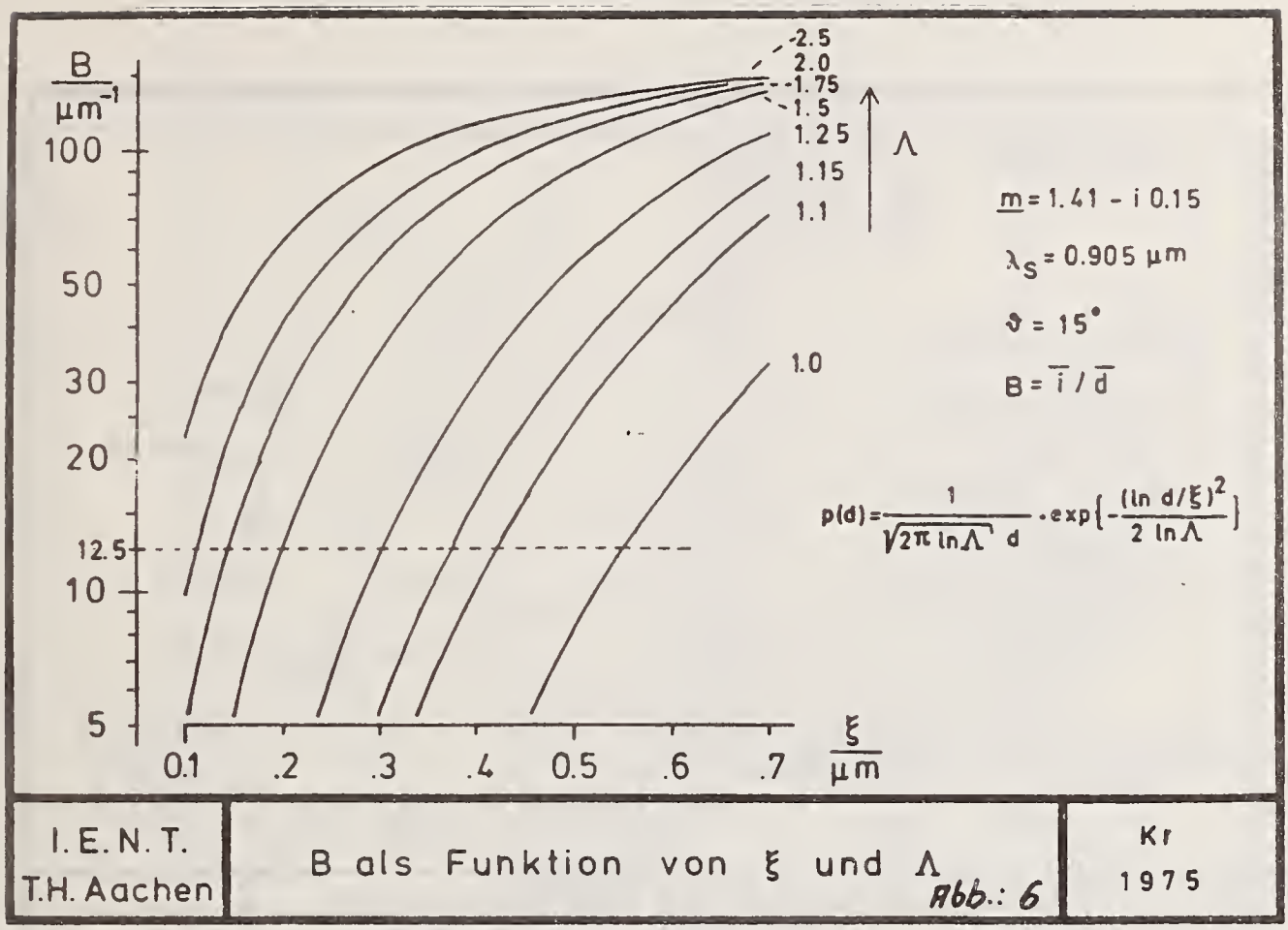

Figure 6. B as function of ξ and Λ

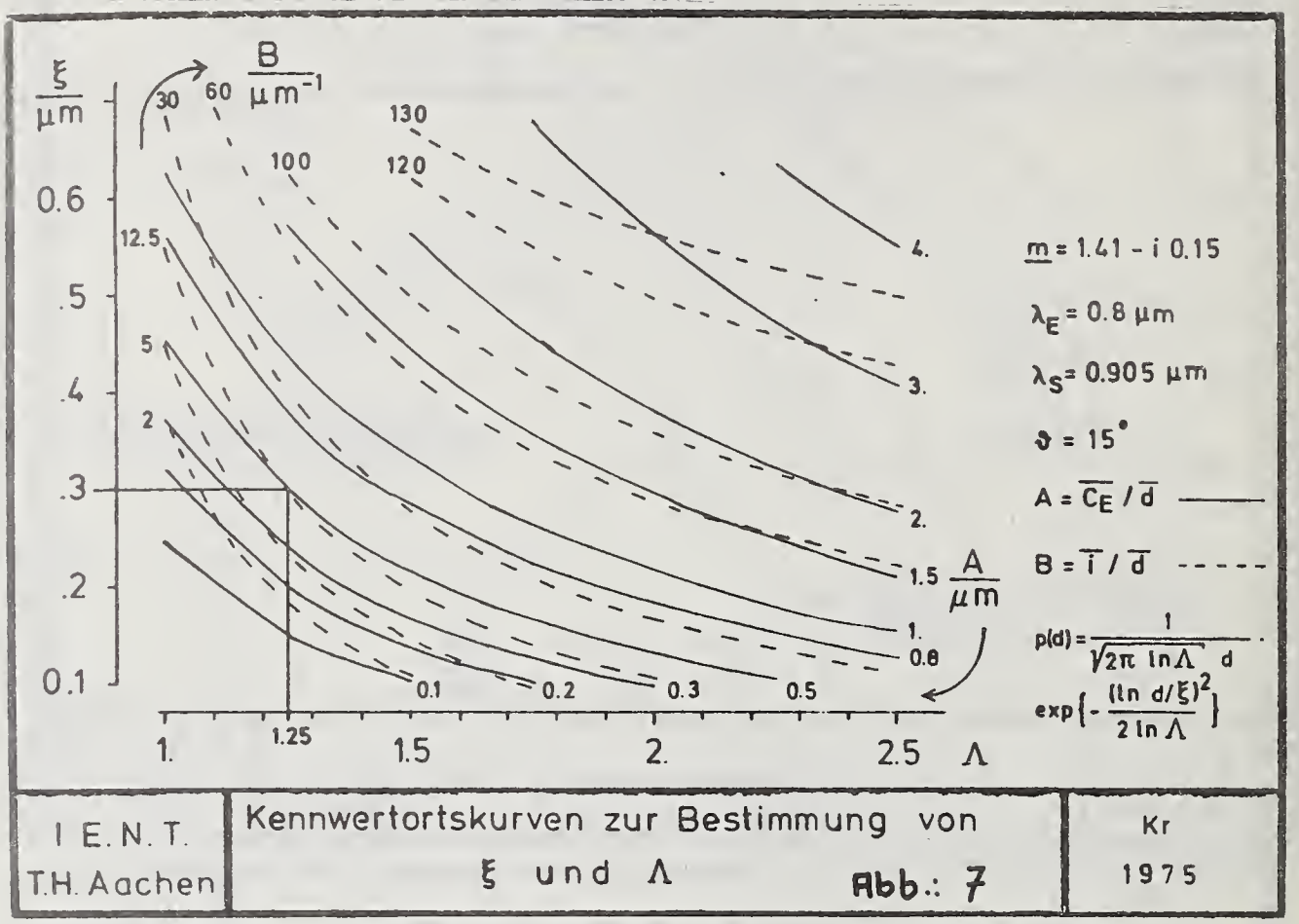

Figure 7. Curves to locate characteristic values, for the determination of ξ and Λ

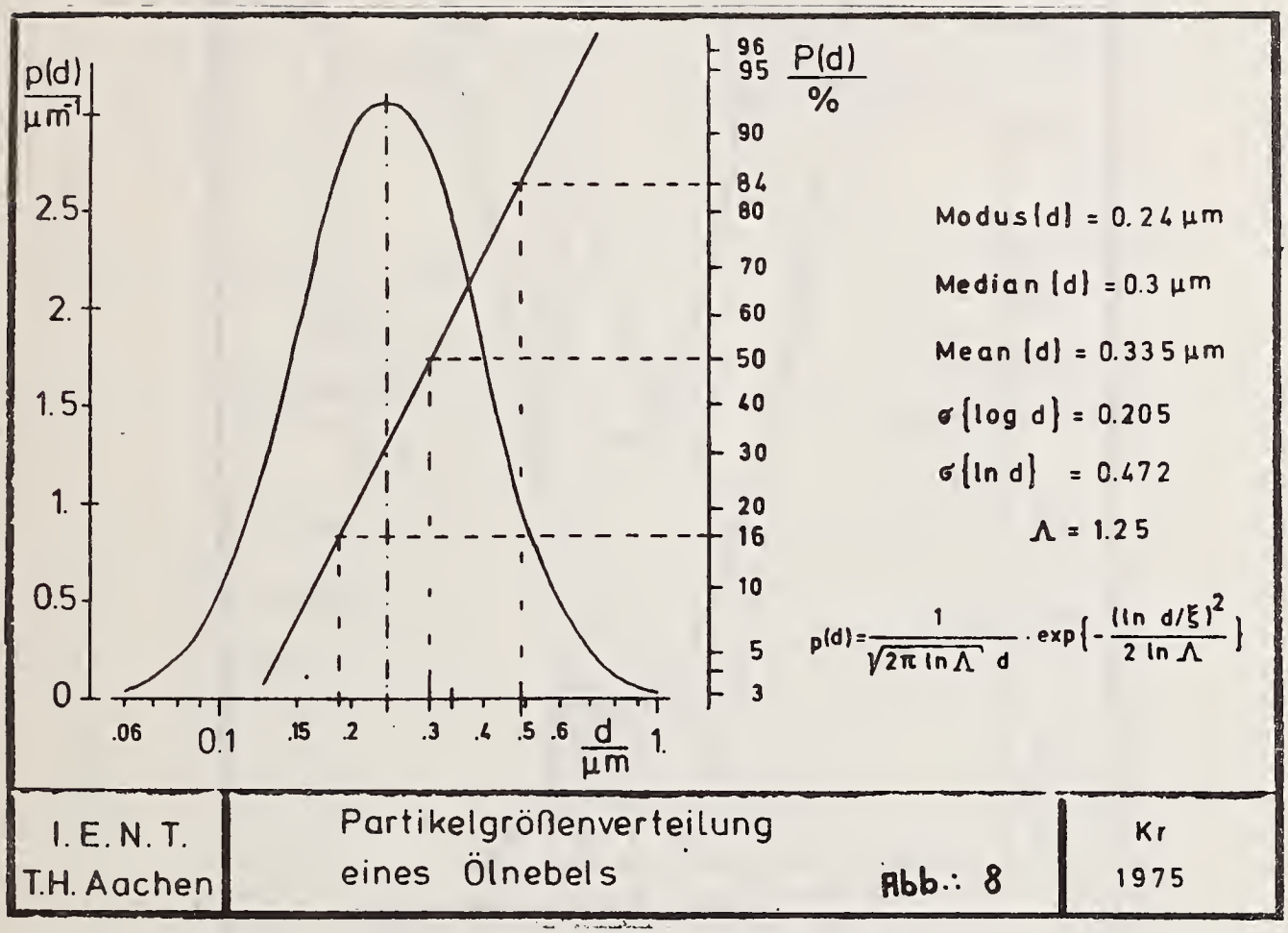

Figure 8. Particle size distribution of an oil mist

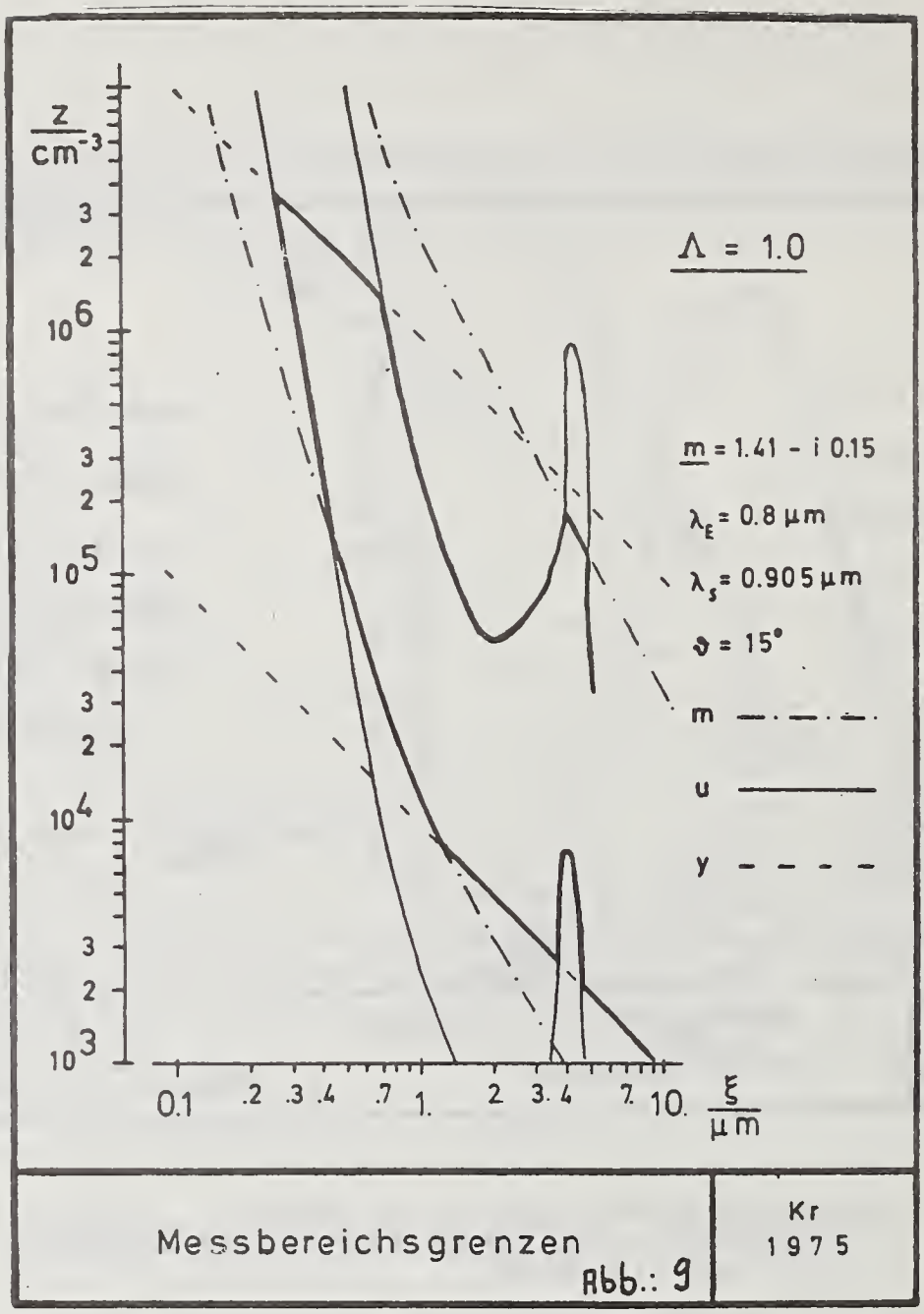

Figure 9. Limits of measuring range

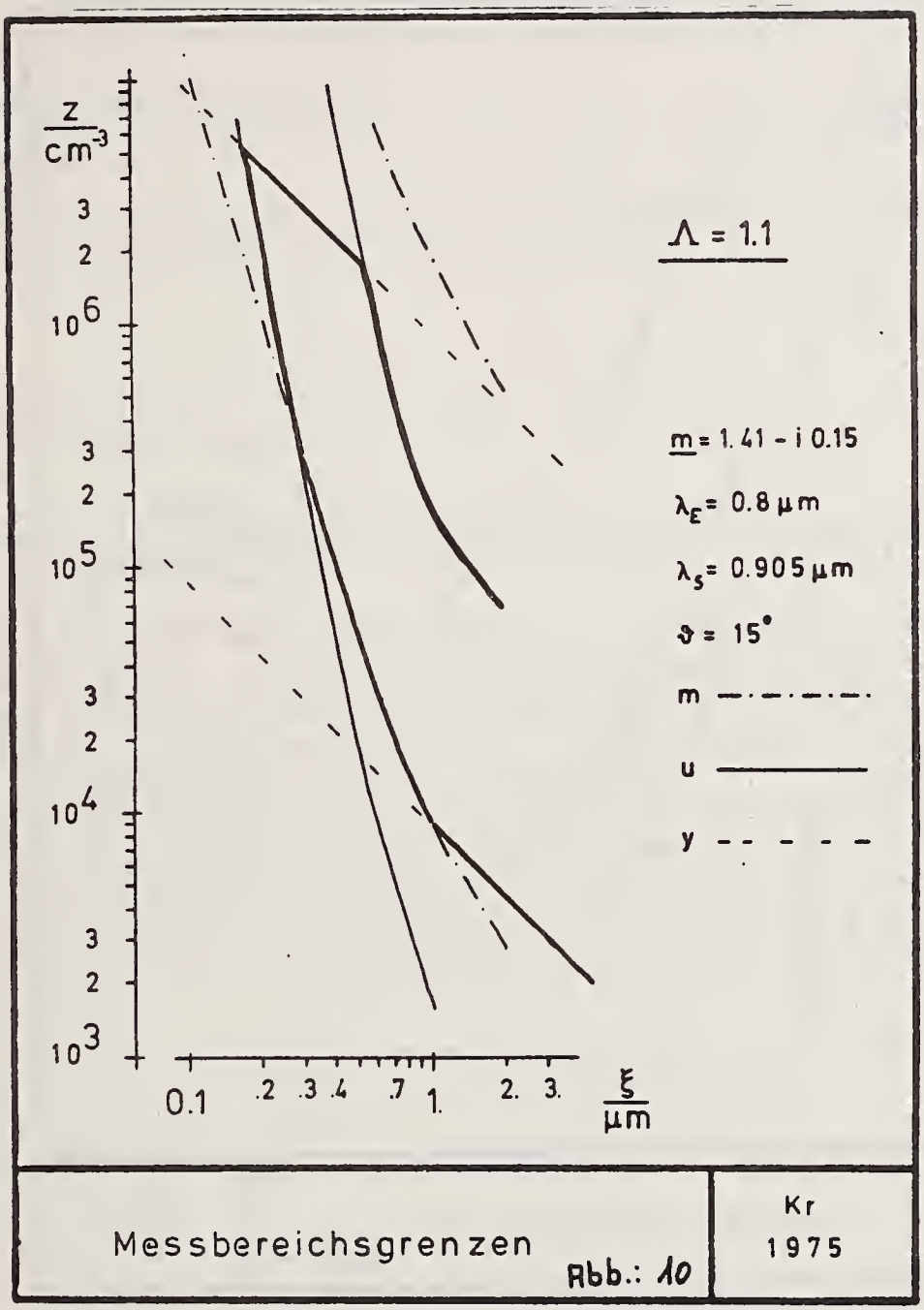

Figure 10. Limits of measuring range

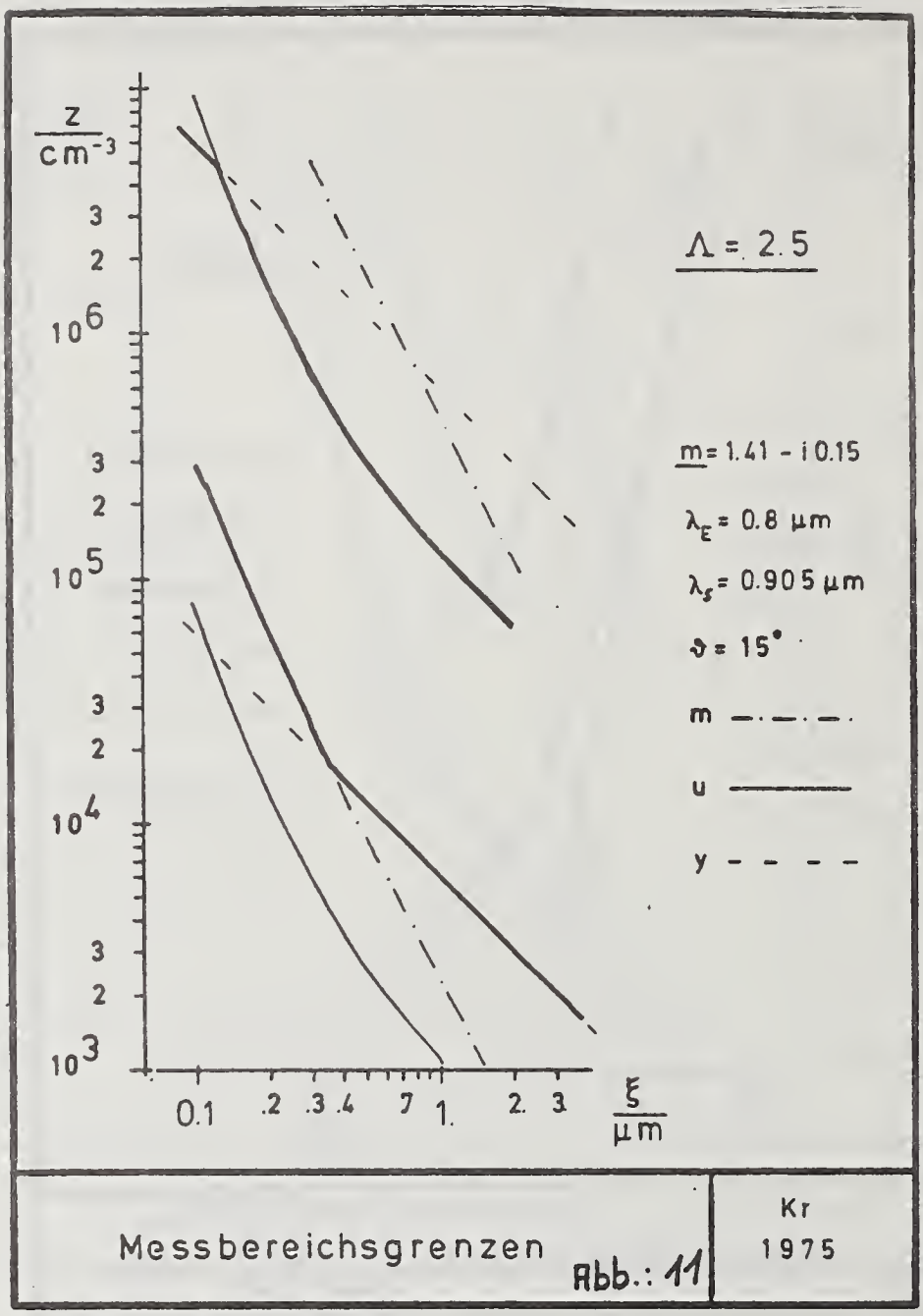

Figure 11. Limits of measuring range

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In assessing the performance of smoke detectors in the laboratory, it is necessary to have standardized smoke measurement devices which function according to the same principles as the smoke detectors under test. In developing these measurement devices, a need exists to determine, as precisely as possible, the effects of the smoke characteristics on the measurement devices. This paper presents the correlation between smoke characteristics and comparative measuring devices important in smoke detector test work and how these measuring devices can also be used as aerosol measuring devices.

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)* Aerosols; ionization chambers; light attenuation; scattered light; smoke detectors; test methods.

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