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NATIONAL BUREAU OF STANDARDS REPORT

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A LABORATORY METHOD OF EVALUATING THE EXTINCTION EFFICIENCY OF POWDERS ON SMALL SCALE FIRES

by

C. S. McCamy and T. G. Lee

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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A LABORATORY METHOD OF EVALUATING THE EXTINCTION EFFICIENCY OF POWDERS ON SMALL SCALE FIRES

ABSTRACT

A method of evaluating the fire extinguishing effectiveness of powders on a laboratory scale is described and some experimental results are given. The method involved dispensing powder in the air at a controlled rate and slowly introducing a small heptane flame into the falling powder stream under controlled conditions. Various rates of powder application were used to determine the minimum effective rate, which is used as a measure of effectiveness. The method has been used to study the effect of particle size and chemical nature on effectiveness. Some data indicate that the results may not be extrapolated to large fires.

1. INTRODUCTION

Various chemical and physical mechanisms have been suggested to account for the extinguishment of fires by the application of dry powders (1). Sodium bicarbonate, in a specially prepared form, is in common use and is known among fire fighters as "dry chemical." Apparently sodium bicarbonate came into use because it was believed that upon thermal decomposition in the flame this powder would release CO_2 and smother the fire (2). This explanation appears invalidated by quantitative experiments with sodium bicarbonate and experiments in which fires were extinguished by materials to which the explanation is inapplicable (3). As a result of more recent work, the shielding of the fuel from the radiant energy of the flame and the interruption of combustion chain reactions have come to be considered likely mechanisms (4). Other studies have contributed data related to the problem of determining the mechanism of fire extinction by means of dry powders (5, 6, 7, 8, and 9) but the problem remains unsolved. An understanding of this mechanism should contribute not only to improvements in the technology of dry powder but to a better understanding of fire extinction in general.

One method of attacking the problem is to measure the effectiveness of various materials as extinguishing agents and correlate the effectiveness with the chemical and physical properties of the materials. Knowing the properties of effective materials, one is better able to formulate hypothetical mechanisms. This paper describes a laboratory method of evaluating the effectiveness of powders on a small scale and presents some of the first results obtained. The method was simple in principle. While powder is dispersed in the air at a controlled rate, a small flame was slowly introduced into the falling powder stream. In some cases the flame was extinguished. A number of trials were made, using different discharge rates, to determine the minimum rate which would bring about extinction. This minimum rate provided a basis for comparing the effectiveness of various powders.

2. APPARATUS AND PROCEDURE

The essential features of the apparatus are shown in Figure 1. The dispenser was a thin-walled brass cylinder 5 cm in diameter and 7 cm in height, with a fine stainless steel screen at mid-height, upon which the powder was placed. The screen had 100 to 200 meshes per inch, as necessitated by the particle size and flow properties of the powder. The dispenser was connected to an electromechanical vibrator of adjustable amplitude. The rate of discharge of powder was governed by the amplitude of vibration. To help maintain a uniform powder load over the whole screen, a circular brass plate 1/4 inch thick, with a uniform pattern of 1/16 and 3/16 inch holes through it was placed on the screen. The powder fell in a vertical stream 3.8 cm in diameter.

A brass cup having an inside diameter of 29 mm and a depth of about 7 mm was used as a burner. Normal heptane was chosen as a fuel because it is a fairly representative constituent of gasoline, the most common flammable liquid, but has a nearly constant burning rate in a cup-type fire. At the beginning of each experimental procedure the cup contained 3.0 ml water and 1.0 ml heptane, leaving about 1 mm of the rim above the fuel level.

The burner was placed on a flat carriage which moved horizontally at a uniform velocity of 4.8 cm/sec so that the burner passed through the powder stream. After leaving the powder stream, the burner passed beneath a flat metal plate which smothered the fire if it had not been extinguished by the powder.

To measure the rate of discharge of powder, another cup, identical to the burner cup, was placed on the carriage two inches ahead of the burner cup and the collected powder was weighed on an analytical balance. To calculate the rate of powder application in gm/cm^2-sec from the weight falling in the sampling cup, it was necessary to take into account the size and shape of the cross section of the powder stream, the size and shape of the cup, and the motion of the cup through the stream. The details of this calculation are given in Appendix I.

Previous work (4) had shown that the weight rate of flow of powder in a free-falling stream was proportional to the optical density of the stream at a fixed point. To provide a continuous indication of rate of discharge, the optical density was measured and recorded continuously, using an incandescent lamp as a source, a simple lens and slits to collimate a light beam 25 mm wide and 3 mm in height, a photovoltaic cell, and a potentiometer recorder. This system was calibrated periodically with a series of light filters of known transmittance, mounted on a revolving turret. The photometric system gave the relative intensity of light entering the stream I_o and of that transmitted by the stream I. By definition, optical density D is given by $D = \log_{10} I_o/I$. The variations in the rate of discharge were indicated by the densitometer record and an absolute measure of rate was obtained by weighing the collected powder.

The entire apparatus was enclosed in a cabinet equipped with a viewing window, exhaust blower, spark-gap ignition source, air hose connections for humidity control, a humidity sensing element, and controls for operating the equipment without opening the cabinet. The humidity could be controlled within a few percent at values in the range from 10 percent to 90 percent.

A fixed procedure was established so that the conditions could be closely reproduced from trial to trial. The procedure consisted of the following steps. The dispenser was loaded, the burner was filled, the densitometer recorder was started, and the burner was ignited by an electric spark. The flame was allowed to burn 30 sec before the powder discharge was started and the carriage was set in motion. Since it took 5 sec for the burner to reach the powder stream, the total burning time before the trial was 35 sec. The operator observed whether or not extinction occurred.

An effort was made to bracket the minimum effective rate of application as closely as possible with a number of trials at slightly higher rates and at slightly lower rates. In some cases, all rates higher than a certain value produced extinction and all rates below that value failed. In most cases, however, there was an overlapping of extinction and non-extinction points. The data were analyzed by the statistical method given in Appendix II.

3. RESULTS AND DISCUSSION

The first experiments were done with sodium bicarbonate because it is the material ordinarily used for fire extinguishment. The material was ground and sieved to obtain samples of various average particle sizes. Since the starting material was the commercially available "dry-chemical," the powders contained the additives employed to improve the flow properties and resist caking. The mean diameter of the particles in each sample was determined from the measured air-permeability of the sample. The variation of optical density of the powder stream with rate of application of powder is shown in Figure 2 for sodium bicarbonate having a mean diameter of 26 microns. It may be seen that the optical density was a linear function of the rate of application, within experimental error. In this figure, the encircled points indicate that extinction occurred, while the other points indicate non-extinction. The existence of a minimum effective rate of application is clearly indicated in this figure. This corroborates the observation of such a minimum in full-scale extinguishment tests under experimental conditions quite different from those used here (9).

Much of the spread of the data in Figure 2 is attributed to variations in measured optical density resulting from slight changes in the flow pattern when the dispenser was reloaded or a new flow rate was set. This source of error did not occur in the extinction experiments because the weight-rate was measured by actual weighing for each trial. The slope of the line in Figure 2 was used in correcting the measured rate for any variation in rate between the time of the transit of the sampling cup and that of the burner cup.

The data shown in Figure 3 demonstrate the effect of two factors amenable to study by this method, particle size and chemical nature. Each point indicates the minimum effective rate determined from about 20 separate trials, by the method of Appendix II. The results show that, under the conditions of the experiments, the effectiveness was greater for more finely powdered materials than for coarse materials and potassium oxalate was far more effective than sodium bicarbonate. It is of some interest to convert the rate data from a weight basis to an area basis, to investigate the relationship between the effectiveness of a powder and its surface area, but this is not essential to the method of measurement described here. With this transformation, the curves of Figure 3 become nearly linear but the minimum rate, on an area basis, does not appear to be constant for these experiments.

It should be noted that the results of experiments on the small scale employed here are not necessarily applicable to much larger fires. In several large scale fire tests, the differences in effectiveness between various powders appeared to be considerably less than that indicated by small scale experiments. It seems likely that extinction may involve a number of processes and that the process or processes mainly responsible for bringing a fire under control may depend upon the size of the fire. It is believed that a full understanding of the nature of these processes will require experimentation with fires of various sizes.

APPENDIX I

Method of Calculating the Rate of Discharge of Powder from the Weight Collected in a Cup

Let the cross section of the falling powder stream be represented by a circle of radius a. Let the cross section of the sampling cup be represented by a circle of radius b. The sampling cup moves through the stream at a uniform velocity v. The arrangement may be represented as in Fig 1.

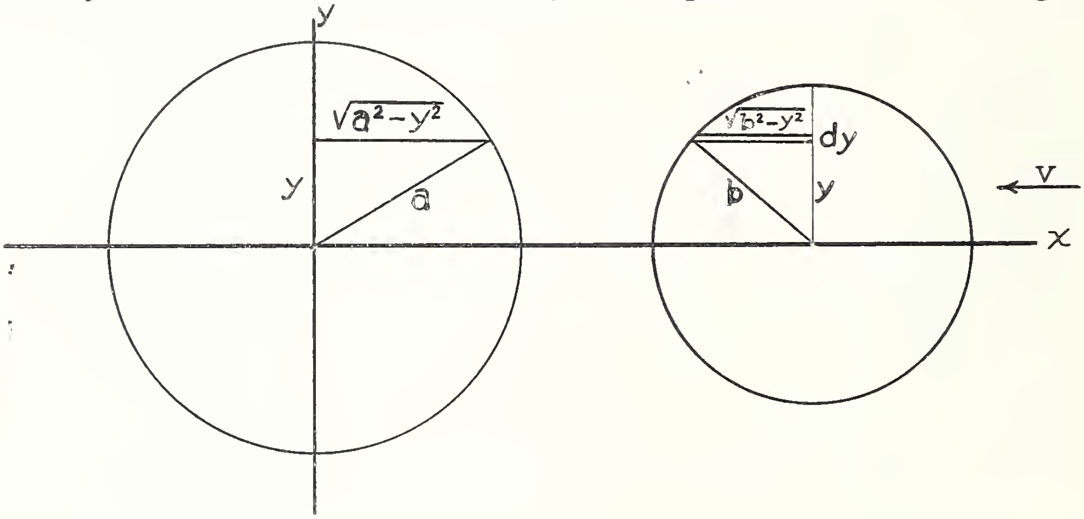

Figure 1. Geometry of the Method

If the powder is falling at a constant rate w, expressible in gm/cm^2-sec, the weight W falling on an area A in time t is given by the equation

$$W = wAt.$$

In the present case, however, we do not have the entire area of the cup receiving powder simultaneously over a fixed time. The effective area and time must be integrated. As an element of area of one quadrant of the cup, we have

$$dA = \sqrt{b^2 - y^2} \quad dy.$$

Any point in that element of area will be within one quadrant of the circle representing the powder stream a time t given by the equation

$$t = \frac{\sqrt{a^2 - y^2}}{v}$$

The weight would then be given by the integral equation:

$$W = \frac{8w}{v} \int_0^b \sqrt{(a^2-y^2)(b^2-y^2)}\ dy,$$

the factor of 8 being introduced because each of the four quadrants of the cup passes through two quadrants of the stream. This is an elliptic integral and, therefore, can not be evaluated in terms of elementary functions.

If we substitute bs for y, multiply and divide by a, and multiply numerator and denominator by the integrand, we obtain the following form, where $k = b/a$:

$$W = \frac{8wab^2}{v} \Big[\int_0^1 \frac{ds}{\sqrt{(1-k^2s^2)(1-s^2)}} - (1+k^2) \int_0^1 \frac{s^2 ds}{\sqrt{(1-k^2s^2)(1-s^2)}} + k^2 \int_0^1 \frac{s^4 ds}{\sqrt{(1-k^2s^2)(1-s^2)}} \Big].$$

The first integral may be put into the canonical form of the complete elliptic integral of the first kind by the substitution $s = \sin \Theta$. The value of this integral, denoted by the symbol K, is tabulated as a function of k (see reference 10).

The other two integrals are known as the Jacobian elliptic integrals of the second and fourth powers respectively. They may be evaluated in terms of elliptic integrals of the first and second kinds and the three elliptic functions, all of which are tabulated (10).

In the present case, $a = 1.90$ cm, $b = 1.45$ cm, and $v = 4.75$ cm/sec. Using these values we find $W = 4.86w$, or to determine the rate of discharge w from the measured weight W, we have:

$$w = 0.206W.$$

APPENDIX II

Approximating the Best Value of the Minimum Effective Rate

Powder is applied to a specified flame at various weight rates w expressed in gm/cm^2-sec. The objective is to determine the minimum weight-rate for extinction, w_m.

The probability of extinction in one trial approaches zero at rates much less than the minimum and approaches 1 at rates much greater than the minimum. The minimum effective rate may be thought of as the rate at which the probability of extinction is 0.5. The probability of extinction E(w) and non-extinction 1-E(w) may be represented by curves such as those in Figure 1, although the exact form of the curves is unknown.

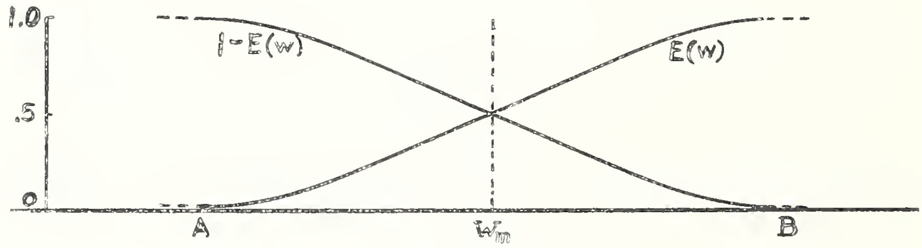

Figure 1. Probability of Extinction E(w) and Non-Extinction 1-E(w) in a single trial.

In any group of trials covering the range about the minimum effective rate, there is some rate at or below which no extinctions occurred. If this rate were determined for each of a large number of groups of trials it would be expected that the values would fall in a group about the most probable value, A. Similarly, there would be some rate B representing the most probable value of the rate above which no non-extinctions occurred. Usually, no extinctions occur at rates below A and no non-extinctions occur at rates above B, therefore for the purpose of data analysis, we may make the simplifying approximation that E(w) is 0 below A and 1 above B.

The foregoing theoretical representation is the basis of the interpretation of a single group of observations. The data for the group consists of a closely spaced series of values of weight rate and an indication of whether or not extinction occurred in each case. Each extinction point is evidence that the minimum rate is less than that tried and may be indicated on the scale of weight-rates by the "less-than" symbol $<$. Correspondingly, non-extinction may be indicated by the "greater-than" symbol $>$. A representation of one such group of trials is given in Figure 2.

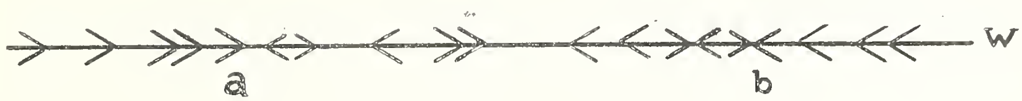

Figure 2. Graphical Representation of One Group of Trials

We find an actual rate "a" at or below which there were no extinctions and a rate b at or above which there were no non-extinctions. All evidence outside the interval ab agrees that w_m is in the interval ab; the data in the interval admit w_m in the interval but do not agree on the location in the interval. If there were no points between a and b we might assume a = A and b = B, but we have points between a and b which may give some information about the position of the interval ab with respect to the theoretical interval AB.

The more the interval ab is shifted toward high values of weight-rate, the more probable are extinctions within the interval. Therefore, in the data analysis, the more extinctions there are among the trials in the interval, the more likely it appears that the interval ab is shifted toward high values and, correspondingly, the more it appears that the best value of w_m is toward the lower end of the interval ab.

It is not enough, however, to consider just the number of extinctions or even the ratio of the number of extinctions to the total number of trials within the interval. The position of the points is as important as their number. For trials at rates just slightly less than b there would be a higher probability of extinction than there would be for trials elsewhere in the interval. For this reason, greater significance should be attached to extinctions occurring in trials lower in the interval. Likewise greater weight should be given to non-extinctions appearing at higher values in the interval. Each point should be assigned a significance proportional to its probability of not occurring, which is one minus the probability of its occurrence.

Not knowing the form of the probability function E(w), we can not take into account the exact variation in probability. For simplicity, we approximate E(w) by a linear function which equals zero at A, and equals one at B. On this basis, the probability of extinction is proportional to displacement from A in the interval AB.

Since A and B are the most probable values of a and b, respectively, we take the interval ab to be the interval AB, as a first approximation. Then, by use of the frequency of extinctions and non-extinctions, weighted on the basis of approximate probabilities, we may interpolate w_m in the interval.

Since we wish to take into account the number of extinctions and their position on the w scale, and the corresponding data on the non-extinctions, we form the summations:

$$x = \sum_{n=1}^{j} (w_n - a) \qquad a < w_n < b$$

and

$$y = \sum_{e=1}^{k} (b - w_e) \qquad a < w_e < b$$

where w_n is a weight-rate at which non-extinction occurred, j is the number of non-extinctions within the closed interval ab, w_e is a weight-rate at which extinction occurred, and k is the number of extinctions in the closed interval ab. The value of x is proportional to the number of non-extinctions and their displacement on the w axis away from a. The value of y depends in a similar way on the extinctions. With these factors accounted for linearly, we combine the effects of x and y linearly so that non-extinctions tend to increase the value of w_m in the interval ab and extinctions tend to decrease the value of w_m, in the following equation for the interpolation of w_m between a and b:

$$w_m = a + \frac{x}{x+y}(b-a).$$

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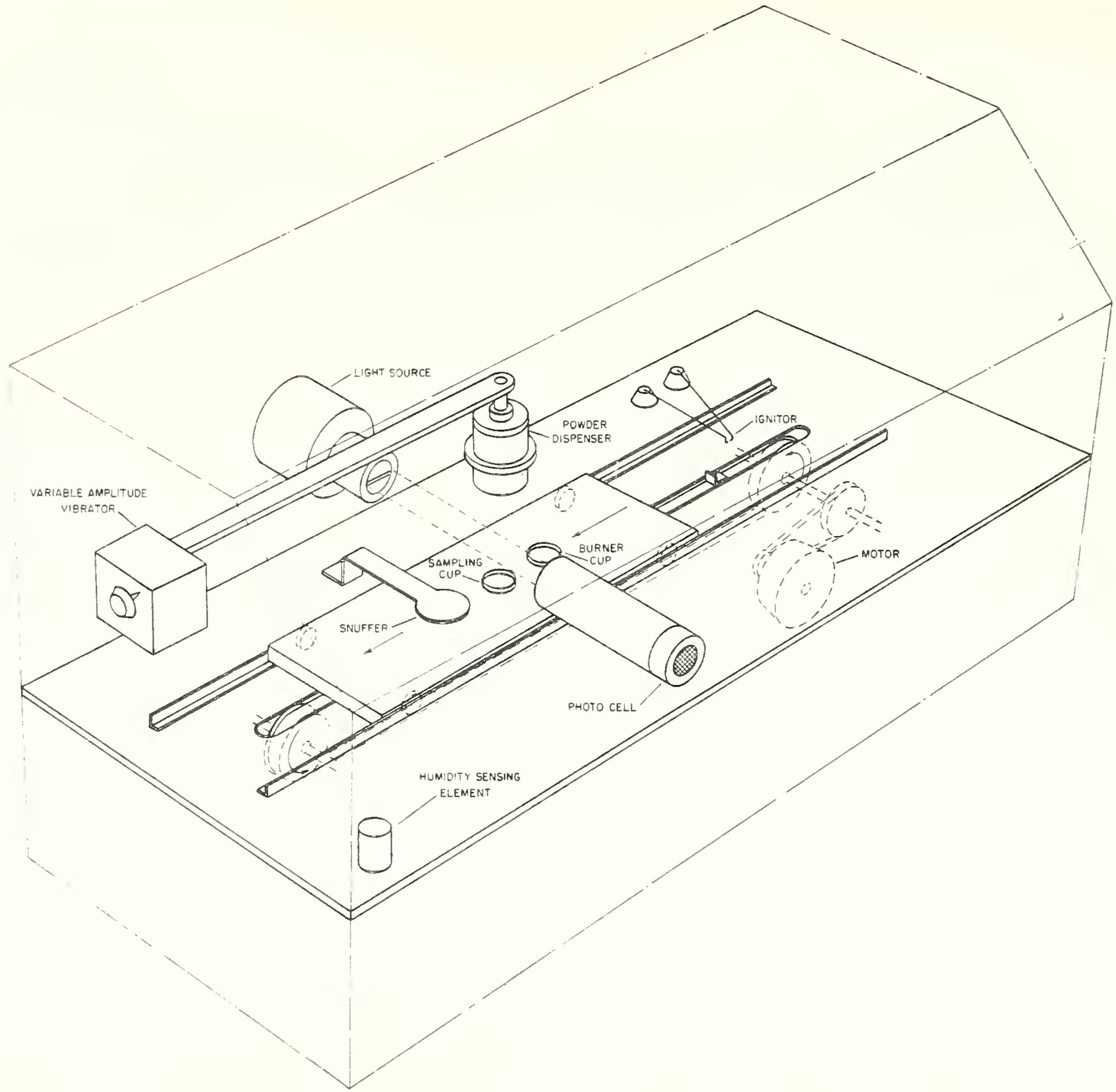

FIG. 1 APPARATUS FOR EVALUATING THE FIRE EXTINCTION EFFICIENCY OF POWDERS

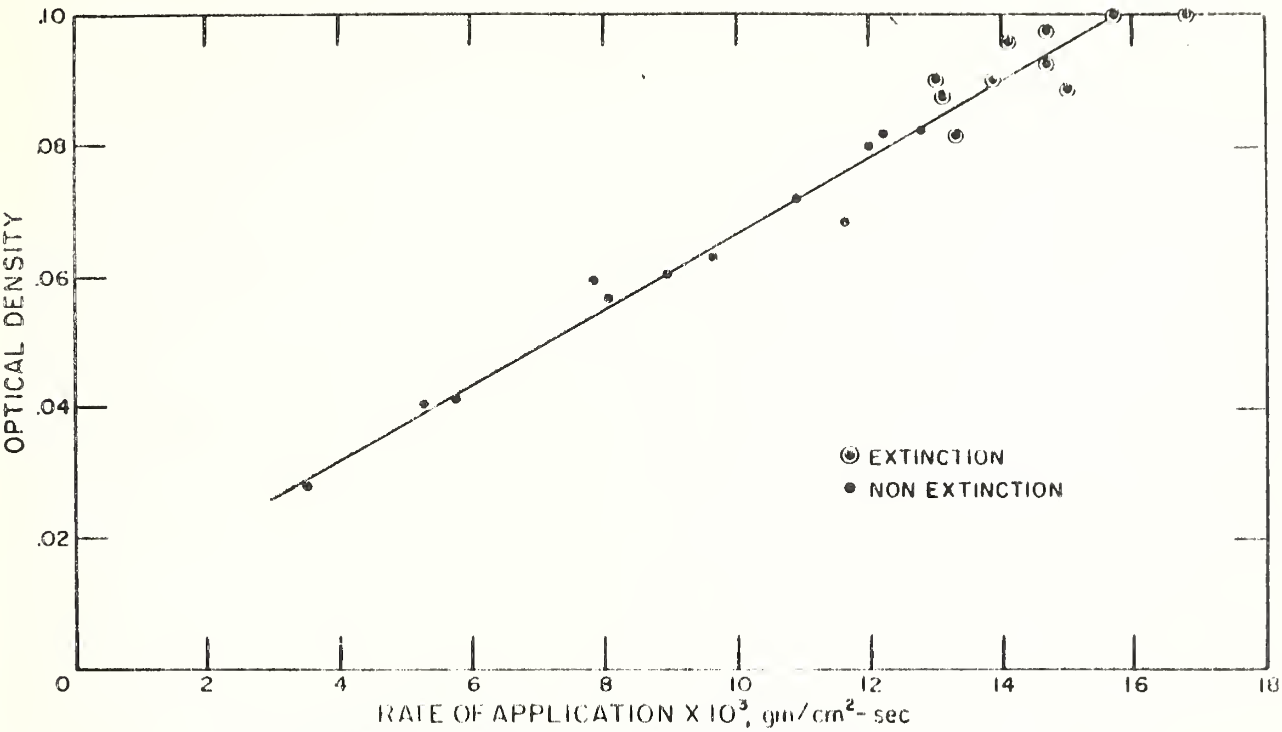

FIG. 2 OPTICAL DENSITY OF POWDER STREAM VS RATE OF APPLICATION FOR 26-MICRON $NaHCO_3$

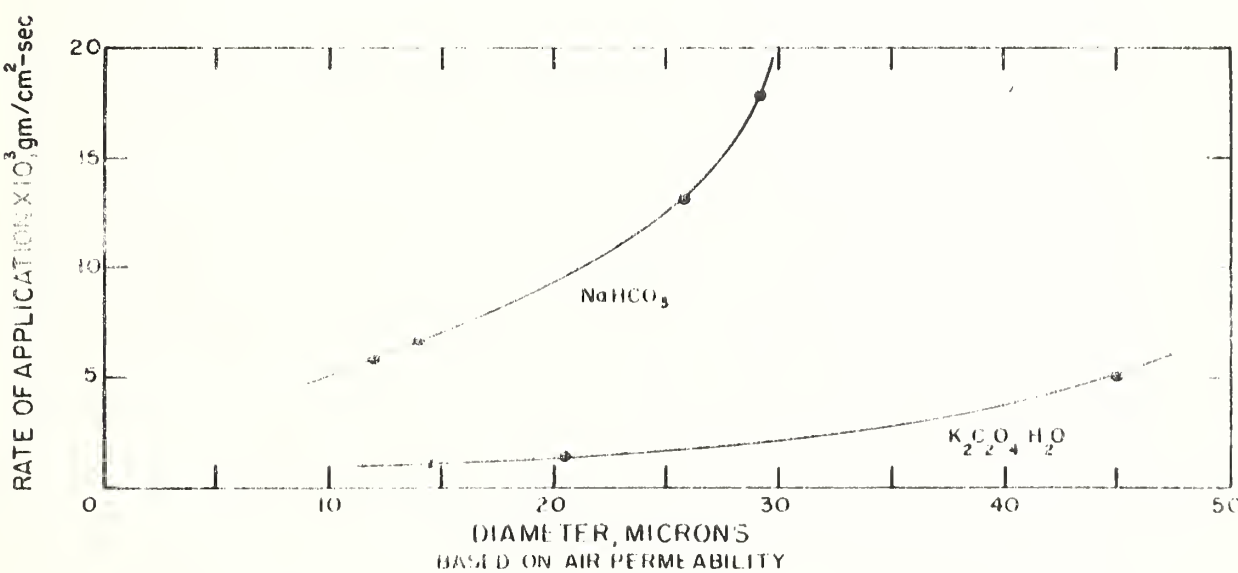

FIG 3 MINIMUM RATE OF APPLICATION OF POWDER FOR EXTINCTION VS MEAN DIAMETER, BASED ON AIR PERMEABILITY MEASUREMENTS

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