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NATIONAL BUREAU OF STANDARDS REPORT

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SOME OPTICAL PROPERTIES OF FINE POWDER USED FOR DRY CHEMICAL FIRE EXTINGUISHMENT

by

C. S. McCamy

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Fire Protection Section
Building Technology Division

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ABSTRACT

In an effort to shed some light on the mechanism of extinguishment of fires with dry chemical, the transmittance and diffuse reflectance of commercial dry chemical dispersed in air were measured in two spectral regions, the visible and near infrared. The size distribution of particles in the powder was also determined. The results indicate that the absorption of the dispersed dry chemical is high enough to reduce substantially the energy radiated from the flames to the fuel.

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1. INTRODUCTION

The effectiveness of dry chemical extinguishers in fighting gasoline fires has prompted considerable speculation concerning the mechanism by which the extinguishment is effected (1,2,3,4). A dry chemical extinguisher is a device designed to distribute a dry powdered substance on a fire, the substance currently employed commercially being very finely ground sodium bicarbonate treated with one or more of several materials to improve its flow properties. The earliest theory of dry chemical extinguishment and probably that which prompted its initial development was the theory that the sodium bicarbonate decomposed in the fire and the released carbon dioxide displaced the available oxygen. There is considerable evidence to discredit this theory(3,4).

Another emergent theory which remains plausible is that the dispersed powder hinders the heat transfer by radiation from the region of combustion to the unburnt gases and the liquid fuel. The present investigation concerns this theory, therefore, it will be stated more explicitly. In normal combustion on the free surface of a liquid fuel, the flame front moves downward with respect to the vaporized fuel. The unburnt vapors move upward with respect to the liquid surface. These two velocities are equal, on the average, causing the flame front to have a fixed average position a short distance above the surface. The flame front advances with respect to the gaseous fuel at a rate determined, in part at least, by

the rate of heat transfer from the combustion zone to the nearby vaporized and unvaporized fuel. The diffusion of oxygen and fuel, the rate of intermediate reactions preceding oxidation, and other factors presumably enter into the establishment of the equilibrium, but it is postulated here that the transfer of radiant energy is a primary factor and that significant interference with that process reduces the supply of preheated fuel, and eventually brings about extinguishment.

With this as a working hypothesis, it became of interest to investigate the optical behavior of the powder in the dispersed state. In particular, it became important to determine how much of the energy in an incident beam would be transmitted undeviated and how much would be deflected through various angles.

The energy might be deflected by either or both of two processes, scattering and diffuse reflection. "Scattering" is the technical term applied to a particular mechanism of deflection which occurs when the dimensions of the suspended particles are small compared to the wavelength of the incident energy. The intensity of scattered radiation is inversely proportional to the fourth power of the wavelength and is proportional to $1 + \cos^2$ of the angle between the incident and the scattered rays. When the dimensions of the particles are large compared to the wavelength of the incident energy, the energy is diffusely reflected and the angular distribution and intensity depends upon the gross properties of the material composing the particles. The intensity of the reflected energy is inversely proportional to the diameter of the particles. For a given mass of material, the intensity of the deflected energy increases as the particle diameter approaches the wavelength of the incident energy - whether the approach is from the longer or shorter side. These phenomena are discussed in more detail in reference (5) and in textbooks on optics.

The determination of the prevalent mode of deflection was of interest because it might reveal in a qualitative fashion the relative sizes of the effective particle diameter and the wavelength of the bulk of the radiant energy and thereby suggest a way to improve extinguisher performance.

2. APPARATUS AND METHOD

2.1 Recirculating System

An approach which was found unsatisfactory will be described briefly in order that the experience gained thereby may be a matter of record. A metal cylinder about one foot in diameter and 1 1/2 feet in height was equipped with blowers

at the top and bottom to recirculate and maintain turbulence in the enclosed air and the sides of the enclosure were equipped with quartz windows so that powder could be kept dispersed in the air while being irradiated and observed through the windows. It was found that the blowers changed the form of the powder, apparently by grinding, as was evidenced by a noticeable change in the flow properties of the powder. In the modified form, the powder deposited on the windows and sides of the enclosure. Although the optical effect of the powder on the windows was easily measured in still air after the dispersed powder had been allowed to settle to the bottom of the enclosure, the measured values under such static conditions were not believed to represent the values applicable to the dynamic state. In view of these difficulties, another experimental method was sought.

2.2 Falling Powder System

It was found that commercial dry chemical would remain on a fixed 100 mesh sieve but would flow quite readily if the sieve were vibrating. This fact made it possible to dispense a stream of powder which could be irradiated and observed without windows. In the system adopted, the powder was contained in a light metal cylinder 4 1/2 inches in height and two inches in diameter, open at the top and bottom. The cylinder was allowed to rest on the center of a sieve 8 inches in diameter having 100 meshes to the inch (.0059 in. openings) and was kept from moving from the center by thin rods attached to the cylinder and extending radially to the rim of the sieve but fitting the rim loosely. A six volt dc vibrator was arranged in such a manner that a clapper attached to the armature struck the rim of the sieve, causing the sieve to vibrate. No powder was dispensed when the vibrator was not energized and the rate of discharge could be varied by adjusting the position of the vibrator with respect to the sieve rim and the potential difference applied to the vibrator.

When falling dry chemical strikes a surface, a small amount of the powder rebounds and drifts about in the air. To avoid any interference from this source, an industrial vacuum cleaner was equipped with an 8 inch conical attachment and used to remove the powder as it fell. The opening was fitted with a sieve having 28 meshes to the inch to smooth and distribute the air flow. This sieve was located 8 inches below the dispensing sieve. At this distance, the cleaner system had no apparent effect on the free fall of the powder in the first three inches of fall.

The falling powder stream contracted from 50 mm diameter at the 100 mesh sieve to 40 mm diameter an inch below the sieve. The diameter remained fairly constant over the range from one to three inches below the sieve. Even in still air, the stream waivered slightly about its central position.

2.3 Effective Rate of Application of Powder for Extinguishment

Commercial extinguishers have been tested at the NBS and the discharge pattern observed. The rate of discharge of dry chemical varies with the extinguisher and is not constant over the entire discharge period of the extinguisher. A typical case provides a suitable rate for experimental purposes. A typical hand held 20 lb extinguisher directed horizontally at a height of three feet distributes powder over a horizontal area approximating an ellipse having axes of 10 and 20 feet. It discharges powder at an average rate of one pound per second. Although the center of the stream probably contains more powder than would be necessary, most of the outer area of this pattern must be considered too thinly covered for effective fire fighting. Let it be assumed that if the entire discharge were uniformly concentrated in an ellipse having axes one-half of those of the ellipse mentioned above, the rate of application would be effective over this entire area. The effective ellipse would have an area of 5650 square inches. One pound, or 454 grams, of powder is discharged per second; therefore the application rate is 0.08 gm/sec-in^2.

The manner of application in actual fire fighting is not predictable except that the operator approaches as close as possible and directs the stream at the base of the flames with a side to side sweeping motion. The flames are swept back, extinguishment being effected over a small segment at any one time. Over that small area, with the extinguisher at close range, the rate of application is instantaneously higher than that calculated above. It has not been established whether or not the higher rate is necessary. It seems reasonable to assume that the rate calculated above is of the right order of magnitude for experimental purposes and that in practice a higher rate may be employed. The results of this study are reported in such a form that they are applicable to various rates.

As mentioned in section 2.2, the falling powder stream in the experimental system constricted to a diameter of 40 mm at the point of observation. This stream, then, had an area of two square inches so, to simulate the application rate assumed above, the powder dispenser was adjusted to provide a flow rate of approximately 0.16 gm/sec.

2.4 Optical System

For the visible region of the spectrum the optical system consisted of a light source, a photovoltaic cell, and a potentiometer recorder.

The light source was a 100 watt incandescent lamp enclosed in a ventilated housing and a two lens projection

system designed to produce a beam of light of nearly uniform cross section. The beam was directed horizontally with its center line two inches below the dispensing sieve. Where the beam traversed the powder stream it had a square cross section 30 mm on a side. Power was supplied through a constant voltage transformer and an autotransformer so that the lamp voltage could be controlled.

The receiver used to measure the amount of light was a photovoltaic cell having a flat circular sensitive surface 2 inches in diameter. This cell was set in the end of a steel tube 2 1/8 inches in diameter and 6 inches long. This restricted the angle of view and precluded stray light. The receiver was supported in such a manner that it could be rotated about the powder stream while remaining directed at the stream. An angular scale was provided so that the receiver could be set at any angle with respect to the incident beam from 0° to 150°. The use of larger angles was impossible since this would require the source and receiver to be in the same place.

The output of the receiver was recorded on a continuously recording potentiometer with a wide range of sensitivity. The linearity of the response was established by measurements of the illumination due to a small source at various distances and the use of the inverse square law of illumination.

The lamp was a commercial grade 100 watt, 120 volt, tungsten filament bulb operated at rated voltage. This provided a source with a color temperature of 2740°K, which was used in conjunction with the uncorrected photovoltaic cell to obtain an effective spectral distribution similar to the relative visibility curve for the normal human eye but shifted about 0.05 micron toward the long wavelengths.

For the infrared portion of the spectrum, the system consisted of a heated wire source, a thermosensitive radiation detector, and a potentiometer recorder.

The source was a specially wound conical heating element operated at about 1200°K. The wires were wound on the inside and outside of a porcelain cone. The cone was placed in a metal container and the open base of the cone was oriented in the direction of an aperture from which the radiation emanated. Viewed through this aperture, the source appeared to be a closely wound spiralled helix of hot wires.

A thermosensitive radiation pyrometer was used as a detector. It was a Leeds and Northrup instrument with a mica window and a concave mirror which focused the energy on a thermopile.

The output of the receiver was recorded on the same potentiometer used in the measurements in the visible spectrum. The linearity of the instruments were established as before.

2.5 Energy Spectrum Emitted by Burning Hydrocarbons

Almost invariably, accidental fires result in diffusion type flames. Previous investigations (6) have shown that the spectral distribution of the energy emitted by hydrocarbon diffusion flames is similar to that of a blackbody at 1470°K. This distribution has a maximum at a wavelength of about 2 microns and 94% of the energy is included in the wavelength region below 9.5 microns. By means of an optical pyrometer, it was possible to estimate the temperature of the wire heater element. This element was adjusted to about 1200°K, giving a spectral distribution with a maximum at about 2.4 microns. The temperature of the heater was not increased because this might have damaged the heater element. The spectral distribution probably was augmented slightly on the long wavelength side of the maximum by the energy radiated by the porcelain cone which was at a lower temperature. This enrichment at the longer wavelengths was more or less compensated by the absorption of the mica window on the receiver. The transmittance of a thin mica sheet is known to drop off gradually from about 98% at 2 microns to about 50% at 8 microns and to zero at 9 microns (and to rise again to about 30% in a small region around 12 microns) (7).

2.6 Experimental Procedure

A sample of powder was passed through a 48 mesh sieve to eliminate any very large particles and a 100 gram portion was weighed to 0.1 gram. The weighed portion was placed in the cylinder above the sieve. The receiver was placed in line with the incident beam and the lamp was adjusted so that the recorder gave full scale deflection on the least sensitive scale. The vibrator and a stopwatch were started simultaneously. When a sufficient indication had been obtained, the receiver was moved around to other positions, 15° at a time. After this traverse the receiver was returned to the original position to confirm the initial reading and check instrumental drift. The rate was obtained by dividing the total weight by the total time. Numerous tests showed that the rate of discharge was nearly constant as evidenced by the constancy of the recorded transmittance, furthermore the recorded values were averaged over about 30 seconds; therefore, use of the average discharge rate seems justified. A second run was taken without powder so that any small systematic response due to stray energy could be subtracted from the indicated values.

3. OBSERVATIONS

3.1 Light Deflected by Commercial Dry Chemical

The light deflected through various angles was measured using commercial dry chemical. It was found that 85% of the light was transmitted directly. The percentage deflected through various angles is listed in table I. The sum of the values shown is less than 100% because some of the incident energy was absorbed by the powder and some of it was deflected through small or large angles at which no observations were made because of the limitations of the instrument.

Table I. Energy Deflected by Dry Chemical at Various Angles

Angle	Visible		Infrared
Ø Degrees	Observed Relative Intensity	Integrated Percent of Flux	Observed Relative Intensity
0	85	85	81
30	0.14	1.05	
45	0.066	0.70	
60	0.059	0.77	0.23
75	0.048	0.70	0.10
90	0.040	0.60	0.08
105	0.029	0.42	0.15
120	0.029	0.38	0.13
135	0.026	0.28	
150	0.040	0.30	

The method of calculating the integrated percent of flux may be described in terms of the following coordinate system. Let the Z axis coincide with the center of the incident beam and be similarly directed. Let the Y axis coincide with the center of the powder stream and be directed downward. Let the X axis be perpendicular to these axes and be directed to form a right-handed system. Let the usual corresponding spherical coordinate system be used to indicate the direction of deflected rays, the angle Ø being measured at the origin from the Z axis to the ray in question and the angle θ being measured in the XY plane from the X axis to the projection of the ray on the XY plane.

The relative intensity of the deflected energy within a given solid angle was observed at various angles, Ø, in the XZ plane, i.e. with Θ equal to zero. Assuming that energy would be deflected uniformly with respect to Θ, this value was used to integrate with respect to Θ from 0 to 2π. The integrated values indicate the percent of the total light deflected through various angles, Ø.

3.2 Deflection of Infrared Energy by Commercial Dry Chemical

The infrared energy deflected through various angles was measured, using commercial dry chemical. It was found that 81% of the energy was transmitted directly through the powder stream. The relative amounts deflected through various angles are listed in table I. No measurements were made at smaller or larger angles because of the inherent limitations of the instrument. The data are presented graphically in figure 1. The angle subtended by the sensitive element of the receiver was not sufficiently precisely known to warrant integration with respect to Θ.

3.3 Independent Determination of Fineness of Commercial Dry Chemical

A sample of the commercial dry chemical was examined in the fineness laboratory at the National Bureau of Standards. Microscopic examination revealed particles ranging from less than 10 microns to more than 50 microns in diameter. The material was elutriated in a Roller Analyzer. The results, shown in table II, indicate the distribution of particle diameters with nearly half the weight of the material in particles having diameters exceeding 40 microns.

Table II. Distribution of Particle Sizes in Dry Chemical

Range of Particle Diameters microns	Percent by weight	Percent by projected area
0-10	3±1	16.2
10-20	14±3	25.2
20-40	38±5	34.3
>40	45±3 (by difference)	24.3

4. ANALYSIS

The data concerning energy deflection in the visible and infrared portions of the spectrum are shown in figure 1 together with the distribution to be expected if true scattering were the principal mechanism. It may be seen that there is little resemblance between the observed distribution and that for scattering. Furthermore, since the intensity of scattered light is inversely proportional to the fourth power of the wavelength, a blue coloration normally accompanies scattering. This coloration was not found. It may be inferred that the mechanism is diffuse reflectance and that the effective particle diameters are greater than the wavelength of the radiant energy involved. This is corroborated by the fineness determinations by elutriation. Since the intensity of reflected energy is inversely proportional to the diameter of the particles, assuming the weight concentration is held constant, it may be concluded that the use of dry chemical with a higher percentage of fine particles would increase its effectiveness in reflecting energy. Ideally the particles should have a diameter equal to the wavelength of the energy. In the case of hydrocarbon flames this would be about 2 microns. It must be borne in mind that the particles must be delivered to the fire in this fine state of subdivision. Fine particles are of no value if they agglomerate, for then they are effectively larger particles.

Since reflection depends upon the cross sectional area of particles rather than their weight, it is of some interest to consider the relationship between the percent by weight in particles of a certain size and the percent of total cross sectional area in those particles. It may be shown that

$$A_j = \frac{W_j}{d_j \sum_{i=1}^{i=n} \frac{W_i}{d_i}}$$

where A_j is the percent of the total cross sectional area in the particles of diameter d_j (assuming particles of spherical shape), W_j is the percent of the total weight in such particles, and there are n different particle diameters in the sample.

Applying this equation to the weight distribution in table II, the area distribution is found. Where particle diameter enters into the equation, the center of the range was used except for the last range where 50 microns was used. The results are given in table II.

This analysis emphasizes the fact that even small amounts of material can contribute a considerable amount of area if the particles are very fine and that a slight increase in percentage by weight in the small sizes can greatly increase the area.

The measurements of reflected energy are primarily of value insofar as the relative distribution reveals facts concerning particle size. The measurements of transmittance, on the other hand are of more significance considered as absolute values. The transmittance was 85 percent for visible radiation and 81 percent for the infrared region. This difference is to be expected since the reflection increases as the wavelength approaches the particle size.

The attenuation of electromagnetic radiation of a given wavelength may be described by the following equation whether it is due to scattering, reflection, or absorption:

$$I = I_o e^{-abc}$$

where I is the intensity of the transmitted beam, I_o is the intensity of the incident beam, e is the base of Naperian logarithms, "a" is the absorbancy index of the material causing attenuation (the term is here extended to include processes other than absorption), b is the path length of the radiation in the attenuating medium, and c is the concentration of the material causing attenuation. The absorbancy index depends upon the wavelength of the incident energy and upon the properties of the material, such as the particle size discussed earlier.

The concentration of powder in a stream depends not only upon the weight of material passing through a unit of area per unit of time, but upon the velocity of the stream and the deflections and turbulence of the stream. In practice, the stream is usually directed at the base of the flame. Some powder remains there, some rebounds or is swept up by the turbulent gas stream into the cloud above the fuel, and some goes past the flames and is lost. In this case, the factors determining the concentration are too numerous for practical analysis. In the experimental arrangement, the particles fell downward in a laminar stream and did not rebound. Then the concentration was simply determined by the weight rate of discharge and the velocity. By use of Stokes Law, it was calculated that the terminal velocity of sodium bicarbonate particles falling in still air at standard temperature and pressure ranges from 0.065 in./sec for spheres 5 microns in diameter to 6.5 in./sec for spheres 50 microns in diameter. The theoretical equation of motion of such particles predicted that, for all practical purposes, the particles could be considered to be at their

terminal velocities when they fell past the level of the incident beam. Since the large particles were present in greatest numbers and fell faster, they tended to create air currents that swept the lighter particles along. For this reason, the stream velocity was considered to be about 6 in./sec. The powder concentration is the ratio of the weight delivered per second to the volume filled per second, i.e., 10 gm/sec divided by 12 in^3/sec, or 0.83 gm/in^3.

On the basis of these values, the infrared absorbancy index of commercial dry chemical dispersed in air may be calculated. Let $I_o = 100$, $I = 81$, $b = 1.57$ in., and $c = 0.83$ gm/in^3. Then $a = 0.16$ in^2/gm. Using this value of "a", the transmittance T may be calculated for various cloud thicknesses and concentrations, as follows:

$$T = \frac{I}{I_o} = e^{-abc}$$

$$\ln \frac{1}{T} = abc = 0.16bc.$$

A range of values is given in table III.

Table III. Infrared Transmittance of Dry Chemical Clouds of Various Thicknesses and Concentrations (Calculated)

Concentration gm/in^3	Thickness, inches 6	12	18	24
	transmittance in percent			
0.1	90	83	75	68
0.5	62	38	24	15
0.83*	45	20	8.9	4.0
1.0	38	15	5.6	2.1
5.0	0.83	0.0067	--	--

*This is the concentration used in the experiments and it is believed that it is somewhat lower than is actually employed in fire fighting.

In an open gasoline spill fire on an area four feet square, flames often rise six to eight feet in the air. Dry chemical may be applied in a cloud 18 inches deep at the base of the flame. In that event, practically all of the energy radiated in the direction of the gasoline would be intercepted by the cloud and the transmittance of the cloud would probably be less than 10 percent. It seems reasonable to conclude that this effect might account for the extinguishment of the flame.

Although the evidence thus far does not prove that the radiation barrier effect accounts for the extinguishment, it lends considerable support to this hypothesis.

In the light of the results of this investigation, further experiments can be envisaged which should yield valuable information on this subject. The most direct approach and the one which, it seems, should give the most conclusive evidence concerning this hypothesis would be the direct measurement of the energy transmitted from the flame to the gasoline before and during extinguishment. This would require some sort of open burner with a viewing port in the bottom arranged in such a manner that a radiometer could be placed below the burner.

Experiments could be designed to determine whether or not there is a correlation between particle size and extinguishment effectiveness. A general correlation may be observed in the results reported in reference 4. It would be of considerable interest to try particles of much smaller average diameter than have been used heretofore.

If this hypothesis is to be further established, it should be possible to extinguish fires by dispersing the powder in the fuel gases only without placing powder in the ignition zone. It is not readily apparent how such an experiment would be arranged, but it might be worth an attempt.

It may be of some value to attempt extinguishment while supplying just enough heat from an external source (such as hot wires) to vaporize the required amount of fuel.

The results of such a series of experiments should contribute a great deal to the explanation of the mechanism of extinguishment.

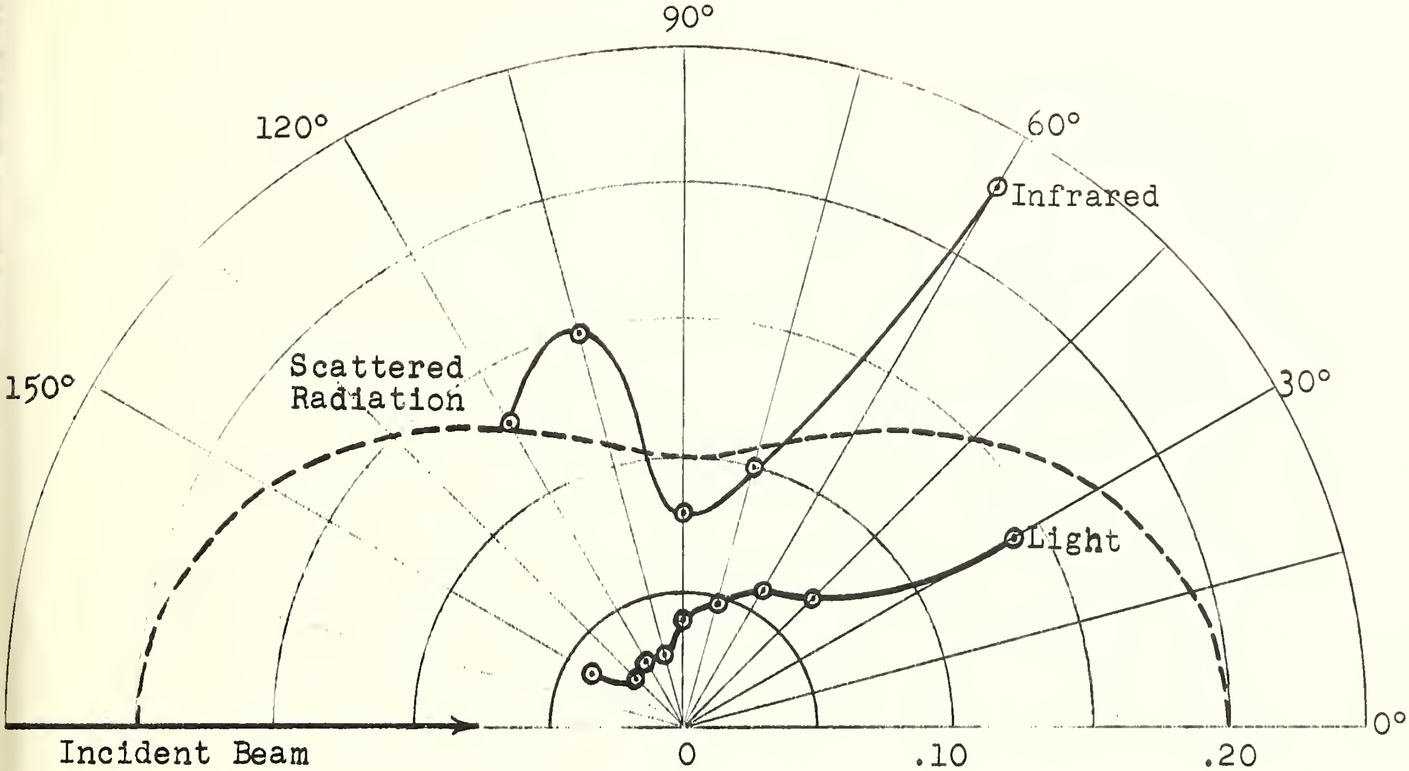

Figure 1. Observed Relative Intensity of Energy Deflected by Commercial Dry Chemical and the Pattern to be Expected as a result of True Scattering

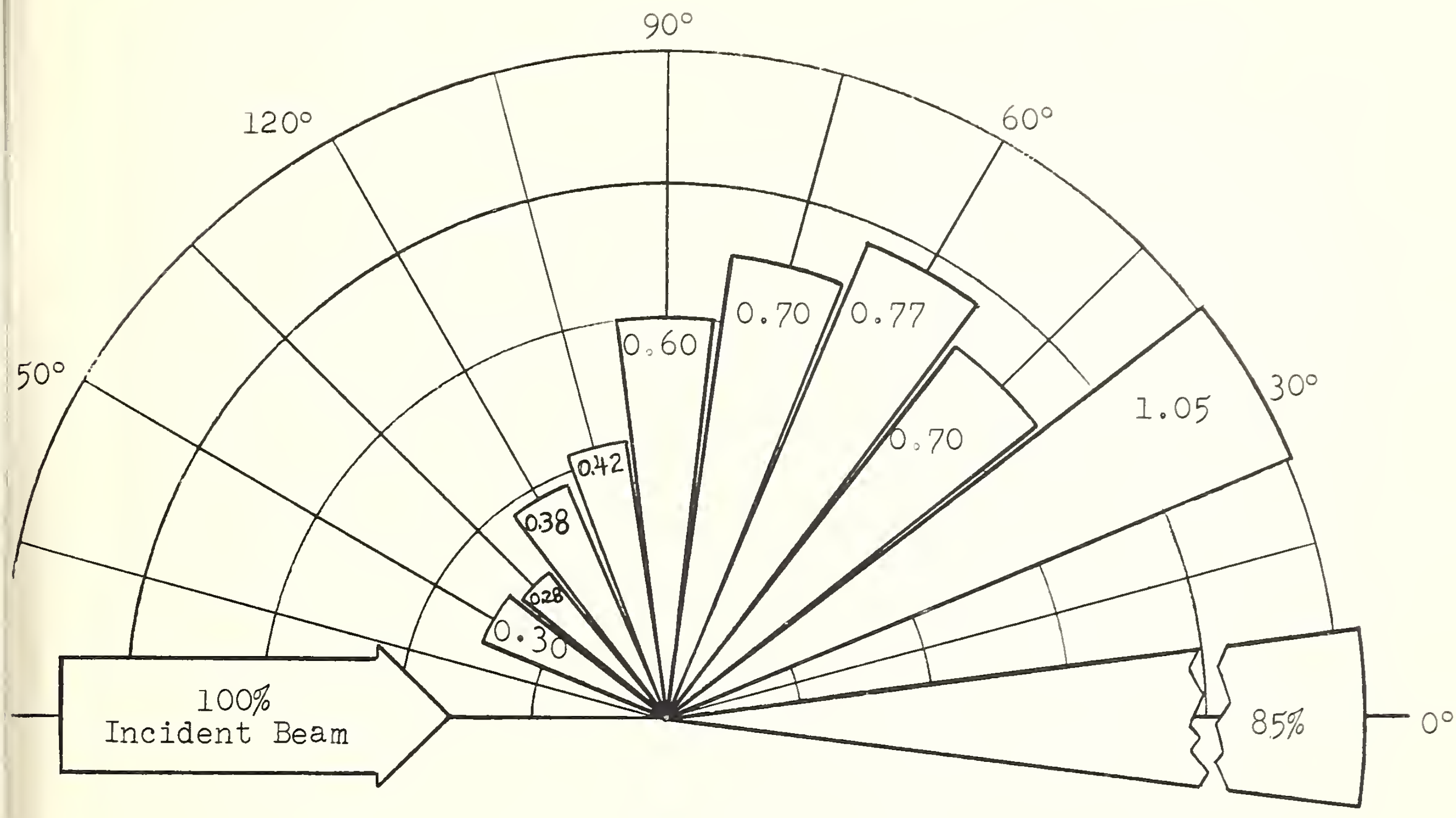

Figure 2. Percent of Incident Light Deflected Through Various Angles

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