AD-766 301

TRANSMISSION OF 2.0 TO 3.4 MICRON INFRARED RADIATION IN ICE FOG

Harold W. O'Brien, et al

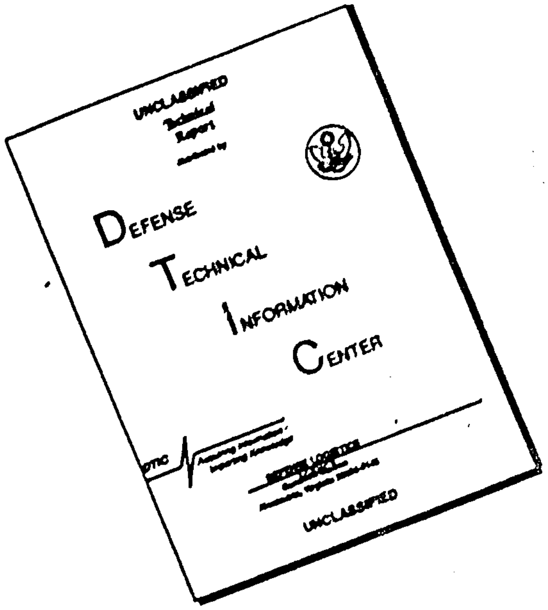
Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire

July 1973

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

SR 189

Special Report 189

AD 766301

TRANSMISSION OF 2.0 to 3.4 MICRON INFRARED RADIATION IN ICE FOG

Harold W. O'Brien and Motoi Kumai

July 1973

PREPARED FOR
U.S. ARMY MATERIEL COMMAND
DA PROJECT 1T061102B52A
BY

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

TRANSMISSION OF 2.0 TO 3.4 MICRON INFRARED RADIATION IN ICE FOG

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Harold W. O'Brien and Motoi Kumai

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
July 1973	11	9

8a. CONTRACT OR GRANT NO. b. PROJECT NO. DA Project 1T061102B52A c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Special Report 189 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	U.S. Army Materiel Command

13. ABSTRACT

Limited measurements were made of the transmission of infrared radiation (2.00- to 3.40-micron wavelengths) through ice fog. The experimental results are compared with the spectral transmission predicted by Mie theory for ice spheres and for water fog. The experimental measurements of attenuation by ice fog tend to agree, within the experimental error expected, with values predicted by Mie theory for ice spheres. The present studies are adversely affected by the limited state of the art in making accurate measurements of ice fog concentration, and by inadequate control of environmental CO_2.

14. Key Words

Ice fog
Infrared radiation
Mie scattering
Near infrared radiation

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified
Security Classification

TRANSMISSION OF 2.0 TO 3.4 MICRON INFRARED RADIATION IN ICE FOG

by

Harold W. O'Brien and Motoi Kumai

Introduction

A considerable amount of work was done in Fairbanks, Alaska, in the late 1950's and the 1960's to find the principal causes of ice fog and to study the nucleation and growth of ice fog crystals (Kumai 1964, Kumai and O'Brien 1965, Benson 1965). Generally speaking, ice fog in Fairbanks is the product of man's activity. The nuclei and water vapor that form ice fog are produced by man in the course of daily living, by home heating, vehicular exhaust and factory effluents. As the arctic population increases, stimulated in part by oil discoveries, the ice fog problem becomes more critical. Operating aircraft under conditions of low visibility is obviously hazardous. When the ice fog is very dense even surface travel is hampered. Obviously the most desirable and the only ultimately acceptable solution to the ice fog problem is to eliminate ice fog or at least reduce its formation. However, until such time as this is accomplished attempts should be made to reduce its effects. One way to do this is by attempting to see through the ice fog to improve travel under low visibility conditions.

Ice fog crystals have diameters generally comparable to the wavelength of infrared radiation (2-20 microns). Water vapor, carbon dioxide, and other atmospheric constituents coexisting in ice fog have absorption bands in the infrared. And ice fog crystals have complex indices of refraction which are dependent on wavelength. Therefore the transmission of infrared radiation through ice fog will necessarily depend on wavelength. Mie theory predicts the scattering which will take place when a given wavelength of radiation is transmitted through a volume containing spheres of known size distribution, concentration, and index of refraction. One might, then, calculate the scattering coefficients for typical ice fog size distributions and concentrations for wavelengths throughout the near-infrared and infrared spectrum in order to predict the effectiveness of each wavelength in penetrating ice fog. However, ice fog crystals are not truly spherical and their complex index of refraction is not thoroughly known over the infrared spectrum.*

This project was begun with the intention of determining whether the transmission of near-infrared and infrared radiation through ice fog could be adequately predicted by Mie theory and if not to experimentally establish relationships between the wavelength of incident radiation and the depth of penetration in ice fog. Ultimately, because of refrigeration breakdown and the need to use the optical equipment for other projects, the scope of the project was limited to include only the 2.0- to 3.4-μ wavelength spectrum.

This report has been prepared to present the results of this limited study, and to discuss the problems involved in this type of study for the consideration of future researchers in this field.

---

*Some work has been published on complex indices of refraction of ice in the infrared. Irvine and Pollack (1968) provide a critical review of literature published to that date.

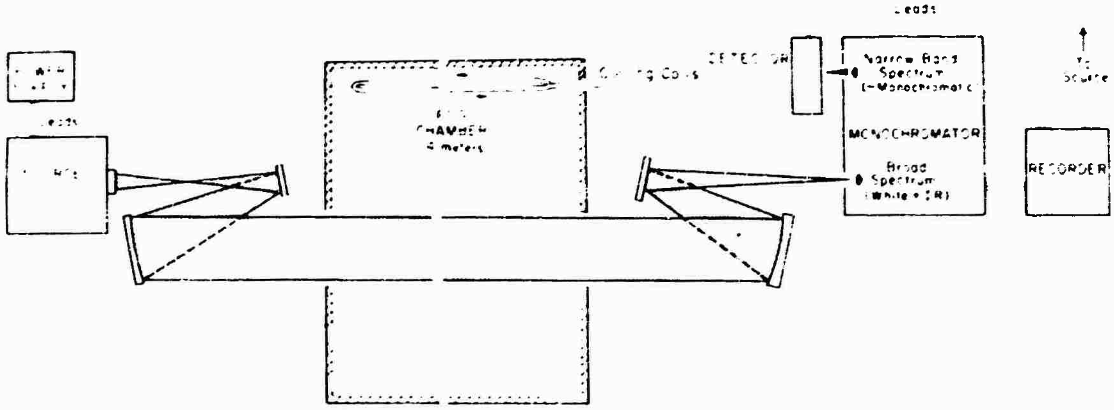


Figure 1. Experimental apparatus.

Instrumentation

Optical components. Infrared radiation from a Perkin-Elmer IR glower source, chopped at 13 Hz, was transmitted through a 4-meter cold fog chamber to a Perkin-Elmer E-1 monochromator, and the selected wavelength subsequently focused on a thermocouple detector. A schematic representation of the experimental apparatus is shown in Figure 1.

Because the spectrometer was originally designed for short path lengths, on the order of a few centimeters, it was necessary to design an optical system to adapt the instrument to the longer path length. The system had two units, each consisting of one flat and one concave gold plated, first surface mirror. The first unit converted the source radiation to a nearly parallel beam which, after traversing the fog chamber, was received by the second mirror unit and focused on the monochromator slits.

Cold fog chamber. The fog chamber was 4 m long and 1 m square in cross section with 11.4-cm holes at each end for beam entrance and exit. The holes were used in lieu of transparent windows to eliminate the problem of frost accumulation on material windows. Plexiglas windows were installed in the sides of the chamber for viewing the evolution, apparent homogeneity and dissipation of the fogs produced. Fog samples were extracted through access panels in the sides of the chamber for microscopic measurements of size distribution and concentration Copper cooling coils were arranged horizontally along the length of the box near the top of the chamber, well clear of the optical path.

Fog sampling instruments. An impactor was designed with an extended arm which permits sampling of the fog in proximity to the optical path. The impactor consisted of a 30-cc glass hypodermic syringe which drew the fog sample through a 1-mm aperture, causing ice fog crystals to impinge upon a collector plate. The collector plate was a glass slide (5 × 25 mm) to which a thin film of silicone oil was applied. The ice fog crystals were trapped by the oil, permitting photomicrography of the samples.

Environmental temperatures. Although the experiments were conducted entirely within a large coldroom, it was not feasible to maintain all components at the coldroom temperature. The monochromator, detector, receiving optics and system electronics were maintained in a small Styrofoam-insulated room within the coldroom. This "monochromator room" was electrically heated to approximately 20°C and the monochromator was internally thermostatically controlled at 32.2°C ± 0.3°C. The source and source optics were maintained in a smaller but similarly insulated and heated room.

As the simulation of natural ice fog requires temperatures lower than those attainable in the large coldroom, the temperature in the fog chamber was reduced to about −40 C by circulating refrigeration brine through the chamber's accessory cooling coils.

The coldroom itself was kept cold for two reasons: the cold chamber coils alone would be insufficient to produce the necessary low temperature in the chamber, and also the fog sampling and photomicrography of the samples must be accomplished at low temperatures (about −35° C or colder) to eliminate melting and reduce sublimation of ice fog crystals prior to completion of the photomicrography.

Experimental methods

Procedure. These initial experiments were conducted at selected fixed wavelengths from 2.00 to 3.40 μ. Measurements were made at 0.20-μ intervals with approximately 0.001-μ spectral slit widths.

Before transmission measurements were made, a natural deposition of ice was permitted to accumulate on the cooling coils and inner walls of the fog chamber. Thus, the initial condition of humidity was considered to be saturation with respect to ice.

The spectral slit width and electronic gain controls were adjusted to permit a chart reading of 100% transmission with no fog in the chamber. After a suitable baseline had been established, water vapor was admitted to the chamber through several orifices, producing a thick ice fog and reducing the transmission to zero. When the fog had mixed uniformly and gradually dissipated until the transmission exceeded 30%, frequent fog sampling (by impactor) was done until the fog had completely dissipated. Generally the impactor sample withdrawn consisted of 10 cm^3 of ice fog. At the time of each sampling, a deliberate brief interruption of the transmitted beam caused a pip on the chart recording for later correlation of transmission with ice fog density. The impactor samples were immediately photographed under an optical microscope. From the resulting photomicrographs, determinations of ice fog size distribution and crystal concentration were made. This procedure was repeated for each new wavelength considered.

Technical problems. Several difficulties were encountered in making these measurements. The first problem was producing and maintaining a stable fog. The term *stable fog* is used here with a connotation of dynamic stability; that is, an attempt was made to establish a dynamic equilibrium between the rate of fog formation and the rate of dissipation so that the size distribution and concentration of the ice fog remained fairly constant long enough for a given spectral region to be scanned. At the time these measurements were made such a stable fog could not be maintained. Measurements were made at individual wavelengths during a fog which was dissipating after having been created by injection of steam into the cold fog chamber. We are testing a new fog generating system which we hope will maintain stable ice fogs for considerable periods of time, so that broad spectral regions may be scanned.

Another problem encountered was measuring the size distribution and concentration of the ice fog crystals. Transmittance or scattering methods were avoided because they would obviously defeat one of the purposes of the project: determining the applicability of Mie theory to ice fogs. The impactor method used is undesirable from two viewpoints. We have no absolute method of calibration although the collection efficiency of the impactors may be evaluated by using several stages (Kumai and Francis 1962). Also, the photographic recording and subsequent measurements are very time consuming, and if impactor intake volumes are not chosen which are appropriate to the ice fog concentration, overcrowding of crystals on the sample can lead to difficulties in interpreting and counting the crystals and aggregates.

Another factor which would tend to influence the comparison of our measurements with Mie theory is the size and incompleteness of collimation of our beam. By adjusting the focusing mirror, we maintained the beam at approximately constant cross section. However, the source used does not qualify as a point source and a considerable degree of nonparallelism of rays within the beam is to be expected.

Experimental results and discussion

Ice fog crystals formed in a fog chamber at −40°C are shown in Figure 2 and their size distribution appears in Figure 3. The crystal shapes and size distribution are very similar to natural ice fog samples found in Fairbanks, Alaska (Kumai 1964, Kumai and O'Brien 1965). Single crystals were found to include "spherical," hexagonal plate, and columnar. Crystal aggregates were also found, presumably caused by sintering of individual crystals during collisions in the high density fog.

The attenuation coefficient b at a given wavelength λ is related to the transmittance T in the following manner:

$$T = I/I_0 = \exp\left(-\int_0^x b_\lambda \, dx\right)$$

where I_0 is the incident light intensity (no ice fog), I is the apparent light intensity (with fog of a given concentration), and x is the path length through the ice fog. If the fog is considered homogeneous throughout the optical path

$$T = \exp(-b_\lambda x)$$

and

$$b_\lambda = (-\log_e T)/x$$

Curves were plotted of b_λ vs ice fog concentration (Fig. 4) for each wavelength. From these curves the values of attenuation coefficient, interpolated at a concentration of 100 crystals cm^{-3} (a reasonable concentration for simulating natural ice fog) were plotted against wavelength (Fig. 5). The theoretical values of attenuation by ice spheres (Kumai and Russell 1969) and by water fog of the same concentration are also plotted in Figure 5 for comparison.

The experimental values of attenuation obtained by this measurement tend to agree, within limits of expected experimental error, with values predicted by Mie theory. The largest errors were found in the 2.40- to 2.80-μ range due to the change of concentration of CO_2 gas during the experiments. In making an initial run at 2.60 μ it was noted that the presence of a technician in the monochromator room caused a reading of decreased transmission due to exhaled CO_2 entering the monochromator. Thereafter runs were made with no operator in the room. At that time there was no indication that CO_2 exhaled by the fog sampling team was infiltrating the fog chamber in significant quantities. However, in view of the fact that maximum disagreement (33.6%) between measured and theoretical values occurs at 2.60 μ, it may well be the result of fluctuations in CO_2 content in the coldroom. The same rationale probably applies to the difference observed in the 2.40-μ measurements, since these measurements were made before the magnitude of the CO_2 problem was appreciated. The beginning of the CO_2 absorption band is near 2.40 μ and it is conceivable that the high measurement of attenuation (22% above the theoretical value) is due to a high CO_2 concentration in the monochromator room. It might also be noted that some CO_2 absorption occurs near 2.00 μ and although good agreement is shown, the slightly higher measured attenuation may again be due to CO_2 absorption.

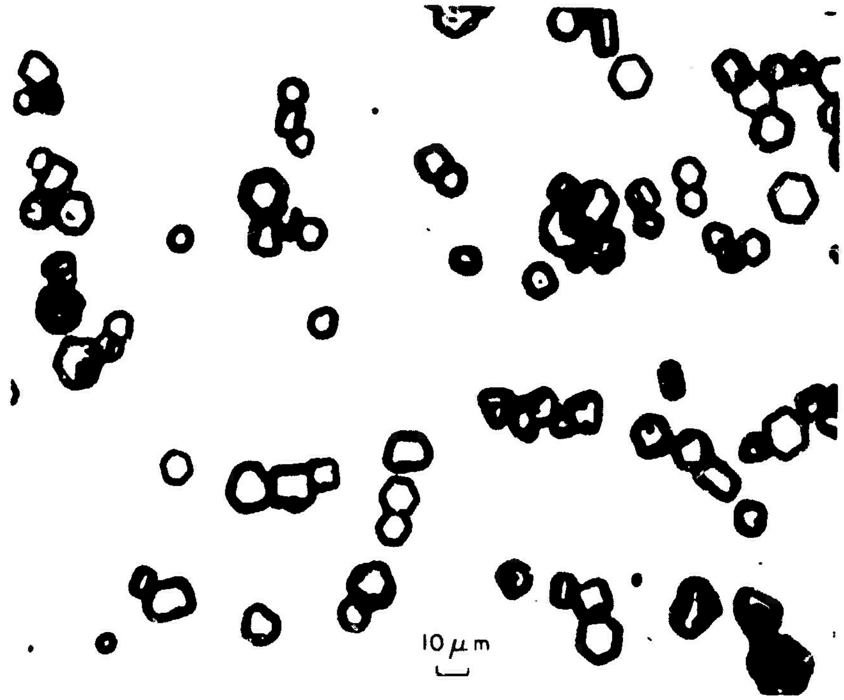


Figure 2. Typical ice fog crystals formed in the laboratory cold chamber.

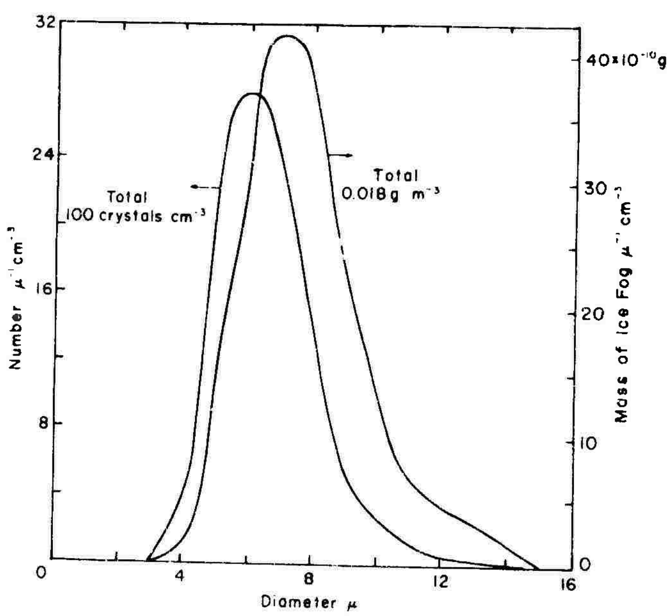


Figure 3. Typical size distribution of ice fog formed in the laboratory cold chamber. Normalized to 100 particles cm^{-3}.

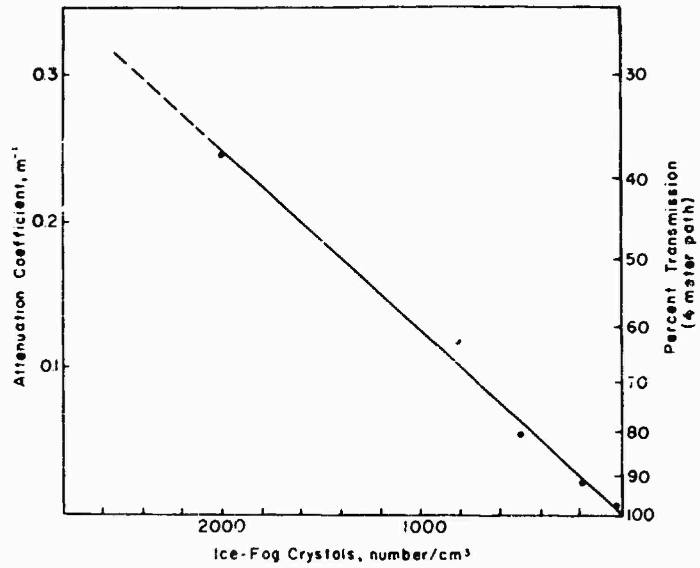


Figure 4. Decrease in attenuation during dissipation of an ice fog; 2.20-μ wavelength radiation.

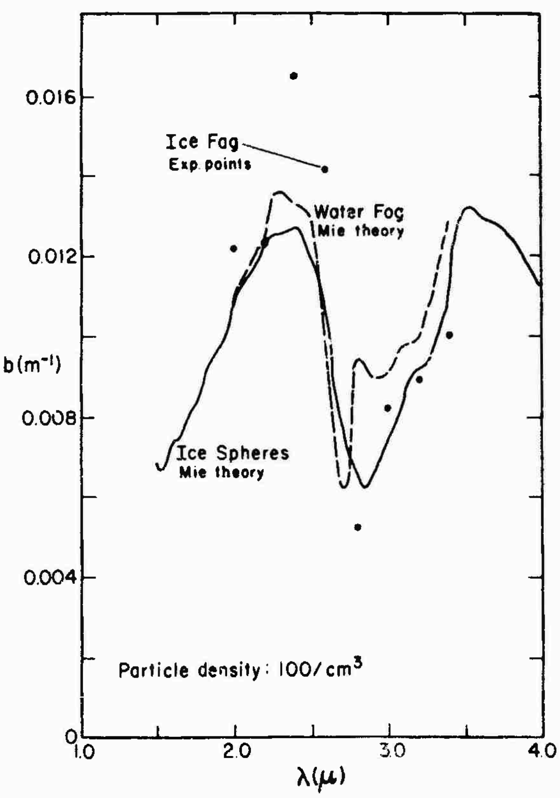


Figure 5. Attenuation of 2.00- to 3.40-μ radiation by 100 crystals cm^{-3} of ice fog compared to the theoretical attenuation due to the same concentration and size distribution of water fog and ice spheres. Size distribution shown in Figure 2.

It is more probable, however, that this discrepancy, as well as the low measurement at 2.80 μ, is due principally to other causes such as inaccuracy in fog concentration determination.

These results created interest in trying to define more closely the sources of differences between theory and measurement in the 2.40- to 2.80-μ region. Future experiments with more closely controlled conditions, particularly with respect to environmental CO_2 levels, will be planned.

Conclusions

Tentatively, we conclude that in the region from 2.00 to 3.40 μ Mie theory satisfactorily predicts the attenuation due to ice fog crystals (Kumai 1964, Kumai and O'Brien 1965). We tend to concede that the differences noted between measurements and theory are probably due principally to extraneous CO_2 in our experiment and to inaccuracy in ice fog concentration measurement methods. However, there is still some uncertainty as to the relative influence of factors involved in using Mie theory, such as the assumption of sphericity of particles,* considering single scattering only, and possible inaccuracies in the complex index of refraction used for ice. A new formulation of the Mie theory computer program is being written which will permit the injection of incremental changes in parametric quantities, thus permitting evaluation of the effects of quantitative uncertainties in size distribution, complex index, etc.

Additional studies are being conducted to try to improve methods of measurement of particle size distributions and concentrations. Laser measurements are planned at the 1.15- and 3.39-μ outputs from an He-Ne laser which will be compared with noncoherent light transmission measurements to estimate the error introduced by nonparallelism of the source beam.

Literature cited

Benson, C.S. (1965) Ice fog: Low temperature air pollution. University of Alaska Geophysical Institute Report UAG R-173, p. 14-17 (AD 631553). Also U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL) Research Report 121, June 1970 (AD 708544).

Holland, A.C. and J.S. Draper (1967) Analytical and experimental investigation of light scattering from polydispersions of Mie particles. *Journal of Applied Optics*, vol. 6, no. 3, p. 511-518.

Huffman, Paul J. (19[illegible]) Size distribution of ice-fog particles. M.S. thesis, University of Alaska, 93 p.

Irvine, William M. and James B. Pollack (1968) Infrared optical properties of water and ice spheres. *Icarus*, vol. 8, p. 324-360.

Kumai, M. (1964) A study of ice fog and ice crystals at Fairbanks, Alaska, Part I. USA CRREL Research Report 150, Part I (AD 451667).

Kumai, M. and K.E. Francis (1962) Size distribution and liquid water content of fog, northwestern Greenland. USA CRREL Research Report 100 (AD 294195).

Kumai, M. and H. O'Brien (1965) A study of ice fog and ice crystals at Fairbanks, Alaska, Part II. USA CRREL Research Report 150, II (AD 676811).

Kumai, M. and J.D. Russell (1969) The attenuation and backscattering of infrared radiation by ice fog and liquid fog. USA CRREL Research Report 264 (AD 689447).

Ohtake, T. and P.J. Huffman (1969) Visual range in ice fog. *Journal of Applied Meteorology*, vol. 8, p. 499-501.

*Results of Holland and Draper (1967) invite the conclusion that the assumption of sphericity may be acceptable for some purposes when randomly oriented irregular particles are involved.