HOW SILVER IODIDE SEEDING SUPPRESSES HAIL

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1. SOME HYPOTHESES

The results of many hail suppression projects conducted around the world in the past 27 years suggest that 1) silver iodide seeding suppresses hail in some storms but not in others and 2) the seeding effect is largely independent of the amount of silver iodide used, provided some reasonable threshold is exceeded.

A search for a set of unifying principles to help explain the observed results has led this author to the following hypotheses:

1. Silver iodide seeding (at any reasonable rate) does not suppress hail through the glaciation of cloud water in updrafts.

2. Silver iodide seeding is effective if it provides beneficial competition in the regions of hailstone growth.

In a time-dependent situation with short-lived convective cells, competition can sometimes be introduced by seeding early in the life cycle of an individual convective cell to increase the concentration of graupel. If some of the cloud water has already coalesced into precipitation, seeding cannot produce embryos of any importance directly through the glaciation of cloud water, but it can do so readily by freezing supercooled raindrops. This leads to Hypotheses 3 and 4, as follows:

3. The ease with which hail can be suppressed in a more persistent cloud depends upon whether or not the cloud water passes through an intermediate rain phase or whether it is frozen directly to the growing hailstones.

4. If raindrops are sufficiently abundant in a cloud, natural freezing nuclei often produce enough competing embryos to suppress hail naturally.

The above ideas were developed in a tentative form at the Institute of Atmospheric Sciences in the late 1960's and affected the work plans for the North Dakota Pilot Project of 1972 (Miller, 1972). They have recently received support in additional work elsewhere. For example, Young (1975) has concluded on the basis of parcel model calculations that silver iodide seeding to glaciate the cloud water in strong updrafts is not a practical suggestion and, furthermore, that such seeding cannot lead directly to formation of viable embryos if updrafts at cloud base exceed roughly 3 m sec^{-1}.

Browning and Foote (1975) have noted that storms with weak echo regions (WER's) may not respond to seeding because some hailstones follow trajectories which protect them from effective competition; we note that those hailstones grow by direct accretion of cloud water without an intervening rain phase.

The balance of this paper deals principally with Hypotheses3 and 4, that is, it examines the role of the freezing of raindrops in the formation and suppression of hail.

2. ACCUMULATION ZONES

Appleman (1959), Ludlam (1959), and others have speculated on the possibility of natural hail suppression mechanisms involving competition among natural precipitation embryos, including raindrop embryos formed by coalescence of liquid droplets. Rain held aloft by strong updrafts was seen as potentially important to the hail growth mechanism by Marshall (1961) and Ludlam (1959). Ludlam's (1959) observation of developing rain showers in storms in Italy followed by (as he theorized) lifting of some of the raindrops to colder regions and their merging into large hailstones is reminiscent of the observations in the Soviet Union (Sulakvelidze et al., 1967). The unfortunate association which the Soviet authors made between accumulation zones and regions of decreasing updraft speed with height, which apparently resulted from the limitations of their one-dimensional cloud model, can best be passed over. Suffice it to say that in nature the accumulation results from differences in terminal speeds among the hydrometeors present, and can occur below an updraft maximum as well as above it (e.g., Danielsen et al., 1972). It should also be noted that the accumulation zones seen by radar may sometimes consist of solid precipitation rather than rain.

Suppose cloud water moving with an updraft is suddenly converted to rain. An elementary mathematical treatment shows that the rainwater concentration ℓ_R above the transition zone is greater than the cloud water concentration (ℓ_c) in the air arriving from below. The relationship is

$$\ell_R = \ell_c \left(\frac{V}{V-V_t}\right) \qquad (1)$$

where V_t is the terminal speed of the raindrops and V is the updraft speed. In nature the rainwater zone may be rising or falling depending on the relationship between V and V_t and is also subject to deformation by various combinations of vertical and horizontal divergence/convergence and vorticity fields in the cloud circulation. Nevertheless, the rain zone will persist and intensify through the accretion of cloud water arriving from below (hence the name accumulation zone) providing a positive feedback effect. As Sulakvelidze et al., (1967) point out, the presence of precipitation is a destabilizing influence in a convective cloud in that precipitation fields tend to become more concentrated with time unless relieved by the fallout of the largest particles. The precipitation streamers occasionally seen inside weak echo regions (e.g., Marwitz, 1972) are evidence of such a tendency.

An idea of the likely thickness for a "mature" accumulation zone of either rain or hail is given in Fig. 1, which shows the fractional depletion of the cloud water in a model cloud updraft by a monodisperse hail screen of 1 gm^{-3}. (Very similar results would be obtained if the calculations had been made for a rain screen.) The efficiency of the precipitation in acting as a screen decreases approximately with the square root of the particle diameter. The formula for the cloud water depletion rate is

$$0.3 \frac{V_t}{2\rho DV} .$$

where ρ is the density and D is the diameter of the collecting particles. Since V_t for the hailstones varies as $\sqrt{D}$, the fractional depletion rate varies approximately as $1/\sqrt{D}$. This relationship can be seen in Fig. 1. The slightly higher fractional depletion rates at the low temperatures are due to the lower air density and, hence, the greater fall speeds for the precipitation particles at the higher altitudes.

Since the largest raindrops are about 5 to 6 mm in diameter, we are interested here in the extreme left-hand side of the diagram. A small rainwater concentration of 1 gm^{-3} can extract over 25% of the upward moving cloud water in 1 km. Since rainwater concentrations increase with time to reach several grams per cubic meter, both in nature and in many cloud models, it is evident that in many cases the fractional depletion rates approach or exceed 1 km^{-1}. Of course, the cloud water is not completely taken out in 1 km because it decreases with height in an exponential fashion and, furthermore, additional cloud water is being condensed. Nevertheless, the depletion rate of 1 km^{-1} for a 20 mx^{-1} updraft implies a local increase in the total water concentration approaching 0.1 g m^{-3} <u>per second</u>.

Figure 1 makes it fairly obvious why radar observations in Switzerland, for example, show the typical accumulation zone there to be only 2.5 km deep (Federe, 1974), regardless of whether the zones consist of rain, hail, or a mixture, and of whether they occur below or above an updraft maximum.

3. FREEZING OF RAINWATER

The freezing of supercooled raindrops in a hailstorm serves the dual purpose of reducing the supercooled water supply and introducing hailstone embryos.

One would require very large numbers of ice nuclei if it were necessary to freeze the raindrops near the OC level as Ludlam (1959) and some others have suggested. In fact, hailstone growth rates down to -10C or so are not at all alarming (Fig. 2), and the rate of conversion of cloud water to hail by stones over 1 cm in diameter is very small. Most of the accreted water (compare Figs. 1 and 2) cannot be frozen to the growing hailstones, and the numerical studies of Dennis and Musil (1973) and Chong and Chen (1974) suggest that it is shed rather than retained. Therefore, as long as freezing can be accomplished by -12C, say, no hail embryos can grow beyond 1 cm diameter in a reasonable time of 10 minutes or so. This relaxed temperature requirement permits the AgI crystals to cause nucleation through direct sublimation and by condensation-freezing as well as by collision-freezing (Blair et al., 1973), insuring that almost all nuclei will have a chance to act. The key point is that a large raindrop sweeps out roughly 1 ℓ s^{-1}, so once the crystals of 2 - 3 μm diameter reach a concentration exceeding 1 ℓ^{-1}, the raindrops will not last long. Considering a rather high rainwater concentration of 10 gm^{-3} and a need for one ice nucleus per 1-mm raindrop suggests a need for between 10^4 and 10^5 nuclei per m^3. For a zone of 20 to 30 km^3, a need for, at most, 10^{15} nuclei is suggested.

Freezing of the raindrops in rainwater accumulation zones by direct injection of reagent seems to be the explanation for the apparent success of the Soviet hail suppression efforts. Sulakvelidze et al. (1967) thought their rockets yielded 10^{12} nuclei per gram of PbI_2 at -5C and used a few hundred grams of reagent per zone. The proposed testing of the concept on a randomized basis in Switzerland by Federer (1974) and his associates should provide a valid test of the technique. Their assumption that 10^5 to 10^6 nuclei per cubic meter active at -5C will be required appears excessive to this writer, but may be due to a postulated requirement for collision-freezing. In any case, such concentrations should insure rapid freezing of the rainwater.

If one assumes the AgI particles are to be introduced by seeding in the updraft with an AgI-NH_4I-acetone generator, a different model becomes appropriate. These generators yield around 5 x 10^{13} particles per gram. One nucleus per liter of inflow air is sufficient provided the nuclei are activated in time to be themselves concentrated into the accumulation zones along with the cloud particles. As the air flux into the median hailstorm of the northern Great Plains is 3 x 10^{11} g sec^{-1} (Dennis, 1970), a total generator output of 3 x 10^{11} nuclei sec^{-1} is indicated. The indicated AgI consumption per hour is then 0.06 g sec^{-1}, or 200 g h^{-1}. While the required ice nucleus output is readily obtainable from a single generator, the need for proper distribution of the AgI crystals might still impose a need for multiple sources.

4. WEAK ECHO REGIONS AND HAILSTONE SCREENS

A more difficult situation is posed when a combination of strong updrafts and cold cloud bases prevents the formation of rain in the lower part of the cloud and hail grows directly from cloud water with graupel particles serving as the hailstone embryos. This appears to be the situation around many weak echo regions (WER) (English, 1973; Browning and Foote, 1975). The hailstones immediately above the WER are then free from competition, and seeding to produce additional embryos cannot alter this situation.

It has been hypothesized that early seeding could produce additional graupel particles, but it is necessary to consider what seeding might do after a severe hailstorm has developed complete with a WER.

Musil and Dennis (1970) considered a hailstone screen consisting of dry hailstones growing from cloud water while balanced above an updraft maximum. Here we consider both wet and dry growth and ignore vertical and horizontal convergence to see how rapidly the hail mass would increase due to accretion alone (Fig. 2). Again we see that large hailstones do not succeed in holding much of the accreted water unless the ambient temperature is lower than, say, -20C. This provides a possible opening for seeding those cases where the top of the WER occurs at a higher temperature, that is, lower in the cloud than the-20C level. The basic process is this: Each 1-cm hailstone near the bottom of the screen collects approximately one million cloud droplets per second and sheds them in the form of roughly one raindrop plus satellite drops per second. Thus, a significant fraction of the cloud water is turned to rain (Fig. 3)* This is one reason why rain generally appears in hailstorms, <u>even in clouds where the initial precipitation formation is through the Bergeron process</u>. As the raindrops are shed, their temperature is near 0C but, with the aid of evaporation, their temperature drops to near the ambient value in well under a minute (Watts, 1971). However, if the shed raindrops contain only natural freezing nuclei which become effective at temperatures below -15C, the chances are that each raindrop will remain liquid until it encounters another hailstone some distance above the first. Some of the water will freeze to the second hailstone and some will be warmed back to 0C and shed again. In this way, large quantities of supercooled water are passed upward to the -20 to -40C region, where really fast hailstone growth is possible (Fig. 2). Of course, fresh supercooled cloud water is condensed throughout the updraft region to supplement the shed rainwater and the cloud droplets that escape capture near the bottom of the screen.

In this situation there is no high rainwater concentration to be attacked, so continuous updraft seeding seems more appropriate than direct injection. What is required in order to have a silver iodide particle present in each millionth cloud droplet, so that each shed raindrop will have its freezing nucleus? The answer again is, "Something in excess of one ice nucleus per liter of updraft air," leading to the same estimate of required seeding rates as given in Section 3 above. However, if the top of the WER is around -30 to -40C, as in a vaulted supercell, there is no obvious way silver iodide seeding could suppress hail.

5. SUMMARY

This paper has developed some hypotheses concerning the effects of silver iodide seeding upon hailstorms of different types. It suggests that hail can somtimes be suppressed by using small quantities of AgI (say, 200 g h^{-1}) and in other cases perhaps not at all, regardless of quantities of AgI used. The ideas require more rigorous quantitative testing in advanced cloud models, but could already serve as a basis for stratification of data already available from field experiments on hail suppression. Further consideration of the ideas expressed leads to hygroscopic seeding to hasten rain formation, either alone or with AgI seeding, as a possible

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*The calculations for Fig. 2 and Fig. 3 were made assuming the collection efficiency of hailstones for cloud droplets to be 1. If Macklin and Bailey's (1966) lower values are used, the amount of shedding (Fig. 3) is less, but the wet growth rates are unaffected.

hail suppression technique. This possibility has, in fact, already been put into practice by Miller (1972) and Lominadze et al. (1973).

ACKNOWLEDGMENTS

Preparation of this paper was supported in part by the National Center for Atmospheric Research under Contract C-460, Subcontract NCAR 182-71, as part of the National Hail Research Experiment, which in turn is supported by NSF/RANN. The paper was not passed through the complete NHRE review process before its oral presentation and does not necessarily reflect the views of the NHRE management. However, the author does thank Dr. Keith Browning for a subsequent review and useful suggestions.

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FIGURE LEGENDS

Fig. 1. Fractional depletion of cloud water per km by monodisperse hail screen of 1 gm^{-3} in 20 m s^{-1} updraft.

Fig. 2. Fractional conversion of cloud water to hail km^{-1} rise through monodisperse hail screen of 1 gm^{-3} $\left[\begin{array}{l} w = 20 \text{ m s}^{-1} \\ \ell_c = 4 \text{ g m}^{-3} \end{array} \right]$.

The scale labeled "N" shows the number of hailstones per cubic meter required for a hail concentration of 1 g m^{-3} as a function of D. Region above and to left of heavy solid line is dry growth; that to right and below is wet growth region.

Fig. 3. Fractional conversion of cloud water to rain per km by shedding from monodisperse hail screen of 1 g m^{-3}.

FIGURE 1

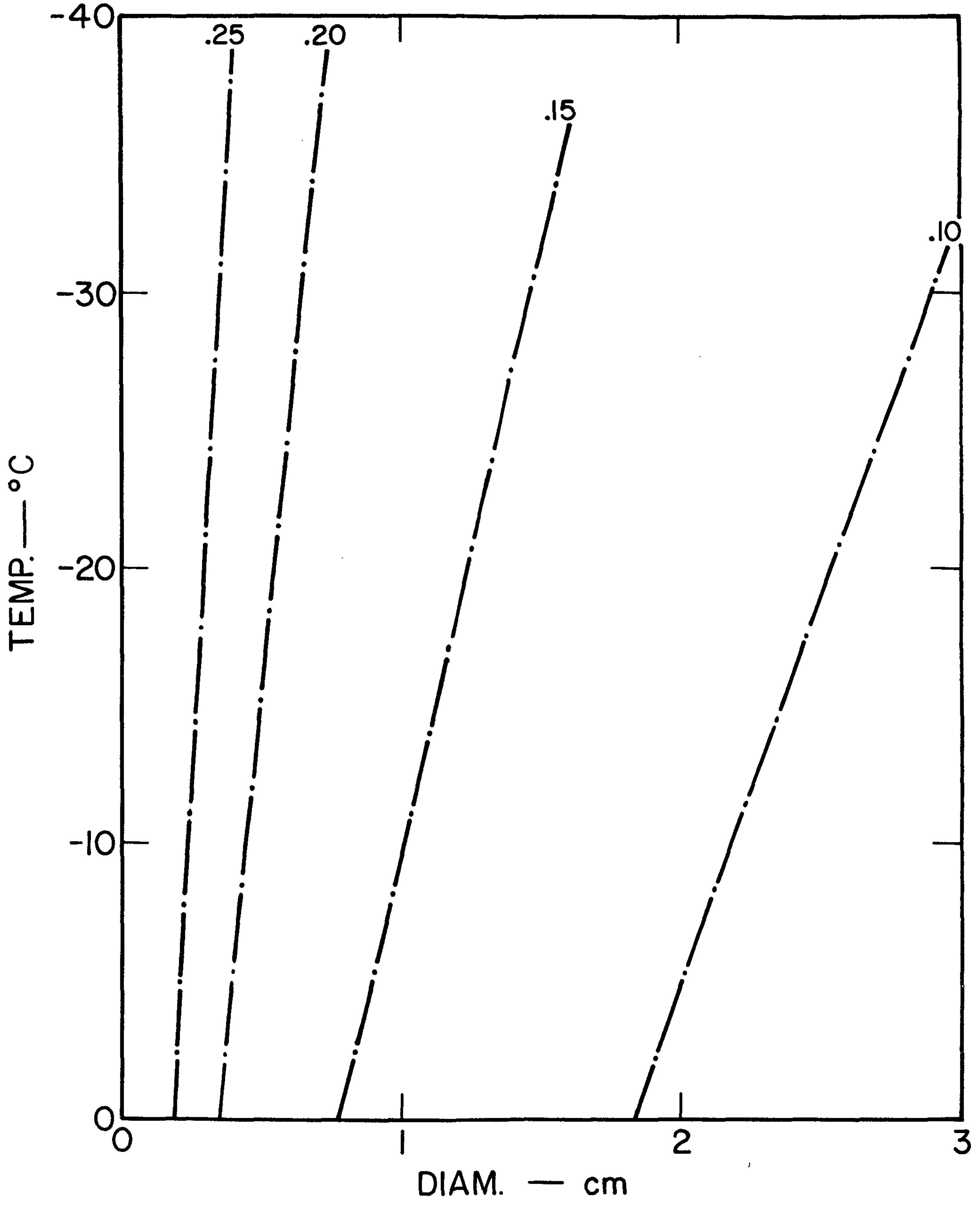
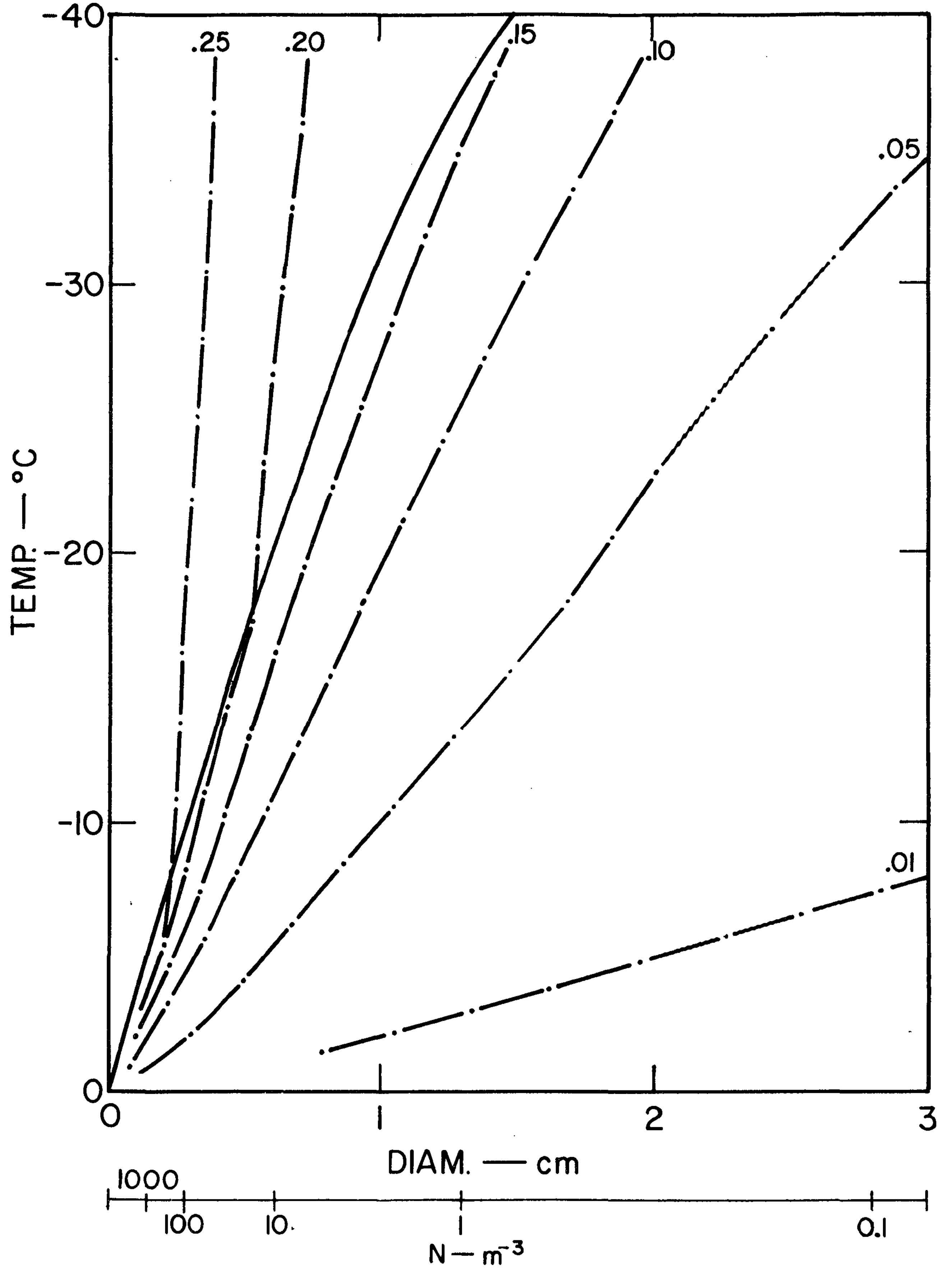


FIGURE 2



-40
-30
-20
-10
0
TEMP — °C
.25
.20
.15
.10
.05
.01
0
1
2
3
DIAM. — cm
1000
100
10
1
0.1
N — m⁻³

FIGURE 3