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MOST PROMISING CONCEPT OF HAIL SUPPRESSION

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ABSTRACT

Two popularly attempted approaches to hail suppression by seeding clouds with AgI nuclei are (1) over-seeding to achieve full glaciation and (2) embryo competition. However, most hail suppression projects based on these concepts were inconclusive: hailfall increased, decreased, or there was no noticeable effect. Such inconsistent results cause one to question the validity of these concepts.

This paper suggests a new concept: freezing a large number of accumulated, millimeter-size supercooled drops by contact nucleation by the timely introduction of AgI nuclei into the heart of the potential hail cloud. The large amount of latent heat of fusion liberated in a short time would increase rapidly the buoyancy and accelerate the updraft. The ice embryos would be carried to higher cloud levels, colder than -30°C. The supercooled droplets from the lower part of the cloud would freeze before reaching such embryos. This, in effect, kills accretional growth of the embryos, eliminating the formation of medium and large size hailstones. Numerical calculations show the effectiveness of this hail suppression concept.

INTRODUCTION

To date, two concepts frequently used in suppressing damaging hail by seeding with AgI nuclei are:

(I) overseeding the potential hail cloud to achieve complete glaciation, and,

(II) the embryo competition.

Most hail suppression projects have shown inconclusive results (NAS, 1973; NHRE, 1976). The hailfall and the crop damage either increased, decreased, or there was no effect. Let us scrutinize, therefore, these two concepts as to their validity. The operational methods used in different projects to deliver AgI particles into a potentially hail producing cloud are: ground generators, burners or flares on an aircraft flying under, around or through the cloud, flares on aircraft flying over the top of the cloud and ground based rockets or artillery shells.

I. OVERSEEING THE STORM:

As we know, the growth of medium and large size hailstones is due to the accretion of supercooled water droplets by hail embryos. One way of reducing further embryo growth would be to freeze virtually all of supercooled water droplets by overseeding the cloud. The nucleating efficiency of AgI particles by sublimation is high, with estimates of about 10^{14} nuclei per gram of AgI at $-20^{\circ}C$. Therefore, in principle, the idea of completely glaciating the cloud is sound. But it is not economically feasible. The supply of AgI nuclei needs to be continuous during the lifetime of the storm, as water droplets would be continuously forming in a strong updraft. Hence excessive amounts, in thousands of kilograms of silver iodide, will be required to overseed one multicellular storm (Kartsivadze, 1968; Battan, 1969a; Gokhale, 1976); this is not economical and much beyond the capability of any seeding system in current use. Besides, it is not practical to suppress hail by overseeding for the following additional reasons:

(i) The use of AgI smoke generators from fixed stations at the ground is a very simple and convenient means of releasing large numbers of nuclei. But the trajectory and diffusion behavior of the smoke are difficult to control due to variations in terrain, intensity of convection, and wind speed and direction. Thus, it is uncertain whether sufficient concentrations of nuclei reach the supercooled region of the cloud.

(ii) The hail growth phenomenon is localized in time and space. AgI particles must reach the heart of the potential hail cloud at the critical time of its development. One of the major doubts about most of the projects employing ground or aircraft generators for seeding is whether artificial nuclei are penetrating in sufficient concentrations to the heart of incipient hail cloud at the critical time.

(iii) The photo-decay of AgI places severe limitations on its use in large scale cloud seeding. The de-activation is caused by the reduction of AgI to metalic silver, and the nucleating ability decreases logarithmically with increasing time of exposure to light. Also, it depends on the type of burner, the temperature of the nucleus production and its size (Mason, 1971).

(iv) Furthermore, the efficiency of nuclei entering the base of the cloud would depend on the mode of nucleation. As immersion freezing nuclei, AgI particles become less effective by 8 to $10^{\circ}C$ (Roulleau, 1957; Hoffer, 1961; Gokhale, 1965).

Thus, the complete glaciation of a hail cloud is prohibitively expensive and logistically impractical.

II. EMBRYO COMPETITION:

The second approach is based on the assumption that the quantity of available supercooled water in a hail producing part of the cloud is essentially constant. The timely introduction of AgI nuclei, increasing their concentrations by two to three orders of magnitude into the cloud, is further assumed to increase the concentrations of hail embryos by the same magnitude. As a result, more but smaller hailstones will be produced, as they will be competing for the available supply of supercooled water. The resulting hailstones would be so small that they would melt completely before reaching the ground.

Two different techniques of introducing nuclei in a hail cloud to achieve the above goal have been attempted:

(i) Soviet scientists seed the region just below the accumulation zone where hailstones are thought to have their major growth. They assume that this is the region in the upper part of the cloud where maxima in radar reflectivity are observed. This region is seeded, by firing the ice nuclei into the clouds between -5 and -10^{0}C levels, with AgI-charged artillery shells. Their reports claim hail reductions between 70 and 90 percent on average (Burtsev et al., 1974; Lominadze et al., 1974).

(ii) A variation of the above technique is to add nuclei in a region lower down in the main updraft area. This lower region is assumed to have natural nuclei and precipitation particles which act as hail embryos. Addition of artificial nuclei in the main updraft is claimed to inhibit hailstone growth because of the competition for the available water supply (NHRE, 1976).

The assumption in the embryo competition hypothesis is that increasing the ice-nuclei concentration in the seeded volume by, say, two to three orders of magnitude would, in a reasonably short time, increase the hail embryo concentration by the same magnitude. Let us examine the accuracy of this assumption.

The sub-micron size nuclei introduced (either at the base or at -5^{0}C level) in a strong updraft would be rapidly carried toward the top of the cloud where the airflow would be divergent, liquid water content would be less than 0.5g m^{-3}, and the temperature colder than -30^{0}C. The ice crystals under these conditions would take a long time to grow to millimeter size hail embryos. The growth of ice crystals by deposition from the vapor phase in air, saturated with respect to water, is too slow to produce millimeter size particles. The mass growth rate decreases significantly with time, due to low vapor availability. Unlike growth by deposition, the mass growth rates of an ice particle by riming and aggregation increases as the particle grows in size. A simple calculation shows that the growth of ice crystals, first by deposition from the vapor phase in mixed clouds and then by riming and/or aggregation, can produce millimeter size particles in about 40 minutes (Wallace and Hobbs, 1977).

During this time, already existing embryos in the hail cloud would grow to medium and even large size hailstones. The typical time reported for millimeter size embryos to grow to hailstone sizes is between 10 and 20 minutes (Sulakvelidze et al., 1967a; Sulakvelidze, 1967b).

Moreover, the major growth of hail embryos is by accretion. If the embryo concentration is low, they do not physically block each other. They will behave as separate entities and will be accreting the supercooled droplets which reach them from the lower part of the cloud. Thus, they will not compete with one another for the available liquid water, which is not constant. The water droplets are continuously formed in a strong updraft and carried toward the region where embryos are suspended. In other words, the competition hypothesis is not valid under these conditions.

In summary, artificially large numbers of millimeter size embryos cannot be generated in a short duration. Hence the competition concept is not valid and cannot yield the desired results. Another approach to achieving hail suppression, which seems more promising, is now discussed.

III. THE PROPOSED CONCEPT

(i) High liquid water contents in the upper parts of hail clouds have been detected by measurements of radar reflectivity factor aloft. Soviet scientists have reported values between 10 and 40g m^{-3} (Sulakvelidze et al., 1965: Sulakvelidze, 1967). Also more recently liquid water content (LWC) of convective storms was measured from an armored aircraft as a part of the operations of the National Hail Research Experiment (NHRE). The electrically heated evaporator indicated regions of 1 to 2 km in extent having LWC of about 12 to 28g m^{-3}. Some incoming water did freeze in the instrument and hence the indicated value was smaller than actual (Kyle and Sands, 1973; Kyle, 1975).

Between the temperature levels of -5°C and -30°C, approximately half of the total LWC is in the form of supercooled water drops. The remainder consists of frozen particles, as discussed in detail elsewhere (Gokhale, 1976, Figure 8-2). Hence it is reasonable to assume that in cases where the total LWC is up to 30g m^{-3}, an amount of about .15g m^{-3} is supercooled water.

(ii) In the author's laboratory the freezing of freely suspended supercooled water drops by contact nucleation was studied and reported in 1972. Water drops were balanced in an updraft (approximately 9 to 10 m sec^{-1}) of a large vertical wind tunnel, and allowed to supercool to ambient temperature. Silver iodide particles were introduced in the updraft.

The suspended drops froze as soon as the particles came into contact with them. The effective temperature for 100% drop freezing was -4 to -5°C. Thus, our experimental observations in the wind tunnel show that millimeter size, freely suspended supercooled drops freeze instantaneously at much warmer temperatures by the contact nucleation mechanism than any other mode of ice nucleation (Gokhale and Spengler, 1972). Soviet scientists have vaguely discussed the effectiveness of contact nucleation (Kartzivadze, 1968).

(iii) The suggested approach to hail suppression consists of seeding the core of a potential hail cloud with AgI nuclei at levels where in-cloud temperatures are between -5 and -10°C. These nuclei will be carried upward by the strong updraft where large numbers of millimeter size supercooled drops have accumulated. Such drops would freeze by contact nucleation and much latent heat of fusion would be liberated in a short time. This will increase the buoyancy, and the air will be accelerated upward, intensifying the strong updraft. The hail embryos will be lifted to higher levels, colder than -30°C. Droplets carried upward from the base of the cloud to -30°C level will naturally freeze before reaching the suspended hail embryos and hence kill their further growth. The embryos eventually will be carried sideways in the divergent air flow at the top of the cloud and reach the ground as rain.

Only a small volume of the cloud, at its heart in the upper part, is to be seeded with rather low quantities of silver iodide. Thus, comparatively small volume at the core of the cloud is displaced upward by 3 to 4 km in height. This is not expected to result in significant increase in storm size or its intensity.

IV COMPUTATIONS AND RESULTS

Following the treatment given by Haltiner (1959) on the theory of convective currents, the acceleration of the updraft due to buoyancy generated by the release of latent heat is calculated by an equation of the form:

$$\frac{d^2z}{dt^2} = \left[\frac{\Delta T}{T} g - k_2 \left(\frac{dz}{dt} \right)^2 \right]$$

The first term in the bracket is the buoyancy term, where ΔT is an increase in temperature of the core of the updraft as compared to the surrounding air due to release of latent heat of fusion (L), and T is the absolute temperature of the air surrounding the core of the cloud. The second term represents the frictional drag which reduces the magnitude of the acceleration. The "friction force" per unit mass may be written as $-k_2W^2$, where k_2 is the coefficient of eddy diffusivity equal to 2.5×10^{-6} cm^{-1} and W is dz/dt, the updraft velocity.

In this case, it is assumed that the time rate of heat and monentum loss by turbulent diffusion would increase with increasing updraft velocity. The most important effect of the lateral diffusion is the loss of heat by the updraft, which lowers its temperature, and thus decreases the buoyancy force. The values assumed for calculations are $T = -15^oC$, $p = 500$ mb and $c_p = 0.24$ cal $g^{-1}k^{-1}$, $W = 11$ m sec^{-1}, $\Delta T = Lw/c_p\rho_a$ per unit volume, where L is the latent heat of fusion equal to 71.9 cal g^{-1}, w is the supercooled liquid water content and ρ_a is the density of air equal to 6.75×10^{-4}g cm^{-3}.

The results are plotted in Figs. 1 and 2. The curves in Fig. 1 are: (i) Supercooled liquid water content (LWC) in g m^{-3} vs. ΔT and (ii) LWC vs. acceleration of the updraft corrected for frictional drag. In Fig. 2 LWC is plotted against time required by the increasing updraft to carry the hail embryos from -5^oC level to -30^oC level (the height is approximately 4 km, assuming the moist adiabatic lapse rate equal to 6.5^oC per km).

V. CONCLUSIONS

The following conclusions are drawn from the curve in Fig. 2:

(i) The time required by the embryos for their upward displacement of 4 km varies between 3.2 and 6.4 minutes when supercooled LWC values are 15 and 5 g m^{-3} respectively. During such short intervals, embryos will not grow to large-size hailstones.

(ii) AgI seeding with the help of rockets will have to continue till the weather radar indicates such a displacement in the vertical.

(iii) However, seeding when the supercooled water in the accumulation zone is less than 3 g m^{-3} may produce very slow vertical displacement, and the increased number of frozen drops would have sufficient time to grow to large sizes. This will result in a net increase in the number of hailstones.

Among the prominent reports of crop damage reduction due to hail are those from the Soviet Union. Soviet scientists seed the accumulation zone with AgI-charged artillery shells or rockets. For various reasons, their spectacular claims of success of hail suppression are difficult to accept at face value. They seem to be only partially successful in reducing hail damage to crops (Batten, 1969b, 1970; Marwitz, 1973). Soviet scientists (Kartzivadze, 1968) attribute their success to embryo competition, but this may not be the case for the reasons discussed earlier. Their technique may result, at times, in displacement of hail embryos upward, thereby reducing hail size in some cases. In summary, their operational technique may be partially successful but their explanation of hail reduction as due to embryo competition is far from accurate.

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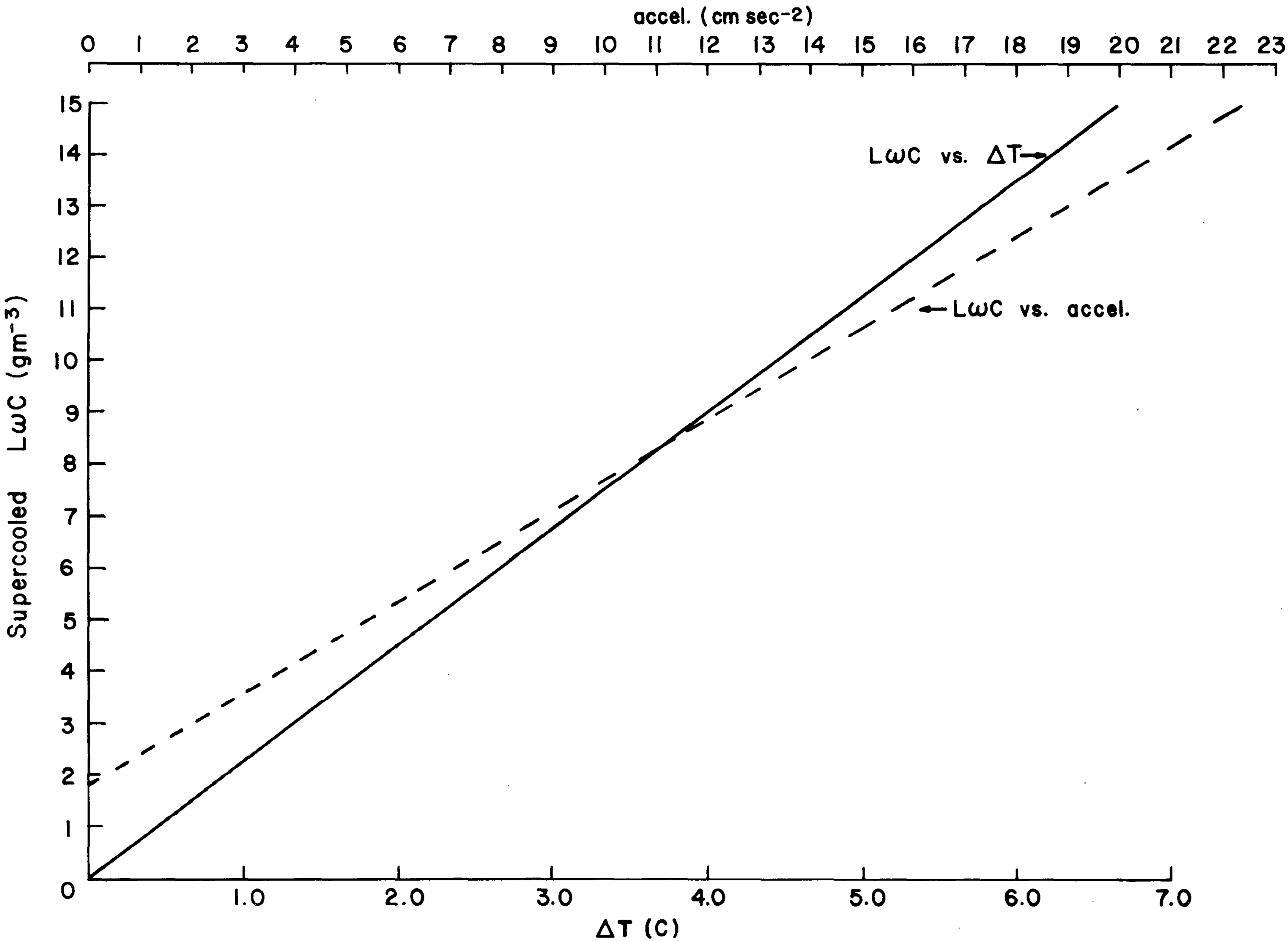
FIGURE LEGENDS

Fig. 1: Plots of supercooled liquid water content (LWC) vs. calculated ΔT and (LWC) vs. acceleration (d^2Z/dt^2) of the updraft, corrected for frictional drag.

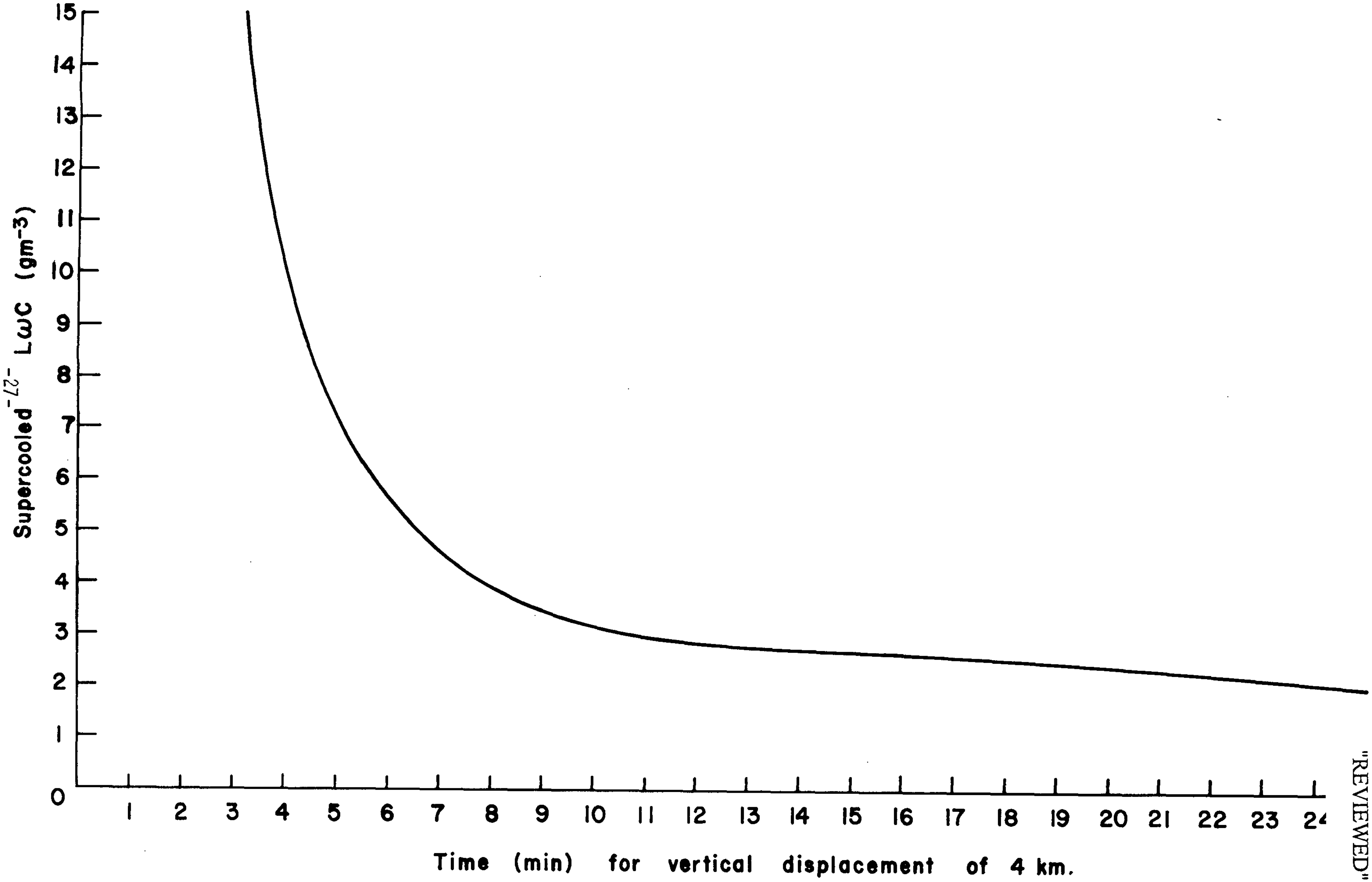
2: Plot of (LWC) vs. time, required by the increasing updraft to carry the hail embryos upward by 4 km.

FIGURE 1.



accel. (cm sec-2)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Supercooled LωC (gm-3)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
LωC vs. ΔT
LωC vs. accel.
1.0 2.0 3.0 4.0 5.0 6.0 7.0
ΔT (C)

FIGURE 2.



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