Artificial rain and local fog dispersal
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ARTIFICIAL RAIN AND LOCAL FOG DISPERSAL

The weather we are presently experiencing in France, particularly in the Paris district, and also the fact that vacation time is approaching, might suggest that a paper on suitable methods of preventing natural rainfall would be more to the point than a discussion of artificial rain. However, it is the latter subject with which I am going to attempt to deal on this occasion.

Since the end of 1946 the general public has been reading in the press about the success of American scientists in producing rain artificially. Journalistic imaginations have been given free rein and the most fantastic reports have been circulated along with all sorts of schemes for utilization, many of which are as far from present or future realization as they possibly could be.

In the meantime, however, practical experiments have been carried out on every continent.

At the outset it should be made clear that, while generally speaking information about the conditions and results of these experiments is rather meagre, it is very probable that the number of failures greatly exceeds the number of successes.

A personal experience may perhaps be cited. One day last September, while I was attending the Aeronautical Exhibition at Radlett, England, advertisements appeared on the front pages of the popular British newspapers announcing that systematic attempts to produce artificial rain would be made the following day. Subsequently the tune had to be changed. Rain did not occur anywhere, and a few terse by-lines explained simply that the results had been negative because "the experiments had not been carried out on the proper type of cloud".

The increasing importance attached to these experiments in all countries indicates that they are something more than a game or a symptom of the will to power of mere human beings ("To make rain or fine weather" is this not, so to speak, to usurp the supreme power?), and something more than a commendable desire not to allow one's own nation to be outstripped by America, where during the last eight years formidable strides have been made in all branches of science and technology, in advance of Europe particularly.

In the course of this discussion we shall try to arrive at the crux of the problem. The phenomena in question, while based on simple physical laws, are often complex. For some of them there is still no satisfactory explanation, for others there are too many and a choice must be made between the different ones. In addition I shall try to place the American research in its proper perspective. The magnitude of the means employed there in dealing with the individual problems is considerable. Nevertheless I hope to show that France, in particular, with much more modest means, has made, and will continue to make valuable contributions to this research.

Following this exposition we shall attempt to outline a concrete programme, indicating both the directions which present research should follow and the future lines along which it should be developed.

Finally, coming to the question of application we shall try to play the prophet, always a dangerous role, and predict what may reasonably be expected from the work now in progress.

For the sake of the uninitiated it will be necessary, of course, to review briefly the underlying physical phenomena and the meteorological basis of the subject, namely, clouds and rain. It is hoped that the specialists will pardon the intentionally sketchy character of the presentation. It is not possible to cover everything in an hour and a half.

Everyone knows that the atmosphere, even when it is clear and without noticeable haze, contains a certain amount of water in the gaseous state, and that clouds, fogs and most mists contain water in the vapour state, and in the liquid state in the form of tiny droplets (the dimensions of the droplets will be discussed later). What is more important, and perhaps not so well known to some, is that water in the solid state, in the form of small ice crystals, is also frequently present. Thus all the phenomena to be studied are governed by the laws of equilibrium or unstable equilibrium of water in the three states, solid, liquid and gaseous.

The vapour pressure of the water contained in a given volume of air is defined as the partial pressure of the water vapour contained in that volume.

At temperatures above zero degrees centigrade a mass of air can only be at equilibrium with the liquid water if the vapour pressure in the air has a very definite value for each temperature. If the temperature falls while the pressure remains constant, some water must condense. This is the familiar process of dew formation. The same effect would be noted if there were a tendency for the vapour pressure to increase. This definite pressure for each temperature is called maximum pressure or saturation vapour pressure. As soon as it is attained the air is said to be saturated. The amount of water vapour contained in saturated air can be calculated. Some results of such a calculation are shown in Figure 3.

To conclude the definitions, the relative humidity of a given volume of air is the ratio of the vapour pressure of the water contained in it to the saturation pressure for the same temperature. It is expressed as a percentage. By this definition saturated air has a relative humidity of 100 per cent. It is very important to note that under certain conditions the air may have a relative humidity greater than 100 per cent. It is then in a state of disequilibrium and is said to be "supersaturated".

At temperatures below zero the processes are similar. Here the phenomenon of sublimation occurs, and equilibrium between the ice and the water vapour can exist only for a definite value of the vapour pressure at each negative temperature.

At constant temperature the vapour transforms into ice when there is a tendency for the pressure to increase. If the pressure falls the ice must evaporate.

The curves of Figure 1 show the values of these pressures at different temperatures and the quantity* of water contained in each cubic metre of saturated air for each positive temperature.

Finally, there is theoretically only one point of equilibrium at which the three phases can co-exist, namely, zero degrees and 4.6 mm. of mercury.

The above applies to the equilibrium of a large plane surface of water in contact with air. The processes are different if the water is in the form of drops (effect of the radius of curvature), or if it contains salts in solution, etc. Thus curves of equilibrium might be drawn using the radius of curvature or the concentration of salts in solution as abscissa and the corresponding saturation vapour pressure as ordinate.

All this appears very simple. Unfortunately, things do not normally happen in this manner. Everyone knows that it is very easy to maintain water in the super-cooled state. In meteorology, indeed, it is the rule rather

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* Translator's Note: There is a discrepancy here in the original document. Figure 1 shows no curve of water content.

than the exception. Liquid water may remain in unstable equilibrium with the water vapour well below zero degrees, and exceptional conditions are required to terminate this unstable equilibrium. A very important point, and it is the accepted theory, is that the unstable curve lies above the sublimation curve. The former, of course, is a continuation of the curve of equilibrium for positive temperatures (cf. Fig. 1).

To conclude this brief discussion of the physical aspects, it is recalled that a change of state of the water at constant temperature, e.g., change from the gaseous to the liquid state, is accompanied by the liberation of a definite amount of heat per gram of liquid water, called heat of condensation.

During the inverse process the same amount of heat will be absorbed. Indeed, cooling by evaporation is a familiar phenomenon. In order to keep a bottle of wine cold during a picnic everyone knows that it should be wrapped in a damp cloth.

An analogous liberation of heat, called heat of fusion, occurs during solidification.

* * *

After these few physical generalities it is necessary to look at the meteorological aspects of the question.

Everyone knows that it cannot rain if there are no clouds and that there are often clouds without rain. These aphorisms probably need to be stated. You will soon understand why.

What is a cloud? It is an aerosol, i.e., a collection of water droplets of various diameter (from a few microns to some sixty microns) suspended in the air (Fig. 4). The proportion of drops of each diameter in the cloud is determined by a definite statistical law. In the majority of well-developed clouds the curve of distribution is a bell-curve analogous to the one discovered by Houghton and Radford (Fig. 5). In this case the most numerous drops correspond approximately to the mean value of the diameter.

In the case of fogs, or clouds which are just beginning to form, the curve may be L-shaped (Fig. 6); the smallest drops are then the most numerous. This will be explained shortly.

The technique of counting and measuring the size of the drops is very highly developed in France. The engineers of the Low Temperature Laboratory at Bellevue, and those working at the Research Station on Mont Lachat, a branch of the O.N.E.R.A., have, with the help of Prof. Brun and Mr. Lucien Demon, discovered some very ingenious ways of collecting the drops in a fog or cloud so that they can actually be counted and measured under the microscope.

Other French research workers, such as Mr. Bricard and Mr. Dessens, have also done a great deal of work on this problem. Formerly the drops were precipitated electrostatically in oil. Today the technique preferred is to use very dense networks of extremely fine threads on which the droplets are caught. Mr. Demon makes the threads synthetically from a solution of plexiglas, while Mr. Dessens prefers to cultivate small spiders which do this work remarkably well.

The mean size of the drops, of course, depends on the type of cloud and the stage of its development. However, a general value of about twenty microns can be given for it.

When the drops become very large they may be expected to fall due to their weight, and this is what actually occurs, for example, in certain wet fogs which are often seen in mountainous country. For drops of twenty microns the rate of fall is relatively slow - 1.3 cm. per second according to Stoke's law. Thus the slightest up-current and the little turbulent vortices in the cloud are sufficient to keep them aloft, like an egg on the water jet at a fair.

Furthermore, if the cloud is at an altitude of 3,000 metres it follows that the drops would take 390,000 seconds, or 110 hours, to reach the ground. A great many things can happen to a small drop of 20 microns during this time.

The number of drops per cubic centimetre of cloud does not vary greatly. It is of the order of 500 to 1,000. The dimensions of clouds, however, do differ greatly. Not infrequently a cloud may be several kilometres thick and some tens of kilometres long.

Another very important characteristic of a cloud is its water content, which is of the order of several grams per cubic metre. Under the auspices of the O.N.E.R.A. an apparatus for sampling clouds has recently been perfected at Mont Lachat. This is a small wind tunnel through which the cloud or fog can be aspirated. The working section contains a metal cylinder with a wire stretched along its axis. The wire carries a very high voltage compared with that of the cylinder and all the water contained in the cloud is deposited on the walls of the cylinder by electrostatic action. This is exactly the same technique as the familiar one for dust extraction. The cylinder is weighed on a small precision balance before and after deposition of the water. Knowing the flow through the tunnel the mass of water contained in a given volume of cloud can easily be calculated.

Mr. Caron 1) has invented another apparatus, called an aquanebulometer, for measuring the relative value of the water content of a cloud. Two versions of this instrument are now being built at the O.N.E.R.A., one for ground measurements at the Mont Lachat Laboratories, and the other for use aboard an aircraft.

To conclude the discussion of clouds a few words are necessary concerning their electrical characteristics. It is well known that clouds, particularly storm clouds, may become electrically charged. The maximum positive or negative charge which a single drop in a cloud may receive is of the order of some 10^{-7} c.g.s. electrostatic units. The electrical field of a cloud may attain several tens of kilovolts per centimetre. It follows that the electrostatic forces of attraction or repulsion between drops are weak.

A few remarks, now, on the subject of rain.

Rain is made up of much larger drops, of the order of a millimetre in diameter. These have a volume easily 100,000 or 1,000,000 times that of the droplets of a cloud or fog.

It will presently be shown how clouds and rain form in nature, but first it is necessary to make a very fundamental observation which I have borrowed from Mr. Roulleau. In popular parlance it is said that a cloud "bursts" when it rains. This is obviously an exaggerated figure of speech, but it is one which might lead us to suppose that a cloud contains a certain quantity of water which can be transformed into rain, and that when the cloud is "empty" the rain must cease. This is precisely the image of Biblical times, for, referring to the flood the Bible says that "the same day were all the fountains of the great deep broken up, and the windows of Heaven were opened and the rain was upon the earth forty days and forty nights".

Many scientists, while knowing very well that a cloud is not a vessel filled with water, have nevertheless reasoned thus.

Now it can easily be shown by calculation that a cloud is able to provide an amount of rain greatly exceeding the amount of water contained in it in the form of droplets. It might be expected that a cloud three kilometres thick, containing three grams of water per cubic metre, would provide only 9 mm. rainfall. But often a cloud of this size yields five times this amount. This statement can easily be verified with the aid of a rain gauge, a very simple instrument, for which, moreover, a jam jar may be substituted.

The very important conclusion to be drawn from this is that such clouds are continually rebuilding themselves at the expense of the water vapour in the surrounding atmosphere. Over a certain period they may be compared to the storage batteries in automobiles, which are continually being discharged while a generator continually recharges them. Or again, they are analogous to the famous bath tub which caused us so much trouble during our final examinations, the one which we vainly tried to fill while the drain faucet remained open.

Thus a cloud now appears to be an indispensable medium for the occurrence of rain, but its actual capacity greatly exceeds that which might be expected from a merely superficial examination of the problem. We are now faced with two fundamental questions:

1. In what manner, and from what causes, does a cloud form in clear atmosphere? This is the study of the so-called condensation process.

2. In what manner, and for what reasons, is rain generated in a cloud? The transformation of a cloud into rain, hail or snow is called precipitation.

These are two very different problems and many difficulties are due to the fact that they have frequently been confused.

How do clouds form?

(a) By the intermingling of masses of homogeneous air, without change of altitude. This first and very old theory is that of Hutton, who used it to explain the occurrence of rain as a result of the confusion just mentioned. Mr. Marcel Brillouin proposed it as an explanation of the formation of clouds. When two masses of clear air at different temperatures and humidities mix, it is possible, under certain conditions, to get a vapour pressure above the saturation point. Condensation may then occur. For example: If one kilogram of air at zero degrees, 50 per cent relative humidity and 2.3 mm. vapour pressure is mixed with two kilograms of air at 30°, 90 per cent relative humidity and 28.6 mm. vapour pressure, the result should be three kilograms of air at a temperature and vapour pressure determined by the law of mixtures, namely, 20° and 19.8 mm. of mercury. The saturation vapour pressure of the mixture is only 17.5 mm. There may be condensation, but when the heat of condensation is taken into account the amount of water which can be produced by this process remains very small. Hence, this would only explain the formation of very light clouds, which are of little interest from the point of view of rain.

(b) Adiabatic expansion.

If an adiabatic expansion, i.e., an expansion without exchange of heat with the exterior, takes place in a mass of humid air the temperature of this air will decrease. Now, from what was said at the beginning of this paper it follows that, provided the cooling is not too intense, liquid water may condense in the form of droplets. Note that we say the droplets "may condense"; they do not do so necessarily. The reason for this will soon be apparent. The heat of fusion,* of course, partially offsets the process. The experiment is well known and is presently being performed in the Wilson cold chamber. It is valuable in connection with nuclear research, because the droplets are deposited on ions or small particles whose paths or trajectories may thus be revealed.

Such expansions can occur in the atmosphere but they may arise from different causes:

1. The general flow about low pressure areas permits the assumption that clouds could form at the centre. The effect, if it existed, could only be a very weak one. This theory was once advocated by Herschel, but has since been abandoned.

2. The expansion may be the result of upward air displacements due to convection. These may be of either thermal or dynamic origin. There may be mass displacements or turbulent displacements. The latter would be something between molecular diffusion due to thermal action and large mass displacements.

These phenomena are very complex and have not yet been completely analysed. However, an attempt will be made to give a qualitative idea of thermal displacement as described in that remarkable work "Physique des Nuages" (Physics of Clouds) by Professors Coulomb and Loisel.

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* Translator's Note: "chaleur de fusion". The author means, obviously, heat of condensation.

It is common knowledge that at low altitudes, at least, there is a negative temperature gradient; in other words, the temperature decreases with altitude at the rate of approximately 0.6° per hundred metres. This is simply because the lower layers of the atmosphere are warmed by contact with the earth, and especially by the earth's radiation, whereas the upper layers themselves radiate more energy than they receive from the sun. I hasten to add that this is true only of the first few kilometres. Also, the density of the air decreases with altitude. Hence a mass of air which tends to rise will cool, and its rise will continue as long as its density is less than that of the surrounding air at the same altitude; thereafter it will tend to descend again, and this depends generally on the gradient. The neutral equilibrium corresponds, more or less, to a variation in temperature of one degree per hundred metres; this is the so-called "dry adiabatic gradient". Actually, even for larger gradients there is still equilibrium, for the expansion is not adiabatic, the air being cooled by thermal exchanges at its boundaries. This brings us to the fundamental process. If the mass of air can rise to the point where condensation occurs, then the heat of condensation will enable it to rise further. This condition exists even in gradients of less than one degree per hundred metres - to be precise, in those which are of the order of 0.6°, i.e., the gradients most frequently found in our own regions. This is called "the wet adiabatic gradient".

With the aid of these very vague data we are now in a position to describe the formation of a cumulus cloud. Everyone is familiar with these clouds, whose dense forms give such fine artistic effects (Fig. 7, 8, 9).

At sunrise the ground becomes heated by solar radiation and in turn warms the air in its immediate vicinity. The gradient near the ground is now greater than the dry adiabatic gradient, and the air begins to rise. This air is replaced by air coming from cooler regions nearby, and these regions, in turn, are fed by still cooler regions above them. Thus a thermal convection is commenced. As it develops its ceiling is progressively raised and the entire bubble of air beneath the ceiling is warmed. At a certain altitude the dew point is reached and condensation may occur. If so, a cumulus cloud begins to form. The heat of condensation now enables the cloud to ascend still further, so that more condensation can occur, even when the gradient of the cloud is no longer adiabatic. The summit of the cloud can then begin to flatten out. This is the process observed, for example, in the cumulus congestus (Fig. 10).

The cloud, of course, may also be carried up by a mass movement of purely dynamic origin, in which case the external growth may be the same as that just described.

Now a word on the formation of clouds by turbulent convection, since this is probably the most important process for the ultimate development of the studies concerning artificial rain. In this type of convection we can imagine the upward movement of a great many small masses of air, the displacement being produced, generally speaking, by more or less regular vortices with horizontal axes. The masses of air thus transported have definite temperatures and humidities, varying according to their place of origin, and it can then be shown that on the average the relative humidity tends to increase considerably towards the upper parts of the atmosphere when they have been stirred by these vortices. If this humidity reaches 100 per cent condensation may occur. This seems to be the process of formation of stratus and strato-cumulus clouds, which are clouds containing less water than those formed in the lower layers of the atmosphere (Fig. 11 and 12).

May I again draw your attention to the manner in which this is expressed. When saturation is attained or exceeded condensation <u>may</u> occur. I have been careful not to say that it must occur. Indeed, when discussing the equilibrium of water in the three states it was stated very specifically that stable equilibrium was the exception and that special precautions were necessary to prevent supercooling or supersaturation. As a matter of fact relative humidities up to 400 or 500 per cent without condensation are quite possible. As far back as 1880 Aitken observed in his laboratory experiments that successive adiabatic expansions in the expansion chamber produced fogs of lower and lower density, and, if the air is filtered through cotton, no condensation whatever takes place. Since that time the accepted theory has been that no condensation is possible unless certain seeds, also called "nuclei" or "condensation centres", are present. Near the ground these seeds are everywhere, but their number decreases rapidly with altitude. According to Wigand, at 1,000 metres there are approximately 2,500 per cubic centimetre, but above 5,000 metres there are no more than 80.

Neither the nature of the condensation centres nor the manner in which they promote condensation is as yet well understood, although there have been many investigations of the problem - C.T.A. Wilson's, Junge's, and especially Langevin's may be cited. At present Mr. Bricard and Mr. Demon are still working on this question. At different times it has been thought that these nuclei might be very small mineral particles, big or small ions, or hygroscopic particles. Last week Mr. Demon informed me that he had concluded a series of experiments at Mont Lachat which seemed to prove that in the case of clouds these centres are often hygroscopic particles.

Mr. Demon obtained some natural cloud droplets with his plexiglas nets and then permitted them to evaporate inside the laboratory. Watching the evaporation under the microscope he observed that an extremely light deposit, visible only now and then by a variation in colouring, remained on the threads. This deposit certainly constituted the much discussed condensation centres, for, when he breathed lightly on the threads droplets again appeared at the places where the particles had been seen, i.e., at the same places where the drops had been previously. However, in my opinion this still does not enable us to say anything concerning the nature of the centres (whether crystalline or amorphous particles, whether ionized or not).

However, the important fact to remember is that these condensation nuclei are indispensable in the formation of clouds, and that clouds such as the cumulus, which begin to form at the ground by the process of thermal convection, never lack these nuclei, for there is a superabundance of them near the ground which are borne upwards by the same process of thermal convection. But the layers of atmosphere above 3,000 metres contain very few, and it is probable that in many cases there are enormous supersaturations at these altitudes just because of this scarcity. By supplying the nuclei it might perhaps be possible to make clouds, the ultimate source of rain; for, after all (please pardon this repetition of an obvious truth), there can be no rain without clouds.

The study of the humidity of the atmosphere above 3,000 metres, in my opinion, is absolutely fundamental. It needs to be investigated systematically, and the O.N.E.R.A. has included this in its programme. At the same time systematic attempts at "seeding" with condensation nuclei, e.g., suitable hygroscopic nuclei, should be made.* It is very probable, I think, that artificial clouds can be created in this way, although there is no assurance that rain could be made to fall from them. However, I must add that this supersaturation is my only hope of creating artificial clouds large enough to yield rain.

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* More than a year ago Mr. Maurin suggested using hygroscopic nuclei in <u>unsaturated</u> atmosphere. I do not think there could be any formation of clouds in such a case.

Indeed, if we were restricted only to the stable equilibrium, we would have to be able to produce artificial adiabatic expansions, for example, by convection. But Mr. Roulleau [3)] has calculated that in order to cause a column of air five kilometres thick and one square kilometre in area to rise for five hours at the rate of 3 cm. per second (which would produce 5 mm. of rain over an area of 100 hectares) it would be necessary to expend an energy of three million kilowatt hours, assuming one hundred per cent efficiency. It is obvious that the solution to the problem does not lie in this direction.

We have now reached the following point: We know approximately how clouds form - by the process of condensation. We also know that there can be no question for us of making clouds artificially by adiabatic expansion although there is some hope if, as is probable, supersaturated zones existing at high altitudes are provided with condensation nuclei.

We come now to the process of rain formation, i.e., the growth of drops from twenty or so microns to approximately one millimetre in diameter. This is the phenomenon of precipitation. For the rain to reach the ground it is clearly necessary that the drops thus formed must not evaporate during their fall.

I am sure that some of you will be surprised to learn that the causes of rain have been known for less than fifteen years. The discovery came later than those of relativity, the wave mechanism, and the neutron. Only the future can tell us whether it is more or less important than these.

Just as small streams unite to make great rivers, it seems reasonable to suppose that large drops are formed by the union of a number of small drops. This phenomenon has been much described. It is the process known as coalescence. Unfortunately, it probably does not exist at all, or at least it is very rare as a cause of natural rain. What, indeed, are the possible causes of coalescence?

1. Aerodynamic attraction of droplets following parallel paths and remaining close to one another during the fall. Bjernknes studied this problem. The forces involved are very weak ones. The drops would have to remain near one another at least for a distance of a tenth of a millimetre and a time of roughly one minute. For this to happen the drops would have to be of exactly the same diameter so that they would have the same rate of fall. It is unlikely that such conditions ever occur.

2. Due to inertia, micro-turbulence could cause collisions between molecules of different diameter. At Trappes Mr. Guy Dady 4) observed an artificial fog with mean drop diameter of 4μ and maximum drop diameter of 15μ for a period of ten hours. Despite the fact that trajectories apparently coincided frequently (once in about every ten seconds), he did not see a single case of coalescence. According to his theory he expected 900! It is probable that surface effects prevent drops of these dimensions from uniting. It should be observed, however, that the average drops in a cloud are larger than those of the fog studied by Mr. Dady.

3. Electro-static effects.

It was long believed that in storm clouds electrical charges kept the drops apart, but that after discharge nothing more prevented their coalescence. We have just seen that this explanation is quite improbable. Furthermore it has been proved that rain begins to fall before lightning occurs. Electrical attractions due to charges of opposite sign are equally improbable. In fact, such charges have no opportunity of occurring together. And finally, the attractive forces of charges of the order of 10^{-8} c.g.s. units, such as are found in electrically charged clouds, are very small.

So much for coalescence. Let us turn now to some much more satisfactory theories based on the idea of the growth of a liquid or solid phase at the expense of the vapour phase. As a matter of fact, if only the saturation vapour pressure of the two phases are different, water may be transferred from the phase of higher pressure to that of lower pressure; in other words there is evaporation from the first and condensation on the second. This happens in several very important cases which will be discussed again in connection with the creation of artificial rain:

1. All other things being equal, the saturation vapour pressure increases with the curvature of the surface of saturation of the two media. Thus drops of large diameter must increase in volume at the expense of small drops, provided the difference of curvature is great enough.

2. Cold drops increase at the expense of warm drops. This is the principle of the cold wall. Indeed, the saturation vapour pressure increases with temperature (Fig. 1, 2, 3).

3. Ice crystals grow at the expense of supercooled water droplets, since (Fig. 1) at constant negative temperature the liquid water-vapour saturation vapour pressure

(unstable equilibrium) is greater than the ice-vapour pressure (stable equilibrium).

4. Drops containing a salt in solution grow at the expense of drops of pure water, because the vapour pressure of the solution is less than that of the pure water. This effect is all the more important because the solution has a lower saturation vapour pressure.

Which of these causes actually produce natural rain?

We have seen that direct coalescence is highly improbable. It appears that in the majority of cases the growth of ice crystals is responsible. This is the familiar theory of Bergeron and Findeisen, first presented in 1933. It is based on a hypothesis which has since been verified many times, namely, that the upper parts of most large rain clouds (generally speaking cumulo-nimbus clouds several kilometres thick) will have a negative temperature. Thus the water in the cloud is normally in a supercooled state, for we know that supercooling is the rule and stable equilibrium is the exception.

But as soon as the droplets find themselves in the presence of some agency which starts the process the ice crystals begin to appear. You are all familiar with the beautiful geometric forms of snow crystals. A few of them are shown in Figure 13. These are able to grow by the above described process - the transfer of water from the supercooled drops to the crystals. As they grow, of course, they begin to fall as snow flakes of various size. If they are sufficiently warmed during their fall, so that they melt but do not evaporate, it rains. If evaporation occurs because the air is too dry and too warm, the water does not reach the ground and we then have the phenomenon of "virga". If the temperature remains low enough all the way to the ground it snows. If there are ascending currents in the cloud which cause the latter to retain the crystals for some time they then have an opportunity to increase in size and the result is hail. This theory was completely confirmed between 1932 and 1937 in America by Stickley 5), who made numerous flight investigations. It accounts for almost 97 per cent of the observed precipitations.

It appears, however, that certain tropical rains and summer rains in mountainous country are best explained by the transfer of water from warmer drops to colder ones in clouds in which there are no negative temperatures at all. Reynolds proved that this could happen, explaining how nocturnal radiation from the top of the cloud, or the cloud's own shadow when the sun is low, could bring about differences in temperature between neighbouring drops within the same cloud. All the other explanations which have been discussed above seem very improbable.

In any case the Bergeron effect is the chief cause of rain.

There is one further point to be clarified. What causes the supercooling in the upper part of the cloud to cease. All that is necessary is for the top of the cloud to rise until it enters the very cold region. It is known, of course, that supercooling generally ceases below -35°C. The drops can then begin to solidify. It is equally possible that the freezing is started by the appearance of certain crystalline agents, certain oxides of nitrogen, whose formation in the atmosphere may be due to lightning discharges in storm clouds with intermediate formation of ozone. The powerful shock waves possible with lightning discharges could likewise lead to freezing. This has been proved by investigations of Mr. Jacques Maurin which will be discussed again shortly.

The crystals created by inoculation in the laboratory are similar in every way to the natural snow crystals of the preceding figure (cf. Fig. 14).

We now know how clouds are formed, and we also know why it rains. We therefore have at our command almost all the knowledge necessary in order to make artificial rain.

First let us suppose that we have clouds at our disposal. But at the same time let me remind you that even if we have no clouds we may still hope to form them if we can find zones in which the humidity is greater than 100 per cent, i.e., supersaturated zones, and if we can supply suitable nuclei for terminating the supercooling. This does not mean that clouds created in this way will necessarily be capable of causing precipitations which will reach the ground. The size of the drops, the temperatures between the cloud and the ground, and the humidity must still be such that the rain will not evaporate during its fall.

For the present, however, let us assume that we have a natural cloud.

Two separate cases must be considered: that of a cloud in which there are regions of negative temperature, and that of a cloud which has no such regions. The first is the simpler case. In order to make rain - nothing could be easier - it is merely necessary to bring about a cessation of the supercooling. We might consider seeding the cloud with ordinary snow. This method is unsuitable because the snow will fuse into lumps, owing to the tendency of the crystals to conglomerate, and will be difficult to scatter. We shall not provide enough nuclei in this way for the snowfall to spread. Carbonic snow, or better still, small pellets of dry ice having a temperature lower than -80°C. are much more satisfactory. By this means supercooling can be brought to an end even in very large clouds. This is the method which has been employed so far. We shall return to the history of the problem and the best ways of applying the principle in a little while. It is easy to see that any very cold substance will give the same result, e.g., liquid air, or any solid particles which have been cooled to very low temperatures. In a few moments I am going to tell you about the results of Mr. Demon's experiments with these various materials.

Another method might consist in inoculating the cloud with insoluble crystalline seeds which are isomorphous with ice and have the same crystal structure. These would also bring the supercooling to an end. The procedure is based on a well known phenomenon, called epitaxis, which is involved in the manufacture of mixed crystals. Until now only one substance, silver iodide, has given results, and what results! This will be discussed again in a few moments.

Finally, recalling that icing clouds, which are simply clouds at temperatures below zero, can be dispersed by powerful shock waves, we could perhaps employ explosives or ultra-sonic waves to terminate the supercooling.

Any of the above methods may bring about rain by the application of the Bergeron theory. All of them have already been used to produce artificial rain, either in nature or in the laboratory, with various results. Can rain also be made with clouds at temperatures above zero? If so, the methods discovered should also succeed when applied to clouds which are partially or wholly at negative temperatures. Needless to say, the inverse proposition does not hold.

First of all, by sprinkling the cloud with large drops we may expect that the growth of these drops at the expense of the small ones in the cloud will lead to eventual rupture as soon as the sprinkled drops become very large and their speed becomes very great, and that the newly formed drops in turn will draw water from new small drops. Thus we can hope to disperse clouds by spraying them with water. The experiment has been tried by Professor Langmuir in America and was successful. Mr. Demon has also verified the results in the laboratory. Of course, if the large drops are colder than those of the cloud, the difference in vapour pressure due to temperature will be added to that due to curvature, so that a more rapid action can be expected. Moreover, if the drops are cold, smaller ones may be employed to gain an equal effect. This is an important consideration when the water supply is to be transported to the cloud by aircraft.

Similarly, by using a salt solution smaller drops can be employed to promote rapid growth and subsequent rupture than if pure water is used. Some very encouraging laboratory results have been obtained on this by Mr. Demon and his co-workers. You will be shown a few curves in a little while.

Finally, with drops of water carrying electrical charges very much stronger than those met in the storm clouds (Prof. Brun, Prof. Pauthenier and Mr. Demon 6) have reported methods whereby charges may be attained which are of the order of 10^{-5} c.g.s. units per drop, i.e., several hundreds of times greater than the charges on the natural cloud droplets) electrostatic forces of attraction sufficient for actual coalescence will be obtained. The experiment has already succeeded in the laboratory. Mr. Demon's results will be shown in a little while.

The interesting point about electrically charged water is that it will probably enable us to initiate precipitations with droplet diameters of the same order of magnitude as those of the cloud itself, i.e., 20μ instead of 200. Thus the quantities of water to be transported by aircraft will be a thousand times less than if pure water were being used to achieve similar results.

All known possibilities of creating artificial rain have now been reviewed. Not all, of course, have been given full-scale trials, but the results of the systematic investigations at the Bellevue laboratory by Mr. Brun, Mr. Demon and their collaborators, enable us to foresee new possibilities of supplementing, and, above all, of systematizing the somewhat haphazard and perhaps premature attempts which have been made following the first experiments by Langmuir.

* * *

We come now, as a matter of course, to an account of the experiments already completed throughout the world in laboratory and field, and to an assessment of their value.

In February 1942 at the General Electric Company, Professor Irving Langmuir and Mr. Vincent J. Schaefer were working on a smoke generator for military use. These two scientists began by calculating the theoretical rate of growth of drops surrounded by air saturated with a vapour of the same substance as the drops, and in 1943 they had the satisfaction of designing a smoke generator whose working characteristics agreed in every particular with their theoretical predictions.

From 1943 to 1945, having become experts on the evolution of fog droplets, they began to study the problem of icing on aircraft. They discovered, among other things, that the mean diameter of the droplets in an icing cloud could be determined from the rate of deposit of frost on rotating cylinders in a wind of given velocity. This was verified by experiment at Mount Wilson. *

I hasten to add that without any communication between the two countries, an experimental station for the study of icing was founded almost at the same time in France on Mont Lachat, on the initiative of Engineer General Poincaré, Director of Aeronautical Research (Groupement de Recherches Aéronautiques), and a team of research workers who developed a fundamental theory in the study of icing, namely the mechanics of suspensions. The latter discovery was the work of Messrs. Brun and Vasseur. This theory, which we have not time to discuss in detail this evening, relates the size of the drops to the amount of ice deposited at each point along a given profile in a wind of known velocity, and does it much more accurately than the theory of Langmuir and Schaefer. At the same time experiments were begun in the wind tunnel at Mont Lachat, shown here, for the purpose of verifying the results. These have been continued ever since using both natural and artificial icing clouds (Fig. 15, 16, 17). At present the method enables us, among other things, to determine the amount of ice deposited on each surface element of an aircraft wing profile for given drop sizes, so that the exact heat required for de-icing at each point on the wing can be calculated. In addition a computation department was set up at the O.N.E.R.A. for the use of the national aircraft firms.

To return to the American research. In the course of the work at Mount Wilson and the experimental flights undertaken in the Schenectady district, Langmuir, who had come to believe that the nuclei which caused supercooling to terminate were very rare at high altitudes, and that supercooling was the rule down to -20°C., got the idea of terminating it artificially.

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* Translator's note: This should read Mount Washington.

During the winter of 1945-46 Langmuir and Schaefer systematically explored icing clouds by aircraft. In the spring of 1946 Schaefer obtained a large cold chamber of four cubic feet which could be cooled to -25°, and the two of them began taking turns at blowing into it. It was established that not a single crystal of ice could be produced in this manner. They then tried to bring the supercooling to an end by introducing various powders, but without success.

Finally, in July 1946, Schaefer got the supercooling to cease with the aid of a needle dipped in liquid air. The boundaries were then narrowed, and it was found that to make the supercooling cease the needle had to be at a temperature of at least -35°. The crucial experiment was at hand. Schaefer 7) 8) injected tiny fragments of dry ice into the fog in his cold chamber. The supercooling ceased immediately, even along the path of a single falling fragment.

In August 1946, Langmuir 9) calculated the theoretical rate of growth of ice particles created in this manner. He came to the conclusion that by flying over a freezing cloud and spraying it with small pellets of dry ice he might hope to terminate the supercooling to a satisfactory extent.

It is important to realize that we are not always concerned with artificial rain, but also with dissipating icing clouds. The studies parallel those which are being carried on in France, but the guiding aim is somewhat different. We shall return to this point.

On 13 November 1946, Schaefer and Talbot seeded their first cloud thirty miles east of Schenectady. The ground temperature was 0°, the temperature in the cloud was -20°, and three pounds of dry ice were scattered. Within five minutes the entire cloud had turned to snow, which fell a distance of 2000 metres and then evaporated in the dry air.

From this time until 7 April 1947, seven seeding experiments were carried out in this manner. Some pictures taken during the tests are shown in Figures 18, 19 and 20. In each case large areas of cloud were transformed into ice. Since the ground temperatures were generally less than 0° the snow sometimes reached the ground. But again, the aim is not always to obtain precipitation. The possibilities are obvious for an aircraft which has to tunnel its way through an icing cloud in order to descend to the ground.

The first large scale success in producing artificial rain was that of Krauss and Squires [10]), who had heard of the early results of Langmuir and his colleagues. This took place near Sydney, Australia, on 5 February 1947. The clouds were at an altitude of 6600 metres and the zero isotherme stood at 5400 metres. The clouds were seeded with crushed dry ice. Rain fell five minutes after the seeding and covered an area of 50 square kilometres. In all eight such trials were made and each time rain was detected by means of radar below the cloud. Six times the rain reached the ground. The reason for this result must be noted: February is a summer month in Australia.

A few months earlier (the end of November 1946) Dr. Vonnegut [11]), another colleague of Langmuir, found that silver iodide was an excellent nucleus for terminating supercoolings. We have already seen why. For his studies he developed an apparatus for generating silver iodide (Fig. 20(a)). He believed that a very small amount of silver iodide would seed a cloud of very large dimensions and the cost would be relatively low, provided the particles were sufficiently dispersed. The following spring he succeeded in dispersing a local fog, which was quite large, using the apparatus shown in Figure 26.

Since the summer of 1947 the Americans have pursued their artificial rain tests on the American scale with the following aids: teams of meteorologists with sounding balloons for locating suitable clouds; commercial dry ice crushers; technicians and special aircraft for seeding the clouds; crews of photographers with specially fitted aircraft for taking still and motion pictures of the development of seeded clouds; specially trained research men to study the rain below the clouds; radar; etc. Figures 21, 22 and 23 show a typical air photograph and the results of the evaluation. The cloud seeding apparatus for dry ice and the silver iodide smoke generator are shown in Figures 24, 25 and 26.

Nothing more was published on this subject in the United States after July 1947, a fact which suggested that the matter had become "restricted". Then, quite recently, in a note of the Academy of Sciences in Washington, Langmuir announced that he had produced rain by sprinkling water on a cloud wholly at a positive temperature. This method was not altogether new. It had already been used to disperse fogs on aerodromes during the last war along with the "Fido" method of evaporation by means of oil burners.

What was done in France during the same period?

Since the foundation of O. N. E. R. A., i.e., at the beginning of 1946, I had been organizing a department of Atmospheric Physics, and at my request Professor Brun agreed to become its director. This department was to continue the battle against icing and the systematic study of the structure of fogs — diameter of drops, water content, electrical characteristics, etc. At the same time the mechanics of suspensions, of which I spoke a few minutes ago, was being evolved.

Before this department was set up, the studies at Mont Lachat had been concerned mainly with the development of direct icing detectors and thermal de-icers. In 1946 it was evident that a more immediately useful line of approach would be, on the one hand, to develop remote detection of the clouds which were at negative temperatures so as to avoid meeting them, and, on the other hand, to find means of dissipating these clouds.

Thus, into the research programme of the O. N. E. R. A. I introduced the same problem as that with which Langmuir was dealing at the same time. However, our orientation was different, for I decided, with the assent of Professor Brun and Mr. Jacques Maurin, engineer in charge of the project, to try to terminate the supercooling of a freezing cloud by using the shock wave of a powerful explosive. While this experiment was being prepared during the winter of 1946-47, Mr. Maurin suggested that supercoolings could also be terminated with the crystals of a substance which was insoluble in water, and that the effect of the shock wave could perhaps be reinforced by having such crystals carried on the wave front. I supplemented this idea by suggesting to Mr. Maurin that crystals of the same structure as ice be used.

About February 1947, rumours reached us of Vonnegut's [11)] preliminary work on silver iodide. Mr. Jacques Maurin, who, together with Mr. Medart, the chief explosives engineer [13)], was preparing penthrite detonators for these experiments, decided to prepare cartridges containing silver iodide as well. Our idea was that the silver iodide would be decomposed into ions by the explosions and that these could then be recombined on the wave front.

The initial experiment on the termination of supercooling by shock waves took place at the beginning of May 1947 (Fig. 27, 28, 29 and 30). It was perfectly conclusive, but unfortunately the cartridges which did not contain silver iodide were used. I say unfortunately, because the experiments had to be interrupted in the spring of 1947 due to lack of frost, and during the 1947-48 season the wind tunnel was being altered and could not be used

Thus the silver iodide detonators have never been fired and are still in the magazine at the Mont Lachat station. There is no doubt that the experiment would have given positive results. .

In 1945 Mr. Brun had directly measured the rate of growth of an ice crystal in supercooled water contained in an isothermal capillary tube, and in May 1947, Mr. Jacques Maurin 14) 15) measured the time required for complete freezing of supercooled drops starting from the moment of introduction of the seed.

At the end of the summer of 1947, Messrs. Brun and Demon, having heard of the early work of Langmuir and of the Sydney experiments, asked me, on behalf of O. N. E. R. A., and in conjunction with C. N. R. S., if they might undertake basic laboratory research on the artificial production of rain. The previous work of these gentlemen made them highly qualified for this study. Furthermore, the Low Temperature Laboratory at Bellevue was suitable for the experiments, and, finally, the research could be followed up at Mont Lachat. I therefore agreed, but without much enthusiasm, I must admit.

Under Professor Brun's direction, and with the assistance of Professor Pauthenier and some other engineers, Mr. Demon now began a series of systematic studies which were extremely fruitful 6) 16). In the supercooled-fog tank at Bellevue he studied the effects of carbonic snow (introduced by injecting liquid carbon dioxide or by using detonators), dry ice, cooled flasks and very cold particles, as well as the results of localized cooling by expansion of compressed air, the introduction of silver iodide and other crystals and the action of ultra-sonic waves (the latter in co-operation with Mr. Palme). The ultra-sonic wave tests were negative.

He examined the effects of electrically charged sand, ultra-sonic waves, hygroscopic salts and a spray of concentrated saline solutions for fog at positive temperatures in the large fog chamber under the upper station of the old funicular railway at Bellevue. The experimental procedure, a very simple one, was as follows: A beam of parallel light was made to traverse the fog and strike a photoelectric cell. The latter was connected to a galvanometer, the deflections of which varied inversely with the opacity of the fog. A fog was now introduced into the refrigerated tank and its normal development was recorded. Then the substance for modifying this fog was introduced and the new curve of behaviour was recorded.

The curves you will now be shown have not yet been edited, although the essential results have already been included in the notes of the Transactions of the Academy of Sciences [16]. They constitute an indisputable and indispensable basis for all subsequent field tests (Fig. 31 to 41). Trials in the mountains will now be carried out.

Mr. Demon is on his way back from Mont Lachat. In spite of the scarcity of good clouds for his experiments he has obtained some results.

The conclusions for the present are that the most effective methods of producing artificial rain consist in:

1. With supercooled clouds,

(a) dry ice in very small fragments, or carbonic snow, dropped directly into the clouds and dispersed horizontally be means of fuses or detonators. This idea is being developed simultaneously by the National Meteorological Bureau;

(b) silver iodide, carried by projectiles or dropped from aeroplanes;

(c) local cooling by expansion of compressed air.

2. For clouds at positive temperature,

spraying of fine droplets of saline solution of hygroscopic salts, and, eventually, electrically charged drops of water (Langmuir's spraying by drops of pure water several hundreds of microns in diameter appears to require amounts of water which are too large in relation to the expected results).

During the same period the National Meteorological Bureau, under the leadership of Mr. Roulleau [3], carried out some laboratory experiments at Trappes, and also held field trials, the aeroplanes being furnished by the S. A. S. M. The trials were supervised by Mr. Eyraud [18]. In all cases either carbonic snow or dry ice was used, but the types of cloud chosen were different, and different sizes of dry ice and different seeding methods were employed. The first seeding took place on 25 March 1947. Thereafter, some twenty flights were made with various results. The most satisfactory experiment was that of 15 January 1948, in the vicinity of Meaux - cloud top altitude, 3,400 metres (growing cumulus); temperature, -17°7; amount of dry ice dropped, 15 kilograms; result, twenty minute rainfall [18] [19].

The work of Mr. Coulomb and that of Mr. Dessens [20] of the Institute of Global Physics should also be mentioned.

In addition, some of the North African colonies have carried out field trials with the help of the Air Force. In general these tests have been rather inconclusive. However, on 19 April 1948, cold water, exact temperature unknown, was used for the first time on a growing cumulus cloud at 5,600 metres altitude and a temperature of -22°C. Rain fell over a radius of five kilometres.

To complete the picture it must also be mentioned that Mr. Camille Rougeron has suggested making the required rain right on board the aeroplanes by means of adiabatic compression and expansion, using the regular engines of the aircraft. According to him it should be possible to terminate the supercooling of clouds in this manner, whether directly, through the escape of cold gases, or by first manufacturing ice. A preliminary draft-scheme of mine indicates that this procedure may be less costly and more effective than carrying dry ice or liquid air.

To conclude this chapter we must also report that General Bergeron, President of the Committee of Scientific Action for National Defence, has taken the initiative in bringing together the research workers interested in artificial rain and those actually working on it, with the object of laying down a programme and dividing up the work. Four business meetings have already taken place at C. N. R. S., with General Bergeron in the chair. Unfortunately O. N. E. R. A. was not officially represented at these meetings.

* * *

Just now the research workers and the practical people were mentioned together for the first time. In the few minutes remaining let us discuss briefly the last problem with which I promised to deal this evening. What is the aim of it all?

Two different results may be achieved:

1. Dispersal of fogs and clouds;
2. Production and modification of precipitations.

First, the dispersal of fogs and clouds. This is a fundamental problem of aeronautics. We may hope to disperse supercooled fogs above aerodromes, for example, by seeding them with silver iodide, or other crystals which may be discovered in future, with dry ice, or, if need be, with liquid air; or the expansion of cold air may be used. Under certain conditions fogs at positive temperature could be dispersed by spraying. For this purpose saline solutions appear, a priori, to give better results than pure water.

Electrically charged drops from a suitable apparatus should also be effective.

The dissipation of an icing cloud, or the boring of a tunnel through it, is very important. Shock waves produced by the explosions of cartridges fired into the cloud, together with dry ice, and especially silver iodide, carried in the detonators, will certainly yield immediate results.

A multitude of details, the methods of application, still have to be worked out. These are purely engineering problems which may be left to the technicians.

Let us now turn our attention to the possibilities of producing or modifying precipitations.

Eyraud has suggested that the size of hail stones could be reduced by timely seeding of hail clouds. This would be a boon to agriculture.

Rain can also be produced. For the moment we are content to help nature along a little bit. In general we attack clouds which are almost ready to dissolve into rain, and which would probably do so without anyone's assistance very soon afterwards. It is true that if the cloud were moving rapidly it would rain somewhere else. We can imagine the epic quarrels and law suits which may occur in future between neighbouring landlords. But let us leave the development of this theme to the song writers.

In certain instances, however, the results can already be exploited by agriculture. In a little while we shall do better. Accurate information will be available on each cloud group in the sky, and the most favourable method of precipitation can be chosen in each particular case for the benefit of the farmers. Of course, the game will have to be worth the candle. Almost certainly only large clouds capable of furnishing considerable rain will be attacked. Whether to scatter dry ice by aeroplane, to atomize luke-warm or cold water, saline or pure, electrically charged or not, these choices will be made by the services concerned to suit the circumstances. The methods proposed by Mr. Rougeron will prove equally interesting, but of course there are still many technical details to be cleared up.

It will be possible to speed up the filling of hydro-electric power dams. Electricity France is following the artificial rain experiments with keen interest. On our part we are ready to help with all the means at our disposal. The recent power cuts are still too fresh in our memories for us to be in any danger of forgetting.

Langmuir has pointed to the feasibility of large-scale, continuous operations against cloud systems, resulting in marked climatic changes over a given region, e.g., the northern part of the United States. This remains a possibility.

It is evident that clouds are indispensable. Without them there can be no rain. A little while ago I voiced my hopes concerning the generation of clouds in supersaturated regions of the atmosphere. This would permit, for example, the eventual production of clouds over certain desert areas, after which the established methods of bringing about precipitation could be employed. We have not quite reached that point yet, but the repercussions of such experiments on life in districts now regarded as desert could be considerable.

We have thus far dealt only with peaceful and beneficial applications. There are others. I have already mentioned the small disputes that might arise between neighbours stealing each other's rain from the clouds above their estates. One can imagine, too, the sabotaging of open air political meetings by rival parties. Concert soloists might become dangerous. All this belongs in the realm of vaudeville, but there are more serious possibilities.

Military applications may be foreseen. Rain does not prevent aerial navigation but it may hinder parachute operations, infantry manoeuvres, artillery observations, etc. Moreover, some electronic waves cannot pass through rain. Interference with some of the radio guided or remotely controlled devices is a possibility.

In a recent article in "Forces Aériennes Françaises" 21) Mr. Rougeron goes beyond this and talks about "meteorological warfare". The Americans have not overlooked this aspect of the problem. I have already mentioned that little has been heard of the results obtained in America since July 1947. There are certainly reasons for this. More than a year ago Vonnegut had already made the following statement:* "The prospects opened up by the use of silver iodide should be brought under rigid control. Legislation should be enacted so that errors may be avoided and malevolent acts prevented. While it is very easy to supervise and limit the dropping of dry ice fragments into the clouds, it will be much more difficult to detect an illegal generator operating anywhere in the district, since it emits an invisible smoke.

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* Translator's note: The source of this quotation could not be found. The words given are thus a re-translation from Mr. Schwob's translation of the original.

Thus hundreds of ever more powerful installations could be constructed by anyone at all, and could be used for purposes contrary to the security of the United States."

What significance has this delicate problem for Europe, and especially for France?

The prevailing rains in France come from the Atlantic. We all know that the west winds bring rain. It is primarily the water of the Atlantic Ocean which provides the rain for Europe and a part of Asia. Naturally, the regions nearest the Atlantic, particularly France, are the best watered, except for anomalies due to mountainous irregularities. Thus France has an annual rainfall of 800 mm., Berlin has 600, Moscow 500, and Stalingrad 250.

If all the countries bordering the Atlantic systematically destroyed all or part of the clouds for several months of the year, certain parts of central Europe could be reduced to semi-desert and entire districts of Eastern Europe and Western Asia to complete desert. The effect on plant life, and particularly on grain growing, would be considerable. It is known that frosts without snow have already caused many famines in Western Europe. For this reason Mr. Camille Rougeron concludes that "Meteorological warfare, in the light of the first attempts at domestication of the atmospheric elements, offers prospects which in extent and power by far surpass those of atomic or biological warfare." In my opinion this is an exaggeration. The possibility of producing clouds from supersaturated regions of the atmosphere at high altitudes might perhaps remain available to countries which were subjected to a "natural cloud blockade".

In conclusion; I said at the beginning of this lecture that it was dangerous to play the role of prophet. Where will man stop? How will nature react to this new intrusion of human beings into a domain formerly closed to them? The great meteorological phenomena are more complicated than our feeble plans and halting explanations might lead us to suppose.

Let us hope that the three thousand year old prediction, discovered by Mr. Icart in an old Tibetan text of pre-Buddhist times, will not come true:

"The passions inspired by forbidden curiosities will lead thee to ignorance. Do not try to measure thyself against the genii who command the rain."

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PHOTOGRAPHS

Fig. 4 and 5 - Science et Vie.

Fig. 7 to 12 - Coulomb et Loisel - Physique des nuages.

Fig. 13, 14, and 18 to 26 - General Electric Research Laboratory.

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FIG. 1, 2
TT-87

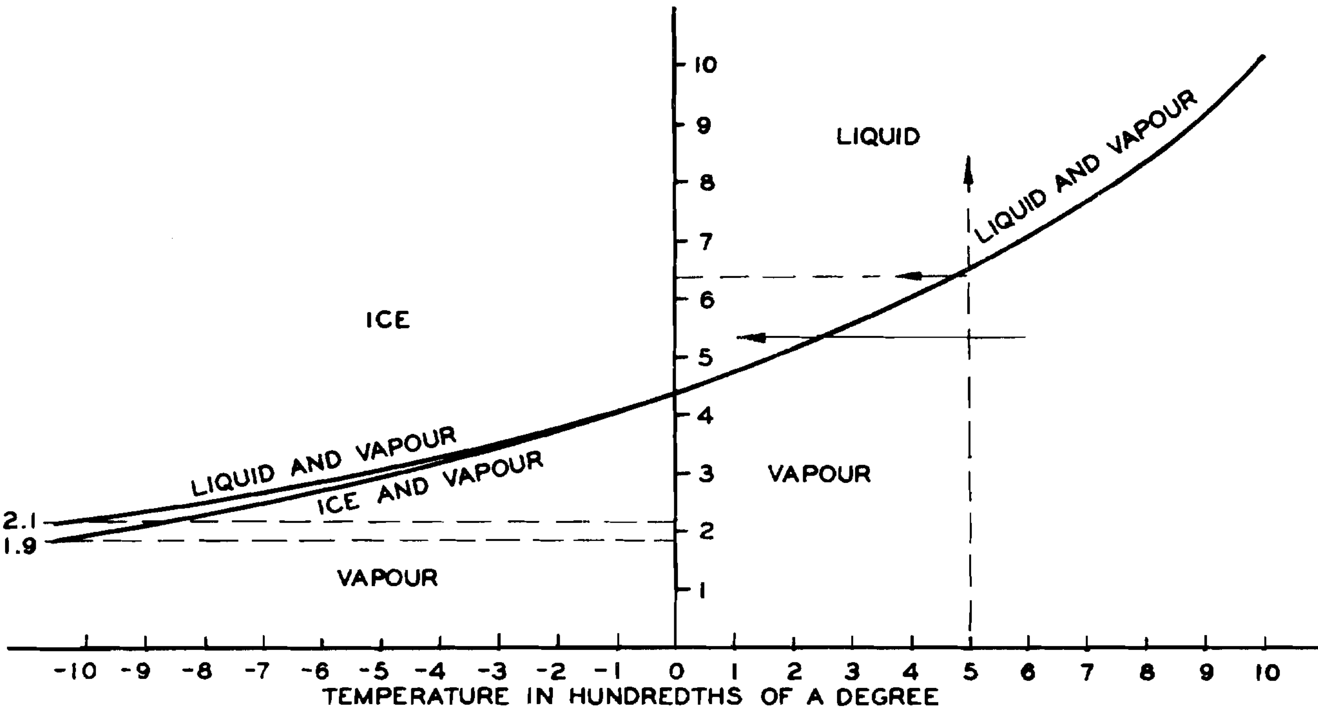


FIG. 1

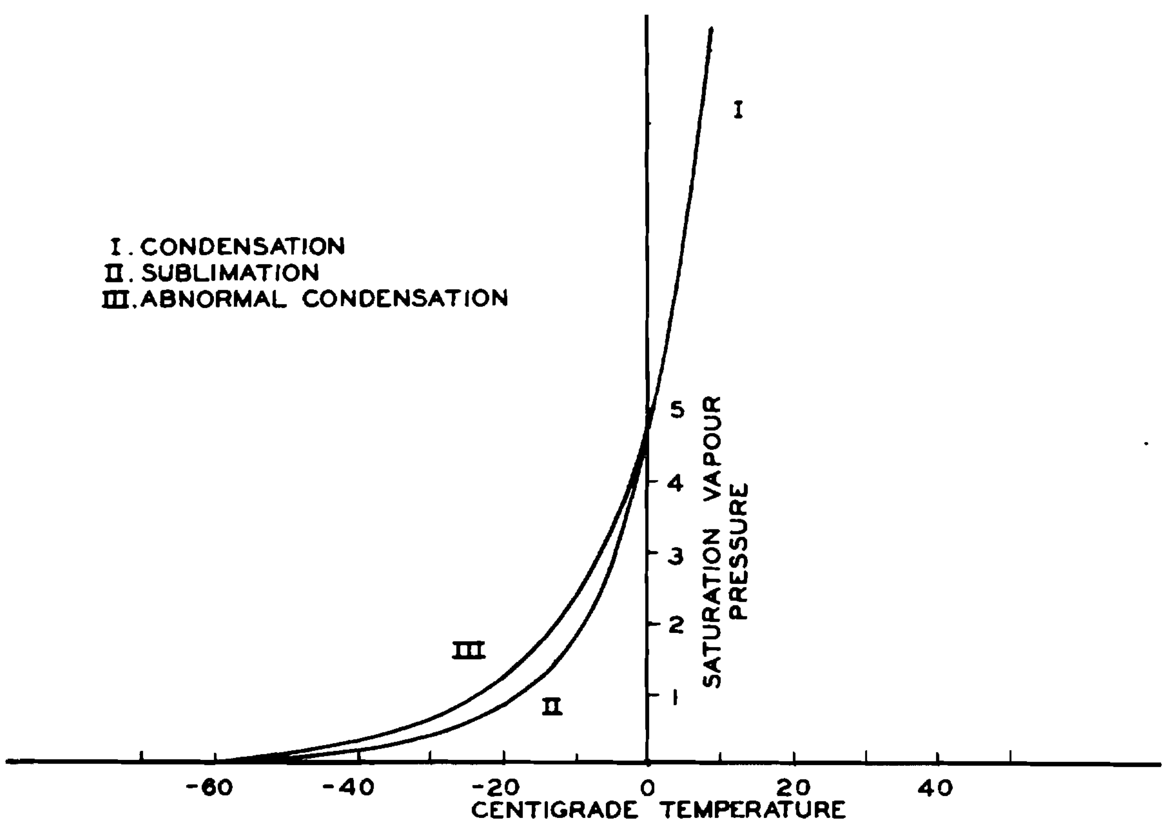


FIG. 2

CURVES OF EQUILIBRIUM OF WATER/ICE AND WATER VAPOUR

FIG. 5,6
TT-87

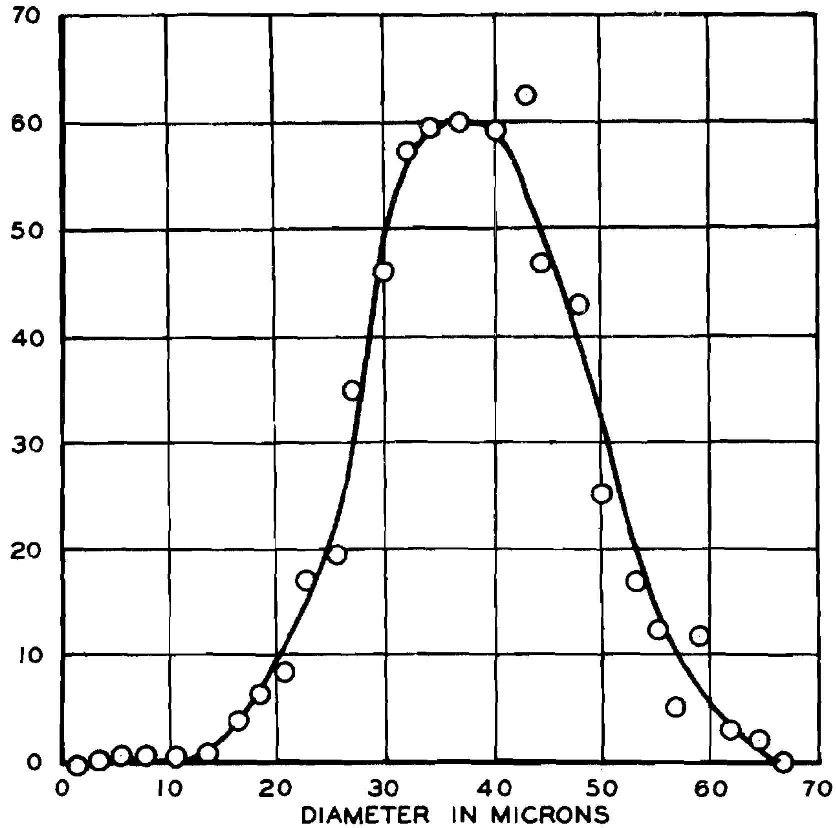


FIG. 5

STATISTICAL CURVE OF WATER DROPLET DIAMETERS IN A FULLY DEVELOPED CLOUD

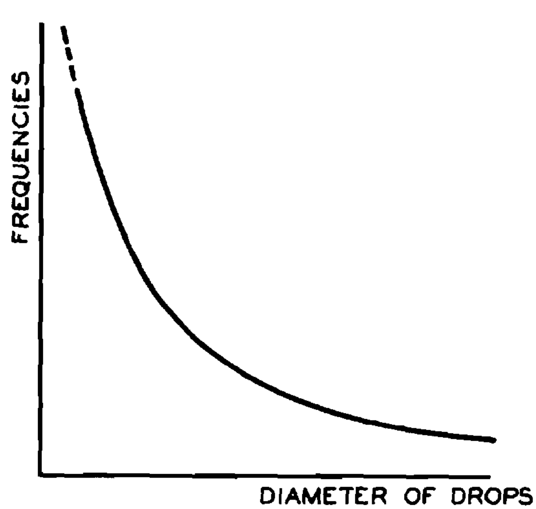


FIG. 6

STATISTICAL CURVE OF WATER DROPLET DIAMETERS IN A NEWLY FORMED CLOUD

Fig. 4

Water droplets in suspension in a cloud - by Houghton (magnified 70 times)

Fig. 7

Cumulus and fractocumulus clouds

Fig. 8

Cumulus congestus

Fig. 9

Dynamic cumulus

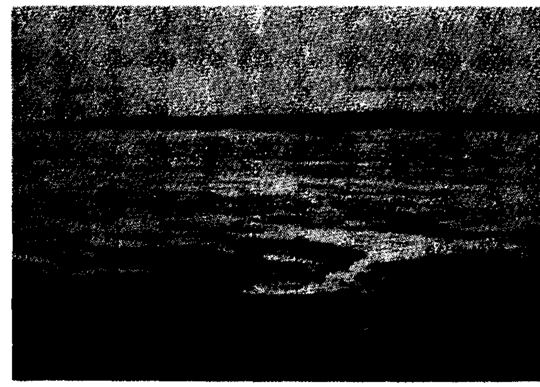


Fig. 11

"Sea" of stratus clouds on the Limagne

Fig. 10

Cumulus congestus

Fig. 12

Stratocumulus

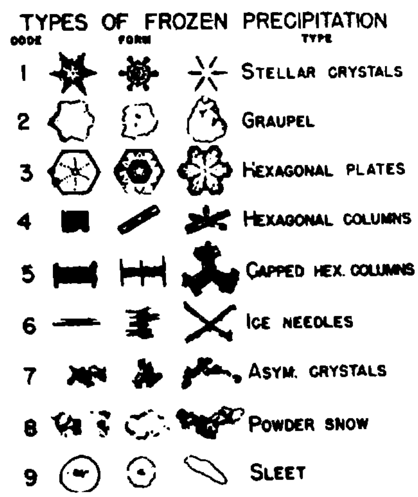


Fig. 13

Various types of natural solid precipitations

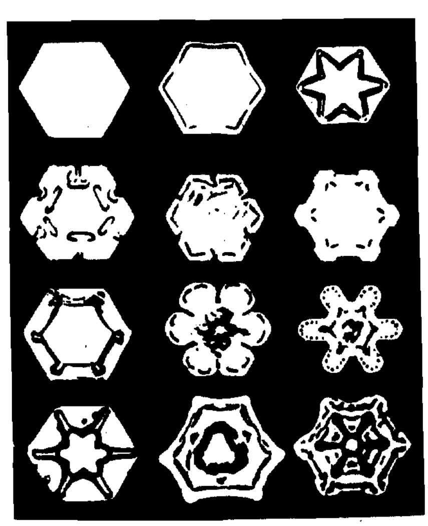


Fig. 14
Examples of solid precipitations produced artificially in the laboratory

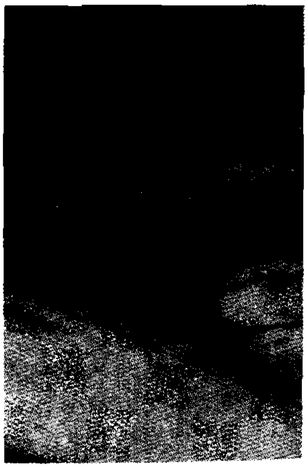


Fig. 15

Fig. 16

Fig. 17

Fig. 15 - 17 - Mont Lachat Station

Fig. 18

Clouds seeded with dry ice-sun reflecting from the ice crystals

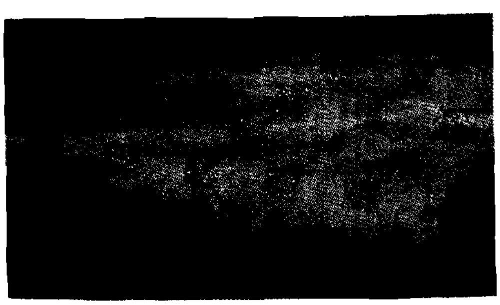


Fig. 19

Clouds seeded with dry ice-southerly direction with sun to south west

Fig. 20

Clouds seeded with dry ice-northwesterly direction with sun to south west

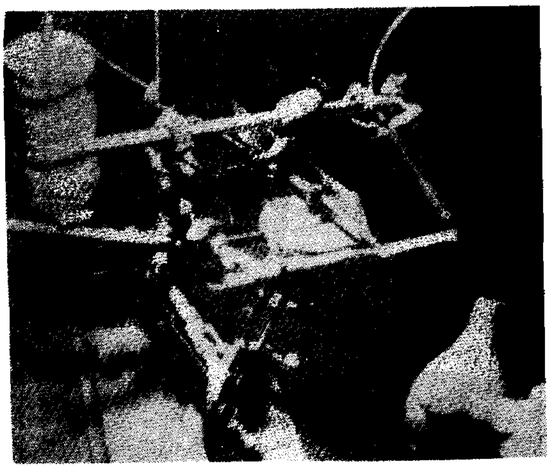
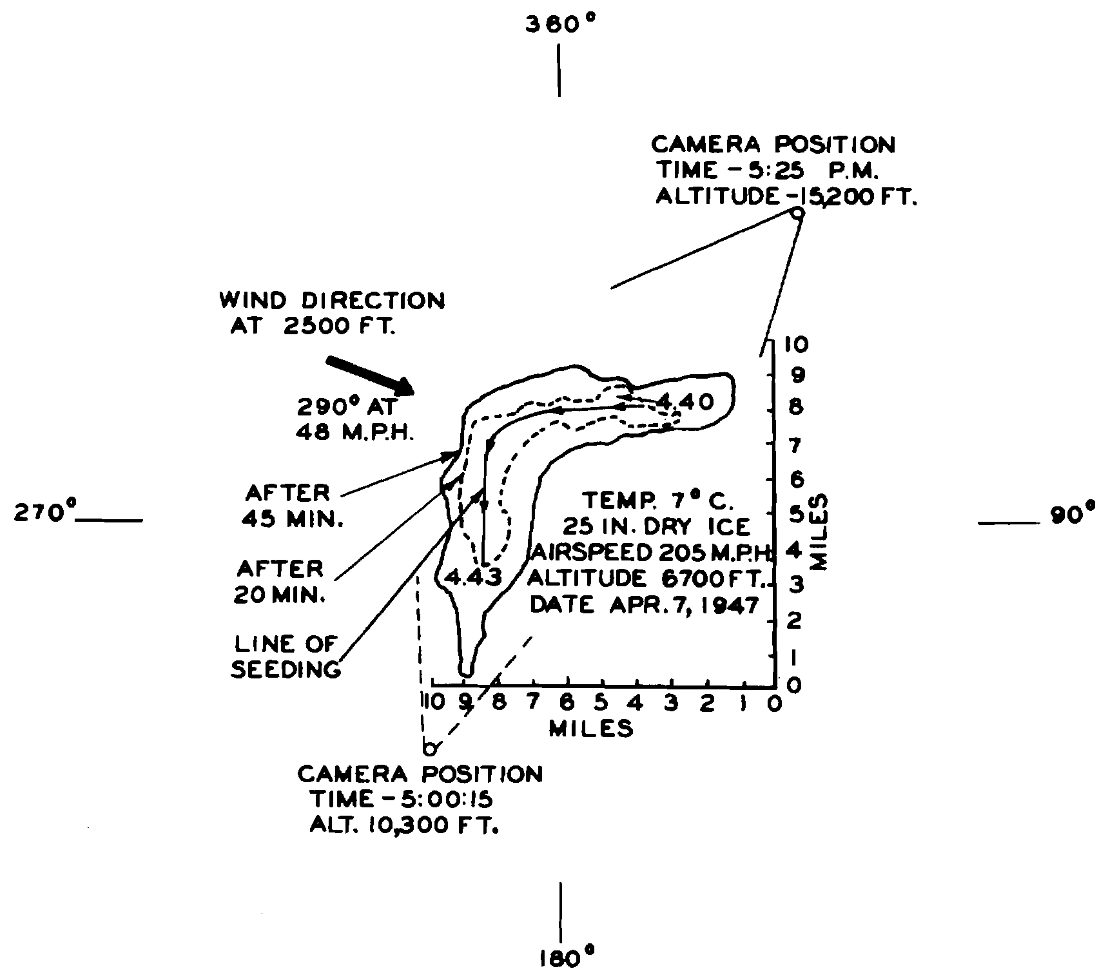


Fig. 20 (a)

Silver iodide generator - laboratory instrument

Fig. 21

Appearance of seeded cloud forty-four minutes after seeding



GROWTH OF SEEDED AREA
IN 45 MIN. PERIOD

FIG. 22

DEVELOPMENT OF SEEDED CLOUD
SHOWN IN FIGURES 20 AND 21.

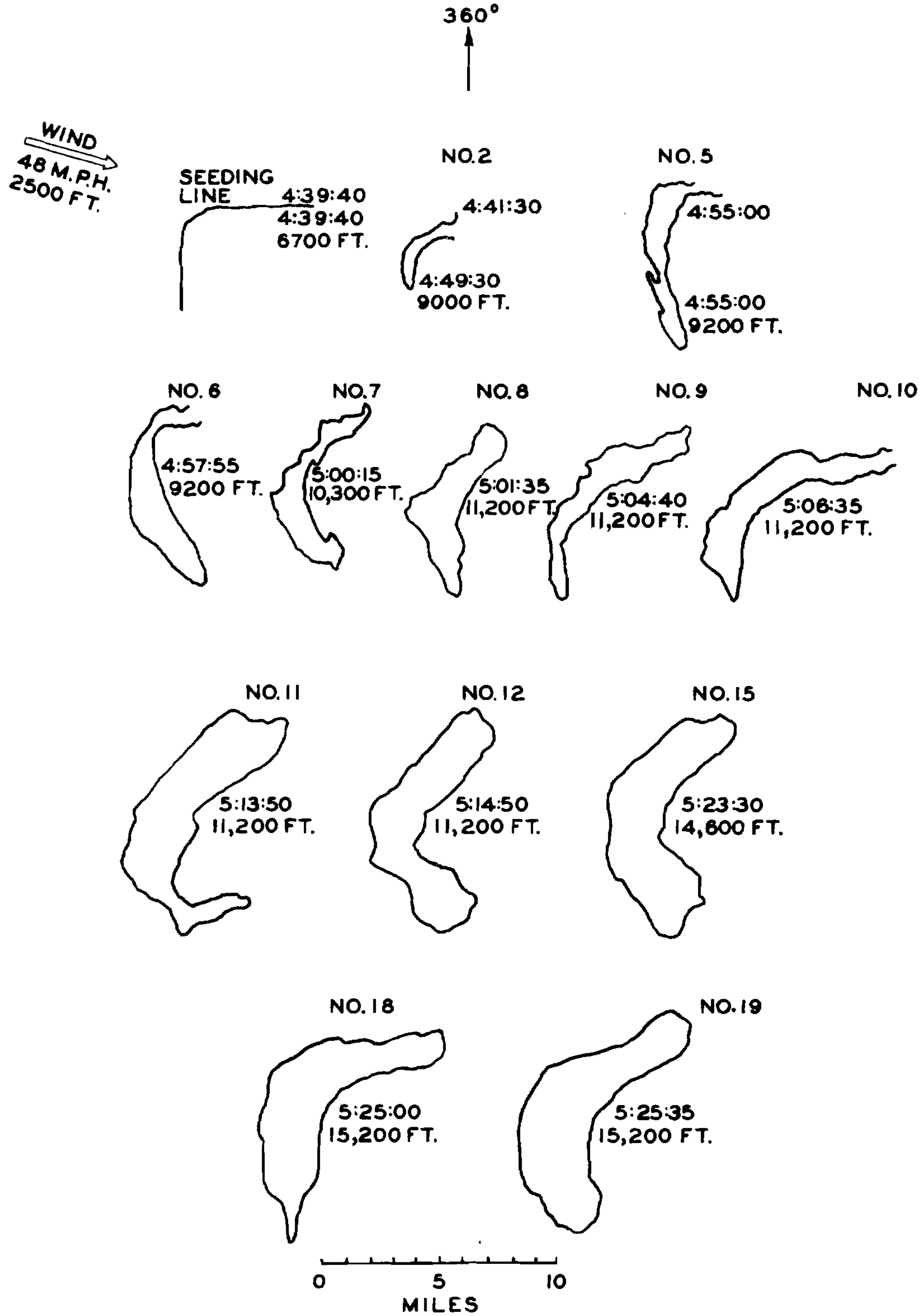
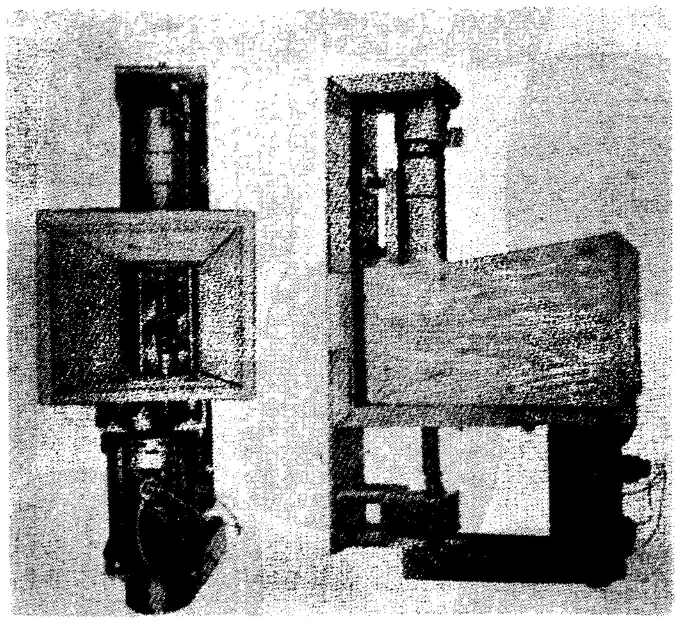


FIG. 23

DEVELOPMENT OF SEEDED CLOUD AS DETERMINED FROM THE PHOTOGRAPHS AND ACCORDING TO ALTITUDE



(plan) Fig. 24 — (elevation) Fig. 25

Dry ice dispenser for flight operations

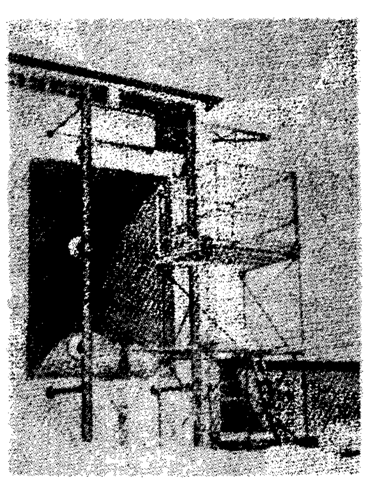


Fig. 27

Dissipation of clouds by shock waves (tunnel entrance and explosives cage)

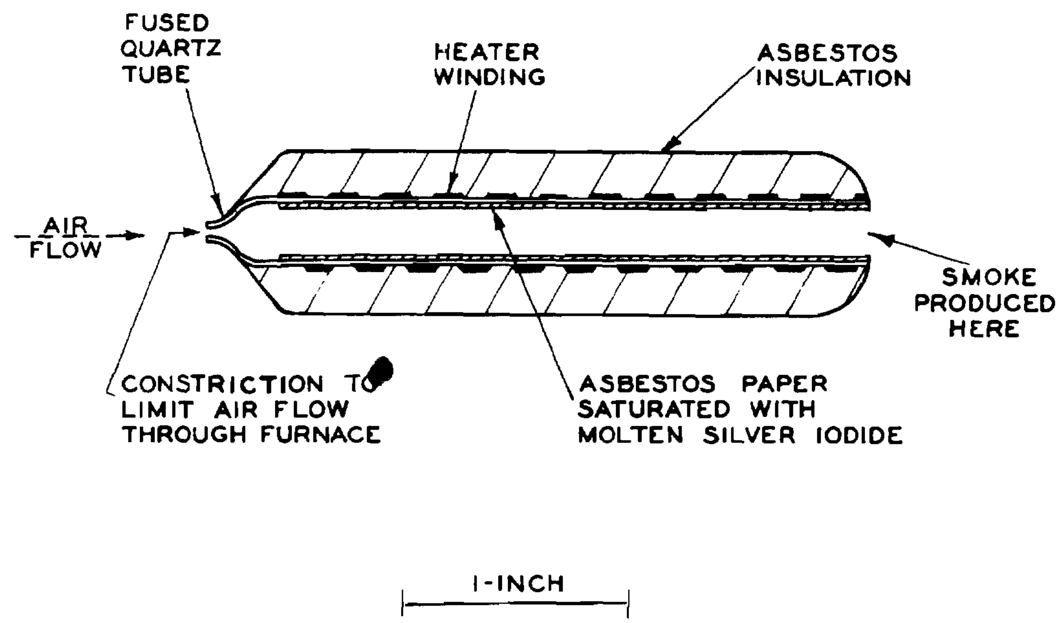


FIG. 26

ELECTRICALLY HEATED SILVER IODIDE GENERATOR FOR FLIGHT TESTS

Fig. 28

Contactor for controlling explosions

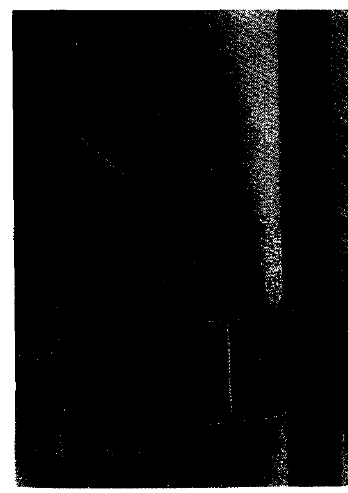


Fig. 29

Streamline shield

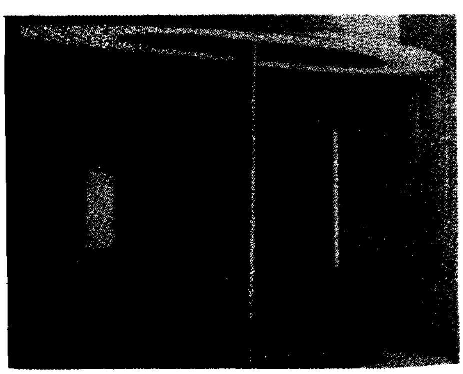


Fig. 30

Test cylinder

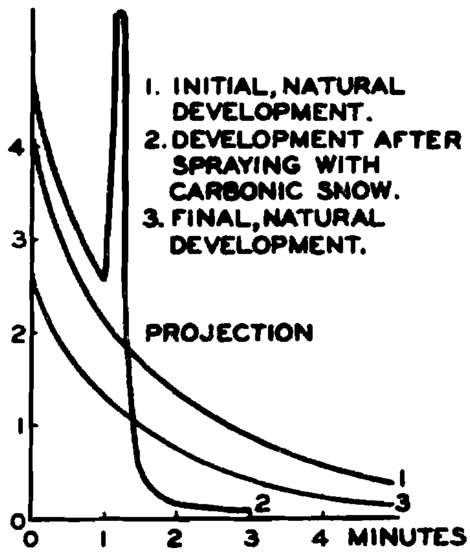


FIG.31

TEST WITH CARBONIC SNOW IN A NEWLY FORMED CLOUD

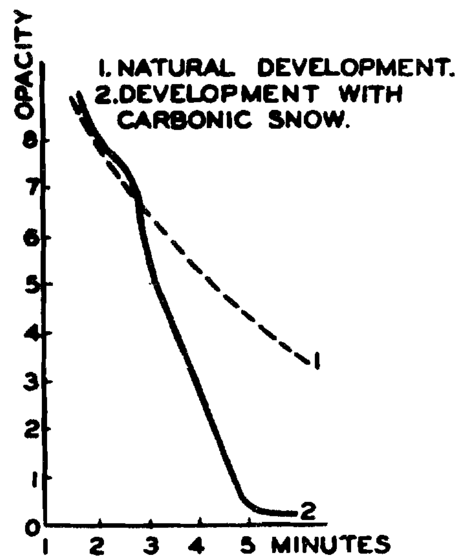


FIG.32

TEST WITH CARBON DIOXIDE GAS RELEASED FROM A CARTRIDGE

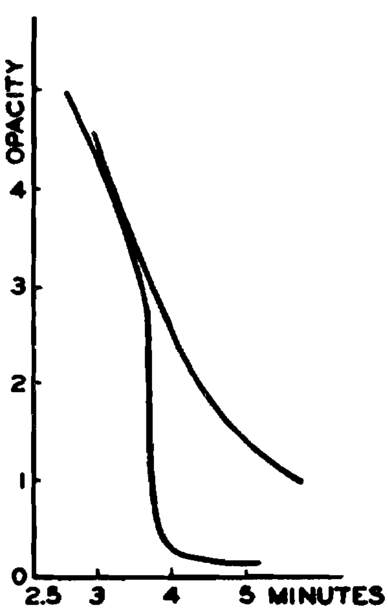


FIG.33

TEST WITH DRY ICE

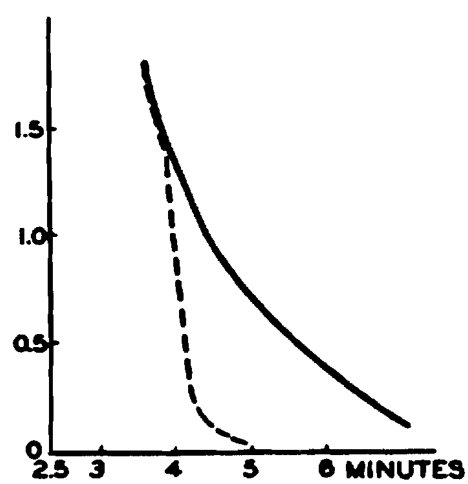


FIG.34

TEST WITH FLASK FULL OF SOLID CO_2

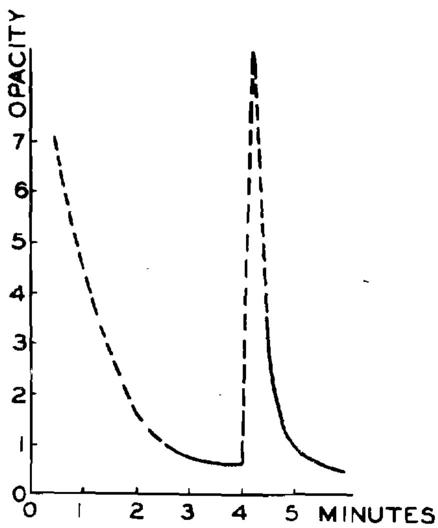


FIG. 35

TEST WITH COLD ZnO PARTICLES

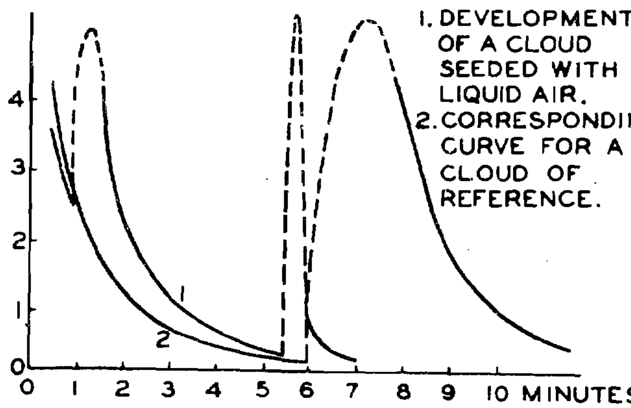


FIG. 36

TEST WITH LIQUID AIR

1. INITIAL, NATURAL DEVELOPMENT.
2. DEVELOPMENT AFTER SEEDING WITH 40 CU.CM. OF SATURATED $CaCl_2$ SOLUTION IN DROPLET FORM.
3. DEVELOPMENT AFTER SEEDING WITH 80 CU.CM. OF THE SAME SOLUTION.
4. FINAL, NATURAL DEVELOPMENT.

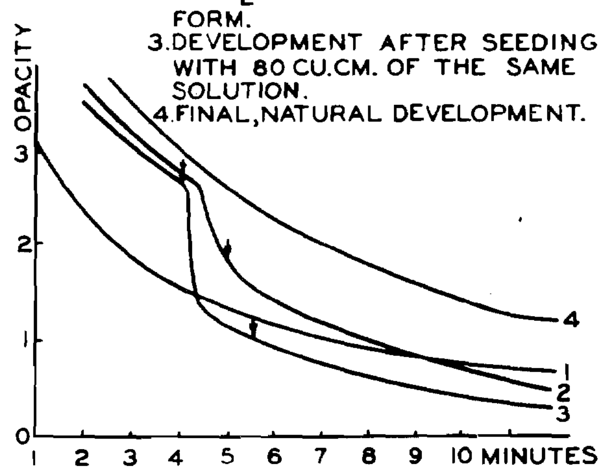


FIG. 37

SATURATED SOLUTION OF CALCIUM CHLORIDE

1. NATURAL DEVELOPMENT.
2. DEVELOPMENT AFTER SEEDING WITH 80 CU.CM. OF CALCIUM CHLORIDE FROM TWO ATOMIZERS EACH WITH PRESSURES OF 1 KG. PER SQ. CM.
3. DEVELOPMENT AFTER SEEDING WITH 80 CU.CM. OF NaCl SAME CONDITIONS.
4. SAME TEST WITH ATOMIZER PRESSURE BELOW 1 KG. PER SQ. CM.
5. NATURAL DEVELOPMENT AT THE END OF TEST.

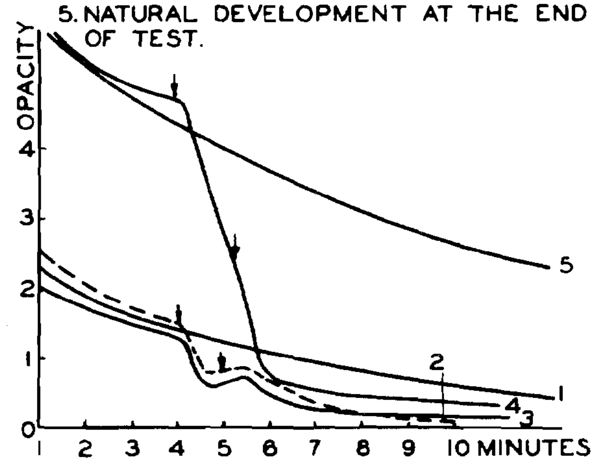


FIG. 38

SATURATED SOLUTIONS OF CALCIUM CHLORIDE AND SODIUM CHLORIDE

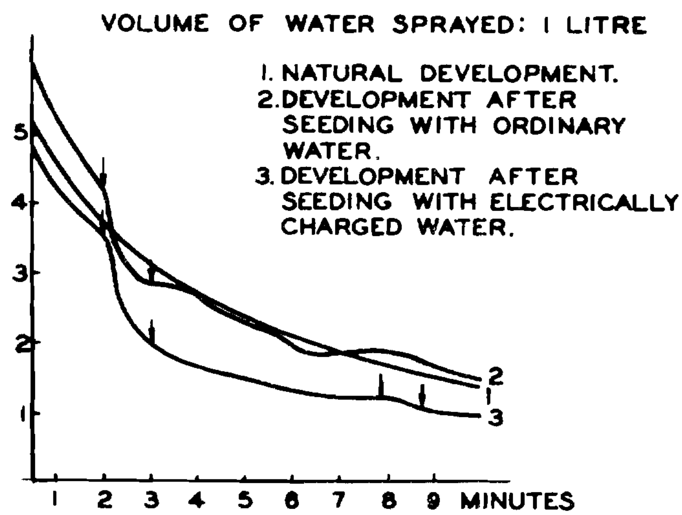


FIG. 39

EFFECT OF SEEDING WITH DROPS OF WATER (50 TO 100 μ M) - ELECTRICALLY CHARGED AND UNCHARGED

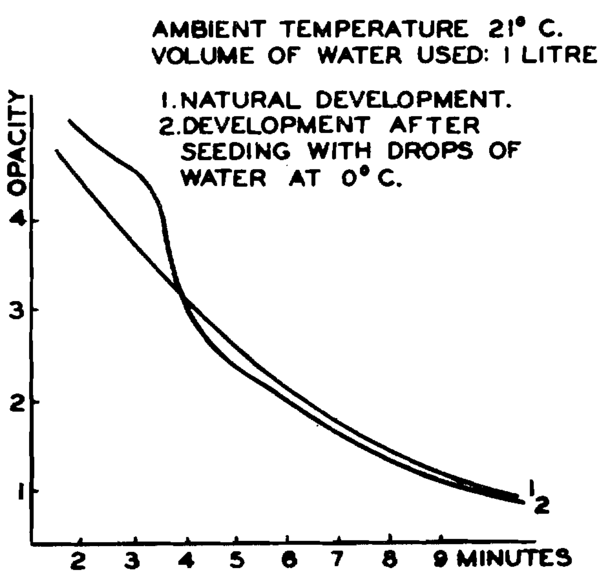


FIG. 40

EFFECT OF SEEDING WITH COLD WATER (0°C.)

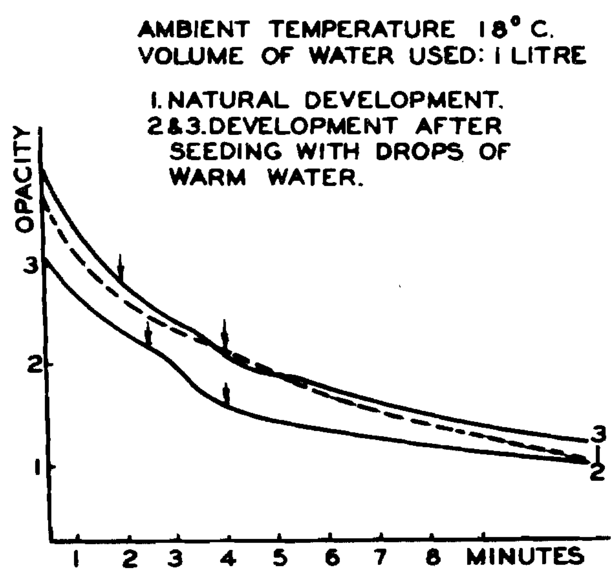


FIG. 41

EFFECT OF SEEDING WITH WARM WATER (55°C.)