CLOUD SEEDING FROM SPACE BY HIGH ALTITUDE ROCKETS

F. Winterberg

Desert Research Institute,
University of Nevada System,
Reno, Nevada 89507

ABSTRACT

A new cloud seeding technique is proposed which promises the smooth distribution of the seeding agent over a large air volume and hence target area. In the proposed method the seeding agent is cast into millimetersize pellets consisting of a mixture of the seeding agent and a chemical strongly reacting under contact with water. Especially promising for this purpose seem to be mixtures with the alkal metals Na, K and perhaps Ca. For 10 kilogram of seeding material about $\sim 10^7$ millimetersize pellets are required. The pellets are lifted with a rocket up to an altitude of $\sim$100 km, and are centered around a high explosive, which after reaching the desired altitude is detonated. The pellets thereby acquire velocities of $\sim 10^5$ cm/sec and are shot into all directions. At an altitude of $\sim$ 100 km the air density is so low that the pellets will travel over long horizontal distances before being slowed down by air friction. As a result the pellets will fall down onto the earth covering a large area which can be easily 100 x 100 km^2 wide. Estimates indicate fall times of less than one hour from the initial height of 100 km to the surface of the earth. If the pellets penetrate into clouds of supercooled fog they will collide with droplets of supercooled water. Estimates show that after falling through a cloud with a thickness of $\sim$1 km the millimetersize pellets will collect on their surface a water volume which is equal to their own volume. Therefore, if the pellets consist in about equal parts of AgI and K the potassium-water reaction will burn them up along their fall through the cloud releasing the AgI in form of a small smoke trail. For an area of 100 x 100 km^2 and for 10^7 pellets these smoke trails are separated by $\sim$ 30 meters ensuring rapid dispersion of the seeding agent by turbulent mixing. By comparison no conventional cloud seeding technique from the ground or the air could achieve so easily such a smooth distribution of the seeding agent over a large target area. The same technique may be also applicable to the seeding of air supersaturated with regard to ice for the formation of cirrus veil clouds. In this case the seeding agent could be possibly released by coating the pellets with a hygroscopic substance which upon the collection of water would trigger a chemical reaction such as the potassium water reaction igniting in turn a pyrotechnic reaction.

The principal problem of present cloud seeding techniques is the smooth distribution of the seeding agent over a large target area and hence air volume. The actual amount which is needed for an effective seeding operation would be rather small. For example, estimates indicate that only a few 10 kg of AgI would be needed to seed an are of $100 \times 100\ km^2$, which is a ridiculously small amount of seeding material considering the size of the target area. In view of these small needed quantities the prospect of artificial weather modification would seem to appear highly promising if an effective means for the dispersion for the seeding material over a wide target area can be found. Present methods for dispersing the seeding agent either work from the ground or from airplanes. In either case a large number of generators or airplanes is required to guarantee a sufficiently uniform initial distribution of the seeding material. After its distribution from either ground based generators or airplanes the dispersion of the seeding agent is caused by turbulent mixing. This mixing process is governed by turbulent diffusion with the characteristic turbulent diffusion time

$$\tau = \frac{x^2}{\ell v} , \qquad (1)$$

where x is the linear distance over which the seeding agent has to be dispersed, ℓ is a mixing length and v the turbulent velocity for the scale of ℓ. If the seeding agent is spread over an area A of the planetary boundary layer one has $A = nx^2$, with n sources for the initial release of the seeding agent and which are separated by the distance x, hence

$$\tau = A/n\ell v \qquad (2)$$

Eq. (2) shows that the turbulent diffusion time is inversely proportional to the number of the sources. This shows that for short diffusion times, and which are required for a good uniform distribution, the number of sources n should be made as large as possible. The required number of these generators or airborne missions may in fact be so large to make the operation either uneconomical or technically impractical.

As an example let us assume that the mixing length is $\ell \simeq 10^5$ cm and the turbulent velocity $v \simeq 10^2$ cm/sec, from which would follow that $\tau = 10^{-7} x^2$ sec. Thus for $x = 10^6$ cm = 10 km one has $\tau = 10^5$ sec $\sim$ 1 day, and for $x = 10^5$ cm = 1 km one has $\tau = 10^3$ sec $\sim$ 1/3 hour, and for $x = 10^4$ cm = 100 meters one has $\tau = 10$ sec. Therefore, the separation in between the sources should be less than 1 km and preferentially 100 meters. From $n = A/x^2$ it thus follows for $A = 100 \times 100\ km^2 = 10^{14}\ cm^2$ and $x = 10^5$ cm that $n = 10^4$, and for $x = 10^4$ cm that $n = 10^6$. These are very large source numbers, even if airplanes are employed for the seeding operation. In case an area of $500 \times 500\ km^2 = 2.5 \times 10^{15}\ cm^2$ shall be seeded, which is a typical area covered by a cyclone, it follows that for $x = 10^5$ cm still $n = 2.5 \times 10^5$ sources would be required. Such a large number of sources seems to exclude the seeding of these storms by conventional means.

In order to make possible a smooth seeding over a large target area, implying a large number of sources, a new technique is proposed shown in Fig. 1 and 2. In this novel technique the seeding agent is cast into small millimetersize pellets which are centered around a high explosive to be launched by a rocket up to a height of $\sim$ 100 km, at which the explosive charge is detonated, ejecting the pellets at high speed into all directions (Fig. 1.). In this way pellet velocities as high as 1 km/sec are easily attainable. At the high altitude the pellets suffer little air friction and accordingly travel over large horizontal distances before being slowed down. The pellets need about $\sim$ 100 seconds to enter the denser regions of the atmosphere after which they begin to fall vertically down.

The advantage of the method based on going into space is obvious. Because of the vacuum of space a very uniform initial distribution of the seeding material over a very large target area and thus air volume is possible. In contrast to conventional dispersion methods depending primarily on the relatively slow diffusion velocities in the atmosphere and requiring a large number of individual seeding generators, here only one primary source is needed to be placed into the payload of a high altitude rocket.

In Fig. 2 the arrangement of the pellets centered around the high explosive is illustrated. The high explosive is placed in the center of the device. The explosive charge may be of the order of a few 10 kg. The pellets are separated from the high explosive by a gap the purpose of which is to soften the shock of the high explosive and to accelerate the pellets less violently. In this way the pellets can be prevented from disintegrating by the detonation shock.

The distribution of the pellets over the target area in general is non-uniform. However, almost any desired distribution, including a uniform one, can be achieved by a nonspherical explosive charge or a nonspherical arrangement of the pellets surrounding the charge. This may be of importance if for example, the center of a storm shall be seeded by a higher degree than its periphery.

The initial velocity of the pellets is supersonic. Their slowing down range due to air friction is therefore determined by the drag for supersonic velocities with a drag force given by

$$F \simeq \pi r^2 \rho v^2 \quad , \qquad (3)$$

where r is the pellet radius, ρ the air density and v the initial pellet velocity. From eq. (3) one computes the slowing down range ℓ due to air friction by putting $F\ell = (m/2)\, v^2$, with $m = (4\pi/3)\rho_p r^3$ the pellet mass and ρ_p the pellet density, hence

$$\ell = 2\rho_p r/3\rho \quad . \qquad (4)$$

putting for the pellet density $\rho_p \simeq 3$ gm/cm^3 and for the pellet diameter $2r \simeq 10^{-1}$ cm, one would have $\ell \simeq 10^{-1}/\rho$ cm. The air densities at the altitudes 50 km, 75km and 100 km are $\rho \simeq 10^{-6}$ gm/cm^3, 10^{-8} gm/cm^3 and 10^{-10} gm/cm^3 with the ranges $\ell \simeq 1$ km, 100 km and 10^4 km. It thus follows that for an altitude of 100 km the air friction is negligible and the pellets are therefore injected into parabolic orbits.

To estimate the maximum horizontal range for the pellets we take trajectories with a horizontal injection velocity. One can easily verify that if $h \gg v^2/2g$, where h is the initial height above the ground at which the pellets are injected into their trajectories, the pellets with a horizontal injection velocity have the largest horizontal range in reaching the ground. For $v = 10^5$cm/sec, $g \simeq 10^3$ cm/sec one has $v^2/2g = 5 \times 10^6$ cm, so that for $h = 10^7$ cm the condition $h \gg v^2/2g$ is fairly well satisfied. Neglecting air friction one then obtains for the maximum horizontal range x_o

$$x_o \simeq (2h/g)^{1/2} v \quad . \qquad (5)$$

For $v = 10^5$ cm/sec, and $h = 10^7$ cm, one has $x_o \simeq 1.4 \times 10^7$cm = 140 km. The horizontal range will be actually smaller since the pellets after losing altitude will enter denser regions of the atmosphere where they will be slowed down in their horizontal motion by air friction. At an altitude of 50 km where the density has increased to $\rho \simeq 10^{-6}$ gm/cm^3 the friction ranges of the pellets have fallen to ~ 1 km, and from there on after having lost most of their kinetic energy the pellets start falling vertically down. In order to get a more realistic estimate of the horizontal range one must therefore subtract in eq. (5) from the value of $h = 10^7$ cm about ~ 50 km $= 5 \times 10^6$ cm and thus would obtain $x_o \simeq 10^7$ cm = 100 km.

The time t_o for the pellets to reach the ground in free fall is given by

$$t_o = (2h/g)^{1/2} \quad . \qquad (6)$$

For the above given values of $h = 10^7$ cm this time is $t_o \simeq 140$ sec. The actual fall times are different because a fraction of the pellets has a vertical velocity component $\leq 10^5$ cm/sec and because of air friction. A pellet with a downward vertical velocity of 10^5 cm/sec would reach the ground in $\simeq 70$ sec. The friction however, will result in larger times. After the pellets have fallen to the altitude of ~ 50 km at which they lose rapidly their kinetic energy, their vertical motion from there on is determined by the balance of the frictional force and the gravitational force, which for sufficiently small Reynolds numbers is determined by Stokes law

$$v = \frac{2}{9} \frac{\rho_p r^2 g}{\rho \nu} \quad . \qquad (7)$$

In eq. (7) ν is the kinematic viscosity which for an ideal gas is given by $\nu = \lambda\bar{c}/3$, where λ is the mean free path with $\lambda \propto 1/\rho$, and $\bar{c}$ the thermal velocity. It thus follows that for constant $\bar{c}$ the product $\rho\nu$ is independent of ρ and hence of the altitude, which would result in a constant fall velocity. However, this conclusion has to be modified for two reasons: 1) Above an altitude where $\lambda > r$ the friction is determined by that of a Knudsen gas for which the friction decreases in proportion to the density. For $r \sim 10^{-1}$ cm this roughly happens above 50 km. 2) For large Reynolds numbers the friction is larger than in Stokes law and hence the fall velocity smaller. The Reynolds number is given by $R = rv/\nu$. At sea level $\nu \simeq 10^{-1}$ cm^2 sec^{-1} and for millimetersize spheres the experimentally determined fall velocity is $v \sim 10^3$ cm/sec, hence $R \simeq 10^3$ so that Stokes law cannot be applied. But since $\nu \propto 1/\rho$ it follows that $R \propto \rho$ such that a decrease in the air density by a factor 10^3 at an altitude of 50 km would make $R \simeq 1$. In this case Stokes formula according to eq. (7) would yield $v \simeq 10^4$ cm/sec, which is about 10 times larger than the experimentally obtained fall velocity at sea level. In summary the fall time is roughly determined by the free fall time to reach an altitude of $\sim$ 50 km which is given by eq. (6) by subtracting from $h = 10^7$ cm the value 5×10^6 cm. hence $t_o \simeq 100$ sec, plus the time required to fall from the altitude of 50 km to the ground. If we assume that the average fall velocity is therefore about $\sim 5 \times 10^3$ cm/sec this would result in a frictional fall time of $\sim 10^3$ sec $\sim$20 minutes. The total fall time is hence determined primarily by the frictional fall time below the altitude of 50 km.

After entering a cloud of supercooled fog the pellets collide with droplets of supercooled water. Along a distance they collide with a water volume given by

$$w = \alpha\pi r^2 s \qquad (8)$$

where α is the ratio of the water volume to the air volume in the cloud and r the pellet radius. From eq. (8) one computes the distance s_o the pellets have to fall through the cloud of supercooled water droplets in order for them to collect up an amount of water volume which is equal to their own volume, by putting $\alpha\pi r^2 s_o = (4\pi/3)\, r^3$, hence

$$s_o = 4r/3\alpha \qquad (9)$$

Typical clouds have a relative water volume $\alpha \simeq 10^{-6}$. With a pellet diameter of $2r \simeq 0.1$ cm it thus follows that $s_o \simeq 10^5$cm = 1 km, which just has the right magnitude for the expected cloud thickness. Therefore, if the pellets are of millimetersize and consist of a mixture of the seeding agent and an alkali metal such as potassium or sodium, they will burn up by contact with the water droplets during their fall through the cloud. This is one reason for the choice of millimetersize pellets.

If it should turn out that a less violent burning should be required this could be achieved by diluting the alkali metals with calcium. Calcium alone would lead to a rapid corrosion of the pellets under contact with water. Rather mixing the seeding agent with an alkali metal one could also coat the pellets with it. In this case, after the coating has caught fire by contact with water droplets of the cloud, some pyrotechnic reaction as for example being used for AgI seeding, could be triggered to release the seeding agent. By making two coatings, one outer with calcium and a second inner with potassium (or sodium), one could make the pellets first fall down into the cloud a certain specified distance during which the calcium coating is being dissolved and after which the potassium gets in contact with the cloud water droplets catching fire triggering the pyrotechnic reaction.

If the seeding material has a volume of $\sim 10^4$ cm^3 this would imply $\sim 10^7$ millimetersize pellets. The pellets entering the cloud covering the area of 100×100 km^2 = 10^{14} cm^2 would be separated by a horizontal distance $x = (10^{14}/10^7)^{1/2}$ cm $\simeq$ 30 meters. Each pellet thereby would create a vertically descending smoke trail releasing the seeding agent. At the small spatial separation of the pellets this would result in a rapid dispersion of the seeding agent in less than 100 seconds by turbulent mixing. The excellent expected dispersion with the easily feasible number of 10^7 pellets, is a second reason for choosing millimetersize pellets.

But even if the pellet diameter is $\simeq$ 0.5 cm this would give $\simeq 10^5$ pellets with a horizontal distance in between two pellet trails of $x \simeq 300$ meters, which would still ensure good turbulent mixing over a period of one hour. But here, the radius would be too large for the pellets during their fall through the cloud to collect up an equal volume of water, and rather a pyrotechnic reaction would have to be triggered as described above. Larger pellets however, have the advantage of shorter fall times and of being less sensitive to the influence of horizontal wind motion.

If the pellets are released at an altitude of $\sim$ 100 km they can seed an area of 100×100 km^2 which by order of magnitude is the size of a hurricane. In case a cyclone shall be seeded typically covering an area of 500×500 km^2, the horizontal range of the pellets must be of the order $\sim$ 500 km. According to eq. (5) this could be done by going to $h \simeq 10^3$ km and at the same time increasing the pellet velocity by a factor 2 to $v \simeq 2 \times 10^5$ cm/sec. Furthermore, for a 25 fold increased target area roughly $\sim$ 25 times more seeding material would be needed. The first and last requirement could be simply satisfied by using a larger rocket. To reach a higher initial pellet velocity could be achieved by filling the gap, shown in Fig. 2, in between the high explosive and the intermediate spherical shell by hydrogen gas under high pressure. Because of its low molecular weight, hydrogen at a given temperature by comparison with other gases has the largest thermal expansion velocity. The detonation of the high explosive will heat up the hydrogen gas to a temperature of several thousand degrees and by its radial expansion will accelerate the pellets to velocities of a few km/sec. The free fall time at an altitude of $h \simeq 500$ km is about $\sim$ 300 sec, and the time for the friction fall in the denser part of the atmosphere the same as before, so that again the seeding operation is completed in less than one hour.

The cost for a rocket capable of reaching an altitude of about 100 km and with a payload of $\sim$ 100 kg is less than $\$10^4$. This is substantially less than the cost which would arise if the same seeding operation is performed by airplanes requiring about $\sim \$10^5$ to achieve a comparable dispersion. A rocket with a payload of $\sim$ 1000 kg seeding material to reach $\sim$ 500 km would cost less than $\$10^5$, whereas the cost to perform the same operation with airplanes could run as high as $\$2.5 \times 10^6$.

It has been suggested to the author by Dr. P. Squires (private communication) that the proposed concept may perhaps be also applicable to the seeding of clear air supersaturated with regard to ice, leading to the formation of cirrus veil clouds. If such cirrus veil clouds could be created over vast areas they would substantially reduce the solar radiation influx due to their large albedo. In this case the seeding agent may be possibly released by coating the pellets with a hygroscopic substance collecting water and which upon contact with water produces heat preventing freezing. The water accumulated in the hygroscopic coating would then trigger a chemical reaction, for example, a potassium-water reaction, which in turn would trigger a pyrotechnic reaction.

ACKNOWLEDGMENTS

The author would like to express his sincere thanks to Dr. P. Squires, for his interest in this work and his valuable comments.

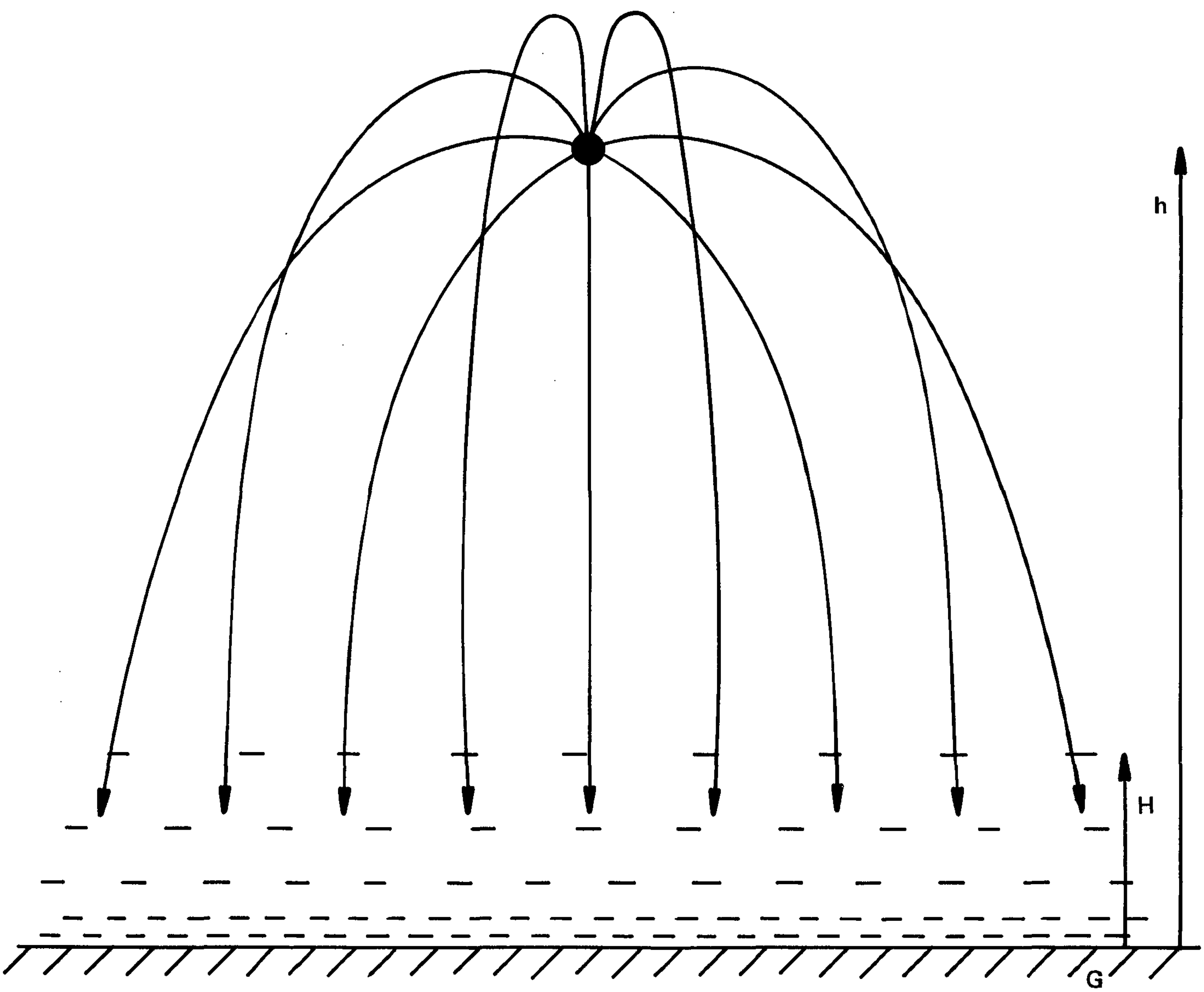

FIGURE 1. The pellet trajectories. h is the height at which the pellets are released by action of an explosive charge. H is the scale height of the atmospheric boundary layer above the ground G.

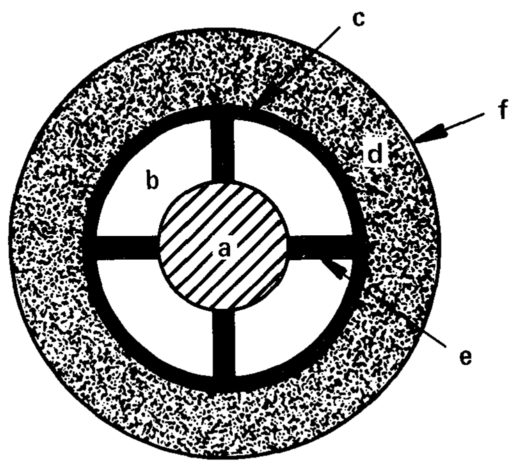

FIGURE 2. The arrangement of the high explosive surrounded by the pellets. a, high explosive; b, gap filled with a gas or vacuum; c, solid spherical shell; d, space occupied by the pellets; e, supporting structures in between the high explosive and the solid shell; f, outer shell of charge.