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Argonne National Laboratory

WEATHER MODIFICATION

by

M. B. Rodin and D. C. Hess

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ANL-6444
Physics
(TID-4500, 16th Ed.,
Amended)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois

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Reactor Engineering and Physics Divisions

December 1961

Operated by The University of Chicago
under
Contract W-31-109-eng-38

ABSTRACT

It is suggested that applying heat directly to a rain cloud, or to a moist air mass with rain potential, may alter the natural precipitation in a given geographical region. The immediate effect of the heat is to increase the buoyancy of the cloud or air parcel. The result, which depends on a number of interrelated factors may be either (a) to cause precipitation where it would not naturally occur, or (b) to suppress precipitation where it would naturally occur. Several possible applications are suggested. Since the heat supplied is supplemented by the latent heat resulting from condensation in the moist air mass, the results may more than justify the cost. However, substantial amounts of heat are involved. The heat can be supplied from fossil fuels, nuclear reactions, or a combination of both; but the logistics favor the use of large nuclear reactors wherever safety criteria can be met. Not only the efficiency and economics of the process, but also its feasibility, can be finally decided only on the basis of information that is not now available.

WEATHER MODIFICATION

M. B. Rodin and D. C. Hess
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I. INTRODUCTION

According to Dodge,[1] the total water available as rainfall on land areas is much more than is required to supply all of man's current needs. In fact, rainfall is estimated to provide about 30 000 gallons of water per day for every inhabitant now on the earth. Since the land mass covers only about one-fifth of the surface of the earth, the total per capita rainfall over the entire earth must be substantially higher. However, the pattern of rainfall does not coincide with human needs. A partial solution to the problem of distribution along the lines suggested in this study could result in substantial benefit to strategically located areas.

The suggested method of altering rainfall is to apply heat directly to rain clouds or moist air masses. (For simplicity, the terms "rain clouds" and "moist air masses" will here be used interchangeably, although it is realized that they are not identical.) The literature discusses various mechanisms by which such heating may induce precipitation. One theory requires ice particles as nuclei for the formation of raindrops in the cloud. This theory could account for rainfall that is reported to have occurred under the following circumstances. As a cloud initially moving over a relatively cool terrestrial surface passes over a hotter area, or over a large natural heat source such as a burning forest, its forward elements absorb heat on their under sides and rapidly rise. The resulting expansion and contact with cooler strata causes the water droplets, which are a few microns in diameter, to freeze into small ice particles and drop back into the body of the oncoming cloud. The ice particles have a lower vapor pressure than water droplets and, in the presence of saturated air in the clouds, rapidly grow to a diameter of several hundred microns and achieve

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[1] B. F. Dodge, Am. Scientist 48, 476 (1960).

settling velocities sufficient to overcome the updrafts in the cloud. The ice particles then fall and melt, reaching the earth as raindrops.[2]

Precipitation may also be achieved by orographic lifting. Under these conditions, a cloud may be forced upward as it moves over a rising land mass, as on approaching a mountain range. The increase in the altitude of the cloud results in cooling due to adiabatic expansion as well as to a colder environment and provides the necessary conditions for precipitation.

On the other hand, clouds which are uniformly heated with comparable amounts of energy do not yield precipitation. Thus, on clear days, one can observe clouds floating undisturbed in the sky, although they are receiving substantial amounts of radiant energy from solar and terrestial sources. Perrie[2] reports that the solar radiation on an early morning fog will cause it to rise and, if the fog was originally sufficiently heavy, to float off as a cloud.

Briefly then, it may be possible either to conserve (for recovery at another time and place) or to dissipate clouds by the judicious use of heat. The result produced on the cloud may be determined by the amount, rate, and method in which the heat is applied.

II. APPLICATIONS

Some of the obvious and well known civilian applications for which this process of modifying weather may be practicable are:

1. To provide water for supplementary irrigation and domestic use.
2. To provide water to supplement hydroelectric power and land reclamation projects.
3. To suppress rain or eliminate cloud cover over a particular area for the benefit of outdoor functions such as athletic events, construction projects, etc.
4. To relieve drought or extended heat waves.

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[2] D. W. Perrie, Cloud Physics (John Wiley & Sons, Inc., New York, (1960).

5. To minimize flood crests by diverting rainfall from threatened areas.
6. To remove fog from airports and harbors.
7. To reduce smog concentrations over highly populated areas.

If the method is feasible, its practical utility will depend on suitable meteorological conditions, wind directions, reliable weather forecasting, and economic considerations. It currently appears that the cost of water produced by this method cannot compete with prices normally paid by domestic and industrial water users. The method is, therefore, probably limited to specialized types of applications. As discussed later, however, the limiting price will vary with the application and the existing conditions; and for many purposes the cost of water is only a small part of the overall economic problem.

A particular advantage of the process is that the cost depends primarily upon the cost of the heat required to lift the cloud and possibly to initiate the precipitation mechanisms, not necessarily on the horizontal distance the water must be transported.

III. ASSUMPTIONS

Several simplifying assumptions have been made in this preliminary discussion. Before the feasibility of the process can be assessed, it is clear that the validity and range of applicability of these assumptions must be tested experimentally. Such a test program may also reveal effects not included here. The principal assumptions made are:

1. A cloud consists of saturated air in which a large number of water droplets or ice particles, with dimensions of a few microns, are dispersed.
2. A cloud can be treated as an independent body suspended in the atmosphere. This assumption does not exclude a continuous exchange of water vapor between the cloud and the surrounding atmosphere or an exchange of air with other adjoining air parcels. Changes in the size and shape of

clouds can be tolerated, as can minor losses of precipitable water during treatment. In fact, for the conservation application, the complete dissipation of the cloud as a result of heating is permissible provided that the moisture will be available at the desired time and place and can be precipitated by further heating or by other means.

3. The effect of introducing heat at relatively high temperature into the cloud should not introduce undesired turbulence. Although clouds are relatively cold ($10^{o}C$ to $-4^{o}C$) at altitudes of interest and changes in the desired temperature are small (from a fraction of a degree to a few degrees), engineering considerations with convection-type equipment require that the transfer of heat into the cloud should be accomplished at significantly higher temperatures. The transfer of heat by a source of infrared radiation would minimize turbulence.
4. Since the over-all temperature difference between the rising cloud and the atmosphere is small, the heat losses to the surrounding atmosphere by conduction and radiation are assumed to be negligible or tolerably small. A necessary requirement may be that the cloud volume must be above a certain critical size for the cloud to maintain its integrity during the processing cycle.
5. The change in altitude of the cloud as a result of heating, if conservation is desired (i.e., if the moisture is to remain available for precipitation), does not significantly disturb the original atmospheric balance. That is, the normal atmospheric processes associated with its original height (such as diurnal heating or nocturnal cooling) do not detrimentally affect the stability of the cloud at the higher altitude during its period of travel.

6. There is a significant temperature gradient in a cloud of substantial height. It is assumed that this temperature gradient will remain nearly constant during the heating period and at the increased altitude of the processed cloud. This assumption does not admit of temperature inversions which may conceivably be encountered in actual practice.
7. Wind velocities vary in the different strata in which a large cloud resides or to which it may be lifted. In such cases, the processed cloud may subdivide into smaller units without significant loss of over-all cloud volume.

IV. THERMODYNAMICS

The optimum conditions for conservation exist when the cloud mass is (a) conditionally unstable, i.e., when the prevailing lapse rate of the surrounding atmosphere approaches, but does not equal, the saturated adiabatic lapse rate in the cloud; and (b) when the absolute humidity of the air in the cloud is high and there is a high concentration of free water.

Consider the case in which a stable increase in altitude of a cloud is desired. As heat is uniformly added, the cloud will rise and be cooled by expansion in the less dense atmosphere. Since the air in the cloud was initially saturated, some water vapor will condense, releasing latent heat and increasing the free water content of the cloud. The latent heat thus released reduces the heating required to maintain the desired temperature difference between the cloud and the surrounding atmosphere. The processing equipment should provide for uniform heat distribution to minimize conduction losses from the cloud to the atmosphere and to reduce the likelihood of initiating convection currents. The amount of heat required to increase the buoyancy of the cloud will vary inversely with the initial absolute humidity of the cloud and with the steepness of the prevailing lapse rate. As noted from Fig. 1, the absolute humidity[3] decreases with increasing altitude (because of decreasing temperature) so that the method normally is more effective for clouds at the lower altitudes. Figure 2 shows the rainfall pattern over the earth. It should be noted that many areas of heavy rainfall are over the oceans where the water is normally lost to man. These areas might serve as noncontroversial cloud farms to supply less fortunate areas.[4]

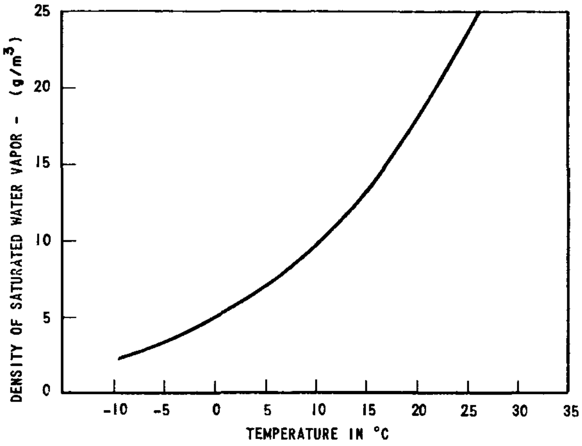

Fig. 1. Graph showing the relationship between temperature and density of saturated water (reference 3). Since the ambient temperature of the atmosphere falls with altitude, it can be seen that the potential amount of condensation decreases with altitude.

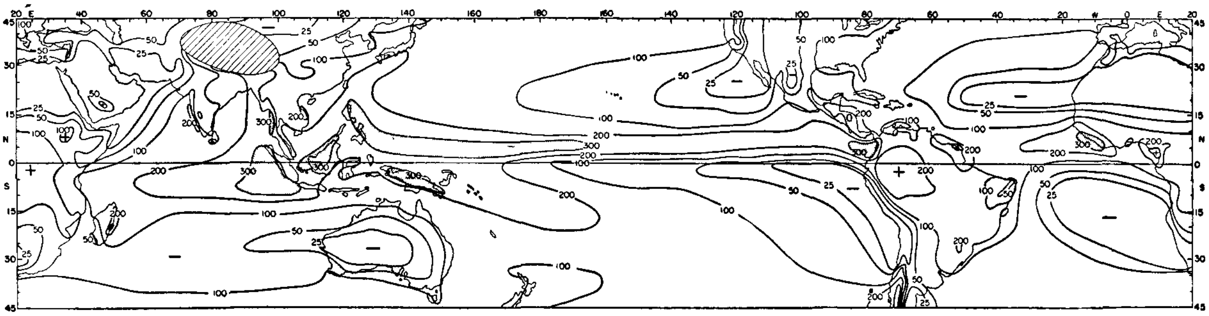

Fig. 2. Map showing the mean annual rainfall (cm) over the earth. Regions with more than 300 cm/year are shaded (reference 4).

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[3] H. L. Hackforth, Infrared Radiation (McGraw-Hill Book Co., New York, 1960).

[4] H. Riehl, Tropical Meteorology (McGraw-Hill Book Co., New York, 1954), p. 75.

V. DESIGN OF EQUIPMENT

Heat may be introduced into the cloud by various means, including systems transferring heat by direct convection or by infrared radiation. The development of detailed engineering designs and complete cost estimates for either system are premature at this time because of the lack of reliable meteorological data, but some fuel costs are estimated. The use of the convection system requires direct contact between the heating apparatus and the cloud mass so that the apparatus must be mobile (carried by a hovering-type aircraft or balloon) and moved with and in the cloud. It appears from published data that nuclear-powered subsonic winged aircraft could be designed and constructed although such aircraft have not yet been built. Small reactors have been installed and flown in winged aircraft. It can, therefore, be assumed that airborne reactors are practical heat sources for both aircraft propulsion (which is not essential) and for convection heating.

The space and weight requirements for the proposed heating system (nuclear) does not appear to be beyond the capability of present-day machines. A reactor having an output in the range of 2000 Mw of heat is probably as large as one would currently plan to use. If the reactor is designed to operate at a power density of 0.5 Mw/liter, its core would be about 2.3 m in diameter by 2.7 m long, a quite manageable size. This power density could be achieved in a reactor core designed to operate with thermal or near-thermal neutrons; the moderator could be either beryllium oxide or a metallic hydride; and the fuel elements might be concentric cylinders of enriched uranium clad with stainless steel. The total space required to house the reactor, reflector, shadow shielding, and associated equipment, and to accommodate the crew does not appear to be excessive.

A crude schematic diagram of a system using an indirect-cycle reactor (which uses liquid metal or fused salt as the primary coolant) for heating and propulsion is shown in Fig. 3. Gas turbines in sizes

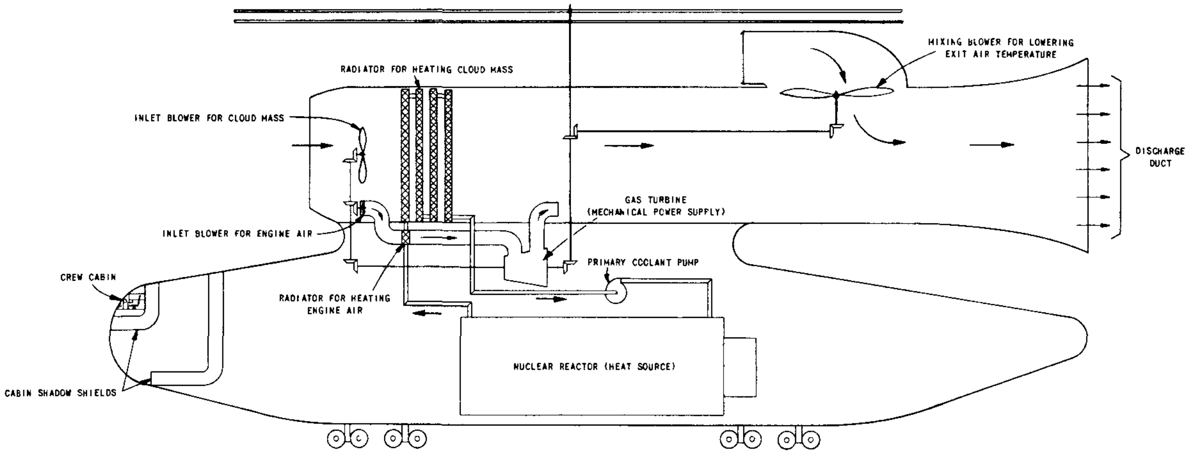

Fig. 3. Schematic drawing showing the layout of a hovering-type aircraft equipped with a nuclear heat source. The craft uses an indirect cycle in which a fluid is heated in the reactor and cooled in radiators by the moving cloud mass.

already built would be adequate to supply all of the blower capacity required to draw in and heat the cloud mass. Some modification may be required, however, in the compressor stages. Less than one-quarter of the reactor output is used in the propulsion system if nuclear heat is used, and the balance of the heat is dissipated through radiators. Most of the heat converted to mechanical energy in the turbine will eventually return to the cloud as heat. The gas temperature at the inlet to the turbines must be 850°C or above to give reasonable efficiencies, although reactor design is simpler at lower temperatures. Within limits, the exit temperature of the heated air can be controlled by dilution. If the cloud is to maintain its integrity, the exit temperature of the heated air should be kept as low as possible in order to avoid unstable conditions. On the other hand, if the purpose is to initiate precipitation the discharge temperature should be kept high enough to initiate convection currents and turbulence. The craft would be maneuvered in the cloud to achieve the heat distribution required. The problem of flying in turbulent air has to be considered.

The reactor would, of course, have to be remotely maintained. For safety of the populations in the areas involved, care must be taken to minimize the possibility of contaminating the cloud, and hence the water, by fission products released by fuel-element failure or by similar incidents. The possibility of an aircraft accident would probably restrict the operation of the machine to sparsely populated areas.

Fossil-fueled systems are probably more easily designed, but introduce problems in logistics, since large quantities of fuel must be delivered to the aircraft in flight and possibly to remote areas. Roughly 2000 Mw of heat output would require 180 tons of fuel oil per hour. The large quantities of water vapor and smoke particles released from the combustion of fuel may provide some fringe benefits since smoke particles may provide a source of condensation nuclei. However, the magnitude of this effect is not known.

Infrared energy sources are probably limited to fixed locations (or large surface vessels) because of the inherently large size and high temperature of the emitters if they are to radiate useful amounts of power. The heating period for a given cloud mass may be relatively short, since it is only the period of time the cloud can be tracked by the ground-based units. The emitters may be heated electrically or possibly by the primary fluid from high-temperature reactors. Application of the system to the dissipation of early morning fog around airports and harbors is favored by the lower cost of off-peak electric power.

The transmission of radiant energy from the ground to a distant cloud is inhibited by absorption in the transmission path. For the wavelengths of interest, this absorption is primarily due to the triatomic molecules (water vapor and carbon dioxide) in the atmosphere. Since atmospheric ozone is practically limited to a layer at an altitude of 23 km, it is not important to this process. It is, therefore, desirable to have the largest possible fraction of energy in the bands of low absorption in the atmosphere, namely, in the wavelength ranges 0.60—0.80, 0.95—1.08, 1.15—1.30, 1.52—1.75, 2.03—2.06, 2.10—2.35, 3.35—4.05, and 4.58—4.75 microns. If the distribution is moved too far toward shorter wavelengths, Raleigh scattering will cause loss from the beam; but in the region chosen it is unimportant. For radiation in these energy bands, the optimum source temperature is about 2200°K. However, reasonable efficiencies can be achieved with temperatures as low as 2000°K, at which construction and operating problems are simpler.

Figure 4 is a plot of the intensity of radiation as a function of

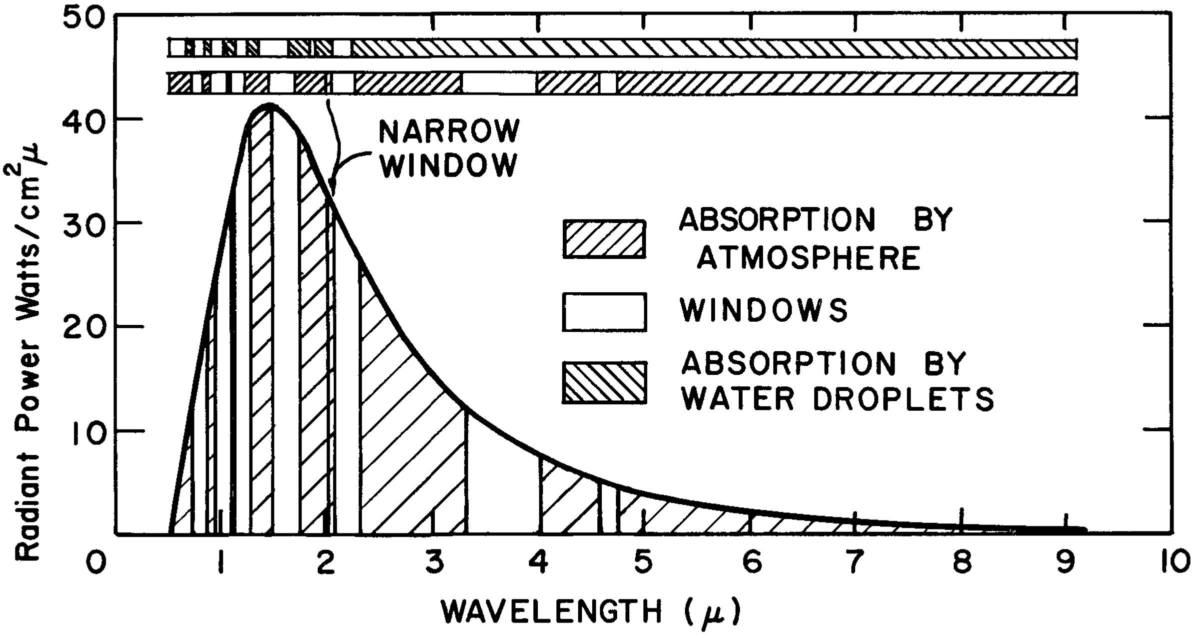

Fig. 4. Curve showing the energy spectrum emitted from a source at 2000°K. Wavelengths absorbed by the atmosphere are indicated by the shaded vertical bands under the curve. The energy in these bands constitute about 60% of the total. The wavelength bands passed by the atmosphere and by water droplets are compared above the curve. The absorption band shown for the water droplets does not include the effects of Mie scattering. The absorption data shown are approximations to give a rough quantitative picture of the absorption in a 20-km path. They were obtained by averaging the results of P. Moon, J. Franklin Inst. 230, 583 (1940); S. Fritz, Transactions of the Conference on Solar Energy 1 (University of Arizona Press, Tucson, 1955); and J. H. Taylor and H. W. Yates, J. Opt. Soc. Am. 47, 223 (1957).

wavelength for a blackbody source at 2000°K. At 2000°K, the total energy radiated from the surface of a blackbody is calculated from the Stefan-Boltzman equation to be 91 watts/cm^2. Over an assumed 20-km tracking distance, water vapor and CO_2 would completely absorb the energy indicated by cross hatching (about 60% of the radiated energy). If it is possible to use radiators that emit selectively in the transparent bands (or some of them), the over-all efficiency of transmission should be increased. Alternatively, it may be possible to use filters that absorb the same bands as the atmosphere and to recover some of the energy they absorb.

Since the radiation reaching the cloud will have been filtered by the triatomic molecules in the path of transmission (and possibly also by a filter at the source), little or no absorption will take place in the vapor phase of the cloud. The absorption bands of water droplets are also shown in Fig. 4. Normally, about half of the energy reaching the cloud would be absorbed by the water droplets, the rest passing on through. Actually, since there will be considerable Mie scattering in the clouds, the fraction absorbed will be closer to unity. (Byers[5] describes a layer of cloud more than 50 m thick as a "blackbody.")

The location of the heating apparatus with respect to natural obstructions should be selected to attain line-of-sight transmission from source to cloud for the longest possible time. The accuracy of the reflector system is not critical since the target will be relatively

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[5] H. R. Byers, General Meteorology (McGraw-Hill Book Co., New York, 1944), p 36.

large. Figure 5 shows a schematic arrangement of an unfiltered electrically heated reflector system.

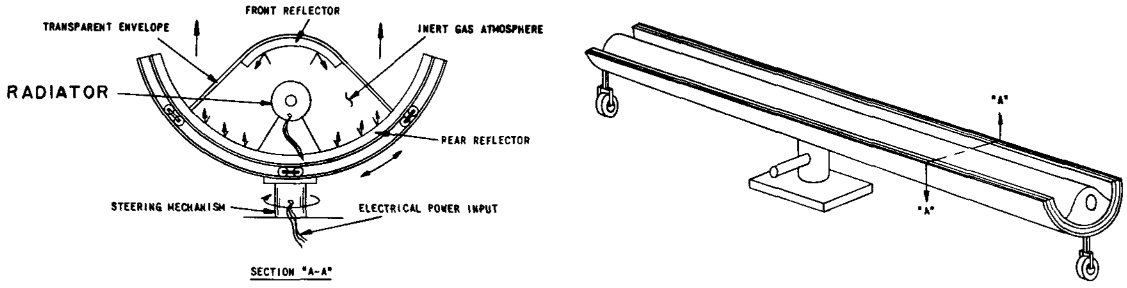

Fig. 5. Infrared source with cylindrical radiator and reflector. For efficient use of the energy, however, the reflector should be spherical or parabolic to give stigmatic focusing. AA', shown at the left of the figure, illustrates some construction features that would be included in the design of the infrared reflector system. The assembled reflector system, including the maneuverable features, is shown on the right.

VI. ILLUSTRATIVE PROBLEM

To illustrate some of the economic parameters characteristic of the process, let us consider the problem of supplying 2.5 cm of rainfall over an area of 100 km^2 (2.5×10^6 m^3 = 6.7×10^8 gal) in one day. Typical costs for water[1] are noted in Table I. In addition,

TABLE I. Average costs for water (as compiled in reference 1).

Water for irrigation	1 cent/1000 gallons ($3.24/acre foot)
Industrial water	2.5 cents per 1000 gallons
Household water	30 cents per 1000 gallons

the cost of transporting water on a large scale is estimated to be 5—15 cents per thousand gallons per hundred miles, the cost in a particular instance depending on the terrain. It should be noted that costs considerably higher than the averages cited in Table I can be economically acceptable. The tolerable cost of water would certainly be higher where the value of land would be substantially increased by a modest augmentation of the normal natural rainfall than in an area where all the water had to be imported. If the water can be used in sequence by several users, as is common practice among communities along rivers, the cost per user can be correspondingly reduced. Thus, economic considerations favor supplying rain to the headwaters of a natural drainage system instead of directly to a single user. A quite different, but no less economically valuable, application is the diversion of rainfall from an area threatened by flood.

It is proposed that a bank of clouds, which would normally yield their precipitation on the windward side of a mountain range, should be heated by air-borne reactors (Fig. 6) to raise them to a favorable air stratum for delivery to the lee side. It is assumed that the altitude of the clouds needs to be increased from 2.0 km where the ambient temperature is 3°C to 2.7 km where it is -0.5°C. It is further assumed that 3 cc of water can be precipitated from each cubic meter of cloud. Table II lists some values for precipitable water in clouds. In addition, the pre-

TABLE II. Observed liquid water content of cumulus-type clouds over New Jersey and Florida during the summer. [From the U.S.A.F. Handbook of Geophysics, Revised Edition (Macmillan Co., New York, 1961), p. 7-7].

Cloud type	Temperature (°C)	Water content (g/m^3)	
		Average	Maximum
Cumulus humilis	10 to 24	1.0	3.0
Cumulus congestus	3 to 11	2.0[a]	6.6
Cumulonimbus	10 to -8	2.5	10.0

[a] Estimated.

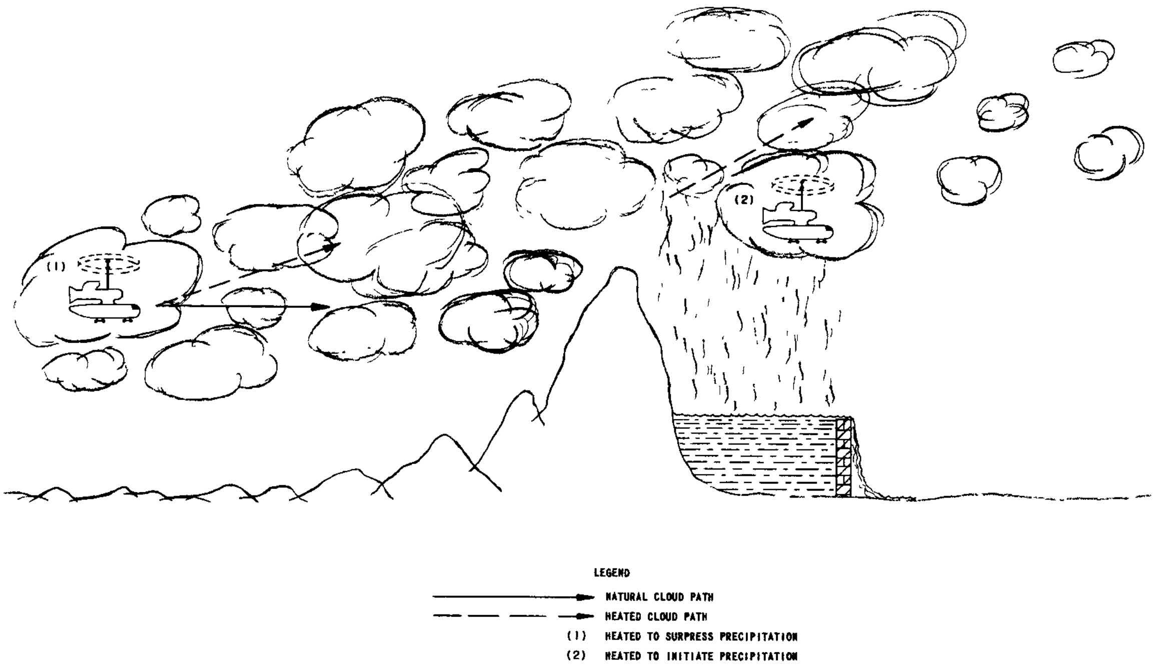

Fig. 6. Schematic drawing of a hovering-type aircraft as it applies heat to a cloud to cause it to rise gradually without turbulence and pass over a mountainous area. At some location down wind, precipitation is initiated by subjecting the cloud to rapid heating to establish convective currents within the cloud.

vailing lapse rate in the area is assumed to be 0.5°C per hundred meters and the saturated adiabatic lapse rate in the cloud is 0.6°C per hundred meters. Thus, the cloud must be warmed 0.7°C to lift it 700 m. The heat required to initiate precipitation when the cloud reaches the desired site is arbitrarily assumed, for lack of a better value, to be half the amount required to raise the cloud under stable conditions. Of course, other potential precipitation methods now being investigated (such as seeding clouds with hygroscopic nuclei or by electrically charging the water droplets) may turn out to be more economically desirable.

The cost analysis is summarized in Table III. For the sake of convenience, cloud masses are measured in cloud units. A unit of cloud is arbitrarily defined as a volume 1 km in diameter and 1 km long (7.8×10^{8} m^{3}). The actual cloud may consist of a fraction of a unit or of several units. The calculations indicate that 450 cloud units are needed and will require 8×10^{4} Mw-hr of heat for lifting. If the heating is to be performed within a 24-hr day, then two 2000-Mw air-borne heat sources are required. One source will be required at a later time to supply the heat (4×10^{4} Mw-hr) to cause precipitation over the desired area. A total of 1.2×10^{5} Mw-hr of heat is, therefore, required.

If the cost of nuclear fuel is assumed to be $0.001/kw-hr, which can be attained currently in stationary reactors, the total cost of heat is $120 000 and the unit cost is 20 cents per 1000 gallons. The cost of the aircraft (including operation, maintenance, depreciation, and other indirect costs) is not estimated, although this is an essential factor in determining the economic feasibility of the method.

VII. CONCLUSIONS

The purpose of this paper is to invite attention to a possible method for modifying and controlling weather. It is concluded that the process offers sufficient promise to warrant further study.

It is clear that an experimental program is required to determine the validity and limits of applicability of the assumptions, to demonstrate the feasibility of the process, and to establish cost data for specific locations and applications. Preliminary data to demonstrate the feasibility of the process should be obtainable from modest experiments.

TABLE III. Economics of weather modification.

1. Assumptions for calculations	
Average altitude, initial	2.0 km
final	2.7 km
Prevailing lapse rate	0.5°C/100 m
Saturated adiabatic lapse rate in cloud	0.6°C/100 m
Ambient temperature at 2.0 km	3°C
2. Assumptions per unit of cloud	
Diameter	1000 m
Length	1000 m
Volume	7.8×10^8 m^3
Average density at altitude of 2.0 to 2.7 km	1.1 kg/m^3
Mass	8.6×10^8 kg
Available water	3 cc/m^3
Total available water	2.3×10^3 m^3
Specific heat of cloud (c_p)	250 cal/°C-kg
Heat required to maintain one unit of cloud at ambient temperature during rise	1.5×10^{11} cal
Cloud units required per day	450
Total heat required to elevate cloud to travel lane	8×10^4 Mw-hr
Heat required to initiate precipitation	4×10^4 Mw-hr
Total heat required to deliver water	1.2×10^5 Mw-hr