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Zusammenfassung

Es wird untersucht, ob eine zwischen zwei feststehenden Platten schwingende Scheibe als Gerät für die Absolutmessung der Zähigkeit von Flüssigkeiten benutzt werden kann. Die dafür bestehenden Theorien, bei denen die Viskosität aus dem logarithmischen Dekrement der Schwingung berechnet wird, sind hier durch die Berücksichtigung der Randeffekte erweitert worden, unter der Voraussetzung, dass der Abstand zwischen den beiden feststehenden Platten klein ist im Verhältnis zum Radius der Scheibe und zur Grenzschichtdicke. Die Theorie stimmt mit den von KESTIN und PILARCZYK experimentell gefundenen Werten auf 0,1% genau überein.

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The Seeding of Cumulus Clouds by Ground-Based Silver Iodide Generators[1]

By VINCENT J. SCHAEFER, Schenectady, N. Y.[2]),
and JOHN H. DIETERICH, Missoula, Mont.[3]), USA.

The control of thunderstorms is a challenging objective in experimental meteorology. For the past five years it has been the long-range goal of Project Skyfire [1][4]).

The lightning storm season in western Montana, northern Idaho, eastern Oregon and Washington normally extends from June to September with the greatest storm intensity occurring in July and August. Over the past twenty year period approximately 70% of all fires occurring in the forests of the northwestern United States were caused by lightning. In 1948 a start was made toward a study of these storms by SCHAEFER and GISBORNE [2]. In 1952 seven time lapse cameras were installed on mountain summits of the Northwest to obtain visual records of the types of storms which occur during the summer

1) Paper presented at 163rd National Meeting, American Meteorological Society, New York City, January 27–30, 1958.
2) The Munitalp Foundation, Inc. of Hartford, Conn., and Nairobi, Kenya.
3) The US. Forest Service, Intermountain Forest and Range Experiment Station.
4) Numbers in brackets refer to References, page 187.

period [3]. Fire lookout towers such as shown in Figure 1 were used for this purpose. The following year lookout observers manning a network of 25 mountain tops in that area attended the first of a series of cloud survey schools sponsored by the US. Forest Service and the Munitalp Foundation [4]. The daily reports of cloud and storm patterns radioed to headquarters of Project Skyfire laid the foundation for a better understanding of the nature of the lightning storm problem in that area.

Although this five-year study established that certain areas were likely to generate storms at specific locations, it also served to emphasize the great variability of storminess and the complexity of the storm types which occurred across the area.

The studies made during the five-year Skyfire cloud and storm survey clearly show the great difficulties which would accompany an attempt to use a purely statistical approach toward establishing the success or failure of cloud seeding techniques for moderating lightning storms. To have any chance for valid results, a statistical program must be based on the premise that a sufficient number of 'pairs' occur which can be treated and untreated for comparative testing.

Highly variable weather conditions and the occurrence of several types of thunderstorms makes it difficult to obtain a number of 'pairs' which are similar in basic characteristics. Therefore, in the 1957 Project Skyfire program, it was decided to carry out experimental cloud seeding on each day meeting operational specifications and to study these results in relation to unseeded conditions in surrounding areas. This approach would broaden the experience in experimental cloud seeding and would provide basic information for the design of future research.

The test area consisted of a pie-shaped region covering about a thousand square miles extending about 50 miles northeast of the Montana-Idaho border with its apex in the vicinity of Lolo Pass in the Bitterroot Mountains as depicted in Figure 2. This area in turn is embedded in the much larger Skyfire network illustrated in Figure 3.

Initial studies of this area were made in August 1956 [5]. Although the mountains and valleys in this area comprise a highly complex terrain, a definite behavior pattern became apparent after a month of field observations and activities.

Based on these observations and experiences, a program was laid out for the 1957 season centered about an assembly of 30 silver iodide ground generators designed by WELLS and FUQUAY [6]. These were placed at 1/2 mile intervals in the form of a cross. By operating those located along the southwest-northeast line, a narrow silver iodide plume of high concentration could be generated. The generators on the northwest-southeast legs on the other hand produced a much wider plume of lower concentration. With such an arrangement a great variety of tests could be made. In addition to producing wide and narrow plumes of relatively high concentration, the effect produced by all thirty generators could be studied as well as that caused by a single one.

By late July it had been firmly established that, although most of the generators were located near the top of a mountain ridge, little silver iodide would be carried aloft until after 11 o'clock in the morning. Previous to this time of the day, the effluent would be carried by drainage winds into the deep valleys extending to the southwest and northeast of the generator lines. This phenomenon might be exploited when fully understood. By operating the generators continuously during the night and early morning hours, large masses of valley air might be loaded with nuclei so that, as thermals develop, the cloud area infected by the generators would extend over a much larger zone; including areas ten or more miles in the direction which would ordinarily be considered upwind of the generator site.

The objective of the 1957 season was directed toward determining the degree of lightning suppression (if any) which might be achieved through cloud seeding operations. Previous studies during the summer months in the northwest had established that the concentration of natural ice nuclei at temperatures warmer than $-20°C$ was either very low or undetectable. These determinations were made, using both surface and airborne cold chambers and by watching supercooled clouds in the area. Except in extremely rare instances, evidence of ice crystals in clouds never was observed until the clouds subcooled to at least $-20°C$. Consequently, the primary objective of the 1957 field program was the determination of whether or not clouds could be consistently nucleated on a massive scale within the test area as contrasted to the adjacent regions. The two small aircraft available to the project were to be used for aerial temperature and moisture sounding of the atmosphere, plume tracing, determining the temperature of cloud tops and bases, the concentration of natural ice nuclei, the behavior of clouds in regions beyond the test area and the degree of thermal activity over and downwind of the generator sites throughout the day.

Project Skyfire Field Activities on an Operational Day

In order to acquire sufficient quantitative data for analytical use in evaluating the results of the seeding of cumulus clouds from ground-based generators, a considerable amount of organizational planning and activity was necessary. A typical day's operation involved the field activity of twelve to fifteen persons. About half of the field staff had a scientific background, the rest being students near or at post-graduate level.

Sounding Flight

The first activity of the day involved an atmospheric sounding flight using a single engined monoplane, the Cessna 180. A recording aerograph was flown to an altitude of 16000 ft shortly after sunrise. The data from this flight was immediately transcribed and in addition a report was made of the condition of the sky in the general area of the test region. This information was then turned over to the forecaster.

Weather Forecast

At about 08·00 M.S.T. a special forecast for the day was completed. This was based on standard weather reports including facsimile weather maps and special local weather data such as obtained by the sounding flight of the previous hour and a special pilot balloon observation made in the center of the test area at about the time the sounding flight was being made. This was obtained by the field crew charged with operating the silver iodide ground generators. This information was supplemented by wet and dry bulb observations made at a group of mountain-top fire lookout stations scattered throughout the area and sent in by radio and telephone as the day's forecast was being prepared.

Based on this information, an hour-by-hour forecast was prepared. This information was presented in schematic form and showed the probable cloud bases and heights likely to occur during the day, the location of the freezing level, the $-4°$C level (where the first effects of silver iodide would occur) and the $-39°$C level (where spontaneous nucleation occurs). The presentation also showed the temperature with height profile, and the wind velocities and directions to be expected. It also included a brief forecast for the area and the location of the major axis of the nearest jet stream.

The forecaster also prepared a summary of the cloud development which occurred on the previous day, the precipitation and the lightning storm activity as reported by the nearly 100 fire weather stations scattered throughout the mountain area and the 22 Project Skyfire special fire lookout stations.

Briefing for the Day's Operation

At 08.15, the project leaders gathered at the airport for a briefing. If the forecast was favorable for an operational day, the project leaders checked over their duties, supplies, the manpower available and, after agreeing on the procedures to follow, departed for their respective observation posts. Since cumulus clouds in the test area rarely formed before 11.30 and the trip to the various locations required about an hour of driving, it was quite feasible to have the posts manned and all observational equipment operating before cumulus activity was underway. At the end of the briefing, word was also sent by telephone to the generator operations crew so they could arrange their activity to fit into the day's schedule.

Manning of Observation Sites

About 11.30, all posts were in operational order. As each station was set up, the word was transmitted by radio to the control station so the individual charged with coordinating activities knew that proper observational data would be obtained. During most of the 1957 field season, the control site was located at West Fork Butte L.O. where both radio and telephone ground line were available. This site is shown in Figure 4. With the latest field information available on the current weather and seeing the condition of the sky, the controller then telephoned the flight crew, who were in standby status, and instructed them on take-off schedule and operational procedure. At this time, the flight observer was given a rough schedule for his operation. This would be supplemented by radio instructions during the flight in the area.

Exploratory Flight Operations

During each operational day, plans called for an exploratory flight during the active part of the day. The Cessna 180 would be flown to the test area, following instructions telephoned from the control site. Ordinarily, the flight was called for when the first small cumulus clouds appeared in the area. Upon take-off, the plane would be headed for the region above the generator lines, climbing as it traveled. In this manner, when that area was reached, the plane would be close to cloud base altitude. The temperature and height at cloud base would be measured and this information relayed to the control station where it was checked against the forecast. Information on up-drafts was also given by the pilot and observer. The plane crew was then released for a period, to attempt to survey the location of the plume of silver iodide particles rising from the ground generators. Measurements were made with a light, portable, cold chamber, samples being taken both in the vicinity of the generators and in areas beyond possible influence of the generators, the latter observations being made to establish the background level of natural ice-forming nuclei in the air which might also modify the clouds, if present in sufficient concentration. The silver iodide plume boundary was generally established by sampling the convective air immediately downwind of the generator line and in similar locations and altitudes farther downwind. After the nuclei observations were completed, the plane was then flown into the test area and observations made of cloud-top elevations and temperatures. In addition, the observer was often requested to determine the nature of the clouds, using optical effects or taking samples of glaciation, virga or precipitation. They might also be requested to survey and report on the behavior of clouds in areas adjacent to the test region and beyond the possible influence of the silver iodide emitted by the ground generators. Occasionally the plane was utilized to do some localized seeding, using either an airborne silver iodide generator or small quantities of dry ice.

The use of the Cessna 180 proved to be eminently satisfactory. Not a single case of difficulty was encountered due to malfunction of the aircraft. Whenever a flight was needed, it was available; and by flying the plane properly, it was found to be eminently satisfactory for scouting, sounding, seeding and general observational use below 20000 ft.

The Use of Time Lapse Cameras

The time lapse camera provides one of the best possible records of the reactions which occur during an operational day. A number of such cameras were used, including a pair of full sky cameras for making triangulation measurements of cloud position, an extreme wide angle camera (84°) for covering most of the test area and the adjacent regions, and several ordinary time lapse cameras with 9·5 mm, 17 mm and 25 mm focal lengths. These were used to obtain detailed observations of reactions occurring in the test area. In a number of instances it was possible to orient the camera so that it included both the plume area and the region adjacent to it. In this manner both seeded and unseeded clouds appeared in the same sequences. Two-second interval periods were used for the reaction studies, 60 to 120 s intervals for the full sky and 84° horizon came as.

The Use of Still Cameras

While rate of growth and cloud location data could be obtained from the time lapse cameras, the 16 mm pictures are too small for illustrative use and ready reference. A group of still cameras were used for this purpose, including 35 mm color cameras, specially constructed panoramic cameras providing about 90° of the horizon on a film $2^1/_4'' \times 6''$, several $4'' \times 5''$ press cameras and a $3^1/_4'' \times 4^1/_4''$ Land Polaroid Camera. This latter camera was used extensively to provide a current record of the typical clouds and effects observed during the active part of the day. The photographs obtained with this camera were used to illustrate the log obtained at the control site and proved to be extremely useful in post-briefing discussions of the operation and for classifying the general nature of the operational day.

The Use of a Mobile Radar Unit

About $9^1/_2$ miles NNW of the control site at West Fork Butte, a mobile radar unit was located on the peak of a grass-covered knob near the top of a long narrow ridge close to the northern edge of the test area. This was an APS-2 10 cm aircraft radar, modified so it could be controlled from within a small 14 ft house trailer. A retractable plastic dome made it weather proof. A time lapse camera photographed a slave scope and related clock, elevation indicator and title board. This radar was activated by portable generators and was operated whenever there were suitable clouds within sixty miles of the area.

The Use of Cloud Theodolites

During the period of 11.30–14.30, which was generally the most active part of the day, cloud growth studies were often made, using cloud theodolites [7]. In addition to rate of growth studies, the exact location and elevation of cloud base and top were determined, using azimuths obtained from control and radar sites. An accurate field map at each site permitted the observers to triangulate the cloud and thus have current information on the cloud behavior, probable temperatures and the likelihood of it being affected by the plume from the silver iodide ground generators.

The Release of Free Lift and Zero Lift Balloons

During the course of an operational day, and especially during the period of initial cloud activity, a number of small 30 g balloons were launched from the several field stations. These were used to determine air motions both in terms of local trajectories and the presence or lack of convective movements.

The balanced or zero lift ballon was particularly useful at the generator site, especially when the lines were first operated. A 30 g balloon was inflated with helium or hydrogen and then weighted with a small tree branch. Twigs or leaves were then removed until the balloon showed just a trace of buoyancy. It was then released and followed by theodolite or binoculars until lost to view. Ordinarily, the balloon could be followed for seven to ten minutes, if convection was underway. Earlier in the day, if drainage winds were dominant, the balloon would either remain near the release point or would quickly be lost from view as it moved down into the valley.

If, at either the control or radar site, the local winds or cloud motions showed a considerable variation from the forecast, a 30 or 100 g free balloon would be released and a pilot-balloon run made to determine any changes which had occurred in the wind field.

Occasionally zero lift balloons were released from the radar site and followed by a 1 m range finder. This method was found to be very useful and extremely easy to accomplish, especially when a thin strip of 1/2″ wide 0·001″ thick aluminium foil was used as the weight. The sparkling foil was an ideal object for obtaining an accurate fix on the balloon location.

The Use of a Tethered Balloon or Kite for Local Wind Observations

Since the wind field in a mountainous area follows an extremely complex pattern and modifications occur quite frequently, experiments were conducted to determine if a method could be devised for making continuous observations.

A 500 g balloon was tethered by nylon cord with smaller balloons on 10 m strings placed at 100 m intervals along the cord. This method provided very good indications of the air motions under conditions of light winds. However, as the wind increased with altitude, the balloon tended to lay over more and more until its usefulness was nullified.

A few experiments with a box kite indicated that such a device would solve this problem. The stronger the wind, the higher such a kite climbs, so that it is quite possible the air motions at least to cloud base could be continuously observed. Small balloons or streamers of different color placed at 200 m spacings would provide indications of the local wind field. Not enough time was available to develop this technique, but it would provide extremely useful data, if successful.

Observations of Local Weather

At each location hourly weather observations were made. These included wet and dry bulb temperatures, wind velocity and direction, condition of the sky, amount and distribution of cloudiness, location and number of lightning strokes, if any, storm tracks and precipitation.

If any special changes occurred between the regular observation periods, these were included in the records. Time of appearance and location of the first cumulus clouds, the first glaciation, virga, precipitation and lightning were also noted.

Observations of Atmospheric Electricity

During the 1957 operation, the main emphasis of the field operation was directed toward the development of adequate observational techniques, to obtain sufficiently detailed records for reconstructing changes which occurred in the clouds over the test area and the immediately adjacent regions, to permit an objective evaluation of cloud modification effects. Although the subject of atmospheric electricity was given a high priority listing, it was not feasible to get the necessary field installations in time for the field operations. Some corona current measurements were obtained from time to time [8]. The results merely emphasized the importance of such measurements and the interesting effects which could be obtained if suitable instrumentation were available. This activity resulted in the decision to pay particular attention to this subject during the 1958 field season.

Data Collection

For each operational day a mass of data was accumulated. To keep this information in order and to make sure that adequate records were being obtained, a folder was prepared for each active day's operation. A check list fastened to the outer cover indicated the completeness of the file. A certain degree of lag in completing the file was inevitable, especially with respect to the photographic records. However – by using nonoperational days to work up some of the current data, the individuals charged with conducting the analysis quickly discovered the importance of closing the gaps and keeping their own contributions up to date. This helped a great deal in having good data for the arduous job of evaluation which was carried out for several months after the field operations ended.

Based on these studies, a number of forms were developed to greatly simplify data recording. These forms not only improved the reporting results but served to insure that the data obtained included the information necessary for satisfactory evaluation operations.

Conclusions

The results of the 1957 field season were highly encouraging [9]. From the field experiences emerged a much better understanding of atmospheric behavior in the northern Rockies. As this knowledge increased we found it possible to anticipate certain reactions and to recognize unique effects which might possibly become as important to the field experimentalist in meteorology as the rain gauge and stream flow measurements are to the flood forecaster and hydrologist.

In previous years attempts have been made to tag and trace air parcels with aerosols made of fluorescent powder [10]. Silver iodide is a far more sensitive and effective substance [11]. It is entirely feasible to produce at least 10^{16} detectable particles from 1 g of material. As experience is gained of the unique effects caused by the introduction of silver iodide into subcooled clouds, it will probably become unnecessary to establish its presence by any other means than the unusual visible changes which occur in them.

The 1957 results of Project Skyfire showed conclusively that it is quite feasible to introduce enough silver iodide into cumulus clouds by suitably located silver iodide ground based generators to produce unnatural effects where-ever the clouds were colder than $-4°C$. The complete change from subcooled cloud droplets to masses of ice crystals occurs rapidly and produces spectacular changes. These are three basic changes commonly seen in clouds being modified by silver iodide. The first effect is the glaciation of the edges as shown in Figure 5. This is observed at the dissipating edges of the clouds. If ice crystals have not formed in these portions, the fringes disappear by evaporation within 60 s, often in a third of that time. If ice crystals have formed, the fringes persist for many minutes as fuzzy diffuse areas of ice crystals forming false cirrus clouds. Optical effects due to the ice crystals are rarely seen.

The second effect which follows the initial glaciation is illustrated in Figure 6. If the cloud base is near the 0°C level 13,000 to 15,000 ft. M.S.L. (of frequent occurrence in the northern Rockies), the shift to ice crystals is often noticed to begin at the bottom of the cloud and progress upwards until the entire cloud has turned to a mass of ice crystals. Natural clouds tend to show the change to ice crystals at the top, the base rarely, if ever, showing this change in phase. The illustration is an excellent example of natural and unnatural effects, since the silver iodide plume causing the change of the middle cloud was from a narrow stream of silver iodide diverted by a local wind shift from a plume whose major axis was at right angles to this local wind development.

The third effect is illustrated in Figure 7 which is essentially an extended phase of the effect shown in Figure 6. In this case a sustained thermal forms a cloud over an active cloud breeding spot. In addition to carrying moisture upward and into the cloud base, silver iodide is also in the rising air. As the cloud droplets subcool to about $-5°$C, ice crystals form and grow at the expense of the cloud droplets. Depending on the concentration of silver iodide carried into the clouds, the ice crystals which form on the iodide particles either immediately use up all of the available moisture, or, if the concentration is low, the crystals which form sweep up some of the droplets to form soft hail or snow pellets (Graupel). Figure 8 illustrates an excellent example of changes in cloud structure due to seeding from ground-based generators.

By shifting clouds to ice crystals continuously at an early stage of their development, as rarely happens under natural conditions, it is hoped that the charge separation process which leads to lightning generation may be disrupted or at least modified to the extent the cloud-to-ground strikes are reduced or prevented. Whether this will be the direction that will be successfull in achieving lightning storm modification can only be answered by additional studies. Besides studying changes in the nature of the cloud particles, more study of the electrical effects occurring in natural and seeded clouds is needed. The 1958 Skyfire program is directed toward obtaining data on the electrical properties of both seeded and unseeded clouds.

Acknowledgments

The authors whish to express their sincere thanks to all personnel associated with Project Skyfire for the cooperation they invariably enjoyed from all while they operated the control station on West Fork Butte during the 1957 field season. Appreciation is also extended to Pat and Roy Carlson, who were the fire lookouts on the mountain, and the personnel of the Lolo Ranger District for the many ways in which they made the job easier.

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Zusammenfassung

Während den Monaten Juli und August 1957 sind 30 AgI-Bodengeneratoren, die bei einem gegenseitigen Abstand von einer halben Meile in zwei gekreuzten Reihen auf einem hohen Kamm der Bitterrooth Mountains längs der Grenze Montana-Idaho angeordnet waren, eingesetzt worden, um das Ausmass der Veränderungen zu erforschen, welches erreicht werden kann, wenn unterkühlte Wolken mit Silberjodid-Rauch beschickt werden.

Auffallende Veränderungen sind wahrgenommen worden, wenn der Generatorenrauch Kumuluswolken verschiedener Grösse erreichte. Die Wirkungen sind von der Leitstation des Projekts Skyfire auf West Fork Butte aus beobachtet und im Lichtbild von den Autoren, die während des ganzen Sommerprogrammes des Skyfire-Projektes den Posten betreuten, festgehalten worden. Die Lage der AgI-Fahnen ist einerseits durch Verwendung von Pilot- und Schwebeballonen, die von den Generatoren aus gestartet wurden, und andererseits durch den Einsatz von tragbaren Kühlkammern, die im Auto oder Flugzeug transportiert wurden, ermittelt worden. Die Ergebnisse der AgI-Impfungen sind derart ungewöhnlich, dass erwartet werden kann, weitere Studien würden die Möglichkeit erschliessen, durch die Beobachtung der tatsächlich sich einstellenden Veränderungen an Wolken, die Rauchfahne örtlich festzulegen, insbesondere wenn die Wolken klein und nicht kälter als $-10°C$ sind.

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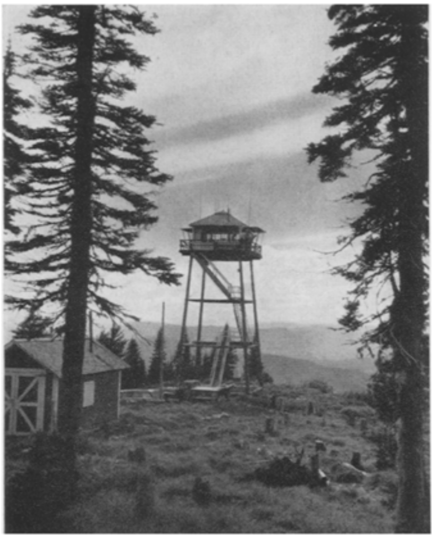

Figure 1
Forest fire lookout cooperating with Project Skyfire. Gisborne Mt. L. O., Idaho.

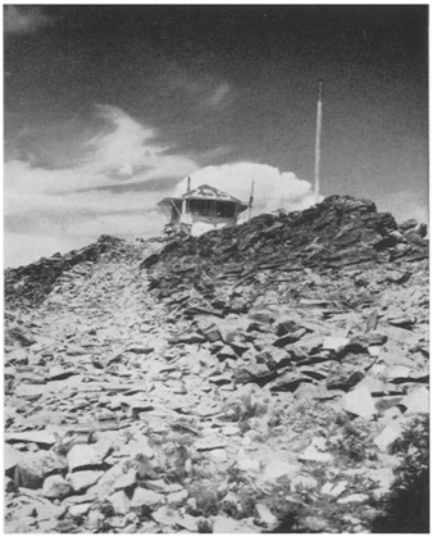

Figure 4
West Fork Butte L. O. Site of 1957 control station of Project Skyfire.

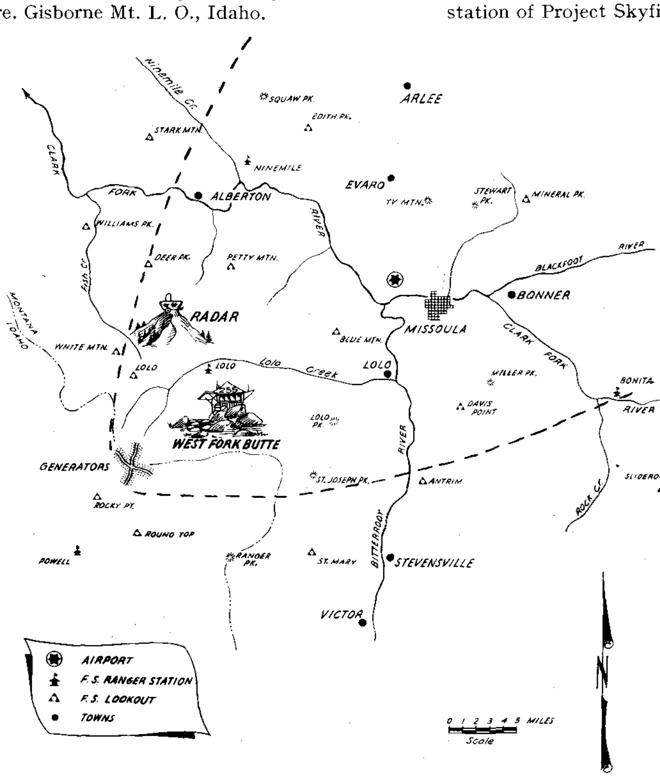

Figure 2
Location of Project Skyfire test area in Western Montana.

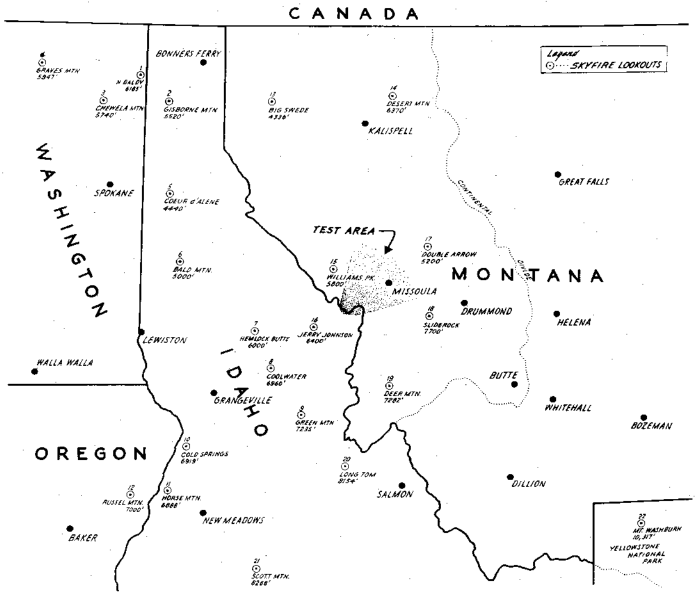

Figure 3
Location of test area with respect to Project Skyfire cloud observation lookout-stations.

Figure 5
Initial modification of supercooled cloud by silver iodide – the ice halo or glaciation halo effect. Note unaffected cloud beyond edge of plume.

Figure 6

Effect produced in a cloud by silver iodide. A narrow finger of the plume reached the center cloud without modifying the clouds on either side. August 22, 1957.

Figure 7

Major effect caused in cloud due to silver iodide seeding by ground generator. August 22, 1957.

Figure 8
Typical example of effective cumulus cloud seeding observed during a Project Skyfire operation.