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Simulated rockets and a system of collection plates were constructed for use in supercooled fog in an attempt to determine the efficiency of liquid nitrogen and silver iodide in producing ice crystals. An experiment comparing the efficiency of ice nuclei formation of a silver iodide "warhead" and silver iodide impregnated gunpowder string was also conducted using an ice nuclei counter.

Liquid nitrogen is capable of producing ice crystals as long as the temperature of the cloud is below 0°C. The threshold temperature of silver iodide for converting supercooled droplets to ice crystals is -5°C. Supercooled fog

with the required -5°C temperature was not encountered during the experiments so that ice crystal data for the silver iodide warhead could not be collected.

The number of ice nuclei produced with the silver iodide warhead was significantly greater than the same quantity of silver iodide impregnated gunpowder string when ignited. Liquid nitrogen was effective in producing ice crystals, but considering cost and handling problems, the efficiency is reduced.

EFFICIENCY OF METHODS OF PRODUCING ICE CRYSTALS IN SUPERCOOLED CLOUDS

by

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The growth of ice crystals in the atmosphere is one of the marvels of nature (1, p. 47).

EFFICIENCY OF METHODS OF PRODUCING ICE CRYSTALS IN SUPERCOOLED CLOUDS

CHAPTER I

Introduction

Methods of cloud and weather modification vary from sympathetic magic, such as the Indian rain-dance, to the more scientific approach of cloud seeding with silver iodide. The effectiveness of either the older or newer approaches is still open to debate. I undertook this thesis in an attempt to answer some of the questions of cloud modification concerning the efficiency of methods of producing ice crystals in supercooled clouds.

Ice crystal formation is important in clouds consisting entirely of supercooled liquid droplets above the freezing level. In order for the Bergeron-Findeisen precipitation process to begin, ice crystals and supercooled liquid droplets must both exist in the cloud. The condensation-coalescence precipitation theory is not relevant in this study.

There are many techniques available to convert supercooled droplets into ice crystals. Experimenters have dropped dry ice from aircraft with successful results. The more common procedure is the use of a ground-based silver iodide smoke generator of some type. Small rockets have had limited use as a tool to modify the clouds. I simulated the rocket approach in this thesis to determine ice crystal production efficiency.

The use of silver iodide rockets for cloud modification was started in November 1950 in France (10). Prior to this time, rockets without silver iodide warheads were used. The purpose was to reduce hailfall by obtaining intense rainfall in limited areas, which reportedly was achieved. Success was also reported in Longkloof, South Africa (9, p. 4352): "In a matter of minutes after rockets are fired, harmless rain falls from menacing hail clouds". However, data from balloon-bomb experiments with silver iodide at Kongwa, Tanganyika Territory, Africa, showed a decrease in precipitation on seeding days(4, p. 13).

Two methods will lead to freezing or crystallization of a supercooled droplet. The first method consists of cooling the droplets below their spontaneous freezing point. I investigated the efficiency of liquid nitrogen as a cooling agent in this study. The second method to produce ice crystals is the use of substances that are effective as ice nuclei. The use of silver iodide is common in this respect, and I used it in this study.

CHAPTER II

Theoretical Considerations

The successful modification of the weather depends to a great extent on understanding how natural changes occur. It is generally accepted that the Bergeron-Findeisen precipitation theory (6, p. 41-42) is the mechanism producing rain in clouds extending above the freezing level. This theory is based on the fact that at temperatures below freezing, the saturation vapor pressure over ice is less than over water. Therefore, in a cloud containing ice crystals and supercooled water droplets, there will be a vapor pressure gradient from the water drops toward the ice crystals. The ice crystals then grow at the expense of the water droplets and eventually grow large enough to fall as precipitation.

Supercooled water clouds have been observed at temperatures as low as -40°C. Schaefer (13, p. 225-226) has shown that the spontaneous freezing of supercooled cloud droplets to ice crystals takes place near -40°C. In January and February 1962, Schaefer (15, p. 48) substantiated this temperature in observations made at Yellowstone Park at temperatures above and below -40°C.

Therefore, a logical approach to convert some supercooled droplets to ice crystals is to cool part of the cloud below -39°C. The use of one gram of dry ice as the cooling agent could generate 10^{16} ice crystals (13, p. 230) if the air is colder than 0°C and supersaturated with respect to ice. Since dry ice vaporizes at -78.5°C and liquid nitrogen boils at -195.8°C, it would appear that the latter element should produce a large number of ice crystals.

Ground-based silver iodide smoke generators have had widespread use in cloud seeding. The theory behind their use is based on the occurrence of natural ice nuclei that produce ice crystals. An ice nucleus is any substance that serves as a nucleus in the formation of ice crystals. Vonnegut (16, p. 593) found that when silver iodide is vaporized, many submicroscopic silver iodide particles are formed. He theorized that 1 gram of silver iodide would produce 10^{14} ice nuclei at -15°C. Laboratory tests with various substances have shown that silver iodide, having a threshold temperature of -5°C, is the most effective substance presently known in producing ice crystals in supercooled clouds.

The precise mechanism by which silver iodide acts to form an ice crystal is still not certain. Vonnegut (17, p. 276) attributed the effectiveness to the fact that silver iodide and ice have the same hexagonal crystal structure. However, Hosler (8, p. 15) demonstrated that conversion of supercooled clouds to ice clouds is possible with substances that do not have the hexagonal crystal structure. Therefore, it seems that the hexagonal crystal shape is not a necessary condition. All of the chemicals used by Hosler consisted of large polarizable ions or molecules. Therefore, if a thin film of water molecules formed on the silver iodide particle, an ice-like structure would be formed. Since silver iodide is highly polarizable,this reduces the surface energy , allowing freezing to occur. Continued growth of the crystal is then by direct growth of the ice phase.

Rockets were first used in cloud modification with the idea that the effect of the explosion of the warhead would initiate a pressure wave that would cause precipitation. However, Sanger and Spring (12) demonstrated in experiments carried out in Switzerland that there is no apparent effect on the weather due to the explosive warhead. The addition of silver iodide to the black gunpowder warhead gives promise of an effective method of producing ice crystals in supercooled clouds.

The rocket insures that the seeding agent reaches the cloud regions where the ice nuclei can become effective. Ground-based generators do not have this positive feature, since they require some type of convection to carry the ice nuclei up into the supercooled cloud area. Because of this, present verification of the effectiveness of cloud seeding on precipitation increase is generally not statistically significant (5, p. 579). Elliott (5, p. 580) showed the role of air-mass stability in precipitation and cloud-seeding with data from the Santa Barbara Weather Modification Project. He divided the data into stable and unstable cases. The stable cases showed no apparent difference between the seeded and non-seeded rates while the unstable cases showed a much greater precipitation rate over the non-seeded rates. The silver iodide rocket could prove to be effective under both stable and unstable conditions.

CHAPTER III

Experimental Procedures

I conducted two experiments. The first experiment was designed to test the efficiency of the production of ice crystals in supercooled fog with liquid nitrogen and silver iodide simulated rockets. The second experiment compared the efficiency of ice nuclei production of the silver iodide warhead and an equal amount of silver iodide impregnated gunpowder string.

Using supercooled fog, it is possible to simulate rocket explosions on the ground and make observations of the efficiency of production of ice crystals. I used the Schaefer "vapor method" (14, p. 413-414) of replication in sampling ice crystals produced. Microscope slides were prepared by dipping them in a 2% solution of Formvar 15-95E, a polyvinyl formal, and ethylene dichloride. I found that drying the slides in front of a radiant electric heater resulted in slides that were not cloudy.

Figure 1 shows the simulated rocket warhead. The casing was an ordinary 135mm aluminum film container and the explosive was silver iodide impregnated black-gunpowder

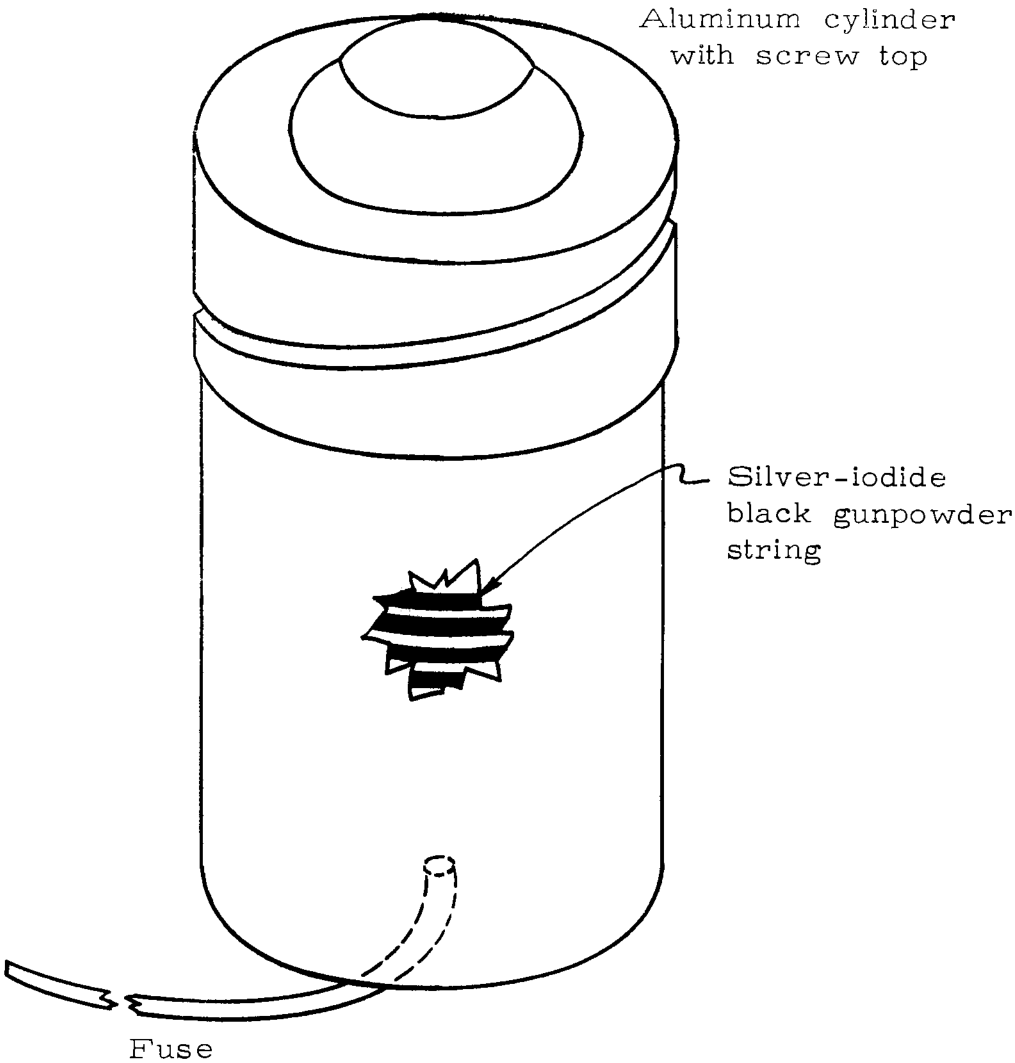

FIGURE 1

Simulated Rocket Warhead
Scale: Double-size

string. The fuse was the black-gunpowder string without silver iodide. It was necessary to make the silver iodide by preparing a solution of silver nitrate and mixing this with a solution of sodium iodide. Combining the two solutions resulted in a silver iodide precipitate. I then added the silver iodide to acetone to make a 10% solution by weight. In order for the silver iodide to dissolve in the acetone, I added one part of sodium iodide for four parts silver iodide to the solution. The black gunpowder string was soaked in the silver iodide acetone solution and then dried. Since sunlight will decompose silver iodide, appropriate precautions were taken. Each warhead consisted of a silver iodide impregnated gunpowder string weighing 9 grams. The fuse was inserted into a small hole in the bottom of the case first, and a knot tied to prevent the fuse from slipping out. The fuse burned at a rate of 15 seconds per foot; therefore , I used two feet of it to insure a safe retreat after igniting the warhead fuse.

Figure 2 illustrates the construction of the simulated rocket liquid nitrogen dispenser. Again, I used two feet of fuse in order to have 30 seconds to leave the immediate area. The fuse was pulled into the center of the mortar to insure

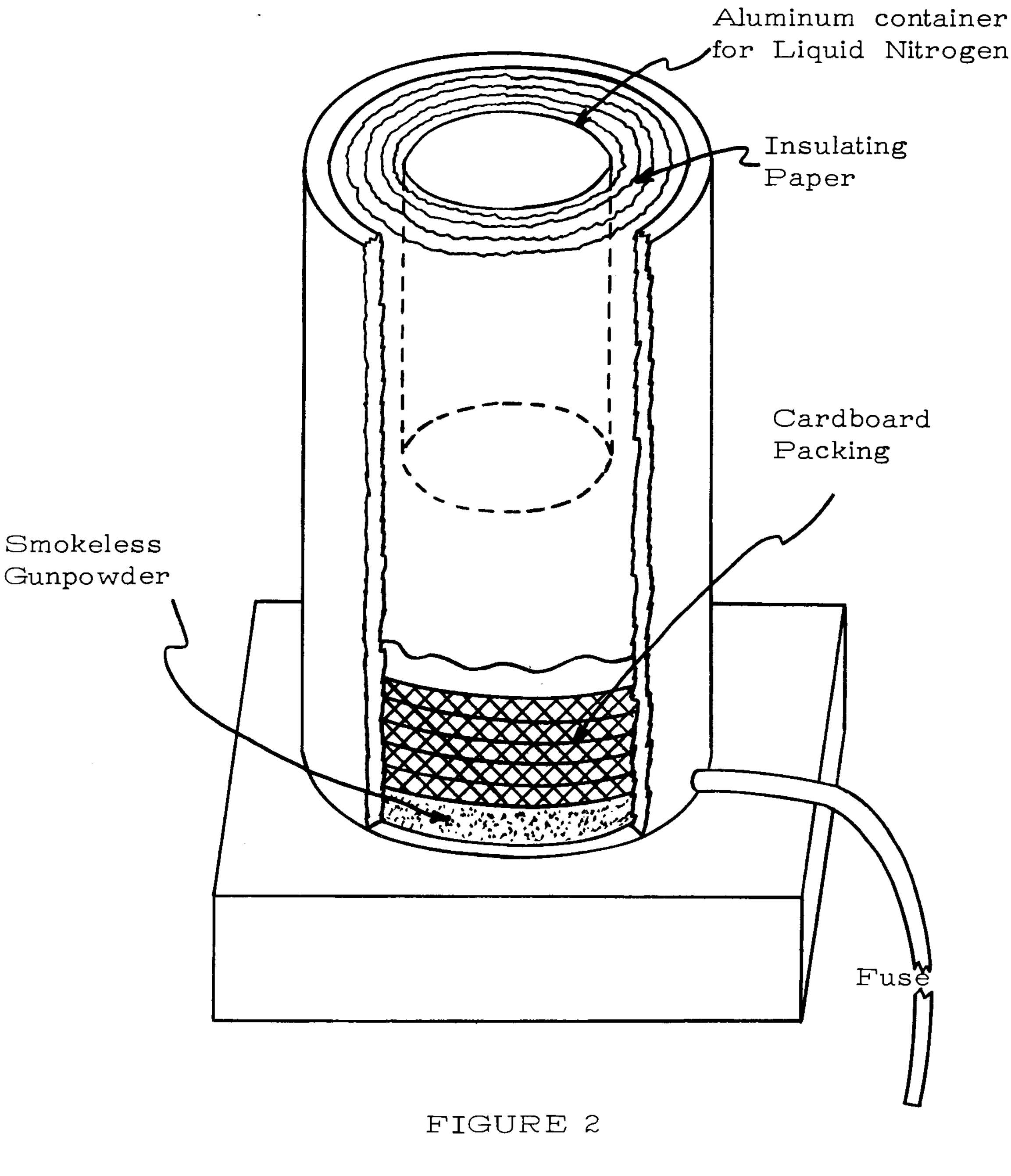

FIGURE 2

Simulated Rocket
Liquid Nitrogen Mortar
Full Scale

rapid burning of the shotgun shell powder used as the propellant. Five pieces of cardboard packing was sufficient to give the liquid nitrogen a lift of about ten feet. By increasing the packing, a greater height of the liquid nitrogen is possible. The liquid nitrogen container, a 135mm aluminum film container, held 35 ml. The container was wrapped in tissue paper which was taped securely on the container. The paper served as an insulator to retard the loss from boiling of the liquid nitrogen and also helped in lifting the container from the mortar. In the 30 second delay for the mortar to fire, the liquid nitrogen level decreased about 4 ml. The air was cooled by the spraying of the liquid nitrogen due to the tumbling action of the canister.

The synoptic conditions desired with the supercooled fog are calm or light winds and a moderate or heavy fog. A temperature of -5°C or less is required for the use of the simulated rocket warhead and below 0°C for the liquid nitrogen. Since the probability of fog and low temperature is highest near sunrise, this is the best time to conduct the experiment.

The collection plates were set up around the simulated rocket. After waiting about three minutes for the ice crystals to settle, I placed a sponge pad soaked with chloroform within 2mm of the slide for 5 seconds. The formvar is soluble in chloroform vapor, and each ice crystal acts as a nucleus for the polyvinyl to form around. This produces a permanent replication for studying under a microscope to determine the number of ice crystals formed.

I used the U.S. Weather Bureau type ice nuclei counter, shown in Plate 1, in the experiment to test the efficiency of the simulated rocket warhead. The three treatments were: the silver iodide warhead, 9 grams of the silver iodide impregnated gunpowder string, and 9 grams of the non-treated gunpowder string. In random order, I ignited one of the three treatments in the closed box that was used to contain the smoke produced. The inside dimensions of the box were 24 inches high, 15 inches wide, and 44 inches long. A small battery-driven fan inside the box kept the smoke gently circulating. A sample of smoke was withdrawn with a syringe through a hole in the box and 1/8 cc was injected into the ice nuclei counter. I took three samples of each smoke with a time lapse of five minutes between samples.

The ice nuclei counter has a 10 liter refrigerated compartment on top in which I placed the smoke sample. An air pump system increases the pressure of the volume of air in the compartment. The pressure change is calibrated in temperature. I used a compartment wall temperature of

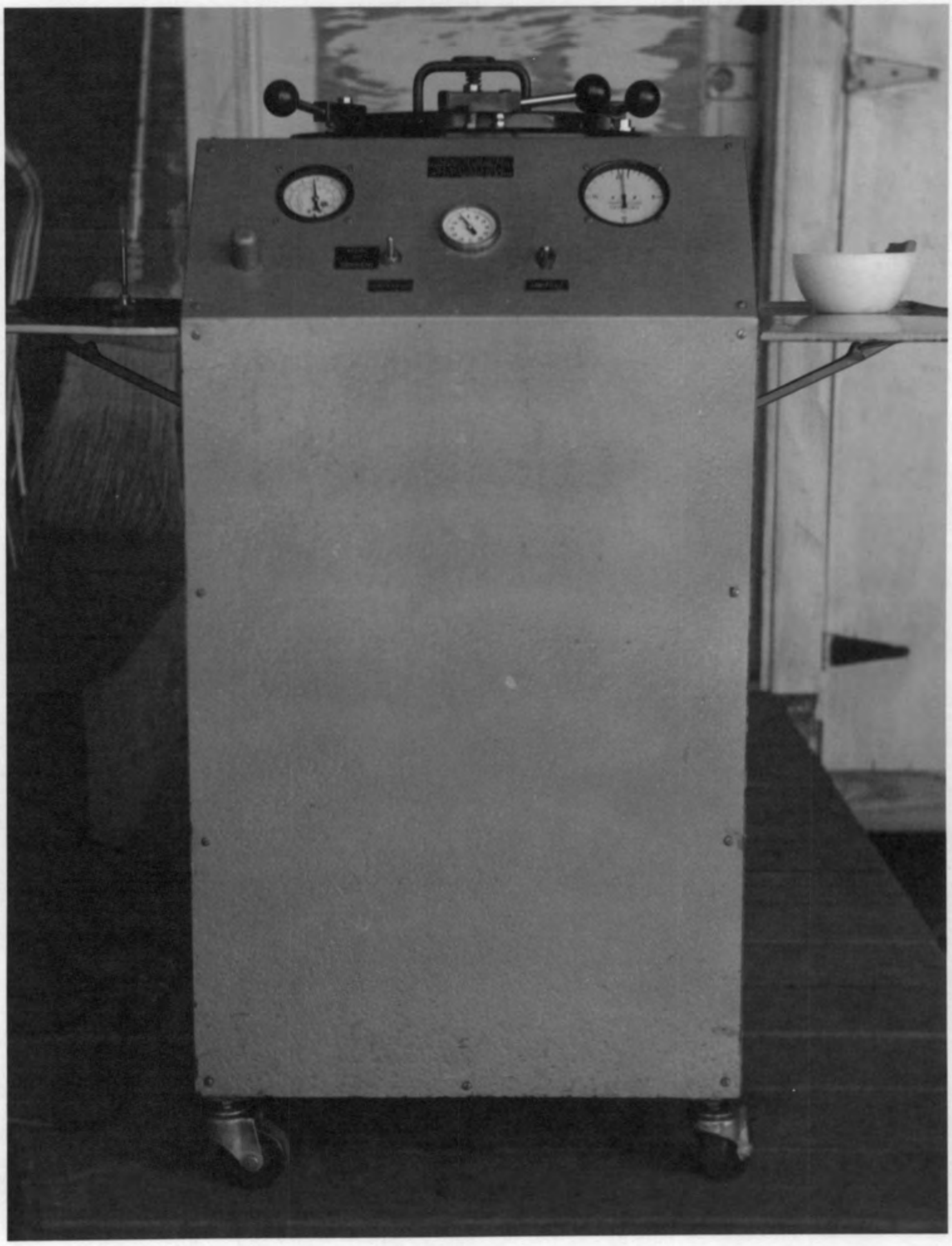

Plate 1

U.S. Weather Bureau type Ice Nuclei Counter used in determining the number of ice nuclei in a sample of smoke from the silver iodide warhead, silver iodide impregnated gunpowder string, and gunpowder string.

-10°C and a pressure difference, in terms of temperature, of -5°C. Therefore, when the pressure was released from the compartment, a supercooled cloud formed that had an ambient temperature of -15°C. A movable tray in the bottom of the compartment with a sugar and water solution is used to count the ice nuclei. When an ice crystal falls into the tray, a crystal starts to grow. When the number of crystals is large, as shown in Plate 3, a person can count one of the small rectangular sections and then multiply by 100 to get the total number. When few ice nuclei are present, the resulting growth of crystals are as shown in Plate 2. In this case, a person can count the crystals on the entire surface of the tray.

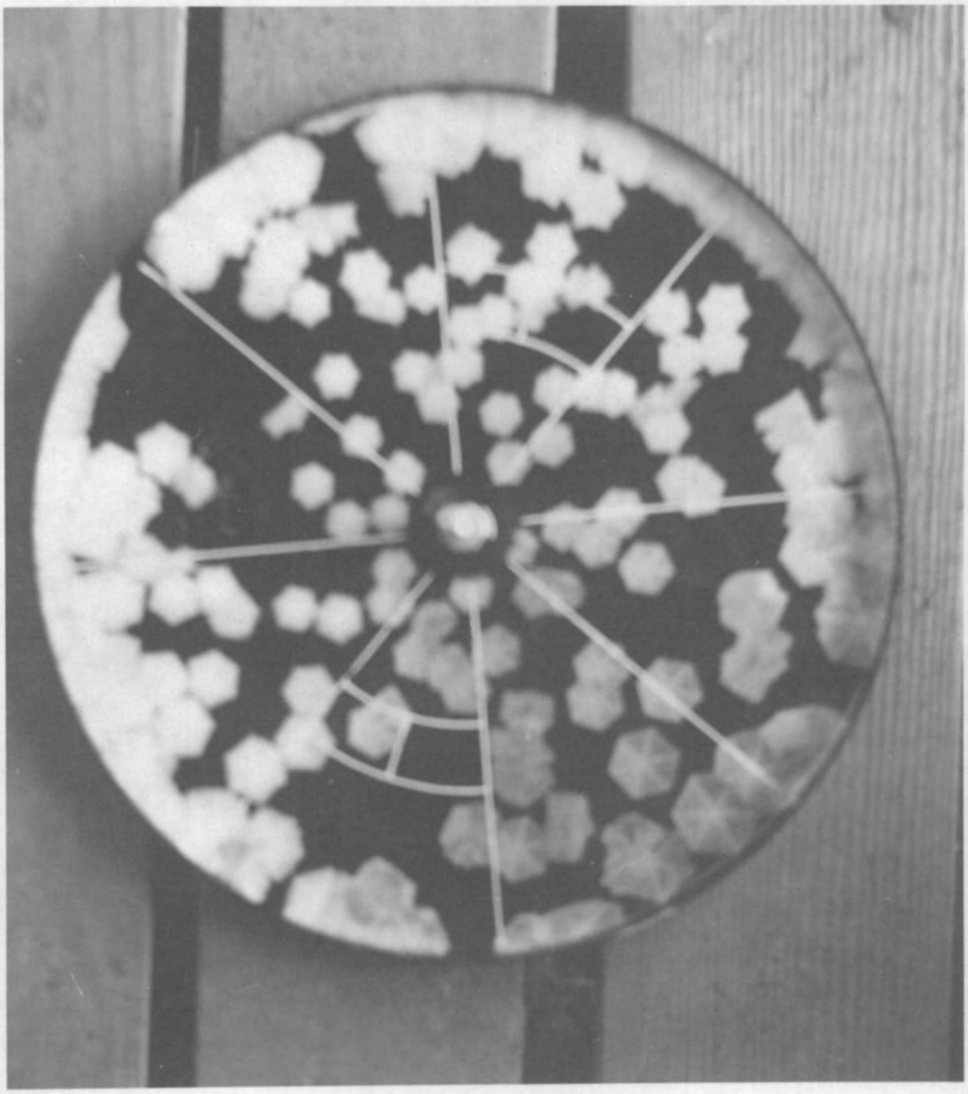

Plate 2

Example of a few crystals in the Ice Nuclei Counter tray formed from a sample of smoke with only a few ice nuclei.

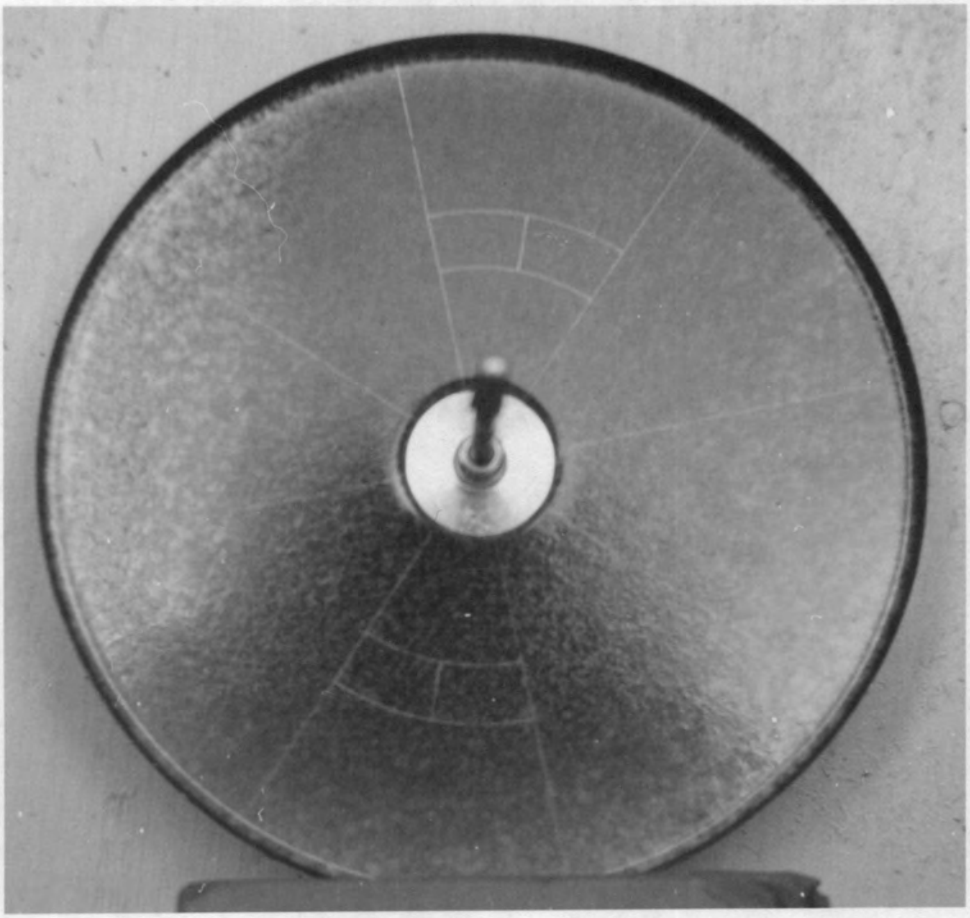

Plate 3

Example of many crystals in the Ice Nuclei Counter tray formed from a sample of smoke with many ice nuclei.

CHAPTER IV

Experimental Results

I pretested the replicating slides using dry ice and liquid nitrogen in a freezer. The pretest qualitatively showed that liquid nitrogen is capable of producing ice crystals. Plate 4 shows a photomicrograph of the ice crystals formed near the liquid nitrogen and Plate 5 shows a photomicrograph of the ice crystals formed near dry ice. I held both slides two inches from the cooling agent for ten seconds.

The first experiment conducted to produce ice crystals with liquid nitrogen in supercooled fog was on 5 March 1963. The location was the saddle below McCulloch Peak and the time around 0630 AM. The synoptic conditions were light fog, temperature -1.1°C, dew point -1.7°C, and wind from the northwest 3-5 kts. The second experiment was conducted on 22 March 1963 near the Santiam Lodge, also at 0630 AM. The synoptic conditions were light fog, temperature 1.7°C, dew point -2.2°C, and wind variable 3 kts. The third experiment with liquid nitrogen was conducted on 23 March 1963 on Mary's Peak at 0645 AM. Conditions were moderate fog, temperature -1.1°C, dew point -1.7°C,

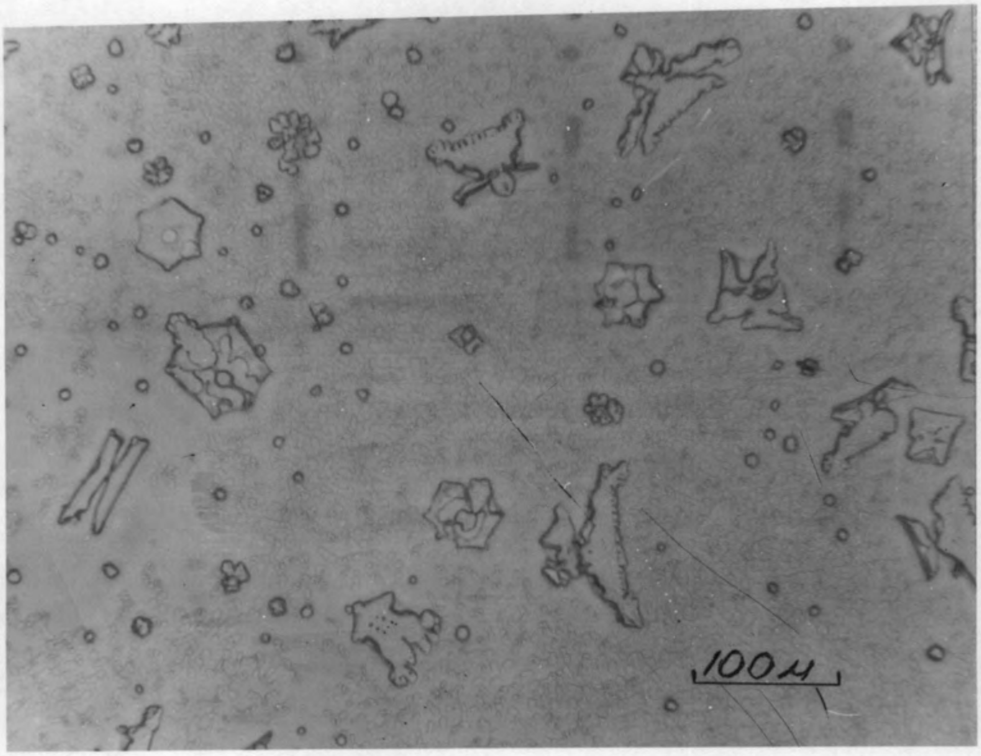

Plate 4

Photomicrograph of ice crystals formed near liquid nitrogen. The average hexagonal plate size is near 50 micron and the frosted hexagonal platelet is 90 micron.

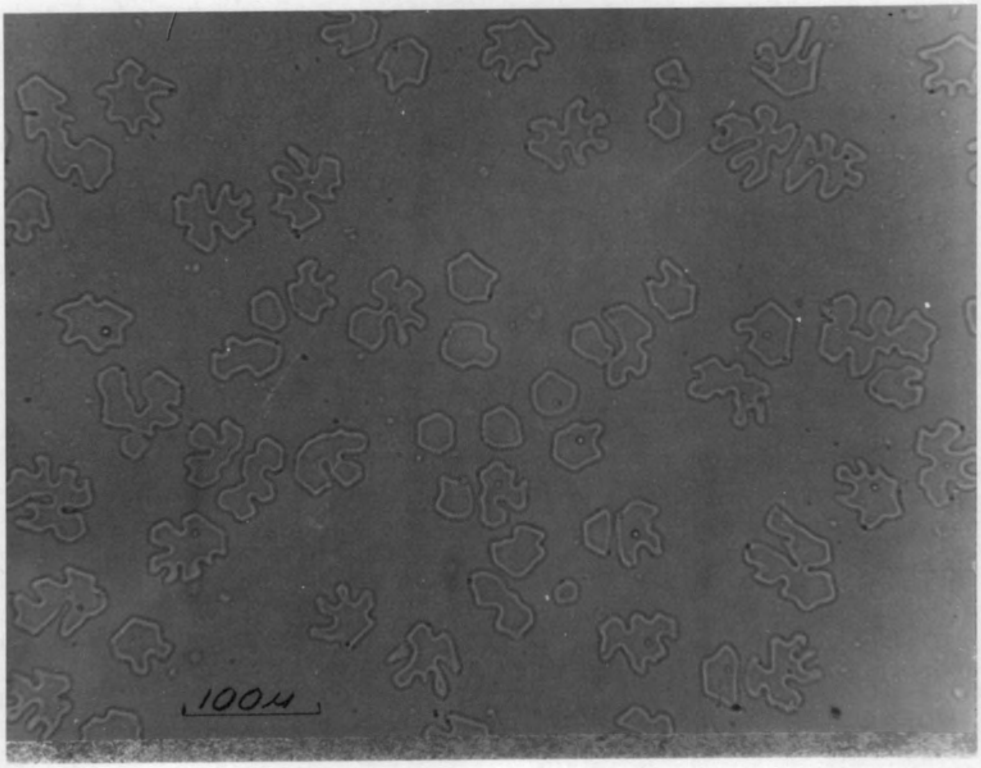

Plate 5

Example of ice crystals formed near dry ice. Hexagonal plates average size is near 35 microns. The irregular crystals range in size to 100 microns.

wind from the southwest 15-25 kts, and occasional light snow. The final experiment was conducted on 9 April 1963 on Mary's Peak at 0600 AM. Synoptic conditions were moderate fog, winds southwest 5 kts, temperature -1.1°C, dew point -1.4°C, and occasional light snow.

I found it necessary to place the collection plates downwind from the simulated rocket liquid nitrogen dispenser in all the experiments since no calm conditions existed. The cloud made by the liquid nitrogen and smoke from the mortar is an excellent tracer with light winds in order to insure that the collection plates are properly placed. After viewing all the slides made during the first three experiments with a microscope, I found that I had collected no crystals. There were occasional droplets, one of which is as shown in Plate 6, which indicates that condensation took place on the smoke particles. With the collection plates placed vertically downwind in the fourth experiment, I collected ice crystals as shown in Plate 7. The photomicrograph, Plate 8, shows in detail two of the crystals collected.

It was observed that even when the wind was barely perceptible, the cloud formed by the liquid nitrogen and smoke would move horizontally. Apparently little or no settling of

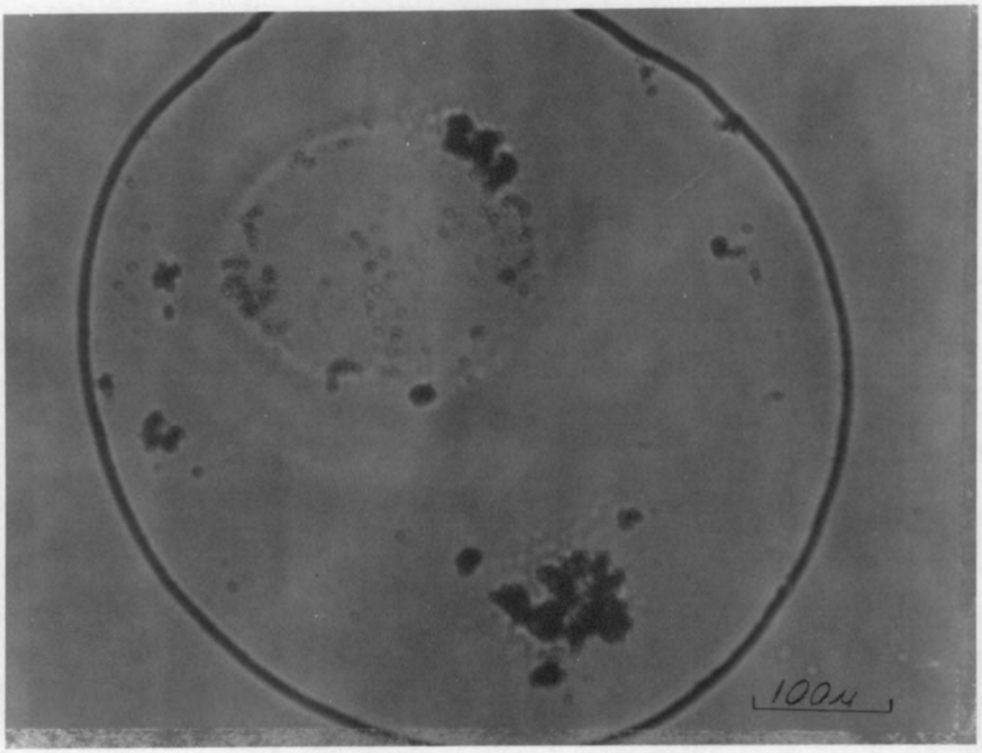

Plate 6

Large drizzle drop, 600 micron diameter, apparently nucleated with smoke from the liquid nitrogen mortar.

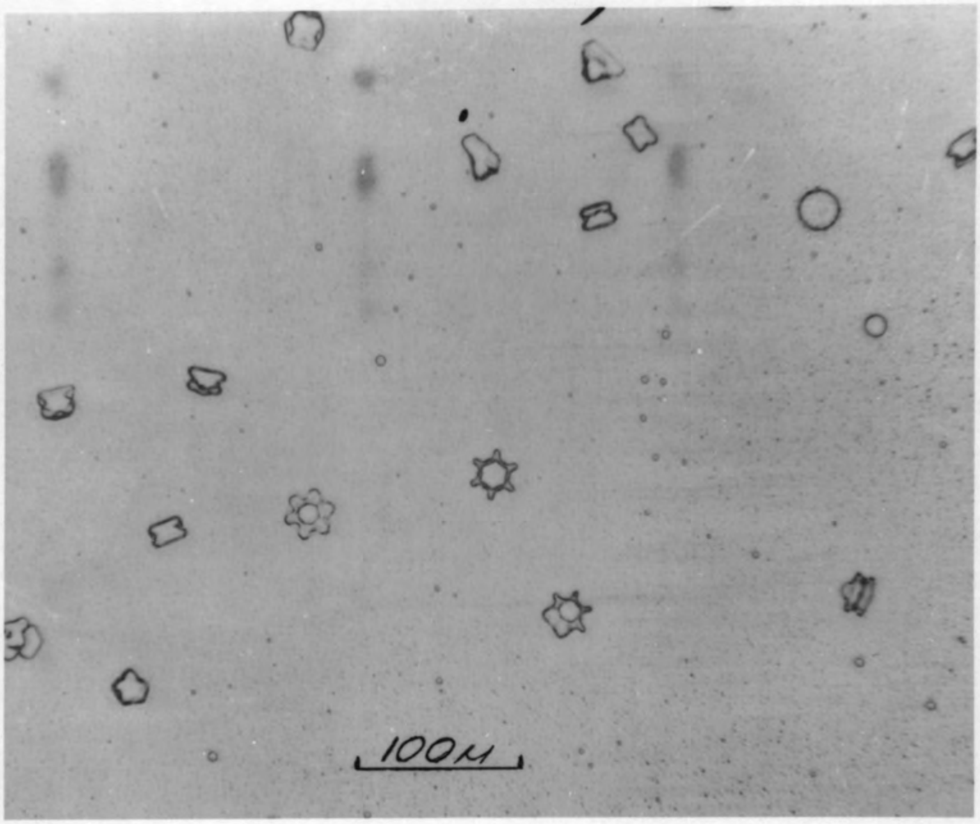

Plate 7

Photomicrograph of replicas of hexagonal columns and plates formed in supercooled fog with liquid nitrogen. Most crystals range in size of 30 to 40 micron diameter. These were fixed 15 seconds after seeding.

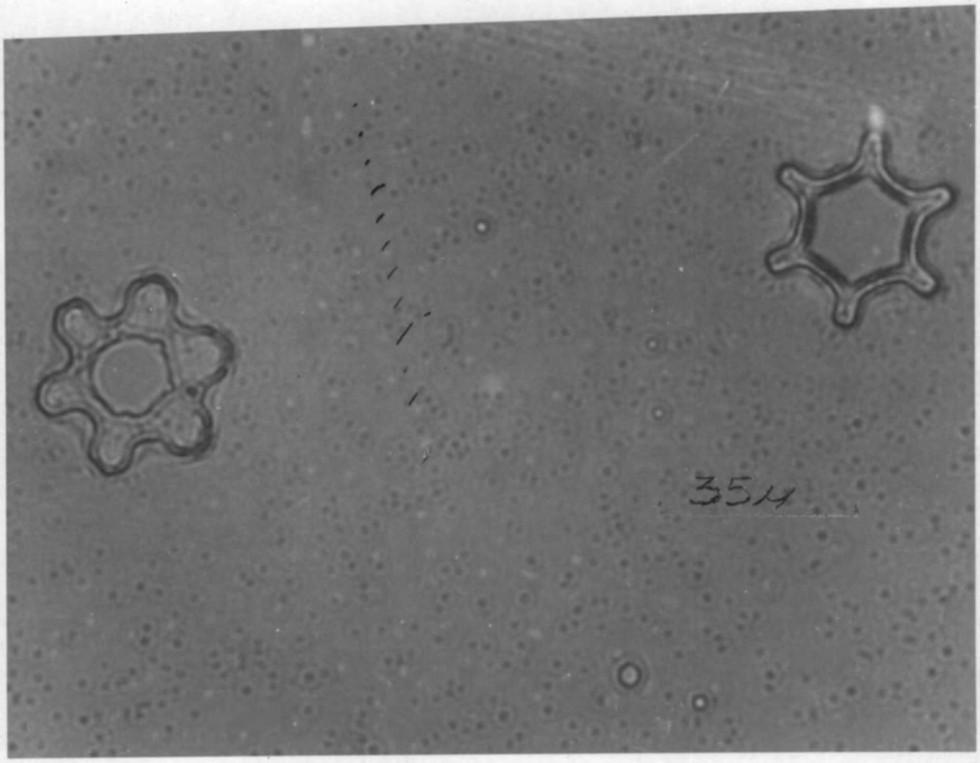

Plate 8

Detail of ice crystals, 35 micron diameter, replicated in supercooled fog. The crystal on the right shows a hexagonal plate and beginning of stellar extensions. The crystal on the left appears to have a frozen cloud droplet 18 micron in diameter as a nucleus.

the ice crystals occurred in a fifty-foot range. Therefore, with the collection plates set up vertically, ice crystal collection was accomplished by impaction instead of settling.

It is possible to calculate an estimate of the number of ice crystals produced per gram of liquid nitrogen based on the experimental data. The average number of ice crystals seen through the microscope was 20; and the viewing area was 42×10^{-4} cm^2. I observed the size of the ice crystal cloud formed by the liquid nitrogen to have the general dimensions of a 3 foot cube. Since 30 ml of liquid nitrogen weighs 28 grams, calculation then gave 1.5×10^6 ice crystals produced per gram.

The above calculations assume that the collection efficiency of the slide is perfect, that is, no crystals are being carried around the slide due to areodynamic air flow; also, that no crystals grew large enough to settle before reaching the collection plates. I assumed that all of the 30 ml of liquid nitrogen was used in chilling the supercooled fog.

Since I did not encounter a supercooled fog with a temperature of -5°C or lower, the silver iodide warhead was not used with the ice crystal collection plate system.

The data collected from the experiment comparing the ice nuclei production of the silver iodide warhead, silver iodide impregnated gunpowder string, and the gunpowder string are shown in Table 1. To give a firm basis for conclusions, I analyzed the data by the hierarchical experiment classification (7, p. 326-330) of the analysis of variance. Square root transformations (7, p. 454-458) of the data were used to equalize the population variances and help fulfill this requirement which is needed for the analysis of variance to be valid. The data were considered the component of variance model (7, p. 214-215). I used the randomized block experimental design (7, p. 196) with five replications. Table 2 shows the analysis of variance.

The 5% significance level was used in all hypothesis tests. I first tested the hypothesis that the different methods of smoke production have no effect on the average number of ice nuclei produced. The critical region was an F-value larger than 4.459 with 2 and 8 degrees of freedom. The computed F-value was 110.7; therefore, the hypothesis was rejected.

The hypothesis that the variance of the time effects within the different methods of smoke production are equal was tested next. The critical region was an F-value larger

Time of Sample	Smoke Source			Average Ice Nuclei With Time Effect
	Silver Iodide Warhead	Silver Iodide Impregnated Gunpowder String	Gunpowder String	
Ignition	82.0	54.6	10.1	48.90
Ignition Plus 5 Minutes	63.1	38.1	6.2	35.79
Ignition Plus 10 Minutes	35.5	27.4	5.4	22.76
Average Ice Nuclei from Smoke Source	60.22	40.04	7.21	

TABLE I

The data collected are summarized above. The data presented are square roots of the average number of ice nuclei formed at -15°C with a sample of 1/8 cc of smoke. (Background count of natural ice nuclei was zero.)

Analysis of Variance

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F-Value
Replication	367.89	4	91.97	
Smoke Production Methods	21,468.62	2	10,734.31	110.7
(Warhead vs. Ag-I String)	(3,050.21	(1)	(3,050.21)	(31.44)
Experimental Error	776.28	8	97.04	
Time within Smoke Methods	7,430.93	6	1239.49	28.2
Sampling Error	1,057.47	24	44.06	
Total	31, 101 .19	44		

TABLE II

than 2.508 with 6 and 24 degrees of freedom. The computed F-value was 28.2 and consequently, the hypothesis was rejected.

I used the individual degree of freedom method (7, p. 226-233) to test the hypothesis that the number of ice nuclei produced with the silver iodide warhead is equal to those produced by the silver iodide impregnated gunpowder string. The computed F-value was 31.44 and the critical region was an F-value of 5.318 with 1 and 8 degrees of freedom. The hypothesis was rejected.

I also made a calculation to determine the total number of ice nuclei produced with the warhead. The volume of smoke contained in the box was 262,500 cc. Using the first ignition average value of ice nuclei produced from 1/8 cc of smoke, the total ice nuclei produced was 1.4×10^{10}. The theoretical value for .25 grams of silver iodide is 2.5×10^{13} ice nuclei.

CHAPTER V

Conclusions and Recommendations

The criteria used in judging the efficiency of liquid nitrogen and the silver iodide warhead are based on the ability to produce ice crystals, the cost, and the ease of handling and storage. The primary yardstick used for determining the efficiency of the methods is the ability to produce ice crystals. The cost-versus-value concept should be used in evaluating weather modification methods. This makes it necessary to consider dollar cost compared to dollar value accrued, which is an involved and complicated procedure. Therefore, a very simple approach to cost is used here.

The ability of liquid nitrogen to produce ice crystals in supercooled fog based on the experiments conducted seems very good. The ice crystal production estimate of 1.5×10^6 per gram of liquid nitrogen is perhaps an underestimate. The cost of liquid nitrogen through the Oregon State University Department of Chemistry is one dollar a liter, or about fifty cents a pound. Dry ice purchased locally at retail prices costs twenty cents a pound. A person must store liquid nitrogen in a thermos or Dewar flask in order to minimize the loss from boiling. Another problem is handling, since the thermos cannot be sealed tightly and one must exercise caution to prevent spilling. Frostbite danger results from the possible quick-freeze effect of accidental splashing.

The number of ice nuclei produced by the silver iodide warhead was significantly greater than those produced by the silver iodide impregnated gunpowder string. The reason for the difference in production can be accounted for by considering the temperature of the warhead explosion, which is more conducive for ice nuclei production. Ice nuclei production is not necessarily equal to ice crystal formation, as the latter depends on the amount of moisture available and the temperature of the cloud. However, the maximum number of ice crystals computed from the average first ignition of the warhead is 5×10^{10} per gram of silver iodide. The cost of the materials in the warhead is low, the rocket itself costing many times more. Danger is remote when the handling and storage restrictions of explosives are followed and proper precautions are taken.

I did not expect the decrease of ice nuclei during the three observations of one smoke source. Some smoke did escape from the box during the time between the samples; however, it was observed to be a very small amount. The box was always full of dense smoke after I took the three samples. Perhaps there is a chemical interaction between the silver iodide particles and the smoke to cause a decay of ice nuclei.

The following conclusions are drawn based on the above considerations:

1. Liquid nitrogen is effective in producing ice crystals in supercooled fog, but the efficiency is decreased due to the cost and the handling and storage problems.

2. The silver iodide warhead is an efficient method of producing ice crystals in supercooled clouds.

As was anticipated, an experiment of sampling ice crystals produced in supercooled fog was extremely difficult. The ideal synoptic conditions required or desired are almost impossible to find. Therefore, it is suggested that future experiments consider the use of a walk-in freezer to simulate supercooled clouds. This would make it possible to vary temperature and moisture conditions and observe ice crystal formation under these controlled conditions. The use of larger replicating slides, like lantern slides, would help in taking the samples.

With the excellent radar equipment available for research at McCulloch Peak, an experiment using silver iodide rockets could be undertaken. A person could observe clouds or areas with the radar while silver iodide rockets are used in a random sampling scheme. The cloud echo could be observed and results tabulated to see what effect the rockets have on the precipitation echoes.

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