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Airborne Expedition to Yellowstone 1966

by

E. X. Berry and K. W. Nielsen

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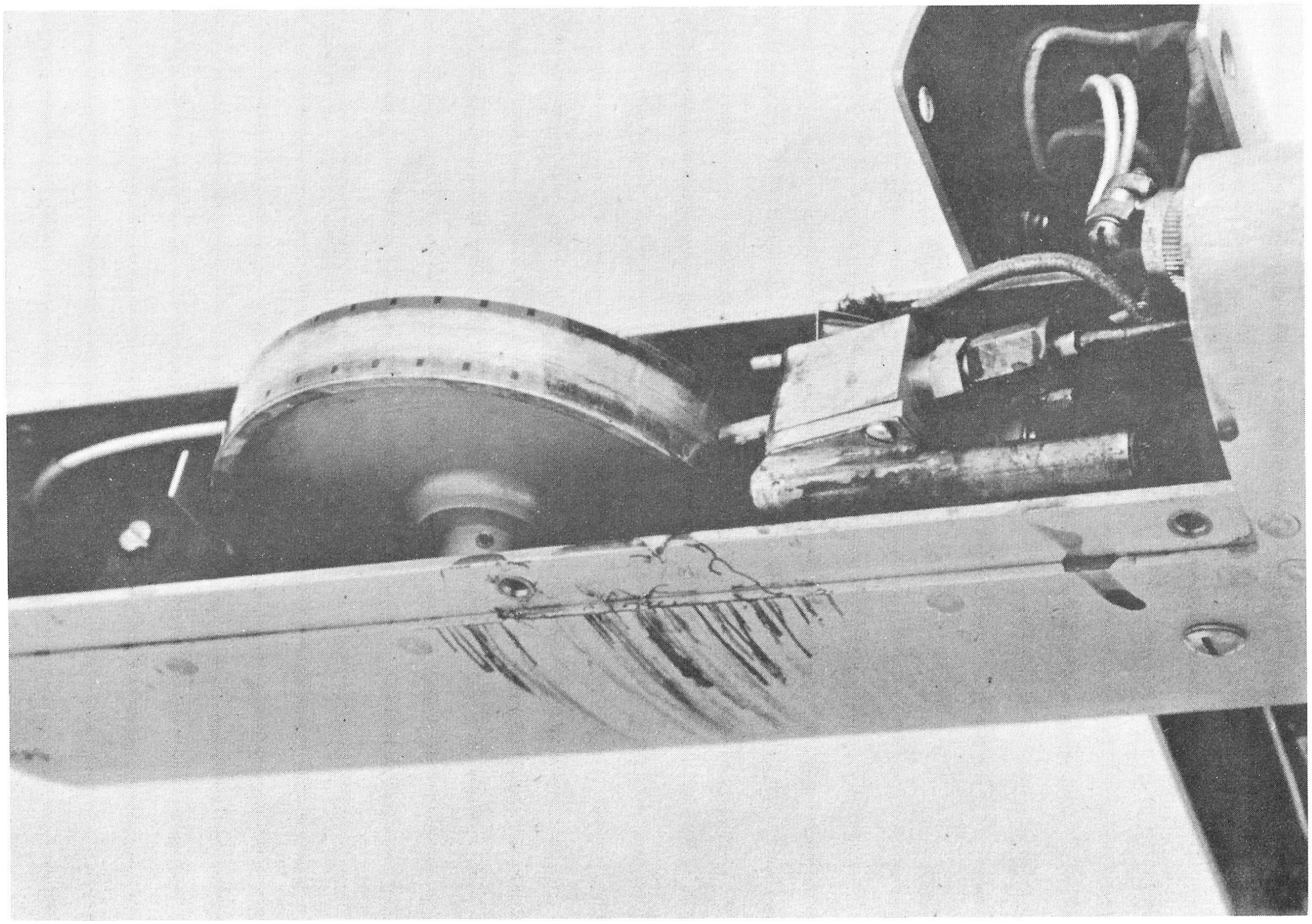


Plate I
The working end of the continuous particle-sampler shows the needle applying liquid Formvar to the clear film as it moves from right to left around the roller. The lever on the left holds the marker for time synchronization of the data and the section on top, when placed in position, allows particles to enter a 3 mm wide slit in front of the roller.

Contents

Illustrations

Plates

Figures

Acknowledgment

The authors gratefully acknowledge the talented aid of the other members of the crew: W. Carver, a graduate student in electrical engineering, who built and operated the airborne electronic system; and T. A. Wells, DRI's all-weather pilot, who capably assured that this team's story could later be told.

Abstract

On 28, 29, and 30 January 1966 a four man crew from the Desert Research Institute flew their instrumented aircraft into the geyser basins of Yellowstone National Park and measured properties of the cloud plumes that rise high above the erupting geysers.

The temperature, liquid water content turbulence, and atmospheric pressure were measured simultaneously and their magnitudes recorded on analog magnetic tape. By means of special timing and event marks, this data was correlated with the water droplets and ice crystals replicated by the continuous particle sampler. The investigation succeeded in establishing the feasibility of airborne data gathering in the Upper Geyser Basin and in collecting useful data.

The typical temperature profile inside the plumes showed a warm core and cool sides. The liquid water content (LWC) was generally maximum at the center, although in the two lowest penetrations a crater-type profile was formed, i.e., much water in the sides and very little in the core. The turbulence parameter $\varepsilon^{1/3}$, showed one or two big increases during the penetrations, which corresponds to the crew's observation of one or two strong bumps during each penetration.

The airborne continuous particle sampler captured the plume's particle profile in great detail. The replicas show clearly the crater profile of LWC and the 0.5 second response time of the LWC device which must be considered in interpreting its output. The particle replicas of the three days were quite different. On the 28th many ice particles were collected at about 1320 MST, and the droplets in the plumes were small and of almost uniform size. On the 30th, with penetrations made at about 0900 MST, a few small bits of ice were found mostly just outside the seeded geyser, and the in-plume droplet spectrum was widely spread. On the 29th the penetrations at about 1020 MST detected no ice and a droplet spectrum intermediate between those of the other two days.

Photos on the 30th show a pronounced wind shear above the valley and the interesting fact that the Upper Geyser Basin (UGB) was clear while all surrounding valleys contained ground fog.

This clearing may be attributed to the seeding or other human activity in the UGB. A plume rising through the fog in Midway Geyser Basin was used as a reference (unseeded) cloud. This cloud was much wider and rose far higher than any in the UGB. It contained slightly larger droplets and was always present.

I Introduction

Each winter since 1960 a group of scientists organized by Dr. V. J. Schaefer has congregated in the Old Faithful area of Yellowstone National Park to study atmospheric phenomena in the cold, clean air above the hot geyser basins. They have learned from experiments in this air, whose natural aerosol have been washed out by the ever present warm water vapor, much about the subtle properties of water and ice and the effects of contaminants on them. So successful has been this regular research expedition that the area has become well known as an important outdoor laboratory for the atmospheric scientist.

On the snowy night of 27 January 1966, a four man crew (Wells, Carver, Nielsen, Berry) from the Desert Research Institute (DRI) arrived in Idaho Falls in preparation for experimental flights through the Upper Geyser Basin (UGB). During the next three days, with prior approval from Dr. Schaefer, the Yellowstone Park Service, and the Federal Aviation Agency, they flew in their instrumented twin engin Beechcraft into the valley and through the plumes that rise above the steaming geysers. They measured a portion of the atmosphere that is beyond the reach of men and equipment on the ground and in so doing added a new dimension to the research in Yellowstone National Park.

The DRI aircraft is equipped with external sensors for liquid water content, temperature, air speed, turbulence, and static pressure. Each of these sensors affects an electric voltage which is amplified and recorded on analog magnetic tape.

The aircraft also carries a continuous particle sampler designed and built by Meteorological Research, Inc. (MRI), and subsequently modified by DRI. The most important modification was the addition of a film marker near the point where particles are collected. This marker is activated by a time signal that is simultaneously recorded on one channel of the magnetic tape. Additional signals in the form of dots and dashes may be impressed on both the sampler film and the magnetic tape by means of pressing either of two buttons located inside the aircraft. These simultaneous signals on sampler and tape allow very close correlation of droplet sampler replicas, sensor data, and observational notes of crew members.

To provide a photographic record of each flight there is mounted in the nose of the aircraft a 16mm movie camera equipped with wide angle lens and modified to take one picture every three seconds.

The Idaho Falls airport proved to be a convenient base of operations, being about one-half hour flight time from the UGB. The UGB is long enough to allow convenient and safe entry and exit for low flying aircraft, although it is here recommended that this performance be limited to pilots with extensive experience.

II Summary of Activities

Two scientists from DRI (T. E. Hoffer and J. A. Warburton) were members of the ground party during this week and, although engaged in their own research, managed to bring along a portable FM transceiver for communication with the aircraft's crew and took time to tell them of the several activities on the ground, such as which geyser was being seeded. They reported later that all observers of the aircraft penetrations saw no visual effect of the aircraft upon the plume, which suggests that the aircraft's exhaust did not seed the plume and that the aircraft's turbulence was probably negligible compared to that of the plume. The ground party also provided the ground temperature data presented in the next section.

January 28th was a practice day for aircraft, equipment, and personnel. After takeoff from Idaho Falls at 1117 MST the pilot vectored the aircraft toward the Upper Geyser Basin (UGB). Light clouds over the mountains required instrument flight, but near the calculated position of UGB a clearing was encountered that permitted visual descent. Once in the valley at 1150 MST several trial passes were made to get the feel of the aircraft's ability to negotiate the terrain and then plume penetrations were made. Radio contact was achieved with the ground party at 1230 MST and more plume penetrations followed. The aircraft left the UGB at 1250 and landed at Idaho Falls at 1320.

Back at the motel the crew reviewed the data, found various difficulties, and made corrections for the following day. The liquid water content data was too noisy to give useful information so filtering was added. The time correlation button had been pressed twice during the flight, which proved to be insufficient to accurately correlate all the data.

January 29th was beset with difficulties. The aircraft was hangared the night before to facilitate an early start but when the crew arrived at 0630 the hangar was locked. The attendant was found at 0715. A quick check showed all systems to be operational, but while taxiing to takeoff the particle sampler stopped and the aircraft was returned to the parking area. The sampler film had broken in two places and required complete re-threading, a job that was much prolonged by the lack of dexterity of the crew's cold fingers. Takeoff, finally, was at 0933 MST.

Once in the air the particle sampler again stopped operating but this time the flight plan was continued. With heaters on, the sampler began working again as we came within sight of UGB. To top off the day a lost screw driver turned up tangled in the magnetic tape, so sensor data was not recorded on this flight. The weather was clear with a high cirrus formation, broken to overcast. Surface temperature at Idaho Falls at departure was -13C, with a strong inversion below about 1000 ft. above the surface. In the UGB photographic conditions were much improved over the day before. During the collection runs it was quite turbulent over the southern ridges and through the geyser plumes.

Several small ice crystals were encountered 2000 ft. above the valley but none were near the plumes. Curiously, only the UGB was clear, while a ground fog was present in all surrounding valleys.

The aircraft landed in Idaho Falls at 1209 MST, whereupon preparations were begun for the next day. The aircraft was hangared, the particle sampler was thoroughly cleaned and re-loaded, and four light bulbs were placed in the aircraft's nose next to the sampler and turned on in the hope of keeping the sampler warm and the film flexible. The nose camera was loaded and the tape deck readied.

The flight of the 30th began well with the takeoff at 0753 and arrival over Old Faithful at 0823. Once again the crew saw that the UGB was clear while all other valleys within 50 miles contained fog. Visibility and color contrast were excellent.

The descent into the UGB showed a distinct temperature inversion. Plate II shows a wind shear at about 600 ft. above the valley floor where the plumes bent sharply. The ridges were less turbulent than the day before but the plume penetrations below the inversion were more turbulent.

Castle Geyser was being seeded from below at this time so several penetrations were made of its plume and of other geyser plumes for comparison. Each plume penetration was preceeded by a coding with the correlation button and a release of the button upon visual entry of the plume. This technique proved to be extremely valuable since it allowed very close correlation of droplet samples, sensor measurements, and the observers notes and photographs. Visual entry of the plume was recorded within a fraction of a second of the LWC rise.

III Geyser Penetrations

Continuous measurements of temperature (with a Rosemont temperature probe), liquid water content (with Johnson-William's hot wire probe), and turbulence (according to a MRI universal turbulence meter) during the flight of 30 January 1966 were recorded on magnetic tape. Several penetrations were made of geyser plumes and the results of a few, being representative of the group, are shown here.

Figure II shows the initial playback of the data from the magnetic tape for 10 minutes of the flight. During this period of time 3 plume penetrations are clearly indicated on the trace of the liquid water content (LWC). (These penetrations are shown in more detail in the figures with which they are labeled, by Figs. V, IV, VIII, respectively.) The upper line shows the temperature along the flight path during this portion

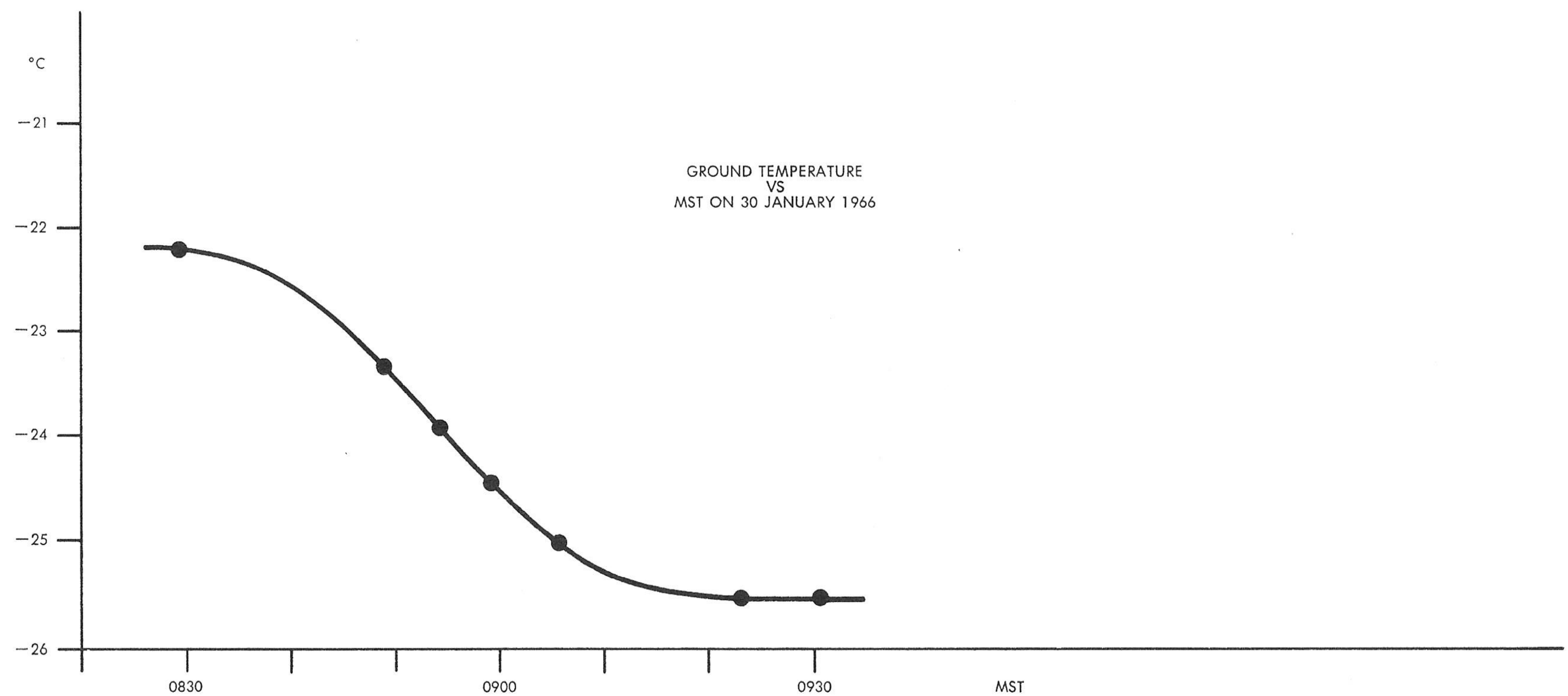


Figure 1
Ground temperature vs. time on 30 January.

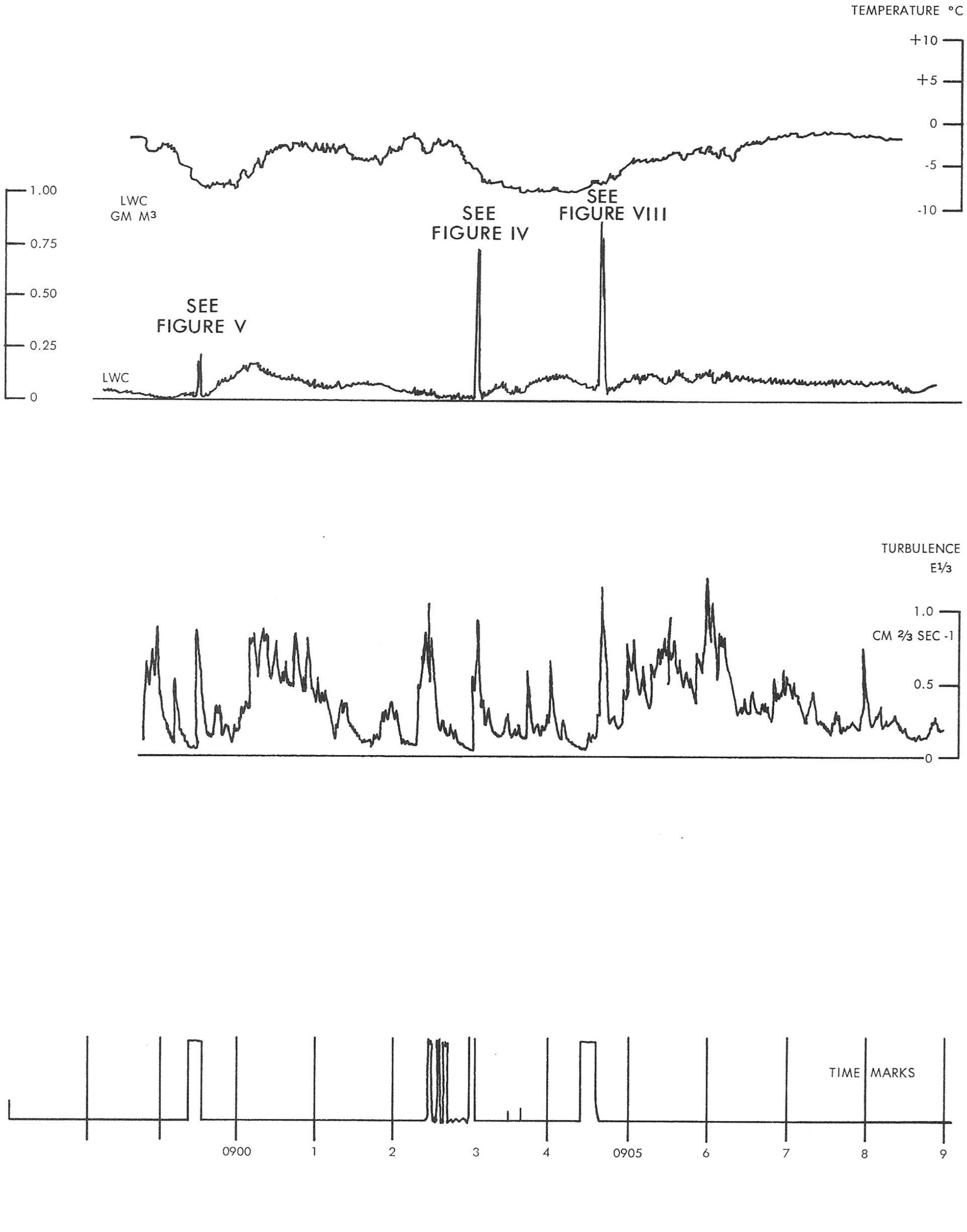


Figure II
Initial playback of temperature, LWC, and turbulence data as recorded from the aircraft.

of the flight. The ground temperature shown in Fig. I as well as knowledge of the aircraft's altitude changes on approaching and exiting a plume indicate a strong valley inversion. The aircraft is equipped with a very sensitive differential pressure gauge which served to indicate changes in altitude very well on 28 January. This device was expected to permit calculation of the temperature lapse rate and the level of each plume penetration. Unfortunately, the reference pressure chamber leaked on this flight and caused the differential pressure to be zero at all times.

The best remaining indicator of altitude is the temperature itself. Figure II shows a drop in temperature as the aircraft descends from over the mountains into the valley prior to a penetration, and a rise in temperature as the aircraft ascends after a penetration.

That the LWC does not go to zero outside the plume is indicative of the light cloudiness in the valley near plume-top level. These light clouds were visible and are recorded in the observer's notes. These clouds seemed to be at the level of the wind shear.

The third line is the turbulence trace. The peak of turbulence associated with plume entry corresponds to the flight crews observation of one or two sharp bumps during each penetration. Other areas of turbulence seem to be associated with a rise in LWC, a fact which may be due to the flight through the shear zone between the still valley air and the wind above.

The fourth line shows the time and synchronization marks impressed on one channel of the magnetic tape. Similar marks are simultaneously impressed on the droplet sampler film in the manner described in Section IV. The single lines at regular intervals are minute marks generated automatically with a timer. The other deviations are coding marks entered manually for the purpose of identifying a particular penetration on the tape data and droplet sampler film.

A great advantage of the magnetic recording system is the ability to expand the recorded information to give a more detailed description of rapid fluctuations. Figures IV, through VIII show six plume penetrations with the time scale expanded 25x and the temperature 4x.

Figures III, IV, and V show the penetrations of Castle Geyser, sequenced from top to bottom to correspond with the probable altitude of entry according to the temperature just before entry. Figures VII and VIII are similarly ordered high and low penetrations of the large plume that projected above the fog from Midway Geyser Basin. This plume is clearly seen in Plate V. Figure VI is a penetration of the Old Faithful Plume.

Corresponding to each penetration are the replicas made by the continuous particle sampler. The time marks on the particle sampler film plus the calibrated speed of the film fix the

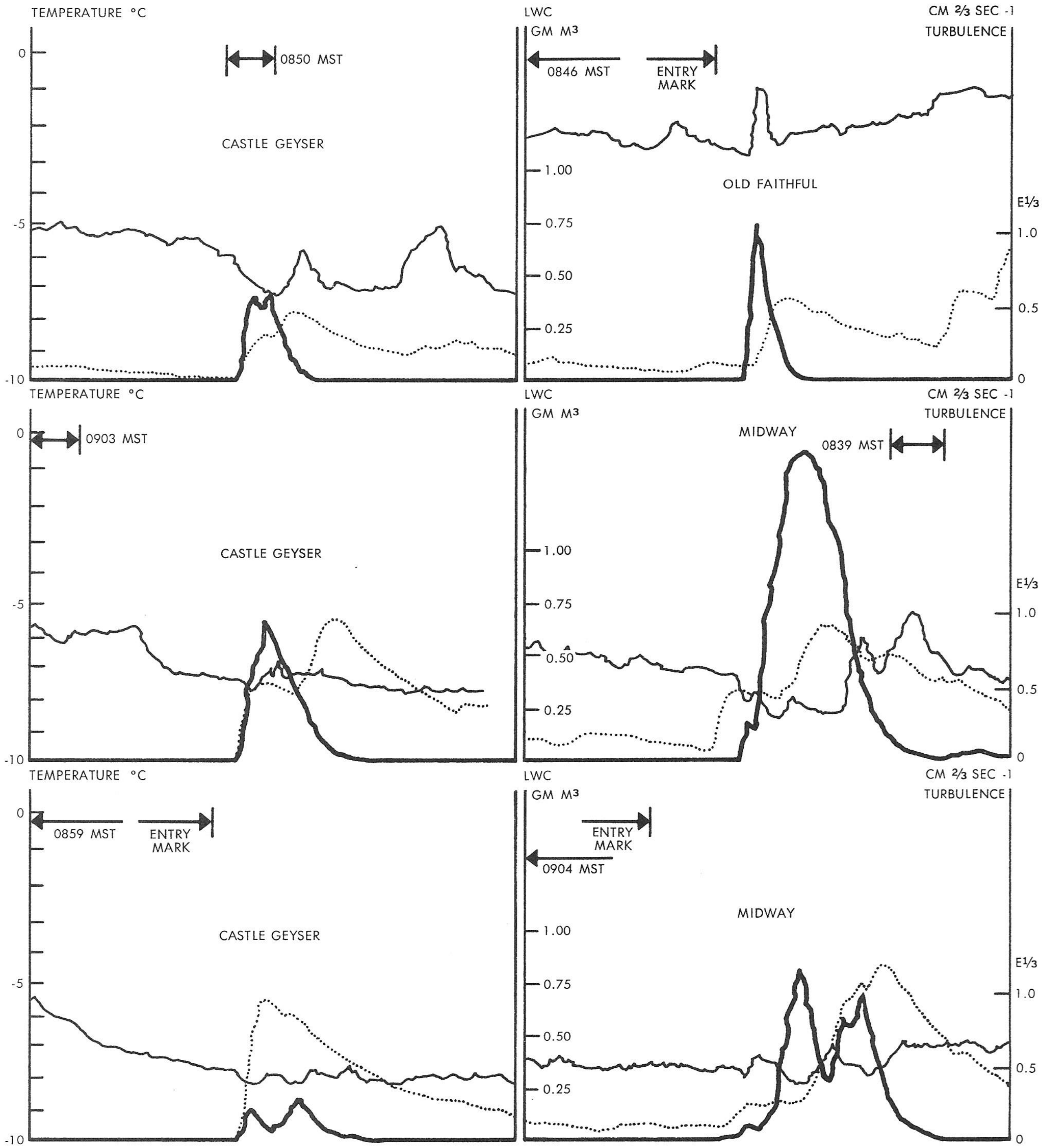


FIGURE III
FIGURE IV
FIGURE V

FIGURE VI
FIGURE VII
FIGURE VIII

1 SECOND REAL TIME

IN ONE SECOND THE AIRCRAFT TRAVELED 70 M,
AND THE SAMPLER FILM MOVED 18 CM = 25 FRAMES.

LWC
TEMPERATURE
TURBULENCE

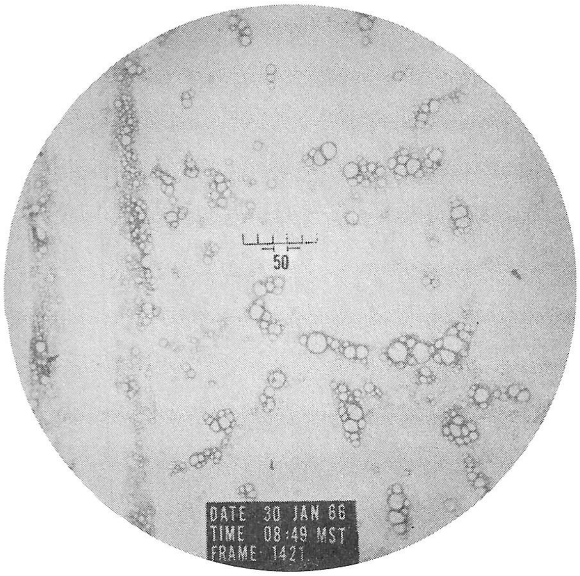
Figures III - VIII
Expanded playback of data for selected plume penetrations.

position of the replicas with the time in Figs. III through VIII to 0.1 second. The total sampler data is far too voluminous to present but selected results are shown and the significant implications discussed below.

First of all, the sampler data indicates that the time response of the LWC device is about 0.5 seconds and the data must be so interpreted. The trailing slopes of all graphs should not tail out, since the plume exit was generally as sharp and distinct as its entry. The length of the LWC trace of Fig. IV, for instance, should be about 2/3 of that indicated. Also, the density of water in droplet form and the droplet sizes themselves at the maximums of LWC of Figs. III, IV, and VI, are very nearly equal to that of Fig. VII, as shown in Fig. IX a, b, c, d, respectively. This indicates that the length of the penetration in the smaller plumes was not sufficient to allow the LWC device to come to equilibrium with its environment. The curve at the top in Fig. VII indicates that equilibrium was approached in this larger cloud.

The two lowest penetrations (Figs. V and VIII) show, curiously, a double peak in LWC. These peaks are real since they also occur in the droplet sampler replicas. The only difference is again in the time response. The sampler data shows that the LWC should momentarily go to zero in the center of the plume.

The temperature data in Figs. III, V, VII, and VIII has nearly an inverse profile to the LWC. The cause may be the cooling



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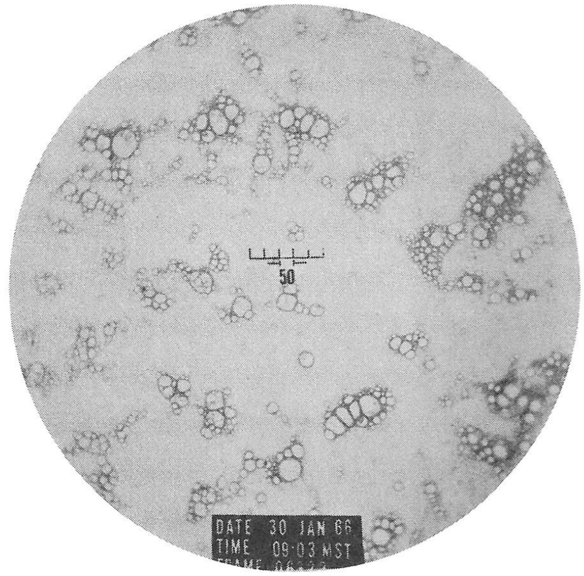

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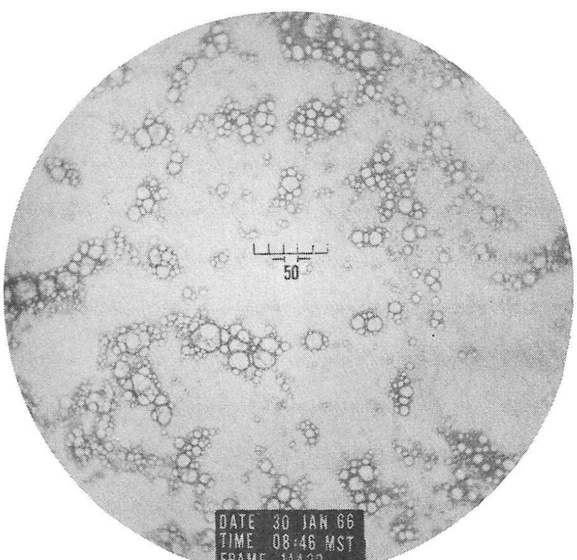

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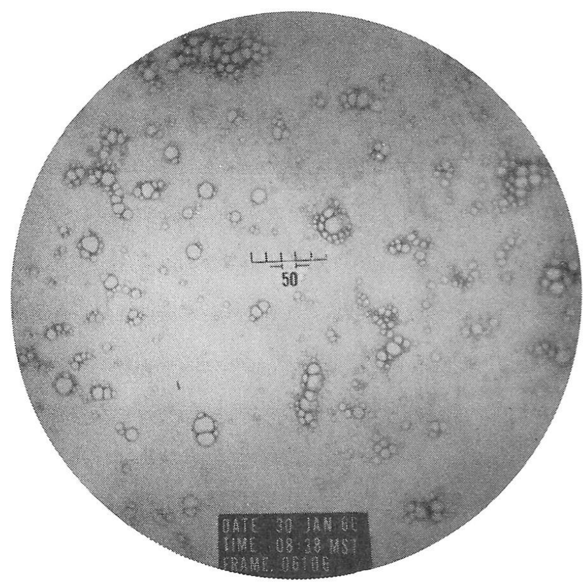

D

Figure IX
The maximum droplet concentrations for each of four penetrations.

of the sensing element of the Rosemont temperature probe by the evaporation of water droplets, but the pattern is not universal. Figures IV and VI show the temperature rising with LWC. This is especially true of the Old Faithful plume (Fig. VI) where the temperature at the center is 2C higher than the surrounding air. The typical plume pattern that may be gathered from these figures is one with a core temperature about 1C higher than the wall temperature at the same altitude. The only exception is the uppermost penetration of Castle geyser (Fig. III). Here, of course, the hot core may have disappeared due to entrainment of cold air on the way up. The typical temperature profile suggests the theoretical flow patterns of plume convection: a fast rising core with slower rising walls mixing with the outside air. We see from the curves that the Rosemont temperature probe has a response time of well less than 0.1 second.

The dotted line in these figures is a measure of the cube root of the energy dissipation rate $\varepsilon^{1/3}$ due to turbulence according to the MRI Universal Turbulence Meter. This device takes the derivative of the air speed that is recorded by a small, free propeller set in the airstream and averages the absolute value of this derivative over a few seconds.

While the turbulence parameter $\varepsilon^{1/3}$ fluctuates erratically during the course of the flight (as is demonstrated in Fig. II) the fluctuations during plume penetrations take on a somewhat regular pattern. Here we see a distinct rise in $\varepsilon^{1/3}$ that is closely associated with the rise in LWC. In most cases there is a second rise near the end of the penetration. Since $\varepsilon^{1/3}$ is a non-negative parameter we have no way of knowing whether the second bump is due to an airspeed fluctuation that is the negative of that causing the first bump (as might be expected from the symmetry of the plume).

The trailing slope of the curves indicates the instrument response time of about four seconds, which is very slow for the detail desired here. Also, the design of this instrument is based upon the assumption of isotropic turbulence, an assumption which is not valid for fast rising plumes. The fluctuations measured here are those in the horizontal component of the air velocity.

Seeding activities characteristically begin early in the Upper Geyser Basin. Seeding with dry ice began at the base of Castle Geyser at 0830 and continued until 0900 MST. The ice found during the flights of the 30th was small ($5\mu x 30\mu$), irregularly shaped, and scarce. Most ice was found at the edges of the seeded geyser plume, although lone ice crystals were found widely scattered above the valley. Samples of the ice crystals found at the edges of Castle Geyser are shown in Fig. X. Scattered ice, not directly associated with a plume is shown in Fig. XI.

The sensitivity of the continuous particle sampler to changes

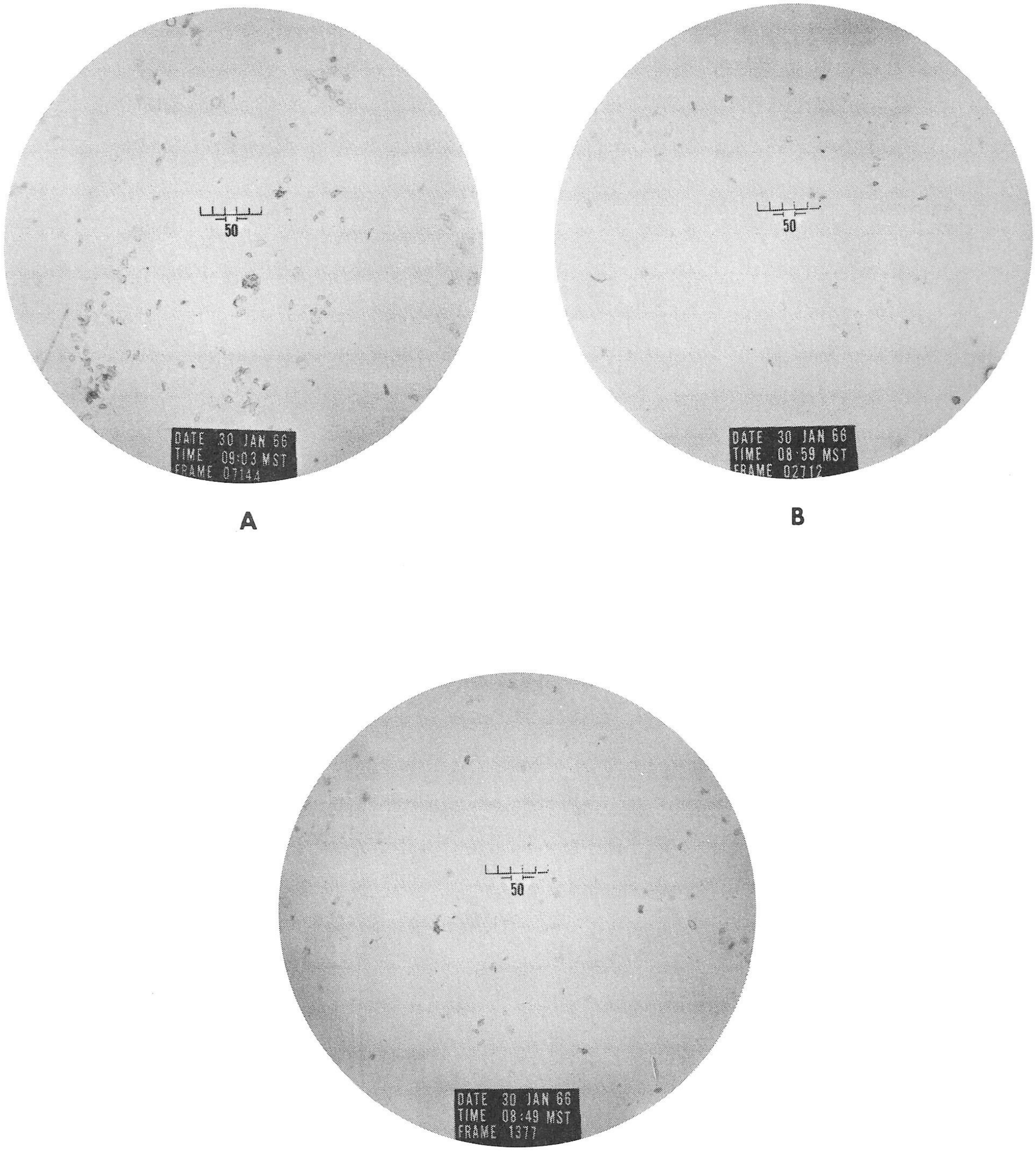

Figure X
Ice crystals at the edge of the plume above Castle Geyser.

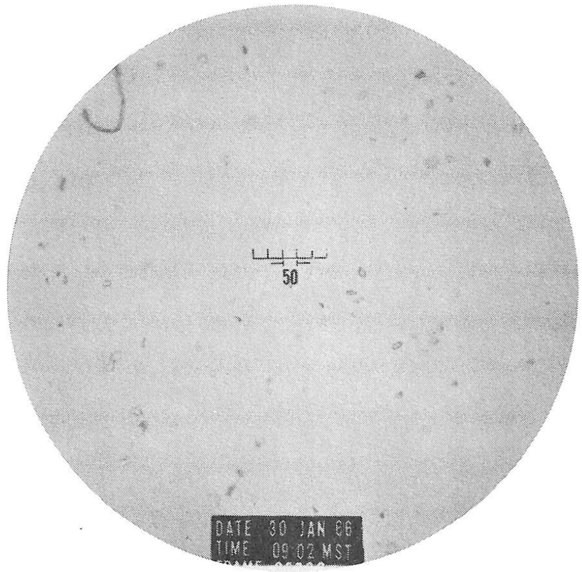

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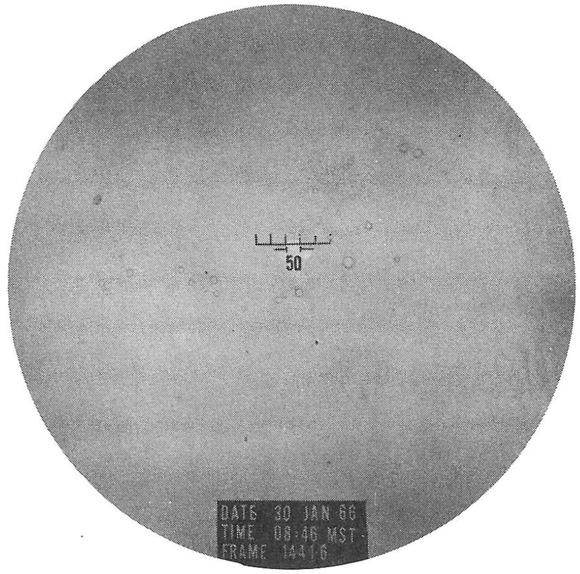
Figure XI
Ice crystals not near plumes.

in droplet densities is demonstrated by the following. The first small peak in the LWC of Fig. VII is seen in the sampler records. The sharp boundary of droplets is illustrated for the Old Faithful penetration in Fig. XII. Shown in (a) is the first frame wherein droplets are detected. One frame later (b), corresponding to a distance of 3 meters into the plume, the great increase in the number of droplets is seen. The peak of this penetration has already been shown in Fig. IX c. This peak comes nine meters after Fig. XII b. These two frames are representative of the relation of the droplets at the peak to those on the side of a plume. We see that the number of droplets increased significantly and their diameters slightly. Droplets in the plume varied in size from 6μ to 60μ diameter, with a mean of about 15μ near the edges and 35μ inside.

The 28th was a day during which the crew learned to cope with the new situation. Exact correlations are lacking and therefore no confident statements can be made about a particular geyser penetration. However the replicas taken by the particle sampler differ so much from those of the 30th that a few illustrations are in order to show the high degree of natural variations in the plumes of the UGB. Samples of ice crystals found on the 28th are shown in Fig. XIII. No such quantities of ice were encountered on the 30th. Also different on the 28th was the droplet distribution inside the plume. The maximum concentration of such droplets are shown in Fig. XIV.



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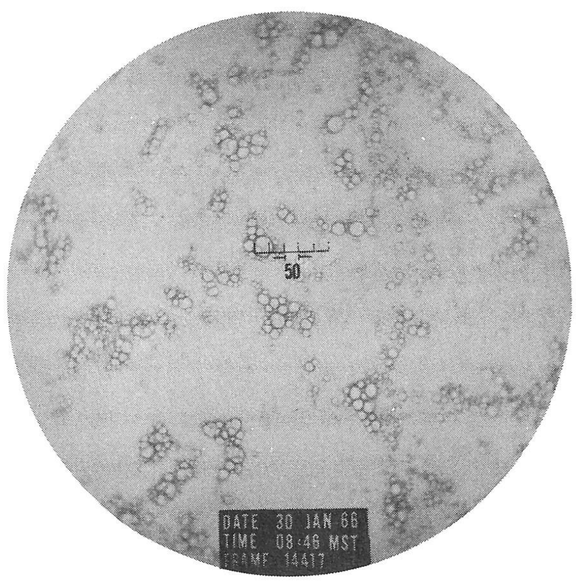

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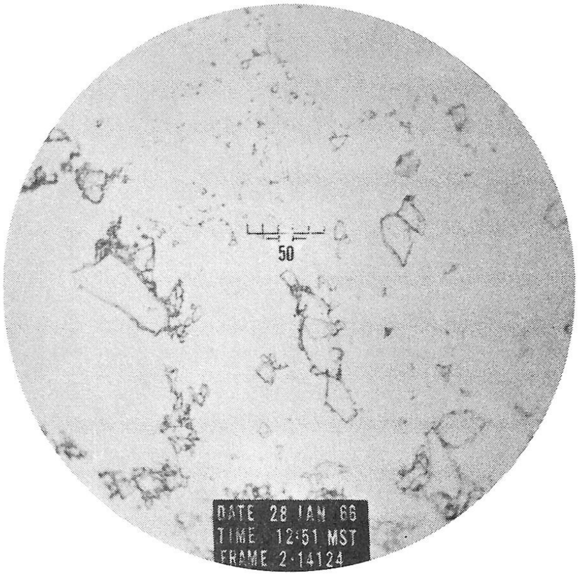
Figure XII
Old Faithful penetration. The spatial distance between a and b is 3 meters. Fig IXc shows the distribution 9 meters further.



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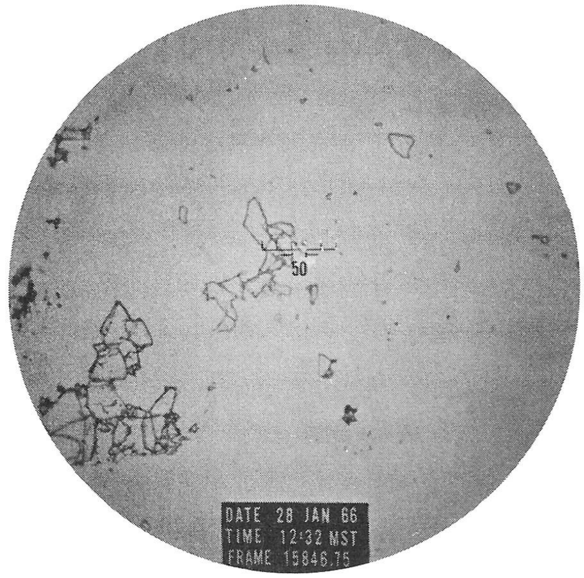

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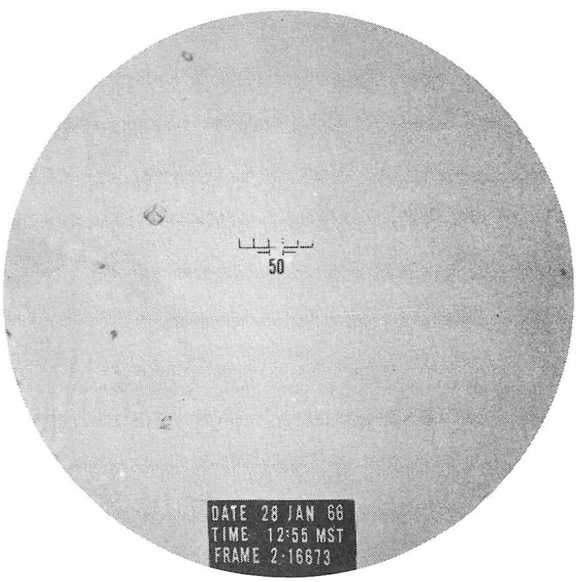

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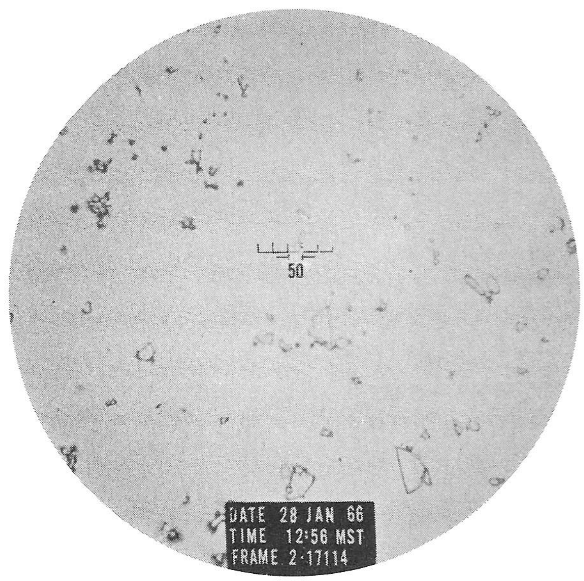

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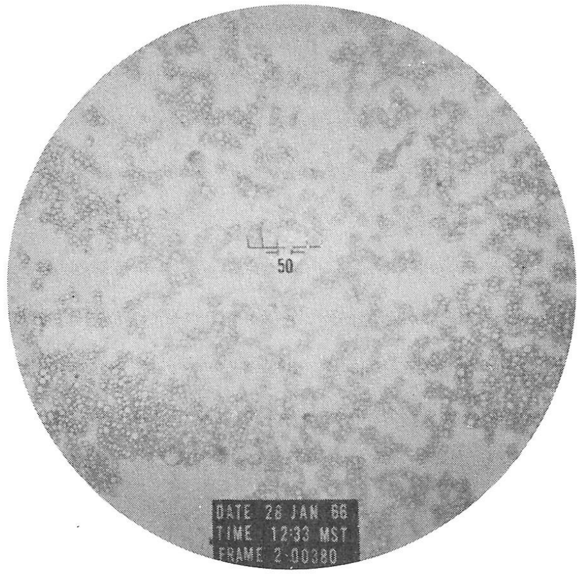
Figure XIII
Ice crystals found on 28 January 66 about 1230 MST.



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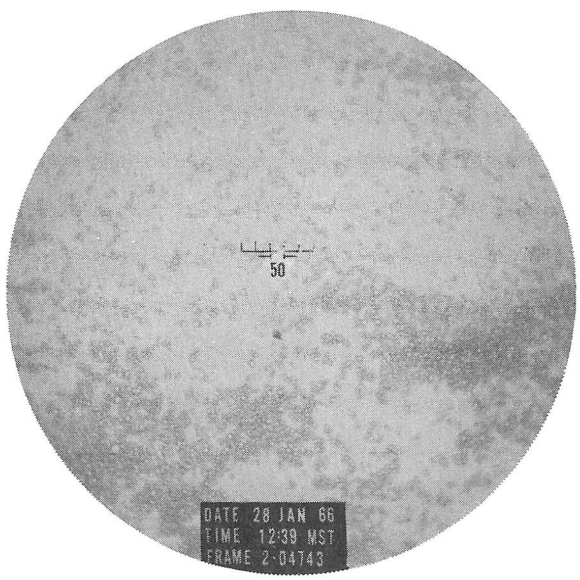

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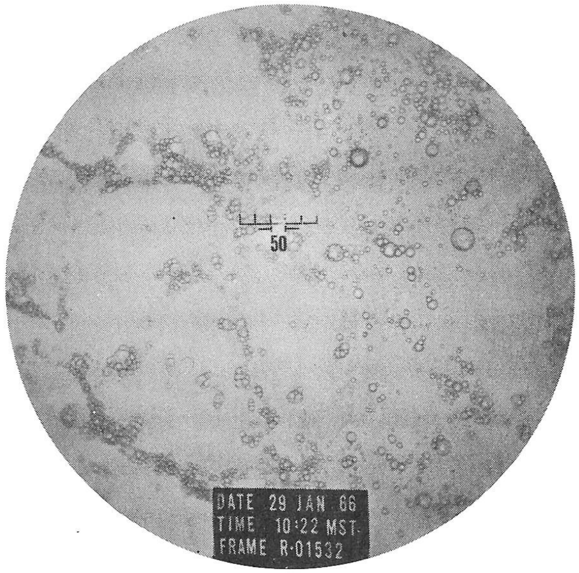
Figure XIV
In-plume droplet replicas on 28 January 66, about 1230 MST.

The distribution is almost mono-disperse with a high concentration of 10μ diameter droplets, which is significantly different from the broad distribution of sizes found on the 30th.

The difference may be in some way due to the time of day, since the measurements on the 30th were made near 0900 MST, while those of the 28th were taken about 1230 MST. Indeed the replicas of the intervening day which were taken at an intermediate time (1020 MST) show intermediate characteristics to the 28th and the 30th. Examples are shown in Fig. XV. No ice was found near the plumes on the 29th. Future investigations could be designed to test some of the possible causes of the various particle distributions.



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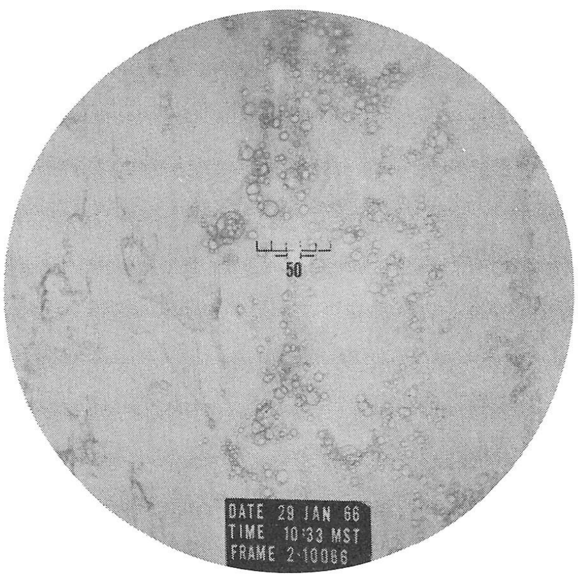

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Figure XV
In-plume droplet replicas on 29 January 66, about 1020 MST.

IV Equipment Evaluation

On the right side of the aircraft's nose is a horizontal wing-like arm about one meter long. Near the end of this arm, facing the airstream, is a slit 3 mm wide and 10 mm high, behind which is passed the clear celluloid of a 16 mm movie film that has been coated with a solution of Formvar in Chloroform. This plastic captures the free particles in the air that happen to enter the slit and hardens around them forming a permanent replica of the airborne particles, whether water, ice, or dirt.

This was the first test that DRI had made of the new particle sampler in very cold weather. The test exposed some of the weaknesses of the sampler that had not appeared in the laboratory and previous field testing, and some that would not arise at all in warm conditions.

The primary difficulty was the inability of the machine to operate at sufficient speed or at all when stored at temperatures below about -10C. Much of this difficulty could perhaps be remedied by the use of cold weather oils. Further difficulty arose from the film base which became hard and brittle when cold and subsequently cracked and tore. Since space near the threading wheels is scarce, bare hands are required for loading, a very difficult job when the metal, electric motors, aircraft batteries, and the crew's fingers are cold. Several times the brittle film snapped and the job had to be redone. The removal of the sampler from the aircraft's nose is out of the question since this is a three hour job on a warm day. The only practical solution seems to be to keep the whole sampler warm at all times. Four 75-watt light bulbs placed in the nose of the aircraft next to the sampler kept it warm enough for operation on the 30th.

The Formvar application system did not seem to be troubled by the cold. Once a good coating was obtained (as verified by looking through the intake slot) it always stayed good throughout the flight. All heaters were systematically turned on after the slightest airspeed was obtained. This seemed to significantly warm the machine and in the case of the 29th was probably responsible for its restarting in the air after 30 minutes of being frozen.

In spite of these difficulties the droplet sampler was certainly the most useful single data instrument on board. The continuous method of sampling, as opposed to a single shot method, allowed the capture of the detailed variations in the particle distributions during the penetrations. The film marking system allowed accurate time correlation of the sampler data with the sensor data on magnetic tape. The replicas from this continuous system yield to convenient and rapid scanning through a stop-motion 16 mm projector with a magnifying lens.

The magnetic tape data system proved to be very advantageous in the comprehensive analysis of the experiment. Tape recording speed of 1 7/8 ips allows over two hours of continuous recording with a response time faster than any of the sensing instruments. Playback of data onto pen or oscillograph recorders can be made at 15 ips (or eight times real time) with selective signal amplification and chart speeds. Thus any portion of the record can be expanded for a closer investigation.

The operation of the 16 mm time lapse movie camera in the aircraft's nose was very successful, although a method of taking pictures faster than one frame per three seconds would be desirable for any future project involving as rapid changes of view as the geyser penetrations. Detail was lost by the three second picture interval since in this time the aircraft traveled some 200 meters.

V Project Evaluation

The airborne expedition to Yellowstone Park successfully demonstrated the capability and utility of airborne research as a supplement to the ground based experiments. The aircraft has the ability to move across the basin more rapidly than most natural changes and therefore obtains a set of data that is almost momentary. It can sample at chosen altitudes with the minimum limitation being only a legal one, and yet rise high enough to allow a perspective to be gained of seeding effects not available to an observer on the ground. The data recording system resolves changes in a 10 meter distance which is ample for most atmospheric research efforts, and this can be decreased for many measurements if desirable.

The continuous particle sampler was shown to be a very useful instrument for showing how particle size, type, and number vary over short distances in such small clouds as geyser plumes. Several practical problems to the all-weather operation of this instrument were found and many straight forward solutions to them were discovered. This was the first field test of the film marker's ability to allow correlation of sampler data with electrically recorded sensor data. The result was better than expected; correlations to 0.01 seconds were performed in the analysis.

Uses of an aircraft for future study might include the following: (a) The measurement of air flow patterns in plumes could be compared to theoretical models of plumes containing liquid water. An investigation could be made into the cause of the varying number and size of droplets and ice crystals found on the different days. (b) The effects of aircraft seeding could be compared with those of ground seeding. Both ground fog and geyser plumes could be seeded. (c) Additional equipment which would be useful on the aircraft would be a nuclei counter, a device for measuring the electric field, a gust probe to measure air motions independently of the aircraft's motion, and an infra-red temperature sensor to provide a check on the in-plume temperature.

For the Desert Research Institute this expedition marked the first successful operation in the comprehensive gathering of atmospheric data. It was a bench mark sought after for more than a year, and one that was achieved by the development of proper equipment, care in the use of the equipment, and the development of cooperative teamwork among the crew members. This concentrated field operation put the DRI months ahead in its subsequent field experiments.

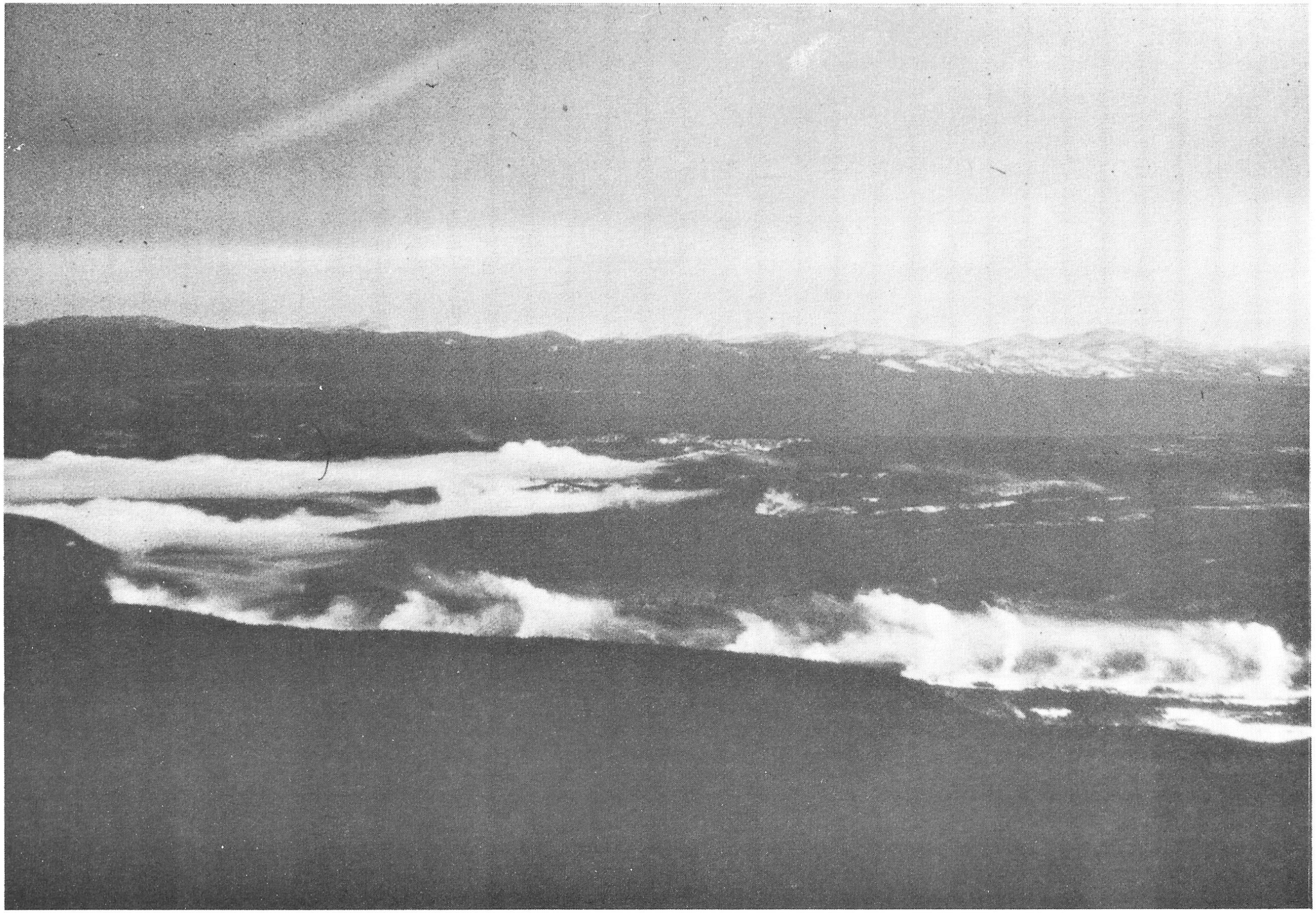

Plate II
Wind shear above the geyser basin is shown by the sharp bending of the plumes.

Plate III
A dual eruption generates plumes typical of those penetrated.

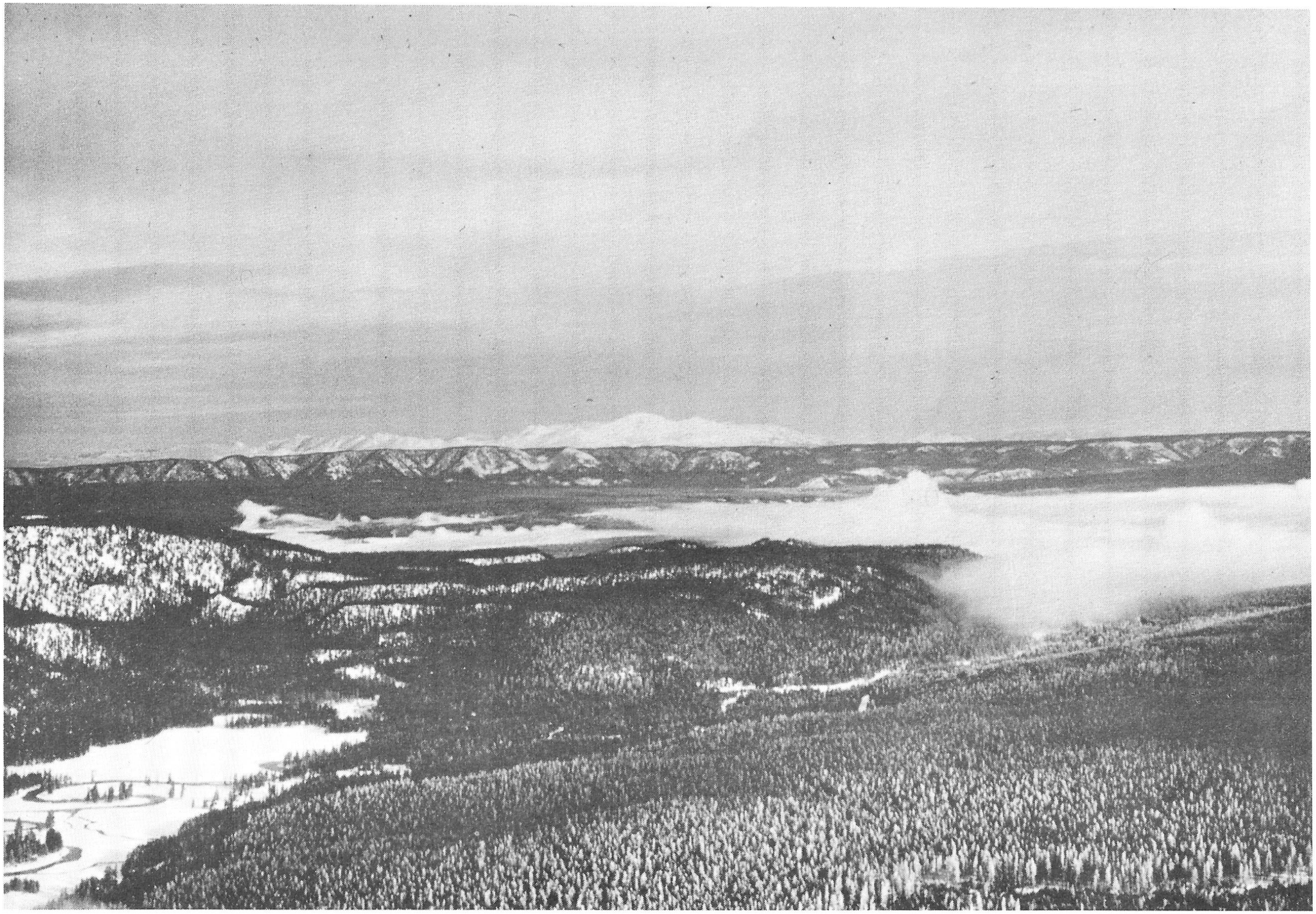

Plate IV
Fog remains in Midway Geyser Basin after that in Upper Geyser Basin has cleared. The large plume coming through the fog is shown closer in Plate V.

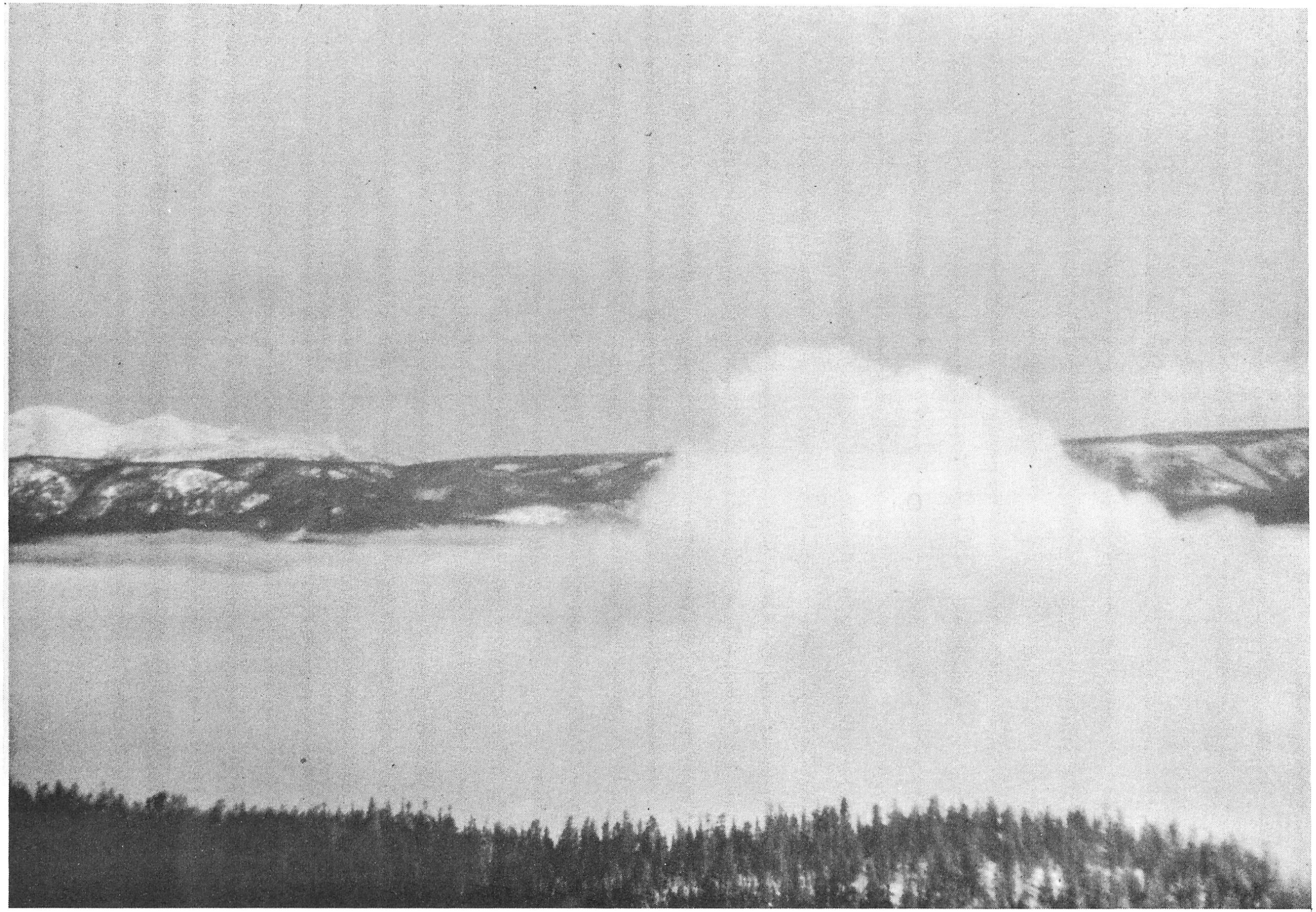

Plate V
This large plume projecting through the fog in Midway Geyser Basin was used as the reference, unseeded plume.

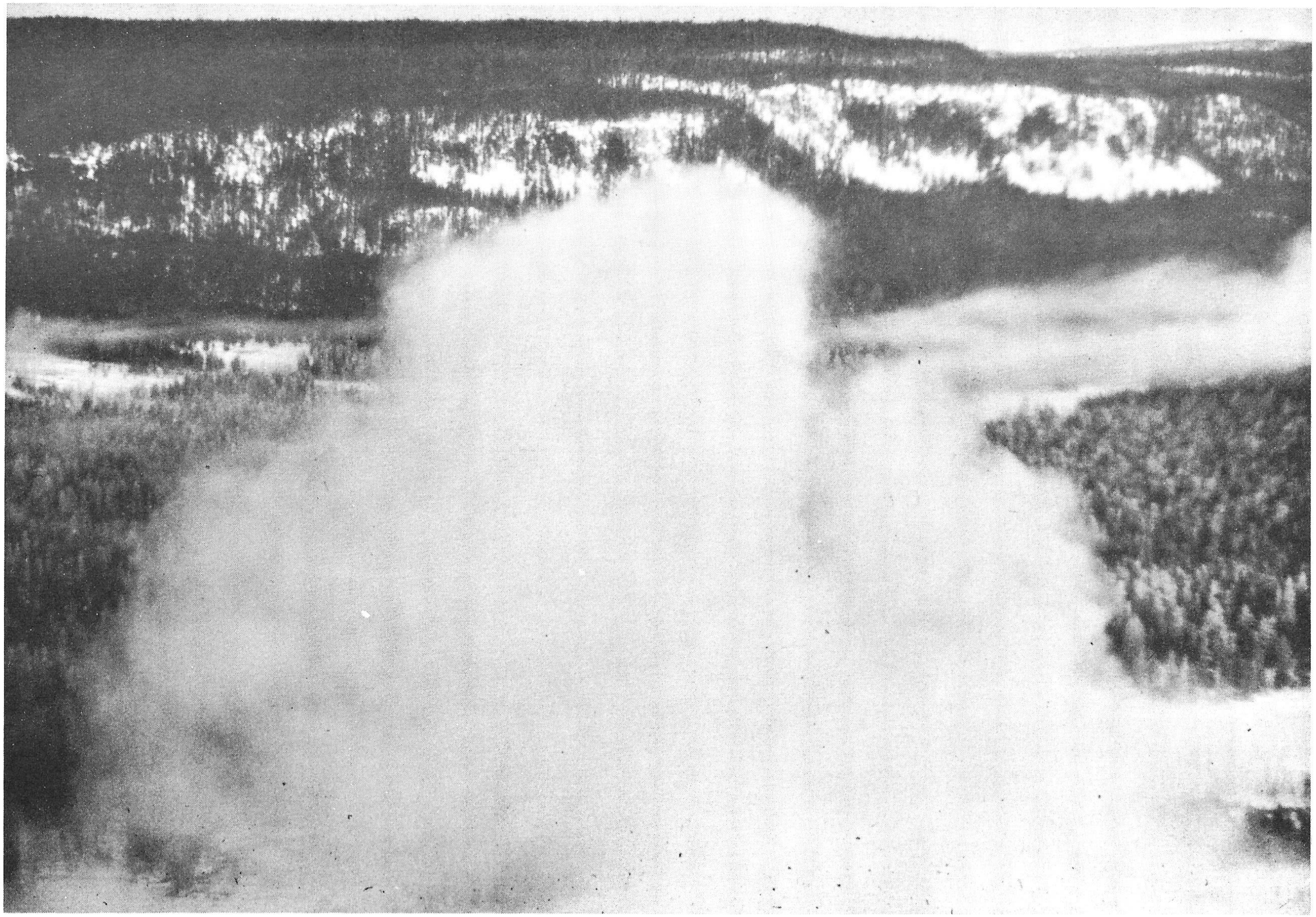

Plate VI
This plume above Castle Geyser was seeded from below with dry ice.

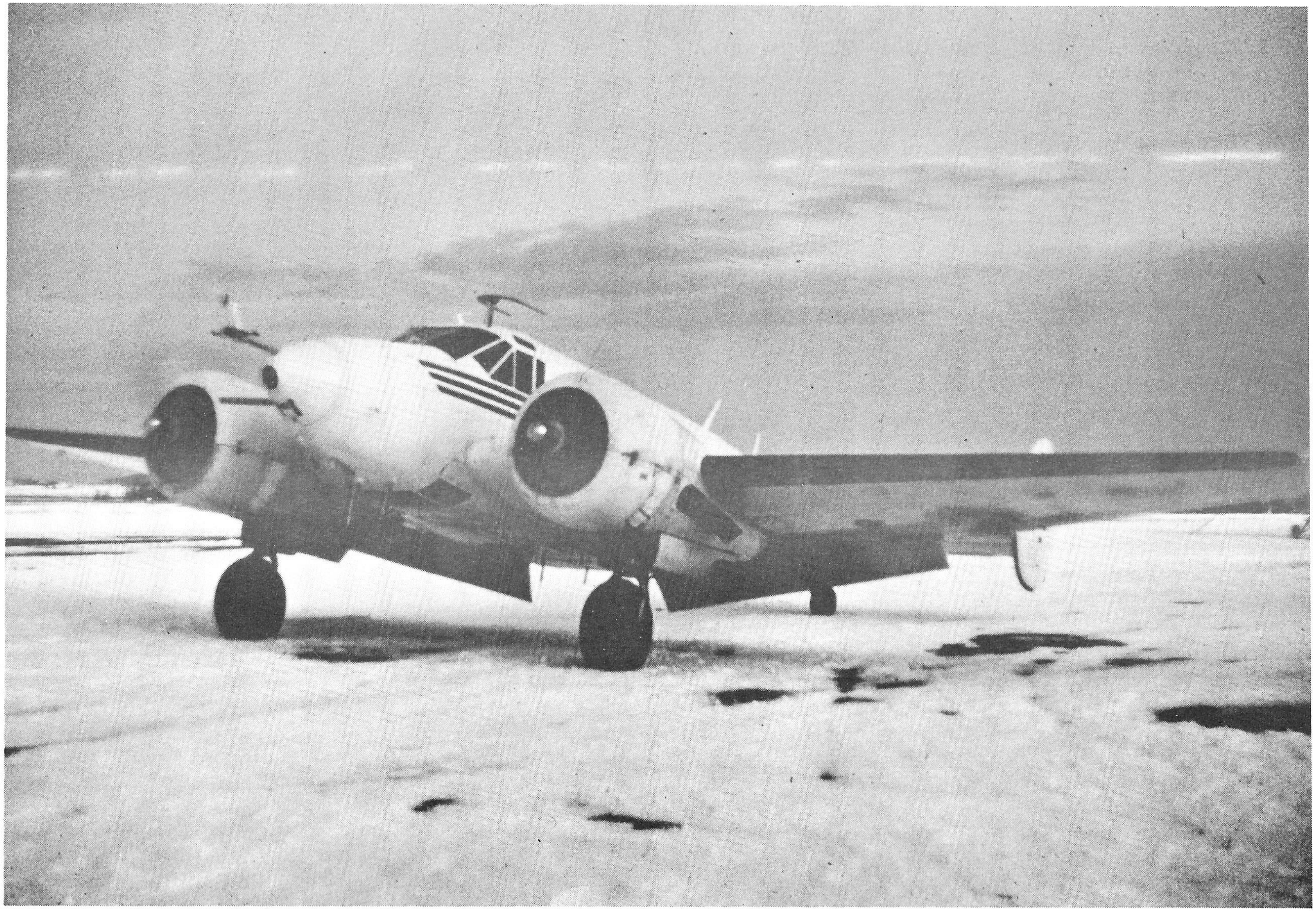

Plate VII
The DRI Beechcraft is ready for takeoff at Idaho Falls. Atmospheric sensing instruments are on the nose boom and the particle-sampler arm is at the right of the nose.

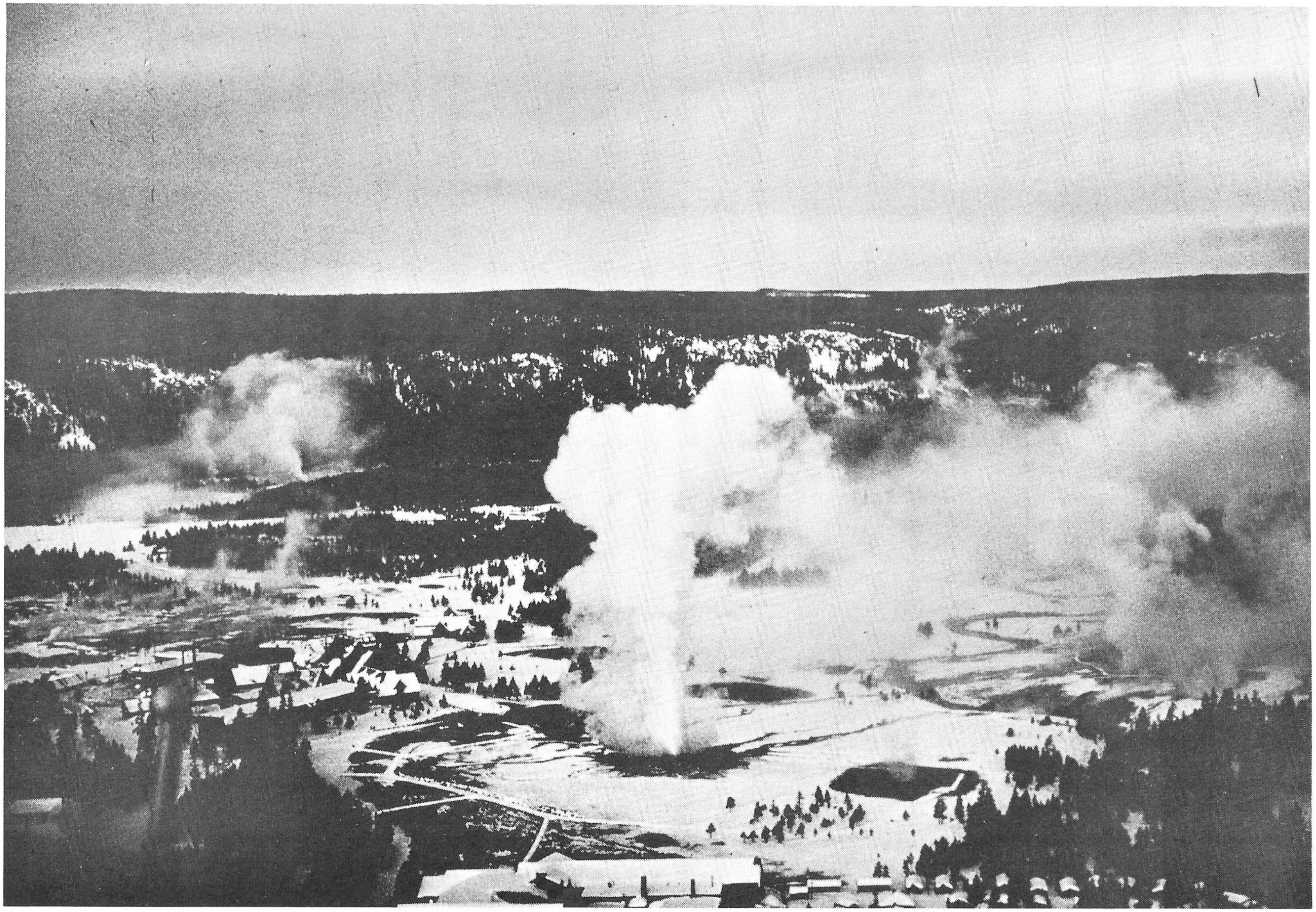

Plate VIII
The airborne sensors are shown in the lower left prior to a penetration of the plume above Old Faithful.