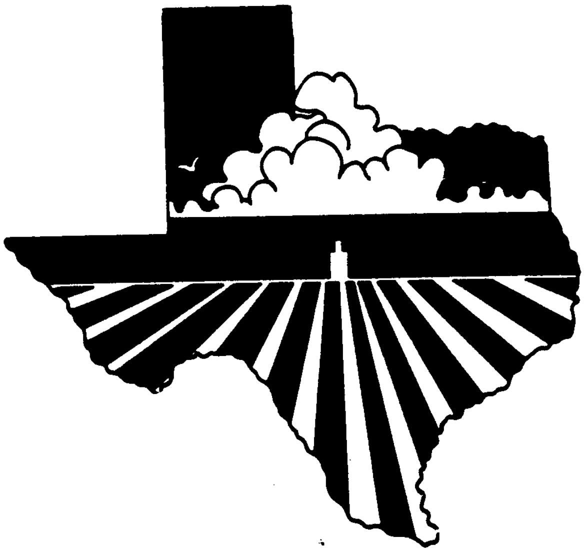
OPERATIONAL SUMMARY OF TEXARC 1994

The Texas Experiment in Augmenting Rainfall through Cloud Seeding

August 1-September 1, 1994

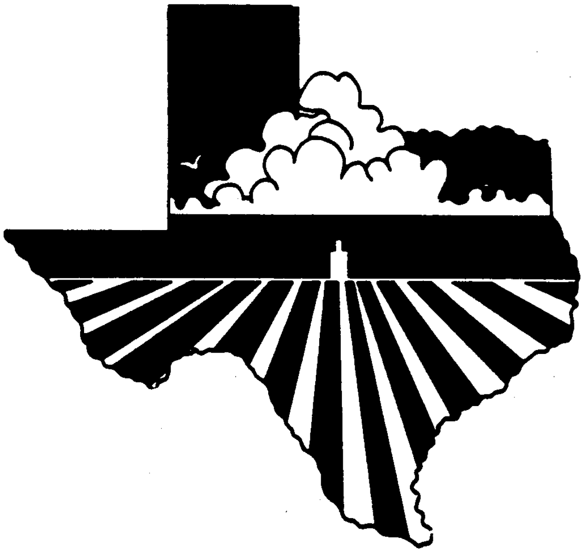


Texas Natural Resource Conservation Commission
Austin, Texas 78711-3087

OPERATIONAL SUMMARY OF TEXARC 1994

The Texas Experiment in Augmenting Rainfall through Cloud-Seeding

August 1 to September 1, 1994



TEXARC Headquarters:

Big Spring Industrial Airpark
2000 Airpark Drive West
Big Spring, Texas 79720

Prepared by:

George W. Bomar
Senior Technical Specialist
Texas Natural Resource Conservation Commission (TNRCC)
P. O. Box 13087
Austin, Texas 78711-3087

and

Dr. William L. Woodley, Ph.D., C.C.M., President
Woodley Weather Consultants
11 White Fir Court
Littleton, Colorado 80127
(303) 979-7946; (303) 973-3446 FAX

March 1, 1995

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

DEFINITIONS

Chief Scientist - The individual (William Woodley) who will made, from the vantage of the seeder aircraft, all decisions relative to the conduct of seeding missions, including the declaration of an experimental unit and managerial guidance to both aircraft throughout the conduct of a mission

Convective Cell - The basic element of convective cloud systems, consisting of a single updraft and downdraft couplet. The convective cell has been selected as the treatment unit of the TEXARC Project.

Experimental Unit - The convective elements, convective cells, and small multiple-cell convective systems, treated within a circle having a 25-km radius and centered at the location of the convective cell which qualified for the first treatment.

Objectives of TEXARC - The primary objectives of the Texas Experiment in Augmenting Rainfall through Cloud-seeding are to increase rainfall from the experimental unit over what would have occurred naturally, to document the physical and microphysical processes operative within the treated convective towers, and to assess the utility of the new Doppler radar as an analytical tool for cloud-seeding research.

Operational day - An operational day was declared principally on the recommendation of the Project Forecaster that convective cloud systems would develop and that seeding had the potential to induce increased vertical growth of convective clouds. Upon declaration of an operational day, all project personnel stoodby for operations and the research radar was operated in the continuous base-scan mode.

Project Manager - The individual (George Bomar) who made final decisions on all matters concerning the conduct of the TEXARC field experiment.

Randomization - The scheme to govern the way in which the TEXARC Project was conducted. It is predicated upon aircraft penetrations of convective clouds that establish the fact that suitable liquid-water contents and updrafts exist and that the formation of one or more small multiple-cell convective systems is imminent. Once a candidate cloud is identified, instructions in a randomly-arranged series of envelopes dictates whether or not silver iodide is actually dispersed by the seeder aircraft.

Small Multi-cell Convective System - A radar echo containing two or more reflectivity maxima, generally within a common echo boundary, but having no horizontal dimension greater than 100 km. It forms the basis of the experimental unit of the TEXARC Project.

Suspension Criteria - Conditions under which seeding would be suspended in order to avoid contributing to a hazardous weather situation. The criteria have to do with severe thunderstorms, tornadoes, and excessive rains capable of producing flash floods.

Target area - A circular area of radius 125 km, centered at Big Spring. A circle with radius of 30 km, within which randomized cases will not be selected, centered at the Skywater SWR-75 radar site near Big Spring, is removed, leaving a total area of about 46,260 sq km.

Treatment - The result of the randomization scheme which determines what action is taken upon the experimental unit. The treatment will be either to seed convective cells within the experimental unit or to consider the experimental unit as a control and sample convective cells without seeding.

Treatment Unit - A convective cell within the experimental unit which meets the seeding criteria of liquid water content and updraft velocity. It is the convective cell which receives the "seed" or "no seed" treatment and in which any effects of seeding should first manifest themselves.

OPERATIONAL SUMMARY OF TEXARC 1994

1.0 OVERVIEW

Since the State of Texas joined with the U. S. Bureau of Reclamation 25 years ago to develop and demonstrate a technology for augmenting summertime rainfall in semi-arid West Texas, a concerted, but discontinuous, research effort has ensued to quantify the effects of timely seeding of supercooled convective clouds. Although funds have been lacking most of the time, substantial progress has been made in pursuit of this goal. Meanwhile the need to explore various non-structured approaches, such as weather modification, for securing additional supplies of fresh water for a burgeoning population remains as acute as ever.

Texas' admission in 1992, by action of the U. S. Congress, to NOAA's Atmospheric Modification Program (AMP) made it possible for Federal and state resources and expertise to be combined to conduct a much-needed, albeit limited, field program during August 1994. With this renewed commitment to demonstrate the efficacy of glaciogenic seeding of convective clouds to enhance summertime rainfall, a team of researchers returned to semi-arid West Texas in the period August 1 through September 1, 1994. Seeded and unseeded convective clouds were monitored simultaneously by ground-based radar and by cloud physics instrumentation mounted on an all-weather T-28. Seeding was accomplished from a second aircraft. This effort to refine and demonstrate the efficacy and utility of cloud-seeding technology is known as the **T**exas **Ex**periment in **A**ugmenting **R**ainfall through **C**loud Seeding (**TEXARC**) Project.

While operational cloud seeding has been performed in the South Plains of Texas in virtually every summer since the Colorado River Municipal Water District (CRMWD) first began rainfall-enhancement activities in the summer of 1970, experimental cloud seeding--the kind required to develop fully the technology and vouch for its cost-effectiveness--has been performed sporadically during the past ten years. A brief (one month) program of randomized cloud seeding in 1990 in the vicinity of Big Spring is the most recent weather-modification research effort. Data collected during that series of experiments in the late summer of 1990, coupled with data collected during similar experiments carried out in the summers of 1987 and 1989, have now been thoroughly analyzed. Results of that analysis are reported later in this document.

Armed with the findings from the study of data from 1987, 1989, and 1990, researchers have revised the conceptual model for convective-cloud development and precipitation in West Texas, and initial tests of the hypothesis were conducted during field work in August 1994. The research included a resumption of randomized cloud seeding similar to that achieved as recent as 1990. However, a new and critically-important component was added to the field program design: In-cloud penetrations using a T-28 cloud-physics measuring platform. The goal was to collect data from treated clouds to allow investigators to understand more fully the dynamical and microphysical processes responsible for the formation of rainwater and how those processes can be augmented to provide additional rainfall on the ground.

2.0 RECENT HISTORY OF CLOUD-SEEDING RESEARCH IN TEXAS

The testing of dynamic cold-cloud seeding concepts for the enhancement of rainfall has been conducted in west Texas on an intermittent, as-funds-permitted basis since the summer of 1986 (Rosenfeld and Woodley, 1989; 1993). Attention was focused initially on evidence for seeding effects on convective cells, which are the treatment units for the experiments. A total of 183 cells (93 seeded and 90 non seeded) have been identified and their properties computed through analysis of three-dimensional, volume-scan, C-band radar data using cell tracking software. The results indicate that AgI seeding increased the maximum heights by 7%, the areas by 43%, the durations by 36%, and the rain volumes by 130%. Cell merger occurred nearly twice as often in the AgI-treated cases. The rainfall and merger results are significant at better than the 5% level using re-randomization procedures. Additionally, it was found that AgI-treated cells produced more rainfall than untreated cells of the same height.

Time-height reflectivity composite cross-sections for the seeded (S) and non-seeded (NS) cells revealed stronger reflectivities aloft immediately after seeding for the AgI-treated cells. This region of enhanced S reflectivities expanded and descended with time, reaching the earth's surface by 40 min after initial seeding.

The next step focused on the areas surrounding the treated cells. A new and improved "focused area" approach, involving calculations for radii of 7, 10, 15, 25, 50 and 100 km around each treatment position was developed and applied. The rainfalls from the S cells exceeded the rainfalls from the NS cells at radii < 10 km early in the treatment period, and this apparent effect spread to larger radii with time. These results are consistent with a positive effect of AgI treatment on rainfall that begins on the cell scale, where the seeding takes place, and spreads outward with time.

Analysis of the 34 (17 S and 17 NS) small mesoscale convective clusters (i.e., the experimental units) obtained to date produced ratios of S to NS rainfalls of 1.37, 1.27, 1.37, 1.26, and 1.27 for the time periods 0-30, 0-60, 0-90, 0-120, and 0-150 min, respectively, after initial seeding. None of the results has strong P-value support due to the small sample size.

The ratios are larger and more significant, when the five experimental units that failed to meet the qualification criteria are eliminated from the sample.

The value of these results lies not so much in the apparent rainfall increases, but in the insights that they have provided, which are now manifest in the revised dynamic-seeding conceptual model that is discussed by Rosenfeld and Woodley (1993). Not only have these new results provided new understanding of the physical processes that are likely operative in west Texas clouds, they have underscored the importance of continuing this experimentation in August 1994 under the acronym TEXARC.

3.0 THE DESIGN OF THE 1994 EXPERIMENT

Funding in recent years has not permitted physical studies of west Texas clouds. The results cited above have been made using a C-band volume-scan radar and a minimally-instrumented seeder aircraft; no other state-of-the-art instrumentation has been available to the effort due to a lack of funding. With the entry of the State of Texas into the NOAA Federal/State Cooperative Program in Atmospheric Modification Research, however, an additional, substantial, and much-needed source of funding has materialized. As a consequence, in Fiscal Year 1994, the State of Texas took its first steps in implementing the research program that has been described both by Rosenfeld and Woodley (1993) and in a multi-year proposal submitted to NOAA/AMP.

3.1 Goals and Objectives

The TEXARC Project is intended to develop and demonstrate an effective technology for the enhancement of rainwater from summertime convective clouds in the southern U. S. Great Plains region. The specific objectives of the research effort in 1994 were:

(1) To document the physical processes that are operative within vigorous supercooled convective towers before, during, and following treatment with silver iodide. The use of the T-28 in penetrating the core of each treated convective cloud will enable investigators to test the hypothesis that seeding with AgI accelerates the formation of ice-phase precipitation. It is expected that the effect of seeding will be a function of cloud-base temperature.

(2) To conduct randomized seeding operations on convective clouds and complexes. The determination, and comparison, of various cloud properties--including rain volume, reflectivity, cloud-top height, cloud area, and cloud duration--of both seeded and unseeded clouds will

enable investigators to corroborate and/or modify the revised dynamic-seeding conceptual model developed in the wake of results from the experiments of 1987, 1989, and 1990 experiments.

(3) To contribute to a national effort (The U. S. Weather Research Program) to develop an accurate predictive capability for both naturally-occurring and modified precipitation episodes. TEXARC in 1994 will assess output from the WSR-88D radar of the National Weather Service in Lubbock in consonance with seeding experiments conducted within the reach of the NEXRAD facility.

(4) To coordinate the activities of the research project with the operational program in the Big Spring vicinity, so that no research or commercial interests are seriously compromised.

3.2 Resources

In addition to a team of highly skilled technicians and scientific investigators, key components of the research infrastructure that were deployed during August 1994 included the T-28 cloud-physics research aircraft from the South Dakota School of Mines & Technology, a twin-engine pressurized aircraft from Weather Modification, Inc., for on-top seeding of growing convective clouds, the 5-cm "Skywater" weather radar unit operated in a volume-scan mode and also used as a tool for identifying the experimental unit and guiding the aircraft to the unit, the NEXRAD weather-radar facility at the Lubbock Weather Forecast Office, and the State's recording rain-gage network.

Because the first few steps in the revised dynamic seeding conceptual model involve seeding-induced glaciation followed by the formation of graupel particles which are sustained aloft by the invigorated seeded updraft (Rosenfeld and Woodley, 1993), documentation of this chain of events requires a very rugged cloud physics aircraft in conjunction with a dual-polarized radar that can measure the difference between horizontally and vertically polarized precipitation reflectivity (Z_{DR}). The T-28 aircraft is ideal for this phase of the planned, long-term, physical studies in Texas. Additional funding will be required, however, to secure the participation of a dual-polarized radar, possibly as early as the summer of 1995. In the interim, much can be learned solely from internal cloud measurements by the instrumented T-28.

3.3 Timing and Location of Experiments

The planned series of experiments over the area shown in Figure 1 began on Thursday, August 4, 1994 and continued through

September 1, 1994. Both the seeder and research aircraft were deployed out of the Big Spring Municipal Airport, which served also as the site of project headquarters. The Skywater radar system was maintained at Howard County Airport, 6 miles northeast of downtown Big Spring and 10 miles east-northeast of the Municipal Airport.

The research site consisted of a large portion of the southern U. S. Great Plains, from the vicinity of Lubbock in the far north, the Texas-New Mexico border to the west, the Edwards Plateau to the south, and the low rolling plains of west central Texas to the east (Fig. 1). The TEXARC project site is represented by an area within a circle of 100-km radius, centered at Big Spring, where the Skywater radar system is positioned. A region with a 30-km radius, also centered on the radar site near Big Spring, is removed from the area because cells located within the inner area and having tops above 12 km AGL cannot be seen by the radar in its normal volume-scan mode.

3.4 Key Personnel

Those individuals who participated in field the activities included the following: the Chief Scientist (Dr. William Woodley), a co-Principal Investigator (Dr. Daniel Rosenfeld), a Research Scientist (Dr. Gerald Jurica), a radar meteorologist (Ray Jones), a rain-gage technician, a crew of six persons operating and maintaining the T-28 research aircraft, the pilot of the seeder aircraft, a radar technician to ensure the operation of the Skywater system throughout the research period. The Project Director (George Bomar) served also as forecaster. The Chief Scientist is responsible for overall management of technical aspects of the experimentation, including the function of scientific observer on the seeder aircraft.

3.5 Type of Experiments

The effort described in this report was exploratory in nature, meaning that is was a flexible, interactive, guided search for evidence of treatment effects, as well as a better understanding of what microphysical and dynamic processes contributed to that effect. Once this objective has been achieved, later experimentation can be confirmatory in nature, wherein a well-defined, inflexible process with a sharp focus on replicating (confirming) a result, can be repeated with a minimum for variability and bias.

The research was performed in conjunction with the operational rainfall-augmentation program of the CRMWD. However, the manner of doing the research did not compromise the objectives of either program.

The research scheme was intended to document the physical processes in vigorous supercooled cloud towers before and after randomized treatment. Treatment was accomplished from a seeder aircraft by ejecting 10 or more AgI flares (20 gms of AgI per flare) into the vortical top of the subject cloud tower. The T-28 cloud physics aircraft made a pass through the subject tower immediately prior to its treatment and repetitive passes through the tower afterwards, in most cases at the level of initial treatment. Care was exercised to avoid Aircraft-Produced Ice Particles (APIPs) in the cooled regions near the propeller tips, but it is likely that APIPs were produced on some occasions. During the monitoring phase of the cloud-physics experiment, the seeder aircraft flew a pattern to photograph the subject tower with a hand-held still camera and with an aircraft-mounted video camera. The observations made by the T-28 will be subjected to exhaustive analysis and the results will be interpreted in the context of the conceptual model.

It is hypothesized that AgI seeding will accelerate the formation of ice-phase precipitation in treated clouds, rendering the condensed water into a form (likely graupel) that is less dense than rain water and that will be carried aloft by enhanced vertical motions in the cloud and for longer periods compared to liquid precipitation. The result is hypothesized to be larger, taller, and longer-lived clouds that produce more precipitation. The role of the T-28 was to document the microphysical evolution of treated and untreated clouds to verify the accelerated developoment of the ice phase and its prolonged maintenance aloft in treated clouds as compared to untreated ones.

3.6 Definition and Selection of the Experimental Unit

The continuing experiments were carried out in accordance with the design described by Rosenfeld and Woodley (1993) over an area centered on the Skywater radar. In every case, the experimental unit was the small multiple-cell convective system within a circle having a radius of 25 km and centered at the location of the convective cell, which qualified the unit for treatment. The treatment decisions were randomized in blocks on a unit-by-unit basis and all suitable convective cells within the unit received the same treatment -- silver iodide (AgI) in the case of a seed (S) decision or simulated AgI in the case of a no seed (NS) decision.

The selection of the experimental unit was based upon the following criteria:

1. A preliminary sampling pass shall establish that convective cells in the area contain liquid water contents ≥ 0.5 g m^{-3} and updrafts $\geq 1,000$ ft min^{-1}.

2. No cloud or cell within the experimental unit at the time of initial treatment shall have a top reaching above 10

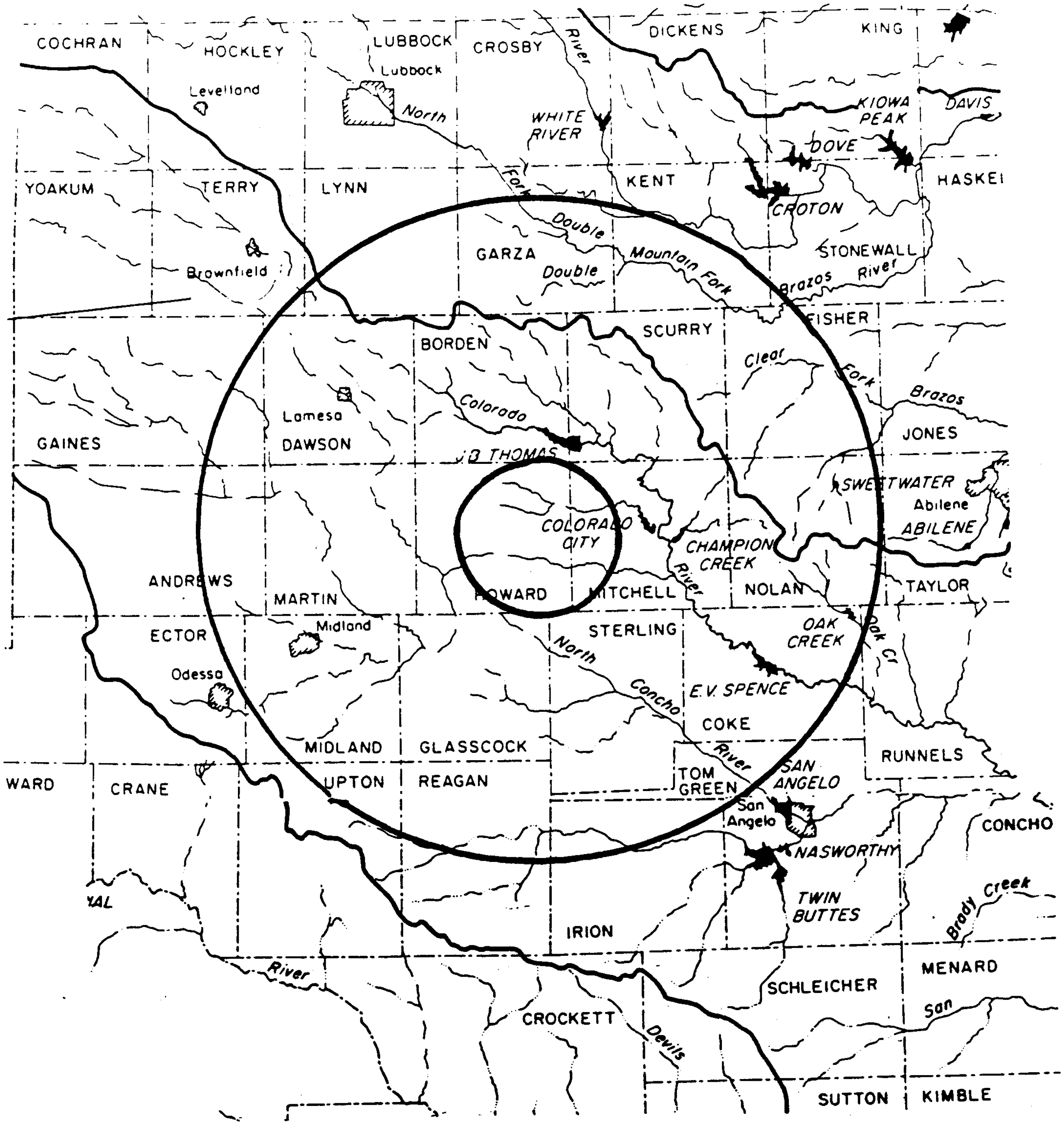


Fig. 1. Research site for TEXARC, a 100-km radius circle centered at Big Spring. A 30-km radius circle, centered at the location of the Skywater radar near Big Spring, is removed, leaving a total area of 28,574 sq km.

km AGL.

3. At least some of the subject cells shall have top temperatures of 10°C or colder.

4. At the time of selection, the center of the experimental unit shall be at least 40 km from cumulonimbus clouds displaying radar reflectivities > 50 dBz.

During the experimentation on a particular experimental unit, the following applied:

1. The center of the experimental unit shall always be at the location of the convective cell that qualified the unit. This position is advected with time with the mean speed of the convective cells in the unit.

2. All untreated cells contained entirely within the 25-km circle become potential seeding targets and, by definition, become a part of the experimental unit.

3.7 The Methodology

During the randomized experimentation, suitable supercooled convective cloud towers within the convective cells received either simulated AgI treatment or actual AgI treatment near their tops (typical tops heights of 5.5 to 6.5 km and top temperatures -6°C to -10°C). The seeding devices were droppable flares that produced 20 gm of AgI smoke during their 1 km free-fall through the upper portion of the cloud. Between 1 and 10 flares normally were ejected during a seeding passs, more on some occasions. The flare ejection button was pressed approximately every second while the cloud liquid water reading was > 0.5 g/m^3 and the aircraft was in updraft (the 5 m/sec requirement applies only to the initial qualification pass). In the simulated seeding passes no flares were ejected when the button was pressed, but the event was recorded in the aircraft data system. The treatment decision for each experimental unit was revealed after the qualification pass. Thus, all subsequent seedings were not "double-blind". The rationale for this is addressed by Rosenfeld and Woodley (1989).

In the TEXARC design, therefore, the treatment units are the convective cells, which contain cloud towers that meet liquid water and updraft requirements. It is the cell that receives the treatment, and any effect of seeding should manifest itself first on this scale before it is seen in the experimental unit that contains the cells.

A pre-requisite for any anlysis of seeding effect is that some of the cloud systems should remain unseeded and used as controls. The determination of which convective systems were to serve as controls and which were to be seeding was made randomly. The randomization scheme described in the Operations Plan used during research in 1987 (Jurica **et al.**, 1987) was developed by scientists within the U. S. Bureau of Reclamation's Division of Atmospheric Resources. This same scheme was adhered to in 1994.

The randomization scheme consists of drawing an instruction from among four sets of envelopes. The seed decisions ("Seed" and "No Seed") have been blocked into four separate categories, each with its own set of envelopes (labeled A-D). Two pieces of information are needed to identify the category to be used in each case: (1) whether or not the system has an identifiable synoptic forcing signature; and, (2) whether the cloud-base temperature is warmer or colder than 10°C. In matrix form, the randomization is as shown below.

		Cloud-Base Temperature	
		≥ 10°C	< 10°C
Synoptic Forcing	YES	A	B
	NO	C	D

The appropriate envelope series is then tapped for the sets of instructions. The Radar Meteorologist (Ray Jones), who is in custody of the sets of envelopes, then recorded the date and time that the envelope was opened on the small slip of paper containing the seed decision and retained it in a safe place.

The research radar, operating in volume-scan mode, will be used to compare convective system characteristics with and without treatment. The outcome will lead to an evaluation and ultimate confirmation, refutation, or modification of the seeding hypothesis.

During the experimentation, the three dimensional structures of the convective rain cells were monitored and recorded by the Skywater C-band. The radar scaned the whole volume of the troposphere in the target area every 5 minutes. These recorded radar data will be the primary source of information for the evaluation of the effect of seeding. The specifications for the Skywater C-band radar are provided in Rosenfeld and Woodley (1989).

The three-dimensional matrices of radar reflectivity factor, which will be used to specify the history of the three dimensional structures of the cells, were saved in 5-minute time intervals. The conversion of the recorded radar units (DVIP) into reflectivity units will be done as described by Rosenfeld and Woodley (1989).

The continuing focus of the experimentation in 1994 was on individual convective cells within clouds and cloud systems, because the cell is the fundamental building block of all convective weather systems. As in earlier work (Gagin et. al., 1985 and 1986; Rosenfeld, 1987, Rosenfeld and Woodley, 1989), convective cells are defined as entities with at least three closed radar reflectivity isolines, spaced at 1 dBZ intervals, at the cloud-base level. All the radar echoes > 12 dBZ are partitioned between these entities, with the division lines coinciding with the trough lines on the reflectivity map.

During the analysis phase, a special method will be used to study the cells that compose the convective rain systems. This method consists of a package of computer programs that use pattern recognition techniques on 3-dimensional digital radar data to identify the rain cells, track them with time and calculate their properties. The product of the computations is a comprehensive data base of physically meaningful properties of rain cells, which can be used to infer the internal structure and the dynamics of convective rain systems. This includes the production of time-height reflectivity cross-sections of the tracked cells, which are very useful to obtain a physical understanding of the precipitation evolution in the clouds.

3.8 Components of the Research Apparatus

The 1994 TEXARC research was multi-dimensional, with an array of weather-detection equipment and expertise invested in the four components of the research.

3.8.1 Aircraft for Seeding and In-Cloud Measurements

The research was heavily dependent upon the full use of a reliable aircraft to insert the ice-nucleating agent into supercooled regions of the clouds at a time when conversion of water into ice will release the maximum amount of latent heat. To achieve this, a high-performance, pressurized aircraft (Cessna 340) will be deployed as the "seeder aircraft." The Chief Scientist (William Woodley) was aboard the seeding aircraft to select the experimental units and document the seeding activity with photographs and written notes. The Co-Principal Investigator (Daniel Rosenfeld) was normally with him. In addition, a second aircraft, the T-28 from the South Dakota School of Mines & Technology, was deployed to collect key in-cloud measurements to be used in the analysis of seeding effect on microphysical processes active within the treated clouds. The T-28 had space for only one of the pilots either Dan Custis or Charlie Summers.

3.8.2 Surface Radar

The Skywater weather-radar system played a central role in the research, allowing participants to make selections of both the experimental units as well as the treatment units. The Skywater was operated in a volume-scan mode in order to gather uninterrupted data on the initiation, development, and dissipation of storm systems. At the same time, the meteorologists (Ray Jones and Dennis Musil) using the system's PPI scope assisted with aircraft control. The combination of complete data sets for post-hoc analysis, with selective after-the-fact monitoring of storm areas of particular interest, assures the maximum use of the radar during the period of experimentation.

3.8.3 Surface Rain-Gage Network

The only network gathering surface weather data over the project site was the recording rain-gage network, which consisted of 104 Belfort (weighing-bucket) recording rain-gages strategically located over the area. These gages collected and recorded rainfall data, to be extracted from strip charts after the conclusion of field exercises.

3.8.4 Forecasting

Accurate forecasts for the project site, and beyond, were essential to the success of the research endeavor. The type of convective cloud being treated during the research presents a special challenge to project participants, due to its high degree of temporal and spatial variability. The forecasting program utilized synoptic data which the project forecaster assessed each day to project the likelihood of significant convective development within and near the project site. Updated forecasts were issued when weather conditions warranted. Suspension criteria were also in place to avoid contributing to, or even appearing to contribute to, a hazardous weather situation affecting any part of the project site. These criteria are provided in the TEXARC 1994 Operations Plan (Bomar, et al., 1994).

4.0 A TYPICAL SCENARIO FOR A CLOUD-SEEDING EPISODE

The following is a description of the routine that was followed by those participating in various aspects of the field research and who were headquartered in Big Spring (all times are Central Daylight Time, or CDT):

08:30 Debriefing of flight operations from previous day, including examination of plots and tabulations of reduced T-28 data (with Chief Scientist presiding).

10:30 Weather briefing for the day (by the Project Forecaster) followed by announcement of the plan for the day (Chief Scientist).

11:00 Commencement of Skywater radar operations in base-scan mode at Howard County Airport (by Radar Meteorologist), followed by volume scan mode when first echo appears.

4.1 Flight Operations

In the event suitable convective clouds developed that warranted the deployment of aircraft, the following sequence of events occurred:

1) Launch of the seeder aircraft, if suitable clouds existed in the target area, and climb to "seeding" altitude (19,000 to 20,000 ft) to assess the cloud field. The seeder aircraft had an on-station time of 3 to 4 hours, depending on conditions.

(2) If conditions were highly suitable for qualification of a cloud physics unit, the T-28 was scrambled for cloud physics measurements for the duration of its 2 hours on station. In some cases, this was followed by randomized seeding operations to qualify an experimental unit after the T-28 had left the area.

(3) In some instances, the cloud physics and experimental units were conducted concurrently. In no case, however, was AgI seeding for cloud physics done in a NS experimental unit. When the unit decision was "No Seed", a cloud outside the unit boundary was selected for AgI seeding and cloud physics study, so that the unit would not be contaminated by seeding.

The Cessna 340 aircraft, which served as the seeder and command control, was under the direction of Dr. William Woodley. It had about 3 hours on station at a typical flight altitudes ranging between 19,500 and 20,500 ft MSL (-7°C to -10°C).

The T-28 aircraft served as the cloud physics aircraft, having a time on station of about 1.5 hours at a flight altitude of 19,500 to 20,500 ft. It had only a pilot (Dan Custis or Charlie Summers) onboard with the rest of the space occupied by instrumentation, most of which will be operative just prior to takeoff. Because of its limited time on station, the T-28 was scrambled from the command control aircraft when cloud conditions were judged suitable for optimum use of the cloud physics aircraft.

It was deemed important to make microphysical observations in suitable supercooled convective clouds on each day of flight operations. Cloud reconnaissance was made by the Cessna 340 aircraft after reaching flight altitude. When suitable clouds had been located within 125 km of the volume-scanning radar and unit qualification was not imminent, the T-28 aircraft was scrambled from Big Spring for rendezvous with the Cessna 340. In some circumstances, the T-28 was scrambled in anticipation of the formation of suitable clouds within the hour under the realization that a bad forecast would mean a waste of time and flight hours.

After the T-28 had been scrambled for cloud physics measurements, it rendezvoused with the Cessna 340 at seeding altitude. Both aircraft navigated to a rendezvous point using the GPS navigation systems that were onboard both aircraft. The pilot of the Cessna 340 filed a "MARSA" to allow it to join up with the T-28 for coordinated flight operations.

Once the two aircraft had joined up as a flight of two at an altitude of 20,000 ft p. alt. --- the T-28 slightly to the right of the command seeder aircraft --- they searched the area for suitable clouds. If the cloud remained visually suitable during the approach, the seeder aircraft turned away from the subject cloud after setting a GPS navigation point. Meanwhile, the T-28 continued through the cloud for pre-treatment measurements. Upon cloud exit, the T-28 pilot will reported "clear of cloud". The Cessna 340 then made its treatment pass, sometimes along the track of the T-28 and at other times at large angles to its track. The initial treatment decision (AgI or simulated AgI) was determined randomly at the radar site. After the Cessna 340 exited the cloud, it began a climb to 21,000 ft p. alt and moved away for photography, while the T-28 moved back to the cloud for repetitive passes at an altitude of 20,000 ft p. alt. The passes were made at intervals of no more than 2 to 3 minutes from cloud exit to cloud re-entry.

During this phase of the studies, the T-28 pilot received continual updates from the meteorologist at the Skywater radar as to the size (maximum echo height and lateral extent) and reflectivity structure (max reflectivity and reflectivity gradients) of the subject cloud. In most cases, the T-28 was tracked on the radar scope, so that the radar meteorologist could advise the T-28 pilot as to the conditions that he was likely to encounter during cloud penetration.

Cloud penetrations by the T-28 continued as long as warranted as judged by the flight scientist aboard the seeder aircraft. In most cases, the monitoring continued an average of 30 minutes after cloud treatment. During each pass, it was critical that the T-28 be flown at minimum power commensurate with flight safety, in order to avoid the production of ice crystals at the tips of the propellers. Continuing studies by Woodley et al. (1993) suggest that the T-28 should be a prolific producer of APIPs (Aircraft-Produced Ice Particles) at temperatures < -8°C, when it is flown at a slow airspeed at a high power setting. It was important, therefore, to avoid this flight configuration, although APIPs may have been produced despite these attempts to avoid them.

On all days of cloud physics experimentation, a second cloud was selected for cloud physics study. The treatment decision was automatically the opposite of the first. The aircraft flight protocol described above was repeated for the second cloud.

Once the cloud physics experimentation has been completed, the T-28 will return to base for data processing and production. In virtually all cases, the data were available for review and study by 0800 CDT on the following day.

4.1.1 Logistics

Flight personnel and aircraft operated out of Big Spring's McMahon-Wrinkle Industrial Airpark, which is the former Webb Air Force Base, located on the west side of the city of Big Spring. Logistics, aircraft maintenance, and flare storage were handled from this base. Aircraft maintenance, the loading and unloading of the pyrotechnic flares and filling out the appropriate flare usage forms were the responsibility of South Dakota School of Mines and Technology and Weather Modification, Inc. personnel.

4.1.2 Communications

Voice communications between the two aircraft and to the radar site were conducted on radio on 122.9 MhZ. Standard communication practices were observed among project personnel and between FAA air-traffic control. The FAA air-traffic control facility that was contacted for filing flight plans was in San Angelo (800-WXBRIEF; or 915-944-9315). Within the research target, communications between ARTCC controllers and pilots and IFR aircraft were conducted via direct controller-to-pilot communications channels using the appropriate sector discrete frequency. Any needed on-the-ground coordination with the Federal Aviation Agency was carried out by the pilots of the two research aircraft.

4.1.3 Required Measurements by Aircraft

The standard instrument package aboard the T-28 met the needs of the project. This included the measurement of temperature, using both Rosemount and NCAR reverse-flow probes, and cloud liquid water, as inferred from a Johnson-Williams type hot wire and/or from integration of the output of the FSSP.

Measurement of aircraft vertical motion was critical to this effort. Estimates of air vertical velocity were possible using the outputs of the vertically stabilized accelerometer and the various instruments that measure dynamic and manifold pressure.

The measurement of particle sizes, concentrations and habits were essential to the proposed cloud physics investigations. In most cases, the PMS 2D-C probe should meet most programmatic needs. It was anticipated that the initial seeding signature would be either small ice crystals and/or frozen drizzle drops. Some of these particles were expected to be smaller than the 25 micron lower threshold of the 2D-C instrument. This would occur primarily on the first monitoring cloud pass. Subsequently, it was expected that the primary hydrometeor would be graupel particles which would grow rapidly to sizes larger than the 800 microns upper range of the 2D-C probe.

Aircraft position was the final essential instrument on the T-28. The Trimble GPS system, which provided aircraft position to an accuracy of at least 100 m in worst case situations, was essential to couducting the cloud physics investigations. Without it, there could be no certainty that the T-28 had sampled in the same cloud tower that received real or simualted treatment.

4.1.4 Flight Personnel and Responsibilities

Key personnel for the conduct and management of seeding and cloud-measuring missions were the Chief Scientist, the pilots of the T-28 and seeder aircraft, the mechanics and other crew members of the T-28. The Chief Scientist (William Woodley) operated on-board the seeder aircraft; his colleague, the Co-Principal Investigator (Daniel Rosenfeld) accompanied him.

The pilots and mechanics were responsible for the safety of flight operations. The former operated the aircraft, communicated with the FAA and follow the instructions of the Chief Scientist as long as those instructions were deemed by the pilots to be consistent with flight safety. The mechanics, along with the pilots, were responsible for the airworthiness of the aircraft. Whenever possible, aircraft maintenance was scheduled so as not to conflict with the conduct of research work.

The person loading and storing the pyrotechnic flares (Roger Tilbury) kept careful records of the pyrotechnic expenditures, including notations of all misfires in the flare rack beneath the fuselage of the aircraft.

4.1.5 Data Recording and Processing Requirements

Much of the data reduction and processing that will be needed for analysis of internal cloud structure before and after simulated treatment was done in near real-time in Big Spring thanks to the dedication of the people involved. Further processing can be done either at the SDSM&T and/or by the principal investigators on either VAX or PC computers.

4.2 Weather Radar Operations

The SWR-75 Skywater radar, provided by the U. S. Bureau of Reclamation, was an integral part of the TEXARC experiment. It operated at 5.4 cm wavelength and had a 1-degree pencil beam.

4.2.1. Radar Capabilities

The Skywater radar has a DVIP (digital video integrator and processor) unit to convert returned analog signals to digital values and record them on 13-mm (0.5 in) magnetic tapes. The recorded values are averaged over log video with no STC or range correction. The DVIP permits contoured log video that has been range-corrected between 10 and 256 km (0 to 28 dBZ are added), to be displayed in multiple shades of gray, thus allowing recognition of varying reflectivities within an echo. A color display system is also available whereby six colors can be assigned to any one of the 14 DVIP levels from -10 dBZ to 55 dBZ. Two identical color displays are present in the radar, and one of these displays will be photographed.

A key feature of the Skywater's capabilities is the one allowing a volume-scan of the research target. This capability has a range of 2.5 to 5 min. for 12 individual tilts depending on whether 16, or 8, samples, respectively, are averaged. The maximum tilt angle for the TEXARC project was 18°, such that clouds having tops near 12 km could be detected at 30-km range. The scan sequence included the following: a base-level 1° scan taking 20 sec. to permit 16 samples per average, followed by 17 scans in 1-degree increments, to 18 degrees, each taking 12 sec. and permitting 8 samples per average. A single complete volume scan from 1° to 18° took approximately 4 min. 40 sec.

The Skywater incorporates an L-band (30-cm) radar unit which permits the radar to record unique transponder codes of the seeder and research aircraft on magnetic tape with the echo video from the C-band radar unit. Because of the wide vertical angle of the L-band antenna, aircraft are usually displayed and recorded on every rotation of the C-band and L-band antennae, which are mechanically-linked together. This feature permits exact location of the aircraft as a function of time and allows for reliable determination of which cells within the convective systems have been seeded.

The Radar Meteorologist (Ray Jones) operated the Skywater system in a continuous, volume-scan mode beginning as early as 1100 CDT each day, unless notified that no seeding operations were planned for the day. The observations, along with aircraft positions, were recorded on magnetic tape and used later to identify and track cells within the experimental units.

Personnel connected with the T-28 worked with the Radar Meteorologist to assist the pilot of the T-28 and the Chief Scientist aboard the seeder aircraft with the identification and tracking of convective systems on the Skywater's PPI scope. Radios at the radar facility were used for communication with both aircraft. Prio to launch of the aircraft, the scan modes included 360-degree base scans, sector scans, and RHI scans to obtain echo tops. After launch, the radar was operated in volume-scan mode.

4.2.2 Radar Maintenance and Calibration

Both the calibration and maintenance of the SWR-75 radar is of critical importance to the research endeavor. The Bureau of Reclamation, under an Agreement with the TNRCC, provided the services of a technician (Glen Cascino) specially trained to repair and maintain the radar in satisfactory working order. Although he could not be on-site during field operations, he was on-call at his headquarters in Denver for travel to the research site as expeditiously as possible to effect any needed repairs to the Skywater system. Mr. Cascion traveled to Big Spring prior to the onset of field operations on August 1, 1994 for calibration of the radar and to ensure the system was in good working order.

Routine calibration of the radar was done at least once per week by inserting known signals into the DVIP unit and recording the output on tape. Later, the recorded DVIP values will be related to the known dBZ input values using regression procedures. The resulting equation will then constitute the radar calibration for the period for which it is valid.

4.2.3 Operational Procedures

The Skywater radar was operated daily during the project, with initial activation at about 1100 CDT. The data-gathering mode of the radar was continuous volume scans with 18 elevation angles beginning at 1° and ending at 18°. Each scan, taking approximately 4 min. 40 sec. to complete, was recorded on magnetic tape along with aircraft positions provided by the L-band radar unit. The "blue sky eliminator" on the radar was set to eliminate those radials and bins that did not contain meteorological data. The changing of tapes was made as quickly and efficiently as possible so as to minimize the loss of data.

Communication between the two aircraft and radar personnel intensified once suitable clouds had been found and penetrated. Cloud-pass information was radioed from the aircraft to the radar van after each pass. The information disseminated consisted of time and location of the pass, as well as the character of the cloud tower (i.e. liquid water content, updraft speed, and comments).

Once suitable convective clouds had been identified and the experimental unit (units) defined, the treatment decision was determined by the radar meteorologist using sets of randomized seeding instructions that had been previously furnished to the project by the Bureau of Reclamation. A seeding decision will be obtained from the set of randomized seeding instructions, as discussed earlier.

The definition and selection of the experimental unit, which have been spelled out previously were of critical importance. Both the Chief Scientist and the radar meteorologist had to know the definition by heart so as to avoid violating the experimental guidelines. Seeding of the designated convective system continued as long as the cloud system exists and satisfies all of the rules.

In the case of a cloud physics unit, the randomized treatment decision was determined by the flip of a coin. Then, the second cloud of the pair had a treatment decision the opposite of the first.

4.2.4 Radar Personnel and Responsibilities

The primary duty of the Radar Meteorologist (Ray Jones) was to ensure that the radar was calibrated and operating properly at all times. This required a program of scheduled maintenance plus the ability to troubleshoot problems as they arose. He was also responsible for taping the radar observations, changing tapes with a minimum of data loss and completing a summary log for each data tape, when it had been filled with data.

4.2.5 Handling of Radar Data

The success of the TEXARC project is contingent upon the avoidance of faulty data-handling procedures. Losses in critical radar data mean that time, money, and effort expended in identifying and seeding convective clusters will have been lost to the research effort. To minimize this possibility, an on-site check of the taped radar data was made after each day's operation. This was accomplished by playing the data back through the recorder onto a CRT display. By making spot checks of the data, an individual with meteorological experience is able to assess whether the observations appear "reasonable."

After the data had been checked in the field, the tapes were stored for later editing into the A-file archive format. Subsequently, investigators will use these files, the radar calibration data, and their own software to derive measures of cloud properties such as sizes, areas, rainfall rates, and rain volumes.

4.3 Rain-Gage Deployment

A matrix of recording rain gages, strategically located over a large sector of the research site, was operated during the 1-month field program to collect rainfall data over intervals as small as 15 minutes. The rain-gage network, consisting of 102 Belfort weighing-bucket gages that record rainfall amount on paper strip charts, is characterized by an array of gages with a mean gage spacing of 10 km.

The radar data will be used to quantify the amount of rainwater reaching the ground from both seeded and untreated convective clouds. This year, however, the data will be used for another important reason: to discern the degree to which the National Weather Service's new Doppler radar system (WSR-88D) can, through its cumulative rainfall algorithms, assist researchers in quantifying the amount of rainwater falling on the research site.

4.3.1 Pre-operation refurbishment

An effort to refurbish parts of the rain-gage network was made in the 2-week period preceding the start of field operations. A survey made of the network during the summer of 1993 revealed that as many as 20 of the gages required replacement or repairs. Spare parts, including new chart drives, were installed at some locations by the rain-gage technician. In at least a dozen instances, whole new gages, with new concrete bases, were installed at sites where gages have been missing since 1990.

Prior to August 1, the technician, provided by the Colorado River Municipal Water District, recalibrated each of the gages. Strip charts were loaded on the gages beginning the week of July 24-28 to ensure that data were obtained by August 1.

4.3.2 Maintenance procedures

The routine used in past years of experimentation (1989, 1990), in which all of the gages are serviced systematically at some point during the workweek (Mon-Fri), was followed again in 1994. On each weekday the technician followed a prescribed course of travel, removing used strip charts and installing new ones on about 20 gages per day.

At the time the gage was serviced, the technician noted the following on the used strip chart: the date, the time off, and the name (initials) of the operator. If the gage was found to be inoperable, the reason for failure was noted. When a new gage was mounted on the clock drive, the operator noted the following: the time on, and the name of the operator (initials). The bucket used for the weighing-bucket gages was filled with water so that the gage registered approximately two (2) inches of rainfall on the chart. The gage pen was inked and the clock fully wound. The filling of the bucket and the subsequent evaporation of the water over the week facilitated estimates of the amount of solar insolation and, hence, rainfall occurrence.

4.3.3 Winterization

The rain-gage technician proceeded with winterization of the rain-gage network at the completion of cloud-seeding experimentation. Starting with the Thursday route, on September 1, 1994, the technician removed the used strip chart from each gage but did not install a new one. Both buckets and clocks were removed from the gages at this time. This winterization procedure continued through Wednesday, September 7. Further winterization, including wrapping the gages and, possibly, physical removal of some gages from their respective sites, ensued later, as time and opportunity allowed.

4.4 Forecasting

Since having personnel and equipment in the proper place at the right time is critical to the success of any experimental endeavor, it was important that accurate weather forecasts be formulated and issued in a timely fashion to the project. To this end, synoptic weather data (surface and upper-air) was accessed and analyzed daily by the Project Forecaster prior to the conduct of the formal briefing held each day at 10:30 a.m. CDT. The Forecaster provided best estimates of temperature and wind conditions at key altitudes within the project site, as well as the likely location and time of significant convection. From this forecast, personnel were apprised of the status of the project (a "standdown," "standby," or "go" day) at the conclusion of the briefing.

On occasion the Project Manager/Forecaster was away from the research site, thereby requiring that he formulate the forecasts remotely and transmit the information to the Chief Scientist, who then issued the forecast at the daily briefing at project headquarters.

4.5 Doppler Radar and Rainfall-Intensity Studies

A stated aim of the new U. S. Weather Research Program (USWRP) is to make use of a modernized weather-observing network, such as that now being achieved by the National Weather Service, in improving local and regional weather forecasts and warnings. Meanwhile, the Atmospheric Modification Program (AMP) of NOAA has, as one of its primary objectives, the goal of developing an accurate predictive capability for both natural and modified precipitation episodes.

Thus, to facilitate the collaboration of USWRP and AMP personnel, resources, and interests, a component of research having to do with estimates and measurements of rainfall was incorporated into the 1994 TEXARC Project. With the installation of the new Doppler radar system (WSR-88D) at the National Weather Service Forecast Office in Lubbock, it was possible to begin assessing the potential contribution of this system in quantifying the effects of opportunistic cloud seeding for rainwater augmentation.

The work that was performed by researchers at Texas Tech University in support of the project consisted of two parts:

(1) Real-time support of cloud-seeding operations at Big Spring, including timely interpretation of Doppler radar signals by the TTU investigators concurrent with treatment operations at the research site; and,

(2) Collection and study of both archived WSR-88D and recording rain-gage data for the purpose of making intercomparisons of the two sets of data.

The interpretation of Doppler radar, in real-time mode, was intended to provide project leaders with additional information of potential value prior to, and during, each treatment event. The examination of both archived Doppler data and rain-gage records was aimed at generating rainfall estimates whose validity is corroborated by observed rainfall measurements from the rain-gage network.

Observations and input, provided by TTU investigators on a real-time basis using the WSR-88D, was passed along, as weather conditions and operational status warranted, via telephone to either the Project Supervisor, the Chief Scientist, or the Co-Principal Investigator.

Level 2 archival data from the Lubbock WSR-88D was collected on casette tape from the Weather Forecast Office by the TTU Principal Investigator or his assistant following each treatment event. The Level 2 data subsequently will be matched up with recording rain-gage data, to be given the TTU PI by the CRMWD meteorologist, for the specific treatment event.

A report summarizing the results of the intercomparisons of the two data sets will be distributed during the spring of 1995.

5.0 DATA COLLECTION AND MANAGEMENT

This section deals with the integration, documentation, quality control, and storage of the field data. Any individual, concerned with the data generated from the field research, should find answers to questions about the handling of data or, at the least, be directed to the appropriate location to find those answers.

5.1 Flight Data

The data-acquisition system on the Cessna 340 seeder aircraft recorded data initially on hard disk and these data were transferred to floppy disks for later transfer and archival. The derived parameters were recorded at 1-sec intervals. Post-flight printouts of data at 1-sec intervals permitted in-the-field verification of the performance of both the various sensors and the data-acquisition system. The original flight disks are archived at Woodley Weather Consultants with copies at the Hebrew University of Jerusalem in Jerusalem, Israel.

The thorough documentation of aircraft activities is of paramount importance for case evaluation. Documentation of where the aircraft flew, when seeding occurred, where it occurred, and how much seeding material was used was provided by the Chief Scientist. In addition, he documented the characteristics of clouds considered for selection as experimental units.

The aircraft data provided by the T-28 system of the South Dakota School of Mines and Technology were being processed when this report was being written. The T-28 data set is expected to be available for analysis in the spring of 1995.

5.2 Radar Data

The Radar Meteorologist was responsible for calibrating the radar prior to the onset of research activities on August 1, 1994. He then performed a calibration check of the radar each operational day. This check was performed as early in the day as possible, given that the radar had to warm up before the calibration check. Tapes generated by the calibration were labeled, recorded, and stored for later processing.

All maintenance tasks performed on the Skywater radar by the meteorologist were recorded in the radar log. Information about the weekly calibration and the daily calibration check were recorded in the log. Recorded items included: date, time, cause of task, task performed, and result of task performed. Any changes made to system settings or calibration were clearly documented.

After the calibration check had been performed, the radar was operational and the data were recorded in a volume-scan mode. For each tape generated, the Radar Meteorologist recorded the following information in the Operations Log: date, Julian day, recorder in use, start time (GMT), stop time (GMT), number of records recorded, number of errors recorded, number of end-of-files recorded, tape identifier, operator and comments. At the end of each day, the meteorologist will record a summary of operations.

Each tape was physically labeled by the Radar Meteorologist with a tape identifier after recording had been completed. To minimize the likelihood of the data being misplaced, the tapes were stored in protective canisters.

A careful log of data tape shipments will be maintained by the Radar Meteorologist. Original project tapes were taken, in the custody of Danny Rosenfeld, to the Hebrew University of Jerusalem in Jerusalem, Israel.

5.3 Rain-Gage Data

Data from the rain-gage network were digitized in the weeks following the conclusion of field work. Each strip chart was read and rainfall totals for each 15-min period of the week were entered onto a precipitation data form by the Radar Meteorologist. For the sake of consistency, the same individual digitized all rain-gage strip charts.

5.4 Forecast Products

The Project Forecaster and Chief Scientist provided a daily summary of the weather within and in proximity to the research site and maintained a file of weather data for each day on which an experiment was performed. The summary contains an assessment of the state of the atmosphere in the region of West Texas throughout the day, describing the type and location of pertinent features in the vertical and horizontal structure of the atmosphere. In addition, a description of cloud development provided estimates of the time clouds began to form, the type of clouds present, their development and motion, and the location of their initial formation.

5.5 Data Handling Assignments

The working order of the Skywater radar was the responsibility of Glenn Cascino, of the Bureau of Reclamation, while the radar data were handled by Ray Jones. The seeder aircraft data were the responsibility of William Woodley, while the cloud microphysics data were handled by the crew of the T-28 under the direction of Dr. Andy Detwiler. George Bomar was accountable for the forecast data, and Ray Jones and the Raingage Technician were responsible for the rain-gage data.

6.0 OPERATIONAL SUMMARY

6.1 Overview

The cold-cloud randomized seeding effort of TEXARC 1994 began on August 4 and ended on September 1, 1994 for a total of 29 days. There were 11 flight days and the expenditure of 36.1 flight hours by the Cessna 340 in this period during which 19 cloud physics units were obtained. Of this total, 7 of the 19 received AgI treatment and the 12 unit balance received

simulated AgI treatment. In addition, 4 experimental units (1 S and 3 NS) were qualified in TEXARC 1994. Which units were "Seed" and which units were "No Seed" was dictated randomly after it had been determined that each prospective experimental unit satisfied the qualification criteria. A total of 86 flares were expended in the S units and 256 flares were simulated in the NS units for averages of 86 and 85 per unit, respectively. The usage of of flight time and AgI flares versus time is plotted in Figure 2. A summary of the action taken on flight days is provided in Table 1.

Table 1.
Summary of Action Taken on Flight Days

Date	CBT (°C)	Flt. T (°C)	# Flts. C340/T-28	Phys. Units S	NS	Expt. Units S	NS	D/S
8/4	10	-8	1/1	0	2	0	0	0
8/5	13	-9	1/1	0	2	0	0	0
8/8	13	-5	1/1	1	1[a]	0	0	0
8/14	10	-9	1/1	1	2	0	0	0
8/15	12	-9	1/1	1	2	0	1[b]	0
8/20	12	-9	1/1	2	1	0	0	0
8/22	14	-7	2/1[c]	0	0	0	1	0
8/23	12	-8	1/0	0	0	0	0	1
8/24	11	-7	1/1	1	1	0	0	0
8/31	17	-8	2/1	1	1	1	0	0
9/1	18	-8	2/0	0	0	0	1	1
Totals			14/9	7	12	1	3	2

[a] One cloud was seeded accidentally with one flare and it was not used as either a S or NS and is not reflected in this table

[b] A portion of the unit was out of range of the radar at the time of its qualification. The cells within range of the radar and in the unit will be used in the cell analyses. The unit itself cannot be analyzed.

[c] The T-28 returned to base due to generator failure.

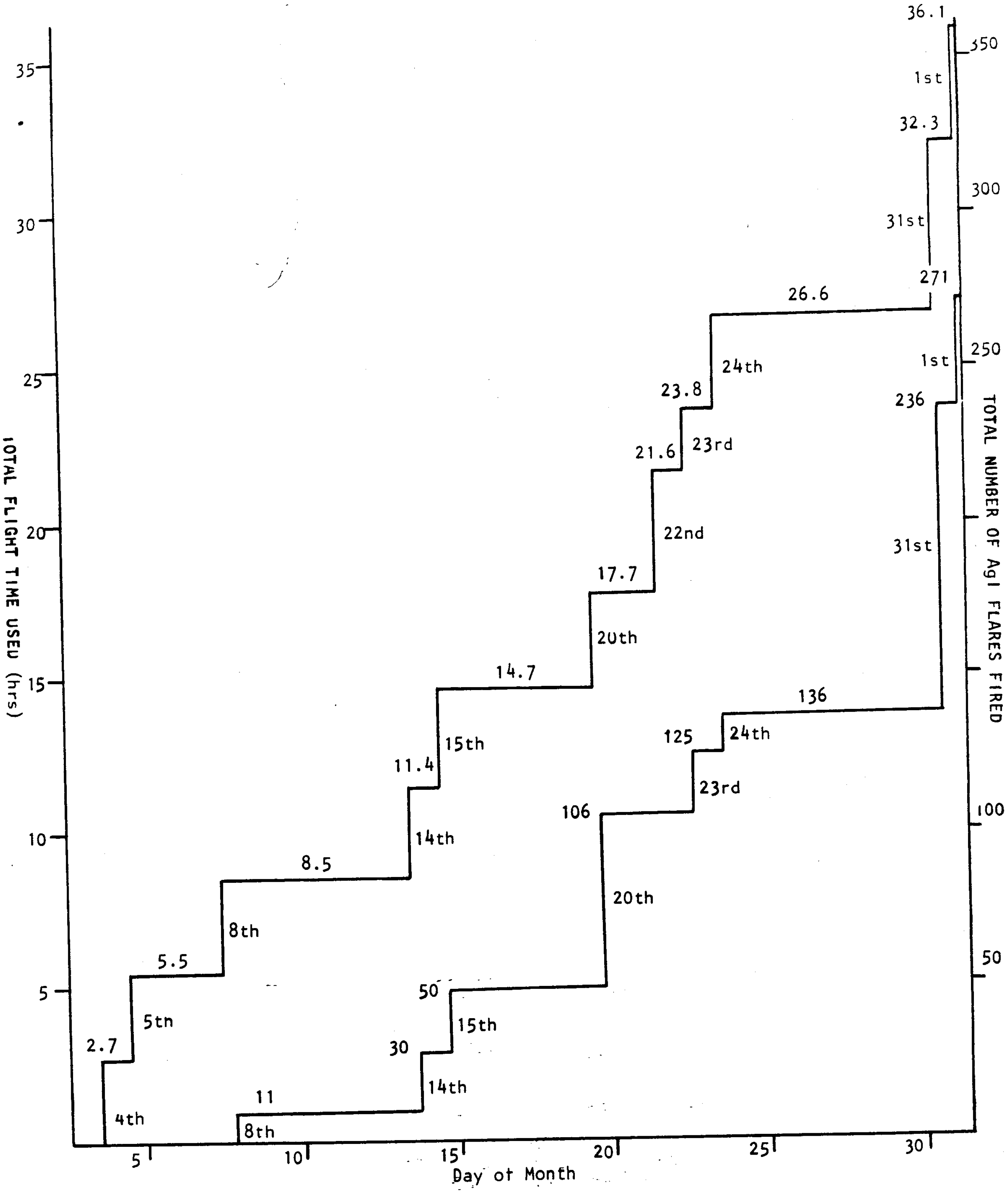


Figure 2. Plot of the expenditure of Cessna 340 flight hours and AgI flares versus time in TEXARC 1994.

6.2 The Weather During TEXARC 1994

Much of West Texas was plagued by drought for most of 1994, and the summer, especially, was lacking in notable rain events. By the time TEXARC experiments got underway in the first week of August, the southern High Plains and Permian Basin of Texas were in the throes of a moderate drought, which intensified further as summer gave way to autumn.

6.2.1. Prevailing Synoptic Situation. The vast subtropical ridge that migrates northward out of Mexico in early summer and produces long spells of hot, dry weather had largely spent itself when cloud-seeding experiments were begun on August 4. Fortunately, the ridge was only marginally influential on the weather in the TEXARC site for most of August 1994. It had previously been a most dominant weather factor a few weeks earlier--in June and July.

The ridge swelled to its maximum heighth and breadth and became anchored over West Texas in late June, when temperatures soared to record levels across much of the southwestern U.S. During the fourth week in June, the subtropical ridge forced afternoon temperatures well beyond 112 F over the TEXARC site. On successive days, Big Spring registered a maximum temperature of 115 F or higher. Not far removed from the TEXARC site, at Monahans, the hottest temperature ever recorded in Texas' weather history was measured: 120 F. On the same day, a high temperature of 119 F in southeastern Mexico established a new, all-time high temperature mark for the state of New Mexico. For much of the summer preceding the onset of TEXARC experiments, the skies had been largely devoid of rain clouds.

By August's first week, the ridge had backed off somewhat from the TEXARC site, and it remained only a peripheral influence for the balance of the month. As a consequence, the month as a whole was one of the cooler months of August in West Texas in recent years. That is because upper-level winds on the downwind side of the subtropical ridge--anchored over the "Four-Corners" region of the southwestern U.S.--were sufficiently strong to channel a batch of cooler, Canadian air into Texas on four distinct occasions in August.

Seldom does the late summer period yield four frontal passages in the southern High Plains of Texas. Yet, in August 1994 cold fronts not only penetrated the TEXARC site, but they were vigorously pushed well beyond (south) the site on the same or following day. While the fronts furnished the dynamics for deep convection, none of them stalled within or near the project site--a development that would have doubtlessly contributed to an abundance of seedable events during the month. In fact, the push behind the fronts was so substantial that the frontal boundaries actually traversed the project site too quickly, thereby creating only a momentary outbreak of showers and thunderstorms. Each time drier, more stable polar air ensued, thereby sealing off the research site from significant convection for several days.

In addition to the four frontal surfaces that impacted the research site during August, a pair of upper-level perturbations in prevailing westerly winds invoked enough cold air aloft to destabilize the atmosphere and foster deep convection. Yet, the atmosphere was not sufficiently loaded with moisture to permit the perturbations to instigate a widespread, concentrated rash of heavy showers and thunderstorms. The convection was rarely even semi-organized, and much of it failed to grow to depths deemed essential for experimention.

The sequence of approaching cold fronts and upper-level troughs was almost rhythmic, as is demonstrated by the following tally of surface and upper-air features impacting TEXARC during August 1994:

Thu. Aug. 4	Surface cold front moving SE-ward
Mon. Aug. 8	Upper-air disturbance moving SW-ward
Sun. Aug. 14	Surface cold front moving S-ward
Sat. Aug. 20	Surface cold front moving SSE-ward
Sun. Aug. 21	Upper-air disturbance moving SE-ward
Wed. Aug. 31	Surface cold front moving S-ward

Typically, in August in West Texas, active cold fronts are quite rare, though by the end of the month, autumn's first outbreak of polar air in some years does reach as far south as the Permian Basin. The more dominant trigger for deep convection is an upper-air disturbance (a cold-core low), many of which migrate not from the Rockies eastward into West Texas but from the Gulf of Mexico westward as an inverted subtropical trough. **Remarkably, West Texas was not impacted by an inverted trough propogating westward out of the Gulf of Mexico as an element of the easterlies until the second week of September.**

The superabundance of frontal intrusions contributed negatively to TEXARC objectives in another way as well. The unusually frequent exchange of continental and maritime air masses over the TEXARC site prevented any appreciable buildup of subtropical (even tropical) moisture until the one-month series of experiments was virtually concluded. A span of eleven days occurred between frontal passage on August 20 and another frontal intrusion on August 31, when the month's most widespread and heaviest rains were noted in and beyond the TEXARC site. This explains why TEXARC participants were kept waiting for much lower cloud bases (6,000-7,000 ft.) and concomitant warm cloud-base temperatures (16 -18 F) until the very last day of the field experiments.

By the time the month's fourth cold front reached the research site on August 31, enough tropical moisture had been imported to allow surface dew-points to climb into the mid 60s--and even the high 60s in the research site's southeastern quadrant. The boundary layer had been fed enough tropical moisture, in fact, that cloud-base heights had been lowered some 2,000-3,000 ft. from the 9,000-10,000 ft. level that characterized convection for the first 28 days of the month. Until the month's last frontal intrusion on the 31st, cloud-base temperatures had consistenly been measured in the range of 10 C to 14 C. (In fact, on August 14, cloud-base temperatures within the research area were observed, remarkably, as cold as 9.5 C!) On August 31, as the strongest of the month's four cold fronts punched through the research site, a marked influx of tropical moisture had lowered cloud bases to a welcome 6,500 ft. and had raised cloud-base temperatures to a delightful 17 C!

The interaction of a deep, moist surface layer and a pronounced convergence line on August 31 produced the month's lone large-scale rainstorm. Every recording rain gage within the TEXARC site caught a measureable amount of rainfall on that day, and rainfall was heaviest (2.0 to 2.6 inches) in the vicinity of Snyder in the research site's northeastern quadrant. Not surprisingly, the episode yielded the most lucrative seeding candidates for the entire month.

6.2.2. Verification of Terminal Forecasts. Each day the terminal forecast, issued by the forecaster at the morning briefing of TEXARC personnel, was evaluated in light of resultant weather events within the project site on that day. On the whole, forecasts for either "standdown," "standby," or "prepare to operate (Go)" conditions had substantial merit (Table 2).

The project forecaster specified a "green light" for operations on eight of the month's 28 days; he foresaw conditions on those days that would warrant the deployment of aircraft. On six of those occasions, his declaration of "go" at the late-morning briefing of all project participants proved to be prophetic.

However, on two other occasions (Aug. 16 and Aug. 21), his prediction of suitable deep convection within the project site was not borne out by the resultant weather for the day. On August 16, he projected the formation of towering Cu and a few Cb's in the southern quadrant of the TEXARC site in the vicinity of a quasi-stationary front that was expected to drift back slowly northward over that quadrant during the course of the afternoon. The front had moved through the project site two days earlier, and it was thought that upper-level support for moving the front farther south did not exist. However, the subtropical ridge remained west of the TEXARC site, and northerly winds aloft

Table 2.
Summary of Terminal Forecasts and Verification

Date	Forecast	A/C Launched?	Resultant Weather
4	Go	Yes	TCUs w/ showers SE quadrant
5	Go	Yes	TCUs w/ showers S/SE quads
6	Standdown	No	No significant convection
7	Standdown	No	No significant convection
8	Go	Yes	TCUs/few Cbs on eastern flank
9	Standdown	No	No significant convection
10	Standby	No	Cu vertically suppressed
11	Standby	No	Cu vertically suppressed
12	Standdown	No	Mostly small Cu
13	Standdown	No	A few small Cu
14	Standby	Yes	Numerous Cbs NE quadrant
15	Go	Yes	Numerous Cbs SE quadrant
16	Go	No	Cbs failed to show
17	Standdown	No	No significant convection
18	Standdown	No	No significant deep cnvctn
19	Standby	No	No significant deep cnvctn
20	Go	Yes	Cb line developmen SE quad
21	Go	No	Cbs failed to show
22	Standby	Yes	Several Cb's in SE quadrant
23	Standby	Yes	Some Cb's in SE quadrant
24	Standby	Yes	A few marginal Cb's only
25	Standby	No	Cb's too distant
26	Standdown	No	No significant convection
27	Standdown	No	No significant convection
28	Standdown	No	Only shallow Cu
29	Standdown	No	Only shallow Cu
30	Standdown	No	No significant convection
31	Go	Yes	Most profitable day of month

were sufficiently strong to ease the front farther south and increasingly more distant from the site. The front never truly stalled and retrograded, thus depriving the southern quadrant of the forcing mechanism needed to spawn deep convection.

Somewhat similar weather conditions prevailed on August 21, when the forecaster again missed with a prediction of suitable convection. The morning Midland sounding revealed a deep near-surface layer of very moist air (precipitable water of 1.60 in.) over the project site, and synoptic weather data pointed to a semi-stationary front on the southern periphery of the project site. Again, the front was expected to remain within range of the project site during the course of the afternoon, and the resultant motion of the weak convergence line was likely to trigger significant Cb development, particularly in the southeastern quadrant. However, airflow aloft was just potent enough to keep the frontal boundary out of range of the project site, and the Cb's that formed were too distant to be of value to TEXARC personnel.

It was most fortuitous for the project that personnel were either put on a stand-by status or told to prepare for an afternoon launch by the forecaster and Chief Scientist on each of the days when aircraft were launched. Perhaps the most notable success of the forecasting effort was avoidance of declaring a day as non-operational, only to have personnel scrambling to launch when deep convection materialized unexpectedly. It would have been nothing short of disastrous, given the short duration of the field project, to have had personnel in a "standdown" mode when thunderstorms developed over the project site.

The closest the project came to having personnel in an awkward position to respond to developing convection came on August 31, when thunderstorms abruptly erupted in the neighborhood of Big Spring only a short time after the morning briefing had concluded. The forecast for the day had called for operations commencing around 1400 LDT. Fortunately, the staff had not scattered for lunch and was able to muster for the unexpectedly early onset of experimental activities. It is noteworthy that, on the 12 days when a "standdown" was declared, on none of those days did significant deep convection materialize and catch personnel ill-prepared to respond.

6.3 The Experimental Units of 1994

Only 4 experimental units were qualified in 1994, 1 Seed and 3 No Seed, bringing the total to 38 (18 S and 20 NS) since randomized cold-cloud experimentation began in Texas in 1986. A portion of one of the 3 NS cases in 1994 was out of the 159-km range of the radar at the time of its qualification, so the actual useable case total is 37 (18 S and 19 NS). The locations of the qualification passes for the 1994 cases is provided in Figure 3. Summary information for these cases is provided in Table 3. A journal of each random case is provided in Appendix A and relevant data for each Cessna 340 cloud pass is listed in Appendix B.

The weather during TEXARC in August 1994 was quite dry (see previous section) with relatively high cool cloud bases. It appears that in-cloud rain drop coalescence was weak on all days except August 31, 1994. This is based on visual observation and on an initial look at T-28 internal cloud measurements. A good quick indicator of whether it is likely that coalescence is active in a cloud is its cloud-base temperature (CBT). A preliminary quick look at the cloud physics data obtained in 1994 suggests that a west-Texas cloud having a CBT ≤ 10°C is unlikely to contain raindrops. In the range 10°C < T < 15°C, some coalescence activity and raindrop production is likely, especially at the warmer temperatures. For CBTs ≥ 15°C, coalescence is likely to be active in west Texas. This is the range when dynamic seeding should work best for the reasons discussed by Rosenfeld and Woodley (1993).

By this criterion, 1994 was not a particularly good year for dynamic seeding, as can be seen in Figure 4, which provides the CBTs for all experimental units prior to 1994 (solid bar) and for those cloud physics and experimental units obtained in 1994 (open bar). Note that all but three of the 36 experimental units obtained in past years (2 of the 36 could not be analyzed because of radar problems) had CBTs ≥ 14°C whereas only 3 of the 9 cloud physics and experimental units in 1994 had CBTs ≥ 14°C.

6.4 The Cloud Physics Units of TEXARC 1994

TEXARC 1994 was the first year of detailed cloud physics measurements since the research cloud seeding program began in 1986. It represents a milestone in this continuing program that began under the acronym SWCP (The Southwest Cooperative Program) and continues today as TEXARC. The rationale for this component of the program and its design and implementation have been addressed in earlier sections of this document.

The T-28 cloud physics aircraft used in TEXARC 1994 was provided by the Institute of Atmospheric Sciences of the South Dakota School of Mines and Technology (SDSM&T). A complete writeup of the TEXARC 1994 cloud physics program by Dr. Andy Detwiler and his colleagues at the SDSM&Technology is provided in Appendix C. A quick look summary at some of the microphysical data obtained during the first pass through each of the cloud physics units is provided in Table 4.

As is typical of most cloud physics investigations, not all of the instrumentation worked throughout the program. The Johnson-Williams hot wire liquid water device was not operative on August 4 and 31, 1994. The estimates of cloud liquid water from the FSSP instrument are the only ones available on these two days. In the absence of ice particles, which can "confuse" the FSSP instrument as to what is water and what is ice, the FSSP is thought to provide a better estimate of cloud water than the J-W because it responds to a wider range of droplet sizes. A "good rule of thumb" is that the J-W estimates of cloud water are a factor of two less than those provided by the FSSP.

The Humphrey accelerometer went bad part way into the flight on August 5, 1994. Pitch, roll, and acceleration were lost for the rest the of flight along with parameters that depended on them, such as the updraft computed using the Kopp method. The Humphrey accelerometer was operative again on August 24, 1994.

Thus, on August 8, 14, 15, and 20 updraft must be estimated by the Cooper method and/or by examining the rate-of-change of aircraft altitude with time.

On August 8, 1994, the research pitot was apparently plugged by an insect during the take-off run. Lack of accurate dynamic pressure, combined with the missing Humphrey accelerometer on this flight, rendered unusable the computation and measurements of indicated airspeed, true airspeed, FSSP droplet concentrations and liquid water concentration, Cooper updraft, Kopp updraft, pitch, roll and acceleration.

In addition to instrumentation problems, the weather itself provides limitations for the TEXARC cloud physics investigations. The cloud physics units on August 4, 5 and 8 consisted of clouds that were negatively buoyant at the -8°C to -10°C temperature levels. They were short lived and, therefore, poor subjects for study. This was also the case of August 24, 1994.

The best days for study are August 14, 15, 20 and 31, 1994. The best of the best was August 31, 1994, on which there were two quality cloud physics units with vigorous supercooled clouds and active coalescence processes. This is type of cloud addressed in the current dynamic-seeding conceptual model as applied to Texas. Cloud-base temperatures on this day were 17°C.

The three clouds on August 20, 1994, were also of high quality. The cloud base temperatures were 12°C and there did not appear to be much rainwater in these clouds, since coalescence was not as active. One of the three clouds achieved cumulonimbus stature following seeding, which was not unusual considering the other cumulonimbus clouds in the vicinity.

The clouds on August 14 and 15, 1994, were generally of lesser quality in terms of vigor. Those on August 15 were at the edge of the range of the radar. Cloud-base temperatures ranged between 9.5°C and 12°C on these days, implying that coalescence was probably not very active in those clouds. Only by analysis will we know for certain.

Considering the quality of the clouds and the data, the units on August 20 and 31, 1994, have been identified as having highest priority for analysis and for subsequent computer modeling. When all analyses have been completed, we likely will a good picture of west-Texas supercooled clouds. This will include: typical cloud water contents, droplet concentrations at both cloud base and in the supercooled region, typical equivalent droplet diameters, fairly crude estimates of draft characteristics, particle sizes and types as a function of cloud size and age, and differences as a function of the cloud's base temperature.

Table 3.
Summary of Randomized Cloud-Seeding Cases in 1994
(See Rosenfeld and Woodley, 1989; 1993 for Comparable Tabulations for the other Texas randomized units)

Date of Treatment	**Cloud-Base Temp.** (C)	**Qualification Pass Time** (LST)	**Qualification Pass Position** (Lat/Long)	**SLWC/UD** $GM/M^3/FtMin^{-1}$
Aug. 15	12	16:04	31 02.7/101 33.5	0.9/1423
Aug. 22	14	16:41	31 33.9/101 30.9	0.8/1217
Aug. 31	17	19:16	31 24.9/101 07.1	1.3/1666*
Sep. 1	18	15:23	32 38.0/102 06.4	1.1/1012

	Treatment Decision (S/NS)	**No. Flares Fired**	**No. Treated Towers**	**Time of Treatment First** (LST)	**Time of Treatment Last** (LST)	**Dur.** Min.
Aug. 15	NS	101(0)	16	16:13	17:27	74
Aug. 22	NS	76(0)	12	16:51	17:55	64
Aug. 31	S	86(86)	12	16:22	20:13	51
Sep. 1	NS	79(0)	13	15:30	16:55	85

Notes: In the "No. Flares Fired" column, the first number for the seed (S) cases is the number of flares attempted and the second number (in parentheses) is the number of flares actually fired. For the non-seed (NS) cases, the first number refers to the number of times that a button was activated to simulate seeding; the second number (in parentheses) is zero, because no actual seeding was done and no flares left the rack.

* The updraft reading is not reliable because the aircraft stalled during cloud penetration and the pilot had to lower the nose and apply power during the pass.

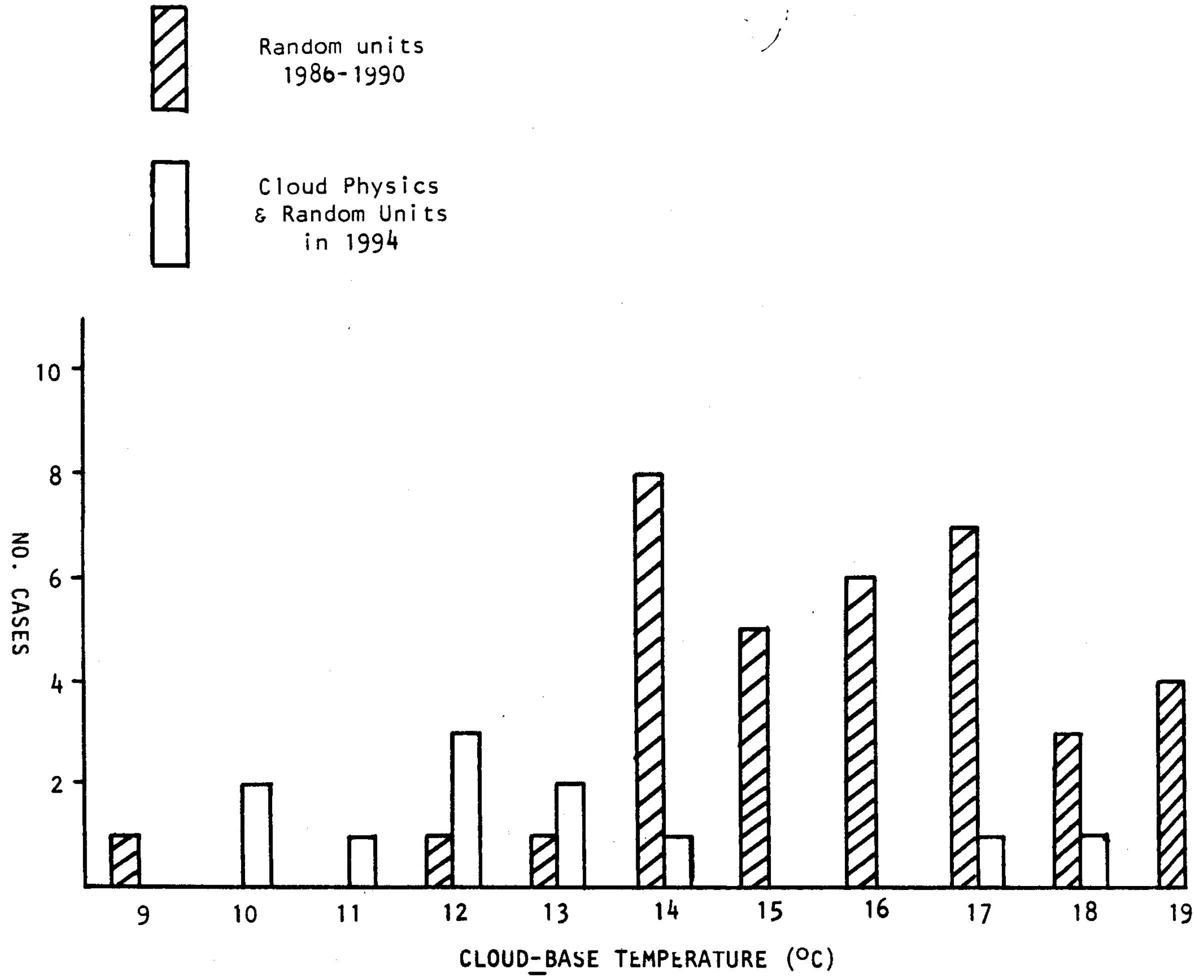


Figure 3. Frequency plot of the cloud-base temperatures of all of the random units obtained in west Texas since 1986 (lined bar) and the cloud-base temperatures of the cloud-physics and experimental units obtained in TEXARC 1994 (open bar).

Table 4.
First-Look Microphysical Measurements on the First Cloud Pass in Each Cloud-Physics Unit

Date	Flt #	Time CDT	CBT C	JW MAX gm/m	FSSP MAX gm/m	FSSP MAX con (#/cm)	FSSP MAX EQUIV. DIA. microns
8/4	632	1727	10	-	3.0	362	28.6
	632	1730	10	-	3.8	335	30.4
8/5	634	1726	13	1.4	3.9	256	35.3
	634	1738	13	1.6	3.7	303	35.7
8/8	635	1506	13	1.0	3.7	243	36.0
	635	1614	10	0.9	3.2	268	30.0
✓8/14	637	1557	9.5	1.8	3.5	304	33.1
	637	1623	9.5	1.5	4.3	234	40.1
	637	1655	9.5	1.9	3.6	273	34.5
✓8/15	638	1657	12	2.1	3.6	176	37.9
	638	1713	12	2.4	4.9	381	37.8
	638	1735	12	1.3	4.3	330	36.7
✓8/20	639	1646	12	1.5	2.9	300	30.7
	639	1707	12	1.3	2.6	296	30.2
	639	1740	12	1.6	2.8	517	27.4
8/24	641	1747	11	2.9	3.2	149	37.0
	641	1824	11	2.3	3.8	124	35.4
✓8/31	642	1528	17	-	6.6	267	44.1
	642	1557	17	-	7.7	191	46.0

A major unknown is whether a seeding signature will be detected in these clouds. In several instances, particularly on August 31, 1994, the clouds grew rapidly following real or simulated AgI seeding. Thus, after no more than 5 minutes the seeded portion of the cloud was well above the penetration altitude of the T-28 cloud-physics aircraft. If there were a seeding signature in these clouds, we likely did not detect it. This will be focus of the cloud-physics studies.

6.5 Skywater Radar Operations

Prior to the onset of experiments on August 4, a Bureau of Reclamation radar technician was dispatched from Denver to the TEXARC site to check out the Skywater radar system and to perform repairs of one of the two tape drives (A). Tape drive A was dismantled and cleaned, and a loose connection within the tape-drive assembly was repaired. The servo unit of the radar was greased. On July 29, the radar was calibrated, and color intensities, running from -10dBz to 55dBz, were readjusted. Because the "single record" mechanism on the Transmitter/Receiver Control Panel had malfunctioned, the three calibration tapes made during August were recorded in volume-scan mode. However, after the "single record" mechanism was cleaned on August 19, it began to function properly, so the final three calibration tapes were made with the single record capability. The radar's minimum detectable signal was near -77dBm, with a reverse power of -7dBm and a forward power of +0.5dBm.

On August 20, it was discovered that tape drive B would not load the magnetic tape when in "playback" mode. However, the drive would load in "record" mode, but the light indicating "write" on Recorder B would not illuminate. When volume scans were started, Recorder B would record. However, when loaded for playback, Recorder B would not play back. Data recorded on Tape Drive B would play back on Tape Drive A. This could be attributable to a switching problem in the computer. Fortunately, it did not affect data recording. A listing of radar-data tapes collected during the month is given in Table 5.

Throughout the month-long project, Tape Drive B was preferred over Tape Drive A, due to A having a history of not turning as freely as B, in spite of the repair work attempted during the month on Tape Drive A. It is evident that serious consideration needs to be given to a refurbishment and upgrading of the Skywater system prior to the conduct of experiments in the summer of 1995. Even a modest investment of funds would enable the system to be PC-compatible and remove reliance on tape drives that are becoming increasingly obsolete.

6.6 Lubbock WSR-88D Radar Operations for TEXARC

Doppler radar data from the Lubbock WSR-88D facility were obtained, by Texas Tech University personnel from the National Weather Service's Archival II system, for those days when TEXARC aircraft conducted flights within the project site. Once rain-gage data from the TEXARC recording rain-gage network were received and processed by TTU personnel, an examination was made to determine the degree to which the NEXRAD radar accurately estimated the amount of precipitation that fell to the ground during experimentation. The cooperation of NWS personnel, led by Mr. Andy Anderson, in recording and providing TTU investigators with the data throughout the duration of field experiments, was exemplary.

The results of this analysis will be forthcoming to the TNRCC in a Final Report to be submitted by the TTU Principal Investigator in the spring of 1995.

Table 5.
Big Spring Skywater Radar Inventory of Magnetic Tapes

Date	Tape I.D. No.	Rcdr. Used	No. Rec. Taken	Err.	Start CDT	Stop CDT	EOF
7/29	2492669	A	351*		No Time Set		0
8/4	023237-37-02-044	A	12586		16:09:17	17:48:36	2
8/5	745691004	A	19809		13:48:22	18:57:41	2
8/6	2819888	B	1183*		No Time Set		0
8/8	TR6-4-17-90-6-NO	B	8858		13:17:03	16:31:21	2
8/12	25E3200FC19TRA5	B	1275*	X	No Time Set		2
8/14	1089042506	B	19803		13:06:23	18:05:42	2
	18301	A	4377		18:06:23	19:00:43	2
8/15	3466049-89	B	6526		15:03:35	19:42:54	2
8/19	2891310	A	39*	X	No Time Set		0
8/20	2813455	A	19015		15:52:59	19:17:17	2
8/22	2192902	B	7679+reset		14:31:15	20:05:34	2
8/23	2239161307	B	3258		17:33:00	19:42:19	2
8/24	3089053302	B	8967		15:48:37	18:57:44	2
8/26	114/3040412	B	39*		No Time Set		2
8/31	3035217	B	19???		15:04:49	16:11:52	0
	2413070	A	20099		16:12:33	17:21:53	2
	20740072616	B	19631		17:25:59	19:05:18	2
	2074072617	A	7175		19:06:46	19:36:06	2
	3089054002	B	19036		19:36:46	20:51:06	2
	2275183801	A	19884		20:51:46	22:01:06	2
	123456789	B	20675		22:01:46	23:12:	0
9/1	3103764	B	20950		14:40:07	16:24:25	2
	2891246	A	6733		16:25:05	16:54:25	2
	3089053302	B	19528		16:56:34	18:35:53	2
	T0306250BPI	A	1776		18:36:33	18:50:52	2
	3089053402	B	2943		18:51:33	19:35:53	2
	18301	B	39*				2

* denotes calibration tape

6.7 Recording Rain-Gage Operations

Prior to the onset of research activities on August 1, the Colorado River Municipal Water District's meteorologist, Ray Jones, and rain-gage technician, Wesley Cox, prepared the network of 106 Belfort recording rain gages for use in the project by installing a clock (chart drive) and bucket in each gage, then calibrating each gage. In addition, new recording rain gages were deployed at 20 of the sites. The clocks installed were those that had been used in previous years. Some of the gages did not function properly because the clocks did not work. The technician made an effort to disassemble and clean the gages, but in many instances was not successful in getting the gages to work. Spare, but used, chart drives were provided, but in some instances they also did not work satisfactorily. Gages that proved to be inoperable were: TB2, TB3, TE8, TE9, TF2, TF6, TG5, TH7, TI1, TI2, TI5, TI6, TI7, TJ4, TJ6, and TJ8.

Most of the recording rain-gage network received below average rainfall for the month of August 1994. Most sites collected less than 1 inch of rain, due to the dominance of high pressure aloft that kept deep convection from proliferating on the majority of days of research. Much of that rainfall stemmed from an approaching cold front, and accompanying upper-atmospheric trough, that instigated widespread thunderstorm activity on August 31.

On August 4, a weak cold front pushing southward through the area produced only spotty showers, with the gage location TJ8 collecting the heaviest total (0.42 inch). On August 8, an upper-level disturbance moving southwest generated showers, most of which delivered less than one-quarter of an inch of rainfall.

After a spell of dry and hazy weather conditions on August 9-13 brought on by east to northeast flow aloft, a cold front intruded into the northern reaches of the project area on August 14, then pushed through the project area the following day, providing rainfall of no more than 0.10 inch generally. That brief period of instability was followed by more dry weather during August 16-19.

Another cold front punched into the project area on August 20 and caused a major eruption of deep and widespread convection, much of which formed in the southeastern quadrant of the project area and then migrated southward out of the area. None of the recording rain gages collected precipitation from this squall-line event. However, on the following day, August 21, an upper-level disturbance moving southeast in the wake of the front set off numerous moderate thunderstorms in the western and southern sectors of the project area. The rain-gage network in these sectors registered only light amounts of rain (less than 0.5 inch), though TA6 (just south of Big Spring), received 0.76 inch of rain.

The period of August 22-30 was mostly rain-free, with isolated showers developing mainly south and southwest of the rain-gage network. Then, a major change in the weather occurred on August 31, when the fourth cold front of the month surged into the project area. For the first time all month, virtually every gage collected some rainfall. Heaviest amounts were recorded at TK7 (2.65 inches) and TK2 (2.07 inches), just west and southwest of Snyder.

For the whole of the month, rainfall over the project area, as detected by the rain-gage network, was for the most part below normal. Only three rain-gage sites received above-normal rainfall, with TK7 collecting the most of any location: 2.67 inches.

7.0 CONCLUDING OBSERVATIONS

Given the prevailing drought that afflicted West Texas during the 1994 growing season, it was almost remarkable that, on more than half of the days during TEXARC, sky conditions warranted personnel being put on at least a "standby" status. Granted, on more than a few of the days (10) when aircraft were deployed, the convection that was investigated and sampled proved to be of only marginal value to the project. Still, an appreciable number of cloud-physics units, as well as a pair of randomized units, were gained out of a largely uneventful month. Moreover, far too many of the cases were of clouds having high bases and cold cloud-base temperatures.

Fortunately for the project, the climatic regime for the region shifted discernibly just before the month ended, affording investigators one day (August 31) when convection was of a dramatically different calibre. Given that the whole of the project site caught rainfall that was woefully subpar (many rain-gage locations had only one bonafide "rain day"), personnel still were able to find enough attractive convection to exhaust the available flight hours on the seeder aircraft. Had the area's weather borne some semblance of normalcy during August, the project may have had to terminate the seeding dimension of its experimentation prematurely due to the lack of flight time. In all, the Chief Scientist made very judicious use of the aircraft, expending enough flight time to thoroughly check out marginal conditions early in the month, yet leaving sufficient time to capitalize on the bountiful convection that formed at month's end.

7.1 Considerations in Siting TEXARC Headquarters.

It is conceivable that, had TEXARC headquarters been situated elsewhere than Big Spring (say, in San Angelo or even Junction) during August 1994, substantially more deep convection would have been within range of TEXARC personnel and hardware. After all, because the fronts that pushed through the project site mired down well south and east of the southern periphery of the site and failed to retrograde northward back through the site, suitable convection appeared abundant on many days in the Concho Valley and western and central Edwards Plateau--or just beyond the reach of project aircraft and expertise stationed at Big Spring.

In 1995, assuming the southern High Plains is penetrated by a few, or several, frontal surfaces in the late summer, these fronts may behave very much unlike the variety that characterized the late summer of 1994. In fact, if the late summer of 1995 bears some semblance of normalcy, these fronts will stall, and retrograde, over the current TEXARC site, creating more than a few opportunities for deep convection well within range of persons and plane headquartered at Big Spring. It may well be that a headquarters in a location well to the south or east would lie beyond range of such favorable weather.

Besides, the thrust of rainfall-enhancement work in Texas over the past quarter century has centered on the Big Spring area, where additional rainwater is direly needed in many years. The research endeavor to understand, and quantify, the potential of silver-iodide seeding of summertime convection is needed most to address atmospheric conditions in semi-arid (even arid) regions of the state. Already, a rather substantial archive of randomized units has been gleaned from the area within 150 km of Big Spring. It makes more than a little sense to build upon the scientific base that has already been well established.

7.2 Recommendations for Future Experimentation.

The assessment of experiments conducted during August 1994 had led to the following recommendations for similar experimentation in 1995.

7.2.1. Upgrade the Seeder Aircraft. With the prospect of more substantial funding for TEXARC 1995, more money should be obligated to upgrade the capabilities of the seeder aircraft and its instrumentation. In doing so, the following should be considered:

a) Aircraft

1) Rugged and strong
2) On-station time of 3-4 hours minimum at 20,000 ft while carrying a crew of three
3) Time from takeoff to 20,000 ft $\leq$ 30 minutes
4) Ceiling of 30,000 ft when fully loaded
4) Good de-icing capability
5) Completion of 100-hour inspection prior to use in the program.

b) Aircraft Instrumentation

1) Minimum of 200 AgI flares that fire from back to front, with flare counter, plus special switch to activate when simulating seeding. The simulated seedings are to be recorded on the data system.

2) State-of-the-art data recording and after-flight processing system.

3) Forward-looking video camera with date and time shown at all times. Capability to record radio transmissions to and from the aircraft as well as aircraft intercom.

4) Measurement of temperature and dew point with extra points for temperature probe that does not get wet in flight.

5) Hot-wire device or equivalent for the measurement of cloud liquid water. Extra points for instrument that estimates water content in drops > 50 microns diameter.

6) Ball variometer or equivalent for the estimation of cloud drafts. Range should be ≥ ± 2,000 ft/min. Extra credit for more accurate means of estimating cloud drafts.

7) FSSP or equivalent for the measurement of the cloud droplet spectrum.

8) PMS 2D-C probe for the measurement of particle sizes > 50 microns.

9) Capability for overnight turnaround for all recorded data, so that it can be examined by, scientific personnel prior to the next day's operation.

10) Instrumentation to sense SF_6 gas that has been released from the ground or from another aircraft (possibly an aircraft operating at cloud base).

7.2.2. Test the Potential of CCN Seeding for Precipitation Augmentation. There are many days during the warm convective season in west Texas when deep convection does not occur. Nevertheless, most of these days have fields of cumulus clouds, with depths ranging from 2 to 4 km or even greater, that do not produce rainfall. Cloud base temperatures for such clouds are normally in the range of 5°C to 15°C, and coalescence is active only at the warm end of this range.

Recent work in South Africa suggests that coalescence can be activated in such clouds by seeding with CCN nuclei that are produced by burning special hygroscopic flares that are affixed to the wings of aircraft flying beneath young growing clouds. The large CCN particles in the flare effluent are then activated preferentially as they enter cloud base at the expense of smaller natural CCN particles. This has the effect of broadening the droplet spectrum such that rain drops are formed earlier and lower in the cloud, when only more numerous small particles would have been present without the seeding.

The efficacy of such a process can readily be tested in TEXARC 1995 without a significant expenditure of funds over and above what is already intended. Seeding can be accomplished from the CRMWD Piper Aztec, sampling of the cloud-base droplet distribution can be done from the AgI-seeder aircraft, which is equipped with a PMS FSSP probe, and observations of droplet sizes in clouds at various levels above their bases can be made by the cloud-physics aircraft. The only additional costs, therefore, would be for the CCN flares and for flight time for the Aztec and its pilot.

On days judged suitable for the CCN experiment, the center of a field of very young clouds will be identified from the AgI-seeder aircraft and a circle of 25 km radius will be drawn around that central point. The pilot of the Aztec will then draw a treatment decision from the appropriate block in a set of randomized treatment decisions and carry out the instructions. If it is to "Seed", the Aztec will be flown radially from one boundary of the unit to the other through its center and CCN flares will be burned continuously along with the release of SF_6 gas. If the decision is "No Seed", the procedures will be exactly the same except no CCN flares will be burned.

Once the experiment has commenced, the AgI seeder will climb to about 500 ft above cloud base and make continuous samples of drop size distribution within the unit. Radial patterns that are comparable to those of the CCN seeder will be flown.

The same will be done by the cloud-physics aircraft (assuming such aircraft is not the same craft used for AgI seeding) flying at various levels in the clouds of the unit. Cloud-physics instrumentation will also "sniff" for the SF_6 gas. Its detection will serve to focus attention on those parcels of air in which it is found in a search for a seeding effects.

Both the Midland WSR 88-D and Skywater radars will have the unit under surveillance while scanning in a volume-scan mode. The timing, height and intensity of first echo will be of greatest interest.

The second unit of the day is to have the opposite treatment decision of the first, so that both a S and NS unit will be obtained on each day. Only the pilot of the Aztec and the overall Project Manager (George Bomar) are to know the treatment decision until all analyses have been completed, whether in the field or at some later date.

It is expected that the drop size distribution will be different for the clouds in the CCN-seeded unit. It is expected that the distribution will be broader with a tail at the large end as compared to clouds in the unit that received only SF_6 gas. At higher levels, this pattern should persist with more, larger drops in the clouds that received CCN seeding. In addition, first echoes should be lower, broader and longer lasting in clouds that received CCN seeding.

7.2.3. Conduct TEXARC 1995 for a longer period. The weather during TEXARC 1994, generally, was an aberration with very dry conditions and high, cool cloud bases. Big Spring, Texas normally receives about one-third of its 18 inch annual precipitation in the 2-month period of August (2.02 in.) and September (3.91 in.), so there is every reason to believe that cloud conditions will be more suitable during these months in 1995. The biggest problem of TEXARC 1994 was failure to obtain clouds in which coalescence was active. It was not possible, therefore, to examine the conditions that are thought to be operative after on-top glaciogenic seeding. This should not be the case in 1995. If funds permit, the period of experimentation should be extended into September; an ideal time frame would be from August 1 through September 15.

An alternative plan would be to focus on the late spring and early summer periods that are also quite wet in west Texas. Selection of this option would mean having to contend with severe weather and all the risks that entails. Further, the T-28 aircraft is not available in the spring because of its commitment to the Oklahoma research program.

7.2.4. Test the Utility of a Jet Aircraft. A cloud physics jet aircraft would be extremely useful in the TEXARC effort. Two applications come immediately to mind:

a) Following the treated volume upward after seeding to determine whether the internal changes are consistent with the dynamic seeding conceptual model (see Rosenfeld and Woodley, 1993); and,

b) Determining physical cloud top for AgI-seeded and non-seeded clouds for comparison with radar-measured tops of the same cloud. It is expected (by at least Woodley) that the difference between the visual cloud tops of seeded and non-seeded clouds will be greater than the difference in echo tops. Use of the Citation would provide a way to determine whether this is true.

It may be that TEXARC 1995 cannot afford an extended period of participation by a cloud-physics jet aircraft. It likely can, however, afford a one-week demonstration period in which the aircraft's capabilities and that of its crew (i.e., pilots, technicians and scientists) could be showcased. If the period is picked judiciously, based on a forecast of favorable cloud conditions, valuable scientific data should be obtained as well.

On the other hand, it may be that the program in 1995 can afford one aircraft (possibly a jet) that would be able to perform both seeding and sampling missions. At least 40 hours of flight time for AgI seeding and sampling is considered to be an essential minimum.

8.0 REFERENCES

Baumgardner, D. and S. Skinner, 1989: Forward Scattering Spectrometer Probe (FSSP) Calibration and Maintenance Procedures Manual, NCAR Research Aviation Facility.

Baumgardner, D., W. Strapp and J.E. Dye, 1990: Evaluation of the Forward Scattering Spectrometer Probe. Part II: Corrections for coincidence and Dead-Time Losses, J. Atmos. Ocean.Tech., 7, 659-665.

Baumgardner, D. and M. Spowart, 1990: Evaluation of the Forward Scattering Spectrometer Probe. Part III: Time response and Laser Inhomogeneity Limitations, J. Atmos. Ocean. Tech., 7, 666-672.

Bomar, G. W., 1987: Summary Report: The SouthWest Cooperative Program, Phase I. Texas Water Commission, Austin, Texas, 37pp.

Cerni, T.A., 1983: Determination of the Size and Concentration of Cloud Drops with an FSSP, J. Climate and Appl. Meteor., 22, 1346-1355.

Cooper, W.A., 1988: Effects of Coincidence on Measurements with a Forward Scattering Spectrometer Probe. J. Atmos. Ocean. Tech., 5, 823-832.

Detwiler, A. and R. Hartman, 1991: IAS Method for 2D Analysis and PC's. Bulletin of the Institute of Atmospheric Sciences of the South Dakota School of Mines and Technology.

Gayet, J-F, Brown, P.R.A., and F. Albers, 1993: A Comparison of In-Cloud Measurements Obtained with Six PMS 2D-C Probes. J. Atmos. Ocean. Tech., 10, 180-194.

Jurica, G. M. and W. L. Woodley, 1985: The Design of the SouthWest Cooperative Program Rainfall-Enhancement Experiment. Texas Water Commission, Austin, Texas, 140 pp.

Jurica, G. M. and W. L. Woodley, 1987: Operations Plan for the Southwest Cooperative Program, 1987: Texas Water Commission, Austin, Texas.

Kopp, F.J., 1985: Deduction of Vertical Motion in the Atmosphere from Aircraft Measurements. J. Atmos. & Oceanic Tech., 4, 684-688.

Lawson, P. and A. Cooper, 1990: Performance of Some Airborne Thermometers in Clouds", J. Atmos. Ocean. Tech., 7, 480-494.

Riggio, R. F., W. O. Alexander, T. J. Larkin, and G. W. Bomar, 1983: Texas HIPLEX Summary Report: 1975-1980. Texas Dept. Water Resources report LP-184, 127-129.

Rosenfeld, D., and W. L. Woodley, 1989: Effects of Cloud Seeding in West Texas. J. Appl. Meteor., 28, 1050-1080.

Rosenfeld, D., and W. L. Woodley, 1993: Effects of Cloud Seeding in West Texas: Additional Results and New Insights. J. Appl. Meteor., 32, 1848-1866.

Spyers-Duran, P., 1968: Comparative Measurements of Cloud Liquid Water Using Heated Wire and Cloud Replicating Devices, J. Appl. Meteor., 7, 674-678.

Strapp and Schemenauer, 1982: Calibrations of Johnson-Williams Liquid Water Content Meters in a High-Speed Icing Tunnel, J. Appl. Meteor., 21, 98-108.

Woodley, W.L., T.J. Henderson, B. Vonnegut, G. Gordon, D. Rosenfeld and S. M. Holle, 1992: Results of Studies of Aircraft-Produced Ice Particles (APIPs) in Supercooled Fog over Mono Lake, California. Part II: New results from Winter 1991-92. Final Report from Woodley Weather Consultants to the National Science Foundation and under Grant No. ATM-9023009, 169 pp.

Woodley, W.L., T.J. Henderson, B. Vonnegut, G, Gordon, R. Breidenthal and S.M. Holle, 1991: Aircraft-produced Ice Particles (APIPs) in Supercooled Clouds and the Probable Mechanism for Their Production. J. Appl. Meteor., 30, 1469-1489.

SCIENTIFIC DIARY OF EVENTS ON FLIGHT DAYS IN TEXARC 1994

August 4, 1994

The morning dawned in Big Spring, Texas with broken altocumulus clouds in NE-SW bands with the individual cloud elements moving from the NE to the SW. By late morning cumuli, had formed beneath the dissipating altocumuli. They too were in short NE-SW bands and remained quite shallow into the early afternoon. The surface wind was from the N and NE.

All project personnel were on site at the Big Spring Airpark for the second project briefing. Today's briefing began at 0930 CDT briefing. Besides Dr. Rosenfeld and myself, this included George Bomar from the TNRCC, Roger Tilbury and Scott Brause of Weather Modification, Inc., and Ken Hartman, Dennis Musil, Dan Custis, Gary Johnson, Andy Detwiler, Jill Munro and Shannon Stocks of the South Dakota School of Mines and Technology. Gerry Jurica and Matt Kensey of Texas Tech University were at the first project briefing yesterday.

The meeting focused on the Operations Plan, primarily the flight procedures to be followed for the cloud physics and unit experiments. A coordination test flight was scheduled for 1500 CDT with the Cessna 340 seeder aircraft serving as the lead and command control aircraft with the T-28 to follow.

The cumuli had developed further by mid-afternoon with some of them achieving congestus and/or towering stature in NE-SW bands. A few weak isolated showers had formed on the scope by 1500 CDT. Takeoff of the Cessna 340 was at 1543 CDT and cloud base was noted at 10,200 ft p. alt. (11,000 GPS altitude) at a temperature of about 10°C. The top of the scattered to broken altocumulus layer was at 17,000 ft. p. alt.

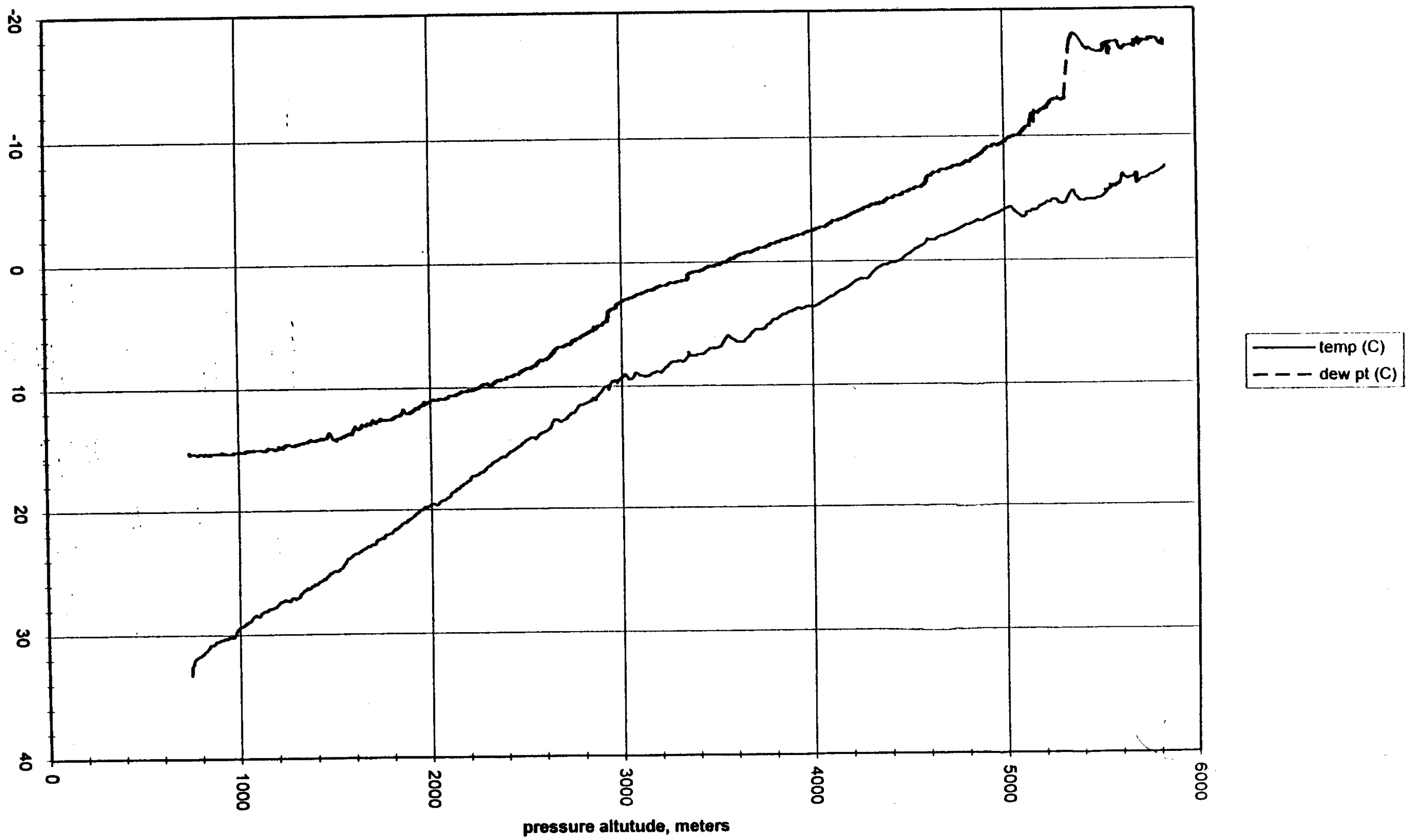
Once above the layer cloud, a scattering of fairly hard cumuli could be seen, especially to the N and NE where some low-level anvil material could be seen. The best area for our purposes appeared to be about 50 n.mi. SSE of Big Spring, and we orbited among a scattering of hard cumuli in this area after scrambling the T-28. The temperature at our flight altitude of 19,000 ft p. alt. (20,200 ft GPS altitude) ranged between -7°C and -8°C.

Once the T-28 had joined up with the Cessna 340 we joined up into formation --- the T-28 on our right --- we identified two cloud towers for coordinated study. The first tower was in its dying stages, but we worked it anyway to practice our flight patterns. We took the T-28 up to the cloud and then broke to the left while he penetrated. We in the Cessna 340 continued in a 360° to the left and followed behind in a simulated seeding pass. Then we moved out of the way while the T-28 made two passes in succession through the cloud. It was dying rapidly and I am not certain that the same cloud tower was penetrated on successive passes.

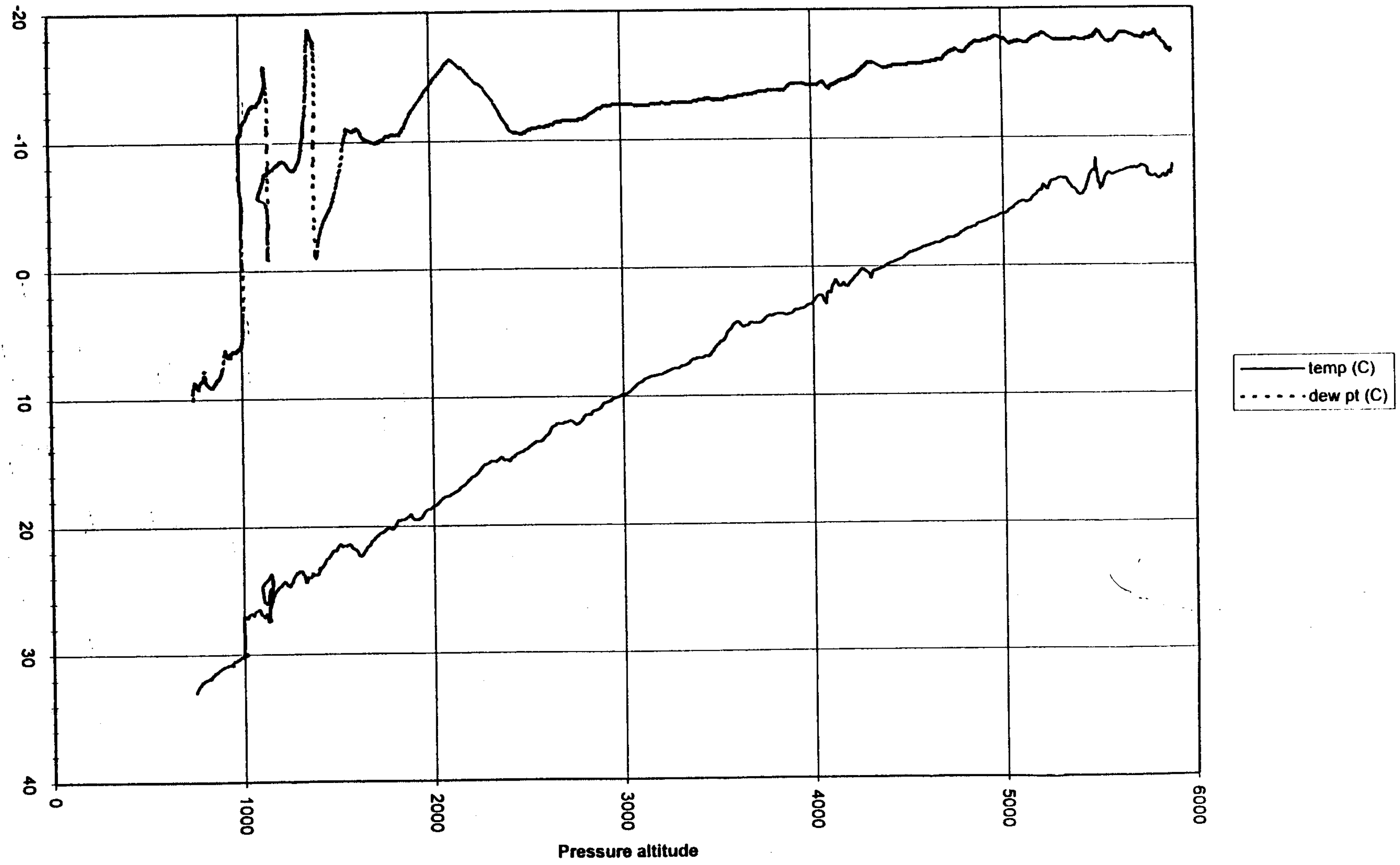
The second cloud was somewhat more vigorous. This time we followed the T-28 on its first pass through the cloud and we simulated seeding. The T-28 followed with four monitoring passes that were spaced no more than 3 minutes apart. Later viewing of the plots from the T-28 data system revealed a classic continental cloud with mean drop sizes at cloud base of about 8 microns and at -8°C the mean drops sizes were about 20 microns in diameter in concentrations of 300 cm^{-3}. The drop spectrum was quite narrow. The maximum water contents were generally around 1 gm/m^3 and the clouds did not appear to contain much ice. Later analysis revealed that the clouds contained little, if any, rain water. It would have been interesting to see how such clouds would have reacted to AgI seeding. Perhaps we will have the opportunity tomorrow.

We landed at 1806 CDT after a very successful first coordination flight. The T-28 crew worked well into the night to produce products that could be viewed the next morning.

flight 8/4/94 ascent



8/4/94 decent


-20
-10
0
10
20
30
40
0
1000
2000
3000
4000
5000
6000
Pressure altitude
temp (C)
dew pt (C)

August 5, 1994

The sky was clear at sunrise except for some cumulus and stratocumulus clouds to the distant N and NE. The winds were light from the NE at < 10 kts but they increased somewhat after sunrise. The surface dew point in Midland was in the low 60's. At this point it does not appear that the pattern has changed too much. We are at the SW extremity of a front that stretches NE to E of the Great Lakes, but its effect should be confined to NE Texas and to the NE of there.

I am not too concerned about the weather as yet, since I would like to obtain a few test cases under a dry regime that produces continental clouds with high and cool bases. It is especially important that we seed such clouds so that we can contrast their microphysical response to the more tropical clouds that we hope to obtain later.

By 1400 CDT there was a field of small scattered to broken towering cumuli in all directions from Big Spring with the largest clouds to the distant SE-SW. The largest clouds were producing small echoes with tops up to 6 km. All clouds were moving from the NE.

Although takeoff had been scheduled at 1400 CDT, I decided to wait an hour in the hope that the flares being shipped by Federal Express from Atmospherics, Inc. will arrive in time for the flight. We have flares in our stock that have been supplied by WMI but they are different from the TB-1 flares that we have used in the past. In our collective view, it would be a mistake to use different flares for the microphysical studies and then make inferences with respect to past results of our experimentation that was conducted using the old TB-1 flares. We may decide to switch to a different flare at some point in the future, but now is not the time for such a switch.

The AgI flares from Atmospherics, Inc. had not arrived by 1500 CDT --- Federal Express had actually tried to deliver the flares around noon but they had the wrong address --- so we decided to fly without them. Danny Rosenfeld and I took off in the Cessna 340 at 1537 CDT and began a track to the SE, since we had seen TCU from the E-S-SW before takeoff. Maximum echo tops at that time ranged up to 28,000 ft between Big Spring and San Angelo. Cloud base was at 9,000 ft p. alt (9,915 GPS altitude) at a temperature of 13°C. The temperature at our ultimate flight altitude of 20,000 ft p. alt was between -7°C and -8°C.

Upon reaching altitude, I noted a decaying Cb area to the SE and newer hard towers to its W and SW and to its N and NE. Danny Rosenfeld voted that we fly SW, but I opted for the northern area, because it was closer to the radar. As it turned out, Danny's area would prove to have been the better initial choice. Between 1615 and 1630 CDT, we made two cloud passes with the Cessna 340 in the area about 35 n.mi ESE of the radar, while we waited for the T-28 to join with us. The clouds appeared to be fairly hard as they grew on the northern flank of a decaying cloud that once appeared to be a small Cb. The maximum JW water contents ranged between 1.0 and 2.0 gm/m^3, but the cloud updrafts were rather weak. Even at close range it was difficult to discern obvious upward motion in the clouds. These clouds were reminiscent of the clouds on the dry hot days in Thailand prior to the onset of the monsoon --- April 18, 1993, comes immediately to mind.

The towers themselves remained hard in appearance from up to 15 minutes, and then they decayed without obvious precipitation --- the type of cloud that might respond to AgI seeding intervention based on a static-seeding conceptual model. Had we had flares, I would have seeded one or two of these clouds on a random basis using the dynamic seeding conceptual model as a guide. It is questionable, however, whether a dynamic response could be expected in such clouds. Our seeding results to date in both west Texas and in Thailand, suggest that seeding in such cases does not invigorate the clouds and produce more rainfall. Seeding certainly did not invigorate the clouds in Thailand on April 18, 1993, despite their persistent hard appearance and their rather high JW supercooled liquid water contents (SLWC). It is important, therefore, to see what happens to such clouds microphysically following seeding intervention.

The T-28 had joined up with us in the Cessna 340 for formation flight at 1640 CDT, but the clouds were diminishing in intensity, height and lifetime at that time. During most of this period, the T-28 flew about a mile ahead of us and I directed its movements from the rear. As it turned out, this did not work as well as it had on the previous day and some confusion developed as to what portion of which cloud was the subject of my interest. I would seem, therefore, that we should return to formation flight so that there will be no doubt as to which cloud is of interest.

We ultimately flew back to the SW to a point about 60 n.mi to the SSW of the radar where there was a field of hard growing cumuli to the N and NE of two small Cbs. The first pass by the T-28 took place in close quarters to other clouds at 172640 CDT. The reverse-flow temperature at the pass altitude of about 6050 m ranged between -8°C and -10°C, which appears to be 1 to 2°C colder than the reading of our Rosemount temperature probe. I should also add that our Romemount probe appears to be wet, resulting in evaporative cooling and temperatures that are too low. Maximum FSSP droplet concentrations and equivalent diameters from the T-28 data were 259 cm^{-3} and 23.5 microns, respectively.

After exist of this cloud, the T-28 made a 90° left turn and then a 270° right turn to come back to the cloud and entered a larger cloud in the process. Meanwhile, we entered the cloud at 1728 CDT on what would have been a randomized seeding pass had we been equipped for seeding. The cloud was not particularly strong with an updraft of about 500 ft/min and a SLWC of just over 1 gm/m^3.

During the inadvertent pass into the larger clouds, the T-28 measured more SLWC and more updraft than had been measured on its first pass into the intended cloud. The second pass into the subject cloud at 173030 CDT did not show too much change in any parameter. No ice was evident in the 2D-C images.

We then moved away from the cloud as it dissipated and merged with other hard towers nearby. A second motivation was to give Dan Custis in the T-28 time to get rid of the ice that had built up on the aircraft during the three prior successive passes. The T-28 had descended to about 17,000 ft due to the ice buildup on the aircraft.

By 173810 CDT, the T-28 had entered another cloud upon my direction. It was more isolated than its predecessor and NE of its position by perhaps 5 n.mi. It appeared hard and had a top of about 23,000 ft, which was taller than is desirable for such cloud physics studies. It would have been better to obtain a young tower that was just growing through our flight altitude, rather than one that had already achieved its maximum growth. When the randomized effort begins, it will be important to be more restrictive in choosing cloud candidates.

The pass into the cloud by the T-28 produced a maximum JW SLWC of 1.6 gm/m^3, FSSP droplet concentrations of up to 270 cm^{-3} and equivalent sizes of about 25 microns. The accelerometer on the T-28 appears to have failed at 1726 CDT, rendering the calculation of updraft by the Kopp method unusable. Although a few ice particles were noted on the 2D-C imagery, the cloud appears to have been mostly water during this pass.

The Cessna 340 followed the T-28 into the cloud at 1741 CDT, noting SLWC values > 1.0 gm/m^3, weak updrafts, small graupel and some turbulence. The cloud was already beginning to decay at this time.

The last pass into this cloud was made in this cloud at 1744 20 CDT. It was subsiding further at this time. The SLWC values had decreased to < 1.0 gm/m^3, the FSSP concentrations had decreased to 200 cm^3, and the graupel counts had increased with a few particles > 800 microns. It is possible that this cloud was producing a light shower at its base.

We left the area to return to Big Spring at 1755 CDT and landed at 1815 CDT. Cloud base on return was 10,000 ft p alt.

I took several pictures today. They are documented below.

Photo #	Time of Photo (CDT)	Subject of Photo & Comments
1.	1617	Picture of cloud 1 Area of hard cumuli
2.	1717	Picture of cloud 2 This cloud was never penetrated
3.	1725	Prospective cloud Cloud was not penetrated
4.	1727	Cloud 3 before penetration of cloud 3 by T-28
5.	1730	Cloud 3 after penetration of cloud 3 by Cessna 340
6.	1738	Cloud 4 Picture at time of first penetration by T-28

APIPS (Aircraft Produced Ice Particles) generation by the T-28, while it was laden with ice, must be a concern of ours today. Based on my APIPs research, it is quite likely that the T-28 produced APIPs in the clouds, when it was in a high drag (high ice loading) and high power configuration. The T-28 should be similar to the U. of Wyoming King Air in APIPS production, and the King Air produces APIPs at temperatures as warm as -8°C to -9°C when it is flown at maximum power in a high drag configuration (gear and flaps down). By extrapolation, therefore, I would expect the T-28 to behave in a similar fashion when it struggling against an ice load and flying at maximum power.

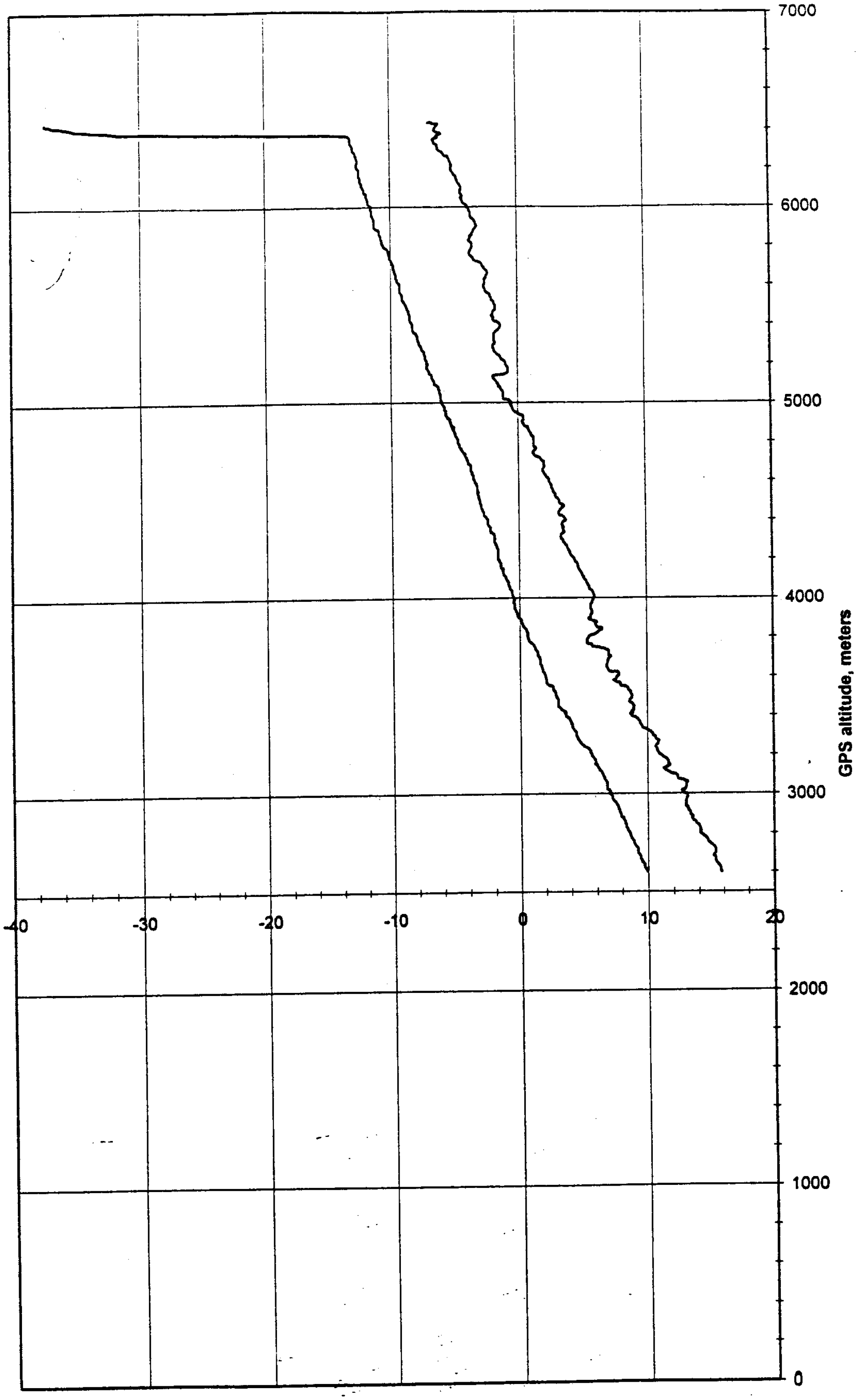
The Cessna 340 and the T-28 flew in formation between 1640 CDT and 1645 CDT today, and we noted that the temperatures changes were very well correlated visually in the plot (see relevant figure in notebook). The temperatures were, however, offset relative to one another with the reverse-flow thermometer on the T-28 reading up to 1°C colder than the Rosemount temperature on the T-28. In turn, the Rosemount temperature on the T-28 was about 1°C colder than the reading of the Rosemount thermometer on the Cessna 340. If it were a matter of taking a vote on the matter, at this point I would vote for the Rosemount thermometer on the T-28 as providing the correct readings. Additional comparisons are needed before any conclusions can be reached.

The T-28 pass data for this day are in the daily notebook. The plots show what appears to be a classic continental cloud with relatively high JW SLWC values and no rainwater. Ice does form in these clouds through what should be a natural ice-nucleation process. Graupel was noted in the larger clouds.

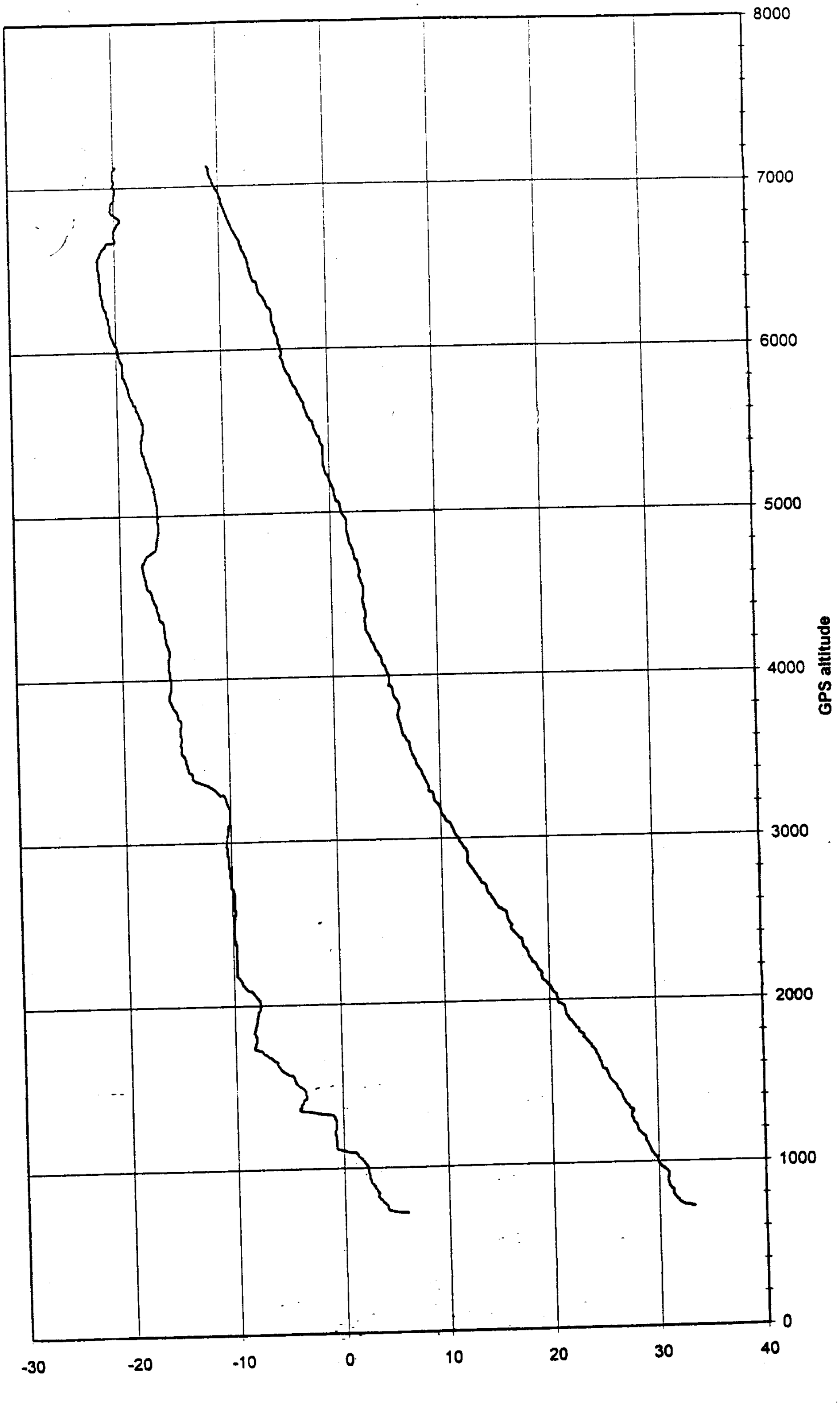
The clouds would appear to be natural candidates for either base AgI seeding using a static seeding conceptual model and/or the approach that utilizes hygroscopic seeding flares that are burned at cloud base while affixed to the wing of the seeder aircraft. Based on the South African research, these flares change the CCN distribution such that only the larger particles are activated. The cloud then becomes more maritime in character with more coalescence, more rain-sized drops, more ice multiplication and ultimately more rainfall.

It would be easy to test the efficacy of cloud based seeding of high-based continental clouds with hygroscopic flares in west Texas. If the experimental period is expanded to three months in 1995, it is recommended that a hygroscopic component be added to the ongoing effort that makes use of AgI flares. Cloud base temperature might be the determining factor as to which experiment is to be conducted on a particular day. Even with the hygroscopic experiment, it is recommended that the seeding be conducted over a small area such as that currently being used for the AgI experiment. An area with a radius of 25 km should provide enough cloud candidates in which one might look for seeding effects. Such effects should be sought in the cloud microphysical measurements and in the radar data that will permit isolation and tracking of individual cells.

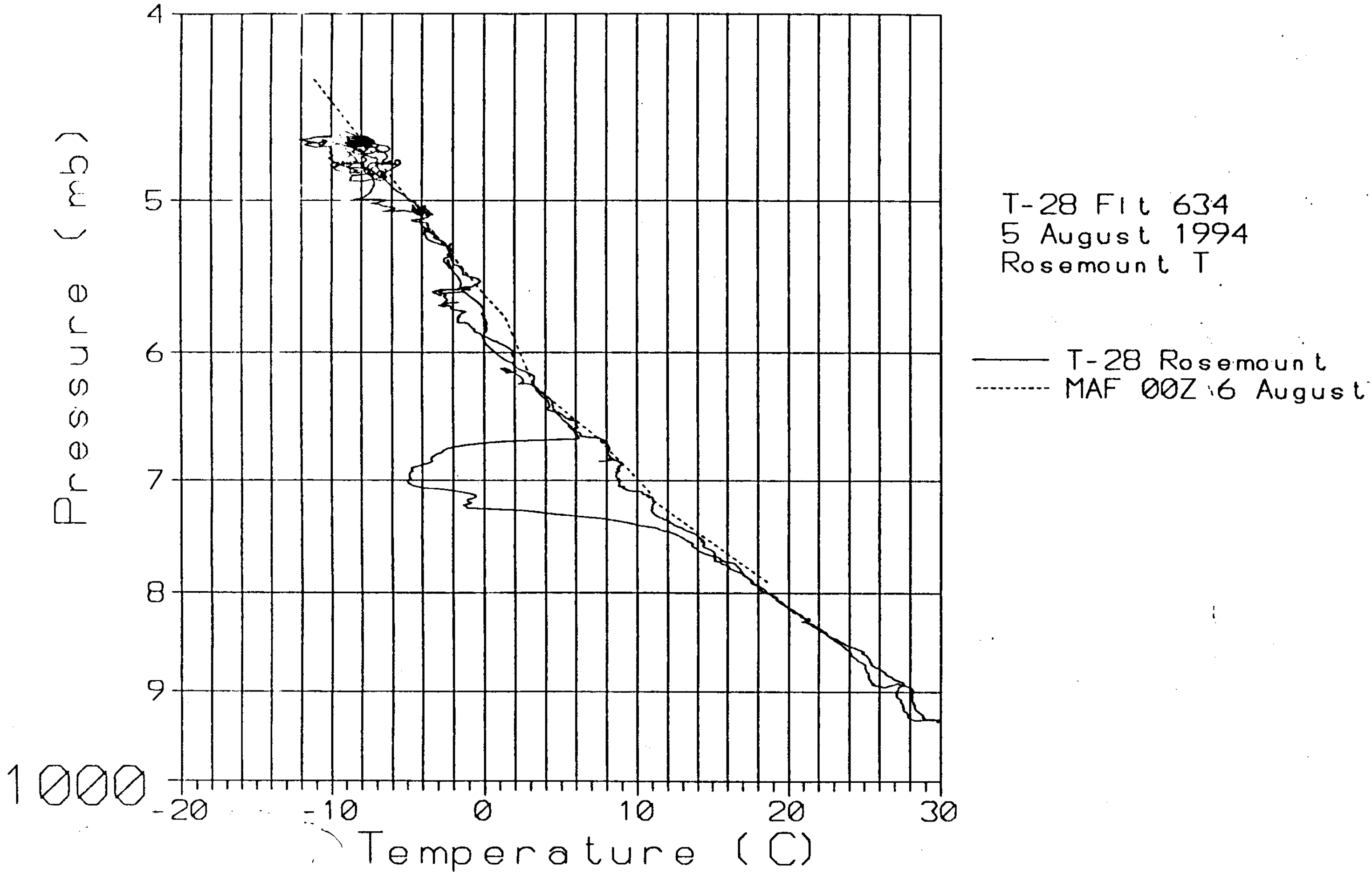
The hygroscopic component of the west Texas experiments should not prove to be too expensive. All of the systems currently in place for the AgI experiment could be used for the hygroscopic seeding experiment. The Piper Aztec currently in use by CRMWD could be used for the cloud base seeding at a rather modest cost. This aircraft probably would not be in use on days that are suitable for hygroscopic seeding since rather little rainfall and little operational seeding occurs on such days.

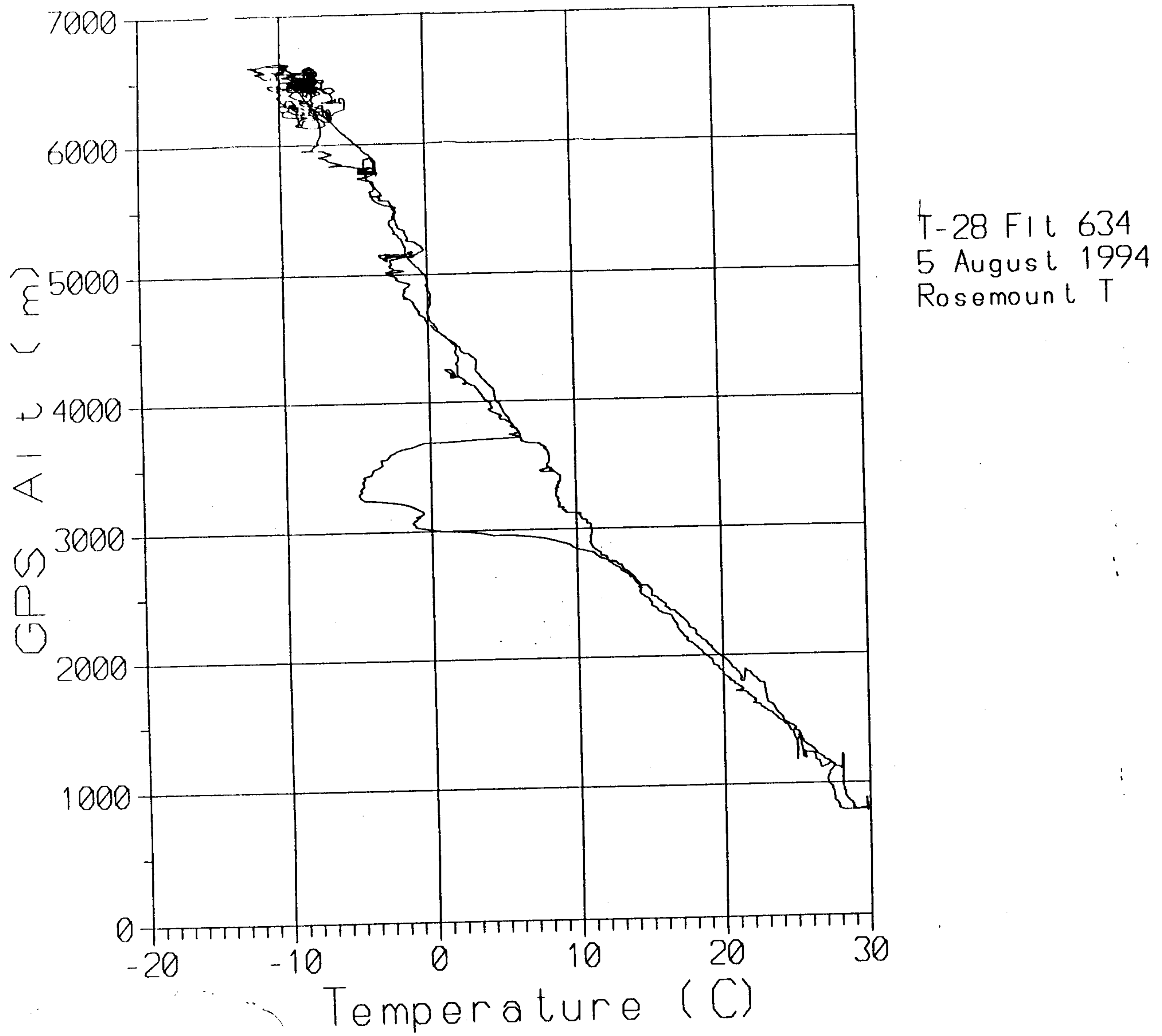


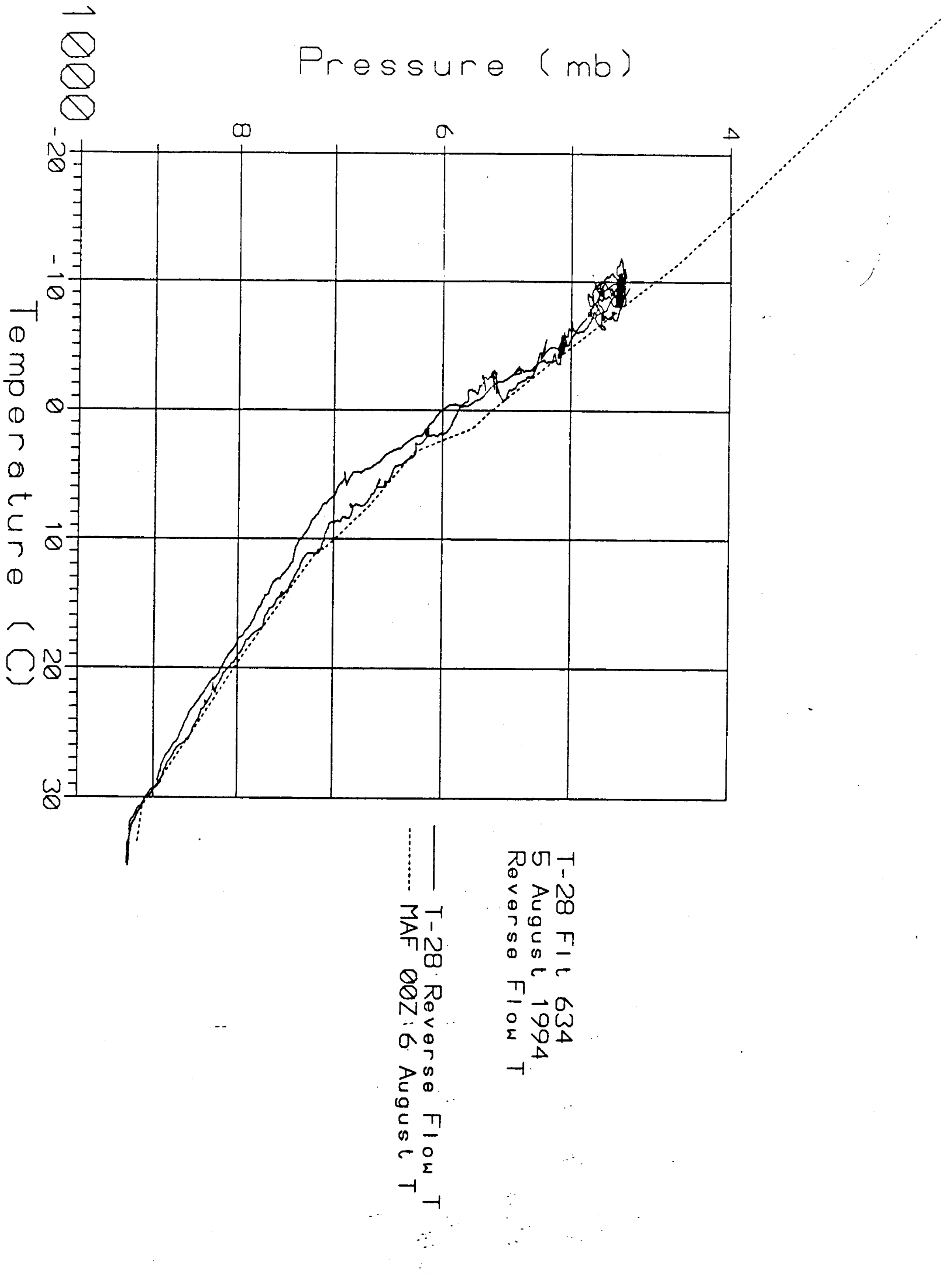
FLIGHT 8/5/94 ascent



FLIGHT 8/5/94 descent

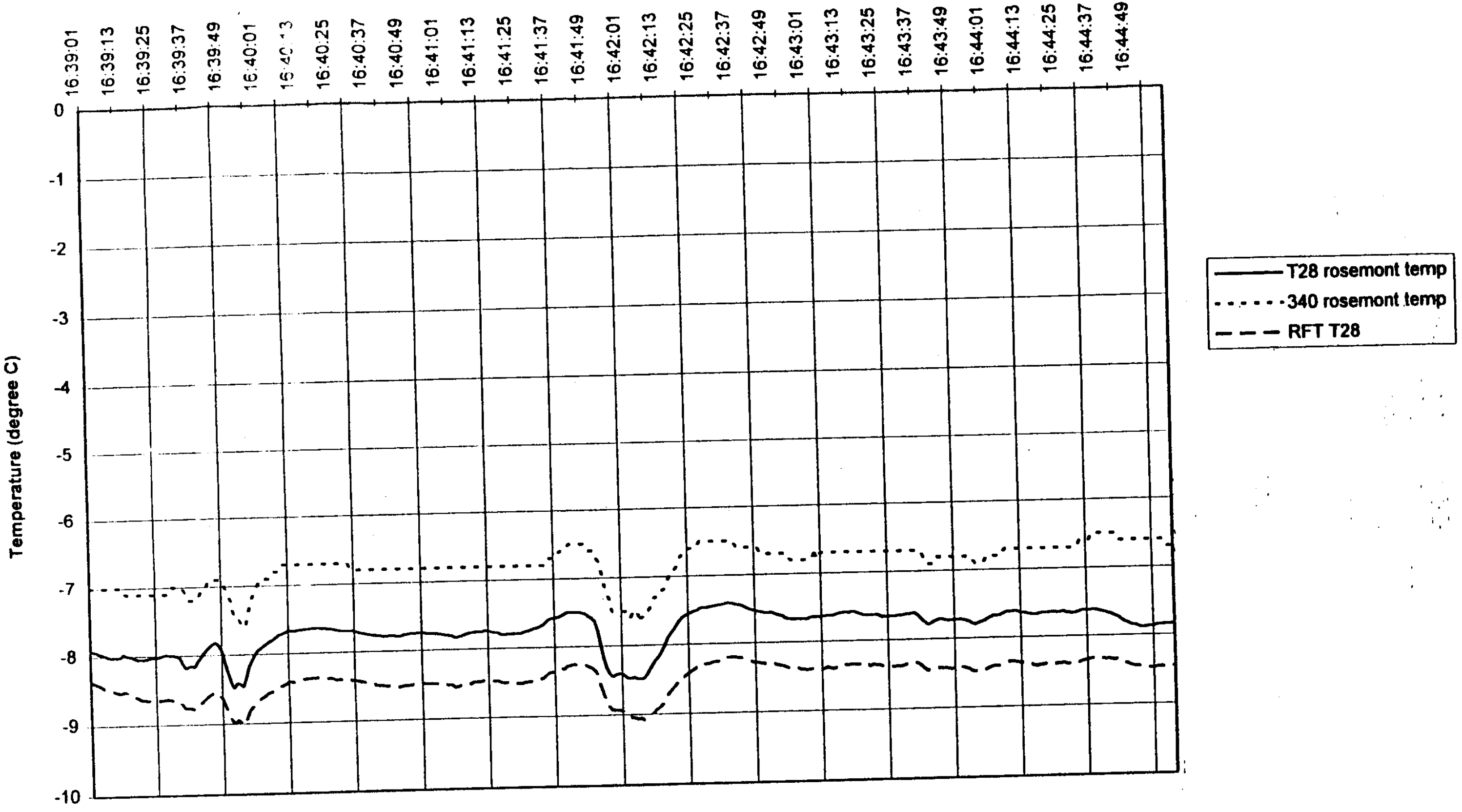

T-28 Flt 634
5 August 1994
Rosemount T
T-28 Rosemount
MAF 00Z 6 August
Pressure (mb)
4
5
6
7
8
9
1000
Temperature (C)
-20
-10
0
10
20
30


T-28 Flt 634
5 August 1994
Rosemount T
GPS Alt (m)
7000
6000
5000
4000
3000
2000
1000
0
-20
-10
0
10
20
30
Temperature (C)

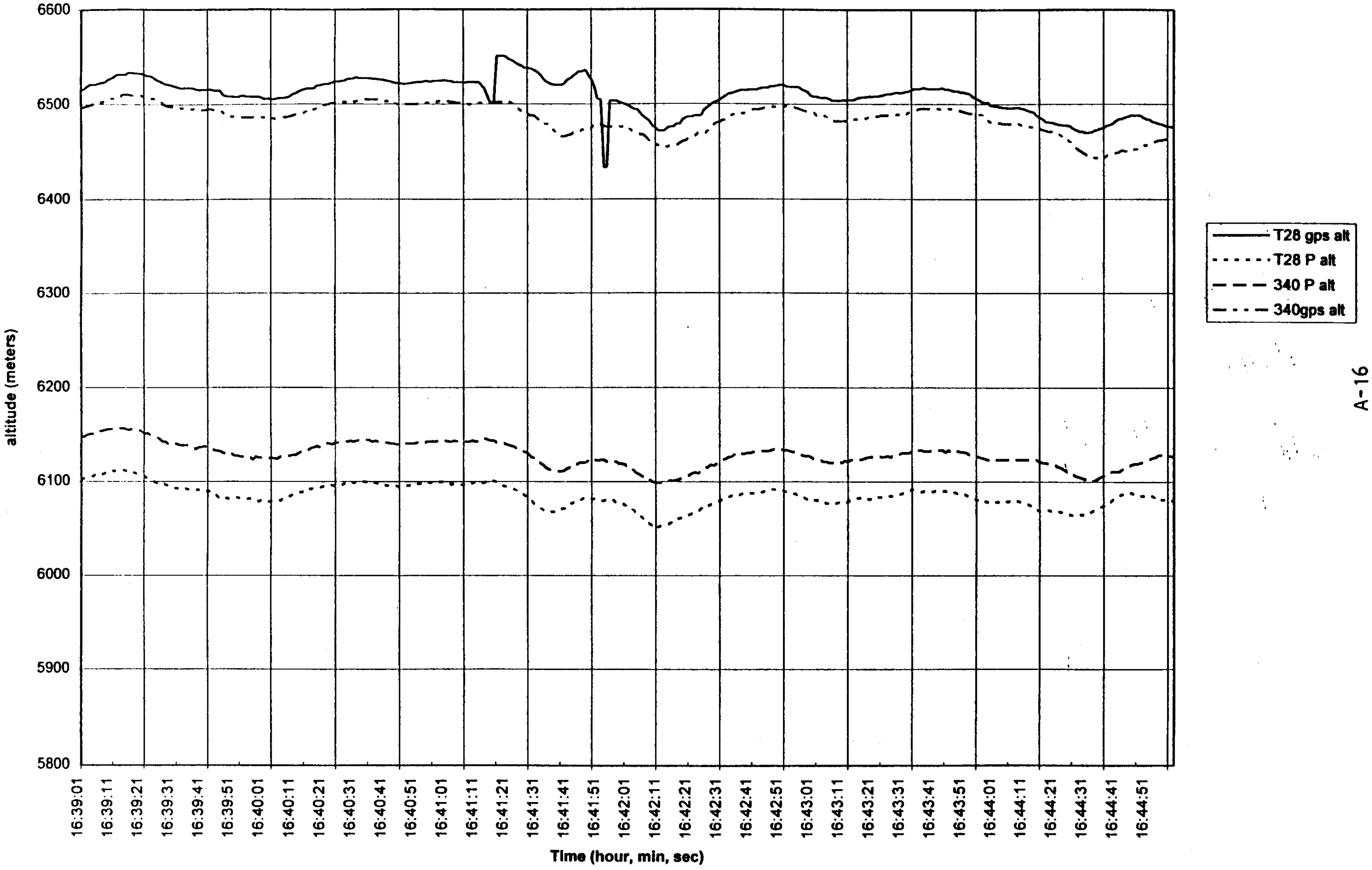


1000
Pressure (mb)
8
6
4
-20
-10
0
10
20
30
Temperature (C)
T-28 Flt 634
5 August 1994
Reverse Flow T
T-28 Reverse Flow T
MAF 00Z 6 August T

Plot comparing temperatures of T28 and 340 on 8/5/94



Plot comparing altitudes of T28 and 340 on 8/5/94



August 8, 1994

The day dawned clear in Big Spring except for some thin cirrus cloudiness. The temperature was in the mid-70's and the dew point was around 60°F. The winds were light from the S. A still-active Cb with its top shearing to the S could be seen on the eastern horizon. This cloud likely corresponds to the echoes to the SE of Abilene that I saw on the early morning radar presentation on the Weather Channel. At the same time, a much larger echo mass existed in east Texas to the E and SE of Dallas. It had been propagating to the SSW during the night.

George Bomar called from Austin, Texas, during the mid-morning hours reporting that Midland's 500 mb temperature had dropped to near -8°C and that the surface moisture increased to the east --- San Angelo's dew point was near 70°F. George felt that we would have suitable clouds within the eastern portions of the target by early afternoon and that we should be ready to fly as early as 1200 CDT.

After our usual 1030 CDT briefing for the day, I scheduled a stand-by for a flight at 1300 CDT and then went to an early lunch. Only a few small cumuli had formed in the target by 1200 CDT, so I delayed our potential takeoff until 1400 CDT. Meanwhile, towering cumuli and Cbs could be seen to the distant E in the vicinity of Abilene.

The cumuli continued their development into the early afternoon and towering clouds could be seen from the NE-ESE within our target area before our takeoff at 1400 CDT as scheduled. During our climb to the east, I noted cloud base at 9,300 ft at a temperature of 13°C. We ended out climb at 19,000 ft p. alt. just to the east of a small Cb which was growing at about 100° and 50 n. mi from the radar. The best clouds were growing on the W flank of this cloud and we made our first penetration in this area at 1444 CDT about 10 n.mi from the core of the Cb. The cloud had JW water contents and an updraft > 1.0 gm/m^3 and 1,000 ft/min, respectively.

Although the tops of the clouds looked fairly hard and active, the lower portions of the clouds were badly sheared to the S and eaten up by the dry air. As a result, the lifetimes of the smaller clouds were quite short, probably less than 5 to 10 minutes in most instances. Thus, most clouds did not live long enough to develop precipitation.

Our first cloud physics study in conjunction with the T-28 began at 150650 CDT when the T-28 penetrated cloud 2. Just prior to his pass, we had flown in formation --- the T-28 to our right -- up to the cloud and then broke to the left as the T-28 continued on through. During the approach, I had been debating with myself as to which cloud was the more suitable --- the one I had picked or another about 5 n. mi. to its W. As it turned out, the one to the W was younger and better, but we were already committed to cloud 2.

We followed the penetration of the T-28 into cloud 2 with one of our own, entering cloud near 1509 CDT. The cloud had water contents near 1.0 gm/m^3 but the updrafts were not particularly strong. The randomized seed decision --- determined by a flip of the coin by Ray Jones at the radar --- was "Seed" and I ejected 10 AgI flares into this cloud during the pass. Cloud top was < 1,000 ft about us, so its top temperature was probably around -10°C.

The cloud died immediately after our seeding pass without further growth. Its dissipation was very rapid and I saw no visual evidence of glaciation. The T-28 re-entered what he thought was the cloud at 151335 CDT, but he had actually penetrated the more active cloud to the west. The 2D-C probe was not working properly on the T-28, so we have no record of cloud particles in this cloud. The foil impactor was working and we have a record of some small graupel particles.

We then left this area and flew NNW then W then SW and then S in a search for additional suitable clouds. The T-28 penetrated a cloud that I numbered #3 at about 1547 CDT. We flew in formation once again on the approach to the cloud and we passed it on the left as the T-28 entered. It too was dissipating just before penetration.

I then selected cloud #4, which was SSE of cloud #3 by about 15 n.mi. Again, the cloud looked fairly hard on top, but it was small in radius and it was being attacked on its S side by dry air. The T-28 entered this cloud at 155435 CDT and we followed at 155617 CDT. The treatment decision was to have been "No Seed" but Roger Tilbury and I had a miscommunication, and I mistakenly fired one AgI flare into this cloud from what I thought was a dead flare position. Therefore, the cloud has to be considered a seed cloud despite the treatment decision. The T-28 penetrated the cloud again at 155910 CDT during its dying stages.

By this time, the T-28 was very low on fuel, but we still managed to find another cloud that I numbered #5. We followed the same flight procedures, and the T-28 penetrated this cloud at 1614 20 CDT at about the time that it had reached its maximum growth. It was fairly hard initially but quite narrow. We penetrated this cloud at 1616 CDT for a simulated seeding pass, "ejecting" 6 flares. The T-28 repenetrated at 161830 CDT and then headed for home.

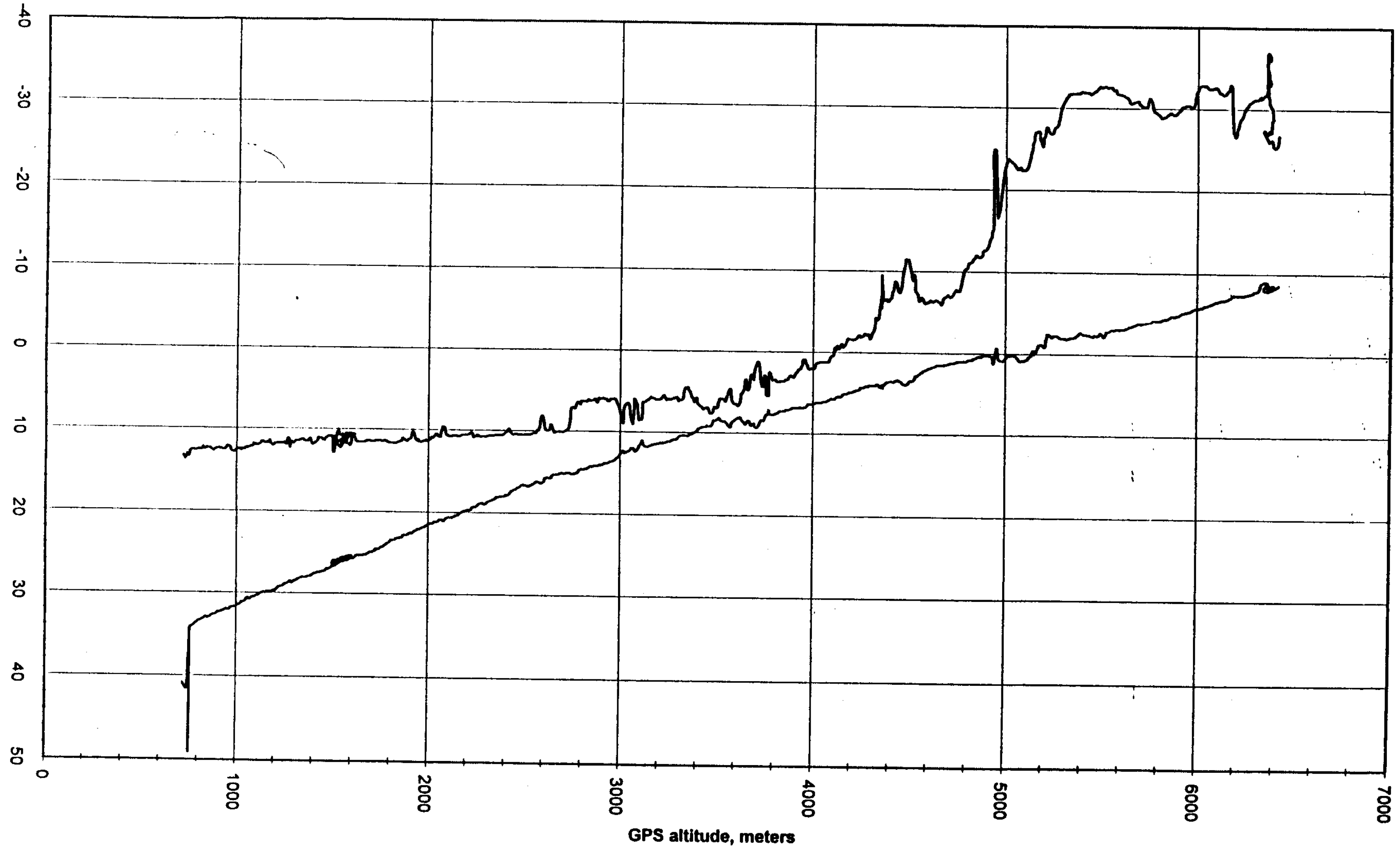
We in the Cessna 340 left the area at 1630 CDT and landed at Big Spring at 1647 CDT. Cloud base on the return was at 11,000 ft at about 11°C. By 1700 CDT, TCU were visible to the distant E and to N-NE. The clouds to our NE continued to grow into the late afternoon and early evening. Ray Jones launched a seeding mission on them at one point but did no seeding. The clouds eventually passed over the NW portions of Big Spring bringing brief heavy rain and some lightning and thunder as they tracked to the SW toward Midland. Midland received 0.33 in later that night.

With the benefit of hindsight, we took off too early for our cloud physics mission today. Our launch time was strongly influenced by the existence of the Cb system to our E, which suggested that extensive deep convective activity was beginning earlier than we expected. Instead, it died and at least 3 hours elapsed before deep convection generated once again. The clouds that we encountered in this time period were too small, weak and sheared to be good candidates for cloud physics investigations.

I took several pictures today. They are documented below.

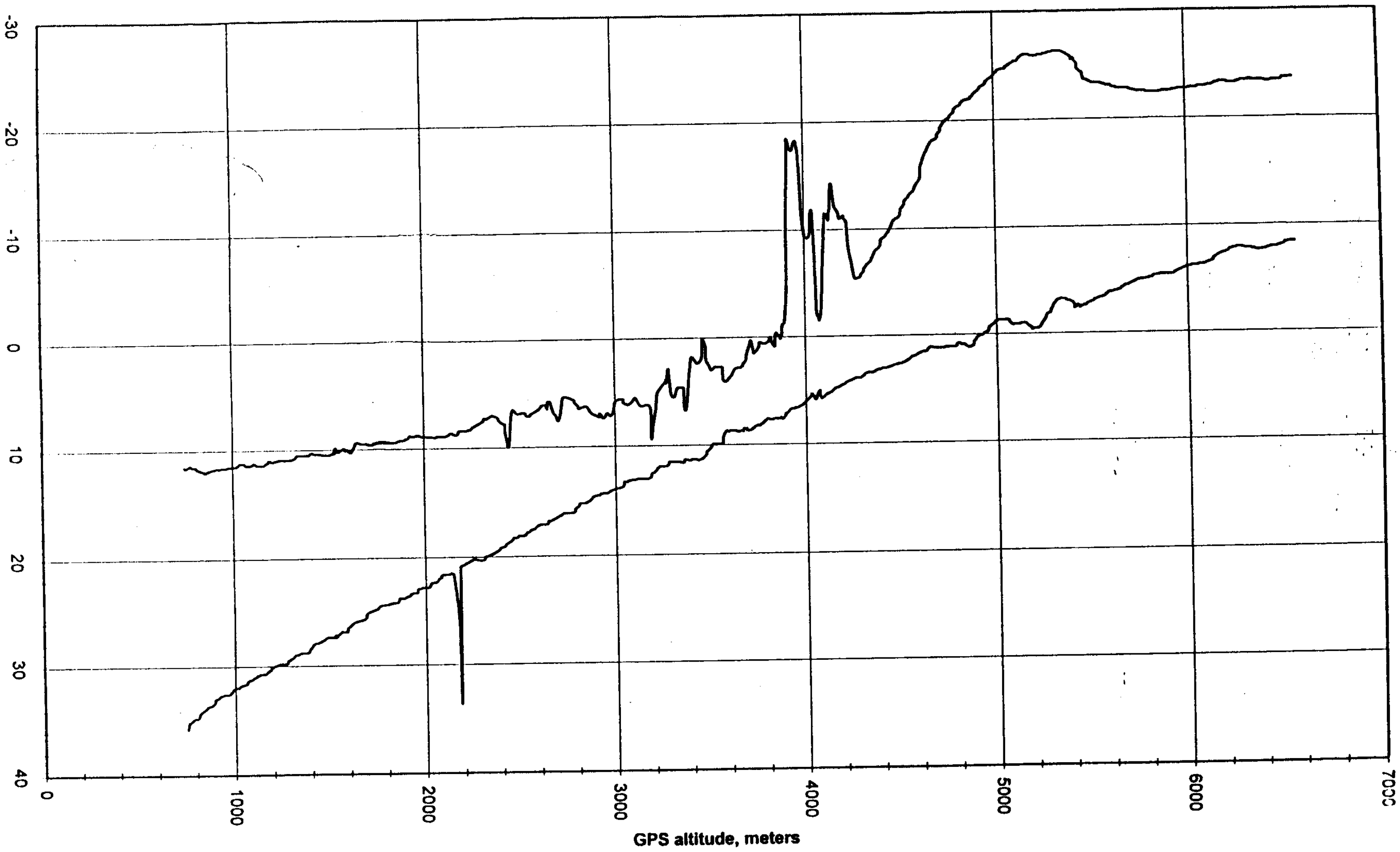
Photo #	Time of Photo (CDT)	Subject of Photo & Comments
7.		Picture of Dr. Rosenfeld and Cessna 340
8.	1442	Picture of cloud 1, a nice tower
9.	1506	Picture of cloud 2 before entry by T-28 & before AgI seeding with 10 flares
10.	????	Cloud 2
11.	1547	Cloud 3 Picture before penetration by T-28
12.	????	Cloud 3
13.	1554	Cloud 4 Just before pass by T-28
14.	1601	Cloud 4 After second pass by T-28
15.	1613	Cloud 5 Picture one min before first penetration by T-28
16.	1614	Cloud 5 T-28 can be seen entering cloud
17.	1618	Cloud 5 Dead cloud

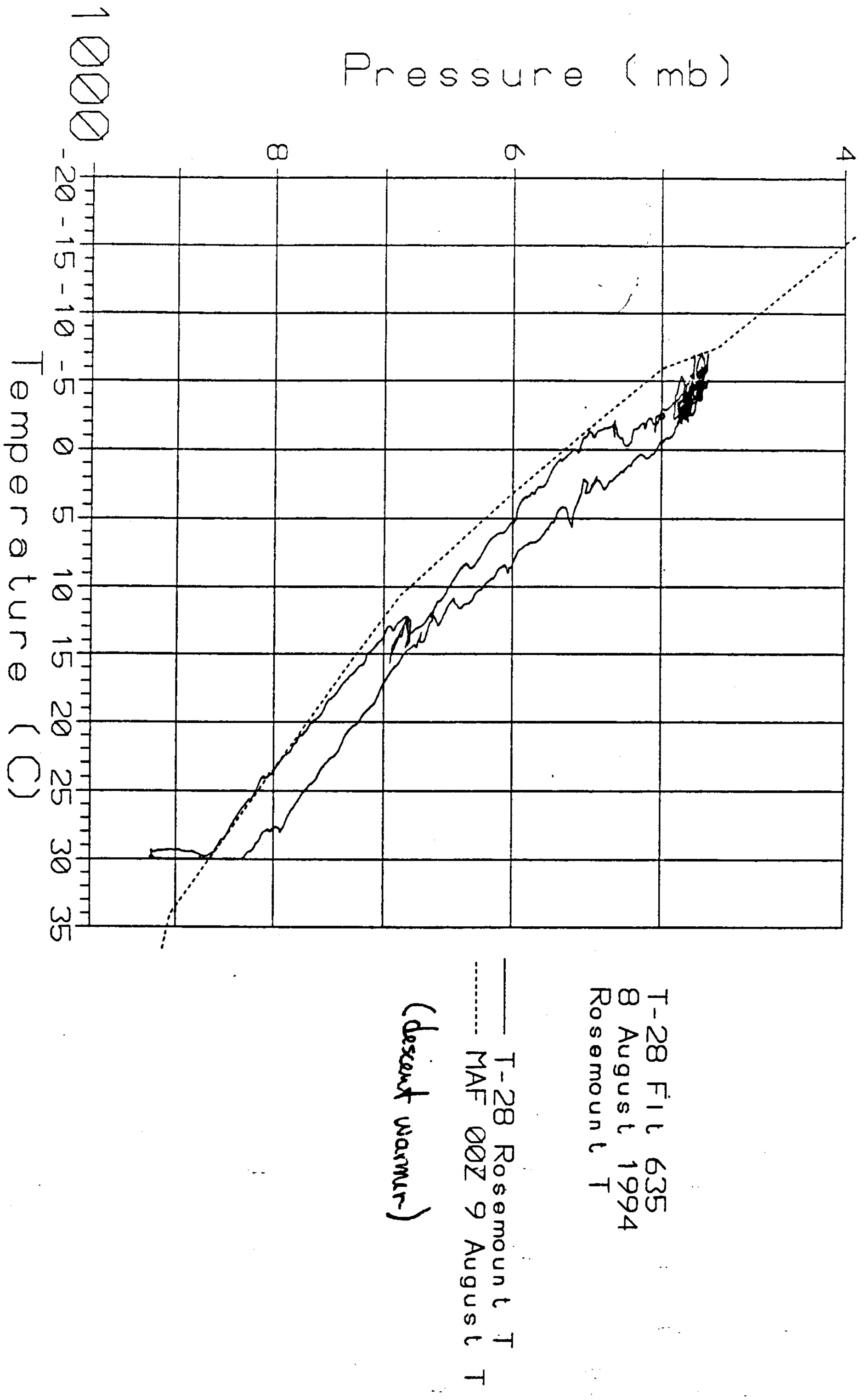
FLIGHT 8/8/94



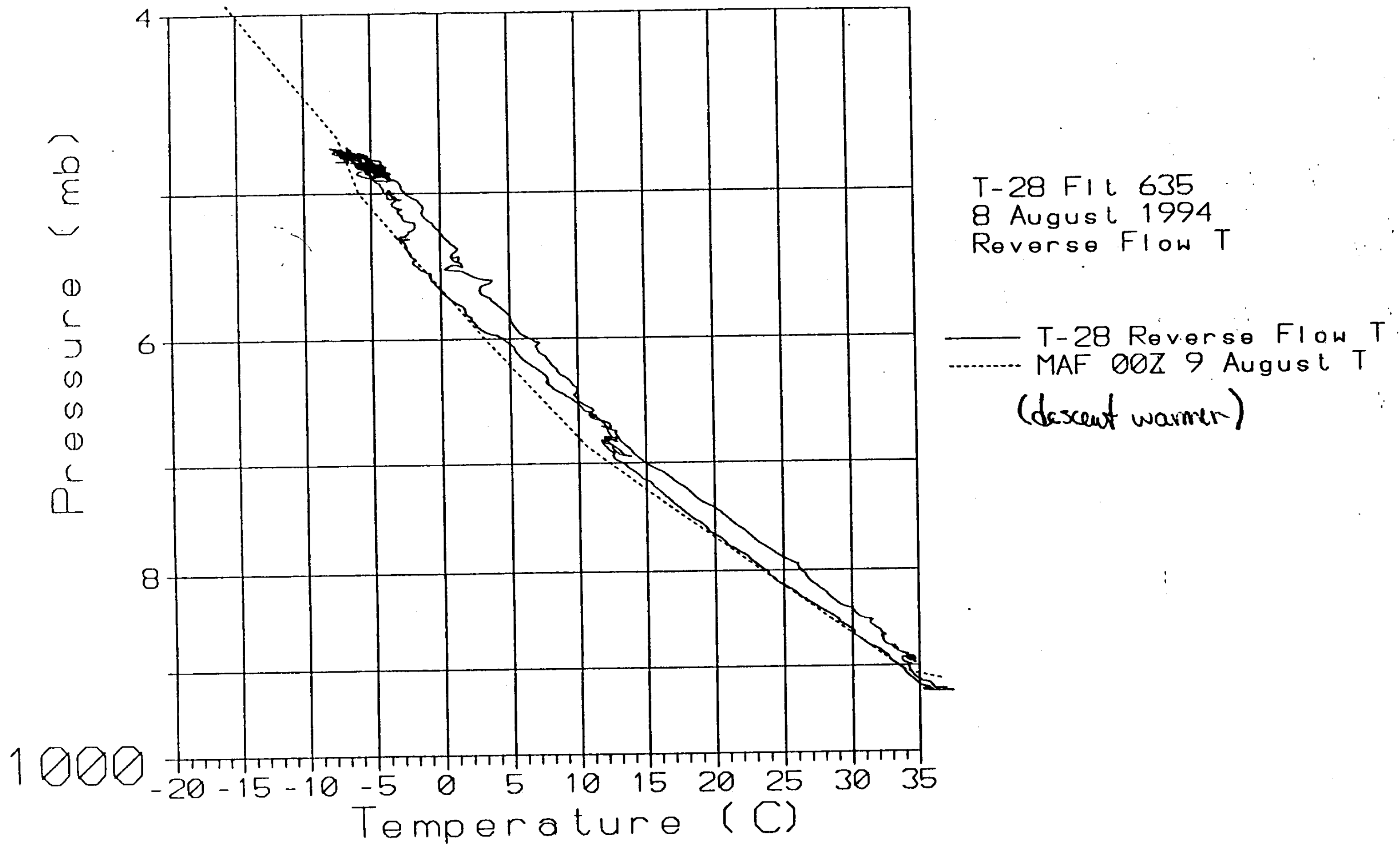
-40
-30
-20
-10
0
10
20
30
40
50
0
1000
2000
3000
4000
5000
6000
7000
GPS altitude, meters

FLTIGHT 8/8/94 descent





(descent warmer)



(descent warmer)

August 14, 1994

It was mostly clear in Big Spring this morning except for scattered altocumulus clouds and haze. There was more altocumulus cloudiness to the NW-NE in the direction of the cold front that is moving south through the Texas panhandle. The surface temperatures were in the upper 60's and the dew points in the mid to upper 50's.

George called in from Austin at 0930 CDT this morning and gave his forecast. The main feature was a trough and dry line that lay from Hobbs, NM to S of Lubbock to near Wichita Falls, TX. The front itself was approaching Amarillo and was forecast to pass through our area tonight. The sounding was still quite dry except for a near saturated area at 680 mb, which was the level of the altocumulus clouds. The winds at low levels were from the S, but they backed into the NE at 20 to 30 kts at 700 and 500 mb. This means that the clouds will be subject to strong wind shear, likely making the smaller clouds unacceptable for study. The convective temperature today is 90°F and the forecast high is 95°F.

After the abbreviated weather briefing, we set a standby for takeoff at 1300 CDT in the event that convection fires early along the trough and dry line. It is more likely that we will not fly until later in the day. Cloud bases are likely to be high and cold, dictating randomization from the block with cold cloud base temperatures with synoptic forcing.

The first cumuli formed in the local area just after noon and the first echo was noted with a top to 5.5 km about 70 n. mi. to the SE of the radar down towards San Angelo. I delayed takeoff until 1400 LT or later, depending on the rate of echo development. The surface trough line passed through our area about 1230 CDT and the winds shifted to the N. The dew points were in the mid to upper 60's to our SE. The forecast area of convection was to our SE in the region of higher dew points and surface convergence. The cumuli were moving from the NE ahead of the front to the N.

By 1400 CDT there was an echo of 40 dBz intensity about 70 n.mi NNE near Post, Texas. Its top was 22,000 ft and it was moving SSW. This report suggested that the clouds had developed enough to warrant flying even though there were no TCU visible from Big Spring. We readied ourselves for takeoff at the threshold of runway 350°, starting the video camera at 1449 CDT, and took off at 1453 CDT. The surface winds were from the NE at about 5 kts.

We noted cloud base at 10,000 ft at a temperature of 9.5°C during the climb, putting us into the synoptically-disturbed, cold-cloud-base block in the event that we decided to randomize for an experimental unit later in the day. We encountered a layer of cloud between 17,000 and 19,000 ft during the climb. It appeared to have been formed from cumuli that penetrated into this stable region, died and then provided their cloud material to the layer of cloud. It had water contents up to 0.5 gm/m^3 and it appeared to be mostly water even though the temperature near its top was -5°C to -6°C at an altitude of 19,000 ft.

Once we were above this layer, we could see a scattering of cumuli that were penetrating through it, particularly to our N and NE during our climb to the N. These clouds were the ones near and to the NE of Post, Texas, that Ray Jones at the radar had brought to our attention before takeoff. Farther to the distant N and NNW was another line up around Lubbock that gave heavy rain to the Lubbock area during the afternoon. Virtually all of the Cbs looked rather soft and glaciated, likely due to the prolonged struggle that they had with the stable layer in growing to Cb stature. All clouds appeared to be shearing to the SW and this was especially detrimental to the smaller clouds.

Farther to the ESE-SSE were fairly hard looking cumuli. Some were at or slightly above our flight level. I watched them closely for development since they were in the area ahead of the trough line that had passed Big Spring earlier. After a time, Danny Rosenfeld and I decided that we should stay in our current region where we had some forcing that might help some of the clouds overcome the stable region. As it turned out, that was the right decision.

I scrambled the T-28 after only a few minutes above the cloud layer. Meanwhile, we climbed to 20,000 ft p. alt where the temperature was a rather warm -6°C. By 1350 CDT, the T-28 had joined up with us. We then aligned on cloud 1 with the T-28 penetrating at 1557 CDT and we followed at 1559 CDT. The cloud was not very strong, so I did not request a randomized treatment decision. The T-28 then made two more passes through it.

We then flew to the W at the southern end of an old weak Cb line, where a number of cloud possibilities had been pulsating for some time. We ultimately decided on a clustering of cumuli that had been producing some fairly hard towers for some time. Each previous tower had appeared to be suitable for up to 10 minutes before it dissipated and dropped back into a rather glaciated mass of cloud below.

The first pass through cloud 2 by the T-28 took place at 1623 CDT. It was the central tower of three in the cluster. The cloud looked fairly good, so I requested a treatment decision from Ray Jones at the radar while the T-28 was making its pass. The decision was NS and we penetrated the cloud at 1625 CDT and simulated the ejection of 6 flares. Considerable graupel was encountered during this pass, but there were still water contents up to 1.0 gm/m^3. The cloud had only weak updrafts. The T-28 then made 5 monitoring passes. The cloud slowly took on a rather glaciated appearance, looked as though it was going to die, and then developed a glaciated tower that grew into the cirrus anvil that had advected over it from the NE. It subsequently merged with this upper cloud and became indistinguishable from the overall anvil mass.

In retrospect, cloud 2 had not been an ideal cloud because of the presence of ice during the initial monitoring pass. I had no way of knowing for certain before we penetrated it, but I should have been suspicious based on the age of the overall cloud mass from which it grew.

The next cloud (cloud 3) looked a little better, although it too had grown out of a cloud mass that had existed for some time. The T-28 penetrated it at 1654 CDT and we followed at 1656 CDT, measuring up to 1.4 gm/m^3 and updrafts up to 800 ft/min. This cloud was younger than its predecessor and I detected very little ice hitting the windshield during the initial penetration.

The treatment decision for this cloud was to be opposite of the previous decision for cloud 2, so I attempted to eject 9 AgI flares during the pass. I did not get an arm light on several flare positions as I moved through the rack in search of flares. In addition, we appeared to have multiple flare firings, when I actually found a live flare. Upon inspection of the rack after the flight, I found that 19 flares had actually left the rack with 8 unfired flares interspersed. This was very troubling to me, and it was something that will have to be investigated tomorrow. There is no doubt, however, that the cloud received a strong dose of AgI, but the flares had not been put where I had wanted to put them.

The T-28 made 5 more passes after our seeding pass, as Charlie Summers, the relief pilot for Dan Custis, continued to do a good job. Cloud 3 appeared to stay strong for a time and then collapsed back to the level of the cloud layer. I did not see an obvious visual glaciation signature, although passes by the T-28 confirmed that ice was present. Certainly, it is not a classic seeding response from any standpoint. In fact, cloud 2 looked more like a seeded cloud than cloud 3, although it had far more ice during the initial monitoring pass.

Had we been in a position to qualify a unit today, I likely would have qualified cloud 3 as the center of the experimental unit. I probably would complained afterward because of the lack of cloud response, but I think that it would have been the correct decision.

As I think about dynamic seeding concepts, it appears to me that cloud 3 did not glaciate rapidly enough to develop the increased buoyancy that would have been needed to support the additional precipitation loading that had developed following seeding. This observation helps reconcile virtually all attempts at dynamic seeding worldwide. A cloud will grow if the additional buoyancy from seeding is more than is needed to support the additional precipitation loading. It will stay at roughly the same height when the additional loading is just balanced by the increased buoyancy. The cloud will die, as in the case of cloud 3, when the loading exceeds the increased buoyancy. If glaciation proceeds slowly, as is the case apparently in continental clouds, seeding will often lead to cloud dissipation.

The Cessna 340 began its return to base at 1712 CDT, noting SLWC values of 0.5 gm/m^3 in the layer cloud during the return. Cloud base was noted at 10,500 ft at a temperature of 9.0°C. We landed at 1733 CDT and intended to refuel and takeoff again for an experimental unit. Inspection of the aircraft revealed that the underside of the right wing was covered with oil and that up to 4 qts of oil had been vented from the right engine. Roger Tilbury immediately grounded the aircraft until the problem was determined and solved.

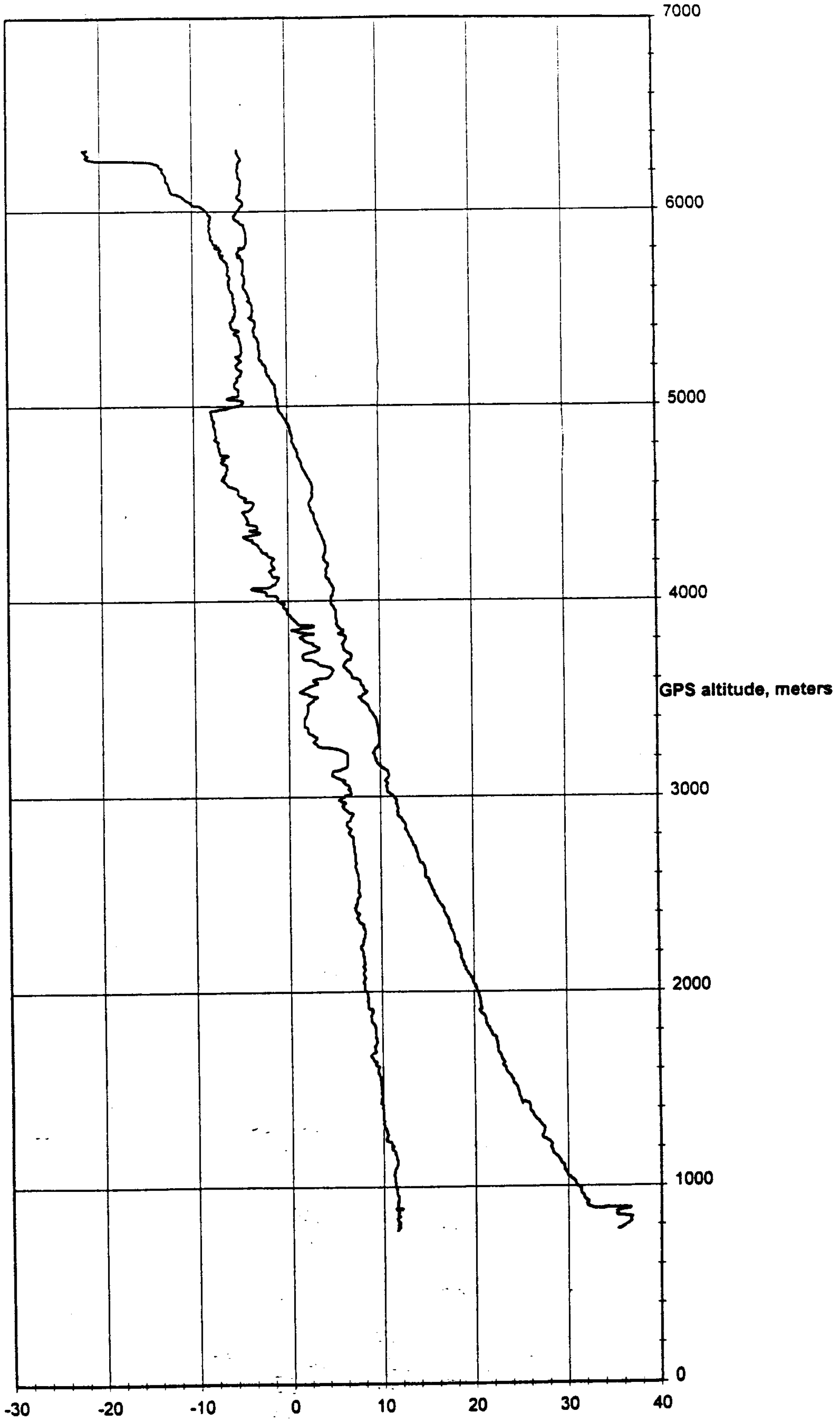
Although I was upset about this turn of events at the time, it does not appear that we lost an opportunity to obtain an experimental unit. The convective clouds appeared to decrease in both number and intensity into the early evening and it is doubtful that we would have been able to qualify a unit in any case. The wind increased from the NE in Big Spring at about 1900 CDT, and it is possible that this was frontal passage.

I took several pictures today. They are documented below.

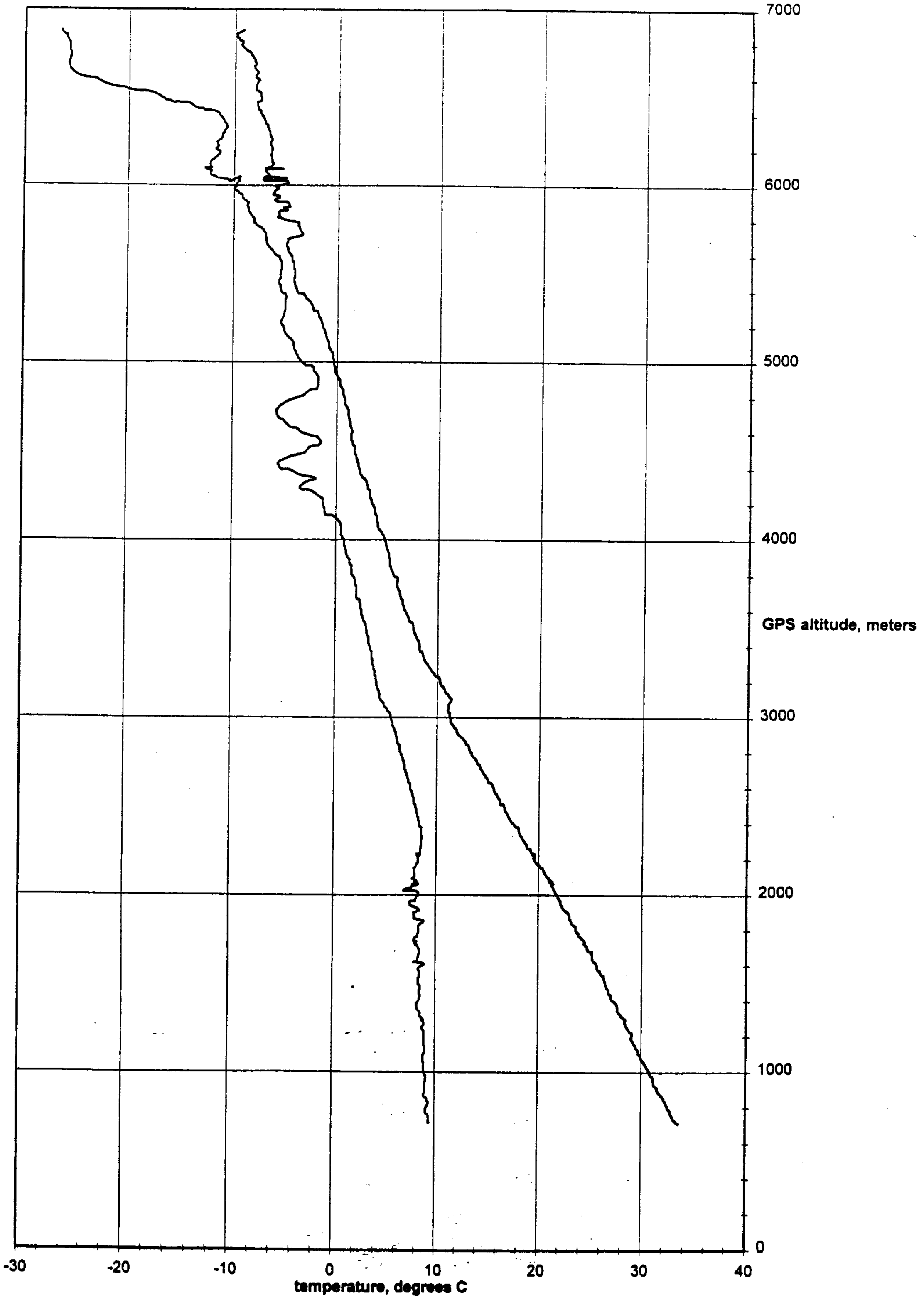
Photo #	Time of Photo (CDT)	Subject of Photo & Comments
18.	----	Picture taken in Lubbock at the NWS office on Friday, August 12, 1994
19.	1557	Cloud 1 This cloud was not suitable
20.	1622	Cloud 2 Just before pass by the T-28
21.	1625	Cloud 2 Before sim. seeding by Cessna 340
22.	1633	Cloud 2 8 min after sim. seeding
23.	1643	Cloud 2 Now a mushy Cb
24.	1655	Cloud 3 Picture at time of first penetration by T-28
25.	1700	Cloud 3 4 min after AgI seeding with 19 flares
26.	????	Cloud 3 Not growing much

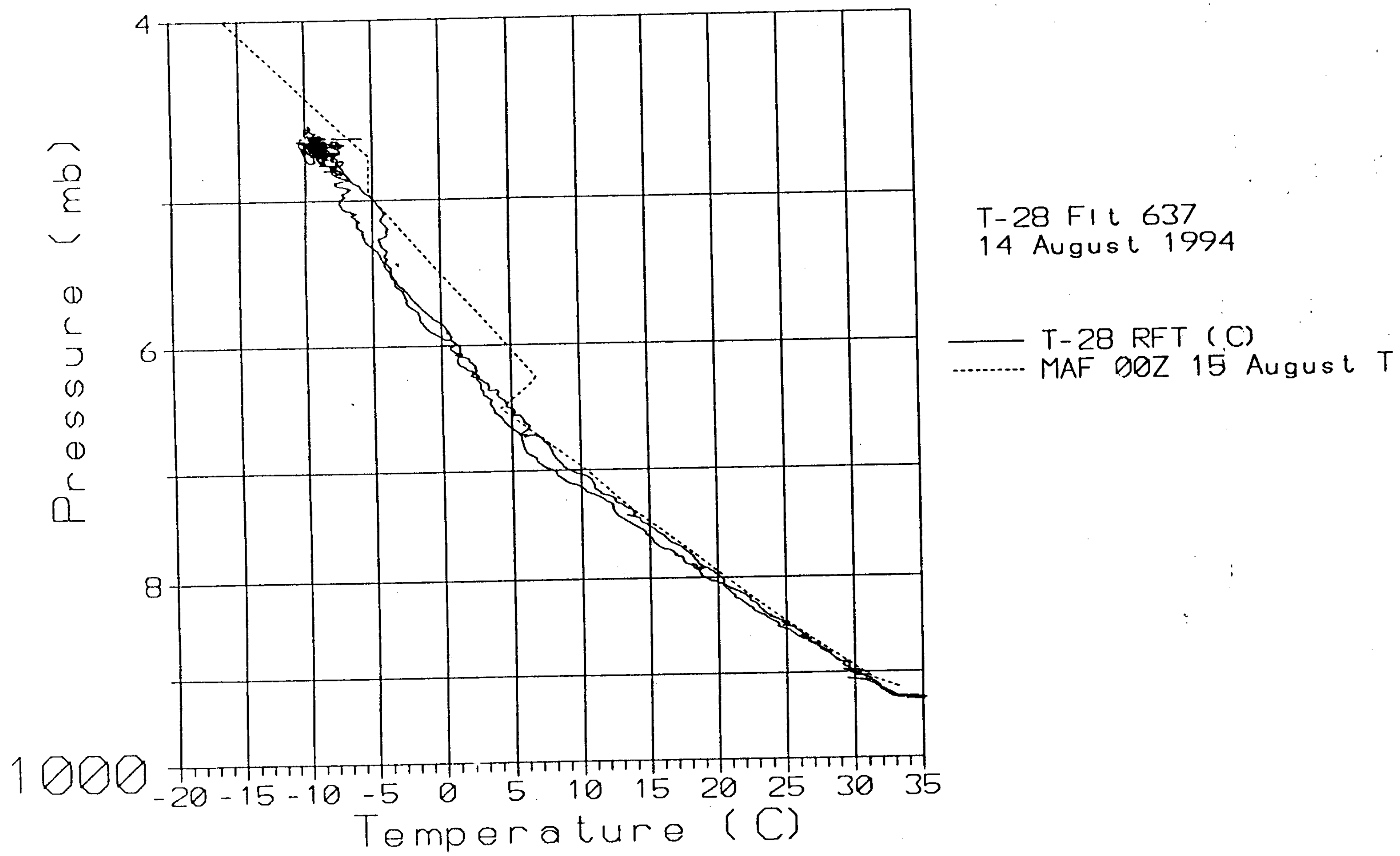
My diary for today would not be complete without a discussion of APIPs. The calculations that I have made to date suggest that at a temperature of -10°C the T-28 will produce more ice crystals than the Univ. of Wyoming King Air, when both aircraft are flown at maximum power in a high drag situation. It is quite likely, therefore, that the T-28 produced ice crystals in both clouds 2 and 3 today, when it was operated at maximum power to compensate for the high ice loading on the airframe. This is something that we must factor into our thinking during our analysis.

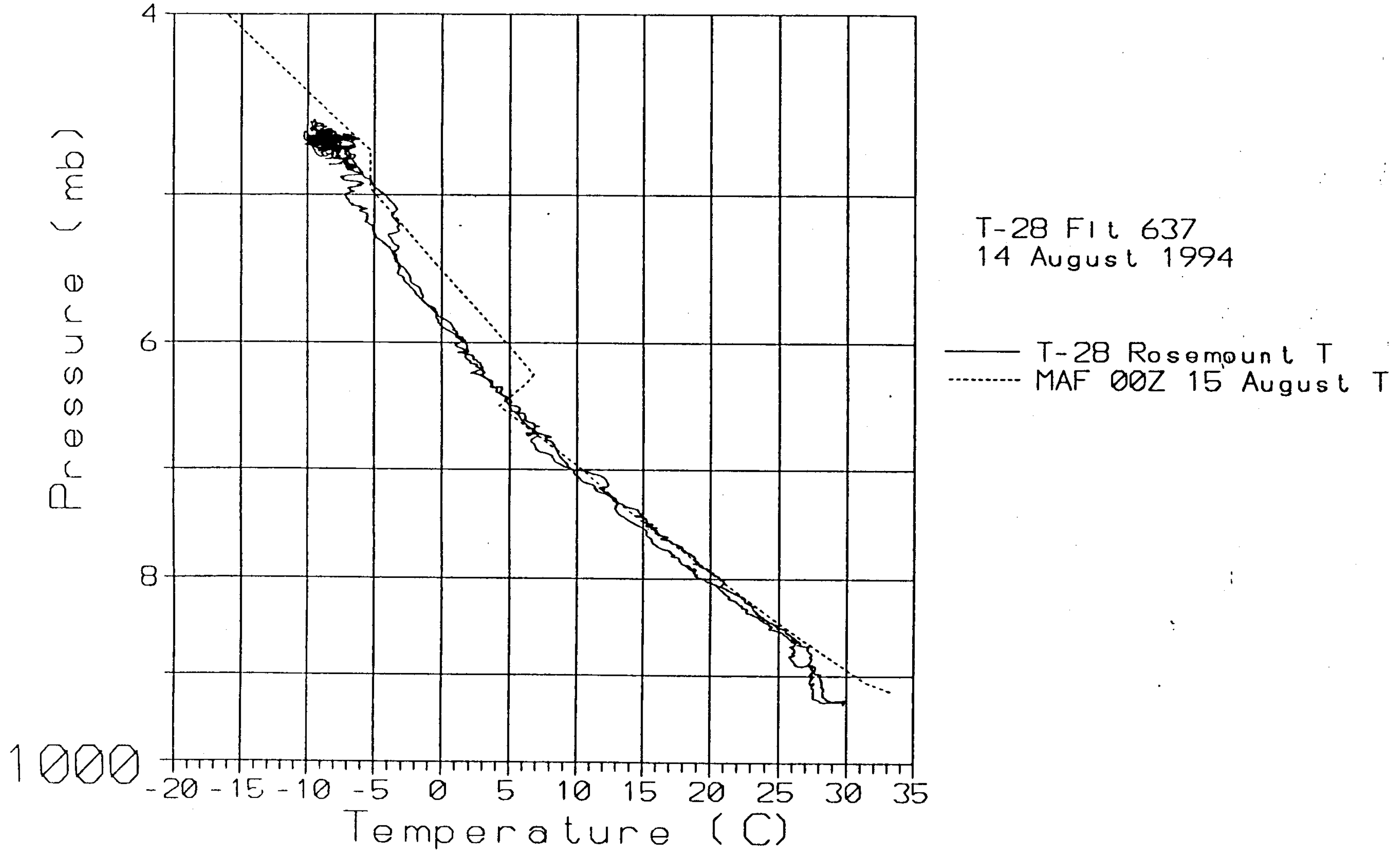
FLIGHT 8/14/94 ascent



FLIGHT 8/14/94 descent




T-28 Flt 637
14 August 1994
T-28 RFT (C)
MAF 00Z 15 August T
Pressure (mb)
4
6
8
1000
Temperature (C)
-20
-15
-10
-5
0
5
10
15
20
25
30
35


Pressure (mb)
4
6
8
1000
-20 -15 -10 -5 0 5 10 15 20 25 30 35
Temperature (C)
T-28 Flt 637
14 August 1994
T-28 Rosemount T
MAF 00Z 15 August T

August 15, 1995

It was overcast this morning with multiple layers of cloud with the lowest stratocumulus layer moving briskly from the E. The surface wind was from the E at 10 to 20 kts in the air mass behind the front that passed early last evening. The early-morning temperature in Midland was 71°F and the dew point was 65°F. We had received virtually no rain since yesterday.

By 1330 CDT, we were still overcast with layers of stratocumulus and altocumulus clouds in Big Spring with an ENE wind of 10 to 15 kts. There were a few areas of weak embedded showers or light rain. Although George Bomar had forecast good conditions in the target area in his morning weather briefing that he sent to me by FAX, it was not looking good for any operations. The front had apparently passed too far to the SE to allow for convergence in our target area. In addition, the lack of solar insolation precluded any significant cloud development in the target area.

It was overcast in the local area at 1430 CDT, but it was clear in San Angelo with a dew point that was holding in the upper 60's. In addition, there was an isolated echo to the distant S over 70 n.mi. away. This information suggested to me that we might encounter suitable clouds along the SE and S margins of the target. This by itself would have been adequate justification for a flight. I thought it was also important to fly to see whether we had solved the oil spillage problem with the Cessna 340 and to see whether the problems with the flare rack were due to my incompetence or to problems with the rack itself.

Prior to our takeoff at 1522 CDT, we set the start time of the video at 1514 CDT, so the elapsed time is to be referenced to that time. We took off under overcast skies with some breaks noted to the W and N. There were no cumuli in the area, so I decided to climb to altitude to search for cumulus clouds in the hope that I could determine cloud base on the return to the airport. The base of the altocumulus was 12,000 ft p. alt. at a temperature of 6°C.

Once we were above the layer cloudiness and flying SE, I could see a line of TCU and a few Cbs to my E-SE-SSW. The cumuli fronting the large clouds to their S appeared to be within striking distance. The temperature at our flight altitude of 20,000 ft p. alt. was -7°C, which is warmer than I would like. We proceeded to a point about 80 n.mi to the SSE of Big Spring and orbited there while I made up my mind what we should do. There were many nice hard cloud towers in this region that were separate from some Cbs farther to the SE and SW. Since they were < 100 n.mi. from Big Spring, I asked for a scramble of the T-28.

Meanwhile, I toyed with the idea of qualifying a unit, despite our position near the boundary of our target area. I was troubled, however, as to what I would do with the T-28, if I qualified a unit before it arrived on the scene. If the decision was to "Seed", I figured that I would have no problem. I could certainly find at least one cloud in the unit that would not be seeded, so that it might be studied for cloud physics purposes. Having done that, I could use one of the seeded clouds for the opposite decision. If the decision was "No Seed" things would get a bit sticky, since I did not want to contaminate the unit with a seeded cloud. I figured, however, that I would still be able to find a cloud suitable for seeding outside the unit and thereby manage to obtain at least a pair of clouds for cloud physics purposes while still obtaining our first random unit of 1994.

Our first pass through cloud 1 was not suitable, but the second at 1604 CDT had an updraft > 1400 ft/min and a water content of 0.9 gm/m^3. This was enough to qualify the unit, if I chose to do so. In looking around, there were many very good looking clouds, and by 1612 CDT I decided to ask for a treatment decision. It was to be selected from the warm cloud base partition with synoptic forcing (i.e., block A). At this point, I was only guessing that the cloud base temperature was ≥ 10°C, which would put us in the warm block --- there was no doubt that the area was synoptically forced by the convergence near the front. The decision was "No Seed", and our first simulated seeding pass was made at 1613 CDT.

We continued the simulated seeding until the T-28 arrived on the scene at 1650 CDT. By that time, we had made 11 simulated seeding passes with the expenditure of 63 flares. Only cloud 2 grew much after the treatment pass and it was contaminated by the ejection of 1 flare during the pass. I heard a weak muffled noise during the pass and both Roger Tilbury and I thought that it might have been a flare even though I had pushed only the fire button without advancing to a live flare. After thinking and saying some unprintable things, I asked that the rack be shut off entirely. This would no longer give us an event marker for the simulated firing of each flare, but at least I would have the assurance that no flare left the rack into a NS unit.

A few of the clouds in the unit grew slowly to small Cb stature during the simulated seeding. They did not appear to be overly strong, but at least one of them could have reached 40,000 ft. New growth in the unit was to the N of the larger clouds.

We had joined up with the T-28 at 1655 CDT for a pass through cloud 10, which would be our first cloud physics test for the day. Naturally, it was a NS since the cloud was well within the unit. I simulated 5 flares into this cloud at 1659 CDT and the T-28 followed with 4 more monitoring passes (total of 5). The cloud died fairly rapidly and we began our search for another cloud.

Cloud 11 was the next cloud for cloud physics study. We penetrated it at 1715 CDT and simulated the ejection of 12 flares after the initial pass by the T-28. The cloud looked stronger and better than cloud 10. It was not long, however, before this cloud too had subsided below the T-28 after its 3rd monitoring pass (4 total passes including the initial pass prior to simulated treatment. While the T-28 was making its passes, we moved away and continued our randomized seeding, stopping after the simulated treatment of cloud 14 at 1727 CDT. By this time, the simulated flare total was 101 flares on 16 treatment passes, meaning that we would have been out of flares had we actually been seeding.

There was only 30 minutes of fuel left for both aircraft before they had to return to the airport, and I was intent on getting a good cloud outside of the unit that would permit actual AgI seeding for cloud physics study. The best I could do was a beautiful cloud on the N or NE edge of the unit. My navigation showed that it was just outside at about 13 n.mi from the original center of the unit, but I would not argue with anyone who would say that it was just a mile or so inside. Despite this uncertainty, I decided to proceed, because of the great importance of obtaining at least one AgI-seeded cloud on this day.

The selected cloud (#15 of the day) was the best looking of the three clouds that had been selected for cloud physics. It was broad and quite hard and an excellent candidate for cloud physics study. The T-28 made its first monitoring pass at 173553 CDT and we followed at 1737 CDT at nearly right angles to his pass and ejected 19 flares.

The seeded cloud stayed very hard looking until 1749 CDT, about 12 minutes after seeding. It gave the appearances of having been invigorated internally, but it really never grew all that much. After 1749 CDT, it was obvious visually that it was glaciating. Unfortunately, the T-28 had to leave the cloud at 1744 CDT after having made only 3 passes following seeding, so if the cloud was glaciating internally, it will have to be evident within 7 minutes following seeding --- a later cursory look at the 2D-C data suggested that glaciation was taking place.

Following the monitoring of cloud #15, we spiraled down to cloud base even though we were short on fuel. Cloud base was noted at 9,000 ft at a temperature of 12°C. I had guessed right; we really were in the warm-cloud block (i.e., CBT $\geq$ 10°C). We then continued on to Big Spring with a low oil-pressure reading on the right engine, the same engine that had dumped oil on the last flight. By the time that we landed at 1819 CDT, the oil pressure was so low that Roger Tilbury had to throttle the right engine back to an idle and essentially land on one engine. After we had shut down, we inspected the underside of the right wing near the engine and saw that it was covered with oil. In addition, there were only about 2 qts of oil in the engine itself. We are lucky that we got back when we did. Otherwise, we might have been on one engine for much of the trip back.

From my perspective, it had been a rather successful day. We had managed to obtain three clouds for cloud physics study plus an experimental unit. On the negative side, the unit was near the edge of our target such that a portion of it was outside digitization radar range for much of its history. In addition, one of the clouds in the unit had received 1 AgI flare for reasons that are unknown to me at this writing. Further, the cloud that was seeded with AgI for cloud physics purposes was very close to the unit boundary when it was seeded.

I took several pictures today. They are documented below.

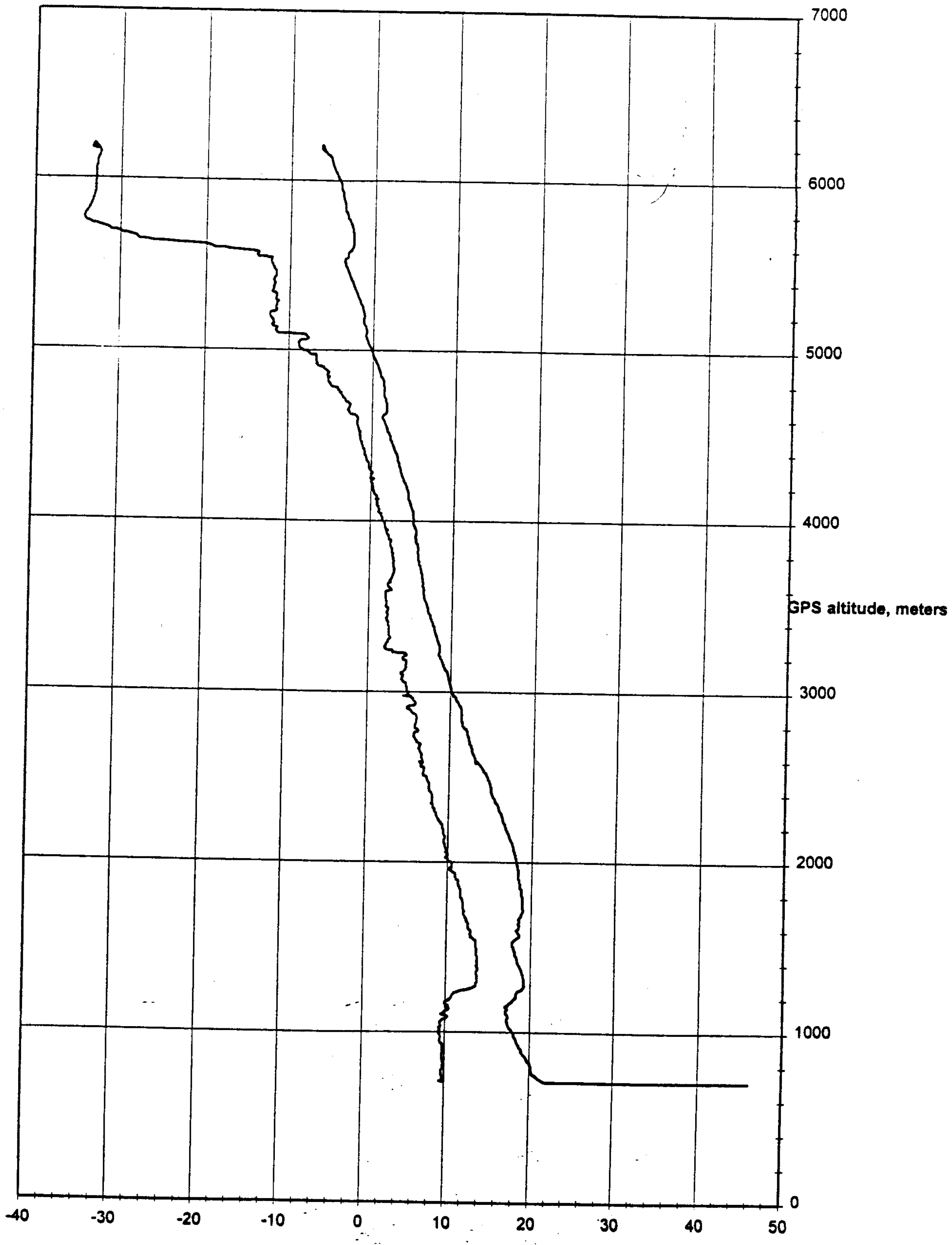
Photo #	Time of Photo (CDT)	Subject of Photo Comments
27.	1604	Cloud 1 Before sim. seeding pass that qualified the unit
28.	1656	Cloud 10 Before entry by T-28
29.	1659	Cloud 10 Before sim. seeding
30.	1701	Cloud 10 in foreground, T-28 seen entering cloud
31.	1712	Cloud 11 Before penetration of cloud 11 by T-28
32.	1716	Cloud 11 After sim seeding pass by Cessna 340
33.	1735	Cloud 15 Picture before first penetration by T-28
34.	1740	Cloud 15 Picture 3 min after AgI seeding with 19 fl
35.	1743	Cloud 15 Picture 6 min after AgI seeding

I continue to be concerned about the APIPs potential of the T-28 in this project. It appears that it is operated at maximum power on most cloud penetrations, especially when the aircraft is loaded with ice, as is the usual case. My calculations indicate that this aircraft should be a prolific producer of ice crystals under these conditions at an ambient temperature of -10°C.

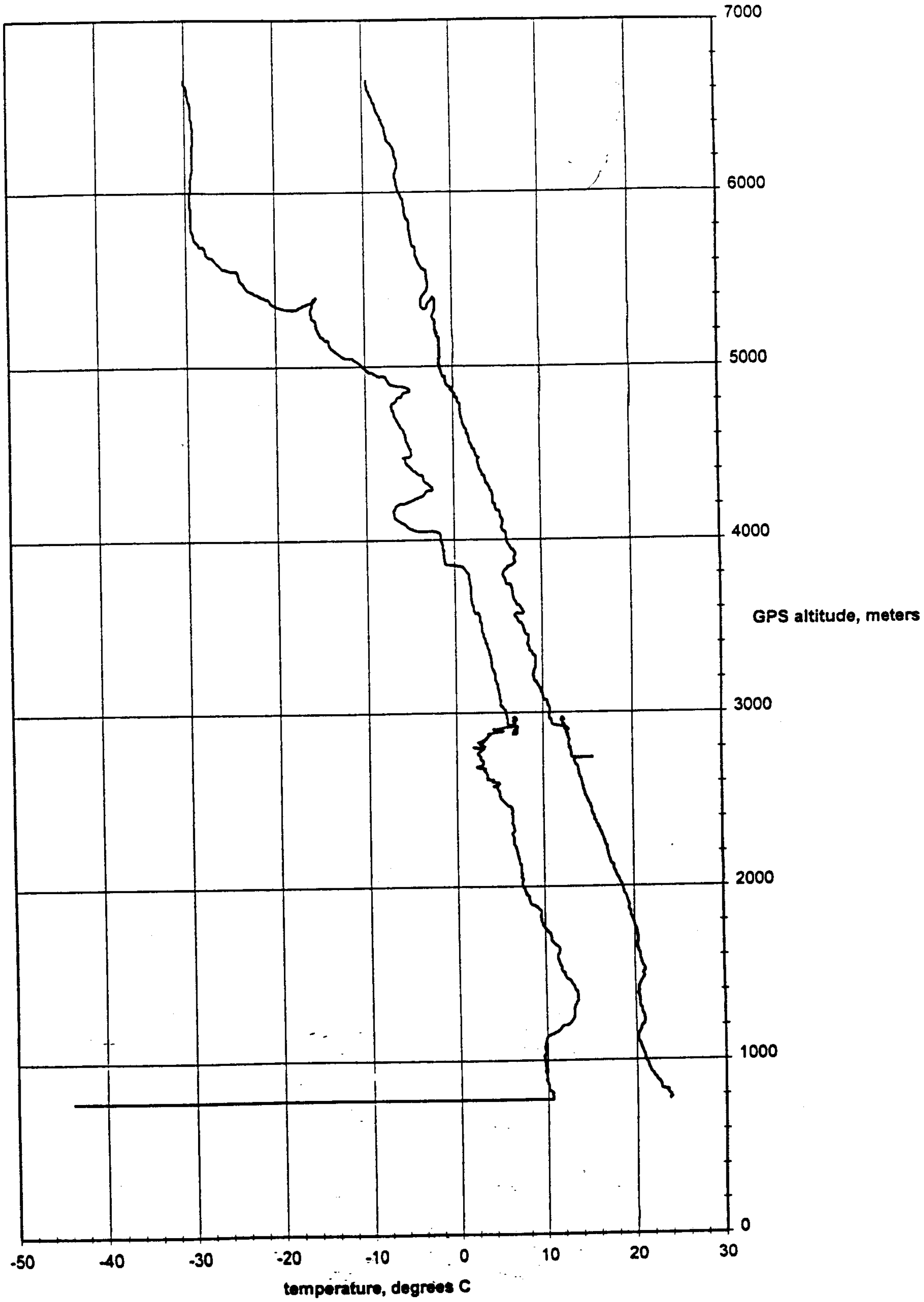
During the discussions with Dr. Bob Czys, while he was visiting here in Big Spring, he mentioned that he seems to remember a case in 1989 when a cloud that had been randomly seeded with sand had very high quantities of ice crystals. The ambient temperature was -10°C and the monitoring aircraft after treatment was the T-28 --- the T-28 made no pre-treatment pass. Bob has kindly offered to make the data available to me and Dr. Andy Detwiler has offered to process any additional data that might be needed for that flight. It may make a good case.

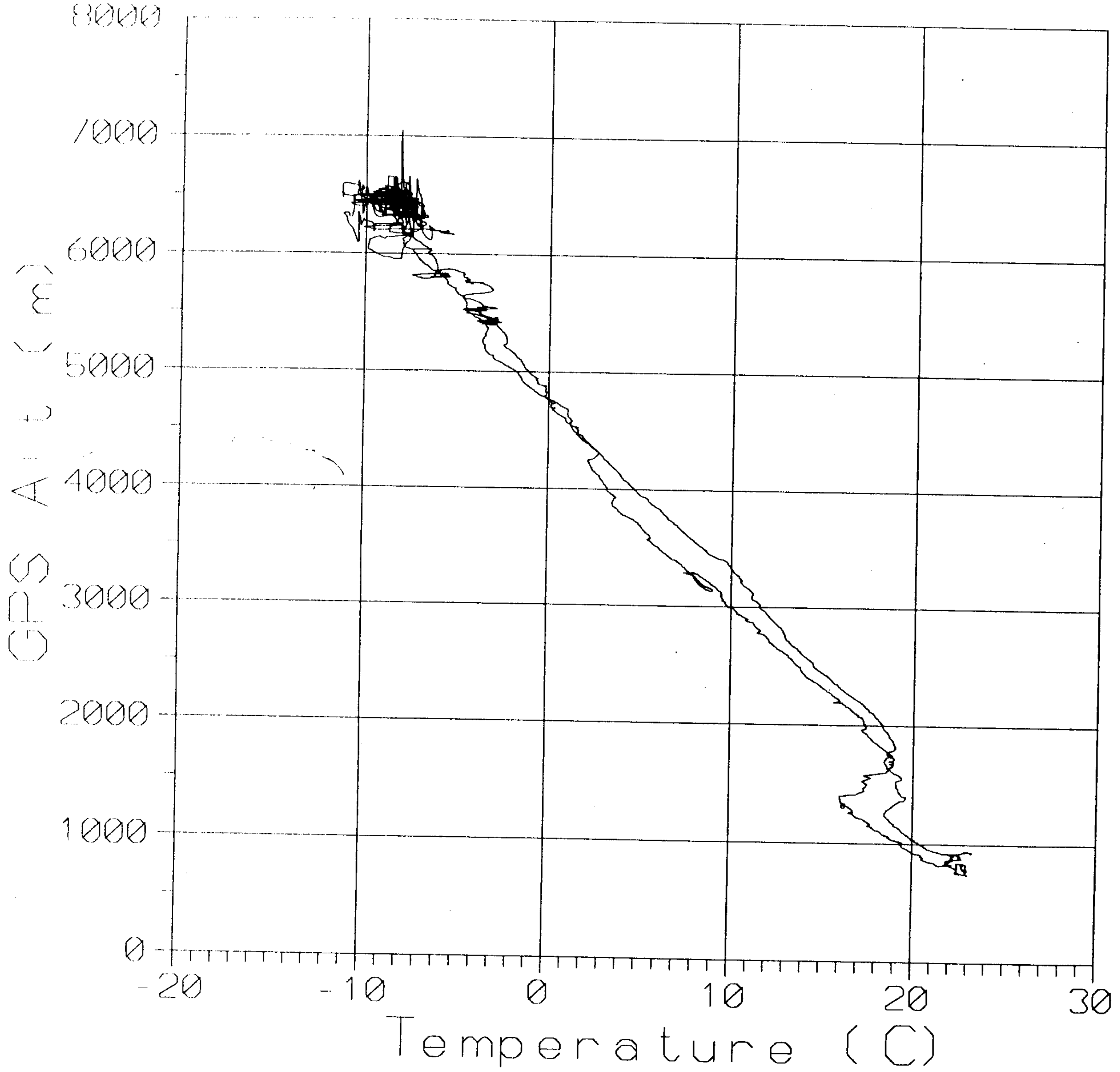
Joe Golden, Bruce Boe and Bob Czys leave Big Spring tomorrow to return to their offices. We had a great visit all around. Meanwhile, Dr. Paul Smith from the South Dakota School of Mines and Technology arrived for a visit. He will be here until Friday, August 19, 1994. Paul is the T-28 Facility Manager. I have asked him whether he might be able to bring the T-28 to Mono Lake during the planned APIPs studies this winter. He did not seem to think that it would be much of a problem. From my perspective, it is vital to test this aircraft for APIPs production. I have supplied him a letter requesting support of the T-28 for tests this winter.

FLIGHT 8/15/94 ascent

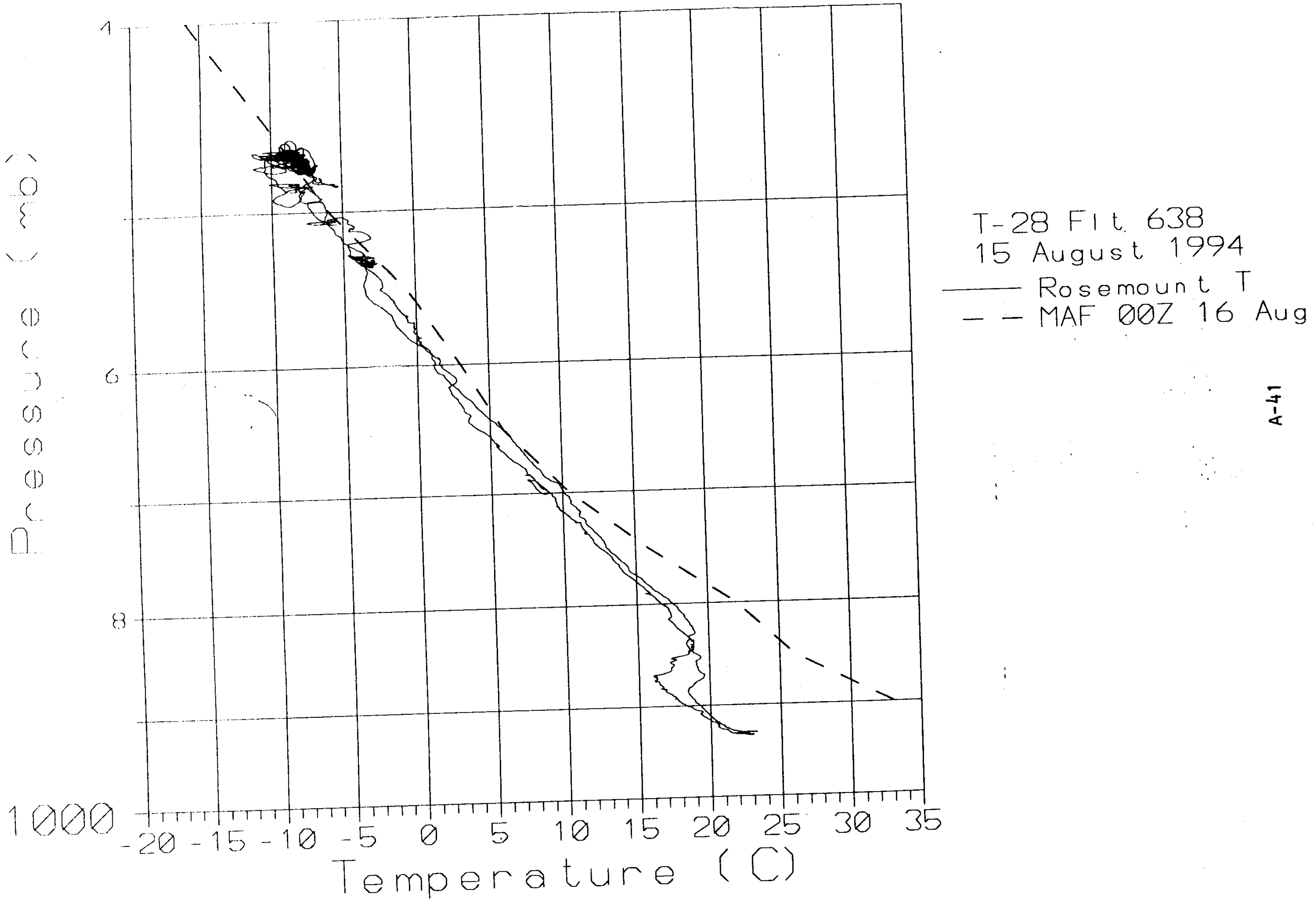


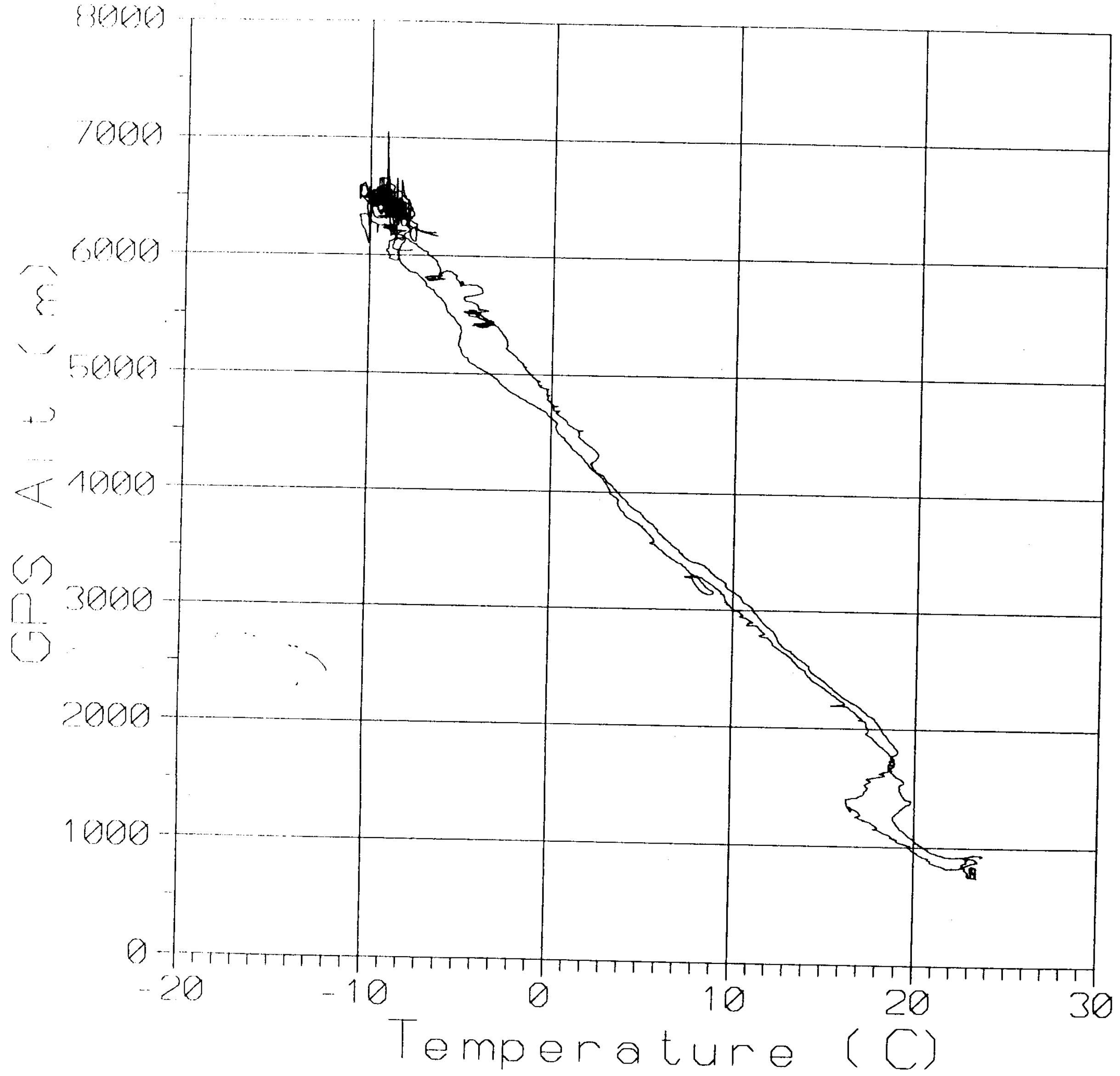
FLIGHT 8/15/94 descent



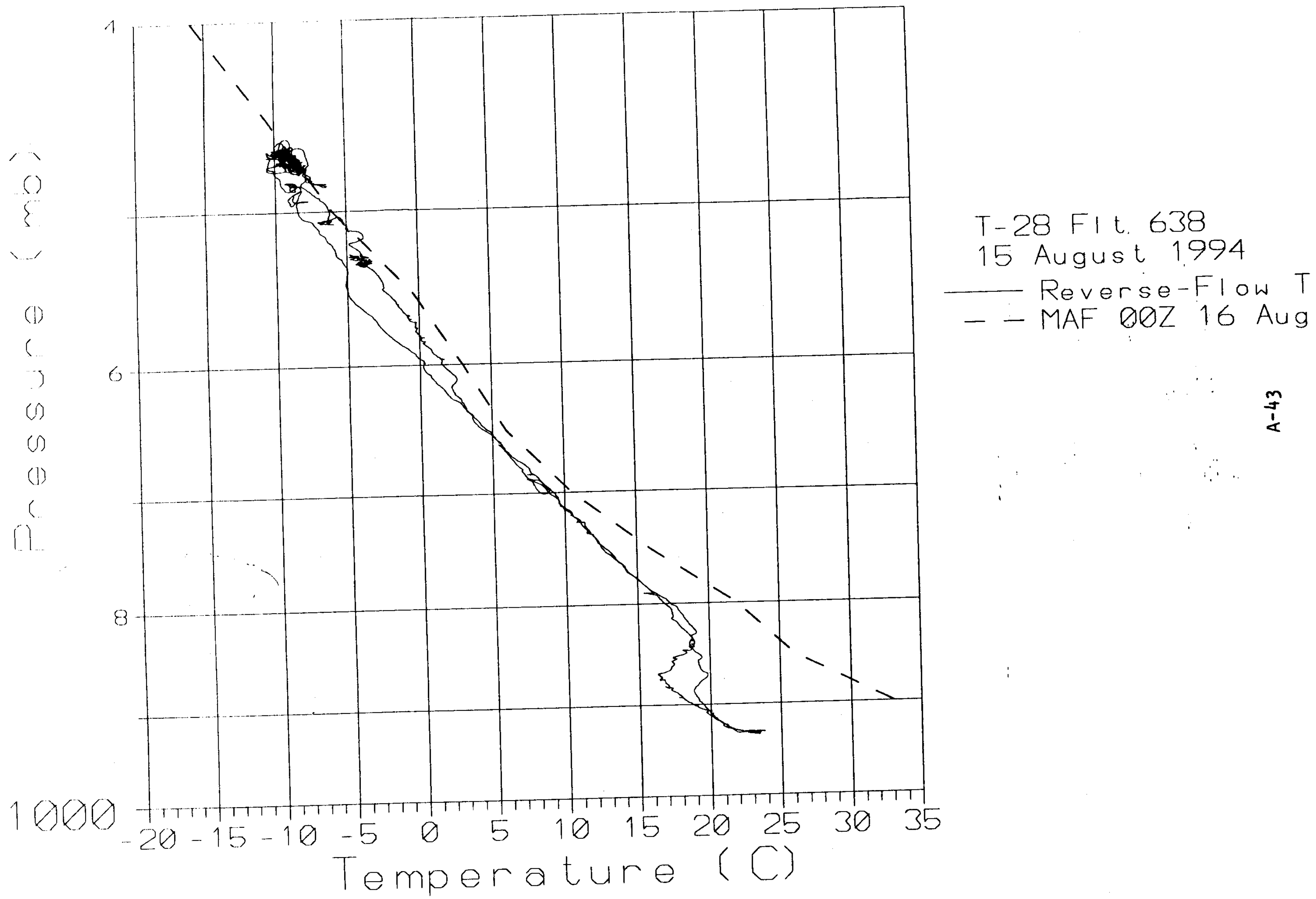


T-28 Flt 638
15 August 1994
Rosemount T


Pressure (mb)
4
6
8
1000
-20
-15
-10
-5
0
5
10
15
20
25
30
35
Temperature (C)
T-28 Flt 638
15 August 1994
Rosemount T
MAF 00Z 16 Aug



T-28 Flt 638
15 August 1994
Reverse Flow T


T-28 Flt. 638
15 August 1994
Reverse-Flow T
MAF 00Z 16 Aug
Pressure (mb)
4
6
8
1000
-20
-15
-10
-5
0
5
10
15
20
25
30
35
Temperature (C)

August 20, 1994

Big Spring had mostly cloudy skies before sunrise this morning and the sky cover had decreased to broken shortly thereafter. The clouds consisted of a few cumuli, thick altocumulus and thin broken cirrus. The altocumulus layer appeared to be moving from the WNW. The radar showed a scattering of light showers, especially to the NE of Big Spring. The showers were apparently being produced by the altocumulus layer as they were yesterday morning. The surface winds were light from the N and they are expected to turn into the NE and E later today as the diffuse frontal boundary passes through the area.

The plotted sounding showed very dry conditions up to at least 650 mb and then moist conditions up to 450 mb and then somewhat drier above. The most noteworthy feature was a stable region starting at about 480 mb and extending up to 435 mb, beginning at a temperature of -10°C. We now have the GPCM on our computers thanks to Dr. Harry Orville, who is visiting us, and it will be interesting to see how it addresses this sounding.

The GPCM run gave very little dynamic potential with a max of only 0.37 km at a cloud radius of 9.3 km. For larger radii, the clouds reach 14 km. The dew point in San Angelo this morning was 70°F, so it is obvious that conditions change very rapidly with distance. It is important to keep this in mind when considering the morning run of the Midland sounding.

The first cumuli formed in the local area at 1300 CDT with patches of altocumulus castelanus and anvil cirrus above. The surface wind was from the NNE. A few TCU could be seen to the distant S. The satellite image showed a developing line of cumuli along the border of New Mexico and Texas.

By 1430 CDT, the winds had increased to 10 to 20 kts from the NE in Big Spring with some blowing dust. The cumuli were concentrated to the SE and there were extensive patches of thick altocumulus and altocumulus castelanus. The temperature in San Angelo was 99°F and the dew point was 67°F. Although not much had developed, attention was being focused on the area between Midland and San Angelo.

By 1500 CDT, the cumuli to the SE about 40 n.mi were showing some vertical growth and I set take off for as soon as we could get the aircraft ready to go. It was obvious to me that a convective line was just starting to form between us and San Angelo.

We started engines at 1540 CDT and set the camera to start at 1549 CDT. Our sky had thick but broken altocumulus and altocumulus castelanus NW-N-NE-ESE with lesser upper cloud and a line of TCU developing to the SE-S. We climbed out toward the line, finding cloud base as 10,500 ft at a temperature of 12°C. We ultimately topped most of the layer clouds and the smaller cumuli at 18,000 ft on our climb to 20,000 ft, where the temperature was -9°C to -10°C.

We began our work on the SW portion of the line about 75 n.mi to the SSE of Big Spring. We gave no thought to a random unit because the cloud physics work had priority. Further, I probably would not have qualified a unit in this area in any case, because of the strong natural development and forcing. Cloud 1 was selected and the random treatment decision was to "Seed". The cloud was hard on top, but Danny said that its bottom was not very good. The cloud was a few thousand feet above the aircraft during the seeding with 19 AgI flares. More may have been ejected because Danny heard multiple flare sounds.

The T-28 made 6 total passes in this cloud while it just sat there and looked dumb. It slowly sunk down and appeared to glaciate. After it had completely glaciated, there was a large area of scintillating ice crystals. I guess I could blame the lack of growth on the poor base and lack of a sustained updraft. It is also possible that the glaciation proceeded too slowly to support cloud growth.

Our next cloud, which was to have the opposite treatment decision (i.e., No Seed), was selected to the ENE of Cloud 1. It too was quite hard, as it was growing in a strongly forced area. We penetrated it at 1708 CDT and simulated the ejection of 17 flares. It stayed hard for a time and then subsided as new towers grew to its immediate NW and SE. This unseeded cloud initially contained a lot of ice. Farther to the E, there were other hard growing cumuli and to the NE was a mature Cb with tops > 40,000 ft. It was an area of beautiful clouds, but not an area to consider qualifying a unit. I doubt that the rules would have allowed it in any case.

Farther to the W, while we were working cloud 2, was a glaciated mass that we thought was the remains of cloud 1, although I could not be sure that it really was --- Danny is certain that it was our old cloud 1. In any case, new cumuli were growing up through this mass and being seeded long after our primary seeding. We flew through this amorphous mass and saw the scintillation of light as though the sun were shining through diamonds.

The third cloud was selected farther to the WSW away from the really strong development and to the E of another Cb farther W. I should have asked for another random treatment decision, but we had time for only one more unit, and I thought it critical to be certain to obtain yet another AgI-seeded cloud. The cloud had two towers roughly E-W with the western tower the taller of the two. It was probably at least 3,000 ft above us at the time of our seeding pass from W to E. The tower on the E was only a short distance above us during the seeding pass at 1744 CDT. I tried to eject 25 flares on this pass, but both Danny and I heard multiple reports as though more than one flare was firing with each button push.

Cloud 3 stayed hard long after seeding and actually was the first strong growth that I have observed following seeding this year. The cloud ultimately grew into a small Cb as the T-28 made many passes through its center encountering some rough weather, especially multiple flashes of lightning. The T-28 was carrying a huge ice load during many of the cloud passes.

A quick look at the data revealed a very strong seeding signature with this cloud relative to the others on this day. I am not surprised considering the number of flares that were put into the cloud. I intended 25 flares in this cloud and 19 in cloud 1 for a total of 44 flares, whereas later inspection of the rack revealed that we had actually used 56 flares. This means that there really were multiple flare firings for reasons that are unclear to me. Regardless, clouds 1 and 3 were really heavily seeded. I suppose that is better than under-seeding, when you are looking for a cloud seeding signature.

We then began our return to the airport in what we thought would be an uneventful flight. It was not long, however, before Charlie Summers, the relief pilot of the T-28 --- Dan Custis will return on Monday --- declared an emergency when his fuel gauges went to zero. There were a few anxious moments but he did make the airport. Examination of the fuel tanks revealed that he had only about 15 minutes of fuel left. Apparently his fuel vents had frozen over to give an erroneous reading of adequate fuel remaining, but when the ice melted, Charlie got an accurate reading. It was a shock for him to learn that he was about out of gas.

Big Spring had only scattered clouds on landing at 1845 CDT in a brisk ENE wind. The Cb line could be seen well to the SE-S and a few Cbs could be seen just above the western horizon. There were a few patches of altocumulus and stratocumulus with the latter drifting from the E to the W.

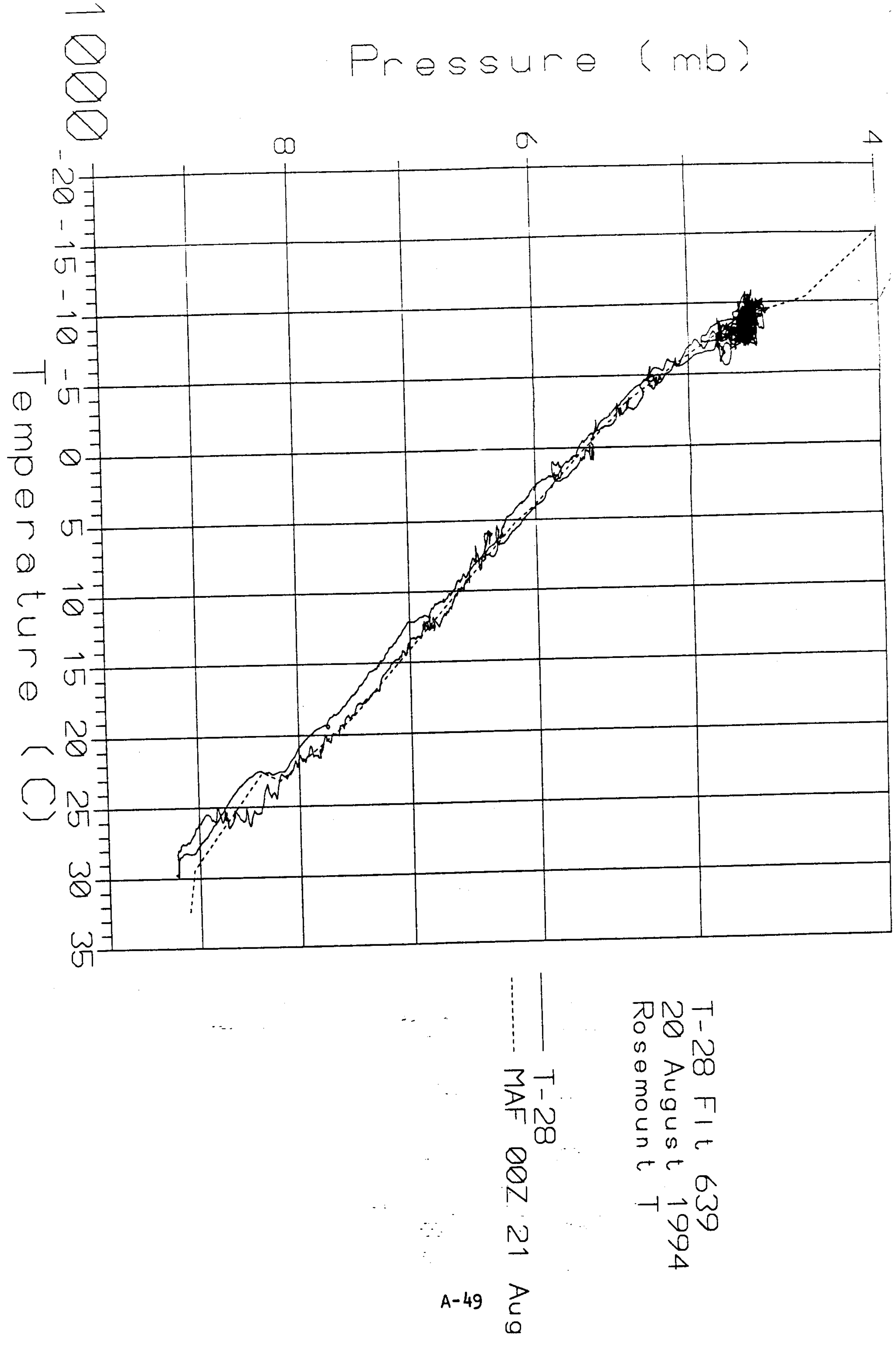
It was interesting to note that the equivalent diameters from the FSSP probe were about 5 microns smaller than previous days. I would guess that this was due to the stronger updrafts that activated more drops at cloud base and these drops in turn did not have as much time to grow in the stronger updrafts.

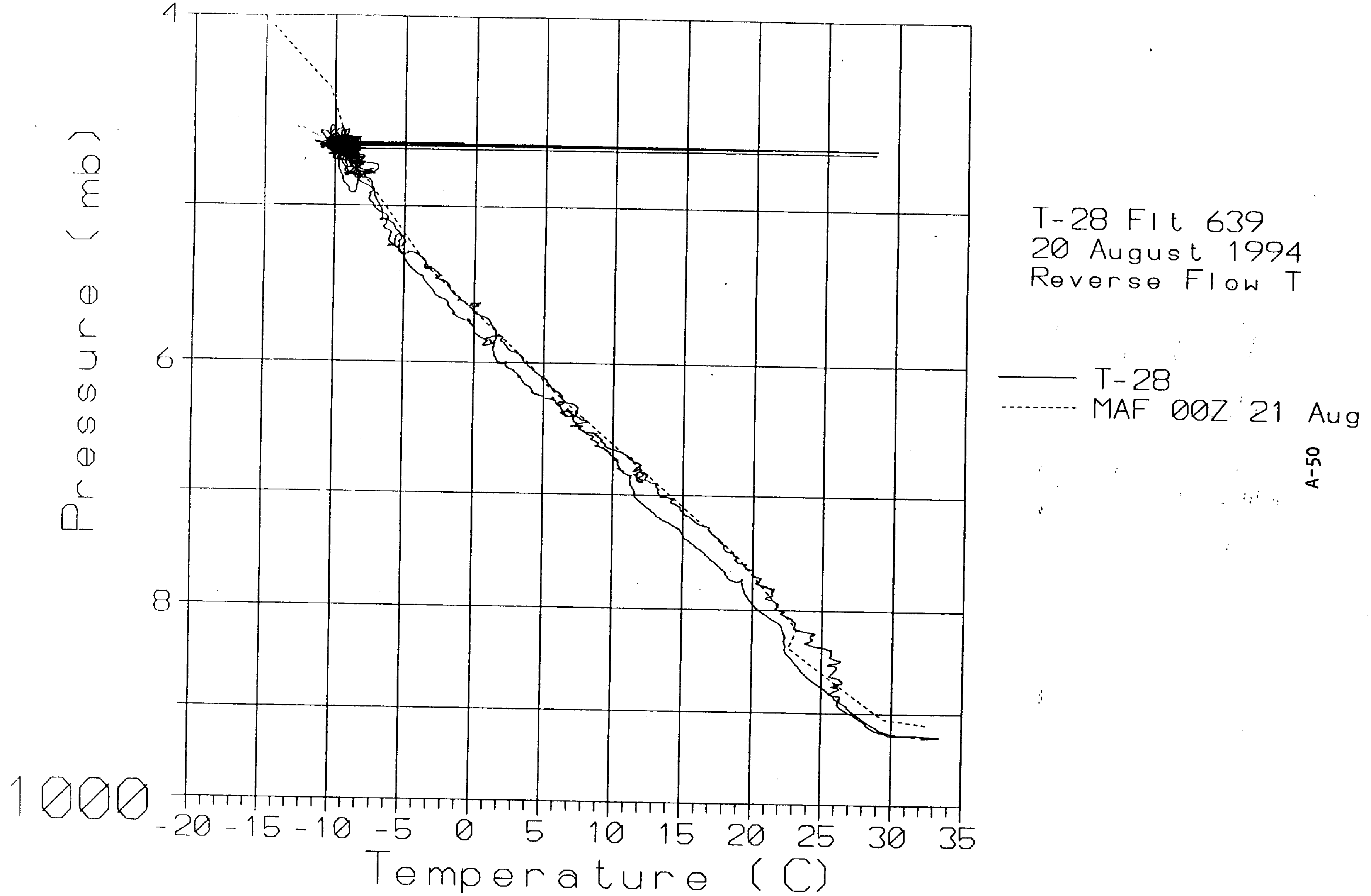
I took many pictures today. They are documented below.

Photo #	Time of Photo (CDT)	Subject of Photo & Comments
1.	1551	Picture looking SE to building Cu
2.	1625	Picture of growing tower to E, some pileus
3.	1647	Cloud 1 before AgI S at 1648 CDT

4.	1650	Cloud 1 at S+2, cloud narrows at base
5.	1655	Cloud 1 appears to be dying despite having received > 19 flares
6.	1657	Cloud 1 is dying
7.	1659	Cloud 1 is dead and top appears glaciated
8.	1701	Cloud 1 at S+13, looks glaciated but below 21,000 ft, the flight level of the Cessna 340
9.	1707	Cloud 2 as T-28 entered, NS cloud-physics unit
10.	1712	Cloud 2
11.	1713	Looking down at the cloud layer that was penetrated by Cloud 2 in its growth phase. This layer may have played a role in the glaciation of cloud 2
12.	1715	Cloud 2, new tower on right
13.	1718	Cloud 2, the lower central part is cloud 2, new towers both left and right
14.	1719	Debris of cloud 1, lots of ice crystal debris.
15.	1722	Cloud 2 center and below, newer towers left and right, but towers in back
16.	1723	Cloud 1, note tower growing up into ice mass and being seeded
17.	1731	Cloud debris from cloud 1
18.	1739	Cloud 3 before T-28 pass at 1740 CDT. Cloud 3 received > 25 flares at 1744 CDT
19.	1746	Pic looking into sun of cloud 3, a large cloud
20.	1750	Cloud 3

21.	1752	Cloud 3, growing
22.	1755	Cloud 3
23.	1757	Cloud 3 developed into Cb
24.	1800	Cloud 3 a Cb with internal lightning
25.	1805	Cloud 3
26.	1808	Cloud 3
27.	1812	Cloud 3 in center distance
28.	1818	Hard feeder towers into natural Cb, Cloud 3 is ugly cloud in center
29.	1900	Pic looking S at W end of line from ground with T-28 and another aircraft in foreground


Pressure (mb)
1000
8
6
4
Temperature (C)
-20
-15
-10
-5
0
5
10
15
20
25
30
35
T-28 Flt 639
20 August 1994
Rosemount T
T-28
MAF 00Z 21 Aug



T-28 Flt 639
20 August 1994
Reverse Flow T

August 22, 1994

Big Spring had scattered to broken altocumulus clouds this morning with light SE winds. The temperatures were in the upper 60's and the dew points were in the low to mid 60's. Of most significance were two areas of showers and thunderstorms that could be seen from Big Spring. The first was to the NW of Lamesa that was moving SE at 15 kts and the second was from the SE-SSW of San Angelo and it was moving E at 15 kts. Although both areas had begun to decay shortly after sunrise, their mere presence indicated that new, and possibly suitable, convective development could be expected later in the day.

The morning sounding showed moist but rather stable conditions with a cloud base of 2.5 km at a temperature of 14.7°C and a 500 temperature of -4.9°C. The convective temperature was 87°C. The GPCM predicts that clouds of 1.5 km radius will reach 5.4 km but that it will take a cloud of 3.5 km radius to reach a height of 7.4 km and realize a dynamic potential of 0.38 km. The maximum dynamic potential in the sounding is 3.23 km for a cloud radius of 4.5 km, which is too large for the real atmosphere. If this run is correct, it indicates that clouds will reach seeding height late in the day with only the largest responsive to seeding. My prediction is that the run is qualitatively correct but that smaller clouds will reach the seeding level.

First cumulus formation took place at about 1130 CDT at about 3,000 ft above the surface and the cumuli grew slowly through 1330 CDT. There was a hint of some TCU activity to the distant SE. Otherwise the cumuli were rather small as they drifted from the SE. Above these clouds were patches of altocumuli drifting from the NW.

By 1430 CDT, a few TCU were evident all quadrants, some of which were penetrating the patches of altocumulus castelanus. The small cumuli were shearing strongly back to the SE under the influence of SE winds at low levels and NW winds at 700 mb. The surface winds were from the SE at 10 to 15 kts and the dew points were in the low to mid 60's.

We were getting ready to fly at 1500 CDT. A few small echoes about 100 km to the S and another about the same distance to the NW had convinced us that it was about time to go. Echo tops ranged up to 7 km. We started engines at 1520 CDT about the same time that the echo to the NW became a small Cb with tops to about 9 km. Its top appeared to be shearing to the SW. At somewhat lower altitudes the clouds leaned strongly to the SE.

Before our takeoff at 1535 CDT we initialized the camera to 1530 CDT, so that the elapsed time on the video can be referenced to this time. Cloud base was noted at 8,500 ft at a temperature of 14°C, which was higher and cooler than I had hoped. It was consistent, however, with the predictions of GPCM and with those of George Bomar.

Once we were above most of the clouds on our flight to the S, I noted that there were several hard looking towers and at least once cloud that was reaching Cb stature. I then scrambled the T-28 for a cloud physics mission. Our first cloud pass came at 1614 CDT on the flank of a small Cb. With an updraft > 1,000 ft/min and a SLWC value > 1 gm/m^3, this cloud would readily have qualified an experimental unit. The parent cloud was too big, however, and I was still holding a cloud physics mission as first priority.

About this time we had a radio message from Charlie Summers in the T-28 that there was smoke in the aircraft cockpit and that he was returning to base. Once this happened, the qualification of an experimental unit became our only option. As an aside, I should mention that the smoke was later determined to be from a small electrical fire in the aircraft generator --- a problem that would put the aircraft down for repairs until at least Wednesday, August 24, 1994.

Our second cloud pass came at 1622 CDT and it was as good or better than the first. Ray Jones in the radar would not approve qualification, however, because the center of the unit was 120 km from the radar and moving away. We then moved farther N, making a pass in another cloud at 1643 CDT. It was located at 170° at 48.5 n.mi. from the radar and also satisfied the qualification criteria. After perhaps 5 min. of deliberation and with approval from Danny Rosenfeld, I asked for a treatment decision (block: warm base, no synoptic forcing) and was told that it was to be "No Seed".

There was a total of 12 simulated seeding passes after unit qualification with the "expenditure" of 73 flares. Six of the 12 were made over cloud top. The clouds looked fairly hard at treatment but only a few grew very much. I doubt that any cloud in the unit grew much above 8 km. The clouds were definitely of high enough quality for a good cloud physics mission had it been possible to conduct one.

None of the clouds today contained as much rainwater as I had expected, but they did have more than on previous days, which is consistent with the somewhat lower and warmer cloud bases. The clouds did, however, appear to glaciate faster than the clouds of previous days. There were several glaciated towers that could have passed for seeded towers. Again, this makes the point that it is not the total ice content in all clouds at a given moment that counts but rather when and where it forms in individual clouds. There was very little ice in the active updraft regions of today's clouds, but ice was quick to form once the updrafts weakened. Thus, although the so-called seeding window was rather narrow, the window was certainly open wide enough to allow for AgI seeding. It would have been interesting to have documented the effect of AgI seeding with the T-28 today.

Our last pass in the unit today was at 1755 CDT, giving a seeding duration of 64 minutes. I am very comfortable with all that was done today. All of the rules were followed, we had ample seeding opportunities, and the seeding duration and flare expenditure are probably at or above the overall average

The unit today was even drier than our first unit that we obtained on 15 August 1994. It too was a NS. Echo disappeared from today's unit at 1800 CDT. Although I had disagreed this morning with George Bomar's classification of this day as one without forcing, I have to admit now that he was right.

We left the unit at 1755 CDT in a mad race to refuel for another mission. Had we had more time on station, I feel very confident that we would have obtained another unit. There were other nice hard clouds to the N and NNE of our dying unit and these likely would have been the center of our new unit.

We landed at 1818 CDT and prepared the aircraft for another flight. Three quarts of oil had been used in the right engine and there was the usual coating of oil on the underside of the wing and landing gear.

We took off again at 1858 CDT after setting the camera reference time at 1855 CDT. There was one lone Cb to the SSW as we climbed out. It was not long, however, before we realized that this cloud, which was into its dying phase, was all that there was in the target area. We flew until 1930 CDT and then began our return to the airport, landing at 1947 CDT. It had been a reasonably productive day, although it would have been better with cloud physics observations.

I took several pictures today. They are documented below.

Photo #	Time of Photo (CDT)	Subject of Photo & Comments
30.	1532	Picture of small Cb to NW before takeoff
31.	1607	Picture of small Cb pointing to SW
32.	1723	Cloud 6, looking glaciated
33.	1827	Growing cloud to SSE of Big Spring airport
34.	1828	Same cloud as #33 but now a Cb
1. (New Roll)	1835	Same cloud as #34
2.	1908	Bottom portion of lone Cb in target, note rain from base

3. 1921 Lone Cb in target, dying

August 23, 1994

The sky was beautiful this morning with sunlit altocumulus castelanus, which were drifting from the E. The temperatures were in the low 70's and the dew points were in the low 60's. The surface wind was from the SSE at 10 to 15 kts. There was very little cloudiness and virtually no echo over the western two-thirds of Texas. The center of the upper high, judging from the movement of the clouds last evening, is over SW New Mexico. By 0845 CDT some small stratocumuli or cumuli had formed to the E. They were moving from the SE.

By 1030 CDT there was still a broken sky cover of altocumulus castelanus whose bases, judging from the sounding, were at 650 mb. The run of the GPCM gave a cloud base of 3.3. km at a temperature of 10.6°C, which is higher and colder than I would like. the surface convective temperature was 94°F. The natural growth at a cloud radius of 1.0 km was 6.9 km. The maximum dynamic potential was 0.97 km at a cloud radius of 2.5 km. This run suggests somewhat earlier and deeper cloud growth today than yesterday, although the rather high convective temperature could be a problem.

All of the above is based on the morning 1200 GMT sounding when the surface dew points was 62°F. By 1000 CDT, however, the surface dew point had risen to 68°F and the dew points were in the mid to upper 70's. At my request, Jill reran the GPCM after changing the surface dew point to 20°F, the dew point at 905 mb to 19°C and the mixing depth to 50 mb. These changes produced a cloud base at 2.6 km at a temperature of 15.7°C.

The first cumuli formed in the local area around 1230 CDT but they had not grown much by an hour later. Initial cloud bases appeared to be about 5,000 AGL, which would give a cloud base of around 7,500 to 8,000 ft above MSL. The surface temperature at Midland at 1300 CDT was 93°F.

The rest of the day was an agonizing wait for suitable clouds as the dew point at Midland dropped to 59°F and the temperature rose to 99°F. There were a few isolated clouds through 1700 CDT, but nothing to get us overly excited. Still, the cumuli to the SW were still developing as of 1700 CDT and I decided to take a look in the event that they developed as I had expected.

We took off in the Cessna 340 at 1728 CDT after setting a reference for the video at 1722 CDT. On board were Roger Tilbury the pilot, George Bomar and myself. We found cloud base at an altitude and temperature of 10,000 ft and 12°C, respectively. During the climb I noted Cbs to the distant SW-W-NW-N-NNE. According to George, those in the western quadrants were along the dry line in extreme west Texas and then northward into eastern New Mexico. Unfortunately, there was not much cloud development worthy of note in our target.

We finally found an area of fairly hard growing cumuli in a short broken N-S line centered on the 200° radial at about 50 n.mi from the Big Spring VOR. We flew around these clouds for an extended period to see whether they would be satisfactory for an experimental unit. Only a few of them produced radar echoes and those that did echo had maximum reflectivity values < 25 dBZ. Our flight level temperature at 20,000 ft p. alt was about -8°C.

Our first cloud penetration took place at 1803 CDT. The cloud was hard in visual appearance and it had over 1.0 gm/m^3. The updraft could not be determined because Roger Tilbury had to put the nose down in order not to violate his 20,000 ft block. After the pass, he requested that his block be extended upward to 21,000 ft to allow us to float with the clouds. The cloud grew to perhaps 25,000 ft but did not produce much of an echo on radar. It then collapsed and died.

Our second pass came in a weaker cloud with about the same results. It had > 1.0 gm/m^3 but only a weak updraft on the first pass. It was becoming obvious that these clouds were not going to be suitable for the qualification of the unit. It occurred to me, however, that they would have been quite suitable for a cloud physics pair had the T-28 been operative. Since we could not do cloud physics, I decided that we could at least do a deliberate seed to document by photography and radar the response of the cloud to seeding. It would give George Bomar his first exposure to dynamic seeding procedures and outcomes.

The deliberate seeding took place in cloud 3 at 1831 CDT. I seeded near the tops of some growing hard towers and avoided the somewhat taller and older tower to their immediate S. As best as we could tell, the updraft was 700 ft/min and the SLWC value exceeded 1.0 gm/m^3. Early in the pass, which lasted over 30 sec, I could see water running on the window, indicating that it had been a wet cloud. I ejected 12 flares and I could not hear any evidence of the multiple flare firings as I had on previous days.

As has been the case on many past seedings, the seeded cloud towers looked even harder and more rounded following the seeding than they had prior to it. It was as though the released heat had invigorated the internal circulations near cloud top, making it take on a hard vortical appearance. The tower also showed some growth, but it was slow. We then pulled away to the W for photography.

By 9 min after seeding the cloud was still hard and growing while a cloud to its N by about 3 miles that had appeared to be comparable at the time of seeding was not growing. That was still the case 12 min after initial treatment. The new growing towers were concentrated on the W side of the cloud.

By 15 min after seeding, the original tower was beginning to decay. The tower looked as though it had glaciated but it was not as obvious to me visually as it has been on other days. At about the same time, however, the cloud was echoing at 40 dBZ, which was easily the strongest echo that had been seen in the target area all day. By 17 min after treatment, however, the apparent glaciation was much more obvious, as the glaciated mass sunk over the southern flanks of new growing towers to its N. The other cloud farther to the N was now in its dying throes.

By 21 min after initial seeding, the cloud still looked hard and vigorous even though the tower that had been seeded originally had disappeared. We made a second seeding pass into the NW flank of the cloud at 1857 CDT but I mishandled the flare rack and ejected only 2 flares. The apparent response to the seeding was not as strong as the first as the overall cloud showed a decrease in intensity.

We made a third seeding pass into the cloud, again on its NW flank, at 1903 CDT and ejected 5 flares. Despite the seeding, the cloud continued to decrease in intensity. The overall flare total had been 19 flares, which was verified by later inspection of the rack. We continued viewing the cloud for a total of 45 min after initial treatment and then headed for home, landing at 1930 CDT.

This case is worthy of study in that we had the development of more precipitation without much additional cloud growth. I would guess that our treated cloud was no stronger initially than cloud 1. In fact, cloud 1 may well have been stronger. I also do not think that cloud 3 (treated) grew much more than cloud 1. Still, it produced more precipitation by staying vigorous longer than cloud 1. It may provide an explanation of how some clouds can produce more rainfall even though they do not show appreciable vertical growth. Rest assured, however, the seeding does invigorate the cloud internally.

I took several pictures today. They are documented below.

Photo #	Time of Photo (CDT)	Subject of Photo & Comments
4.	1748	Picture of hard cloud on climb
5.	1831	Picture of cloud 3 just before firing 12 AgI flares
6.	1836	Seed + 5
7.	1839	Cloud 3 at S + 8
8.	1842	Cloud 3 at S + 11
9.	1844	Cloud 3, S + 13

9.	1844	Cloud 3, S + 13
10.	1847	Cloud 3, cloud now echoing at 40 dBZ
11.	1849	Cloud 3, S + 17
12.	1851	Cloud 3
13.	1852	Cloud 3, has not grown much but producing precipitation
14.	1854	Cloud 3
15.	1856	Cloud 3
16.	1901	Cloud 3
17.	1905	Cloud 3, looking a N side
18.	1911	Cloud 3, dying

August 24, 1994

It was mostly clear early this morning except for a few scattered altocumulus clouds to the N and NE. The winds were light from the SE and the temperatures and dew points were in the low 70's and low 60's, respectively. The morning run of the GPCM gave a cloud base of 2.5 km at a temperature of 14.2°C and a convective temperature of 30.2°C. The predicted natural cloud growth of a cloud with a 1 km radius was 5.3 km and the first dynamic potential of 0.38 km was noted for a cloud radius of 3.0 km. The maximum dynamic potential was 2.46 km at a cloud radius of 4.0 km. All of this suggests that any suitable convection will form quite late in the day. This, plus George's briefing, influenced me to set a standby for takeoff for 1500 CDT.

First cumuli formed in the local area at 1115 CDT, and they had developed to small towering status by 1300 CDT. By 1400 CDT, they were somewhat larger with a few of them producing very light showers. There was no area of concentrated activity in the target, but satellite images showed an extensive area of showers in the Texas Panhandle moving south.

By 1530 CDT, the clouds had not grown too much, but there were a number of warm showers (max reflectivities of 40 dBZ) in the target area. Over the past three hours there had also been one or two Cbs, suggesting that some of the clouds later in the day might be strong enough to thrust the rainwater up to seeding altitude. Based on this, we moved to the aircraft for a flight. Meanwhile, the T-28 was being buttoned up, so there was reason to hope for a multiple aircraft mission later in the day.

We started engines at 1605 CDT, set the reference time for the camera at 1612 CDT and took off at 1618 CDT. There were towering cumuli all quadrants, but they generally had top heights < 6.0 km. After a clear morning sky, the cumuli during the day that had reached a stable layer and died added their debris to a middle cloud layer. Cloud base on climb was noted at 9,200 ft at a temperature of 12°C, which was much higher and cooler than I had expected from the morning sounding.

A few showers were noted on our climb to 20,000 ft p. alt., where the temperature was ~~a~~ warm -6.5°C. The top of the cloud layer that we penetrated on our climb was at about 17,000 ft p. alt. Once above this layer, we could see a field of cumuli penetrating it. Most of the layer penetrations did not last long and then the cumulus towers fell back into the cloud layer. There were strong indications, based on cloud appearance, that this layer contained ice crystals at temperatures of about -4°C. How they got there is another matter. I suspect that the penetrative towers had glaciated at colder temperatures and added their crystal debris to the cloud layer when they collapsed back into it.

It was not long before it was obvious that we were going to have problems finding suitable clouds. There were literally no Cb clouds within about 150 n.mi. of where we were flying and the towers nearby were too short-lived for our purposes. To make matters worse, we had to worry what effect the ice in the cloud layer would have on the cumulus clouds as they came through it.

Despite these concerns, I scrambled the T-28 after we had reached altitude. It had joined with us by 1739 CDT and it was in cloud 2 just after 1747 CDT. The cloud was more of a mound than it was a tower and it was not overly hard, although it did reach our altitude of 20,000 ft for a time. After the T-28 had cleared the cloud, I asked for a randomized treatment decision and was told that it was to "Seed". I subsequently followed these instructions at 1752 CDT, ejecting 10 flares. The T-28 then made several passes into the cloud.

The cloud did not grow much above 20,000 ft and it showed no obvious signs of glaciation, which was not surprising considering that the top temperature probably never fell below -7°C. The cloud did put up a number of towers for at least one-half hour and the T-28 dutifully sampled each one.

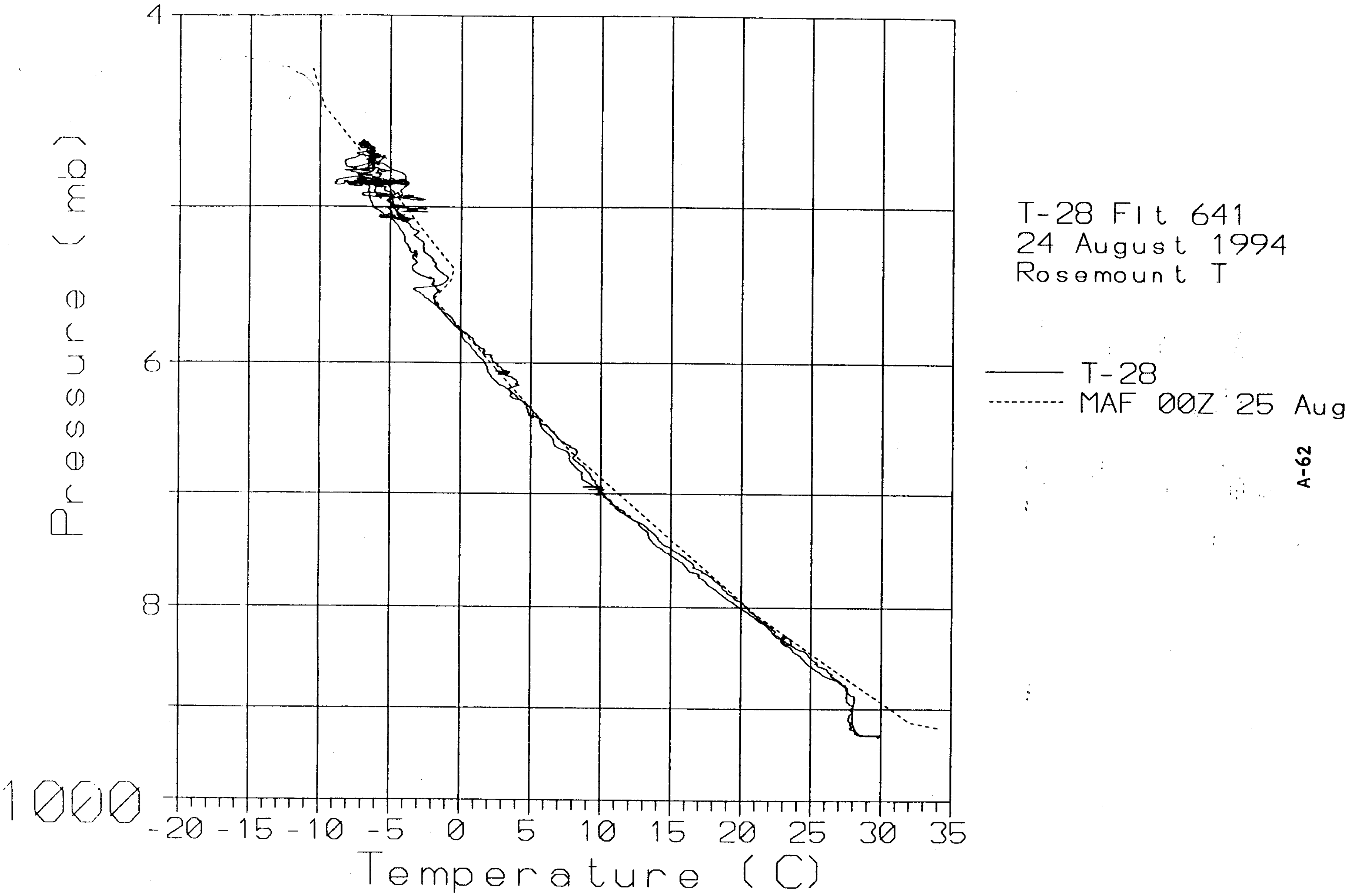
After the sampling of cloud 2, I was told by Dan Custis that the T-28 had only about 15 minutes left on station. I then asked him to penetrate a second cloud mound (cloud 3) about 10 miles to the N of cloud 2. After he had done so, we followed in the Cessna 340 with a simulated seeding at 1825 CDT. Dan in the T-28 then made about four passes before it was time for him to return to the airport. Meanwhile, we watched and photographed the cloud as we had for its predecessor.

Cloud 3 did not behave any differently than cloud 2, although older cloud around its periphery did develop into an ice crystal sheath at temperatures of -5°C. We made two penetrations of this icy mass, flying into the sun on the second and observing a halo and a sun dog, which proved conclusively that the material was ice. We made two orbits for photography and then began our return to the airport at 1845 CDT, landing at 1857 CDT. Inspection of the rack after landing revealed that we had indeed fired 10 flares into cloud 2 as intended and that we had fired another flare on the return when Roger Tilbury bumped the armed flare rack with his knee. Cloud base on return was at 10,000 ft at a temperature between 11°C and 10°C.

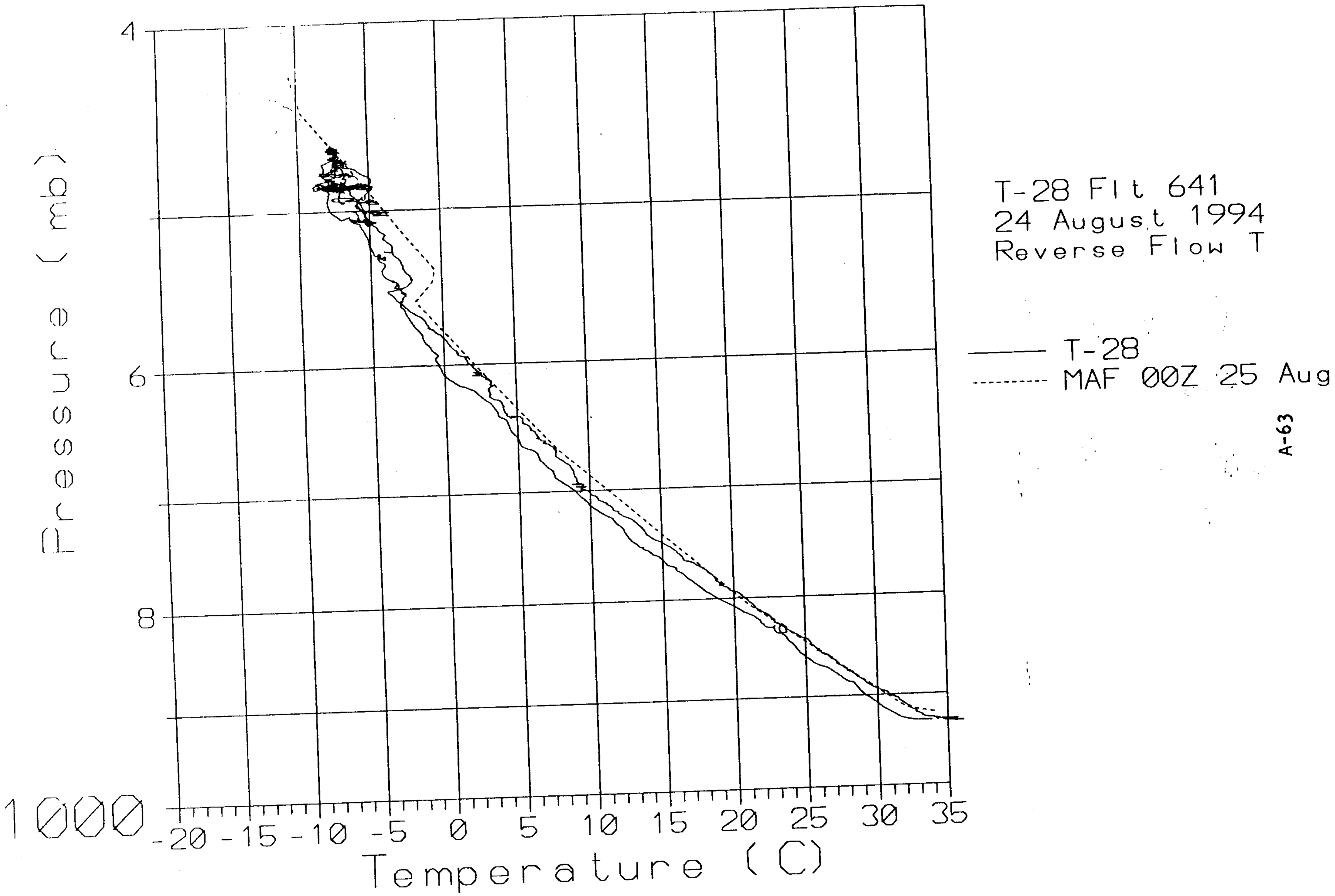
It had been both a frustrating and interesting day. It had been frustrating in that we did not obtain any vigorous supercooled clouds that contained rainwater, nor did we obtain an experimental unit --- there was no way a unit could have been qualified in such clouds. We did, however, obtain a cloud physics pair, although it was not obvious visually that seeding did anything unusual to the cloud. The experience reinforced the notion previously held that convective clouds and their debris in west Texas contain ice crystals, if they manage to live long enough. It appears that such crystals exist at temperatures as warm as -4°C or warmer, but it is not clear that the ice crystals were necessarily produced at these temperatures. They cloud have been produced by the penetrative convection at colder temperatures and then deposited into the layer when the cloud died. This uncertainty might be resolved from the crystalline habit, if such observations are available.

I took several pictures today. They are documented below.

Photo #	Time of Photo (CDT)	Subject of Photo Comments
19.	1647	Cloud candidate that descended below 20,000 ft before it could be penetrated
20.	1752	Cloud 2 before seeding with 10 AgI flares
21.	1756	Cloud 2 at S + 4
22.	1802	Cloud 2 before penetration by T-28
23.	1805	Cloud 2 at S + 13
24.	????	Picture of Danny Rosenfeld for reference
25.	1815	Cloud 2
26.	1823	Cloud 3, 2 minutes before simulated seeding
27.	1830	Cloud 3 at "S" + 5
28.	1833	Cloud 3
29.	1837	Cloud 3, fuzzy looking
30.	1843	Cloud 3 mass with visual evidence of ice crystals



T-28 Flt 641
24 August 1994
Rosemount T



T-28 Flt 641
24 August 1994
Reverse Flow T

August 31, 1995

Big Spring had several layers of scattered to broken clouds this morning, beginning with low stratocumulus clouds about 1,500 ft above the surface and moving from the S. At higher levels were scattered altocumulus clouds moving slowly from the S and thin broken cirrus above. The cirrus was thicker SW-NW-N towards the front, which now lies to the S of Lubbock. Much of the cirrus to the NW-N had the appearance of old anvils, which was not surprising considering that the morning radar depiction had echoes in New Mexico to the W and NW of Hobbs and these echoes extended to the N and then NE into Texas along and to the N of the front. The temperatures and dew points were in the low 70s and mid 60s, respectively. The surface winds were light from the S.

The low morning cloudiness reflected the increase in moisture, and it appears that today may be the first day that we have had clouds with active coalescence processes. It is ironic that we had to wait for the last day of our cloud physics effort to obtain the clouds that we really wanted all along.

The cumuli had turned to stratocumuli by mid-morning and to cumuli by late morning with a Cb with thunder audible to the E by 1130 CDT. To other small Cbs could be seen to the SW. Cloud bases were quite low.

At the weather briefing George Bomar indicated that we had a "Go" day and felt that a takeoff time of 1400 CDT would be about right. Although I really did not disagree with George, I subtracted an hour just to be safe and indicated that we would standby for 1300 CDT. Imagine our collective surprise to see Cbs and TCU from the ENE-SE-S-SW at 1130 CDT with occasional thunder heard to the E. Something had obviously forced the convection earlier than we had expected and we scrambled around to get ready to fly. The forcing mechanism may have been an outflow boundary that the NWS had been tracking toward us through the night from its point of origination to the W of Lubbock.

We managed to get to the aircraft at about 1230 CDT after a hurried lunch. It was still thundering to our E. Mike Douglas in the CRMWD Aztec took off at about that time on an operational seeding mission to the SE to see the cloud mass to the N of Lake Spence. Roger Tilbury, George Bomar and I were in the Cessna 340 shortly thereafter only to discover that the aircraft had no functional left brake, and it was not until 1330 CDT that the brakes were fixed. Meanwhile, the clouds continued to grow and rain with some of that rain falling at the airport beginning at 1255 CDT and continuing on and off until we started the engines at 1352 CDT.

We finally took off at 1404 CDT after first setting the reference time for the camera at 1359 CDT. Cloud base was noted at

6,500 ft MSL at a temperature of 17°C, which was far and away the warmest of the month. We climbed away from the disturbed region to the E and S of Big Spring and ultimately took a position to the NW of the Big Spring VOR within 20 n.mi. The clouds everywhere were very pretty and hard in appearance and very different looking from the clouds of the previous days. That is not surprising since these clouds undoubtedly had active coalescence processes and lots of rain drops and graupel.

We made two cloud passes in the Cessna 340 before the T-28 joined up with us. The clouds had lots of water and good updrafts. Although there were plenty of great clouds in the area, I decided against qualifying a unit, because the area was too strongly forced to expect to see a seeding signal in the rainfall. In addition, my first priority was to obtain a cloud physics cloud pair, and the qualification of a unit would greatly complicate matters.

The third pass of the Cessna 340 came in cloud 3 at 1530 CDT just after the T-28 had entered it. The cloud was on the WSW flank of a large Cb, whose core was about 5 n.mi away. I asked for a randomized treatment decision and was told that it was "Seed" and I did so during the pass, firing 12 flares into this cloud.

The T-28 made five passes in cloud 3 after it was seeded, measuring an updraft of over 4,000 ft/min on one of the passes after seeding and encountering a lot of large graupel that ultimately tore the foil. The cloud grew explosively, but it was hard to be very impressed because of the strong natural growth in the area.

The next cloud (Cloud #4) for cloud physics study was selected when the T-28 had only 30 minutes of fuel remaining. We in the Cessna 340 penetrated the cloud at 1558 CDT and it too was of excellent quality, having 1.5 gm/m^3 of SLWC and an updraft over 1,700 ft/min. I simulated 18 flares on this pass, which lasted 51 sec. The T-28 then returned to the cloud and made 5 monitoring passes after the simulated seeding. He then returned to the airport.

Cloud 4 grew much like cloud 3, which was actually seeded, although not as vigorously. It too developed a glaciated appearance, as I documented its changes photographically. We then began our return to the airport at 1620 CDT with the intention of refueling for a second flight with the intention of qualifying a unit if the conditions warranted. We landed at 1638 CDT.

Although I had been very frustrated with the delay in our flight today, I was pleased with its ultimate outcome. We had obtained a seeded and unseeded pair of clouds under conditions of strong coalescence. We had to wait until the last day of the cloud physics effort to do it, but we did. I should also mention that clouds 3 and 4 were almost a perfectly matched pair, at least that is the way it looks at this writing. Both had lost of graupel later in their lifetimes and both had many small ice crystals, produced either by ice multiplication and/or by the AgI seeding. I had hoped to see an obvious seeding signature today, but my cursory examination of the data suggests that they may not be the case.

I took several photographs during the first flight today and they are documented below:

Pic. #	Time (CDT)	Subject of the Photo & Comments
1.	1447	Cloud 2
2.	1521	Photo of T-28
3.	1528	Cloud 3 just before entry by the T-28
4.	1532	Cloud 3 after receiving 12 AgI flares at 1530 CDT
5.	1534	Cloud 3 at S + 4, note hard towers growing NE and SW of it
6.	1536	Cloud 3 at S + 6, note finger growth, other clouds growing too
7.	1542	Cloud 3 with finger growth merging with parent anvil, the T-28 measured > 4,000 ft/min with this cloud, S + 12
8.	1544	Cloud 3 at S + 14
9.	1556	Cloud 4 about 1 min before entry by T-28, it later received 18 simulated flares at 1559 CDT
10.	1601	Cloud 4 at S + 2
11.	1603	Cloud 4
12.	1604	Cloud 4
13.	1606	Cloud 4 at S + 7, original tower is glaciated out
14.	1610	Cloud 4, growing, note hard towers on the W side

15.	1613	Cloud 4 at S + 14, note tall narrow finger
16.	1617	Cloud 4, glaciating even in the center
17.	1619	Cloud 4, glaciating, S + 20
18.	1625	Hard tower on the return to the airport

It took a while to get the aircraft refueled, reloaded with flares and the data dumped, but we managed to do it and takeoff once again at 1801 CDT. Before takeoff we set the reference time for the camera at 1753 CDT.

We could not determine cloud base on the climb, but our base measurement for the earlier flight still looked valid. Although the area around Big Spring was covered with thick Cb debris, cumuli could be seen to the distant SSE-SSW. There were cumuli to the W and NW as well, but they were attached to mature Cbs.

We climbed out to the S and broke into a less clouded region at about 50 n.mi to the SSW. The temperature at 20,000 ft was again about -8°C. We could not work to the W because the prospective area was too close to old, but still tall, Cbs. We then continued to the S where I found some nice clouds in the sunlight, but they could not be qualified because they were too far from the radar. We made that mistake once this year, and Ray Jones was not about to let me make it again.

We then moved back to the N, making our first cloud penetration at 1908 CDT at 159° at 51 n.mi. from the Big Spring VOR station. The cloud was quite suitable, but it was too close to the old decaying Cb mass to the W and NW. I then moved about 10 n.mi. farther to the S and penetrated cloud 2 at 1916 CDT. The pass lasted 43 sec during which we measured a SLWC max of 1.3 gm/m^3 and a maximum updraft of about 1,665 ft/min. The updraft value is probably not reliable because the aircraft was about to fall out of the sky during the first part of the cloud penetration and the pilot had to apply power to maintain control. The portion of the cloud that we penetrated was not much about our flight level. There were somewhat taller clouds a little farther to the SE.

We then had to decide what to do. The very late hour certainly worked against us in terms of solar heating. On the other hand, we were working in a convergence region in the frontal zone, so there was reason to expect the clouds to persist after dark. After a few minutes of discussion, George Bomar and I decided to ask for a treatment decision and were told subsequently that the decision was to "Seed". We then armed the rack and went to work.

There was not much echo activity in the unit at commencement with all echo tops well below 21,000 ft. The visible tops may have been a few thousand feet higher. It was not long, however, before the cloud 3 complex was growing strongly following seeding. Although the growth was impressive, it was difficult to be overly impressed in view of the vigorous cloud growth that had taken place all day.

We continued to work in the unit until 2013 CDT when the last seeding took place. Most of the clouds had SLWC values up to, but generally < 1.0 gm/m^3. The clouds clearly had much more water, but much of it likely was in rainwater. The updrafts often were over 1,000 ft/min, but they were nothing extraordinary. We seeded clouds progressively to the W of the cloud 3 mass in an attempt to invigorate and broaden the cumulus field and promote merger. The pass at 1956 CDT was noteworthy for its length and an expenditure of 19 flares.

The other cloud pass of note was made in cloud 12 during a prolonged run at 2013 CDT --- the last pass of the night. It was getting quite dark at the time, but the cloud pass did not look overly strong and not too far above the aircraft. Nevertheless it was producing a sizeable echo as we approached it and upon entry we noted the clatter of a lot of ice particles. What really surprised me, however, was the prolonged period of high SLWC values. Assuming the instrument was operating properly --- I have no reason to believe otherwise --- we had 17 secs of SLWC values ranging between 1.8 and 2.0 gm/m^3. Needless to say, I pounded the cloud pretty good with the expenditure of 17 flares. I would guess that the cloud mass that was seeded on this pass was probably seeded at least once earlier. Perhaps we penetrated a cloud that had been invigorated previously. Instances like this certainly bear looking into further.

We began our return to the airport at 2018 CDT after having made 12 treatment passes with the expenditure of 86 flares during a seeding duration of only 51 minutes. The main seeded cloud mass in the unit was flashing like a light bulb with lightning when we left it. We landed at 2036 CDT in a light rain with occasional lightning NW-N of the airport. During the course of the flight I took only 1 photograph at 1944 CDT. It gives a nice view of the cloud 3 complex.

The unit was wet as best as I can tell, and I can hardly ascribe that to the seeding. As chance would have it, the two NS units were much drier than the lone seeded unit of this year. There can be no question, however, that the seeded unit was the more favored of the three. Accounting for the natural variability is still one of our most pressing problems.

September 1, 1994

The day began with a thick overcast consisting of multiple cloud layers and light showers. Radar showed rain and embedded showers stretching in a NE-SW band or area stretching from NE of Abilene to SW-S-E of Midland. The area showed little movement, although it decreased progressively in area and extent after sunrise. We are apparently still in the frontal region that has stalled its SE progress in our area. The surface winds were light from the NE. The temperature and the dew point were in the mid to upper 60's. It represents quite a change after a month of dry, hot, dusty weather. It should be mention that Midland had 1.42 in. of rainfall yesterday, which is likely the greatest rainfall there since May 1994.

The sun had broken through by 1030 CDT and growing cumuli could be seen growing up into the overcast. The rate of cloud growth and the vigor of the clouds, which were embedded in multiple cloud layers was not good for prospects for qualifying a unit today. It is even more disturbed than yesterday.

By noon, we still had a low overcast that was moving from the E. Some upper cloud could be seen through breaks in the overcast. There were also a number of embedded showers, many likely produced by rather shallow clouds under active coalescence processes, since cloud base today is likely on the other of 20°C.

By 1400 CDT, we still had overcast skies in Big Spring with an extensive area of warm rain showers E-S-WSW. There were breaks in the clouds to the N where some relatively small cumuli were growing. I scheduled a flight for 1430 CDT to go up and have a look, although it is hard to be optimistic. The temperature is rather cool but very moist with dew points in the mid to upper 60's.

We took off at 1432 CDT. We were in a hurry because showers and very low ceilings were closing in on us from the south. Roger Tilbury and I were the only people on board since George Bomar was sick with a flu. We found cloud base in the local area at 3,500 ft at a temperature of 21°C. The cumulus bases were a little higher to the NW at about 4,500 ft, but the temperature was still > 18°C. To be conservative I will use 18°C as the official cloud base temperature for the day, although I could be argued into a higher value.

The weather at 20,000 ft about 35 n.mi to the WNW of Big Spring was really quite nice with growing cumuli and virtually no layer cloudiness above our flight level. A broken NE-SW line of Cbs could be seen back toward the SE near and to the SE of Big Spring. I was gradually becoming optimistic about our chances of qualifying a unit despite the disturbed conditions in the area. The temperature at flight altitude of 20,000 ft p. alt. was -8°C, which is what it was yesterday.

Our first cloud pass came at 1519 CDT and the qualification pass for our unit came at 1523 CDT. It had > 1 gm/m^3 and > 1,000 ft/min, so after some deliberation I asked for a treatment decision. There were several suitable targets in the prospective unit and the only large clouds were to the SE-S, but they were far enough away not to cause us any problems. Ray Jones radioed back that the decision for the day was to be "No Seed"; I repeated the decision back to him and immediately (at 1530 CDT) made a pass into a cloud and simulated 12 flares. I do not know what the water content was, because I was sitting in the right seat up front and I could not see the data display in the back of the aircraft. I had made sure to go into the back to watch the display on the qualification pass, but after that I based my simulated seedings on updraft alone. I am pretty good at it by now, and I am not worried that I seeded any unsuitable clouds within the unit.

I made 13 total simulated treatment passes into the unit and "ejected" 79 flares between 1530 CDT and 1655 CDT --- a treatment duration of 85 min with an interlude between 1618 CDT and 1652 CDT when there were no simulated seeding passes because of the absence of suitable clouds. During this period, I flew farther to the W in the hopes of qualifying a unit, but this upset Ray Jones because he feared that the new unit would be beyond acceptable range from the radar. I did find some good clouds, but they were too close to taller clouds to the SE such that unit could not be qualified according to the rules.

The clouds in the unit did not do all that much although perhaps three or four of them did grow into small Cbs. They ultimately showed obvious glaciation, but that occurred late in their lifetimes when the glaciation could not that much good. I would have been interested to see what actual seeding would have done to these clouds. As it was, the unit was rather dry but wetter than the previous NS unit on August 22, 1994.

By 1730 CDT, Roger and I had moved just to the W of Lake Thomas to the NE of Big Spring in order to do some deliberate seeding. Although the clouds were of very poor quality with a very weak mushy appearance, we did make 5 AgI seeding passes between 1731 CDT and 1752 CDT with the expenditure of 36 flares. The clouds did not show much response to the seeding. We then returned to the airport, landing at 1808 CDT. Big Spring still had an upper broken to overcast layer, but most of the low clouds had cleared away. The winds continued light from the NE.

This brought an end to the TEXARC project for 1994. Considering that we have been in operation for only a month, we managed to accomplished a lot, especially our first cloud physics cases. I am disappointed that we obtained only 4 random units and that 1 of the 4 cannot be analyzed as a unit because a portion of it was out of range at qualification. Still, we made progress toward understanding how glaciogenic cloud seeding works in west Texas. I really think that we are on the right track.

APPENDIX B

CLOUD PASS DATA IN THE PERIOD 4 AUGUST THROUGH 1 SEPTEMBER 1994

The Cessna 340 cloud-pass data of TEXARC 1994 follow. Most of the columns are self-explanatory; others are not. The position of each pass is the cloud-entry point and was provided by the GPS navigation system. It is not the center of the cloud tower. Underlined pass values indicate that the pass was a qualification pass for an experimental unit.

The temperature of the pass is an estimate of the mean temperature prior to cloud penetration. The maximum temperature in cloud is the highest point temperature value measured during cloud penetration. In cases when the aircraft was carried upward by a strong updraft, no attempt has been made to "adjust" this temperature back down to the pressure at cloud entry. Likewise, when strong downdrafts carried the aircraft downward, no attempt has been made to "adjust" the maximum observed temperature back to the entry pressure.

The cloud radius was estimated by noting the time of cloud entry and exit to obtain the duration of the pass, by multiplying the pass duration by the mean true airspeed and then by dividing the resultant traverse length by 2 to obtain an estimate of cloud radius. The JW hot wire was used to judge the time of entry and exit. The radius calculation is representative of cloud radius only when the aircraft flew through near the center of the bubble cloud top. If the aircraft flew above the center, the radius estimate is low relative to the true radius.

The maximum JW reading represents the highest 1-sec reading during cloud penetration. The maximum updraft is the highest 1-sec value of updraft as estimated by the Ball Variometer. The instrument saturates at 2,000 ft/min (10 m/sec) and no readings above this value are possible with the instrument in its present configuration. The reader is reminded that the draft estimates are accurate to the extent that the pilot few the aircraft in "straight and level" configuration.

Entries other than 0 (zero) in the "suitability" column refer to the number of seconds during cloud penetration that both the SLWC and the updraft exceeded thresholds of 0.5 gm/m^3 and 1,000 ft/min <u>simultaneously</u>. This threshold is arbitrary and clouds that have 0 suitability in the table were not necessarily unsuitable for cold cloud seeding.

The "number of flares column" refers to the number of AgI or simulated AgI flares that were expended during cloud penetration. The ejection system at times fired more flares than were intended. These multipile firings are not reflected in this listing. Underlined flare totals indicate simulated seeding.

8/4	31	34.8	;	101	23.5	16:40	-7.6	-6.8	1120	1.30	----		0
	31	46.3	;	101	20.2	17:33	-5.0	-5.0	1040	1.10	----		0
8/5	32	05.6	;	100	50.2	17:17	-6.0	-6.2	998	1.20			0
	32	06.0	;	100	50.4	16:21	-6.0	-6.4	396	1.10			0
	31	28.7	;	101	52.7	17:27	-6.5	-6.9	506	1.30			4
	31	26.4	;	101	46.7	17:40	-7.0	-7.1	1200	1.20			5
8/8	32	08.1	;	100	49.7	14:44	-8.5	-7.4	638	1.20	1400		0
	31	57.6	;	101	00.5	15:09	-8.7	-9.3	1426	1.00			10
	31	10.7	;	101	52.7	15:56	-6.0	-6.3	900	1.00			1*
	32	02.6	;	101	56.1	16:16	-6.5	-7.2	581	1.10			6
8/14	32	58.0	:	102	08.2	16:25	-7.1	-7.3	998	1.00	631	0	6
	32	46.2		102	34.5	16:56	-7.0	-7.0	2000	1.40	1552	6	19*
8/15	31	02.3	;	101	33.2	15:57	-7.9	-7.8	931	1.10	630	0	0
	31	02.7	;	101	33.5	16:04	-7.7	-7.5	618	0.90	1423	1	0
	31	04.3	;	101	35.3	16:14	-7.6	-7.9	1650	1.10	930	0	10
	30	57.0	;	101	40.5	16:18	-7.5	-8.0	1700	0.90	957	0	13*
	30	57.5	;	101	39.5	16:21	OVER	THE	TOP		2	-	2
	31	03.0	;	101	37.8	16:23	-7.7	-8.3	450	0.30	510	0	5
	31	00.8	;	101	27.2	16:27	-7.7	-8.4	273	0.40	0	0	2
	31	04.4	;	101	27.8	16:29	-7.7	-8.0	223	0.50	331	0	3
	31	01.9	;	101	30.7	16:32	-8.0	-8.4	450	1.10	148	0	3
	31	01.6	;	101	42.6	16:37	-7.4	-7.5	1019	0.90	600	0	8
	31	01.5	;	101	48.5	16:39	-7.5	-7.3	776	0.80	1078	0	7
	31	02.5	;	101	45.2	16:42	-7.1	-7.6	270	0.20	318	0	5
	31	02.4	;	101	43.2	16:43	OVER	THE	TOP			-	5
	31	06.2	;	101	35.4	16:59	-7.0	-7.5	484	1.20	254	0	5
	31	07.6	;	101	29.7	17:14	-7.0	-7.5	880	1.10	430	0	12
	31	06.9	;	101	39.4	17:21	-10.1	-10.6	600	1.10	84	0	6
	31	06.4	;	101	47.1	17:24	-10.3	-10.8	758	0.90	603	6	
	31	06.4	;	101	25.6	17:37	-7.3	-7.6	2565	1.20	1692		9
8/20	31	22.3	;	101	15.5	16:47	-7.5	-7.1	1980	1.30	1259	4	19+
	31	23.3	;	101	02.5	17:08	-7.5	-7.3	2000	0.80	1875	0	17
	31	03.9	;	101	18.9	16:44	-7.1	-7.0	2021	----	1823	-	25+
8/22	31	26.4	;	101	29.8	16:14	-6.9	-4.2	1080	1.10	1919	4	0
	31	19.3	;	101	43.3	16:22	-6.5	-6.6	3015	1.00	1585	7	0
	31	33.9	;	101	30.9	16:41	-6.8	-7.0	1188	0.80	1267	3	0
	31	39.0	;	101	31.0	16:51	OVER	THE	TOP			-	6
	31	41.9	;	101	43.6	16:58	-6.5	-6.4	808	0.80	405	0	5
	31	38.5	;	101	31.1	17:04	-6.5	-7.0	445	0.20	1121	0	7
	31	46.0	;	101	33.5	17:10	OVER	THE	TOP			-	4
	31	38.7	;	101	23.5	17:14	-6.8	-6.0	2430	1.40	1250	3	12
	31	37.7	;	101	30.4	17:26	OVER	THE	TOP			-	5
	31	46.6	;	101	26.2	17:31	-6.6	-6.8	1305	0.90	542	0	7
	31	35.4	;	101	23.4	17:37	-7.0	-6.7	893	0.60	597	0	5
	31	35.4	;	101	25.0	17:43	-6.9	-6.9	129	0.50	0	0	5
	31	41.6	;	101	18.8	17:46	-6.8	-5.8	1275	0.90	807	0	13
	31	36.3	;	101	24.5	17:52	-7.0	-7.3	352	0.60	228	0	4
	31	34.7	;	101	23.6	17:55	OVER	THE	TOP			-	3

8/23	31	40.5	;	101	58.1	18:03	-7.5	-7.4	1648	0.90	710	0	0
	31	37.1	;	101	58.9	18:22	-7.5	-7.8	354	0.80	553	0	0
	31	33.1	;	101	59.2	18:31	-6.8	-6.3	1615	1.00	1124	1	12
	31	35.0	;	102	04.6	18:57	-7.1	-7.5	1029	1.00	511	0	2
	31	34.6	;	102	06.4	19:02	-6.5	-6.3	475	0.90	475	0	5
8/24	31	43.8	;	101	30.0	17:03	-6.4	-6.9	998	1.00	534	0	0
	31	28.5	;	101	41.1	17:53	-6.0	-6.6	285	1.00	0	0	10
	31	38.8	;	101	34.8	18:25	-5.7	-5.9	500	1.00	146	0	10
	31	42.4	;	101	36.7	18:41	-5.0	-4.9	321	0.10	329	0	0
8/31	31	33.1	;	101	15.6	19:08	-7.2	-6.8	900	1.30	1195	5	0
	31	24.9	;	101	07.1	19:16	-7.2	-5.7	3600	1.30	1666	4	0
	31	27.4	;	101	08.2	19:21	-8.0	-6.8	1408	0.80	1746	1	12
	31	26.0	;	101	07.4	19:27	-5.8	-5.7	748	0.80	272	0	8
	31	21.0	;	101	18.1	19:38	OVER	THE	TOP			-	5
	31	19.5	;	101	15.8	19:41	-8.0	-8.3	428	0.70	328	0	2
	31	21.6	;	101	21.6	19:49	OVER	THE	TOP			-	4
	31	33.3	;	101	10.7	19:55	-8.3	-7.4	2233	0.90	1227	6	3
	31	29.5	;	101	13.1	20:02	-9.4	-9.5	279	0.30	334	0	19
	31	25.2	;	101	15.7	20:05	OVER	THE	TOP			-	5
	31	25.3	;	101	17.1	20:05	OVER	THE	TOP				
	31	25.6	;	101	14.6	20:12	-7.5	-7.8	645	0.40	219	0	9
	31	25.9	;	101	17.6	20:13	-7.5	-5.8	4576	2.00	1374	10	17
9/1	32	36.7	;	102	06.0	15:19	-7.3	-7.6	630	1.20	994	0	0
	32	38.0	;	102	06.4	15:23	-7.7	-6.6	1080	1.10	1012	2	0
	32	35.9	;	102	07.7	15:29	-6.5	-6.0	1032	1.20	1774	17	12
	32	35.6	;	102	09.8	15:35	-6.5	-6.8	528	0.90	431	0	5
	32	25.2	;	102	16.2	15:40	-6.5	-6.7	924	1.30	1300	6	9
	32	33.9	;	102	13.2	15:50	-6.5	-7.3	190	0.90	327	0	4
	32	34.3	;	102	18.0	15:52	-7.0	-7.0	396	1.30	1362	1	7
	32	32.4	;	102	15.2	16:02	-6.5	-6.5	665	1.10	270	0	4
	32	32.0	;	102	18.6	16:06	-6.0	-6.6	475	1.00	108	0	6
	32	39.7	;	102	18.1	16:08	-6.5	-7.3	200	1.00	279	0	3
	32	33.1	;	102	19.5	16:12	-6.5	-7.2	855	1.30	498	0	5
	32	33.3	;	102	19.4	16:14	-6.0	-6.6	760	1.40	974	0	7
	32	34.4	;	102	20.7	16:18	-6.0	-6.6	874	1.30	733	0	5
	32	42.9	;	102	03.6	16:52	-7.0	-7.0	765	1.10	915	0	8
	32	42.8	;	102	04.5	16:55	-6.8	-7.5	523	1.00	571	0	4

Other Cloud Passes Outside the Experimental Unit on 8/31/94

32	36.5	;	102	40.3	16:40	-6.0	-6.0	827	1.30	962	0
32	38.2	;	101	17.1	17:31	-7.5	-7.6		0.50	751	12
32	27.6	;	101	10.2	17:33	-7.0	-7.6	245	1.00	581	8
32	37.9	;	101	09.6	17:36	-7.2	-8.2	230	0.70	0	3
32	40.0	;	101	16.9	17:46	-7.2	-7.5		0.90		8
32	39.9	;	101	11.3	17:51	-7.4	-7.5	644	1.00	531	5

One AgI flare was fired inadvertently into this cloud; no flares should have been fired.

Only ten flares were intended; the nine extra flares came from unexplained multiple firings.

One of the 13 flares ejected on this pass was a live AgI flare; it was fired unintentionally. Note: Cloud passes underscored with a double line on 8/15/94 are cloud-physics passes. The AgI-seeded cloud-physics unit was treated outside the boundaries of the NS experimental unit.

Note: The JW hot wire did not function during the third cloud-physics pass on this day.

APPENDIX C

THE 1994 TEXARC CLOUD PHYSICS MEASUREMENT PROGRAM

1.0 Scientific Chronicle

1.1 Flight 632 on Thursday, August 4, 1994, 1638-1808 CDT

The project aircraft flew south in what was intended to be a VFR check ride to work out the kinks in the coordinated flying that is called for in the ops plan. Significant Cu Cong developed and studies of 2 clouds near cloud top were undertaken, along with a cloud-base pass on a third cloud.

The clouds studied appeared to be negatively buoyant at the 18-19 kft level with weak fluctuating up- and downdrafts, less than 5 m s^{-1}. There was a stable layer near 17 kft in the region where the aircraft worked, with towers pushing through by a couple of thousand feet and then subsiding. Both clouds appeared to have two separate turrets, judging from the aircraft updraft and liquid water data. Very little precipitation was found in them at these levels, but other clouds were raining in the region. There was some lightning in clouds near Big Spring, although none of the aircraft penetrations in the two clouds to the south were through significantly electrified clouds.

As the flight began with the understanding that it would be a clear-air test flight, the J-W was not turned on until the last pass. GPS altitude was not available. Telemetry to the radar site did not work well. Just a few minutes of data were received.

The foil contained only push-throughs, off-and-on (indicating small ice particles trapped between layers as the foil rolled up, but with insufficient momentum to make an impression when they hit the foil. Peak concentrations were a few cm^{-2} on the foil (a few hundred m^3 of sampled air).

The 2DC recorded mostly shed drop images. Some drizzle was recorded on way back to Big Spring after the cloud studies were completed.

The two temperature probes agreed well in penetrations, but RFT was ~1 C warmer outside cloud.

1.2 Flights 633 and 634 on Friday, August 5, 1994

Clouds yesterday were associated with a front that slid S over BGS. On this day it slid back N and dissipated, but was a focussing trigger for some convection.

A short clear-air flight near noon to test telemetry.

Telemetry still didn't work. No data were reduced.

Flight 634 commenced at 1605 CDT and ended at 1810 CDT. The clouds encountered during the flight were pretty weak. The surface video team got near the first target and got some video, but then the cloud collapsed and when the aircraft moved further south to look for better clouds, the surface crew couldn't keep up.

The T-28 did a pass 500 ft above cloud base in a cloud on his way out.

The Humphrey accelerometer went bad part way into flight. Pitch, roll, and acceleration were lost for the rest the of flight (along with parameters that depended on them, such as the updraft computed using the Kopp method).

The telemetry was not turned on.

The T-28 Rosemount temperature reading was about 1°C lower than the WMI Cessna 340 Rosemount temperature reading during a brief clear-air intercomparison. The T-28 reverse-flow temperature was about 1.5°C below the Cessna 340 Rosemount temperature. The T-28 Rosemount probe cools more in cloud than its reverse-flow probe, so on the T-28 the two temperature probes agree well in-cloud.

There was only one cloud officially studied on this flight. There was nothing on the foil during the the first pass at cloud base on the way to the study cloud, nor on the initial pre-treatment pass at cloud top through the study cloud); there were millimeter diameter particles on passes 2 & 3, up to 5 mm graupel on pass 4, and millimeter particles again on pass 5. The foil jammed due to icing near the end of this pass.

Cloud liquid water concentrations up to 2 g m^{-3} were recorded on 340 J-W during its treatment pass. Similar concentrations were measured by the T-28 J-W, with more computed from the recorded FSSP spectra. The T-28 J-W suffered from some icing problems.

The Cooper updraft computation is noisier than the Kopp computation, but should be OK during straight-and-level segments. Some occasional glitches are due to interuptions in GPS data; these interruptions are most common during turns.

The effects of ice melting off the T-28 Rosemount temperature probe could be seen in the recorded temperature profile on descent.

1.3 Flight 635 on Monday, August 8, 1994, 1440-1650 CDT

The surface video team took off in an attempt to intercept aircraft operations. They went past Colorado City and then headed south. They got good video of the first cloud the aircraft worked, just after 1500.

The WMI 340 was off at about 1355 CDT, and the The T-28 was called at 1405 CDT. The aircraft flew first to the southeast. There they worked one cloud with flares, with treatment at 1509 CDT. The T-28 found mainly downdrafts on post-treatment penetrations. Video from the ground clearly shows the cloud collapsing at 1515 CDT as the T-28 pilot reported cloud top collapsing below his altitude (19 kft). The post-analysis conclusion is that he did not re-penetrate the seeded tower, but a neighboring tower.

The aircraft then moved southwestward for another case. The T-28's 1st penetration on this target was at 1559 CDT. After a simulated seeding pass the T-28 attempted to re-enter but tops were collapsing below his altitude.

A third case in a nearby cloud was attempted with a seeding pass at 1616. Again, the cloud was collapsing below the T-28 level when he tried to pass through after the seeding pass.

The research pitot was apparently plugged by an insect during the take-off run. Lack of accurate dynamic pressure, combined with the missing Humphrey accelerometer on this flight, renders unusable the computation and measurements of:

indicated airspeed
true airspeed
FSSP droplet concentrations and liquid water concentration
Cooper updraft
Kopp updraft
pitch
roll
acceleration

Inaccurate true airspeed led to inaccurate clocking of the PMS 2D-C probe, rendering its images only marginally useful.

As an approximation, the data reduction was done using a fixed true airspeed of 90 m/s.

The only graupel on the foil was in the pass after the first seeding. However, the project scientists on board the seeder have concluded that this pass was not through the seeded turret.

There were thunderstorms and lightning in the Big Spring area from near 2000 CDT until almost midnight. They moved in from the north.

1.4 Flight 637 on Sunday, August 14, 1994, 1530-1735 CDT

Charlie Summers replaced Dan Custis as T-28 pilot. He did a late morning short test flight (Flt 636). No data were recorded.

The WMI 340 took off at 1449 CDT and went north looking for cloud physics cases.

There were 3 cases north and west of Big Spring, the last two with 5 or 6 penetrations each. The T-28 also made a near-cloud-base pass on the way out.

The ground video crew were originally sent south, but the crew got turned around and caught up to the first case. They didn't get very extensive video of this case. They also got video from a distance of the second and third cases.

The first case fell apart shortly after treatment.

The second cloud had ice-phase precipitation in it on the initial pass. It was a tower growing out of a lower deck of stratocumulus. This cloud was not seeded. The T-28 started picking up ice in this cloud and carried it on to the third one.

The third cloud had 19 flares dumped into it. It was not visibly affected by the treatment. The T-28 J-W liquid water concentration was more than 2 g per cubic m on the initial T-28 pass through this cloud. The WMI 340 J-W had about 30% less on its seeding pass.

The T-28 didn't lose its last ice until 7 kft altitude on return descent. All icing was milky rime (due to small cloud droplets) on this flight.

The icing caused some erratic behavior of the T-28 J-W.

The tendency of the 2D-C to record empty frames with no elapsed times gets worse as the aircraft climbs. There must be some temperature-related electronic dysfunction.

Data were re-reduced to pick up heater current, which was in the raw data files for all TEXARC flights, but not picked up by the data reduction program prior to this day.

1.5 Flight 638 on Monday, August 15, 1994, 1620-1805

It was cloudy and cool in the AM following a frontal passage after yesterday's missions.

The WMI 340 went out at about 1500.

The aircraft worked 3 cases well to south.

The T-28 passed through a cloud on way up, but well above cloud base. He went through at about 17 kft (-4 C), with tops 3-4 kft above. Much small ice on this pass. The pilot estimated 500 fpm updraft and 2-3 km width.

The first 2 cases were no-seed, and dissipated quickly upon being chosen. In the 3rd case. the pre-seed pass showed a lower concentration of cloud droplets (~200 per cubic cm) than has been typical this summer, and larger sizes . The J-W indicated 1.2 g per cubic m LWC. Some ice particles were seen in the 2D-C data at the edges of the liquid water region. The pilot reported clear ice on this pass.

Rime was milky on later passes. It began to build up more rapidly on 3rd and 4th penetrations. The J-W LWC stayed near 1.5 g per cubic m through these passes. Sh/Or counts increased with each successive pass.

The 2D-C recorded images of rain (liquid or frozen?) on last pass.

The first 2 cases were part of a (non-seeded) experimental unit. It may have been beyond acceptable range. The 3rd case may have been too close when it was seeded and may also have disqualified the experimental unit. Radar coverage may also be problematical.

The WMI 340 landed with zero oil pressure in right engine.

1.6 Flight 639 on Saturday, August 20, 1994, 1617-1840 CDT

There was both convective instability and a humid boundary layer air on this day. The convective clouds that developed were vigorous. The T-28 flight coordinator at the Skywater radar site observed that clouds seem to have visible tops to 30 kft before they echoed on the radar.

The aircraft worked 3 cases to the southeast of the radar. The T-28 penetrated several clouds on the way out. The closest penetration to cloud base was at 163053 CDT at 11.7 kft with the base below at an estimated 10.5 kft. This base was ragged in appearance and graupel up to 3 mm in diameter was indicated on the foil during this pass.

There was aircraft icing in all 3 cases, with the rime being milky. During the second case, the T-28 had to turn hard against a Cb on one side of the subject cloud. The T-28 pilot reported lightning in the third case.

A vigorous cloud was penetrated on the way home after the final pass through the cloud of the 3rd case.

All standard T-28 data were OK, except for those derived from the absent Humphrey accelerometer.

1.7 Flight 640 on Sunday, August 21, 1994, 1610-1615 CDT

This flight was aborted due to generator failure.

1.8 Flight 641 on Wednesday, August 24, 1994, 1711-1846 CDT

The aircraft worked 2 cases to the southeast. Some video of the general area was obtained by the ground video team from a position approximately 30 mi northwest of the subject clouds. The clouds were topping out at about 18 kft, then subsiding and spreading out below this level. Cloud bases were lifting during the afternoon, being about 12°C in mid-afternoon and 10°C by the end of the flight.

The T-28 on-station time was inadvertently shortened by about 20 min because it had not been refueled after aborted Flt 640 and its associated ground run-up time. The thought to refuel was lost in the effort to replace the generator and prepare the T-28 for flight.

The Humphrey accelerometer went back into service on this flight, yielding good readings of pitch, roll, and vertical acceleration. The Kopp updraft computation method was therefore available for the data from this flight.

All particles on the foil were d < 1mm, with low concentrations. Two punch marks denoting boundaries between penetrations were missing due to apparently heavy icing during these passes.

There were more than the usual number of noise spikes in the static pressure data.

The clouds appeared to be negatively buoyant at the penetration level, as in-cloud temperatures were lower than out-of-cloud temperatures. Given the general behavior of these clouds as noted above, the negative buoyancy seems plausible, and not just an artifact due to temperature probe wetting.

The T-28 J-W reading on each initial pass of each of these cases was about twice that of the WMI 340 J-W during the treatment pass that immediately followed. Since even the higher T-28 reading was well below adiabatic magnitude at the penetration level, and since the liquid water concentration computed from the FSSP was yet higher than the J-W value (plausible, given the physical response characteristics of the two instruments), it is believed that the T-28 J-W was not reading too low. The disparity is attributed to the two aircraft penetrating different regions of the same cloud.

1.9 Flight 642 on Wednesday, August 31, 1994, 1455-1635 CDT

Thunderstorms developed in the vicinity of Big Spring by late morning. After quickly solving some brake problems, the WMI 340 was off at about 1330 CDT. The T-28 was delayed by rain at the airport and then got off a little over an hour later.

The aircraft flew 2 cloud physics cases in vigorous convective clouds. Each case seemed to have multiple turrets. Several clouds were also penetrated on the way home.

Although the J-W was turned on, there was a failure in the sensor head and no data were obtained.

Quite large FSSP equivalent diameters and liquid water concentrations were computed for this flight. The FSSP spectra will need careful interpretation, as they were contaminated by spurious counts due to the high concentration of ice particles present in these clouds.

Heavy precipitation and icing caused the foil to rip during the 6th pass through the first case. Particle impressions up to 1 cm diameter were obtained prior to this point on the foil.

APPENDIX D

BASIC T-28 INSTRUMENTATION

The following is a description of instrumentation aboard the T-28 research aircraft of special significance to TEXARC investigations.

The Johnson-Williams Cloud-Water Content Meter

The J-W hot wire probe has been in use since the 1950's. The T-28 probe system was manufactured in the late 1960's. The T-28 system has three heads. During TEXARC, the same head was used throughout due to heater failures on the other two heads. The heaters failed on the third head for the last flight. The sensing wire was broken, then repaired, several times during the experiment. The calibration of the J-W electronics package was checked periodically during TEXARC and found each time to be correct. This is the only field calibration procedure possible with this system. The pilot periodically re-zeroed the J-W in-flight. When the baseline is off from a nominal zero reading, the excursion from the baseline value should be interpreted as indicative of the true water concentration.

Spyers-Duran showed that J-W probes can give accurate indications of cloud water concentration when cloud droplet spectra have median volume diameters less than 30 micrometers, over the range of cloud water concentrations from 0 to 3.5 g m^{-3}. For higher median volume diameters, the J-W underestimates true cloud water concentrations.

The T-28 J-W system was one of those included in the intercomparison tests involving 13 J-W systems from various institutions described by Strapp and Schemenauer. The T-28 instrument in this paper is coded as "G". When the instrument electronics was set for the proper airspeed, the T-28 system response during these icing tunnel tests was shown to be accurate up to 2 g m^{-3}. It was also shown to suffer from icing problems, particularly at lower temperatures. Icing problems also were common during TEXARC, resulting in shorting of the bridge circuit and indications of highly negative liquid water concentrations that persisted after cloud exit. The probe typically recovered sometime after cloud exit and upon the subsequent cloud entry the baseline had returned to near-zero values.

On several occasions during TEXARC it was noted that the T-28 peak water concentration during the initial pre-treatment pass was higher than the peak J-W reading from the WMI Cessna 340 on the subsequent treatment pass. Aside from uncertainty as to whether the two aircraft actually sampled the same region of the cloud top, the intercomparisons of Strapp and Schemenauer also give some background for interpreting this discrepancy. They observed that no more than 6 of the 13 systems tested at -5 C agreed to within 20% with the independently-measured tunnel water concentration with each of the sensor heads for each system. (The T-28 system was not one of the 6.) However, 10 of 13 systems did agree within 20% of the tunnel value with at least one sensor head. (The T-28 system was one of these 10.) Similar results were obtained at -15 C, but with more noise introduced by icing problems. Thus, discrepancies between readings in the same environment from two J-W systems with particular sensor heads may often disagree by as much as 20%, and sometimes by more than this.

Particle Measuring Systems, Inc., (PMS) Forward-Scattering Spectrometer Probe (FSSP)

The FSSP carried by the T-28 is Serial Number 1 of this probe series, manufactured by PMS in 1974.

The FSSP data available for "first look" in the field were revised after the end of the field phase of TEXARC using new channel size assignments. The new assignments were derived using results of the bead tests conducted in the field during TEXARC and following additional suggestions given by Darrel Baumgardner upon consultation following TEXARC. These assignments were significantly different from those employed in the "first look" data, based on calibrations from the previous year.

The bead tests during TEXARC were conducted using two sizes of glass beads, 8 and 31 micrometers diameter. It should be noted that each batch of beads is not ideally monodisperse, but contains a range of sizes as shown in Figure 6 of the paper by Baumgardner and Spowart (1990).

The basic procedure of using transparent beads to calibrate the channel sizes in an FSSP is described in an NCAR report by Baungardner and Skinner (1989). A theoretical calculation is done, using the Mie theory, to predict the energy scattered by these beads into the annulus through which our FSSP receives light scattered from particles going through its sample volume. The voltage thresholds for the pulse height analyzer channels into which the majority of these beads fell were used to define the voltage output of the FSSP photodetector circuit corresponding to these particular scattering signals.

Further Mie calculations, using the index of refraction of water, define the diameters of water drops producing the same scattered light signal on the same arbitrary scale as the glass beads. (A smaller water droplet will produce the same signal in an FSSP as a larger glass bead, due to water's lower index of refraction.) In this manner, two particular water droplet sizes can be associated with two particular voltage outputs of the FSSP photodetector. The mapping of the scattering signal computed on an arbitrary scale computed using the Mie theory for water droplets, to output voltage of the FSSP optoelectronics, is assumed to be linear. As long as one can tie a particular voltage to a particular computed intensity, one can then relate all other computed intensities to voltages. Using the Mie calculations, then, and this mapping of voltages to theoretical intensities, water droplet sizes can be assigned to each of the 16 voltage thresholds in the FSSP pulse-height analyzer.

Our 31 micrometer beads appeared with almost equal probability in Channels 5 and 6. The 8 micrometer beads appeared in Channels 1 and 2, with about 2/3 in Channel 1 and 1/3 in Channel 2. This result was reasonably consistent through three separate bead tests, spaced a week or so apart, during August, 1994. According to the PMS specifications, these beads should appear in Channels 6 and 2, respectively, so our probe apparently was not aligned precisely as PMS expects. This is not a problem, because the calibration procedure can correct for this. Based on the bead results, then, the voltage corresponding to the light scattered by 31 micrometer beads into the FSSP annulus was assumed to be half-way between the pulse-height analyzer thresholds for Channel 5 and for Channel 6. The size thresholds for all analyzer channels were then calculated using the Mie theory and this voltage-to-theoretical-intensity mapping.

According to this calibration, based on 31 micrometer beads, our 8 micrometer glass beads should show up more often in Channel 2 than Channel 1. Since more appeared in Channel 1 than in Channel 2, there is some inconsistency in the performance of our FSSP. Darrel Baumgardner suggested that this may be due to an off-center in-focus sample volume in our particular FSSP (Serial #1, the grandfather of all FSSP's!). Not having a clear optimum choice for resolving this quandary, we chose to assign minimum size thresholds for all but the first two channels using the mapping derived from the 31 micrometer bead results, and fixed the first two channel size thresholds assuming the 8 micrometer beads appeared with equal probability in Channels 1 and 2.

It is then assumed that all accepted droplet passages producing a given output voltage are classified into the channel whose threshold voltage is less than this value with the threshold for the next higher channel being greater than this voltage.

The T-28 FSSP data are then processed two different ways. For our "standard" processing (with bulk activity corrections) we made a further adjustment to the channel size assignments derived as just described. This adjustment was suggested by Darrel Baumgardner. We assume that, due to the typical 90 to 100 m per sec true airspeed of the T-28 during penetrations, and the finite response speed of its optoelectronics, our FSSP is undersizing particles by the equivalent of one channel compared to the sizing done during glass bead calibrations on the ground when particles are moving through the sample volume at much lower speeds. Thus we derived another mapping of theoretical intensity to photodetector output voltage based on the assumption that our 31 micrometer beads would appear equally in Channels 4 and 5 if they were moving through the sample volume at 90 to 100 m per sec. The channel-size assignments derived from this process assign a larger size to each channel than the size-assignments based directly on the bead results without the assumption of undersizing.

Our "standard processing" is done using the channel size assignments computed assuming an undersizing by one channel as just described. The counts in each channel are used, along with the volume mean diameter computed from the upper and lower size limits of each channel, and the sample volume swept out in one second (including a beam fraction correction due to non-uniformity of the laser beam, as measured in the laboratory), to estimate the total liquid water concentration contained within the drop spectrum range sampled by the FSSP (from 2 to 70 micrometers diameter).

The water concentration, as well as the droplet number concentration, are adjusted using the measured probe activity, since the finite electronic processing time in the probe circuitry can result in droplets being missed while the probe is busy recording a droplet that has just passed through the sample volume. The recorded value of probe activity is the decimal fraction of a second during which the probe was actively assimilating data. For the T-28 FSSP this correction is

$$N_c = N_i / (1-0.55*\text{activity})$$

where N_c is the corrected concentration, and N_i is the measured concentration.

Our "calculated" FSSP processing uses the size assignments based directly on the bead test results, i.e. 31 micrometer beads appearing equally in Channels 5 and 6. The recorded channel counts are processed using a procedure described in Baumgardner and Spowart (1990). It is basically a computer simulation of the FSSP. It accounts explicitly for response time limits of the electronics, the non-uniformity of the laser beam, etc. An airspeed-dependent response matrix is computed that tells what fraction of droplets of a given size will fall into each channel of the FSSP. A non-linear inversion routine takes the observed channel counts and computes an estimate of what the "true" droplet spectrum must have been, given the observations and this response matrix. This processing implicitly simulates the undersizing of the FSSP at relatively high airspeeds.

A thorough comparison of T-28 FSSP and J-W cloud water measurements has been done. The FSSP water concentrations calculated by the two methods, the "standard" and "calculated" ones, typically agree very well. The spectra derived by the two techniques are reasonably close in shape, although the "calculated" spectra are slightly larger in the mean, and somewhat broader, than the corresponding "standard" ones. The "calculated" spectra are typically bimodal, whereas the "standard" spectra are not. This bimodality appears quite often when Baumgardner's technique is used on FSSP data. (It is present in the figures contained in Baumgardner and Spowart; 1990, for example.) Its physical interpretation is not certain. The number concentrations computed by both methods are typically within a few percent of each other.

At cloud base, where the spectra are relatively narrow and the largest droplets are less than 30 micrometer diameter, the J-W and two FSSP liquid water concentrations are fairly close, with the FSSP water concentrations usually (but not always) slightly higher.

Near cloud top, when few or no ice particles are present (as evidenced by zero or almost zero 2D-C shadow/or counts and zero counts in the upper FSSP channels), the mean droplet sizes are well above 20 micrometers, and the spectra are quite broad. Here, the FSSP water contents are typically 2x larger than the J-W water contents. This is physically reasonable because examination of the size spectra shows that a significant portion of the water should be contained in droplets too large to be sampled properly by the J-W.

When significant ice particle concentrations are present (as indicated by significant 2D-C shadow/or counts and by low and roughly equal counts in the upper FSSP channels) computed FSSP water concentrations can be 3x or more higher than J-W values. In this last situation, it is reasonable to discount the utility of the FSSP water concentrations and spectral parameters, as the disparity is obviously due to the contamination of the droplet measurements by the presence of ice. There is not a reliable automatic routine to subtract false counts due to ice particles from FSSP channel counts. An example of the spectrum that might typically be produced by sampling in an environment with <u>only</u> ice particles present is shown in the upper left panel of Figure 6 in Baumgardner and Spowart (1990). Although in principle ice particles produce random counts as likely to appear in one channel as another, the response time limits of the probe on an aircraft in flight lead to undersampling of the lower and upper channels. This leads to an estimated spectrum with a broad peak in the middle channels. When this type of spectrum is convolved with a cloud droplet spectrum, it is difficult to retrieve a quantitative estimate of the cloud droplet spectrum alone.

Using an estimate of cloud top values for adiabatic water contents of 4 to 6 g per cubic m in the typical TEXARC sounding, none of our uncontaminated (i.e. pre-treatment) FSSP cloud top droplet spectra produce water concentrations significantly in excess of these adiabatic values. The narrow spectra at cloud base produce FSSP water concentrations in reasonable agreement with the J-W estimates. The factor of two disparity between FSSP and J-W water concentrations near cloud top, where spectra are broader, and when ice is not present, is physically reasonable given the poor response of the J-W to larger droplets. At cloud top, in the absence of ice, then, the FSSP cloud water concentrations are more representative than the J-W concentrations. At cloud top in the presence of ice, the best guess of the true water concentration is probably twice the J-W reading.

PMS Optical Array Probe - 2D Cloud Version (OAP-2D-C)

The 2D-C carried by the T-28 is a pre-serial number model manufactured in 1974. The functioning of this probe is summarized in a bulletin entitled "IAS Method for 2D Data Analysis on PC's" (Detwiler and Hartman, 1991), available from the authors at SDSMT. The primary data recorded by the probe is a series of digital images of hydrometeors along the aircraft track. Particles ranging in size from 50 micrometers to a few millimeters can be imaged (partially, in the case of particles larger than 800 micrometers). Timing information encoded into the image files allows computation of particle concentrations. Software has been provided to the TEXARC science team that allows viewing, processing and analysis of this image data.

An interesting intercomparison involving multiple 2D-C probes flown on the same aircraft is described in a paper by Gayet et al. (1993). They show that older 2D-C probes, like the one used on the T-28, tend to undercount by up to 50% compared to newer probes with faster electronics. The extent of under-counting was not itself dependent on concentration. That is, there was the same fractional disparity between concentrations estimated from old probes compared to those estimated from new probes at both low and high concentrations. Size spectra determined from both older and newer probes are fairly similar. Based on this intercomparison, one might expect the T-28 2D-C to count fewer cloud and precipitation particles than a more modern version of the same probe might have done.

Gayet et al. (1993) also note that different processing software may yield significantly different estimates of particle concentration. Software provided by SDSMT has been compared to just one other independently-developed 2D probe data processing software package, that used by researchers at the University of North Dakota. In most situations, concentrations estimated using the two different software packages on the same recorded probe data are within a few percent of each other. This agreement, of course, does not firmly establish the validity of estimates from either package. However, this agreement is not discouraging, either.

Williamson Foil Impactor

The Williamson foil impactor was one of the first cloud physics instruments mounted on the T-28. It was custom manufactured in 1968 by Williamson Aircraft Co. In its operation a roll of aluminum foil is scrolled past a window while particles entering the window smash into the foil, leaving an imprint that is almost exactly the size of the particle. A grooved backing behind the foil causes the imprints to be filled with lines spaced 0.25 mm apart, aiding in the sizing of smaller imprints. This impactor functions like many of those discussed in the literature. Past experience with the T-28 instrument shows that the collection efficiency is unity for particles large enough to make an impression.

The foil is stationary and the window closed until the pilot activates his "cloud" switch. Upon activation, the window opens and the foil starts moving at roughly 3.45 cm s^{-1}. When the "cloud" switch is turned off, upon cloud exit, the window closes and a small hole is punched into the foil near the take-up spool, a little more than 23 cm ahead of the foil that was actually being exposed as the window closes. When the window is reopened for the next penetration, this same bit of foil will be re-exposed as the foil again starts to transport. Thus, when examining the foil, the actual end of a penetration is slightly more than 23 cm past the punch mark (toward later times), and at this point the foil has been exposed to the end of one penetration and the beginning of the next. Typically, there are no precipitation-size particles at the ends of penetrations, so this overlap presents no problems in data interpretation.

The times the cloud switch is activated and turned off are recorded on the data system. These times then correspond to the times of the punches. Because the transport speed of the foil varies slightly depending on the amount of foil on the take-up spool, ambient temperature, and other factors, it is advisable to determine the transport speed individually for each penetration period, using the length of foil exposed divided by the elapsed time between punches.

Several malfunctions were observed from time to time during TEXARC, as is typical of this instrument. The foil occasionally jams if ice builds up around the window, and sometimes rips if hit by a high concentration of large particles. It also can become heavily wrinkled if ice builds up around the window. Ice build-up around the window may prevent the window from closing completely; in this situation the punch mark will not be made when a penetration ends. In some situations, ice chunks can get wrapped up between foil layers on the take-up spool, also causing wrinkling and perhaps causing missed punches.

All foil was examined in the field and individual penetrations marked off by writing directly on the foil, accounting for the distance between the punch mark and the window. Transport speeds were noted on separate logs. Malfunctions were also noted on these logs.

Particle concentrations can be computed by counting the particle impressions within a certain area of foil, then dividing by the product of the instantaneous true-airspeed of the aircraft, the area of the foil analysed, and the exposure time of the foil as it passed the open window. The exposure time is the width of the window (3.81 cm) divided by the transport speed (nominally 3.45 cm s^{-1}, but varying slightly from penetration to penetration); nominally, about 1.1 s.

National Center for Atmospheric Research (NCAR) Reverse-Flow Temperature Probe

This instrument is a platinum-resistance element mounted within a "reverse-flow" housing. The housing is arranged so that air passing over the sensing element has reversed direction, entering the probe housing from the rear and passing forward over it and then out exhaust ports. The flow reversal hopefully separates air from cloud drops and hydrometeors so that the sensing element remains dry. Probes of this generic design are flown on almost all meteorological research aircraft.

Due to the complex airflow in the probe, the temperature actually sensed is between the dynamic temperature (or total temperature) that would be sensed by a completely exposed sensor moving at the instantaneous true airspeed, and the temperature that would be sensed by a sensor at rest relative to the air in the same environment, called the static temperature. An empircal correction allows an estimate of the static temperature from the sensor temperature. The temperature contained in the T-28 data files is the estimated static temperature.

Lawson and Cooper (1990) show that reverse-flow probe elements frequently <u>do</u> wet in warm clouds, but not very freqently in supercooled ones. Presumably the supercooled cloud water freezes to the housing in the the colder clouds, and is no longer in the air that sweeps over the sensing element after entering the probe from the back, preventing wetting in the supercooled case. Those working with T-28 data over the years have collected anectdotal evidence that the temperature recorded from the reverse-flow instrument is often lowered after several tens of seconds of penetration through supercooled cloud. The cause is not firmly established. Icing on the probe housing may influence the airflow through the probe, changing the assumed relationship between the measured temperature and the static temperature based on clear-air tests. Water may shed off the iced housing and wet the sensor if the surface of the ice deposit is liquid due to more water impinging than can be instantaneously frozen. Other possibilities certainly exist.

In addition to problems with wetting of the sensor, changes in angle of attack of the airflow over the probe during encounters with turbulence, or due to changes in aircraft attitude, or flap configuration, may have some influence on the retrieval of static temperature from the sensed temperature.

The analyst should bear these phenomena in mind when interpreting the reverse-flow temperature record.

Rosemount Temperature Probe

This is a standard aircraft temperature probe, similar in design to the probe on the WMI Cessna 340. It is de-iced, but much more prone to wetting problems than the reverse-flow temperature probe. It is less subject to variations in retrieved static temperature due to variations in angle-of-attack of the impinging airflow.

Comparisons between both the Rosemount and reverse-flow temperatures from the T-28, the Rosemount temperature from the WMI Cessna 340, and the temperatures from the National Weather Service sounding from Midland, nearest in time to time of the flights, showed good agreement, typically, within 1°C between aircraft probes, and within a few degrees C between the aircraft and the soundings. Given the typical spatial and temporal separation between the Midland soundings and the aircraft record, this is excellent agreement. Examples of these comparisons are included with this report.

APPENDIX D

Basic T-28 Instrumentation

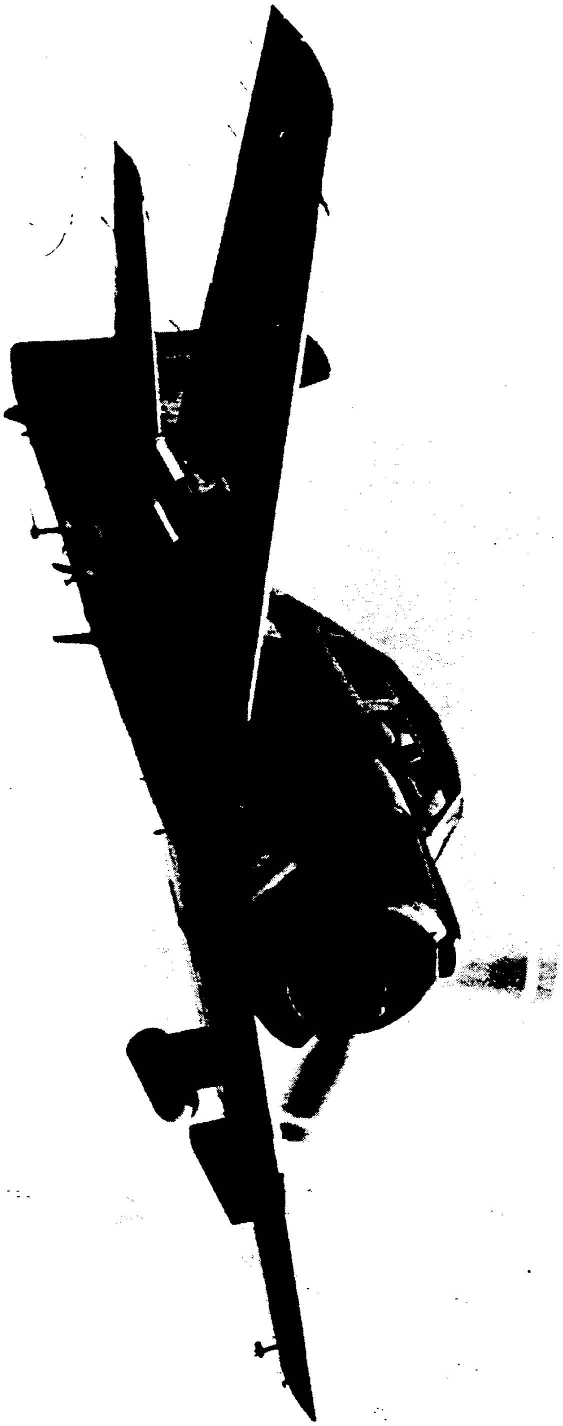
VARIABLE	INSTRUMENT	RANGE	ACCURACY	RESOLUTION (as recorded)	NOTES
STATIC PRESSURE	ROSEMOUNT 1301-A-4B	0-15 psi (0-103 kPa)	±0.015 psi (±0.1kPa)	0.0002 psi (0.002 kPa)	• Bench calibration, 6/93
	ROSEMOUNT 1301-A-4B	5-15 psi (35-103 kPa)	±0.015 psi (±0.1kPa)	0.0002 psi (0.002 kPa)	• Bench calibration, 6/93
TOTAL TEMPERATURE	ROSEMOUNT 102AU2AP	-30 - +30°C	±0.5°C	0.001°C	• Platinum wire • -2 s time constant
	NCAR REVERSE FLOW	-30 - +30°C	±0.5°C	0.001°C	• Diode • Several seconds time constant • Bench calibration, 6/93 • Recovery factor adjusted, 6/93
CLOUD WATER AND CLOUD DROPLETS	JOHNSON-WILLIAMS LIQUID WATER CONCENTRATION	0 - 4 g/m^3	±20%	0.0001 g/m^3	• Accurate if all droplets have d <30 μm
	PARTICLE MEASURING SYSTEMS, INC. FORWARD SCATTERING SPECTROMETER PROBE	Size ~1 < 67 μm Concentration 0 - ~2000 droplets/cm^3	±1 size channel in size and ±1% in concentration at ~50/cm^3	1 size channel	• 15 discrete size channels spread over an adjustable range • Sampling rate 300 cm^3/km • Accuracy of computed liquid water concentration ~ ±50%. Depends on processing.
PRECIPITATION PARTICLE SIZES AND CONCENTRATIONS	WILLIAMSON FOIL IMPACTOR	1 - 20 mm	0.2 mm	0.2 mm	• Sampling rate 1.4 m^3/km
	PARTICLE MEASURING SYSTEMS, INC. 2D Cloud Probe	Size 25 - 800 μm	±25 μm	25 μm	• Computed ice and water mass concentration can vary ±50% with processing technique • Sampling rate: 0.05 m^3/km; DAS can accept ~250 particles/s (2500/km)
	HAIL SPECTROMETER	Size 4.5 mm - 4.5 cm Concentration 0 - 100/m^3	±1 size class	1 size class	• 14 size classes • Sampling rate 100 m^3/km • Alternates with particle camera

APPENDIX (continued)

AIRCRAFT MOTION	HUMPHREY SSA09-D0101-1 VERTICALLY STABILIZED ACCELEROMETER	± 2 g's pitch -50° to +50° roll -50° to +50°	0.004 g 0.2° 0.2°	0.00006 g 0.002° 0.002°	
	ROSEMOUNT 1301-D-1B DYNAMIC PRESSURE	-3 to +3 psi (-20 to +20 kPa)	±0.1%	0.0001 psi (0.0006 kPa)	• Indicated airspeed • Bench calibration, 6/93
	ROSEMOUNT 1221-F-2A DYNAMIC PRESSURE	-2.5 to +2.5 psi (-18 to +18 kPa)	±0.1%	0.0001 psi (0.0006 kPa)	• Indicated airspeed • Bench calibration, 6/93
	GIANNINI 45218YE MANIFOLD PRESSURE	0 to 50 in Hg	±2%	0.008 Hg (0.03 kPa)	• Used in one vertical velocity calculation • Bench calibration, 3/93
	BALL ENGINEERING 101A VARIOMETER	-6000 to +6000 ft/min (-30 to +30 m/s)	±200 ft/min (±1 m/s)	0.2 ft/min (0.001 m/s)	
AIRCRAFT LOCATION	TRIMBLE TNL2000 GPS	(global)	30 m	18 m	
ELECTRIC FIELD	NMIMT Model E-100 DC Electric Field Meter	top/bot ± 650 wings ± 3200 } $\frac{\text{kV}}{\text{m}}$ 5th ± 340		(coarse resolution) 0.01 $\frac{\text{kV}}{\text{m}}$	

NOTE: Many of these instruments do not behave as ideal instruments. The use of one measure of accuracy over the entire range of measurement is, in many cases, questionable. An accuracy representative of the most useful part of the range is given here.

revised 11/94



Explanation of T-28 Pass Summary Table

Date	month/day
Time	hhmmss CDT *The times in the draft report have sometimes been broken into further subunits if it looked like the aircraft penetrated more than one convective element during a pass. These assignments should be regarded as preliminary, as without access to the Cessna 340 track or SKYWATER radar data, it is impossible to be certain which element was actually treated and was the focus of the study.* *T-28 data system time is within 1 sec of WWV time for all flights.*
Case #	as assigned in draft project report *In some cases the draft case # was further modified in accordance with the subdivision of a pass into more than one convective element if it looked like more than one element was penetrated during a pass. Cloud base passes are included in the table, as well as passes through other clouds encountered either on the way out or the way in.*
Pass #	enumerated in the order listed in draft report *There were some modifications where a pass was subdivided. The enumeration also does not include the Cessna 340 treatment pass that follows the initial T-28 pass through a new case.*
Z	average altitude above sea level in meters. *Recorded GPS altitude was used when available. Averages computed based on the period between the pilot's in-cloud and out-of-cloud times recorded on the data system. These times each typically differed by several seconds from those deterimined by Danny Rosenfeld when he examined the data after a flight. Averages would be slightly different if Rosenfeld's times were used. The geopotential altitudes were used for all passes for which GPS altitude was not available (flights on the 4th and 24th).* *GPS altitudes are typically several hundred meters higher than pressure altitudes.. GPS altitudes are comparable to geopotential altitudes computed from soundings and to the altitudes of radar echo features in the radar data (when the height of the radar above sea level is taken into account).*
T	This is the pass-average temperature based on the reverse-flow temperature sensor, rounded to the nearest degree Celsius. *Occasional spikes in the recorded temperature were factored out of the average.*
J-W LWC	Peak value recorded during a pass, g m^{-3}. *The peak value was computed as the maximum exursion above the base line*

	value prior to cloud entry. If the baseline was dramatically different after cloud exit, a linear trend during the pass for the changing baseline was assumed. "m" denotes missing data.
FSSP LWC	Peak value recorded during a pass, g m^{-3}. *The peak FSSP value may not have occurred at precisely the same second as the peak J-W value. Computation are based on data processing following the scheme presented in Baumgardner and Spowart (1990). The FSSP produces multiple counts of fictitious droplets with random sizes when significant concentrations of ice particles are present. Liquid water concentrations based on FSSP data should be regarded as suspect if the 2D-C indicated significant ice concentrations in the same region where the peak FSSP liquid water content is computed.*
FSSP Cnc	Peak cloud droplet concentration during the pass (cm^{-3}). *The peak droplet concentration may not have occurred at the same second as the peak liquid water concentration. Concentrations as high as 50 to 100 cm^{-3} may be computed when ice particles are present in the absence of cloud water.*
FSSP D_{eq}	Equivalent diameter computed from recorded FSSP data (micrometers). *This computation is based on the size spectrum derived using the techniques of Baumgardner and Spowart (1990).*
2D Sh/Or	Peak particle concentration based on the 2D-C/shadow/or count data (liter^{-1}). *A size-independent volume sampling rate of 5 liters sec^{-1} was used along with the recorded shadow/or data to estimate particle concentration. The shadow/or count rate includes both real particles and artifacts due to water shedding from probe tips, fogging of optics, and electronic malfunction. The actual image record should be examined to estimate the fraction of these counts that represent actual particles.* *The region of 2D-C peak concentration was almost invariably not coincident with the region of peak cloud water concentration.The lower limit size to which the T-28 2D-C can respond is not known, accurately, but comparison to FSSP data and published analyses based on similar 2D-C probes suggests that this lower limit is above 50 micrometer diameter at typical T-28 cloud penetration speeds.* *The size-independent sample volume assumption will underestimate the concentration when large numbers of particles smaller than 200 um diameter are present. For these particles, the sample volume is actually smaller than for larger ones.* *In TEXARC clouds, it can be presumed that real particles detected by the 2D-C are nearly always ice particles.*
2D Image Conc	This estimate of concentration is based on an analysis of the image data. Artifact images are not included. A size-dependent sample volume is used, this results in noticeably higher concentrations when mainly small particles

	are present. The estimate of concentration is based on all image data from buffers filled wholly within a penetration. Because the probe does not record image data continuously, the concentration given is neither a peak one-second value (as is the concentration estimate based on shadow/or count) nor a penetration average. See Detwiler and Hartman (1991) for more details.
2D Image Size	Maximum dimension of any non-artifact image within buffers wholly-contained within a penetration period.
2D-C particle types	An "X" indicates that this type of particle predominated during at least part of the pass. Zero-clement images comprise the majority of images on all passes. These are empty images with valid times, indicating a particle large enough to initially trip the probe but too small to be detected on the subsequent scan of the diode array of the probe. These probably are due to either very small ice particles, somewhat larger than 50 micrometers across, or large cloud droplets of similar size.
sh/st	*out-of-focus drop or streak images resulting from drops shedding from probe tips*
tny	*images of ice particles smaller than roughly 200 micrometers.*
gr	*graupel, i.e., images that are consistent in shape with moderate to heavily-rimed ice pellets.*
sn	*snow, i.e., images consistent with lightly or negligibly-rimed ice crystals.*
dr	*drops, i.e., images that are probably from liquid drizzle/rain drops.*
W_{max}	Peak updraft (or downdraft, if there was no updraft) (m s^{-1}) *These values are qualitative and should be regarded as accurate to about +/- 3 m* s^{-1}. *On most flights accelerometer data were not available and updraft was estimated using the so-called Cooper technique. On the first flights (8/4 and part of 8/5) and last flights (8/24 and 8/31) the accelerometer was functioning and a more accurate estimate, using the so-called Kopp technique, could be made. Both techniques are described in Kopp (1985).* *The peak cloud water concentration was normally co-located with the peak updraft during a penetration.*

TEXARC T-28 Pass SUMMARY

Date	Time (LT)	Case #	Pass #	Z (m)	T (C)	J-W LW max	FSSP LWC max	FSSP Cnc max	FSSP Deq (um)	2D Sh/Or max	2D Image conc avg	2D Image size max	Particle Types Present sh/st	tny	gr	sn	dr	W max (m/s)	Comments
8/4	164816	base		3355	6	m	0.6	511	16	47	0	0.0	X					4	Z is geopotential altitude on this flight
	172655	1	1	5788	-8	m	3.1	362	29	5	1	0.2	X		X			3	2 turrets?
	173040	1	2	5801	-8	m	3.9	335	30	0	0	0.0	X					2	
	173308	2	1	5810	-8	m	3.1	295	29	1	0	0.4	X		X			1	2 turrets?
	173541	2	2	5809	-8	m	4.1	396	30	13	2	0.8	X					5	
	173725	2	3	5778	-8	m	3.1	308	29	4	1	0.2	X					3	
	173923	2	4	5802	-8	m	3	370	28	23	2	0.2	X					3	
8/5	161149	base		3150	9	0.2	0.8	443	15	48	2	0.1	X					3	Z is GPS altitude on this flight
	172640	3	1	6454	-10	1.5	4	256	35	10	3	0.5			X			5	
	172815	new	1'	6282	-9	2	4.1	332	34	73	6	1.9	X		X			10	not same turret;? updraft because in turn
	173030	new	2'	6256	-10	1.2	3.2	232	33	109	7	1.8	X					10	
	173810	4	1	6580	-10	2.4	3.8	303	36	107	24	3.8	X		X			5	
	174420	4	2	6484	-9	0.5	2.5	197	34	252	34	1.3			X			2	
8/8	144921	base		3413	12	0.4	0.4	218	16	0	problems with images on this flt due to plugged pitot							3	
	150650	5	1	6371	-8	1	3.8	243	36	3								3	
	151335	5	2	6352	-7	0.7	3.3	412	34	27								-3	Suspicious of disagreement between FSSP & JW
	155435	6	1	6278	-5	1.6	3.8	317	30	5					X			2	
	155910	6	2	6051	-6	0.7	2.7	241	29	2								3	
	161420	7	1	6249	-6	0.9	3.2	268	30	2								4	
	161830	7	2	6176	-5	0.3	1.4	178	31	1								-3	
8/14	153930	base		3558	6	0.2	0.2	110	16	0								2	2D-C times corrupted for cloud base pass and 1st case; concentration estimates impossible
	155710	8	1	6317	-9	1.7	3.6	304	33	1					X			5	
	155853	?	?	6210	-8	1.2	2.5	287	29	1					X			-?	very close to, if not actually,target turret
	160025	8	2	6198	-8	1.2	2	208	30	0					X			2	
	162314	9	1	6454	-9	1.4	4.4	234	40	80	52	2.7	X		X			5	
	162600	9	2	6464	-9	1.4	3.2	197	41	71	45	2.2	X		X			5	multiple turrets
	162914	9	3	6493	-9	1	3.2	169	43	106	32	2.8	X		X			9	
	163243	9	4	6487	-9	3	3	220	32	131	67	2.9	X		X			4	Hit 3 turrets;oldest had ice/little LWC; youngest no ice/lots LWC
	163910	9'	1	6550	-9	m	1.7	56	52	419	58	2.4			X			5	Hit a new turret to west of others
	164115	9"		6622	-9	2.8	3.9	186	38	33	14	0.3			X			m	In a turn
	164230	9'?	2	6670	-9	0	1.2	37	61	423	72	1.4			X			5	Probably no cloud water in here; may not be turret 9'
	165500	10	1	6523	-9	>1.9	3.7	273	35	46	12	0.7			X			10	
	165750	10	2	6527	-10	m	3.7	282	36	69	34	1.2	X		X			6	
	170033	10	3	6493	-10	0.9	4.3	260	39	259	66	1.7	X		X			10	Doesn't start at 165957 as indicated in draft table
	170312	10	4	6496	-10	0.8	4.5	269	36	78	25	3.6	X		X			4	
	170533	10	5	6525	-10	m	3.9	226	37	63	43	2.1	X		X			2	No cloudwater until 170551
	170825	10	6	6429	-9	m	2.3	197	33	90	21	1.8	X		X			-3	
8/15	164513			5822	-6	1.2	2.9	167	36	28	8	2.1	X		X	X		5	Not a good cloud base pass in this day;hit this on way out
	165725	11	1	6504	-10	2.1	3.7	176	38	5	13	1.2	X		X			0	
	165937	11	2	6445	-9	0.7	3	211	36	29	19	1.2	X		X			3	
	170135	11	3	6389	-9	0.6	2.6	124	36	28	28	0.5			X			2	
	170304	11	4	6308	-8	1	3.4	165	37	9	4	0.4			X			3	
	170446	11	5	6316	-8	0.1	1.1	52	36	10					X			0	Only 4s of data!
	171310	12	1	6419	-10	2.4	5	381	38	2	5	0.3	X	X				8	
	171610	12	2	6453	-9	1.3	4.4	199	37	28	8	0.3	X	X				7	
	171812	12	3	6452	-9	1.3	4.1	214	38	34	12	0.4	X	X				4	
	172035	12	4	6324	-9	1.2	3.7	155	37	21	6	0.3		X				2	
	173530	13	1	6493	-10	1.3	4.4	330	37	30	14	1.3	X		X		X	10	Nice cloud edge downdrafts, both sides
	173840	13	2	6514	-10	1.6	4.3	368	38	107	38	1.7	X		X		X	10	More broken, but still see edge downdrafts

	174120	13	3	6474	-10	1.6	4.7	337	36	174	40	1.6	X		X			10	Ditto		
	174309	13	4	6206	-9	1.2	4.2	340	35	243	62	4.1	X		X		X	8	Cloud seems still vigorous, but apparently collapsing? (T28 descending)		
8/20	163053	base		3845	8	0.3	0.4	152	18	6					X		X	4	A few particles up to 3 mm on foil; 2D-C image times not analyzed		
	163139			3972	7	0.5	0.6	222	18	5			X					4	All of this 1st group of passes were thru different clouds on the way out		
	163222			4097	6	0.3	0.4	154	19	1							X	3			
	163459			4622	1	0.3	0.6	145	21	10			X				X	2			
	163606			4997	0	0.7	1	234	23	7			X		X			4			
	163808			5517	-5	0.3	0.5	132	20	0								5			
	164600	14	1	6441	-10	1.4	3	300	30	25	5	0.2	X					12	Cloud edge downdrafts both sides		
	164915	14	2	6485	-10	1.1	2.4	259	30	36	3	0.7	X		X			7	Cloud edge downdrafts both sides		
	165155	14	3	6522	-11	0.9	1.8	242	28	35	7	1.4	X	X				-4	Distinct circulation disappeared or was missed;small pellets on foil		
	165433	14	4	6468	-10	0.4	1.6	225	26	43	11	3.2	X	X	X			4	small pellets		
	165730	14	5	6176	-9	0.4	1.2	197	27	274	56	3.0	X	X	X			2	graupel to 3mm		
	170100	14	6	6447	-10	0.4	1.1	167	31	307	87	1.6		X	X			4			
	170655	15	1	6491	-10	1.2	2.7	296	30	105	68	2.8	X	X	X		X	12	few 3mm round imprints on foil;updraft neg buoy.		
	170935	15	2	6438	-10	1.1	2.9	281	32	86	48	1.7	X	X	X	X		8	round imprints to 5mm;updraft neg buoy		
	171148	15	3	6492	-10	0.6	2.1	265	27	119	103	4.6	X	X	X			8	round imprints to 5mm;downdraft surrounds narrow updraft core		
	171430	15	4	6442	-9	0.4	1.5	248	25	307	133	2.5	X	X	X			4	few more round imps to 5mm		
	171750	15	5	6476	-10	0.3	1	181	28	180	225	1.5	X	X	X			3	cloud #15; 2mm graupel		
	171901	15'		6405	-10	0.7	2.1	281	27	66	(combined w/above)		X	X	X	X		5	another neighboring cloud		
	172135	15'		6502	-10	0.8	2.4	291	30	401	204	3.7	X	X	X	X		-5			
	172221	15	6	6474	-9	0.8	2	277	26	226	(combined w/above)		X	X	X	X		6	Foil to 4mm		
	172520	15	7	6533	-10	0.4	1.4	216	26	316	269	2.9			X			6			
	172609	15"?		6494	-9	1.1	2.6	334	48	455	(combined w/above)		X	X	X			10	Foil to 4mm		
	172823	15"?		6463	-9	1	2.5	291	42	408	154	3.6			X			10	Foil to 4mm		
	172923	?		6430	-9	1.9	2.9	345	38	176	(combined w/above)				X	X		?	Looks like a new turret		
	173210	ragment		6299	-9	0.3	1	167	52	140	44	3.0			X			m	cloud fragment encountered on way from cloud #15 to #16		
	174005	16	1	6453	-10	1.5	3	517	27	53	114	0.8	X					15	classic updraft w/flanking downdraft;broader;updraft neg buoy.		
	174430	16	2	6252	-8	1.1	2	281	27	83	143	1.5	X					10	classic updraft w/flanking downdraft;updraft + buoy. at this level		
	174750	16	3	6407	-9	1.4	3.3	414	28	281	167	1.1	X	X	X	X		10	classic updraft w/flanking downdraft;updraft neut. buoy.;pk icein downdraft;a few big particles		
	175130	16	4	6448	-9	1.2	3.6	362	30	298	199	1.9	X	X	X			10	updraft bkng up; still flnkng dwndrfts;updraft neut. buoy.;pk icein downdraft		
	175435	16	5	6533	-9	0.7	2.4	273	51	565	195	3.0			X	X		5	updraft bkng up; still flnkng dwndrfts;updraft neut. buoy.;pk icein downdraft		
	175810	16	6	6538	-9	0.4	1.9	218	55	906	185	3.5	X		X	X		5	no circ pttn evident		
	180130	16	7	6502	-9	0.2	0.8	96	54	856	74	2.0		X	X	X		3	little CLWC left		
	180500	16	8	6495	-9	0.2	0.9	122	58	847	270	2.9			X	X		5	little CLWC left		
	180835	16	9	6418	-9	0.3	0.9	113	48	588	97	3.8		X	X	X		3			
	181130	16	10	6422	-9	0.7	0.4	45	57	600	59	2.9		X	X			-3			
	181441			6529	-9	3	3	340	30	39	17	4.7	X	X	X			15	classic updraft w/flanking downdraft;updraft neut. buoy.;low ice cnc		
8/24	172028	base + 300'		3264	9	0.1	0.2	113	15	22	0	0.0						0	No GPS -using geopotential altitude for Z for this flight		
	172240	frag		4080	4	1.2	0.6	112	26	2	0	0.0						6			
	174725	17	1	6320	-8	2.6	3.2	149	37	21	10	0.1						2			
	175240	17	2	6361	-8	2	2.5	205	33	4	7	0.1	X	X				2			
	175522	17	3	6260	-8	3	2.9	158	36	36	15	0.4			X			2			
	175840	17	4	6141	-7	2.2	2.7	185	35	41	43	0.2	X	X				2			
	180215	17	5	6169	-7	1	1.3	81	33	45	46	0.3			X			2			
	180540	17	6	6134	-6	1.8	1.9	171	35	38	85	0.1		X				2			
	180910	17	7	6027	-7	1.2	1.7	126	35	35	107	0.2	X	X				-2	2 turrets -1st one is #17		
	181235	17	8	5912	-5	0.7	1.5	92	34	57	116	0.1		X				2			
	181600	17	9	5832	-6	1.8	2.4	164	33	37	111	0.2		X				3	different turret		
	181910	17	10	5825	-6	1.3	2.1	124	35	59	109	0.5		X	X			2	same turret as previous pass		

	182400	18	1	6159	-8	2.2	3.9	183	39	52	121	0.2		X				4			
	182735	18	2	6154	-8	2.3	3.1	125	40	41	126	0.5		X	X			3			
	183125	18	3	6124	-8	1.9	3.5	154	39	30	67	0.3	X	X				0			
8/31	145706	base		2521	13	m	1.2	362	19	0	0	0.0						5			
	152822	19	1	6532	-10	m	6.8	266	44	41	54	0.1		X				14			
	153427	19	2	6411	-10	m	7.4	330	42	56	22	1.4	X	X	X			18	2 turrets;2nd is the one hit on 1st pass		
	153808	19	3	6441	-9	m	6.4	269	42	158	41	3.4	X	X	X		X	14	3 turrets;last 2 same as on previous pass		
	154137	19	4	6567	-9	m	5.3	228	43	398	150	4.5	X	X	X			15	3 turrets again		
	154549	19	5	6507	-9	m	6.7	205	45	141	42	2.7	X	X	X			15	1st convective portion of this pass (N of previous pass)		
	154657	19	5	6502	-9	m	1	85	53	473	(combined w/above)			X	X			14	turret on S end (part of original target region)		
	154953	19	6	6455	-10	m	1.1	62	44	241	247	4.9		X	X			-3	turret on s end, part of original target region;FSSP responding mostly to ice		
	155000	19	6	6416	-9	m	1.3	57	57	566	(combined w/above)			X	X			-3	another part of original target;FSSP responding mostly to ice		
	155020	19	6	6501	-9	m	5.3	191	54	663	(combined w/above)		X	X	X			10	a 3rd part of original target; possibly some cloud water in here		
	155107	19	6	6403	-10	m	4.1	164	46	84	(combined w/above)		X		X			-3	Stuff N of original target		
	155704	20	1	6361	-10	m	7.8	267	46	52	49	0.6	X	X	X			6	classic updraft w/flanking downdrafts		
	160119	20	2	6390	-10	m	6.1	212	46	166	107	4.0			X			9	western of 2 turrets,each w/flanking downdraft		
	160146	20	2	6363	-10	m	4.6	156	45	268	(combined w/above)		X	X	X			9	eastern of 2 turrets		
	160508	20	3	6374	-10	m	6.7	200	50	315	239	1.9	X		X			12	eastern turret		
	160608	20	3	6424	-9	m	8.6	256	44	34	31	0.3						12	western turret		
	160901	20	4	6324	-9	m	8.1	281	46	152	100	2.1	X		X			13	western turret		
	160947	20	4	6371	-9	m	2.8	120	47	329	(combined w/above)			X	X			6	kind of in-between?;eastern turret?		
	160956	20	4	6289	-10	m	0.7	39	61	613	(combined w/above)			X	X			0	eastern turret?;just ice here		
	161340	20	5	6412	-10	m	2.4	131	55	660	266	3.5	X	X	X			-2	eastern turret		
	161441	20	5	6461	-10	m	5.2	173	50	337	(combined w/above)		X		X			12	western turret		
	161722	20	6	6367	-9	m	3.2	138	56	325	147	3.9			X			8	western turret		
	161806	20	6	6349	-9	m	0.9	33	46	349	(combined w/above)				X			-3	eastern turret		
	162041	on way home		6157	-8	m	1.7	82	43	122	74	2.7			X			6	Clouds penetrated on way home		
	162200	on way home		5489	-5	m	2.4	88	49	128	(combined w/above)				X	X		6			
	162255	on way home		4808	-2	m	2.4	146	36	42	(combined w/above)				X			3			

APPENDIX E

List of Variables Recorded or Routinely Computed from T-28 Observations

Each different variable in the data stream is indexed with a unique tag number. Those used for the NDTE are listed here.

Tag	Variable	Remarks
100	**Time**	The T-28 data system is always set to local time, and recorded in a 24-hour format. It is maintained within a second of WWV unless otherwise noted.
101	**Dynamic Pressure 1**	
102	**Dynamic Pressure 2**	Both dynamic pressures are read from the same pitot tube line (with the inlet out on the right wing) using two different but nearly identical sensors. [hPa]
103	**Rosemount Static Pressure 1**	
104	**Rosemount Static Pressure 2**	Both static pressures are read from the same static pressure line (inlet on the rear fuselage) using two different but nearly identical sensors. [hPa]
105	**Rate of Climb**	The instantaneous rate of change of aircraft altitude, read from a standard aircraft variometer. The recorded data are unfiltered and much noisier than the damped cockpit display. [m/s]
106	**Rosemount Temperature**	This is static temperature computed from the reading of a standard, deiced, Rosemount aircraft total air temperature probe. It commonly suffers from wetting and reads low in clouds. [°C]

107	**Reverse Flow Temperature**	This is static temperature computed from the reading of a platinum resistance element placed inside a custom-design "reverse-flow" housing. It does not normally get wet in warm clouds or in regions of high precipitation water concentration. Apparently, ice may sometimes build up to such an extent on the housing that temperature readings are affected even though the sensor is not wetted. [°C]
108	**Manifold Pressure**	Pressure inside the engine manifold (an indicator of power being developed by the engine) is recorded from a standard aircraft engine presssure sensor. [inches of mercury]
109	**Acceleration**	Vertical acceleration is determined by a Humphrey gyro/accelerometer. [g's]
110	**Pitch**	The accelerometer also gives angle of the fuselage relative to horizontal. [deg]
111	**Roll**	Finally, the accelerometer gives angle of the wings relative to horizontal. Angle is positive for a left bank (left wing down). [deg]
112	**J-W Liquid Water**	The J-W probe yields concentration of water in clouds represented in droplets less than approximatley 30 µm diameter. [grams per cubic meter]
113	**VOR**	The VOR gives the direction to the VORTAC (a radio direction-finding beacon used by aircraft) to which it is tuned. [deg]
114	**DME1**	This is distance to the VORTAC to which the #1 DME is tuned. [n mi]
116	**Voltage Regulator**	Voltage of power source for some instruments. [volts]

117	**Heading**	Indicates direction (from magnetic north) towards which the aircraft is heading. [deg]
119	**PMS End Element 1**	Voltage readings of PMS end diodes.
120	**PMS End Element 2**	
121	**Interior Temperature**	Temperature inside the data acquisition system computer in the baggage bay. [°C]
123	**High Voltage Current**	Current discharged through a discharger mounted under the rear fuselage when high voltage power supply is turned on. Current sensor functioned irregularly during the TEXARC.
124	**Heater Current**	Total current consumed by de-icing circuits (A).
130	**Event Bits**	Bits corresponding to various events recognized by the data system, including such things as the in-cloud switch activated by the pilot when visually entering cloud, activation of the cockpit voice recorder, foil impactor, etc.
131	**GPS Warning Codes**	Bits corresponding to various status messages from the GPS system.
140	**FSSP size counts**	This tag contains information concerning the number of counts in each of the 15 available FSSP size channels. [number per channel per second]
141	**FSSP total counts**	The total number of droplets counted by the FSSP during a second.
142	**FSSP average diameter**	The average diameter of all droplets recorded during a second. [μm]

143	**FSSP concentration**	The actual concentration of droplets computed from FSSP counts divided by the volume sampled in 1 s ("Standard method"). A rudimentary correction for probe activity is made. [number per cubic centimeter]
144	**FSSP Water**	The liquid water concentration computed from the FSSP data for a second ("Standard method"). [grams per cubic meter]
145	**FSSP Activity**	The fraction of time the FSSP is active during the current second.
147	**PMS 2DC Shadow Or Count**	The number of times the 2D-C probe was triggered out of its wait state by the passage of a new particle. [number per second]
148	**FSSP Equivalent Diameter**	$\sum_{i=1}^{15}\left[\frac{n_i \cdot d_i^3}{n_i \cdot d_i^2}\right]$ at one second intervals, using "standard method" counts and sizes.
149	**Variance in FSSP Equivalent Diameter**	Variance around the equivalent diameter, computed as $\frac{\sum_{i=1}^{15} n_i \cdot d_i^2 \cdot \left(d_i - d_{eqv}\right)^2}{d_{eqv}^2 \cdot \left(\sum_{i=1}^{15} d_i\right)^2}$ using "standard method" counts and sizes.
150	**Hail size counts**	This tag contains information on the number of particles in each of the 14 hail spectrometer size channels. [number per channel per second]
151	**Slow Particle**	The number of particles rejected because they passed through the hail spectrometer too slowly (indicating they were probably water or ice shed from the probe structure rather than airborne hydrometeors). [number per second]
152	**Hail total counts of (150)**	Total number of particles accepted by the hail spectrometer. [number per second]

153	**Hail average diameter**	The average diameter of all particles accepted by the hail spectrometer in the last second. [cm]
154	**Hail concentration**	The computed concentration corresponding to all particles accepted by the hail spectrometer in the last second. [number per cubic meter]
155	**Hail Water**	The mass concentration computed from the observed particle spectrum assuming spherical particles and a bulk particle density of 0.9 grams per cubic centimeter. [grams per cubic meter]
160	**Top Field Mill (low res)**	The electric field indicated by the low sensitivity channel on the field mill mounted in the aircraft canopy looking up. Field mill data are recorded at 20 Hz. [kV/m]
161	**Bottom Field Mill (low res)**	The electric field indicated by the low sensitivity channel on the field mill located in the baggage bay door looking down. [kV/m]
162	**Left Field Mill (low res)**	The electric field indicated by the low sensitivity channel on the field mill mounted in the left wing tip facing outward. [kV/m]
163	**Right Field Mill (low res)**	The electric field indicated by the low sensitivity channel on the field mill mounted in the right wing tip facing outward. [kV/m]
164	**Top Field Mill (high res)**	The electric field indicated by the high sensitivity channel on the top field mill. [kV/m]
165	**Bottom Field Mill (high res)**	The electric field indicated by the high sensitivity channel on the bottom field mill. [kV/m]
166	**Left Field Mill (high res)**	The electric field indicated by the high sensitivity channel on the left field mill [kV/m]

167	**Right Field Mill (high res)**	The electric field indicated by the high sensitivity channel on the right field mill [kV/m]
168	**Fifth Field Mill (low res)**	The electric field indicated by the low sensitivity channel on the fifth field mill, located under the left wing. [kV/m]
172	**Latitude**	Computed internally in the GPS receiver. [deg]
173	**Longitude**	Also computed internally in the GPS receiver. [deg]
174	**Groundspeed**	Computed internally in the GPS receiver (by differentiating the position data with respect to time). [m/s]
176	**Ground Track Angle**	The direction towards which the aircraft is moving relative to the ground, with respect to magnetic north. [deg]
176	**Magnetic Deviation**	The difference between magnetic north and true north as indicated automatically by the GPS receiver based on the current position. [deg]
177	**Time Since Solution**	The time since the GPS was last able to compute an accurate position solution based on a sufficient number of satellites. The GPS updates position based on dead reckoning if it does not have a sufficient number of satellites in view. [s]
178	**GPS Altitude**	Geometrically computed aircraft altitude. [m]
190	**FSSP Gated Strobes**	Number of accepted droplet counts. [number per second]
191	**FSSP Total Strobes**	Total number of droplet counts. [number per second]
192	**FSSP Reference Voltage**	Reference voltage for FSSP opto-electronics.

200	**Date**	As indicated by the data acquisition system computer clock. [yymmdd]
201	**Month**	mm [integer number]
202	**Day**	dd [integer number]
203	**Year**	yy [integer number]
204	**Flight**	A serial number assigned to each T-28 flight beginning with the "first" research flight. (Flight #1 occurred in 1972.)
205	**Altitude**	The altitude in a standard atmosphere corresponding to the recorded pressure. [m]
206	**Theta E**	The equivalent potential temperature corresponding to the recorded temperature and assuming saturation with respect to liquid water. [K]
207	**Saturation Mixing Ratio**	The mixing ratio of water vapor corresponding to saturation with respect to liquid water at the recorded temperature. [g/kg]
208	**Point dz/dt**	The rate of change of altitude of the aircraft computed by differentiating the pressure altitude with respect to time. This represents an independent estimate of the rate of climb to be compared to tag 105. [m/s]
209	**Indicated Air Speed**	What the airspeed would be if the aircraft were flying at sea level and indicating the observed dynamic presure. [m/s]
210	**Updraft (uncorrected)**	The estimated upward speed of the air relative to the ground computed from changes in the aircraft altitude and other factors, but not corrected for horizontal aircraft acceleration. [m/s]
211	**Calculated TAS**	The true speed of the aircraft relative to the air computed from the observed dynamic and static pressures, and temperature. [m/s]

212	**Updraft Correction Factor**	A correction to the simple (uncorrected) updraft calculation that accounts for horizontal accelerations of the aircraft. [m/s]
213	**Cooper Updraft**	The sum of the uncorrected updraft and the correction factor. [m/s]
214	**Kopp Updraft**	An updraft calculated somewhat differently than the Cooper updraft. In most situations, it yields a less noisy and more physically plausible updraft result for the T-28 than the Cooper method. [m/s]
215	**Geopotential Altitude**	Altitude computed from changes since takeoff in static pressure and temperature. Available for those flights for which GPS altitude was not recorded. [m]
216	**Turbulence**	The turbulent energy dissipation rate estimated from observed fluctuations in true airspeed. [$cm^{2/3}/s$]
217	**Air Density**	Computed from the recorded temperature and static pressure. [kilograms per cubic meter]
218	**J-W Mixing Ratio**	The mixing ratio of cloud water per unit mass of dry air based on the J-W reading and computed air density. [g/kg]
219	**FSSP Mixing Ratio**	The mixing ratio of cloud water per unit mass of dry air calculated from the FSSP water concentration. [g/kg]
220	**Hail Mixing Ratio**	The mixing ratio of hail particles per unit mass of dry air based on the computed hail water and air density [g/kg]

244	**FSSP equivalent J-W Liquid Water**	An estimate of the liquid water concentration the J-W probe should record, based on the observed FSSP droplet spectrum and the assumption that the J-W responds incompletely to droplets larger than 30 µm diameter. [g m^{-3}]
260	**Ambient Vert Electric Field**	The component of the ambient electric field that is vertical in the aircraft frame of reference. Positive means a positive test charge would drift upward relative to the aircraft in the field. [kV/m]
261	**Plane Vert Electric Field**	The field due to charge on the aircraft, computed by summing the readings of the top and bottom mill and normalizing based on self-charging tests. Positive means a positive test charge would be repelled away from the aircraft due to its charge. [kV/m]
262	**Ambient Hor Electric Field**	The ambient field oriented perpendicular to the aircraft along the wings, positive meaning a positive test charge would drift to the right in the field. [kV/m]
263	**Plane Hor Electric Field**	The field due to charge on the aircraft, computed by summing the wingtip mill readings and normalizing. Positive means a positive charge would be repelled away from the aircraft due to its charge. [kV/m]
264	**Ambient Vert Field (roll cor)**	The component of the ambient field that is truly vertical with respect to earth coordinates. [kV/m]
265	**Ambient Hor Field (roll cor)**	The component of the ambient field perpendicular to the aircraft path and truly horizontal with respect to earth coordinates. [kV/m]
272	**Latitude (deg)**	GPS coordinates broken into separate degree and minute components.

273	**Latitude (min)**	GPS coordinates broken into separate degree and minute components.
274	**Longitude (deg)**	GPS coordinates broken into separate degree and minute components.
275	**Longitude (min)**	GPS coordinates broken into separate degree and minute components.
276	**Ground Track Angle (True N)**	The direction of motion relative to the ground with respect to true north, derived from the GPS ground track angle with respect to magnetic north.
341	**Calculated FSSP Total Count**	Observed FSSP total counts with minor corrections made in an attempt to correct for the effects of ice particles on FSSP droplet spectra. Not fully proven. [number per second]
342	**Calculated FSSP Average Diameter**	FSSP average diameter estimated from spectra calculated using the Baumgardner FSSP data reduction procedure.
343	**Calculated FSSP Concentration**	Droplet concentration estimated using the Baumgardner FSSP data reduction procedure. [number per cubic meter]
344	**Calculated FSSP Water**	Liquid water concentration estimated using the Baumgardner FSSP data reduction procedure.
345	**Calculated FSSP Mixing Ratio**	Computed from "calculated FSSP water" (tag 344) and "air density" (tag 217). [g kg^{-1}]
348	**Calculated FSSP Equivalent Diameter**	Computed as for tag 144, but using FSSP spectra derived using the Baumgardner FSSP data reduction procedure. [μm]
349	**Variance of the Calculated FSSP Equivalent Diameter**	Computed as for tag 149, but using FSSP spectra derived using the Baumgardner FSSP data reduction procedure.

APPENDIX F

Descriptions of Summary Plots

[These plots are based on the pass summary Excel worksheet. Note that peak values of one parameter may not have been observed at the same location during a penetration as the peak value of the parameter against which it is being plotted. These plots are useful for looking at general trends in the data, but not for making critical judgements about individual cloud behavior.]

Cloud water maxima vs. Updraft maxima:

> Peak values of cloud water concentration (g m^{-3}) from both the FSSP and J-W probes are displayed against the peak value of vertical wind observed during each penetration. Peak FSSP water concentrations show a general increase with an increase in magnitude of the peak updraft. Values larger than 4 to 6 g m^{-3} are almost certainly suspect, and many of these estimates are probably contaminated by the effects of ice particles producing fictitious droplet counts by the FSSP. The J-W probe does not respond well to larger droplets and some of the disparity between FSSP and J-W estimates for higher updraft penetrations may be due to the presence of a significant fraction of cloud water contained in larger cloud droplets.

J-W cloud water vs. Updraft

> Similar to first plot, but with only J-W cloud water plotted

Peak FSSP cloud water vs. Peak J-W cloud water

> FSSP equivalent diameter (d_{eq}) is used as the plotting symbol in this plot. A generally linear relationship is noted between FSSP and J-W estimates of cloud water concentration, with the FSSP values being consistently higher. The ratio of FSSP to J-W concentrations generally increases with increasing d_{eq}. The high values of d_{eq} along the left hand side of the plot (zero J-W readings) come from penetrations where J-W readings were missing.

Altitude vs. FSSP d_{eq}

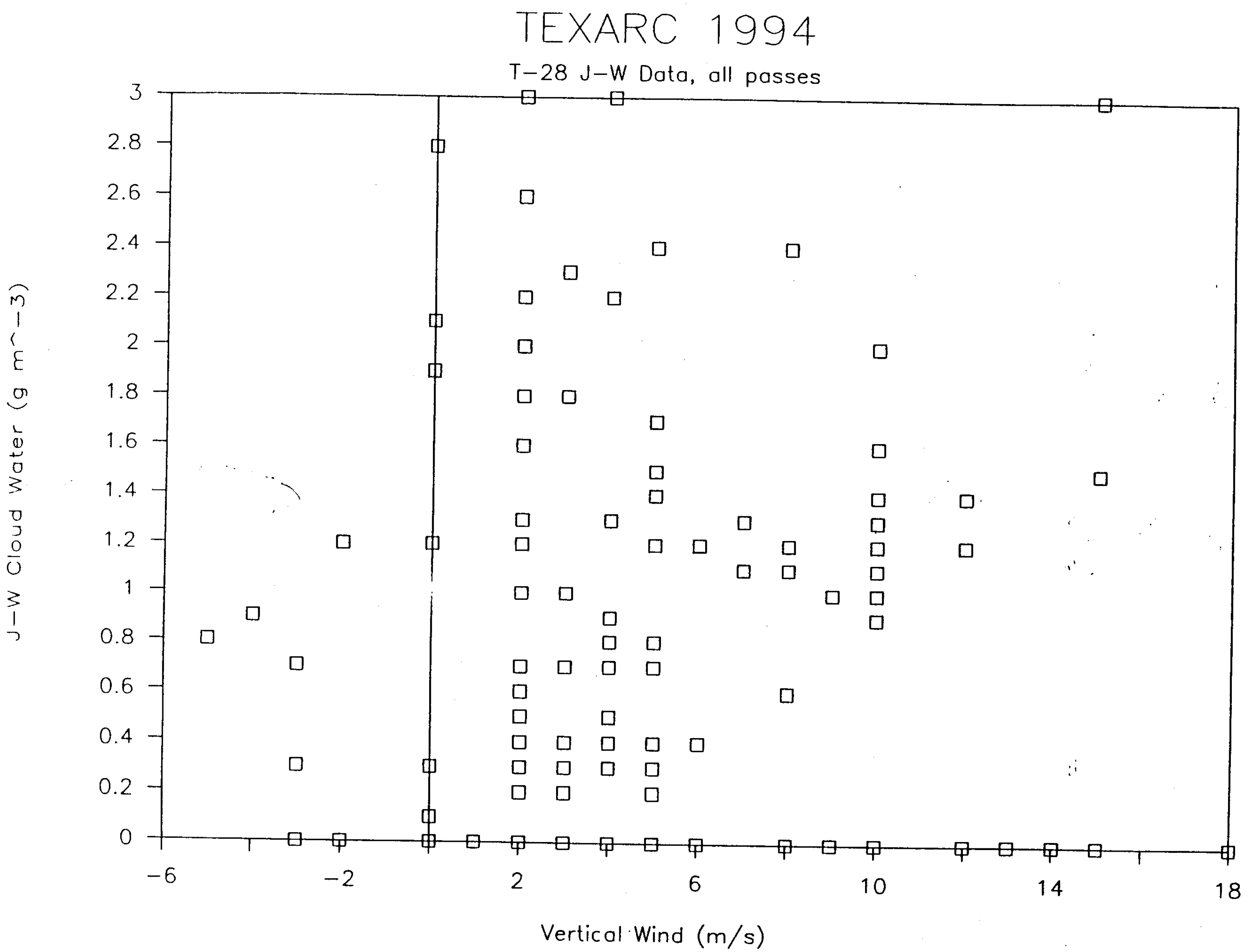
> d_{eq} is seen to increase with altitude, with values of 40 micrometers and higher almost certainly contaminated by the effect of ice particles on FSSP counts.

FSSP Droplet Concentration vs. Peak Updraft

> There is a general trend for increasing droplet concentration with increasing peak updraft speed, although some high droplet concentrations were noted in passes with predominantly downdraft.

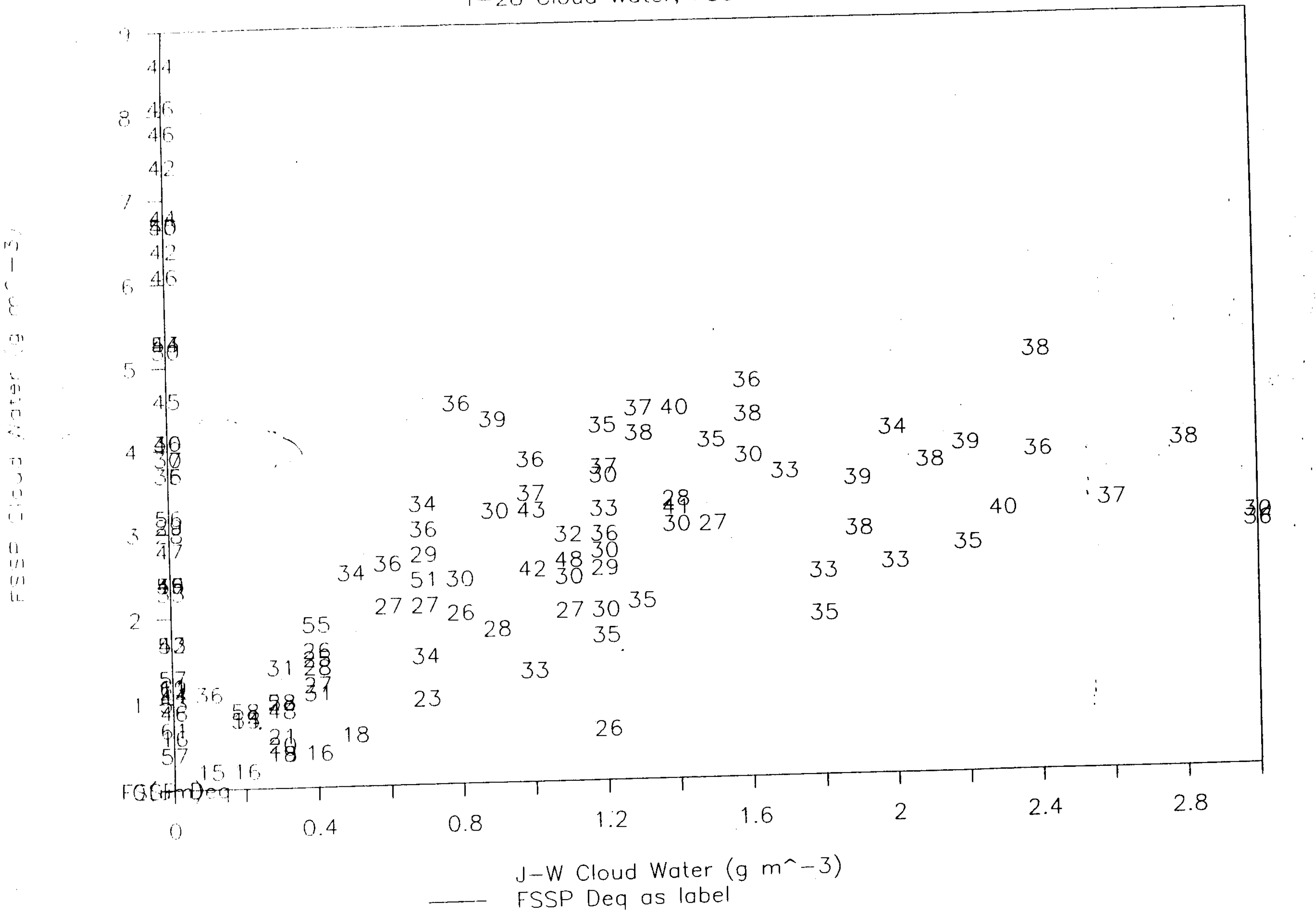
2D-C Shadow/Or concentration vs d_{eq}

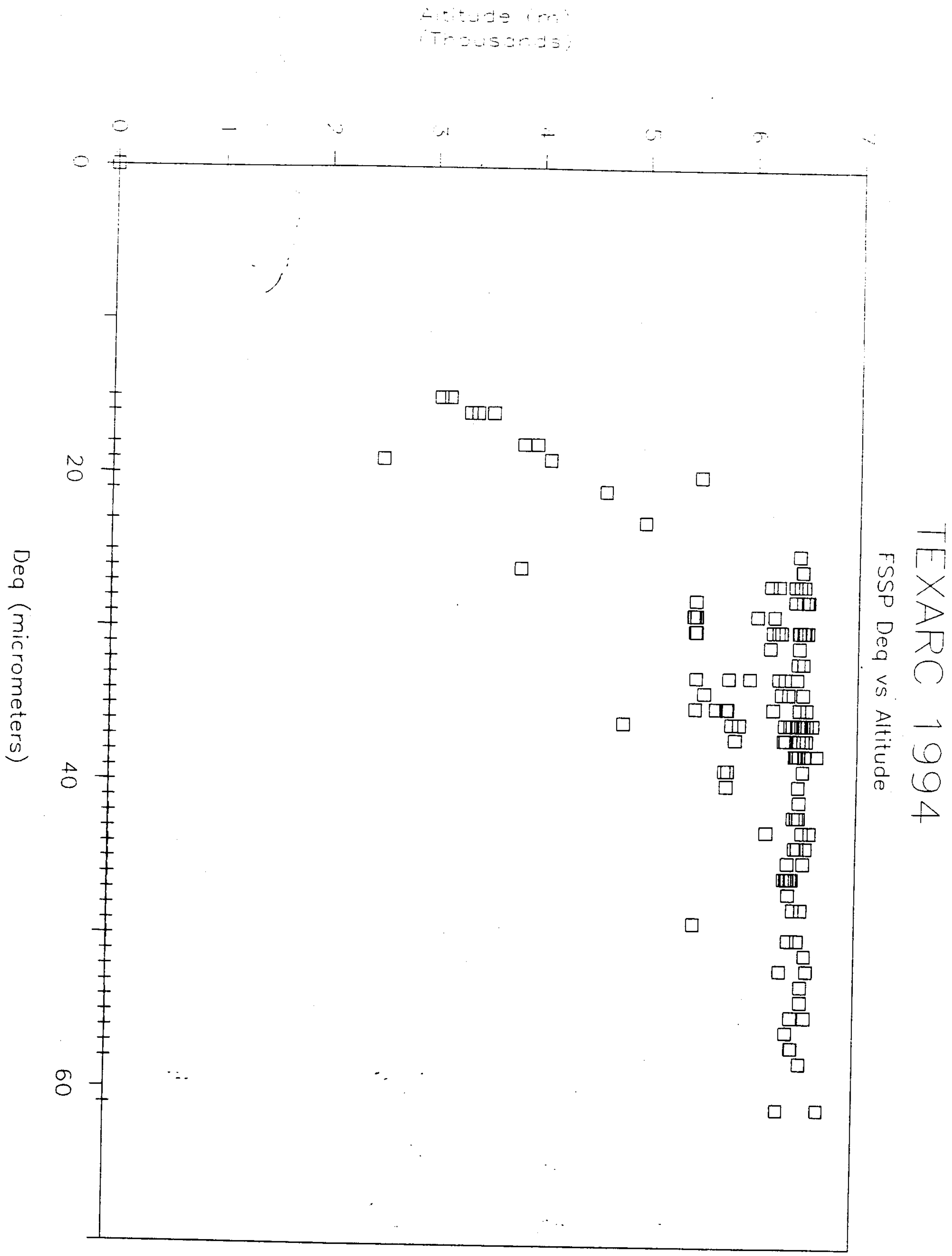
> It is reasonable to assume, for TEXARC clouds, that almost all shadow/or counts are due to ice particles. With this interpretation of shadow/or counts, a clear trend is seen in this plot with higher peak ice particle concentrations associated with higher d_{eq}. This may to some extent be a valid physical relationship among these cloud parameters, but it is also strongly due to the way the FSSP responds to ice particles. It has been shown that ice particles passing through the FSSP intoduce multiple counts equally likely to occur in any of the 15 channels. This results in spurious counts in the upper channels that have a dramatic effect on the computation of d_{eq}.


TEXARC 1994
T−28 J−W Data, all passes
J−W Cloud Water (g m^−3)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−6
−2
2
6
10
14
18
Vertical Wind (m/s)

TEXARC 1994

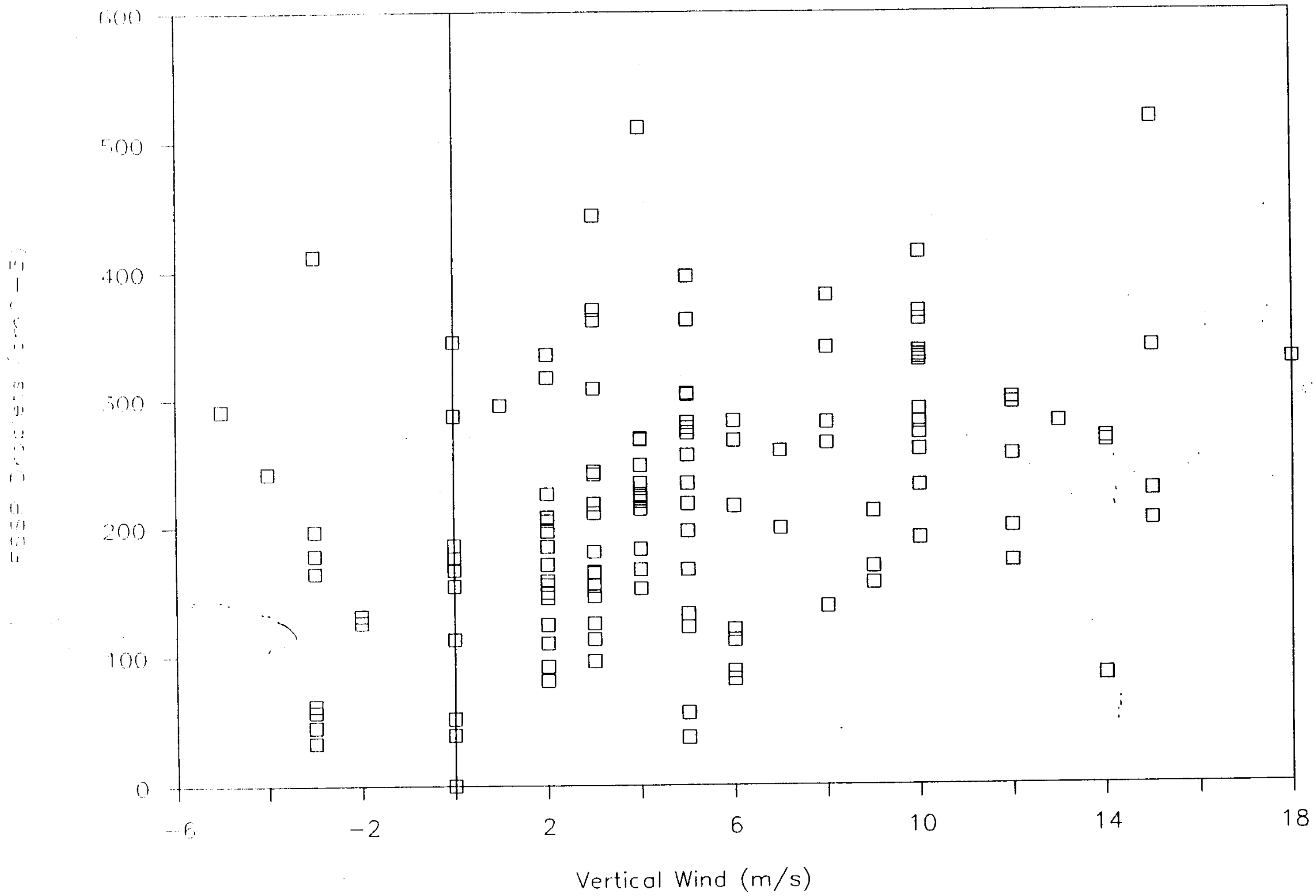
T-28 Cloud Water; FSSP vs. J-W




TEXARC 1994
FSSP Deq vs Altitude
Altitude (m)
(Thousands)
0
1
2
3
4
5
6
7
Deq (micrometers)
0
20
40
60

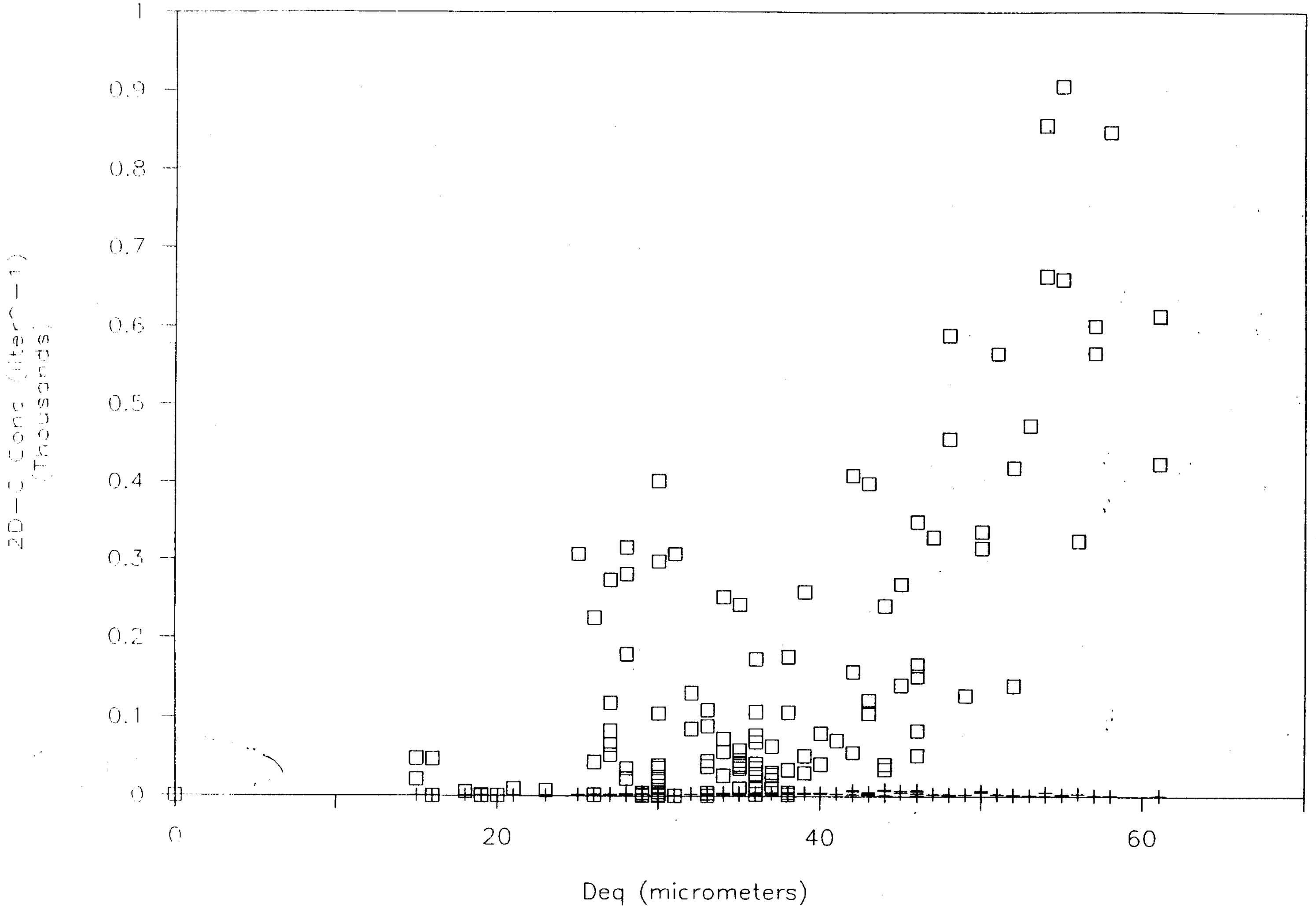
TEXARC 1994

T-28 FSSP Data, all passes



TEXARC 1994

2D-C Concentration compared to FSSP Deq



TEXARC 1994

T-28 Cloud Water Maxes, all passes