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**FINAL REPORT ON THE T-28 ARMORED AIRCRAFT  
DURING THE PERIOD 1 MAR 1975 - 29 FEB 1976**

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## ABSTRACT

This report describes work accomplished on the T-28 project from March 1975 through February 1976. Instrumentation for the T-28 aircraft has been extensively modified in preparation for the planned full research year of 1976.

One of the highlights during the contract period was the successful testing of new instruments on the T-28 during field operations in north-east Colorado in July 1975. Equipment tested included a new recording system, two Knollenberg optical spectrometer probes, a laser hail sensor, and a reverse flow thermometer. A Cannon particle camera was successfully tested following the field season. A complete listing of the instrumentation configuration used during 1975 is provided. Despite the developmental nature of the field work, data gathered in 1975 is of a higher quality than ever before.

Principal accomplishments in analysis of data included work in model comparisons, particle size distributions using data from 1975 and prior years, and short range forecasting of hailstorm development and movement. Work has been initiated on a number of case studies using data from 1975 penetrations. A list of the various analysis tasks is included.

## TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT . . . . .	111
LIST OF FIGURES . . . . .	vii
LIST OF TABLES . . . . .	vii
1. INTRODUCTION . . . . .	1
1.1 Background . . . . .	1
1.2 Objectives . . . . .	1
2. THE T-28 SYSTEM . . . . .	2
2.1 The Aircraft . . . . .	2
2.2 Instrumentation Summary . . . . .	2
2.2.1 Recording systems . . . . .	2
2.2.2 Equipment summary . . . . .	3
3. FIELD OPERATIONS . . . . .	8
3.1 Flight Plans . . . . .	8
4. DATA ANALYSIS . . . . .	12
4.1 Reduction of Data . . . . .	12
4.2 Current Research . . . . .	12
4.2.1 Model comparison (Task 75-1) . . . . .	14
4.2.2 Turbulence and diffusion (Task 75-5) . . . . .	16
4.2.3 Case studies (Tasks 75-7 and 75-10) . . . . .	16
4.2.4 Particle size distributions (Task 75-9) . . . . .	17
4.2.5 Laser hail sensor (Task 75-11) . . . . .	18
4.2.6 Nowcasting (Task 75-13) . . . . .	20
4.2.7 Radar echo characteristics (Task 75-C) . . . . .	22
5. PERSONNEL CHANGES . . . . .	23
ACKNOWLEDGMENT . . . . .	24
REFERENCES . . . . .	25

## TABLE OF CONTENTS (Continued)

	<u>Page</u>
APPENDIX A: Summary of Papers, Reports, and Seminars Prepared During the Contract Period . . . . .	27
APPENDIX B: TABLE B.1: Instrumentation Task Summary . . . . .	29
TABLE B.2: Analysis Tasks in Progress . . . . .	33
APPENDIX C: Summary of NHRE Operational Days - 1975 . . . . .	36
APPENDIX D: List of Personnel Associated with NHRE Project 1 March 1975 - 29 February 1976 . . . . .	38

## LIST OF FIGURES

<u>Number</u>	<u>Title</u>	<u>Page</u>
1	Schematic plan view of a cloud showing the planned penetration track of the T-28 . . . . .	10
2	Vertical section along line N-S in Fig. 1 . . . . .	11
3	Quick recall data as transmitted from Rapid City to Cheyenne over a telecopier . . . . .	13
4	Computed hailstone diameters at the ground as a function of the maximum updraft experienced and the temperature at level of maximum updraft . . . . .	15
5	Sample particle size distribution from Penetration 1 of Flight 80 (9 July 1973) . . . . .	19
6	Sample data derived from observations made with laser hail sensor on 21 July 1975 . . . . .	21

## LIST OF TABLES

<u>Number</u>	<u>Title</u>	<u>Page</u>
1	List of Variables Recorded and Scientific Equipment Used on the T-28 in 1975 . . . . .	4
2	Summary of 1975 Flight Operations . . . . .	9
3	Radar Summary . . . . .	17
B.1	Instrumentation Task Summary, February 1976 . . . . .	29
B.2	Analysis Tasks in Progress, February 1976 . . . . .	33

## 1. INTRODUCTION

### 1.1 Background

This report covers work on the T-28 project during the period 1 March 1975 through 29 February 1976. One highlight during the reporting period was the successful completion of field operations during the period 7 July 1975 to 1 August 1975. Significant developments in T-28 instrumentation were successfully tested during the field season in preparation for the planned full research year of 1976.

The planning and accomplishments of the field operations have been discussed elsewhere (Musil and Sand, 1975; Sand and Musil, 1975), so the T-28 data system and the field operations will merely be summarized in this report for completeness. This report will concentrate on the data analysis and research results pertaining to the T-28 project. A list of papers and reports written and seminars given during the contract period is included as Appendix A.

### 1.2 Objectives

The T-28 has been developed for the general objective of gathering data from the interior of hail-bearing thunderstorms. The specific objectives for the year were:

1. To test the T-28 system during the summer of 1975 in preparation for the planned full research year of 1976.
2. The measurement and analysis of the total water content of hailstorms in terms of distribution with particle size and phase.
3. A preliminary investigation of T-28 data for detection of possible seeding effects.

Many of the objectives stated in previous reports (e.g., measurement of vertical motions, composition of high reflectivity zones, ice water budgets) are still considered valid; however, the specific objectives listed above are refinements of earlier, more general, objectives.

## 2. THE T-28 SYSTEM

### 2.1 The Aircraft

The aircraft performed very well during the reporting period. The actual operations included testing and calibration flights prior to the field season, research flights during the season, and more test flights with the Cannon camera system after the field season.

Most of the maintenance accomplished on the aircraft during the reporting period was preventive. Normal maintenance and FAA required inspections were performed as necessary. Five cylinders were replaced with overhauled units with new cooling fins. All but three cylinders have now been replaced since the 1973 field season. On 31 July the propeller deicing boots worked themselves loose during a research flight. These were replaced by the IAS mechanic following the 1975 field season.

### 2.2 Instrumentation Summary

The T-28 instrumentation was greatly improved during the reporting period. Various new equipment, including a new recording system, was added, all of which provided more interesting data of a higher quality than ever before.

#### 2.2.1 Recording systems

A Precision Instruments data recorder and a Monitor Labs multiplexer are now used as the primary recording unit on the T-28. The recorder uses computer compatible seven-track magnetic tape and records all variables at least once per second. Some variables are recorded twice each second to provide the sampling rate necessary for certain types of analysis such as turbulence calculations. The recording system functioned reliably during the field season, although some grounding problems caused difficulties in recording accurate data. These problems introduced a bias in all data channels which was different in the record and monitor modes and seemed to change with the addition of various instruments prior to the beginning of the season. The system appeared to remain stable during the season, however, so a bias correction could be applied following the field season. Additional work has been done to eliminate the biasing problem prior to the 1976 field season.

A secondary recording system had been planned for inclusion on the T-28 prior to the 1975 field season; however, weight problems with some of the new equipment necessitated the removal of the secondary recorder. In its place a telemetry package was used to permit backup recording of data at the base station at Cheyenne.

An additional recorder, which was part of the Knollenberg probe system (see Sec. 2.2.2) was carried during 1975 because the quantity of data from these probes far exceeds the available capacity of our primary system. Some of the other variables measured by the T-28 are also recorded on the Knollenberg recording system, as well as on our primary system.

An audio tape recorder was carried to record the pilot's comments, hail sounds on the windshield, and all incoming and outgoing radio transmissions.

### 2.2.2 Equipment summary

A list of the variables recorded and the scientific equipment used on the T-28 during the contract period is given in Table 1. An asterisk in the variable column denotes new or greatly modified equipment. Sand et al. (1975) give a detailed description of these pieces of equipment.

Equipment performance was generally good. A summary of T-28 operations during the 1975 field season, which describes the performance of some of the pieces of equipment, can be found in Sand and Musil (1975). Information describing the various pieces will not be repeated in this report; however, some of the remaining problems bear repeating at this point. These are problems which need additional work prior to the 1976 field season. Table B.1 in Appendix B gives a current status report of the instrumentation tasks underway for the 1976 season. The following paragraphs amplify some of the more important tasks.

*Cannon Camera.* The Cannon camera came in overweight and could not be tested on the aircraft during the 1975 research flights. Apart from the weight problem, the aircraft would have had to be placed in an inoperative mode for three to six days for installation of the system. The camera system was installed and tested after the regular season during flights in the Rapid City area. Those flights were accomplished in clouds containing only ice crystals, but the system did appear to work properly.

*Knollenberg Probes.* The Knollenberg system worked well during the summer field season; however, the data from the 2-D probe are too ambiguous to permit the "hoped for" distinction between ice and water. Nevertheless, many valuable and interesting data on particles inside hail-bearing clouds were gathered and are being analyzed.

Two problems which occurred intermittently during the field season were a data rate selection problem and the shedding of water from the nose of the two-dimensional probe. The data rate selection errors



TABLE 1

List of Variables Recorded and Scientific Equipment  
Used on the T-28 in 1975

<u>Recorder Data Channel</u>	<u>Variable</u>	<u>Equipment Used</u>
--	Time	Primary data system internal master clock
0	Pressure Altitude*	Rosemount Model 1301-A-4-B temperature controlled absolute pressure transducer; output amplified x 10 for rate-of-climb calculations
1	Indicated Airspeed*	Rosemount Model 1301-D-1-B temperature controlled differential pressure transducer
2	Instantaneous Acceleration*	Humphrey Model SA09-D-0101-1 vertically stabilized accelerometer
3	Pressure Altitude*	Rosemount Model 1301-A-4-B temperature controlled absolute pressure transducer
4	Pressure Altitude	Ball Model EX-210-B absolute pressure transducer
5	Temperature	Rosemount Model 102AU2AP total temperature probe
6	Temperature*	NCAR reverse flow probe
7	Rate-of-climb	Ball Model 101A variometer
8	Manifold Pressure	Giannini Model 45218YE pressure transducer
9	Heading*	IAS designed device to enable recording of aircraft heading from gyrocompass
10	VOR Bearing	MetroData Systems, Inc., M-8 used to record from Narco MK-12 VOR receiver

TABLE 1 (Continued)

<u>Recorder Data Channel</u>	<u>Variable</u>	<u>Equipment Used</u>
11	DME Distance	MetroData Systems, Inc., M-8 used to record from a Narco UDI-2ARD DME unit
12	DME Distance*	MetroData Systems, Inc., M-8 used to record from a Narco UDI-4 DME unit
13	Liquid Water Concentration	Johnson-Williams liquid water concentration probe
14	Icing Rate	Rosemount Model 871 BG icing rate probe
15	True Airspeed*	NCAR designed true airspeed computer
16	Pressure Altitude	Same as Channel 3
17	Aircraft Pitch Angle*	Humphrey Model SA09-0101-1
18	Aircraft Roll Angle*	Humphrey Model SA09-0101-1
19	Pressure Altitude	Same as Channel 0
20	Indicated Airspeed	Same as Channel 1
21	Instantaneous Acceleration	Same as Channel 2
22	Positive Peak Acceleration*	Humphrey Model SA09-D-0101-1 vertically stabilized accelerometer
23	Negative Peak Acceleration*	Same as Channel 22
24 BCD digits	Hail Sensor*	IAS designed laser hail sensor to detect, size, and count hailstones

TABLE 1 (Continued)

<u>Recorder Data Channel</u>	<u>Variable</u>	<u>Equipment Used</u>
3 BCD digits	Event Codes (9)	IAS designed digital event codes
3 BCD digits	Frame Count*	Frame counter for Cannon particle camera
--	Hydrometeors	Williamson Aircraft Company continuous hydrometeor sampler (foil impactor; 0.25 mm - 20 mm dia.)
--	Precipitation	NCAR designed precipitation sampler to gather samples for laboratory analysis
--	Voice Recorder	SONY audio tape recorder (2-channel) 1) Pilot's comments 2) Hail impact sounds
--	Hydrometeors*	Two Knollenberg optical array spectrometer probes 1) OAP-2D (25-800 $\mu$ m dia.) 2) ASP-100 (2- 30 $\mu$ m dia.)
--	Hydrometeors*	Cannon particle camera
--	Visual Cloud	Super 8-mm movie camera with automatic exposure and remote control

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\*Denotes new or greatly modified equipment.

caused the tape occasionally to fill prematurely, before any cloud was penetrated. There was no way to determine how much tape had been used from the cockpit, so this problem went undetected until after the mission. The shedding problem caused some elongated particle images in the data. Some changes were made by addition of washers on the probe heads which directed the water away from the sampling volume. Both these problems still exist and are being worked on by various participants in the NHRE program.

*Laser Hail Sensor.* The hail sensor was flown on five of the nine research flights during 1975 and produced good data on one flight. The concept seems sound and the design good. Water was found in the electronics following several of the flights on which the instrument did not work. Additional work to seal the sensor pods is necessary prior to the 1976 field season. The instrument shows enough promise to justify continued development and use in future seasons.

In general, the instrumentation on the T-28 is now fairly complete. The present goal is improved performance in future years, with only minor modifications being made to the equipment.

### 3. FIELD OPERATIONS

#### 3.1 Flight Plans

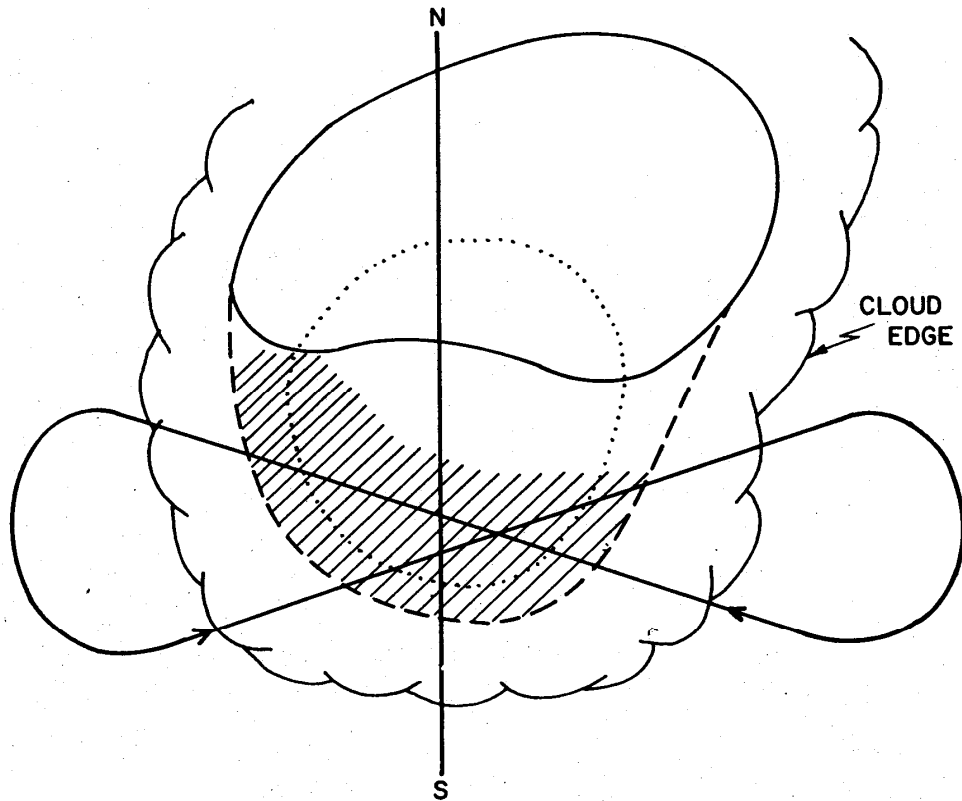
The T-28 participated in the 1975 NHRE field season, which covered the period 7 July 1975 through 1 August 1975. As mentioned previously, the 1975 field season was set up to test newly acquired and developed instrumentation in various thunderstorm environments. The number of flights and the days on which they occurred are shown in Table 2. Also included is pertinent information about the status of various recording systems used on the aircraft.

Two basic flight plans were designed for use during the 1975 field season, one pertaining to penetrations of isolated cloud cells or cloud clusters and the other to penetrations of squall lines. No squall lines occurred during the field season, so all penetrations were in the former type. The procedure used for cloud cells or cloud clusters is shown in a plan view (Fig. 1) and in a vertical section through a portion of that plan view (Fig. 2). This procedure was set up so that it could be used with either multicell storms or supercell storms, since real-time identification is often difficult. No supercells occurred during the field season so all penetrations were in multicell storms. Penetration emphasis was given to attempting to identify a cell early in its lifetime and making several penetrations through it as it matured. This was accomplished reasonably well but required much coordination between the T-28 pilot and the meteorologist located at Grover. Early penetrations usually had to be started visually by the pilot, while later penetrations were vectored from the site at Grover.

The general procedure was to penetrate the storms near the weak echo region with emphasis on quick turn-arounds so as to make as many penetrations as possible at a single level (near 6 km MSL) on a given flight. Safety was considered to be of primary importance during any of the penetration procedures. In that regard, regions with equivalent radar reflectivity factors ( $Z_e$ ) greater than 55 dBz at or above the level of penetration were avoided. This criterion apparently worked quite well as the largest hail encountered during the season was about 2.5 cm in diameter. More caution was exercised early in the season because of uncertainties concerning the radar data, but as more confidence was gained penetration procedures became quite routine and many data useful for analysis purposes were gathered. In fact, the 1975 data are felt to be of the highest quality ever gathered by the T-28 system.

TABLE 2  
Summary of 1975 Flight Operations

Flt. No.	Date	Time (hr)	Penet.	Approx. Research Data Time	PI Tape	Partec Tape	Voice Tape	TM Tape	Remarks
101	4-18	1.0							Maintenance test
102	4-21	1.5							Maintenance test
103	4-22	0.9							Maintenance test
104	4-23	1.8							Vibration analysis and
105	4-24	1.3							gear retraction tests at Jefco
106	4-24	1.2							
107	5-13	1.3							Install encoding altimeter and
108	5-14	1.4			Yes				calibrate VOR/DME system at Cheyenne
109	6-3	0.8			Yes				Instrument test
110	6-4	1.5							Flight check Knollenberg gear and
111	6-7	0.8							Cannon camera at Jefco
112	6-7	1.5							
113	6-13	1.2			Yes		Yes		Instrument test
114	6-24	1.2			Yes	Yes	Yes		Instrument test
115	6-26	1.7			Yes	Yes	Yes		Instrument test and radar track
116	6-26	1.2							test with Grover radar
117	7-6	2.0		1600	Yes		Yes		Ferry A/C to Cheyenne
118	7-7	1.8	7	1700	Yes	Yes	Yes	Yes	Research
119	7-11	1.0	1	1900- 2000	Yes	Yes	Yes	Yes	Instrument test/research
120	7-13	1.9			Yes	Yes	Yes	Yes	Instrument test
121	7-14	1.9	6	1425- 1620	Yes	Yes	Yes	Yes	Research
122	7-15	1.8	5	1500- 1645	Yes	Yes	Yes	Yes	Research
123	7-16	1.9	5	1630- 1815	Yes	Yes	Yes	Yes	Research
124	7-18	1.0			Yes	Yes			Calibrate Pressure Instruments at Laramie
125	7-21	1.9	5	1540- 1730	Yes	Yes	Yes	Yes	Research
126	7-22	2.2	4	1530- 1740	Yes	Yes	Yes	Yes	Research
127	7-23	1.8	5	1430- 1620	Yes	Yes	Yes	Yes	Research
128	7-29	2.1			Yes	Yes	Yes	Yes	Tower fly by
129	7-30	1.6	5	1745- 1920	Yes	Yes	Yes	Yes	Research
130	7-31	1.6	5	1500- 1635	Yes	Yes	Yes	Yes	Research
131	8-1	1.9			Yes	Yes	Yes	Yes	Aircraft track system calibration
132	8-1	1.7							Ferry A/C to Rapid City
133	8-20	0.7							Maintenance test
134	10-3	0.9							Maintenance test
135	10-15	1.1			Yes	Yes	Yes		Cannon camera test
136	10-17	1.2			Yes	Yes	Yes		Cannon camera test
137	10-23	0.8			Yes		Yes		Cannon camera test
138	12-5	0.9			Yes		Yes		Cannon camera test
139	12-5	0.3							Air flow tests for Knollenberg probes
140	12-9	0.7			Yes		Yes		Air flow tests for Knollenberg probes
<b>Totals</b>									
Total Number of Flights							40		
Total Aircraft Hours							55		
Total Number of Cloud Penetrations							48		



2496

Fig. 1. Schematic plan view of a cloud showing the planned penetration track of the T-28. The dotted line encloses the extent of the updraft and the solid line shows the radar echo at penetration level. The dashed line shows the extent of the intense echo at some level above flight altitude (i.e., above weak echo region). The hatched region shows the region of interest for the penetrations.

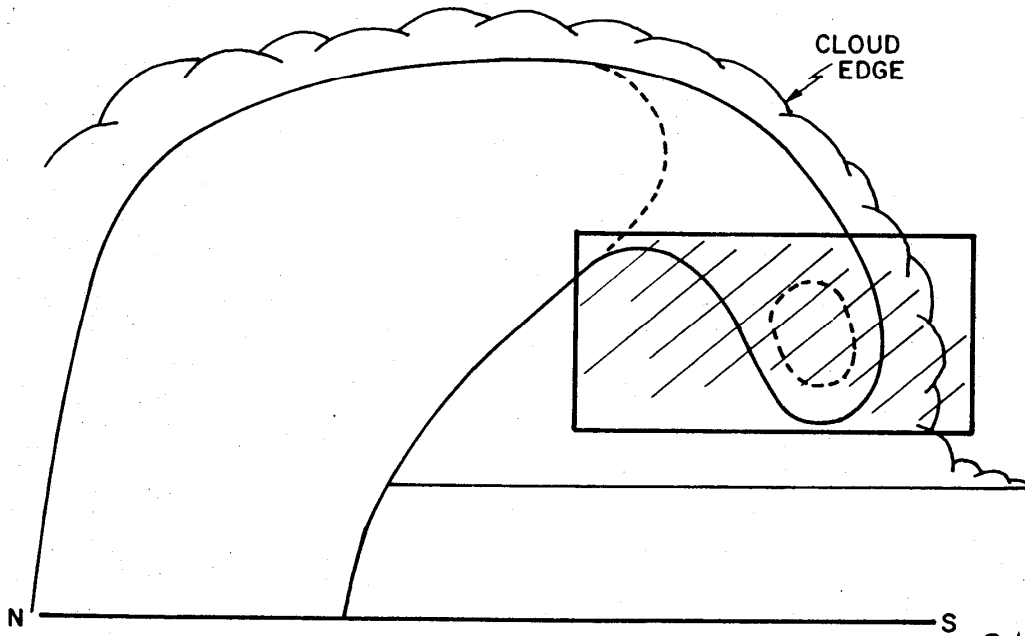


Fig. 2. Vertical section along line N-S in Fig. 1. The hatched region shows the region of interest for the T-28 penetrations. If the storm is a supercell type, the overhang region represents the embryo curtain. If the storm is a multicell type, the dashed lines denote the radar echo, with the dashed line inside the region of interest illustrating first echo formation in a new cell.

### 3.2 Summary of Operational Days

A summary of impressions of the operational days during the 1975 field season recorded by the project meteorologist at Grover is provided in Appendix C. Included is a ranking of the storms, which is in general agreement with the impressions of all personnel concerned with the operations. Case studies have been initiated for the first five days on the list, and although specific results are not generally available at this time, some results will be covered in Section 4 along with a discussion of other analysis tasks.



#### 4. DATA ANALYSIS

##### 4.1 Reduction of Data

Two data reduction modes are used on the T-28 project. The first is a quick recall mode whereby "first look" reduced data can be quickly returned to the people involved with the field project and used for quality control purposes; the second is reduction into a form amenable to detailed analysis following the field season.

During 1975 plans called for recorded data to be sent to Rapid City via telephone lines for the quick recall reduction, with the products shipped back to Cheyenne by Xerox telecopier for use by field personnel. This could not be accomplished because the secondary recorder on the T-28 had to be eliminated and it had the only data format suitable for telephone line transmission. The next plan was to send telemetered data directly over phone lines to the computer at Rapid City, but due to phone line problems this could not be done either. The method finally used was to ship the data tapes from the primary recording system by bus to Rapid City during the evening. The tapes were processed and the analog traces transmitted back to Cheyenne via telecopier the following morning. This method was successful in that no tapes were lost enroute and the data were normally provided for field personnel in less than 24 hours. In fact, an unplanned advantage resulted because the telemetry system would have allowed only 16 of the 24 data channels to be transmitted.

A sample of the returned quick recall data is shown in Fig. 3. In addition to use for quality control purposes, the data can be used for limited analysis purposes during the field project.

The normal data reduction following the field project is rather typical with the measured variables being plotted as a function of time in much the same format as shown in Fig. 3. However, there are fewer restrictions in the data plots, and single variables or combinations of variables can be selected and the plots presented in colors for ease of use.

##### 4.2 Current Research

Analysis tasks currently in progress or proposed for the T-28 project are summarized in Table B.2 of Appendix B with indications of the current status of each task. The table is subject to modifications on the basis of discussions within the IAS and with NHRE personnel. The analysis tasks were outlined to help guide our research activities following the 1975 field project. Although no priority system is

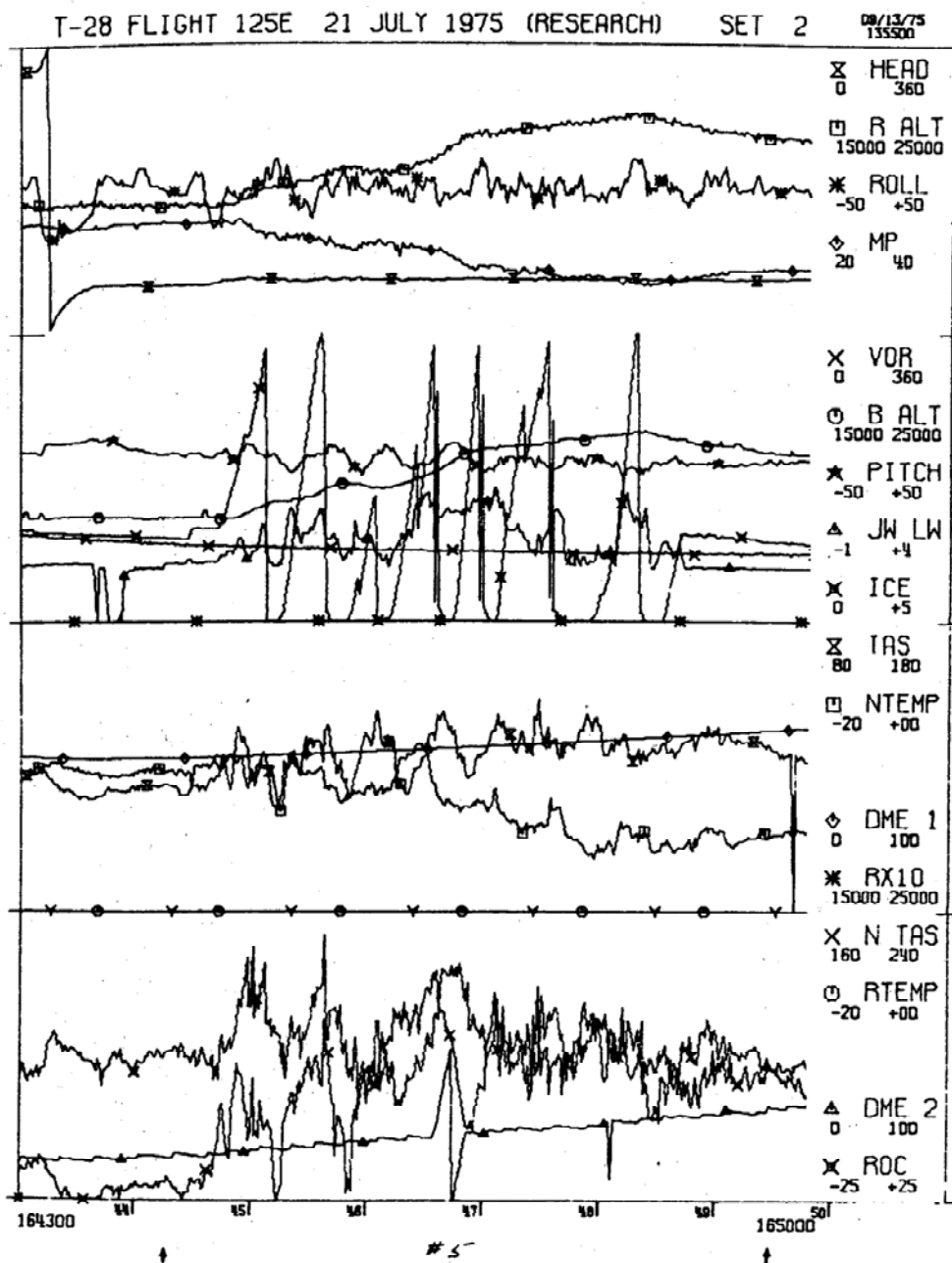


Fig. 3. Quick recall data as transmitted from Rapid City to Cheyenne over a telecopier. Data are from Penetration 4 on 21 July 1975.

indicated designating which tasks shall be performed first, priorities are, in effect, being established as people study the various tasks. Those tasks which are very active at this time are discussed in greater detail in the remainder of this section.

#### 4.2.1 Model comparison (Task 75-1)\*

One of the topics discussed at the NHRE Symposium/Workshop (NHRE, 1975) was the applicability of numerical modeling to the forecast and analysis problems of NHRE. The primary use of models is twofold: one is to forecast hail at the ground as a function of conditions developed by the model, which can be based on radiosonde soundings in the NHRE area. The second use of the models would be in predictions of hail, after the fact, as an aid in the evaluation of the NHRE randomized seeding experiment. If the models can establish certain predictors of hail with a fair degree of confidence, the results can be used to help account for the high natural variability inherent with hail events.

Recent studies by Sulakvelidze *et al.* (1967), Dennis and Musil (1973), and in unpublished Canadian work by B. Maxwell have shown that the vertical velocity maximum and the temperature at which it occurs provide a quite reliable predictor of the largest hailstone sizes from a given set of conditions. For instance, Dennis and Musil used appropriate radiosonde soundings in the steady-state Hirsch model (Hirsch, 1971) to obtain the vertical velocities and temperatures. These parameters were then used in a nomogram (Fig. 4) to determine the expected maximum hailstone size for those conditions. A comparison between the maximum observed hailstone diameter and the maximum diameter determined from the model resulted in a correlation coefficient of 0.76, suggesting that there is some justification for using the combination of the Hirsch model and the nomogram by Dennis and Musil to predict hailstone sizes in advance or to aid in the analysis of the suppression experiment.

Appropriate cloud top data to be fit to the Hirsch model in order to obtain vertical velocity and temperature profiles for use in the Dennis and Musil nomogram for hailstone sizes can be obtained from analysis of NHRE radar data. To pursue this idea further, reduction of the 1974 NHRE CP-2 radar data has begun. Initial plans called for using the 1972 and 1973 radar data also, but problems with the NHRE radar data reduction for those years have minimized this prospect.

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\*Task numbers are keyed to Table B.2 of Appendix B.

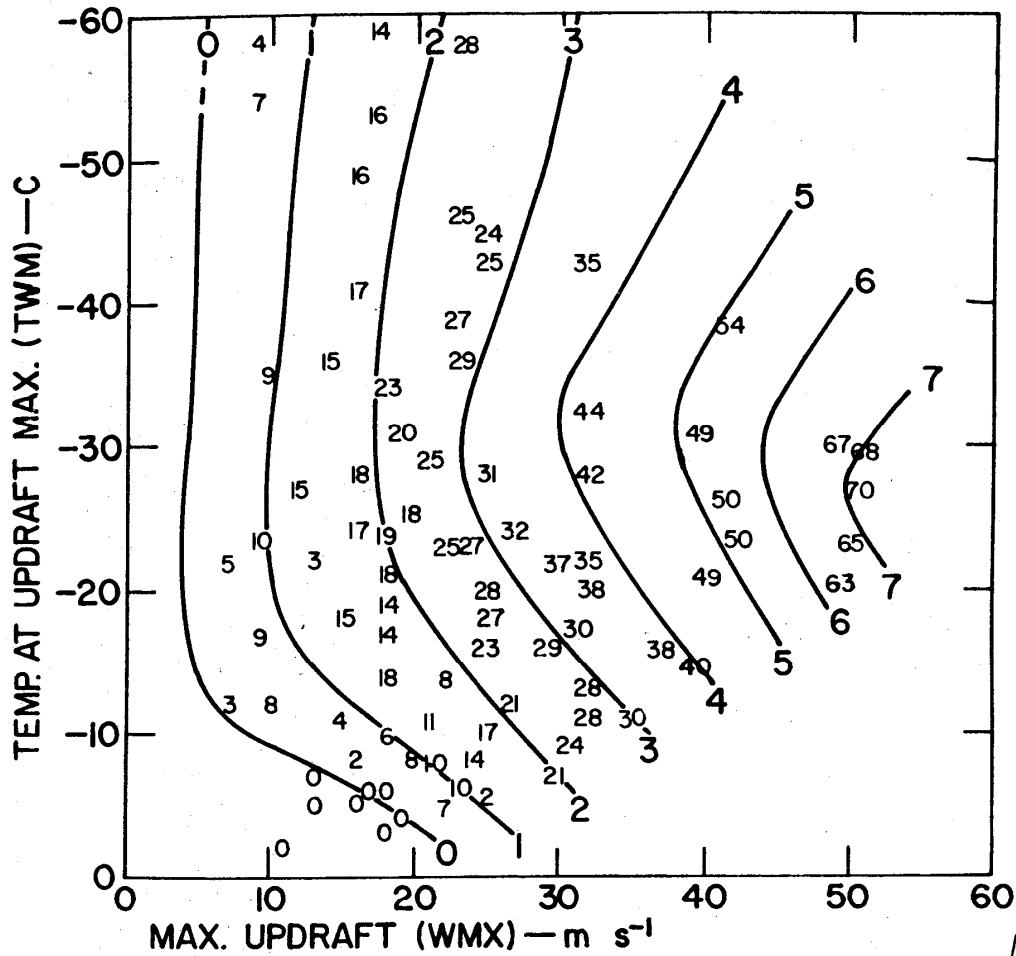


Fig. 4. Computed hailstone diameters at the ground as a function of the maximum updraft experienced and the temperature at level of maximum updraft. Diameters of solid particles at ground are plotted in millimeters for all model runs. Isopleths of computed hailstone diameter are fitted by eye and labeled in centimeters.

The method used is to search the radar data to determine maximum echo heights at various times when activity was present in the NHRE experimental area. At present, data from 7 of the 15 days that are available from 1974 have been reduced and reduction is continuing. After completion, the Hirsch model will be fit to the observed tops and the maximum updrafts and appropriate temperatures will be obtained. Since the storms were in the NHRE experimental area, a rather large data base of hailstone observations at the ground will be available, which can be compared with the sizes predicted from the model.

#### 4.2.2 Turbulence and diffusion (Task 75-5)

A paper on this subject by Sand *et al.* (1976) has been accepted for presentation at the International Weather Modification Conference. The paper will deal with the calculation of the turbulent energy dissipation rates ( $\epsilon$ ) from airspeed fluctuations and use of the results to calculate the diffusion of seeding material due to that turbulence. Fast Fourier Transform (FFT) analysis of the airspeed data is used to derive the appropriate turbulence variables. A 16-point FFT algorithm, with data samples at approximately 0.5-second (50-meter) intervals, provides values of the turbulent energy spectrum over the wavelength range from about 0.1 to 1 km. The results generally conform to the  $-5/3$  power law characteristic of the inertial sub-range, and we assume that the wavelengths significant in the dispersion of seeding material also fall within this range. Preliminary indications are that the dissipation rate at 7 km MSL is about ten times the value normally observed at cloud base. The diffusion calculations are being made by Wayne Sand.

#### 4.2.3 Case studies (Tasks 75-7 and 75-10)

The five best penetration days from the 1975 field season (see Appendix C) have been assigned to various people for analysis using a case study approach. Tasks 75-7(a-d) pertain to days 23 July 1975 (Musil), 16 July 1975 (Knight), 22 July 1975 (Sand), and 31 July 1975 (Heymsfield), respectively. People named in parentheses are responsible for leading the analysis. Study of these cases is just now being initiated, and plans call for a meeting prior to the 1976 field season to discuss individual results and to make plans for further work.

An abstract for the case study associated with 21 July 1975 (Task 75-10) has been accepted for presentation at the International Cloud Physics Conference in July 1976 (Dennis *et al.*, 1976). Analysis to date has consisted of reviewing the radar data for 21 July 1975, including such things as the identification of various cells, heights of first echoes, maximum echo heights, etc. These results are included as Table 3. Data from the foil impactor, laser hail sensor (see

TABLE 3  
Radar Summary

<u>Cell</u>	<u>Time of First Echo (MDT)</u>	<u>End of Cell (MDT)</u>	<u>Duration (min)</u>	<u>Height of First Echo (km MSL)</u>	<u>MEH (km MSL)</u>	<u>Remarks</u>
1	1551	1626	35	7.5	13.2	DSPTD
1A	1601	1613	12	8.8	11.8	Merged with 1
2	1606	1654	48	8.3	13.2	DSPTD
2A	1611	1626	15	8.3	11.6	Merged with 4
3	1611	1627	16	7.2	11.8	Merged with 4
4	1617	1644	27	8.3	12.5	Merged with 2
5	-1627	1651	24	NA	11.5	Merged with 6
6	1640	1720	40	-6.7	13.8	DSPTD
7	-1630	1731	61	NA	14.3	Merged with 8
8	1703	1802	59	7.5	13.7	DSPTD

Sec. 4.2.5) and Doppler radar are being analyzed and will be available as input into the case study. Analysis of Knollenberg data for this date has been accomplished primarily by NHRE personnel and is not discussed in this report.

#### 4.2.4 Particle size distributions (Task 75-9)

Past analysis of foil impactor data (May, 1974; Musil *et al.*, 1976) has shown the commonly observed exponential distributions of precipitation particle sizes. However, when particles larger than about 5 or 6 mm diameter were present, two exponential functions are usually required to describe the distributions. The intercept parameters are generally lower than those for the Marshall-Palmer distribution, and the slopes are also different for the smaller sizes.

The current study deals with problems encountered in the analysis of sample precipitation particle size distributions. A common practice is to apply linear regression analysis to a plot of the distribution on semilogarithmic scales. Sample data, however, tend to be so arranged that problems are encountered at both the small-diameter end, where a roll-off in number concentrations is sometimes observed, and the large-diameter end, where sampling volume limitations cause difficulties. The regression line found will vary according to the way these difficulties are handled in the analysis.

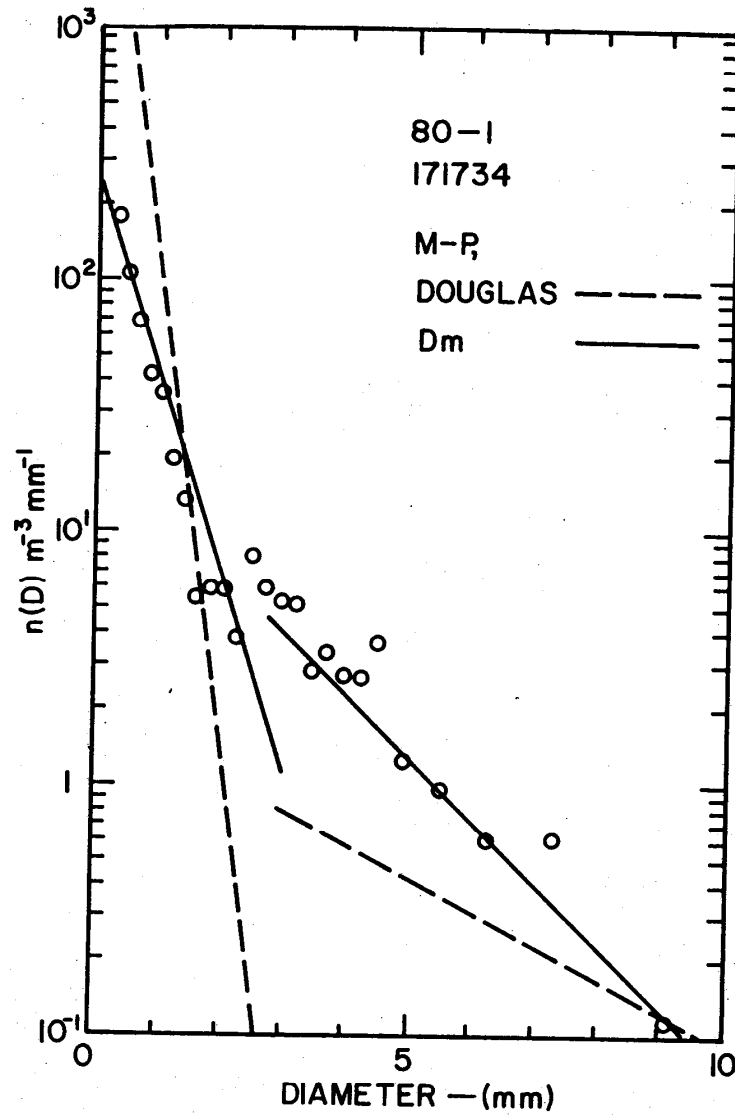
It would seem better to establish a data fit line using some other device. Marshall and Palmer found that raindrop size distributions could be represented by the function  $n(D) = n_0 \exp(-AD)$  where the intercept value ( $n_0$ ) is a constant. Numerous other observers have found that  $n_0$  is not constant (e.g., Waldvogel, 1974), an observation borne out by T-28 foil impactor data (May, 1974). By derivation from the general exponential function given above, it can be shown that the mass weighted mean diameter of an exponential particle size distribution is  $D_m = 4/A$  where  $A$  is the slope of the distribution. Furthermore, since  $n_0 = WA^4/\rho\pi$ , where  $W$  is the precipitation concentration and  $\rho$  is the density, we have two variables that provide a way of estimating the parameters of a best fit line to given sample data. This technique, which is a variation of that developed by Waldvogel (1974), has been successfully applied to some of the foil impactor data obtained in 1973. Separate functions can be obtained for small particles (less than 3 mm in diameter) and large particles (larger than 3 mm) (Fig. 5). Although controversy remains with respect to the phase (liquid or solid) of the particles observed by the foil, this is not critical to the analysis described here.

Work continues on the best way to divide the precipitation between the large and small size categories. Tests are being conducted using different methods of plotting the size distribution functions, but the fits appear to be significantly better than those determined using Marshall-Palmer or Douglas values of the parameters in the size distribution functions.

Further work will involve application of the  $D_m$  technique for use in cloud modeling to replace the assumption of a constant intercept. In other words, both  $n_0$  and  $A$  can vary according to the precipitation water concentration of the distribution. The work described above is a Master's thesis project which is scheduled for completion in May 1976.

#### 4.2.5 Laser hail sensor (Task 75-11)

The optical design of an airborne laser hail sensor was presented in past thesis research (Shaw, 1974). The developmental effort in 1975 resulted in an instrument which was flown and tested on the T-28 for the first time during the 1975 NHRE field season with apparently good data collected for the 21 July 1975 case. The development of the hail sensor and the analysis of the data gathered on 21 July 1975 are being used for an M.S. thesis scheduled for completion in May 1976. Results from this study and from Task 75-9 (see Sec. 4.2.4) are being combined and will be presented at the International Cloud Physics Conference in July 1976 (Smith *et al.*, 1976).



2634

Fig. 5. Sample particle size distribution from Penetration 1 of Flight 80 (9 July 1973). Solid lines represent distribution functions according to  $D_m$  for small diameters ( $<3 \text{ mm}$ ) and large diameters ( $>3 \text{ mm}$ ). Dashed lines correspond to Marshall-Palmer (small sizes) and Douglas (large sizes) distributions.



The study involves analyzing the particle size distributions from the hail sensor for calculations of hail mass concentration, total number concentration of particles, and hail radar reflectivity factors (Fig. 6). Preliminary calculations show reflectivity factors somewhat higher than were measured by the NHRE CP-2 radar, but the results thus far show good correlation of the hail sensor data with the radar data and with the pilot's verbal comments made during Flight 125. The  $D_m$  technique (see Sec. 4.2.4) is also being used here to fit exponential size distribution functions to the observations.

Results thus far have shown hailstone number concentrations up to about  $20 \text{ m}^{-3}$  and hail mass concentrations up to about  $5 \text{ g/m}^3$  in Flight 125. The maximum size hailstones encountered were 2.5 cm in diameter.

#### 4.2.6 Nowcasting (Task 75-13)

One of the topics under discussion at the NHRE Symposium/Workshop (NHRE, 1975) was the problem of short range forecasting ("nowcasting") of hailstorm development and movement. A major problem in operating a hail suppression project is to get the seeding agent to the target area before a dangerous hail situation can develop. If the potential is present, cumulus clouds develop rapidly into hailstorms. Therefore, seeding aircraft must be dispatched to the site of the potential hailstorm before regions of rapidly increasing radar reflectivity are identified. Nowcasting is an attempt to pinpoint the regions where hailstorm development is likely one or two hours in advance.

This task concentrates on surface wind and moisture fields developing prior to appearance of identifiable precipitation echoes to see if recognizable convergence patterns form well enough ahead of a hailstorm to be used as a forecasting tool. The effects of wind and moisture are combined in the continuity equation for vapor density:

$$\frac{\partial \rho_v}{\partial t} + \nabla_h \cdot \rho_v \vec{V} - S = - \frac{\partial}{\partial z} (\rho_v w) \quad ,$$

where  $\rho_v$  is vapor density,  $\vec{V}$  is horizontal wind vector,  $S$  represents sources/sinks,<sup>†</sup> and  $w$  is vertical velocity. This equation will be solved for  $\partial(\rho_v w)/\partial z$ , which is a measure of vertical moisture flux. Regions of maximum vertical moisture flux should be preferred cumulus development regions and therefore should be where hailstorms are likely to develop.

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<sup>†</sup>An attempt is being made to include evapotranspiration effects as a moisture source, although no quantitative data of this type are yet available.

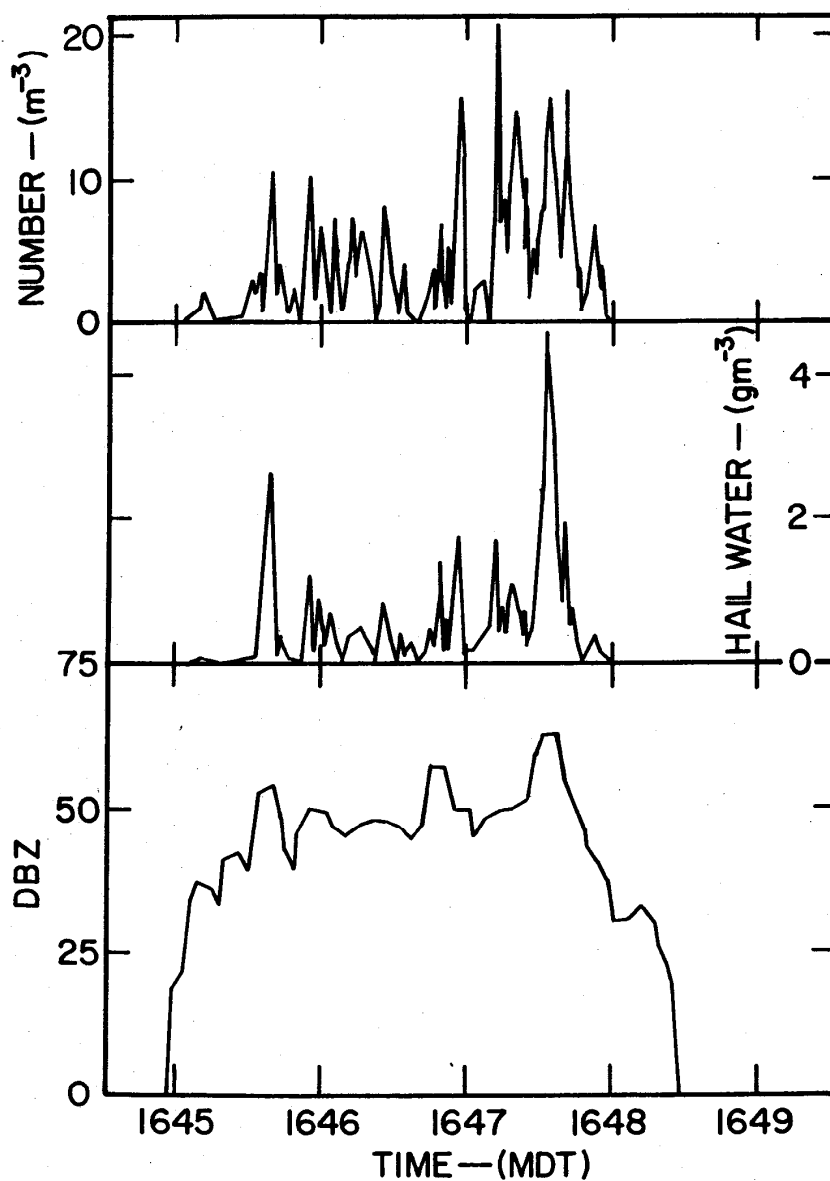


Fig. 6. Sample data derived from observations made with laser hail sensor on 21 July 1975 (Flight 125, Penetration 4). (Hail water and number concentrations are plotted at 1-sec time intervals.) Reflectivity factor data are obtained from a 10-sec running mean output at 1-sec intervals.

The NHRE mesonet data from 28 July 1974 are being investigated and will be used in this study. The data have been screened for erroneous or missing points and are being typed onto computer cards. A program is being written to fit the mesonet data to a 60 km x 60 km grid and solve the above continuity equation.

The work is part of a Master's thesis project and is scheduled for completion during the summer of 1976.

#### 4.2.7 Radar echo characteristics (Task 75-C)

A large sample of radar data, especially from the 1974-75 seasons, is available, from which such things as first echo heights, maximum echo heights, maximum reflectivity factors, reflectivity profiles, etc., can be determined. To our knowledge no such radar climatology yet exists for the NHRE data. Such information can provide valuable input to the NHRE project, both from the standpoint of operations and analysis of data. This study requires additional collaboration between NHRE and IAS personnel. Our suggestion is that the DADS data be used for this purpose since they appear to be accurate enough, are much easier to obtain, and are in a better form than the standard CP-2 data. Coordination is necessary between NHRE and IAS personnel, since some of these things have probably already been done in individual case studies of past NHRE storms (e.g., Chalon et al., 1976).

## 5. PERSONNEL CHANGES

No new staff members were hired for the project during the contract period. Mr. Wayne Sand left the employ of the Institute on 31 December and joined the staff of the University of Wyoming to begin work on a Ph.D.

Work on the project supported by contract funds is listed by individuals in Appendix D.

## ACKNOWLEDGMENT

The information in this report is based on activities of the National Hail Research Experiment (NHRE), which is operated by the National Center for Atmospheric Research (NCAR). The National Center for Atmospheric Research is operated by the University Corporation for Atmospheric Research and supported by the National Science Foundation. The National Hail Research Experiment is supported by Contract No. NSF-C460 between NCAR and the RANN division of the Foundation.

We are especially grateful for the contributions made to the T-28 program by Mr. Wayne Sand, who served as the aircraft pilot and research meteorologist for several years. His enthusiasm, energy, and continuing interest have been instrumental in making effective use of the capabilities of this unique meteorological observing system.

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## APPENDIX A

Summary of Papers, Reports, and Seminars  
Prepared During the Contract Period

Papers

- Dennis, A. S.: Hail suppression concepts and seeding methods.  
Presented at NHRE Symposium/Workshop on Hail and Its Suppression,  
Sep. 21-28, 1975, Estes Park, Colorado.
- Dennis, A. S.: How silver iodide seeding suppresses hail. Presented  
at WMA Meeting, Sep. 4-5, 1975, Calgary, Alberta, Canada.  
[J. Wea. Modif., VII, 2, 50-59.]
- Dennis, A. S., C. Knight, D. J. Musil, and W. R. Sand: Radar and  
related hydrometeor observations inside a multicell hailstorm.  
Accepted for presentation at the International Cloud Physics  
Conference, Jul. 26-30, 1976, Boulder, Colorado.
- Musil, D. J., E. L. May, P. L. Smith, Jr., and W. R. Sand: Structure  
of an evolving hailstorm, Part IV: Internal structure from  
penetrating aircraft. Accepted for publication in Mon. Wea.  
Rev.
- Sand, W. R.: Methods for making significant observations inside  
thunderstorms. Presented at NHRE Symposium/Workshop on Hail and  
Its Suppression, Sep. 21-28, 1975, Estes Park, Colorado.
- Sand, W. R., J. L. Halvorson, and T. G. Kyle: Turbulence measurements  
inside thunderstorms used to determine diffusion characteristics  
for cloud seeding. Accepted for presentation at the International  
Conference on Weather Modification, Aug. 2-6, 1976, Boulder,  
Colorado.
- Smith, P. L., Jr., D. J. Musil, S. F. Weber, J. F. Spahn, G. N. Johnson,  
and W. R. Sand: Raindrop and hailstone size distributions inside  
hailstorms. Accepted for presentation at the International  
Cloud Physics Conference, Jul. 26-30, 1976, Boulder, Colorado.



Reports

Musil, D. J., P. L. Smith, Jr., G. N. Johnson, J. L. Halvorson, C. A. Biltoft, J. F. Spahn, and S. F. Weber: Final report on T-28 armored aircraft during the period 1 March 1975 - 29 February 1976. March 1976.

Musil, D. J., and W. R. Sand: National Hail Research Experiment - armored aircraft work plans - 1975. May 1975.

Sand, W. R., and D. J. Musil: Summary of T-28 field operations - 1975. December 1975.

Sand, W. R., D. J. Musil, and A. S. Dennis: Final report on T-28 armored aircraft during the period 1 March 1974 - 28 February 1975. June 1975.

Seminars

Smith, P. L., Jr.: The internal structure of Colorado hailstorms as revealed by penetrating aircraft. Presented at Massachusetts Institute of Technology, February 24, 1976, and at McGill University, March 1, 1976.

APPENDIX B

TABLE B.1: Instrumentation Task Summary, February 1976

<u>Ident. No.</u>	<u>Priority</u>	<u>Task</u>	<u>Participants</u>	<u>Current Status</u>
75-1	A	Repair accelerometer; bias to 1 g	Johnson	Accelerometer returned by manufacturer; no problem identified; biasing needed
75-2	A	Peak acceleration sensor	Halvorson	Awaiting test
75-3	A	Calibrate heading indicator	Halvorson	Flight check OK; ground calibration needed
75-4	A	Event code system	Johnson, Flohr	Completed
75-5	C	Recorder channel expansion	Johnson, Halvorson	Completed
75-5a	A	Backup recording mode	IAS & NHRE	Knollenberg recorder and Monitor 9100 being modified
75-6	B	Telemetry system	Halvorson, Johnson	Multiplexer expansion parts received
75-6a	B	Intercom and rate of climb to Grover		Equipment available
75-7	A	Hail sensor (water seal, calibration, etc.)	Johnson, Spahn, Leigh	In progress
75-8	A	Knollenberg probe system		
75-8a	A	Flight number, time data to Knollenberg recorder	IAS & NHRE	On schedule; being done in conjunction with 75-5a.

TABLE B.1: Instrumentation Task Summary, February 1976  
(Continued)

<u>Ident. No.</u>	<u>Priority</u>	<u>Task</u>	<u>Participants</u>	<u>Current Status</u>
75-8b	A	Check ram air flow in Knollenberg probe, knowing ram air pressure	NHRE	Completed
75-8c	B	Reduce weight of Knollenberg pylon	NHRE	Scrubbed
75-9	A	Cannon camera		
75-9a	A	Test flight	Sand	Completed
75-9b	A	Frame counter in 9100 recorder	Johnson, Flohr	Completed
75-9c	A	Event mark signal for cloud entry	IAS & NHRE	No report received from NHRE
75-9d	A	Check 9100 data channels for noise from motor brushes	Flohr, Johnson	Completed
75-9e	A	Return camera to NHRE for rework	IAS	Camera returned early February
75-10	A	Eliminate grounding problems	Johnson, Flohr	Awaiting complete system check
75-11	B	Rework patch panel	Flohr, Johnson	In progress
75-12	C	Redesign front pedestal (new switches?)	Leigh, Flohr	Hold

TABLE B.1: Instrumentation Task Summary, February 1976  
(Continued)

<u>Ident. No.</u>	<u>Priority</u>	<u>Task</u>	<u>Participants</u>	<u>Current Status</u>
75-13	C	Weight reduction program	Leigh, Flohr, Johnson	Completed
75-14	C	Substitute static for rotary inverters	Johnson, Flohr	Hold
75-15	B	Install angle of attack indicator	Leigh, Halvorson	In progress
75-16	A	Rework NCAR reverse flow temperature unit	NHRE	Completed
75-17	A	New amplifier for Rosemount temperature unit	IAS	On order; delivery 15 May
75-18	A	Modify output voltage of Rosemount static pressure sensor to $\pm 5$ volts	IAS	Unit at Rosemount; due back 14 April
75-19	B	Additional super-8 camera (one side-looking, one for windscreen)	IAS	To be procured
75-20	C	Install Langer counter	IAS & NHRE	Unit at NHRE for motor change
75-21	C	Tracer release device	NHRE	No requirement established
75-22	C	Embryo sampling device	NHRE	No requirement established

TABLE B.1: Instrumentation Task Summary, February 1976  
(Continued)

<u>Ident. No.</u>	<u>Priority</u>	<u>Task</u>	<u>Participants</u>	<u>Current Status</u>
75-23	A	New schematic diagrams	Flohr	Nearing completion
75-24	B	Ground check program (HP-65)	Johnson, Halvorson	HP-65 ordered
75-25	A	Digital multimeter-battery operated?	Johnson	Received
75-26	B	Tape rewinder	Halvorson, Johnson, Leigh	To be built
75-27	B	Oscilloscope (Sony portable or equivalent)	Smith, Johnson	To be ordered
75-28	C	Shop facility at airport	Dennis	Need money
75-29	A	Cheyenne facilities (hangar, electrical power)	Smith, Johnson	Base shifted to Laramie

TABLE B.2: Analysis Tasks in Progress, February 1976

<u>Ident. No.</u>	<u>Title or Subject</u>	<u>Author(s)</u>	<u>Current Status</u>
75-1 (Old #3)	Model comparisons	Musil	Study initiated using 1974 radar, radiosonde, and mesonet work data
75-2 (Old #7)	Comparison of aircraft and dual wavelength radar locations of hail shafts	Dennis, Smith, and Eccles	PLS to contact P. Eccles; send listing of days with good T-28 data
75-3 (Old #6)	Horizontal winds inside hailstorms	Sand and Halvorson	Under study using 1975 aircraft velocity and radar track data
75-4 (Old #10)	Cold air downflow	Musil and Halvorson	1975 reverse flow temperature data to be examined
75-4a	Check reverse flow temperature vs adiabatic ascents	Musil	Preliminary checks look reasonable
75-5	Turbulence and diffusion from airspeed fluctuations	Sand, Halvorson, and Kyle	Analysis programs operating; abstract accepted at International Weather Modification Conference
75-6	Cloud composition; updrafts, turbulence, ice-water locations, etc.	Sand	Proposed dissertation topic
75-7	Cloud morphology and water budget considerations	Musil, Smith, and Dennis	In progress, using case study approach (see also Task 75-10)
75-7a	23 July 1975 case study	Musil	Being initiated
75-7b	16 July 1975 case study	Knight	Being initiated
75-7c	22 July 1975 case study	Sand	Being initiated

TABLE B.2: Analysis Tasks in Progress, February 1976  
(Continued)

<u>Ident. No.</u>	<u>Title and Subject</u>	<u>Author(s)</u>	<u>Current Status</u>
75-7d	31 July 1975 case study	Heymsfield	Being initiated
75-8	Aircraft icing rates	Sand and Musil	Proposed subject of paper for submission to an aviation journal
75-9	Particle size distributions	Weber, Musil, and Smith	Thesis research in progress; abstract accepted at International Cloud Physics Conference (combined with 75-11)
75-9a	Raindrop size distributions below cloud	Smith, Musil	To be initiated
75-10	21 July 1975 case study	Dennis, Knight, Musil, and Sand	Abstract accepted at International Cloud Physics Conference
75-10a	Particle size life histories	Musil, Laco, and Smith	Reduction of foil impactor data in progress. Flight 125 completed
75-11	Laser hail sensor calibration and data analysis	Spahn, Johnson, and Smith	Thesis research in progress; abstract accepted at International Cloud Physics Conference (in conjunction with 75-9)
75-12	Sampling errors in particle size distribution studies	Smith	In progress; planned paper for 17th Radar Meteorology Conference
75-13	Nowcasting	Blitoff and Musil	Thesis research in progress

TABLE B.2: Analysis Tasks in Progress, February 1976  
(Continued)

<u>Ident. No.</u>	<u>Title or Subject</u>	<u>Author(s)</u>	<u>Current Status</u>
75-14	Update of T-28 instrumentation paper	Sand, Biter, Johnson, Halvorson, and Cannon	To be initiated

The following analysis tasks require substantial contributions from the NHRE staff and are therefore listed as collaborative projects:

75-A	Knollenberg data analysis	Heymsfield, Paluch, Knight, Musil, and Smith	NHRE taking lead role
75-B	Total hydrometeor spectrum	IAS & NHRE	Proposed joint paper
75-C	Radar echo characteristics (first echo heights, maximum echo heights, maximum reflectivity factors, reflectivity profiles, etc.)	NHRE & IAS	In progress at NHRE (C. Knight to verify); 21 July 1975 data reduced by IAS



## APPENDIX C

## Summary of NHRE Operational Days - 1975

General Comments

Penetrations were made on nine days during the season. The storms fall into two rough categories on the basis of observations made at the times of the flights. These were: moderate storms, which occurred on 16, 21, 22, 23, and 31 July and produced hail ranging in size from pea to roughly one inch in diameter; and weak storms, which occurred on 7, 14, 15, and 30 July and had no known hail. In fact, it would be difficult to classify some of the latter storms as thunderstorms.

All of the hailstorms were judged to be of the multicell variety. One of the storms (21 July) appeared to take on quasi-steady characteristics for about a one-hour period during its lifetime.

The following is a subjective ranking of the operational days arranged in descending order of importance:

- |            |            |
|------------|------------|
| 1. 22 July | 6. 14 July |
| 2. 21 July | 7. 15 July |
| 3. 16 July | 8. 7 July  |
| 4. 23 July | 9. 30 July |
| 5. 31 July |            |

7 July - Very weak storms in area, but reflectivity factors seemed unusually high. First operational day of season, some confusion experienced in interpreting radar displays. Penetrations were difficult to coordinate because storms lacked organization and we tended to be cautious because of the high reported reflectivities. No hail encountered and none occurred at ground.

14 July - Storms were difficult to work because they were weak and had relatively short lifetimes with lack of organization. This day was only slightly better than 7 July in terms of storm quality, but penetration coordination significantly better. No hail.

15 July - Rather weak clouds which formed and dissipated rapidly. First two penetrations were in a dissipating storm. Later penetrations got fairly good icing but clouds were still weak and lacked organization. Storm quality about the same as 7 and 14 July with penetration quality similar to 14 July.

16 July - Excellent day. Penetrations 1 and 2 were in hail formation region on south and southeast side of echo in new growth. Penetration 3 was in cell which eventually produced hail at the Grover site.

21 July - Another excellent day. Two of the penetrations were in the overhang region, while two were in developing feeder clouds further from the main echo. Overhang penetrations were within about 2 nm of maximum reflectivity factor at flight altitude (about 50 dBz). Storm seemed quite steady during the last hour of its lifetime.

22 July - Probably the best day of the season. Two penetrations were in feeders, while another was in overhang region. Accumulation of about 2 in (5 cm) ice during the latter penetration. Only three penetrations were possible because of the heavy icing. Near hook cloud on DRI scope at about 1646 MDT.

23 July - Only rapidly moving storm of season. Remarkably persistent with new cells appearing on southwest side. Penetrations were made visually at first in newly developing clouds and later were vectored from GRO as cells merged or became mature storms on their own. An excellent storm worthy of study but takeoff alert was probably half hour late for optimum work on this storm.

30 July - Echoes moved into area from the south and were in a dissipating stage. Penetrations were in extremely weak cells with little organization. Aircraft encountered nearly all ice particles although no hail was encountered in air or on ground despite 60+ dBz values below flight altitude. The decaying state of these storms and their general weakness make this the poorest case of the year. Penetrations were like trying to chase ghosts as they tended to disappear when the aircraft approached.

31 July - Good penetrations in a storm which fed on southwest and south side. First two penetrations were near max dBz in a mature cell and the last two were in younger cells which were merging with main cell. This storm was not quite as persistent as those occurring on 16, 21, 22, and 23 July but, nevertheless, it was a good case.

## APPENDIX D

List of Personnel Associated with NHRE Project  
1 March 1975 - 29 February 1976

<u>Name</u>	<u>Title</u>	<u>Months Charged to Referenced Contract*</u>
<u>Professional</u>		
Arnett S. Dennis	Director	2.21
Jerry L. Halvorson	Junior Research Engineer	8.85
Gary N. Johnson	Research Engineer	7.93
Dennis J. Musil	Research Meteorologist	5.44
Wayne R. Sand	Pilot-Meteorologist	9.41
Paul L. Smith, Jr.	Head, Data Acquisition and Analysis Group	1.71
James N. Simmons	Assistant Director	<u>.70</u>
		36.25
<u>Technical Staff</u>		
Rudolph D. Flohr	Electronic Technician	11.99
Jon E. Leigh	Aircraft Mechanic	<u>10.99</u>
		22.98
<u>Administrative</u>		
Howard L. Elshire		.18
Melvin J. Flannagan		.15
Kathleen M. Newkirk		1.03
Joie L. Robinson		1.35
Carol L. Vande Bossche		.19
Ramona M. Young		<u>.28</u>
		3.18

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\*Some professional staff time on the T-28 project was supported by the State of South Dakota.

## List of Personnel (Continued)

<u>Name</u>	<u>Title</u>	<u>Months Charged to Referenced Contract</u>
<u>Graduate Students</u>		
Christopher A. Biltoft		2.25
John F. Spahn		6.38
Steven F. Weber		<u>5.69</u>
		14.32
<u>Undergraduate</u>		
John T. Grace		.24
Carlton P. Laco		.68
Trond B. Pederson		<u>1.94</u>
		2.86
Total Man-Months . . . . .		79.59