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FINAL REPORT ON HAILSTORM RESEARCH USING THE T-28 ARMORED AIRCRAFT

By: Dennis J. Musil, Paul L. Smith, Jr.,
and Arnett S. Dennis

Prepared for:

Convective Storms Division
National Center for Atmospheric Research
P. O. Box 3000
Boulder, CO 80307

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Institute of Atmospheric Sciences

South Dakota School of Mines and Technology

Rapid City, South Dakota 57701

ABSTRACT

This report summarizes activities of the South Dakota School of Mines and Technology T-28 armored aircraft during the entire contract period extending from April 1971 through December 1979. During this period, the T-28 system participated in field programs of the National Hail Research Experiment and the Convective Storms Division in northeast Colorado, making over 280 penetrations of hailstorms and other thunderstorms.

A review of the history of the T-28 system is made; including such things as the acquisition of the aircraft, modifications made to it, and development of the instrumentation system and flight procedures.

A summary of the characteristics of Colorado hailstorms, as determined mainly from the T-28 data, is also presented.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

This is the final report of hailstorm research conducted by the Institute of Atmospheric Sciences (IAS) of the South Dakota School of Mines and Technology (SDSMT) under Prime Contract Nos. C-760 and ATM 77-23757, Subcontract NCAR 182-71. This research has emphasized investigations of the interior characteristics of hailstorms using a T-28 armored aircraft to obtain in situ observations. This report summarizes activities over the entire period of the subcontract extending from April 1971 through December 1979. It is provided to satisfy contractual requirements and does not attempt to present the scientific work in detail or draw any new conclusions concerning the analysis of data gathered.

Section 2 reviews the history of the T-28 system itself, while Section 3 summarizes the scientific accomplishments under this subcontract. A brief summary is given in Section 4, followed by a listing of the publications prepared under the subcontract in Section 5 and a listing of personnel who contributed to the research in Section 6. References are listed in Section 7.

2. HISTORY OF THE T-28 SYSTEM

Initial work on the T-28 program began about five years before the beginning of the present subcontract and the National Hail Research Experiment (NHRE). For completeness, the history of the development of the system will be traced from the inception of the program through the end of the subcontract period.

2.1 Acquisition and Modification of the Aircraft

The idea of armoring an aircraft for collecting data inside hailstorms occurred in conjunction with Project Hailswath, a cooperative observational program funded by the National Science Foundation (NSF) and conducted in the Rapid City area in the summer of 1966. The South Dakota School of Mines and Technology (SDSMT) acted as the prime contractor and coordinator for Project Hailswath. Following the completion of Hailswath, Dr. Paul MacCready, then President of Meteorology Research Inc. (MRI), suggested that an aircraft be acquired and specially modified to withstand the rigorous environment within hail producing clouds. A proposal for further hailstorm research incorporating this suggestion was submitted by the Institute of Atmospheric Sciences (IAS) to the Weather Modification Program of NSF. Work under the resulting grant, which was called the Hailstorm Models Project, began in 1967.

Under a subcontract from SDSMT, MRI studied the available aircraft and selected a North American T-28A advanced trainer as the most suitable aircraft available for the purpose. The T-28 (Fig. 1) is a low wing monoplane with a radial engine and tricycle landing gear. MRI obtained the aircraft and began modifying it for hailstorm research.

The modifications included shaping and bonding 0.090 inch (2.29 mm) heat treated aluminum sheets to the leading edges of the wings and tail surfaces, and 0.032 inch (0.81 mm) sheets to the upper surfaces of the wings and tail. Wing sections so armored, when tested by firing ice spheres 7.6 cm (3.0 inches) in diameter at the nominal flight speed of 100 m s^{-1}, sustained only minor damage. Armor plating was provided to protect the engine cowling, ignition harness, propeller governor, and pushrod housings. Heavy aluminum grills were installed over the air intakes of the carburetor and oil cooler. The original bubble canopy was replaced by a thicker, reinforced one and the original windscreen was replaced by 0.75 inch (1.90 cm) thick acrylic plastic. The original engine of 800 horsepower was replaced by a 1250 horsepower engine to give better performance at high altitudes. At the same time, a rudimentary meteorological instrumentation system was installed on the aircraft.

Test flights were carried out in southern California and near Flagstaff, Arizona, in 1968 and 1969. The T-28 also participated in

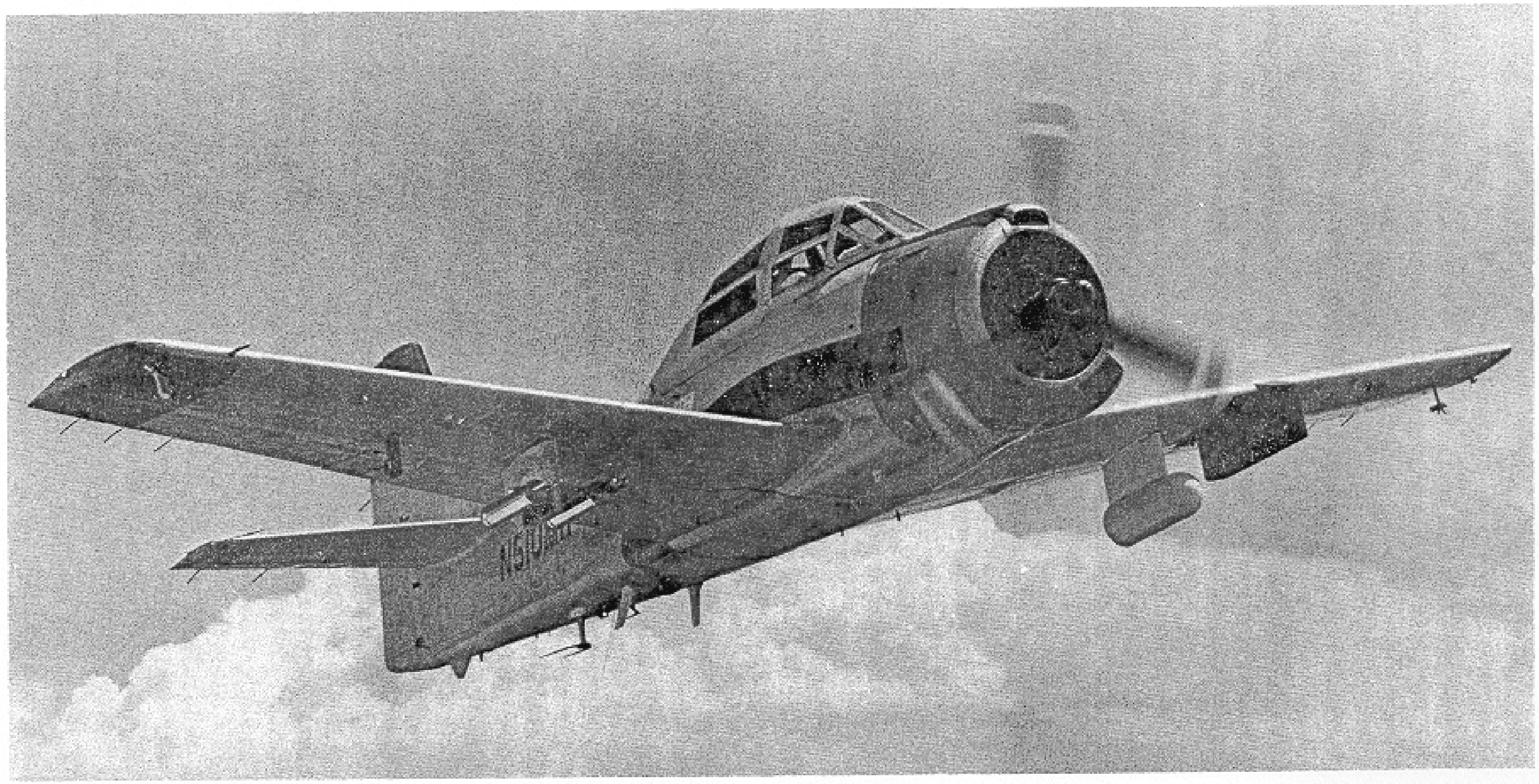

Fig. 1: View of armored T-28 aircraft in flight. Cannon camera device consisting of white pod housing film transport, rotating mirror and control electronics, and black flash system is shown on the aircraft's left wing. The reverse flow temperature device (with exhaust ports) is outboard from the Cannon camera. The FSSP and 2-D Particle Measuring Systems probes are shown on the pylon of the right wing, with the foil impactor located between the probes. Outboard from these instruments are the angle-of-attack and the Johnson-Williams Liquid Water devices. [Photo by Roger Rozelle - AOPA Pilot Magazine]

the final days of field observations under the Hailstorm Models Project near Rapid City in July 1969. The aircraft was then returned to southern California for further engineering work.

2.2 Engine Replacements and Airframe Modifications

In January 1970, SDSMT exercised its option to buy the T-28 from MRI. The aircraft was ferried to Rapid City for the installation of instrumentation for the 1970 Joint Hail Research Project (also called the Northeast Colorado Hail Experiment). In February 1970, the engine failed while the aircraft was on a test flight southeast of Rapid City. It was landed without damage on a highway and towed back to the Rapid City Regional Airport. A reconditioned engine with a 1200 horsepower rating was installed during the spring of 1970.

It then became necessary to modify a wing spar cap to conform to a change order issued by the U.S. Air Force. Investigation revealed that the only practical way to perform airframe modifications on the T-28 was to have the work done at the Naval Aviation Rework Facility (NARF) at Pensacola, Florida. Accordingly, the T-28 was ferried to Pensacola, where the wing spar caps were installed in July 1970.

Following this modification, the T-28 went into the field on the Joint Hail Research Program in late July. Unfavorable weather conditions allowed only three research flights in northeast Colorado, but 15 penetrations were made in increasingly more intense storms. One additional research mission was flown near Rapid City in August 1970.

More engine problems were noted at the end of the 1970 season, which led to further overhaul work during the winter of 1970-71. This was done with a view toward having the T-28 participate in the 1971 dress rehearsal for the National Hail Research Experiment (NHRE), which was scheduled to replace the Joint Hail Research Project in northeast Colorado. However, two engine failures occurred during the 1971 test flights in the Rapid City area, destroying the two engines available for the T-28. The aircraft was landed safely each time, once on a highway and once at the airport, but the engine failures precluded its use during the 1971 NHRE dress rehearsal. A Beechcraft Baron aircraft was leased as a substitute so that the development of the instrumentation package could continue and experience could be gained in coordinating operations within the multi-aircraft NHRE environment. The Baron also carried 24 pyrotechnic flares on wing racks and was used in the development of seeding procedures for NHRE.

A thorough feasibility study showed that the T-28 could not fulfill its mission at the desired operating altitudes of up to 7.6 km (25,000 ft) without a larger power plant. After an extensive search, an engine developing 1425 horsepower and identical to those being used on T-28's in the U.S. Navy was located at a civilian supply source in Long Beach, California. During this study, it was found that substantial airframe modifications would be necessary to accommodate the larger engine. NSF agreed to support this effort with the work to be done at NARF.

The T-28 was disassembled and transported, with the assistance of the NCAR Field Observing Facility, to Pensacola in the fall of 1971. The aircraft was almost completely reworked by NARF. The nose landing gear was replaced and the fuselage strengthened to accommodate the larger engine. The engine was transported to Pensacola and installed along with a stronger propeller in the spring of 1972. Numerous changes were made to such things as the fuel system, oil cooler system, etc. In fact, 17 FAA Form 337's were required prior to relicensing of the aircraft in the restricted category.

Following test flights in Florida, the aircraft was ferried back to Rapid City, arriving on 2 May in time to participate in the 1972 NHRE field season. The engine has performed satisfactorily since that time, and the T-28 participated in each NHRE field season except for 1974. The only continuing problem has been the need to replace cylinders when the cooling fins (which cannot be protected) become badly damaged by hailstone impacts. A paper by Sand and Schleusener (1974) describes the development work on the T-28 system up through the initial years of NHRE.

In the fall of 1977, the aircraft was again ferried to Pensacola where NARF installed a strengthened horizontal stabilizer. This modification was carried out to conform with a manufacturer's safety recommendation. The T-28 then participated in the 1978 CSD field project in northeast Colorado, as well as subsequent thunderstorm research projects in Florida (TRIP '78) and Oklahoma (SESAME '79).

2.3 Instrumentation and Data Handling Systems

It was decided early in the development of the T-28 system that the aircraft should be configured for single-seat operation. This was done to maximize the number of instruments that could be carried without exceeding gross weight limitations and to simplify matters for the pilot should he ever find it necessary to leave the aircraft during an emergency. This decision also meant that data collection had to be automated to the greatest extent possible and that close coordination would be required with a meteorologist directing the missions from the ground.

The instrumentation package carried by the T-28 evolved over the years as new instruments became available. During the first two years of NHRE (1972 and 1973), the aircraft carried an instrument package that was crude compared to today's standards. Measurements of pressure, temperature, cloud liquid water concentration, rate of climb, indicated airspeed, and aircraft location (VOR/DME) were recorded on a small cartridge tape recorder along with various auxiliary quantities. After each flight, the data tape was shipped to Rapid City, where the tapes were read by a minicomputer which in turn produced a 7-track tape compatible with a CDC-3400 computer at SDSMT. Thus, automated data recording and reduction techniques were emphasized from the beginning of the T-28 participation in NHRE.

The aircraft also carried a rain-rate (impact) sensor, an evaporator device for sensing total water concentrations, and a hailstone impact (momentum) sensor during 1972 to obtain information about precipitation particles in the storms penetrated. All of these instruments were eventually discarded in favor of other equipment. However, a foil impactor added in 1973 is still in use and providing useful data despite its well known data reduction problems and sample volume limitations. Other instruments carried on a trial basis in 1973 included an infrared radiometer, a commercial icing rate probe, a formvar replicator, and a hail camera viewing a blackened wing surface. Of these, only the icing rate probe was used subsequently, but it gave only qualitative indications of cloud liquid water concentrations (Musil and Sand, 1974). Therefore when it was damaged by a hailstone impact in 1976, it was not replaced.

Prior to the addition of the foil impactor, the only usable information about hail in the storms came from the pilot's comments recorded on an audio tape recorder, which also provided recordings of hail impacts on the windscreen. Even with the current sophisticated particle sensors, these audio recordings continue to provide valuable information.

The status of the T-28 instrumentation system as of the end of the 1973 NHRE field season is summarized in papers by Sand and Schleusener (1974) and Johnson (1974). In 1974, the decision was made to substantially upgrade the instrumentation system in order to increase its usefulness. In cooperation with technicians from NCAR, IAS engineers and technicians completely reworked the instrument package over the following year.

A new data acquisition system capable of accepting both analog and digital input data and recording on 7-track computer-compatible magnetic tape was installed as the primary data collection system. Instruments that could make more accurate measurements of temperature and pressure were added to the system. Most notable, however, was the addition of two Particle Measuring Systems (PMS) probes, one a Forward Scattering Spectrometer Probe (FSSP) to record cloud droplet spectra, and the other an optical array, two-dimensional probe to record images of precipitation particles up to sizes of about 1000 μm. These two probes were mounted with the foil impactor on a pylon beneath the right wing of the T-28. A separate tape recorder was installed as part of the PMS system to accommodate the large amount of data produced by these probes. To facilitate analysis of the PMS data, the second tape recorder was linked to the primary recording system. Certain basic observations, such as time, pressure, temperature, airspeed, and cloud liquid water concentration, were also included on the PMS data tape, thereby providing an effective backup recording system.

Also in 1975, the capability of the aircraft to measure and record large precipitation particles, such as raindrops, graupel, and hail, was enhanced by the addition of the Cannon particle camera (Cannon, 1976) and an optical hail spectrometer developed by the IAS (Spahn and Smith, 1976). The hail spectrometer was tested during the 1975 NHRE field season and acquired data from the interiors of several hailstorms. The particle camera was first carried on the T-28 in the fall of 1975 and was used in thunderstorm penetrations during the 1976 NHRE field season. Unfortunately, there is only one hard point available under the left wing for these instruments, and the weight and electrical power limitations of the aircraft also preclude carrying both devices simultaneously. The particle camera and hail spectrometer have therefore been used alternately since 1976, depending upon the objectives of a particular flight.

Finally, an attempt was made to improve the system capability for determining vertical air motions. A gyro-stabilized vertical accelerometer unit was added in 1975; it provides indications of the aircraft attitude (pitch and roll angles), and an angle-of-attack vane was added in 1976. The latter had to be mounted under the wing of the single engine T-28, which meant that correction for the downwash angle was necessary (Sarma, 1978). Study of this correction and the updraft calculation procedure showed that sizable errors could still occur in the computed vertical air motions. More accurate results are obtained from a "conservation of energy" approach similar to that used with some other aircraft platforms, including the NCAR/NOAA sailplane.

A complete list of the data gathering instruments now carried by the T-28 is given in Table 1. Much of the instrumentation belongs to the NCAR Convective Storms Division (CSD); however, the equipment is used on the T-28 under a cooperative agreement between SDSMT and NCAR. The instrumentation available on the T-28 is capable of determining hydrometeor sizes and number concentrations over essentially the entire spectrum from cloud droplet through hailstone sizes.

An air-to-ground telemetry system was also developed for the T-28. It permits transmitting selected variables, such as the aircraft altitude and rate-of-climb, to the project meteorologist at the ground. The pilot's voice comments, which are recorded on the cockpit audio recorder, are also transmitted over the same link. The telemetered data assist the meteorologist in evaluating the progress of the penetrations and reduce his need to communicate with the pilot during the penetrations.

The present data handling system provides for reduction of the primary data tapes on a CDC-6400 computer at SDSMT. The PMS data tapes are reduced separately on the CDC-7600 computer at the NCAR Computing Facility. Throughout the history of the T-28 project, quick reduction and examination of the data has been emphasized to detect problems in either the instrumentation or data handling system as soon as possible after they appear. Several approaches have been tried, but the direct

TABLE 1

Variables Recorded by T-28 Instrumentation System

Variable	Instrument	Range of Measurement
State:		
Static Pressure (Altitude)	*Rosemount	0 to 15 PSI
	*Ball Engineering	0 to 27,000 ft (8.2 km) MSL
Total Temperature	Rosemount	-25 to +25°C
	*NCAR Reverse Flow	-25 to +25°C
Hydrometeors:		
Cloud droplets	Johnson-Williams LWC	<50 μm dia (liquid only); 0 to 6 g/m^3
	*Particle Measuring Systems FSSP	3 to 45 μm dia; adjustable
Rain, graupel, snow	Williamson Foil Impactor	1 to 20 mm dia
	*Particle Measuring Systems OAP-2D	31 to 1000 μm
	*Cannon Particle Camera (alternates with hail spectrometer)	Approx. 50 μm up
Hail	Laser Hail Spectrometer (alternates with Cannon camera)	4.5 to 50+ mm dia
Aircraft Navigation & Performance:		
Attitude	Servomechanisms angle-of-attack vane	-15 to +15°
	*Pitch (Humphrey vertically-stabilized accelerometer)	-50 to +50°
	*Roll (Humphrey vertically-stabilized accelerometer)	-50 to +50°
Navigation	Heading indicator	0 to 360° magnetic
	*CESSNA DME	0 to 200 n mi
	*NARCO DME	0 to 100 n mi
	NARCO COM/NAV (2 units)	0 to 360° from station
	*NARCO NAV	0 to 360° from station
Performance	Ball Engineering variometer (rate-of-climb)	-6000 to +6000 ft/min (-30 to +30 m/s)
	*Rosemount dynamic pressure (ind. airspeed)	-3 to +3 PSI
	*NCAR True Airspeed Computer	0 to 250 knots (128 m/s)
	*Humphrey vertically-stabilized accelerometer	-1 to +3 g's
	Giannini manifold pressure	0 to 50 in Hg

*Furnished by NCAR.

method of shipping the T-28 data tapes to the appropriate computer center for processing has proven to be most successful.

Typically, reduced data have been available for examination within 24 hours of a particular research flight when the flights are conducted within a few hundred miles of the computer location. Tapes have been physically transported by auto, bus, or air express from the T-28 base (Greeley in 1970; Cheyenne in 1972, 1973, and 1975; and Laramie in 1976 and 1978). Upon receipt in Rapid City, the primary data tapes are reduced on the SDSMT computer. Beginning in 1973, samples of the reduced data were sent back immediately to the field site by telecopier for examination by the T-28 crew prior to undertaking another mission. Data tapes from the PMS probes were handled separately by NCAR personnel, being carried to Boulder for reduction on the NCAR CDC-7600 computer. The reduced PMS probe data were generally returned to the T-28 base the morning following a research flight.

2.4 Flight Procedures

The development of flight procedures and coordination procedures for the T-28 aircraft missions required an effort comparable to that involved in maintaining and improving the instrumentation system. Safety was always stressed as the most important factor in the development of flight profiles. The decision that the penetrations would be directed by a meteorologist at the ground with access to good quantitative weather radar data was a major factor in assuring the safety of the penetration procedures. The IAS project meteorologist at the NHRE field headquarters had the responsibility for monitoring weather conditions and ordering the launch of the T-28 aircraft when weather conditions appeared to warrant its use. The project meteorologist then had the responsibility of directing the T-28 during penetrations of the desired portions of the storms, as well as keeping the aircraft and pilot out of the most dangerous situations.

The first T-28 missions in 1970 were designed to test the capabilities of the aircraft and to gain experience in designing and directing aircraft flights involving the penetration of large convective clouds. By the end of the 1971 NHRE dress rehearsal, it was concluded that to penetrate hailstorms with the desired precision would require a radar display system capable of simultaneously displaying the T-28 track and weather echo information. The data display system (DADS) developed by NHRE personnel provided this capability, but it did not become available until near the end of the 1973 field season. Thus during the early years of NHRE, the penetrations involved more or less aiming at the middle of the storm being penetrated.

As the DADS developed, the penetrations became more and more precise. The DADS system permitted the project meteorologist to assess the three-dimensional characteristics of the storm being penetrated, as well as to see the current position of the T-28 on the same display. It then became possible to penetrate selected regions of the storms, such as a weak echo region, while avoiding regions of very high radar reflectivity. Experience showed that while the latter regions (which usually contain sizable hail) can be penetrated safely by the T-28, the damage that results to instrumentation and equipment reduces the amount of useful data obtained. In general, regions with equivalent radar reflectivity factors exceeding 55 dBz were therefore avoided, if such a reflectivity was observed at or above the intended flight path of the penetration.

Multi-level penetrations were made during the 1972 and 1973 NHRE field seasons, beginning at 24,000 ft (7.3 km) MSL and descending in 2,000 ft (0.6 km) intervals until 16,000 ft (4.9 km) MSL was reached. Subsequent to 1973, the penetrations were made at a single level in each storm, usually near 20,000 ft (6.1 km) MSL. The single-level method was adopted because of the difficulty in finding continuity in data collected on the multi-level penetrations. The main cause of the difficulty was that too much time passed during the completion of one flight profile, and the storms changed significantly in the meantime. In addition, upon the completion of one profile, there was usually not enough time to climb back up to altitude for another series of penetrations.

It was also found that straight-line penetrations are usually the most satisfactory because of the possible loss of radio communications during a penetration. This would preclude passing directions from the meteorologist to the pilot for a turn at the proper time. Changing the heading during a penetration also requires changing the aircraft attitude, which causes difficulty in interpreting some of the data, such as updraft calculations.

3. SCIENTIFIC ACCOMPLISHMENTS

The major purpose of research based on data collected by the T-28 in northeast Colorado has been to determine the precipitation mechanisms in thunderstorms and hailstorms. The early investigations concentrated on questions such as ice versus liquid water concentrations and updraft structures in hail producing storms, as well as the composition of high radar reflectivity zones. In later years, the emphasis evolved toward determining temperature, updraft, and hydrometeor charcteristics at mid-levels (5-7 km MSL) in the storms and their implications regarding the formation and growth of precipitation. Interpretation of the T-28 observations was greatly facilitated by the availability of supporting radar data, both conventional and Doppler, as well as other comprehensive surface and upper air meteorological data. The research was carried out on a cooperative basis with scientists at NCAR and other participants in NHRE.

3.1 Summary of Field Operations

The first routine use of the T-28 was in northeast Colorado during the 1972 NHRE field season, although some penetrations were accomplished in 1970 in both Colorado and South Dakota. Table 2 shows a compilation of flights and penetrations by years while the T-28 was participating in NHRE and the follow-on CSD experiments in northeast Colorado. Other projects are included for completeness and because some NCAR-CSD personnel were involved with the T-28 work in other places, especially in Florida and Oklahoma.

The flights listed in Table 2 include checkout, maintenance, and equipment test flights as well as research flights. The numbers of penetrations are therefore a better guide to the amount of scientific data collected by the T-28. Through the 1979 SESAME season, the total number of penetrations had mounted to 422, indicating that the T-28 has proven to be a reliable platform for making in-cloud measurements in thunderstorms and hailstorms.

3.2 Characteristics of Colorado Hailstorms

3.2.1 Early investigations

T-28 observations made during the 1972 and 1973 NHRE field seasons were necessarily somewhat qualitative because of limitations in the aircraft instrumentation and data recording system. Nevertheless, substantial analyses of data collected during those early years were carried out and important contributions were made to the study of the formation and growth of hail in Colorado storms.

TABLE 2

Operational Summary by Years

Year	Flights	Cloud Penetrations	Program
1970	40	20	1. N.E. Colorado Hail Experiment 2. Hailstorm Models - Rapid City
1971	21	--	Engine problems - no research flights
1972	54	83	NHRE - N.E. Colorado
1973	38	27	NHRE
1974	8	--	No field program
1975	40	48	NHRE
1976	50	60	NHRE
1977	18	--	No field program
1978	47	108	1. Convective Storms Division (CSD) - N.E. Colorado 2. Thunderstorm Research International Program (TRIP) - Florida
1979	27	76	SESAME - Oklahoma

that these accumulation zones, with liquid water concentrations up to 15-20 g m^{-3}, were regions in which hailstones could grow very rapidly. Accordingly, the general plans for T-28 operations in 1972 and 1973 emphasized penetrations of the high reflectivity regions to determine the nature of the precipitation particles within them.

There were some initial indications of high water mass concentrations in the storms (Kyle and Sand, 1973), but these have subsequently been discounted because of the inadequacies of the evaporator-type instrument used to obtain the measurements (Smith, 1976). Observations from the foil impactor carried on the T-28 since the 1973 field season show typical water concentrations of 1-4 g m^{-3}, although there was one extreme value near 12 g m^{-3} (May, 1974). The hail spectrometer data (Spahn and Smith, 1976) tend to support the lower values.

Although the initial interpretation of the foil impactor data suggested the presence of some liquid precipitation particles (May, 1974), it was found that the high reflectivity zones of northeast Colorado hailstorms are composed predominantly of ice particles (Sand, 1976). The interpretation of the foil imprints in terms of liquid versus solid particles was subsequently questioned by Knight et al. (1976). Later observations with the Cannon particle camera and the PMS 2-D probe firmly established that the high reflectivity regions at temperatures of -10 to -15°C consist almost exclusively of solid particles rather than supercooled raindrops. This information, together with observations collected by the NCAR/NOAA sailplane in northeast Colorado, plus analyses of embryos of hailstones collected at the ground (Dye et al., 1976), showed that the Sulakvelidze hailstorm model is not applicable to northeast Colorado hailstorms.

Early analyses of T-28 data related variables such as the pilot's subjective assessments of hail encountered in the storms to measured updrafts and supporting radar data (Sand et al., 1973; Musil et al., 1973). The findings showed that hailstones tend to be located along the edges of major updrafts in regions of high radar reflectivity gradients, in agreement with Marwitz (1972), although later investigations also showed sizable hail in the updrafts (Musil et al., 1976a; Smith et al., 1976). The updraft regions contain significant amounts of supercooled cloud liquid water, especially in regions of weak reflectivity (Sand, 1976).

3.2.2 Hydrometeor characteristics

Since 1975, particle size measurements have been made routinely throughout the entire hydrometeor spectrum from cloud droplet through hailstone sizes. The newer instruments permit more definitive discrimination between liquid and ice particles, while the digital data recording capability afforded by the PMS probes and the hail spectrometer permit more automated analysis of the observations. Accordingly, the attention of the analysis turned to more detailed studies of the nature of the hydrometeors in Colorado storms, particularly within the updrafts.

The early flights of the T-28 provided some evidence that the updraft regions are largely echo weak and that the water there consists predominantly of small cloud droplets (Sand, 1976). A few ice particles were occasionally encountered in the updrafts near the -10°C level but, in general, a distinction can be made between the updraft regions characterized by supercooled cloud droplets and downdraft regions characterized by snow and graupel particles. The latter were usually falling from higher levels in the cloud (Musil et al., 1976a). There were, however, numerous cases of millimeter-sized dendritic ice crystals appearing in the updrafts near the -10°C level. The inference was that a recirculation mechanism is necessary to generate these particles because simple calculations show that they could not have grown to the observed sizes in a single vertical pass through the updraft region (Musil et al., 1976a). Data regarding storm air motions, from the NHRE Doppler radar systems, supported this interpretation of the microphysical data from the T-28 instrumentation system. A recirculation process apparently occurs quite frequently in Colorado hailstorms (Jameson, 1979; Kropfli and Miller, 1976; Browning and Foote, 1976).

Study of the size distributions of precipitation particles in the storms (Musil et al., 1976a; Smith et al., 1976; Weber, 1976) showed that the distributions tend to be exponential when the particles are no larger than a few millimeters in diameter. When larger particles are present, the distributions tend to become bi-exponential, with a distinct break at about 3 mm diameter. Recent work at the CSD with data for particles ranging from some tens of micrometers to a few centimeters in diameter, as measured by three different sensors (PMS 2-D probe, foil impactor, hail spectrometer), has shown remarkably continuous distributions spanning four orders of magnitude in particle size.

Generally, hailstones are likely to be found near the boundary between updraft and downdraft regions. Hailstones are occasionally encountered in the updraft regions also, where they are frequently mixed with cloud liquid water suggesting an adequate opportunity for further growth (Smith et al., 1976). Musil et al. (1978) showed that the hydrometeor data can be used to compute cloud liquid water depletion times and hydrometeor growth rates. These findings have special relationships to the Browning and Foote (1976) supercell storm model.

Spahn and Smith (1976) described measurements of hail made with the hail spectrometer. They found indications that the hailstone size distributions are also exponential, at least up to the maximum size encountered in 1975 (2.5 cm). Miller et al. (1978) continued this work by comparing airborne and surface measurements of hail for cases where larger particles were found by the T-28, and the distributions departed appreciably from exponential form. Weber (1976) developed a novel method for analyzing large amounts of particle size data and applied it to foil impactor observations. Smith and Laco (1978) extended this work to develop improved techniques for fitting the observations.

3.2.3 Vertical air motions

Characteristics of vertical air motions observed in northeast Colorado hailstorms between 5-7 km MSL (Musil et al., 1977) showed the most frequent maximum velocities occurring between ±10 m s^{-1}. Typical maximum updrafts in Colorado hailstorms seem to be of the order of 10-20 m s^{-1}, while the updraft speeds occasionally exceed 30 m s^{-1}. Downdraft speeds are generally comparable to the updrafts when the latter are less than 20 m s^{-1}, but no downdrafts stronger than about 20 m s^{-1} were observed. Cloud liquid water concentrations in the updrafts are typically less than the adiabatic values, but occasionally adiabatic or greater cloud water concentrations occur.

A number of model updraft profiles were fitted to various observed thunderstorm updraft profiles (Kyle et al., 1976). The results indicated that the axisymmetric jet model seemed to give the best fit.

3.2.4 Turbulence in the storms

The association of hail with regions near the boundaries between updrafts and downdrafts led to speculations regarding the possible role of turbulence in such regions in controlling hailstone growth. The amount of turbulence in the storms is also of interest in connection with the spread of seeding material in hail suppression work. The T-28 indicated airspeed data have been processed by a Fast Fourier Transform technique to obtain information on the intensity of turbulence within Colorado thunderstorms (Sand et al., 1976). The available results indicate that the turbulence follows the -5/3 spectral law reasonably well. Typical values of the turbulent energy dissipation factor, ε, are of the order of 500 cm^3 s^{-2} but maximum values exceed 10^4 cm^3 s^{-2}. These numbers are in reasonable agreement with those published in the literature for cumulonimbus clouds in other regions.

3.2.5 Case studies

As a principal source of in situ observations from the interiors of Colorado storms, the T-28 provided valuable data for the case studies which form a major part of the NHRE and NCAR/CSD analysis effort. Personnel at SDSMT made major contributions to this effort, and many of the conclusions discussed in the preceding subsections resulted from work on the various case studies. Some examples of case studies in which SDSMT personnel were involved are outlined below.

22 July 1972. This case study was the first cooperative analysis effort under NHRE. The hailstorm was of moderate intensity and showed some supercell characteristics. Several groups contributed to this

study; airflow and moisture budget beneath the storm (Foote and Fankhauser, 1973); precipitation characteristics of the storm (Phillips, 1973); and vertical wind measurements using dropsondes (Bushnell, 1973). The T-28 penetrations (Musil et al., 1973) showed multiple updrafts and hail occurrences indicating multiple regions of hailstone growth. The hail was consistently encountered near the edges of the updrafts and was accompanied by high cloud liquid water concentrations as evidenced by the moderate-to-heavy aircraft icing rates at those times.

9 July 1973. This investigation was another NHRE cooperative effort that dealt with the data from a multicell hailstorm. The analysis was coordinated and a synthesis of several contributions to this case study was made by Browning et al. (1976). The T-28 observations (Musil et al., 1976b) provided detailed information about the interior characteristics of the storm. Most of the precipitation-sized hydrometeors in the storm were identified as ice particles; however, particles thought to be liquid were found in the updrafts of developing cells at temperatures as cold as -12°C. The downdrafts were composed exclusively of ice particles.

21 July 1975. This case study (Musil et al., 1976a) concerned another multicell storm. It was clearly established that a recirculation mechanism was at work in the storm. Both air motion data from a Doppler radar system and microphysical data from the T-28 instrumentation supported that interpretation.

23 July 1975. This study of another multicell storm was carried out as a Master's thesis project at SDSMT (Jameson, 1979). Using essentially the same combination of data sources that was used for the 21 July 1975 study, it was shown that this storm also exhibited strong recirculation features. There were good indications in the Doppler radar data that the updraft diverged aloft.

22 July 1976. This was one of the best documented case studies from the NHRE work in northeast Colorado. Several observation platforms were brought to bear on this storm, and several articles have been written describing it. Results of the various contributions to the case study have been summarized by Foote et al. (1978). The storm had a transitory but well developed weak echo region, which was penetrated several times with the T-28. Characteristics of the updraft region were described in great detail by Heymsfield et al. (1978). The analysis showed hail to be growing near the edge of the main updraft in this storm, with a near absence of ice particles in the updraft core, which was well defined by a weak echo region.

4. SUMMARY

Over the course of this subcontract, the T-28 armored aircraft was developed into a unique research system. It has proven to be a reliable and safe platform for making in-cloud measurements in storms containing hailstones up to several centimeters in diameter. Although the instrument pods carried on the aircraft and the cooling fins on the engine cylinders have received some hail damage on a number of occasions, no significant structural damage to the aircraft has been experienced.

A special effort has been made to build up a stock of spare parts to insure keeping the aircraft in good running condition. Engine cylinders, starters, voltage regulators, fuel pumps, tires, and other items have been accumulated. At the present time, the aircraft has logged nearly 400 hours since its last major overhaul. It is expected that several hundred hours of useful life remain in the engine before any major work is required. With a major overhaul, the useful life can probably be extended beyond 1000 hours.

The T-28 participation in the NHRE and NCAR/CSD programs in northeast Colorado yielded valuable information about the interior characteristics of the hailstorms in that region. Nevertheless, many of the facets of the hailstorm processes are still a mystery. We still have inadequate knowledge of hail growth mechanisms, as well as of how hailstorms might be modified. Continued physical studies of hailstorms are needed to help answer the many questions which still exist about how hailstorms form and evolve. The need for measurements from the interiors of hailstorms will continue, and the T-28 has shown itself to be a suitable platform for obtaining such measurements. Techniques for analyzing and interpreting the T-28 and other related observations have advanced to the point where meaningful scientific information about hailstorm processes can readily be obtained from well organized field research programs.

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1 May 1971 - 31 December 1979

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6. LIST OF PERSONNEL ASSOCIATED WITH NCAR 182-71

1 May 1971 - 31 December 1979

	Months Worked Under Referenced Contract
Professional	
James H. Boardman	.02
John W. Callahan	.46
Arnett S. Dennis	5.37
Jerry L. Halvorson	38.96
John H. Hirsch	3.84
Gary N. Johnson	45.59
Joseph H. Killinger	18.19
James R. Miller, Jr.	10.52
Dennis J. Musil	50.55
William G. Myers	15.10
Garth A. P. Peterson	4.51
John Prodan	9.94
Wayne R. Sand	51.28
Sumedha Sengupta	.72
Richard A. Schleusener	5.90
James N. Simmons	3.52
Paul L. Smith, Jr.	12.80
	277.27
Technical	
Wallace D. Amborn	.45
Leonard N. Block	8.96
Melvin J. Flannagan	.27
Rudolph D. Flohr	42.93
Kenneth E. Jasper	9.57
Jon E. Leigh	76.17
	138.35
Administrative	
Karen Brown	1.24
Howard L. Elshire	.19
Melvin J. Flannagan	2.43
Sheryl K. Hunter	.90
Patricia A. Lemer	3.31
Kathleen M. Newkirk	1.17
Joie L. Robinson	8.31
Carol Vande Bossche	2.12
Ramona M. Young	1.50
	21.17

LIST OF PERSONNEL ASSOCIATED WITH NCAR 182-71

1 May 1971 - 31 December 1979
(continued)

	Months Worked Under Referenced Contract
Consultants	
Gary N. Johnson	5.44
	5.44
Graduate Students	
Christopher A. Biltoft	3.19
Terry C. Jameson	4.69
Carlton P. Laco	14.65
Jane E. Malo	4.69
Edwin L. May	8.34
R. A. Sarma	10.26
William S. Shaw	12.00
John F. Spahn	9.55
Steven F. Weber	8.81
	76.18
Undergraduate Students	
Robert Buchanan	.23
John Callahan	.06
Andrew Furiga	2.72
John T. Grace	3.73
Jerry L. Halvorson	6.58
Donald Holzwarth	.17
Stephen F. Issacson	.11
Kenneth E. Jasper	10.66
Dennis Johnson	.21
Ronald E. Klein	1.98
Carlton P. Laco	1.02
Edwin L. May	1.93
Trond B. Pedersen	6.34
Steven F. Weber	.91
Roman L. Zylla	.37
	37.02
Total Man-Months	555.43

7. REFERENCES

(References not listed in this section can be found in Section 5.)

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