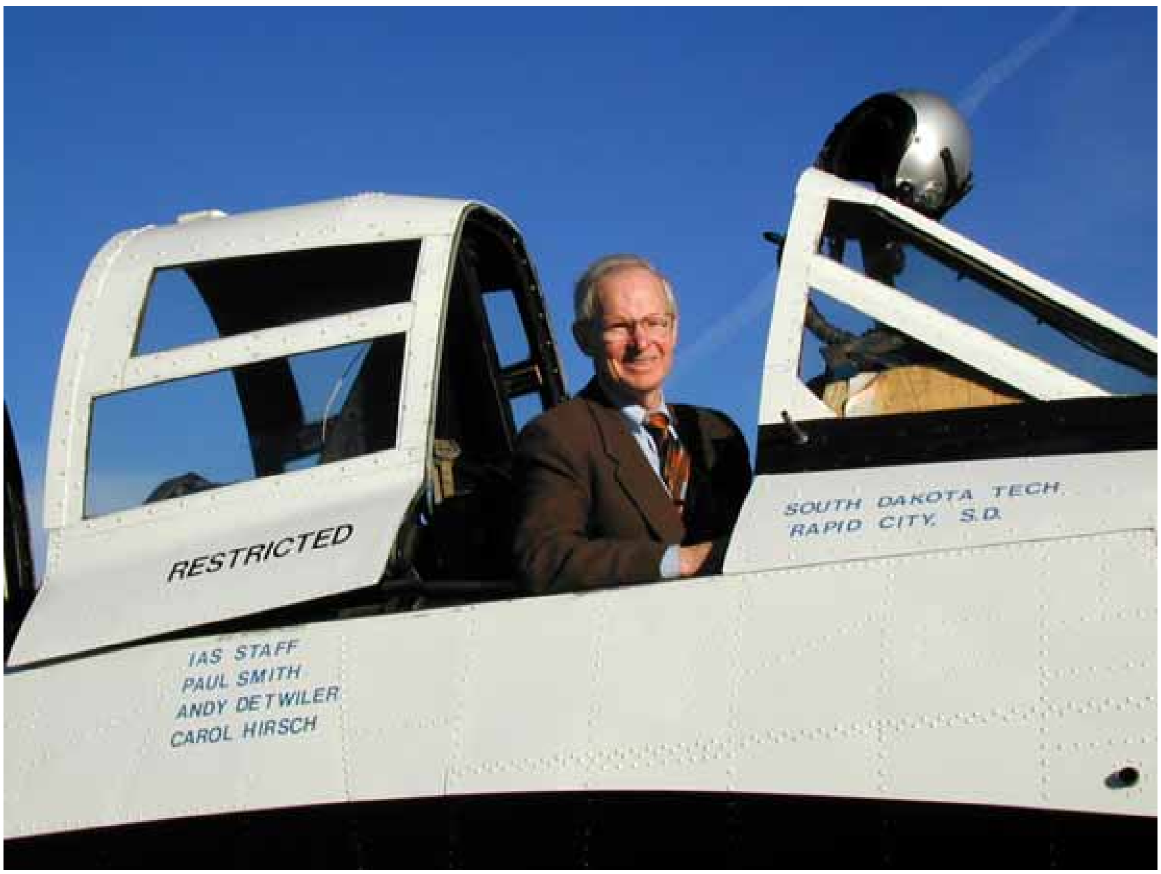
Report SDSM&T/IAS/R-99/05 December 1999

SUMMARY OF
STORM PENETRATING AIRCRAFT WORKSHOP

21-22 October 1999



Edited by: Paul L. Smith and Andrew G. Detwiler

TABLE OF CONTENTS

ABSTRACT

This report summarizes the presentations and discussions at an October 1999 Storm Penetrating Aircraft Workshop. The purpose of the workshop was to identify future scientific needs for a capability to obtain measurements from the interiors of mature convective storms, and potential ways to meet those needs. Science needs for such a capability, provided in recent years by the armored T-28 aircraft, were identified in the areas of cloud and precipitation physics, storm structure and kinematics, atmospheric chemistry, atmospheric electricity, and the verification of radar algorithms. Investigations under the National Aviation Weather Program also have need for such capability. Improved performance characteristics, especially in altitude and endurance, are desirable, and eventually a new platform (probably some military-type jet aircraft, or perhaps an unpiloted vehicle further in the future) will be needed to replace the T-28. The best short-term prospect for obtaining enhanced data from storm interiors involves efforts to enhance the T-28 system.

Cover photo: Dr. Paul MacCready in the cockpit of the T-28

1. Introduction

This report summarizes the presentations and discussions at a Storm Penetrating Aircraft workshop held in Boulder, Colorado 21-22 October 1999. The purpose of the workshop was to provide guidance to the National Science Foundation (NSF) Division of Atmospheric Sciences and the South Dakota School of Mines & Technology (SDSM&T) regarding the future scientific needs for a capability to obtain measurements from the interiors of mature convective storms, and ways to meet those needs. The aforementioned organizations have been providing an armored T-28 aircraft platform to penetrate such storms and obtain measurements, under a series of cooperative agreements that have been in effect since the mid-1980's. The aircraft, owned and operated by the SDSM&T, is provided as a national facility to support research sponsored by the NSF or other agencies. It has been allocated under the same procedures used for other lower atmospheric observing facilities, at the National Center for Atmospheric Research (NCAR) or other universities, supported by the NSF.

As the scientific needs for such measurements evolve and the facility ages, occasional review of the basis for these cooperative agreements is appropriate. Such review might involve consideration of the desirability of extending, modifying, or possibly terminating the operation of the present storm penetrating aircraft; the prospects of replacing the current facility with a different platform; or perhaps an entirely different approach for making observations in storms. The workshop was intended to provide a forum for discussion of such matters. Appendix A contains the workshop agenda, while Appendix B lists the participants in the SPA workshop.

2. Background

The value of a storm penetrating aircraft capability to support atmospheric research was examined by a Special Advisory Panel convened by the NSF Division of Atmospheric Sciences in Rapid City, SD, in May 1985. Appendix C provides a summary of the key recommendations from that panel. Following that meeting, an SDSM&T proposal to NSF led to the initiation of the first T-28 facility cooperative agreement that took effect in 1987.

The advisory panel recognized the need for capabilities beyond those that could be provided by the T-28. As a consequence of the panel recommendations, the issue of storm penetrating aircraft requirements and capabilities was revisited during a 1987 workshop that examined the composition of the aircraft fleet operated by the NCAR Research Aviation Facility. The report of that workshop (Johnson and Cooper, 1989) summarized the various science needs, the capabilities desired of a storm penetrating aircraft, and some potential candidate aircraft. Of the latter, the A-6E aircraft (or EA-6B electronic warfare equivalent) received particular attention during the workshop as a successor storm-penetrating aircraft to the T-28 currently in use.

No new developments in the storm penetrating aircraft (SPA) arena resulted from that workshop, and the operation of the T-28 under NSF-SDSM&T cooperative agreements continued into the 1990's. Meanwhile, at another workshop to examine the NCAR RAF fleet, held in February 1992, the SPA issue was discussed once again (Radke and Spyers-Duran 1992). Continuing need for an SPA capability to support atmospheric research was recognized, and no readily accessible alternative to the T-28 was identified at that time.

3. SPA Workshop Presentations

3.1 Keynote address

In a stimulating keynote address, Dr. Paul MacCready described the early development of his interest in atmospheric studies through model aviation and early experiences in soaring. Dr. MacCready's company, Meteorology Research Inc. (MRI), conducted activities in weather modification through the 1960s. As part of Project Hailswath in Rapid City in 1966, he evolved the idea of developing a piloted storm penetrating aircraft to investigate the interior characteristics of hailstorms. As part of a subsequent NSF-funded Hailstorm Models Project, MRI undertook the work of acquiring and modifying the T-28 for storm penetration work. Robin Williamson played a major role in the engineering work. The preparation work was completed and the aircraft was delivered to the SDSM&T in early 1970 for participation in on-going hail research activities in the Northern High Plains.

Dr. MacCready then went on to describe subsequent MRI work in weather modification and the work his current company, Aerovironment, has been doing in man-powered and solar-powered aircraft; unmanned aeronautical vehicles, including one being developed for flight on Mars at the 100th anniversary of the Wright Brothers flight at Kitty Hawk; and miniature flight vehicles. These developments were illustrated by slides and video demonstrations. As such capabilities evolve, they may be able to assume some of the functions demanded of a storm penetrating aircraft.

3.2 Overview of T-28 facility

The T-28 facility staff then presented an overview of the subsequent development of the T-28 system, its current capabilities, and recent and projected future uses. Paul Smith, T-28 facility manager, began by reviewing the history of the T-28 development following the inception of the idea in Project Hailswath and outfitting of the aircraft by MRI. The principal early uses of the aircraft were under the National Hail Research Experiment and associated endeavors in northeast Colorado from 1970 through 1978. The primary focus of this work was cloud physics, emphasizing hail development, and weather modification. Subsequent involvement in other individual research projects, many supported by NSF and some by other entities, continued through the mid-1980's. These included hail research projects in Canada and Switzerland; continuing work in cloud physics and weather modification; new activities in severe storm investigations and atmospheric electricity; and an initial project involving the correlation of aircraft observations with those from polarimetric radar.

As the difficulty of maintaining continuity of support under the project-by-project mode became increasingly apparent, the NSF convened the Special Advisory Panel in May 1985 to assess the situation. Their recommendations led to the initiation of the series of facility cooperative agreements under which the T-28 has been operated since 1987. Research areas supported by the aircraft functioning in the facility mode have included hail and weather modification research (that has declined in the late 1990's); increasing activities in atmospheric electricity and verification studies associated with the polarimetric radar; and enhanced interest in studies related to aviation weather hazards, including hail and convective turbulence.

The T-28 is one of several NSF-supported lower atmospheric observing facilities that typically receive about two requests for project support each year, with an average of one allocation for field work in a typical year. The annual project flight hours have exceeded 100 hours in only one year. The T-28 is not well-suited for wintertime work, but has supported one wintertime investigation of the potential for production of aircraft-produced ice particles (APIPs).

Charles Summers, T-28 chief pilot and chief of maintenance, then reviewed the status of the T-28 aircraft and avionics. The T-28 is a single (radial) engine aircraft (Fig. 1) armored for protection from hail up to 3 inch (7.6 cm) diameter encountered in flight and resistant to the effects of lightning strikes. Anti-icing is provided for the propeller and carburetor intake, but it has no structural de-icing capability. Experience has shown that the T-28 can continue to operate effectively with 2-3 cm of accumulated structural icing; in summertime operation, descent below the 0°C isotherm suffices to melt off accumulated ice, with attendant interruption in the acquisition of the desired data from the storm interiors. The general maintenance reliability of the T-28 is indicated by the fact that it has been able to fly about 98% of the requested research missions in recent years. The T-28 airframe has logged only 5520 flight hours; the same engine type is used in DC-3s, many of which are still in service, so rebuilt engines are obtainable if needed.

The aircraft can reach about 25,000 ft (7.6 km) altitude, but would have very little on-station time at that level. Useful operating altitudes are generally limited to about 23,000 ft (7.0 km) or below. Flight durations of more than 3 hours are possible; however, fuel consumption rises at altitudes above about 14,000 ft (4.3 km) when the high-speed supercharger must be engaged. Consequently, useful on-station times at higher altitudes seldom reach 1.5 hours.

The payload available for user instruments, beyond the standard complement of instruments listed in Table 1 below, is currently about 70 kg. A plan to replace the current heading indicator on the T-28 with a horizontal situation indicator will eliminate the need for primary and backup rotary inverters that supply power to the heading indicator; this would free up another 25-30 kg. The flight endurance may also be extended by about 0.5 hr by providing an optional fuel bladder that could be carried in the rear cockpit. The added fuel weight of some 85 kg would have to be balanced against the need for user payload instruments or the option of removing part of the standard instrument complement.

Table 1. Instrumentation Table

VARIABLE	INSTRUMENT	RANGE	ACCURACY	RESOLUTION (as recorded)	NOTES
Static Pressure	Rosemount 1301-A-4B	0-15 psi (0-103 kPa)	±0.015 psi (±0.1kPa)	0.0002 psi (0.002 kPa)	
	Rosemount 1301-A-4B	5-15 psi (35-103 kPa)	±0.015 psi (±0.1kPa)	0.0002 psi (0.002 kPa)	
Total Temperature	Rosemount 102AU2AP	-30 to +30°C	±0.5°C	0.001°C	• Platinum wire • 2 s time constant
	NCAR Reverse Flow	-30 to +30°C	±0.5°C	0.001°C	• Platinum RTD element • Several seconds time constant
Cloud Water and Cloud Droplets	DMT Liquid Water Concentration	0 - 4 g/m^3	±20%	0.0001 g/m^3	• Sampling rate 4 l/km • Sensitive to droplets µm<40 diameter
	Particle Measuring Systems, Inc. Forward Scattering Spectrometer Probe	Size 1 < 67 µm Concentration 0 - 2000 droplets/cm^3	±1 size channel in size and ±1% in concentration at ~50/cm^3	1 size channel	• 15 discrete size channels spread over an adjustable range • Sampling rate 300 cm^3/km • Accuracy of computed liquid water concentration ~±50%. Depends on processing.
Precipitation Particle Sizes And Concentrations	Particle Measuring Systems, Inc. 2D Cloud Probe	Size 25 - 800 µm	±25 µm	25 µm	• Computed ice and water mass concentration can vary ±50% with processing technique • Sampling rate: 0.05 m^3/km; DAS can accept ~250 particles/s (2500/km)
	SPEC High Volume Precipitation Spectrometer	0.2 - 48 mm size	0.2 mm vertical 0.4 mm horizontal	0.2 mm vertical 0.4 mm horizontal	• Volume sampling rate ~1 m^3 s^{-1} (~10 m^3 km^{-1})
	SDSM&T Hail Spectrometer	Size 4.5 mm - 4.5 cm; Concentration 0 - 100/m^3	±1 size class	1 size class	• 14 size classes, and images • Sampling rate 100 m^3/km
Electric Field	NMIMT Model E-100 DC Electric Field Meter	top/bot ± 650 wingtips ±3200 5th and 6th ±340 kV/m		(coarse resolution) 0.01 kV/m	

Aircraft Motion	Humphrey SA09-D0101-1 Vertically Stabilized Accelerometer	+3, -1 g pitch –50° to 50° roll –50° to +50°	0.004 g's 0.2° 0.2°	0.00006 g 0.002° 0.002°	
	Rosemount 1301-D-1b Dynamic Pressure	–3 to +3 psi (–20 to +20 kPa)	±0.1%	0.0001 psi (0.0006 kPa)	
	Rosemount 1221-F-2A Dynamic Pressure	–2.5 to +2.5 psi (–18 to +18 kPa)	±0.1%	0.0001 psi (0.0006 kPa)	
	Giannini 45218YE Manifold Pressure	0 to 50 in Hg	±2%	0.008 Hg (0.03 kPa)	• Used in backup vertical velocity calculation
	Ball 101A Variometer (rate of climb)	±6000 ft/min (30 m/s)	±5%	0.2 ft/min (1 mm/s)	Used in backup vertical wind calculation
	Crossbow 3-Axis Fixed Accelerometer	±4 g in all 3 directions	±0.2%	3.05 x (10^{-4} g's)	
Aircraft Location	Trimble 2000 Approach GPS	(global)	30 m	18 m	Upgraded for IFR certification
NOTE: Many of these instruments do not behave as ideal instruments. The use of one measure of accuracy over the entire range of measurement is, in many cases, questionable. An accuracy representative of the most useful part of the range is given here.					

Gary Johnson, instrumentation engineer, described the meteorological instrumentation (Table 1) and data acquisition system on the T-28. This normal instrument complement provides measurements of state variables (p,T); vertical winds; hydrometeor characteristics for particles from cloud droplets through hailstone sizes; and ambient electric fields. The newest additions include a DMT cloud water sensor and a high volume precipitation spectrometer.

Various aircraft navigation and performance variables are also recorded for use in data analysis. The data acquisition is handled by a Pentium II category computer with interfaces to all of the primary meteorological and navigational instruments on the aircraft. Recording is presently done on an internal hard drive. Key variables are also telemetered to the ground during flight to assist scientists directing the T-28 flights in deciding how to proceed with their investigation.

Qixu Mo, facility postdoctoral scientist, described recent advances in the electric field measuring capabilities of the T-28 system. Through detailed analysis and intercomparison flights with the New Mexico Institute of Mining and Technology "SPTVAR" aircraft, a system configuration has been established and calibrated to deal with the problems caused by charge building up on the airframe and corona discharges from the aircraft in the presence of strong ambient fields. Details of this work have recently been published (Mo *et al.* 1999).

Andy Detwiler, facility scientist, then summarized the recent history of field projects supported by the T-28 (Table 2). The emphasis of recent projects has been on studies of storm electrification; *in situ* observations to support development and validation of hydrometeor classifiers for polarimetric radars; and investigations of turbulence associated with convective storms to support the National Aviation Weather Program. This presentation was followed by a video compiled by Rand Feind, facility computer specialist, from the most recent summer 1999 Turbulence Characterization and Detection Project.

Table 2. Recent Field Projects Requiring an SPA

1993	North Dakota Thunderstorm Experiment (NDTE)
1994-1995	Verification of Rotation in Tornadoes Experiment/Measure, Interpret, and Ground-truth Hydrometeors in Thunderstorms (VORTEX/MIGHT)
1994	Texas Experiment in Augmenting Rainfall through Cloud Seeding (TEXARC)
1994-1998	Mono Lake APIPS Studies (MOLAS)
1997	Electric Field Measurements - coordinated with Langmuir Laboratory, NMIMT, Socorro, NM.
1998	Microphysical/Electric Field Instrumentation Enhancement – coordinated with CSU-CHILL, Greeley, CO.
1999	Turbulence Characterization and Detection Program

4. Working Groups

The workshop then divided into three working groups, to deal with issues of science needs for a storm penetrating aircraft (SPA), the capabilities required of such an aircraft, and potential platforms. Summaries of the discussions in each working group appear below. Applicable comments from plenary discussions have been incorporated under the various topics to simplify the structure of this report.

4.1 Science needs

This working group, chaired by Jeffrey Stith, discussed the various areas of scientific need for observations from the interiors of mature convective storms. There is no alternative to *in situ* measurements for some aspects of research related to convective storms. For example, radar echoes tend to be dominated by the larger hydrometeors present and provide little information about the accompanying smaller particles (cloud droplets, precipitation embryos). Observations of the smaller particles are needed to understand the conversion of cloud water (and cloud ice) to precipitation particles of various sizes and also the generation of the particles that enter storm anvils. Highlights of the discussion can be summarized in five main topic areas.

4.1.2 Cloud and precipitation physics

The primary research areas under this heading requiring observations from the interiors of mature convective storms involve studies of:

- The processes of growth of hydrometeors in the storms.
- The relationships (or interactions) between precipitation particles and cloud water (and cloud ice, where relevant) inside the storms.
- The initiation and development of ice particles in these clouds (a long-standing issue that has yet to be well understood).
- The role of relative humidity (over ice vs. over water) in the hydrometeor development inside the storms. New laboratory data suggest that this role may be significant, but reliable airborne observations of relative humidity within-storm have not heretofore been available.
- The origin of hail embryos and the growth of hail (which was the basic impetus for the initial development of the T-28, and is still an open question). *In situ* data will be essential if recent indications that hail develops in very narrow zones (100 m or less) are correct.

For many such questions, observations from storm interiors at altitudes that reach at least the –40°C level are needed.

4.1.3 Storm structure and kinematics

Observations of storm structure and three-dimensional internal motions are needed to support research in several areas:

- The structure and etiology of tornadoes and waterspouts. Of particular interest are
  - (1) the sizes and concentrations of droplets in the associated funnels, and
  - (2) wind measurements, since vortex winds tend to centrifuge particles outward and distort the wind estimates obtained by remote sensing techniques.
- The occurrence and distribution of turbulence in association with convective storms. This is a continuing question, of special interest to the National Aviation Weather program.
- Studies of microphysical, chemical, and electrical processes.
- Within-storm observations of winds, turbulence and microphysics, for verification of results from storm models and NWP models that include explicit storm processes.

4.1.4 Atmospheric electricity

The fundamental questions about charge generation in thunderstorms will require observations from storm interiors, such as those that could be obtained by a storm penetrating aircraft equipped to measure ambient electric fields and particle charges. Areas of scientific interest include:

- The formation and decay of lightning in storms, and possible triggering of lightning by the aircraft.
- The formation of NO_x and its transport in these storms, a question that crosses the boundaries of atmospheric electricity and atmospheric chemistry.
- The formation of sprites and anomalous luminous events.
- The validation of storm models that include electrification processes.

4.1.5 Verification of radar algorithms

The capability to classify hydrometeors in storms using remote sensing observations from polarimetric radars has been improving for two decades. *In situ* data from an SPA are needed to support the continued development and validation of these algorithms. A capability to "retrieve" storm internal structures from Doppler radar data has evolved, and observations are needed to validate the retrieval products. The required observations include particle types (including phase), sizes, and concentrations as well as wind and particle motions. Verification of particle phase transitions (drop freezing, hailstone melting) is also of importance in validating these algorithms.

4.1.6 Atmospheric chemistry

As noted in Section 4.1.3, the study of lightning chemistry (particularly NO, NO_x) is of substantial importance to both the atmospheric chemistry and atmospheric electricity communities and requires observations from storm interiors. Also of importance are:

- The transport of various chemical substances in and by convective storms.
- Studies of heterogeneous chemistry and particle formation.
- The electromagnetic spectra involved in photochemical processes.
- Observations to verify results from storm models that include chemical processes.

4.1.7 Other

There is an ongoing need for studies related to the National Aviation Weather Program, such as efforts to improve understanding of the capabilities and limitations of commercial airborne weather radars. Observations of other dramatic atmospheric phenomena may be appropriate for an SPA platform. These include volcanic emissions, fires and smoke plumes from such things as biomass burning, and even military plumes generated by explosives.

4.2 SPA capabilities

Discussion in the Capabilities group, chaired by Perry Wechsler, centered around general platform capabilities and instrumentation issues, with some attention given to desired software and data product questions.

Principal technical performance capabilities desired of a storm penetrating aircraft are summarized in Table 3. The ability to withstand hail and lightning strikes is important, as are ruggedness and stability in turbulence. Substantial hail damage has occurred to non-hail-protected aircraft involved in convective-storm investigations in the northern High Plains (CCOPE, 1981; North Dakota Cloud Modification Project, 1984 and 1995; North Dakota Tracer Experiment, 1993). The requirement to withstand hail would require substantial modification of any platform selected.

A combination of fast access to the storm areas and slow penetration speeds would permit more time inside the storms. Such capability also would permit more on-station time, moderate the problem of hail impacts, and help to maintain the integrity of current particle-sampling technologies. Greater on-station time would not only increase the potential for success in waiting for a storm to develop but also enhance the possibility of shifting to an alternate target.

The matter of de-icing requires some study; while it would clearly be desirable, the conflict between the need to withstand hail and the fragility of de-icing equipment does not admit of a ready solution. Preliminary tests of the material composing a weeping-wing anti-icing system are encouraging.

Adequate space should be provided for the requisite measuring equipment and data systems. The ability to carry one or more observers would be useful for many types of investigations, and could increase the ability to operate independently of ground direction. The advantages of an observer need to be weighed against safety considerations in severe-storm penetrations. A two-way telemetry capability might substitute for part of the desired observer functions (mission decisions, scientific observations) to permit safer operations in more hazardous conditions.

Table 3: Desired SPA Performance Capabilities

Altitude:	To reach at least –40°C, with useful rate of climb through at least 30,000 ft (9.1 km)
Crew:	Observer desirable; Pilot only preferred, for safety and instrument payload considerations
Deicing / Anti-icing	Sustained flight in known icing conditions
Electrical "hardening":	Isolation of fuel cells causing buildup of static charge
Endurance:	3-5 hours on station
Hail resistance:	Withstand 3 in (7.6 cm) hailstones in flight
Lightning resistance	
Payload:	200 kg or more for instrumentation
Power:	2 kW or more for instrumentation
Space:	For instrumentation, data systems, and possibly observers

In general, the capabilities of a storm penetrating platform should include the ability to provide measurements of the quantities listed in Table 4, including state variables, hydrometeor characteristics, three-dimensional winds, the platform location and its attitude and motions. Additional measurements of electrical quantities (fields, particle charges) and chemical variables will be needed for some projects. The discussion favored a modular approach to providing the measurements, for several reasons:

1. By including only those instruments necessary for a particular project, the payload/power capabilities of the platform are maximized.
2. Careful specification of the module interface requirements facilitates development and integration of user-supplied instrumentation.
3. General module specifications allow instrument packages to migrate between platforms.

The problem of wetting of temperature sensors inside clouds has yet to be adequately resolved, and a means of reliably measuring the humidity in storm interiors has yet to be devised. The primary problem in humidity measurement is the difficulty of aspirating the sensor without interference from accreted water or ice. Effort is needed to enhance confidence in the various hydrometeor sensors.

The operation of a storm penetrating platform generally requires a variety of supporting data, since the platform alone rarely will provide all of the needed observations for a research investigation. Needed supporting capabilities are likely to include a good platform tracking capability, for which the GPS system has proven to be adequate. The services of a quantitative ground radar for guiding penetrations into mature storms has been found useful, and essential in storms that may contain sizeable hail. The radar data also provide a valuable 3-dimensional framework within which to orient and interpret the observations from penetrating platform.

Table 4. Desired Measurement Capabilities		
Category	**Quantity**	**Comments**
State variables	Pressure	Redundancy desirable (also for T)
	Temperature	Sensor wetting issue inadequately resolved
	Water vapor (Humidity)	Suitably robust sensor not identified; aspiration problem requires solution
Hydrometeors	Types	Determination of liquid, ice, or mixed-phase desired
	Sizes	Cloud droplets through hailstones
	Shapes	For particle identification, radar characteristics
	Concentrations	Large sampling volume desirable
	Masses	Inference from image data needs improvement
Winds	Vertical wind Horizontal wind	} including gusts
Electrification	Electric fields	
	Charge on hydrometeors	
Chemical	Trace constituents	CO, CO_2, NO, NO_x, ozone, SF_6 tracer
Location of platform	3-dimensional	GPS adequate for horizontal position
Attitude and motion	Angle of attack Heading Pitch Roll Airspeed Rate of climb	

In the absence of observers in the platform, the ability to telemeter key data to the ground for use by the scientists guiding the penetration tracks is extremely useful. Means for coordinating multiple observing systems, such as other aircraft, sounding systems, or mobile ground crews, is usually important in multi-facility field operations of the sort in which the storm-penetration system is likely to be involved. This requires a ground-to-air communication capability with some kind of control center function. In complex situations coordination could be aided by the availability of additional flight crew on the SPA.

In studies of storm electrification, a three-dimensional lightning mapping capability can permit directing the flights into the most relevant areas to investigate electrical charge accumulation. Electrical studies typically also require capability for measurement of ambient electric fields as well as measurement of particle sizes, concentrations and charges.

In the area of atmospheric chemistry, it was noted that mounting and operating air chemistry devices on a SPA platform presents unique challenges. In addition to the need for minimizing size, weight and power consumption, these devices must also be ‘stand alone’ to a large degree. Some control may be possible using telemetry, but for the most part this equipment must operate accurately and safely without intervention. The ability to dispense tracer materials (e.g. SF_6 or radar chaff) can be useful for some investigations. Slow penetration speeds facilitate the longer integration times needed for some chemical measurement systems. Slow speeds also increase the time inside the storm and thereby the amount of useful data.

The need for supporting personnel, data systems and software to put the data into form suitable for analysis as well as integration and synthesis of data from other systems should not be overlooked. This includes both the real-time acquisition, telemetry and display software, and the data product.

- *Real-Time Software*: The acquisition, telemetry and display software must be closely linked to the modular instrumentation approach. This results in efficient data transmission as well as self-documenting data acquisition and recording.

- *Data product*: The data product must be a ‘user friendly’ format such as NetCDF. This allows use of many data processing packages which have already been written as well as simplifying the creation and use of filters that can produce ASCII or other desired outputs.

Finally, it was noted that the range of observational capabilities required might actually require more than one storm-penetration platform, with different platforms providing different sets of capabilities.

4.3 Platforms

The Platforms group, chaired by Arnold Ebneter, discussed general characteristics as well as potential T-28 enhancements and possible alternative platforms.

4.3.1 General considerations

There is a general break at an altitude of about 30,000 ft (9.1 km) in the types of aircraft that can operate in the troposphere. Operation at higher altitudes will require jet aircraft, which generally operate at higher penetration speeds. The higher-performance aircraft generally cost more to operate, and require longer runways, more hangar space, and increased ground support in terms of equipment and maintenance staff.

There is also a "stress break", with general aviation aircraft limited to about +3.8 g rating (though some utility aircraft are rated to +4.4 g). To obtain a sturdier airframe requires an aircraft designed for military applications.

For a military-type aircraft, it is desirable to find something that is near the end of its military service life but not yet condemned to the boneyard, so that the spare parts system is still functioning. Some military support for operation and maintenance of the aircraft might be available. On the other hand, aircraft which are expected to have another 10 to 20 years of useful military service may not be accessible to the atmospheric research community. A major concern for keeping high-performance military aircraft in operation will be frequent-use or expendable items, such as drag chutes or igniters for seat ejectors, which must be available in a timely manner.

Penetration of storms by an aircraft at its maximum operating altitude is not likely to be practical because of drag due to instrument installation as well as controllability considerations. Payload flexibility would be an asset, which suggests the desirability of modular instrumentation packages. The question of releasing expendable sensors (e.g. dropsondes) would need review with each aircraft type under consideration. Another concern is the potential effect of lightning on avionics in some of the newer aircraft systems.

The possibility of a collaborative arrangement involving multiple agencies and multiple institutions should be considered, as it could involve greater use of the facility at lower unit cost to each participant. The tradeoff between a full-scale storm penetrating capability, including the ability to withstand sizeable hail, versus a lesser storm penetration capability that might yield a broader capability to support a greater variety of projects, should be examined. Pilot training and information provided to the pilot of the storm penetrating aircraft during operations are important for successful operations over the long term.

In recent times certification questions, with respect to aircraft operated as public aircraft, have arisen. The funding trail, from federal or other sources to the ultimate operator of the facility, becomes a concern. Operation under the Restricted category (FAA Part 91), as the current T-28, requires a type certificate data sheet for the aircraft. Operation in the Experimental category, as the New Mexico Tech "SPTVAR", is renewable annually but involves a list of conditions that can be somewhat constraining.

4.3.2 T-28 enhancements

The feeling was expressed that the T-28 continues to provide a cost-effective storm penetration platform. It fills a unique and valuable science role and can continue to do so, even in its present configuration. The age of the aircraft is a concern, but flight hours have been limited and replacement engines are available if needed. Advances in technology make instruments and data systems smaller, lighter, faster, and less power-hungry, so some of the T-28 constraints become less serious over time. Altitude and flight duration limitations constitute the major drawback, with the inability to operate over water more than a few miles from land a concern for some situations. One option for enhanced storm-penetration capability is to enhance the existing T-28 SPA.

- The addition of *wing extensions* to the T-28 would provide added lift, yielding greater payload and altitude capabilities, along with additional fuel capacity which would increase the available flight endurance. Such extensions have been provided for a photographic version of the T-28, and the engineering work done to accommodate that might facilitate further modification of the present T-28 SPA facility.

- Further efforts at *weight and drag reduction* through modification of external instrumentation mounting schemes would also help in this direction.

- The addition of an *extra fuel bladder* in the rear cockpit could provide an additional half hour of on-station time for the aircraft.

- A "*weeping wing" anti-icing system* would widen the range of flight environments in which the T-28 could operate.

- Improvements in the *wind and turbulence measuring capabilities* would make the T-28 more useful for some investigations.

It was suggested that a systematic end-of-life study is needed for the T-28, to provide a better understanding of the conditions under which it can continue to be operated into the 21st century.

4.3.3 Candidate jet aircraft

It was pointed out that the Citation II operated by the University of North Dakota can provide some storm-penetration capabilities, though not where sizable hail might be encountered. It has anti-icing provisions, can reach 43,000 ft (13 km) and has a relatively slow penetration speed (160 kts IAS) for a jet aircraft. Several potential candidates for a replacement storm penetrating aircraft were discussed at the workshop. Among them are:

- The *Lockheed T-33*. As of the early 1990's, over 1000 of these aircraft were in service world-wide. Its J-33 centrifugal flow engines handle hail well, and aircraft are available for prices in the range of $200,000. (L. Radke noted that a T-33 that has been used for research studies is in the possession of the Canadian National Aeronautical Establishment.) The two-seater version provides space that could be used for sensors or recording equipment, and additional equipment space is available in the nose area. The T-33 would provide rapid access to the regions of interest but can operate at indicated airspeeds of 200 knots or even slower to facilitate operation of sensing equipment and reduce the potential extent of hail damage.

  Concerns about the T-33 include its excessive fuel consumption and limited climb and endurance characteristics. Some T-33's have been re-engined with more modern and less thirsty PW300 turbofans, gaining improved performance. However, the PW300 may be more susceptible to hail damage than the J-33. It was also noted that the pressurization capability in the T-33 is limited. The radome's ability to withstand hail is uncertain, but a strengthened fiberglass radome (which would degrade the on-board radar performance) could be used instead.

- An *F-106* was used by NASA Langley for lightning research in recent years. The F-106 production ended in 1960, and it has been out of military service since the late 1980s. The aircraft has J-75 engines, and two-seat versions were produced (J. Huning determined that the NASA Langley aircraft is now in a museum).

- The *A-10* has several desirable characteristics, including its rugged design with provision for carrying external stores mounted on wing hard points. About 700 of these aircraft were produced through the early 1980s, and many are still in service. Its TF-34 engines are still in production. Thirty two-place versions were built. Some of these aircraft are now with Air Force Reserve or Air National Guard units, but others are being recalled from the boneyard so the availability to the scientific community would have to be ascertained.

  A substantial A-10 scientific payload capability can be obtained by removing the large gun, which weighs something over 2000 kg. However, the result might be a center-of-gravity problem that would require carrying some dead-weight ballast. The altitude limits are uncertain, and the ability of the engine to ingest hail, as well as ice that might flake off the nose and the wings, has yet to be established.

- The *A-6E/EA-6B* that was examined in some detail at the Second NCAR Fleet Workshop probably needs to be retained under active consideration. Some are still in service. They have rugged external mounting points suitable for instrumentation. These aircraft are somewhat difficult to operate at speeds less than 300 kts.

Aircraft that were not thought to be particularly suitable candidates for an SPA include:

- The *F-101*, which was used for some Project Roughrider studies. These aircraft have been out of service since the mid-1970s. Though its J-57 engines are resistant to hail, the F-101 is a high-speed, swept-wing aircraft with no wing stations readily accessible. It also requires an expendable drag chute for landing.

- The *F-4* was produced in great numbers (more than 5,000) through about 1979, and some are still in service. However, its J-79 engines are susceptible to hail ingestion.
- The *S-3* was another suggested candidate that uses the same TF-34 fan jet engines as the A-10. Some 187 S-3A's were built by the time production ended in 1978. Some of the S-3A's were later retrofitted as S-3B's and ES-3A's. This twin-engine aircraft is well suited to reconnaissance and submarine-chasing missions, but further investigation would be required to establish its suitability for use as an SPA.

- Several *propeller-driven aircraft* were discussed, including the Beech 36, S-2, E-2, OV-1 and OV-10. Some of these might be accessible, but none of them have enough altitude capability to represent a substantial improvement over the T-28 system.

Unmanned aeronautical vehicles (UAV) were also discussed. The current UAV systems have a life expectancy that is too short to warrant serious consideration for a storm-penetrating platform. Furthermore, protection of these current vehicles for penetration into regions of hail or lightning would add too much weight to make them practical. Evolution of UAV capabilities is anticipated, however, and they may be able to satisfy some of the requirements for an SPA in the future. Operation of instruments on other SPA platforms like the T-28, including control-by-telemetry, can serve to provide experience and prototype testing for instruments that might eventually be carried on the UAV platform.

5. Summary and Suggested Actions

For some aspects of convective-storm research, there is no alternative to *in situ* measurements. Thus a storm-penetrating aircraft (SPA) or some equivalent capability is needed to support such research. On-going science areas that require this kind of capability include:

- Cloud and precipitation physics
- Storm structure and kinematics
- Atmospheric electricity
- Verification of radar algorithms
- Atmospheric chemistry

Investigations under the National Aviation Weather Program also have need for an SPA capability.

The armored T-28 can fulfill some of the scientific requirements, but falls short in altitude and endurance capabilities. Efforts to upgrade the T-28 in these respects may be fruitful, since for many of the requirements there is no currently available alternative. To provide increased capability, and to replace the T-28 when its operation is no longer viable, will require a development program beginning with detailed investigation of possible options. Most of the potential candidates involve aircraft originally designed for military service, though no single preferred platform was identified. Eventually unmanned aeronautical vehicles may provide the needed capabilities, but their evolution to that stage is a long way in the future. In the meantime, operation of a piloted SPA like the T-28 or a successor can meet many of the scientific requirements while prototyping instrumentation and telemetry control techniques that could eventually apply to a UAV platform.

The following actions are suggested by the discussions at the Workshop:

- Investigate, and implement as appropriate, potential T-28 upgrades, including
  - Wing extensions
  - Internal fuel cell
  - Weight/drag reduction

- Conduct a systematic End-of-Life study for the T-28.

- Initiate a detailed investigation of the requirements, boundaries and options for candidate platforms to replace the T-28 and provide enhanced SPA capabilities.

References

Johnson, W.B. and W.A. Cooper, 1989: Meeting Review: The Second NCAR Research Aircraft Fleet Workshop. NCAR/TN-332+PROC, National Center for Atmospheric Research, Boulder, CO, 84 pp.

Mo, Q., R.E. Feind, F.J. Kopp, and A.G. Detwiler, 1999: Improved electric field measurements with the T-28 armored research airplane. *Journal of Geophysical Research,* **104**, 24,485-24,497.

Radke, L.F. and P. Spyers-Duran, 1992: Meeting Review: Third NCAR Research Aircraft Fleet Workshop. NCAR/TN-374+PROG, National Center for Atmospheric Research, Boulder, CO, 79 pp.

APPENDIX A: Workshop Agenda

Workshop on Storm Penetrating Aircraft

Co-Chairs: Dave Carlson, NCAR ATD; Paul Smith, SD School of Mines

Location: NCAR Foothills Laboratory, 3450 Mitchell Lane, Boulder, CO [off 47th St. near Longmont diagonal].

Plenary sessions in Building 2, Room 1022

Thursday morning (21 October):

0830 – 0845:	Introductory remarks
0845 – 0915:	Keynote address: Paul MacCready
0915 – 0930:	Discussion
0930 – 0945:	How we got where we are – T-28 history (Paul Smith)
1015 – 1115:	Where we are – current T-28 capabilities, recent uses, and future prospects Aircraft and avionics (Charlie Summers) Instrumentation and data acquisition (Gary Johnson) Electric field measurements (Qixu Mo) Recent and planned projects (Andy Detwiler) Video (Rand Feind)
1115 – 1215:	Introduction of Working Groups Science needs (Jeff Stith, group leader) Required SPA capabilities (Perry Wechsler, group leader) Potential platforms (Arnold Ebneter, group leader)

Thursday afternoon (21 October):

1315 – 1445:	Working group sessions (above three topics) Science needs: Room 1002 Capabilities: Room 1003 Platforms: Room 2133
1515 –	Working groups continue T-28 inspection (optional) NCAR RAF Hangar, Jeffco Airport

Friday morning (22 October):

0830 – 0900:	Plenary discussion
0900 – 1115:	Working groups
1115 – 1200:	Plenary (summary and recommendations)

APPENDIX B: List of Participants

Beasley, Bill
University of Oklahoma
100 E. Boyd, Rm. 1310
Norman OK 73019
email: wbeasley@ou.edu

Bluestein, Howie
University of Oklahoma
100 E. Boyd, Rm. 1310
Norman OK 73019
email: hblue@rossby.metr.ou.edu

Boe, Bruce (mail submission)
ND Atmospheric Resource Board
900 East Blvd. Ave.
Bismarck ND 58505-0850
email: bboe@water.swc.state.nd.us

Carlson, Dave
NCAR
P.O. Box 3000
Boulder CO 80307
email: dcarlson@ucar.edu

Carr, Fred (E-mail submission)
School of Meteorology
University of Oklahoma
100 E. Boyd St., Rm 1310 SEC
Norman OK 73019
email: fcarr@ou.edu

Cooper, Al
NCAR
P.O. Box 3000
Boulder CO 80307-3000
email: cooperw@ucar.edu

Detwiler, Andy
Institute of Atmospheric Sciences
SDSM&T
501 E. St. Joseph Street
Rapid City SD 57701-3995
email: andy@ias.sdsmt.edu

Dye, Jim
NCAR
PO Box 3000
Boulder CO 80307-3000
email: dye@ucar.edu

Ebneter, Arnold
18428 146th Ave NE
Woodinville WA 98072
email: N5125C@aol.com

Feind, Rand
Institute of Atmospheric Sciences
SDSM&T
501 E. St. Joseph Street
Rapid City SD 57701-3995
email: feind@ias.sdsmt.edu

Hubbert, John
Research Associate
Elec. & Computer Engineering
C109D Engineering
Colorado State University
Fort Collins CO 80523
email: hubbert@engr.colostate.edu

Huning, Jim
Division of Atmospheric Sciences
National Science Foundation
4201 Wilson Blvd., Rm 775S
Arlington VA 22230
email: jhuning@nsf.gov

Johnson, Gary
Institute of Atmospheric Sciences
SDSM&T
501 E. St. Joseph Street
Rapid City SD 57701-3995
email: garyj@ias.sdsmt.edu

Kennedy, Pat
Dept. of Atmospheric Science
Colorado State University
Ft. Collins CO 80523
email: pat@lab.chill.colostate.edu

Kessinger, Cathy

NCAR
P.O. Box 3000
Boulder CO 80307-3000
email: kessinge@ucar.edu

Knight, Charlie
Mesoscale & Microscale Meteorology Div.
Microphysics Group
NCAR
PO Box 3000
Boulder CO 80307
email: knight@ucar.edu

Knight, Nancy
NCAR
PO Box 3000
Boulder CO 80307-3000
email: knightn@ucar.edu

List, Roland
Department of Physics
University of Toronto
60 St. George St.
Toronto M5S IA7
Ontario CANADA
email: list@atmosp.physics.utoronto.ca

MacCready, Paul
Aerovironment, Inc.
222 E. Huntington Drive
Monrovia CA 91016
email: ccm@aerovironment.com

Miller, L. Jay
NCAR
PO Box 3000
Boulder CO 80307
email: ljmill@ucar.edu

Mo, Qixu
Institute of Atmospheric Sciences
SDSM&T
501 E. St. Joseph Street
Rapid City SD 57701-3995
email: qmo@ias.sdsmt.edu

Nelson, Steve
Program Director for Mesoscale Dynamic Meteorology
Division of Atmospheric Sciences
National Science Foundation
4201 Wilson Blvd.
Arlington VA 22230
email: snelson@nsf.gov

Radke, Larry
NCAR/ATD/RAF
P.O. Box 3000
Boulder CO 80307
email: radke@ucar.edu

Rhoda, Dale
Lincoln Laboratory
Massachusetts Institute of Technology
244 Wood Street
Lexington MA 02420-9108
Phone (781) 981-5500
email: daler@LL.MIT.EDU

Rose, Lynn
AEROMET, Inc.
P.O. Box 701767
Tulsa OK 74170-1767
email: lynnr@aeromet.com

Schleusener, Richard
315 Berry Pine
Rapid City SD 57702
email: dickelaine@aol.com

Schuur, Terry
National Severe Storms Laboratory
1313 Halley
Norman OK 73069
email: Terry.Schuur@nssl.noaa.gov

Sinclair, Pete
Atmospheric Science
Colorado State University
Fort Collins CO 80523

Smith, Paul
Institute of Atmospheric Sciences
SDSM&T
501 E. St. Joseph Street
Rapid City SD 57701-3995
email: psmith@ias.sdsmt.edu

Stith, Jeff
NCAR
PO Box 3000
Boulder CO 80301
email: jstith@raf.atd.ucar.edu

Summers, Charlie
Institute of Atmospheric Sciences
SDSM&T
501 E. St. Joseph Street
Rapid City SD 57701-3995
email: rapidtrail@aol.com

Warner, Tom
4435 West Glen Place
Rapid City SD 57701
email: tom@sharonandtom.com

Wechsler, Perry
Atmospheric Sciences
University of Wyoming
Laramie WY 82071
email: wex@uwyo.edu

Winn, Bill
Department of Physics
NMIMT
Socorro NM 87801
email: winn@loon.nmt.edu

Woodley, Bill
Woodley Weather Consultants
11 White Fir Ct.
Littleton CO 80127
email: woodley@compuserve.com

Zimmerman, Pat
Institute of Atmospheric Sciences
SDSM&T
501 E. St. Joseph Street
Rapid City SD 57701-3995
email: zimmer@ias.sdsmt.edu

Zrnić, Dusan
National Severe Storms Lab
1313 Halley Circle
Norman OK 73069
email: dusan.zrnic@noaa.gov

Appendix C:
Summary of Conclusions and Recommendations from the NSF Special Advisory Panel[18] Meeting in Rapid City, South Dakota, on 13-14 May 1985

The NSF Special Advisory Panel conclusions and recommendations were:

1. That the T-28 has had wide usage for storm core penetration in both national and international programs.

2. That major advances have been made in our knowledge of storm processes as the result of T-28 data in combination with other observational field data analysis. The storm penetration *in situ* data has been critically important to these analyses.

3. That the study areas for application of a storm penetration aircraft include:

   - Precipitation mechanisms. The major part of thunderstorm precipitation growth occurs in the >35 dBZ radar reflectivity regions.

   - Storm structure and dynamics.

   - Atmospheric chemistry and trace gas-aerosol particle transport, especially in storm updrafts/downdrafts.

   - Storm electrification

   - Remote sensing verification for improved analysis and interpretation of ground-based remote sensing measurements.

4. That measurements made from penetrating aircraft in the >35 dBZ volume of storms are essential to interpret and understand the precipitation and dynamical processes occurring.

5. That the T-28 penetration aircraft has flight capability limitations that cannot be improved – altitude, endurance, payload, etc. The T-28 should be upgraded for support of the atmospheric sciences for the near term (5 years) and a more capable storm penetration aircraft be acquired and developed for T-28 replacement.

---

[18] Stanley A. Changnon, Chair

6. That the operational research requirements for a replacement aircraft specify:

   - A twin-engine aircraft stressed for aerobatic flight.
   - The capability for flight into regions of large hail.
   - Engine reliability in regions of heavy rain, hail, icing, and lightning.
   - A research altitude capability to 45,000 ft, flight endurance of 4-5 hrs.
   - Multiple crew.

7. That the cost of the replacement aircraft development is in the range of $3 to $4 million.

8. That development and operation of the replacement aircraft involve a need for committed scientific leadership and staff skilled in the technical aspects of research aircraft. This and the need to share overhead costs, give argument for developing and operating the aircraft at a larger aircraft facility.