11B.4 THREE DECADES OF IN SITU OBSERVATIONS INSIDE THUNDERSTORMS

Andrew Detwiler, P. L. Smith, G. N. Johnson, D. V. Kliche, and Tom Warner

South Dakota School of Mines and Technology, Rapid City, SD

The South Dakota School of Mines and Technology (SDSMT) armored T-28 aircraft was developed as a result of a successful proposal submitted in 1967 to the National Science Foundation by R. Schleusener and P.B. MacCready to develop an aircraft for *in situ* observations in hailstorms. The motivation was to better understand the microphysical and dynamical processes governing the development and growth of hail in thunderstorms. In that era there was intense interest in the use of cloud seeding techniques to diminish the production of damaging hail from vigorous High Plains thunderstorms, but there were no tools suitable for obtaining detailed microphysical information within these storms to address the various hypotheses proposed to explain hail production and possible suppression. R. Williamson and his associates did the initial engineering studies, identified a suitable airframe, acquired the aircraft and modified it with armor and other features. The microphysical instrumentation on the aircraft initially included a Johnson-Williams cloud water meter, and a formvar replicator and a foil impactor custom designed and built by R. Williamson. This instrumentation allowed the aircraft to document microphysical characteristics of storm interiors covering the spectrum from cloud droplets to hailstones. This initial development phase was completed at a cost of roughly $1/3 M.

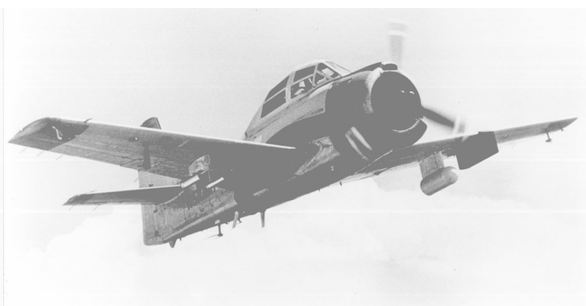
Research flights began in 1970, and the aircraft became fully operational in support of the National Hail Research Experiment (NHRE) in northeastern Colorado in 1972. Between 1972 and 2003 it participated in more than two dozen cooperative field programs focused on convective storm phenomena. *In situ* observations in hailstorms in northeastern Colorado, southeastern Montana, central Switzerland, eastern Alberta, central Oklahoma, and western and central North Dakota contributed fundamentally to the understanding of how hail develops. Beginning in the 1980's the aircraft became a valuable tool for verifying *in situ* the polarimetric radar signatures from various classes of hydrometeors in convective storms, furthering the understanding of hydrometeor signatures in polarimetric weather radar data, and as a result, facilitating observations of precipitation development and growth, particularly those processes involving hail, in entire storm volumes. Combinations of *in situ* hydrometeor instrumentation as well as a gas analyzer for tracer studies were employed in cloud seeding studies beginning in 1987 and extending into the mid-1990's. In the 1990's capabilities for electrical observations were developed to support fundamental research into convective storm electrification. After 2000 the aircraft was used for studying some of the chemistry associated with lightning discharges.

*Corresponding author: Andrew G. Detwiler, IAS, SDSM&T, 501 E. St. Joseph, Rapid City, SD 57701-3995. E-mail: Andrew.Detwiler@sdsmt.edu

Image circa 1970 showing startup at Rapid City Regional Airport. Note foil impactor under wing.

An early image shows the J-W cloud meter under the right wing

In this presentation, key insights developed using *in situ* measurements acquired with this aircraft are summarized, along with examples of publications describing these results in more detail. In almost all cases, the aircraft observations were a key component of the study but the entire picture could only be put together through combination of observations with those from other observing systems, such as radars, radiosondes, surface mesonets, and often with results of numerical simulations. Only a small number of publications can be cited here, and the authors apologize for not being able to include references to the many dozens of excellent papers made possible in whole or in part through involvement of the armored T-28 in their work.



T-28 launching from Patrick AFB in Florida during TRIP-78 in 1978. The Cannon particle camera is under the left wing, while J-W, foil impactor, and PMS 2D-C and FSSP probes are under the right wing. This is the instrument configuration used in Colorado and Florida projects from 1975-1978, and in Switzerland in 1982-1983.

***Early history and development of the armored T-28 aircraft through the NHRE era is documented in two publications*:**

Sand, W. R., and R. A. Scheusener, 1974: Development of an armored T-28 aircraft for probing hailstorms. *Bull. Amer. Meteor. Soc.,* **55**, 1115-1122.

Johnson, G. N., and P. L. Smith, Jr., 1980: Meteorological instrumentation on the T-28 thunderstorm research aircraft. *Bull. Amer. Meteor. Soc.,* **61**, 972-979.

Hail in North American High Plains and Swiss hailstorms grows by the riming of cloud water onto hail embryos, usually in a single pass across and falling through and around an updraft region. These hail embryos may be graupel particles or supercooled raindrops.

Browning, K.A., J.C. Fankhauser, J-P. Chalon, P.J. Eccles, R.G. Strauch, F.H. Merrem, D.J. Musil, E.L. May and W.R. Sand, 1976: Structure of an evolving hailstorm, Part V: Synthesis and implications for hail growth and hail suppression. *Mon. Wea. Rev.,* **104**, 603-610.

Foote, G.B., 1984: A study of hail growth utilizing observed storm conditions. *J. Climate Appl. Meteor*., **23**, 84-101.

Heymsfield, A.J., 1983: Case study of a hailstorm in Colorado: Part IV. Graupel and hail growth mechanisms deduced through particle trajectory calculations. *J. Atmos. Sci.*, **40**, 1482-1509.

Heymsfield, A.J., and D.J. Musil, 1982: Case study of a hailstorm in Colorado. Part II: Particle growth processes at mid-levels deduced from *in situ* measurements. *J. Atmos. Sci.*, **39**, 2847-2866.

Kennedy, Patrick C., and A.G. Detwiler, 2003: A Case Study of the Origin of Hail in a Multicell Thunderstorm Using In Situ Aircraft and Polarimetric Radar Data. *Journal of Applied Meteorology,* **42**(11), 1679–1690.

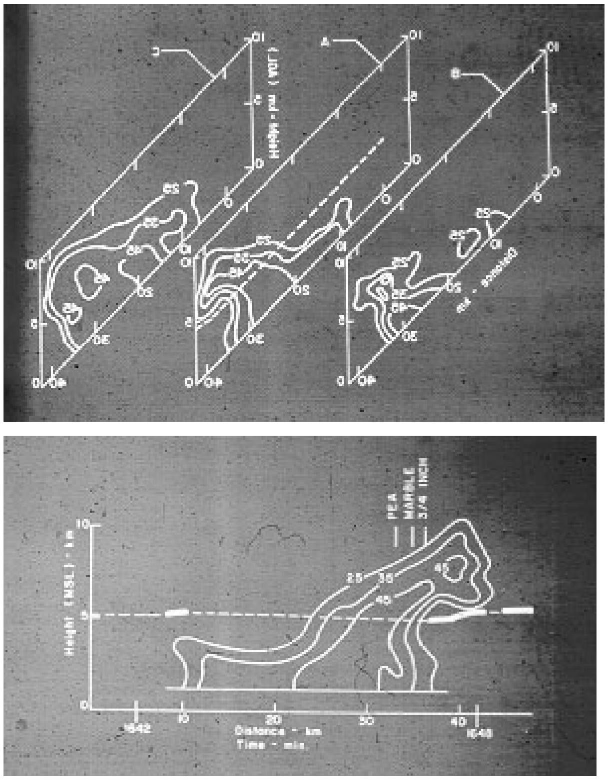
Knight, C. A., and P. Squires, 1982: *Hailstorms of the Central High Plains. I: The National Hail Research Experiment.* Colorado Associated University Press, Boulder, CO 282 pp.

Knight, C. A., and P. Squires, 1982: *Hailstorms of the Central High Plains. II: Case Studies of the National Hail Research Experiment.* Colorado Associated University Press, Boulder, CO 282 pp. 245 pp.

Musil, D.J., E.L. May, P.L. Smith, Jr., and W.R. Sand, 1976: Structure of an evolving hailstorm, Part IV: Internal structure from penetrating aircraft. *Mon. Wea. Rev*., **104**, 596-602.

Musil, D.J., W.R. Sand, and R.A. Schleusener, 1973: Analysis of data from T-28 aircaft penetrations of a Colorado hailstorm. *J. Appl. Meteor*., **12**, 1364, 1370.

Waldvogel, A., L. Klein, D.J. Musil, and P.L. Smith, 1987: Characteristics of radar-identified big drop zones in Swiss hailstorms. *J. Climate Appl. Meteor*., **26**, 861-877.



The combination of detailed radar reflectivity maps and aircraft observations during NHRE yielded observations of hail development in detail unprecedented at the time.

Shedding of cloud water from growing wet hailstones can lead to the production of new hail embryos in a prime hail growth environment:

Heymsfield, A.J., and M.R. Hjelmfelt, 1984: Processes of hydrometeor development in Oklahoma convective clouds. *J. Atmos. Sci*., **41**, 2811-2835.

Rasmussen, R.M., and A.J. Heymsfield, 1987: Melting and shedding of graupel and hail. Part III: Investigation of shed drops as hail embryos in the 1 August CCOPE severe storm. *J. Atmos. Sci*., **44**, 2783-2803.

Studies using artificial gaseous tracers show that glaciogenic seeding material released into updrafts at cloud base often is transported into regions targeted for enhancement in ice production. The degree of dispersal varies inversely with transport speed.

Huston, M.W., A.G. Detwiler, F.J. Kopp and J. L. Stith, 1991: Observations and model simulations of transport and precipitation development in a seeded cumulus congestus cloud. *J. Appl. Meteor.*, **30**, 1389-1406.

Bloomer, M.C. and A.G. Detwiler, 1996: Implications from the North Dakota Tracer Experiment of 1993 for the glaciogenic seeding of supercooled convective clouds to suppress hail. *J. Weather Modification*, **28,** 86-91.

In situ observations facilitate refinements in the treatment of microphysical processes in numerical models of hail storms:

Kubesh, R.J., D.J. Musil, R.D. Farley and H.D. Orville, 1988: The 1 August 1981 CCOPE storm: Observations and modeling results. *J. Climate Appl. Meteor*., **27**, 216-243.

***Documentation of environmental conditions in classic supercell storms, including weak echo regions, echo-free vaults, hail shafts, and other regions of interest**:*

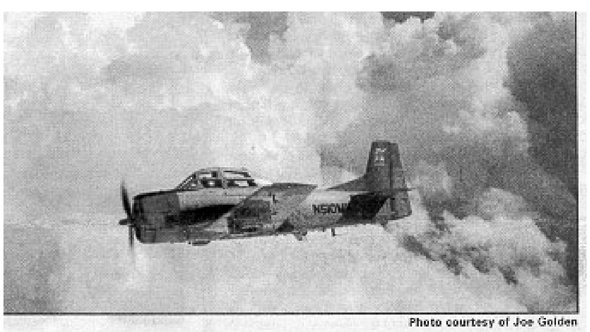
Musil, D.J., A.J. Heymsfield, and P.L. Smith, 1986: Microphysical characteristics of a well developed weak echo region in a High Plains supercell thunderstorm. *J. Climate Appl. Meteor*., **25**, 1037-1051.

At the Swiss Air Force Base in Emmen during GROSSVERSUCH, Switzerland, 1982

Take-off from Ft. Collins-Loveland Airport during the Turbulence Detection and Characterization Project in 1999

Many classes of hydrometeors in hailstorms can be discriminated and spatially mapped throughout the storm volume using S-band polarimetric weather radars. Results contained in numerous publications on this topic and the role of the T-28 in acquiring data to verify polarimetric techniques are summarized in:

Bringi, V. N., and V. Chandrasekhar, 2001. *Polarimetric Doppler Weather Radar. Principles and Applications.* Cambridge University Press, NY. 636 pp.



Investigations of development of the ice phase in towering cumulus clouds following glaciogenic seeding during TEXARC, Big Spring, TX, 1994

Electrification in thunderstorms is accelerated as the ice phase develops. In situ data are consistent with the hypothesis that the non-inductive ice-ice collision process dominates the early phases of electrification of most thunderstorms. The ice phase is well-developed prior to electrification sufficient to result in lightning.

Ramachandran, R., A.G. Detwiler, J.H. Helsdon, P.L. Smith and V.N. Bringi, 1996: Precipitation development and electrification in Florida thunderstorm cells during CaPE. *J. Geophys. Res.,* **101**, 1599-1619.

French, J.R., J.H. Helsdon, A.G. Detwiler, and P.L. Smith, 1996: Micro-physical and electrical evolution of a Florida thunderstorm. Part I: Observations. *J. Geophys. Res.,* **101**, 18961-18977.

Bringi, V.N., K. Knupp, A. Detwiler, L. Liu, I.J. Caylor, and R.A. Black, 1997: Evolution of a Florida thunderstorm during the Convection and Precipitation/Electrification Experiment: The case of 9 August 1991. *Mon. Wea. Rev.,* **125**, 2131-2160.

Paul MacCready in the cockpit of the T-28 at Jefferson County Airport during the Storm Penetrating Aircraft Workshop in 1999

These items are meant only to indicate some examples of research involving the armored T-28. Many other publications treat these issues, and many processes other than those addressed above have been studied using armored T-28 observations.

The availability of a suitable platform stimulated the development of many innovative instruments for *in situ* observations in harsh thunderstorm environments. Key instruments involved in hail studies included the Williamson foil impactor, the optical array hail spectrometer developed at SDSMT, and the hydrometeor camera developed by T. Cannon at NCAR. The PMS FSSP carried by the T-28 was a pre-production model, and the PMS 2D-C optical array probe was one of the earliest production models. Both have survived more than 3 decades of thunderstorm penetrations. A suite of electric field meters developed by W. Winn at the New Mexico School of Mining and Technology have provided more than 15 years of observations in some of the harshest conditions in which such instrumentation has ever operated. Dozens of other commercial and custom instruments developed by investigators around the world were deployed on the T-28 for one or more field studies.

In closing, we wish to recognize the dedication and innovative spirit characterizing crew and scientists who have worked with the armored T-28 since 1967. Beginning with MacCready, Schleusener and Williamson, and extending to 2004 and the current staff (some of whom are coauthors of this report) it has been through the consistent excellence of their efforts that this platform has been able to contribute so much to the scientific study of convective storm phenomena.

Acknowledgements: Preparation of this report is made possible through Cooperative Agreement ATM-0099344 between SDSMT and the NSF, and the editorial assistance of Ms. Connie Crandall.

Fly-by of Mt. Rushmore in Rapid City, in 2003, with the aircraft instrumentation in the standard configuration used for projects in 2002-2003. Note inlet on top of canopy for sampling gases. This inlet was used in sulfur hexafluoride thunderstorm circulation tracer experiments in 1987, 1989, and 1993, and in observations of lightning-produced nitric oxide in 2002-2003.