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ARMORED T-28 RESEARCH AIRCRAFT FACILITY

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1. DEVELOPMENT AND HISTORY

The original concept of a meteorological research aircraft capable of penetrating hailstorms was developed and promoted by Paul MacCready beginning in the late 1950's. At the time, this was widely regarded as not feasible. The hail researchers who had been developing a hail suppression program in the Soviet Union considered storm penetrations by an aircraft as too dangerous. They did not send research or seeding aircraft into hailstorms but relied on rockets and artillery shells to deliver their seeding materials into what they thought would be appropriate locations in the storms. Within the American research community, the mainstream thought was similar to that of the Soviets, namely that penetrations of hailstorms by manned aircraft were too dangerous.

The idea of developing a storm penetration aircraft persisted, however, and began to approach reality following Project Hailswath in 1966, when the National Science Foundation provided funds to support a detailed investigation. MacCready commissioned an associate, Robin Williamson, to do the aircraft feasibility study.

Williamson considered all aircraft in the military and civilian fleet of the Viet Nam war era. All aspects of aircraft operation including survivability, maintainability, costs, and performance were analyzed. Strictly on the basis of performance characteristics, he concluded that the best aircraft for hailstorm penetrations would be a Douglas "Dauntless" dive bomber, a World War II combat aircraft. His second choice was a T-28 military trainer, developed in the late 40's as a high-performance, prop-driven, pre-jet trainer. When costs and maintainability were factored in, however, the T-28 was judged to be the overall top choice.

Some of the prime deciding factors in Williamson's study were:

(1) Aircraft equipped with reciprocating engines were better suited to severe-storm penetrations than those equipped with jet engines, being less susceptible to hail and ice damage.

(2) Twin-engine aircraft were not superior to single-engine aircraft. Williamson's philosophy was that if the environment is so severe that one engine goes out, the second will soon be lost, too.

(3) No existing airframe was designed to survive impacts of more than 3/4 inch hail, so any aircraft chosen would require additional armoring. The lower speed of prop-driven aircraft meant that thinner metal plating would be required on the leading edges of the aircraft to

survive hail impacts. The added armor that would be required on faster jet aircraft countered the advantage of their higher-performance powerplants.

(4) De-icing capabilities were not considered critical because very high supercooled liquid water concentrations were expected and it would be impossible to de-ice completely anyway. Williamson was more concerned with wind shear and turbulence than icing.

(5) While the Dauntless had more power and a stronger airframe (it could stand 12-g accelerations), the T-28 was adequate for penetrating the anticipated turbulence and strong shear.

(6) At the time, T-28's were much more plentiful than Dauntless dive bombers and T-28 parts were readily available in the supply pipeline.

Using the results of Williamson's study, MacCready finally sold his idea to the National Science Foundation (NSF) in 1967. MacCready's company, Meteorology Research, Incorporated, under contract to the Institute of Atmospheric Sciences' NSF-funded Hailstorm Models Project, acquired and registered a T-28. Williamson Aircraft Co. (headed by Robin Williamson) contracted to outfit the aircraft for hailstorm penetrations. This work began in 1968 and was carried on through 1969. The basic modifications to the aircraft are discussed in Section 2 and in Sand and Schleusener (1974).

After the modifications were complete, the T-28 was capable of performing hailstorm penetrations to altitudes up to about 25,000 ft (7.6 km), and was able to withstand impacts of hailstones up to 7.5 cm in diameter at 100 m s^{-1} relative speed with minimal damage. Some meteorological instrumentation was installed and the aircraft made some test flights during the summer of 1969 at Rapid City, South Dakota, and Flagstaff, Arizona, for the primary purpose of determining its capacity for carrying heavy loads of structural ice. It was found that the aircraft could handle up to an inch of ice with only a relatively small increase in speed to maintain controllability. Since the T-28 was to be used in summer thunderstorms where a layer of warm air would be present between icing zones and the ground, icing was not felt to be a major problem.

At this time, ownership of the T-28 passed to the Institute of Atmospheric Sciences at the South Dakota School of Mines and Technology. The Institute's Director, Dr. Richard Schleusener, was a leading figure in the U.S. hail research effort at that time and had actively supported MacCready's concept of an armored aircraft for hailstorm penetrations.

In 1969, a military technical order (TO) revealed that the aircraft needed strengthening of the wing main spar to keep it airworthy. This order came as a result of extensive military experience with T-28 aircraft including some wing failures during high-g aerobatic maneuvers. The T-28 was therefore sent to the Naval Air Rework Facility at Pensacola, Florida, for wing spar strengthening.

The T-28 returned to active duty in time to make a few cloud penetrations prior to the end of the 1970 hail season in Colorado. These operations with the Joint Hail Research Project proved the viability of the T-28 as a thunderstorm research platform. Fifteen cloud penetrations into increasingly larger storms were made to build confidence in the system.

Engine problems and other experiences in 1971 led to the conclusion that the T-28 required a significant change in the engine and an updating of the basic aircraft. As a result, in 1972 the aircraft was sent back to the Naval Air Rework Facility at Pensacola, Florida, to be upgraded with extensive airframe updating and installation of a more state-of-the-art engine (R-1820-86A) and a stronger propeller. These changes increased engine power from 1200 to 1425 horsepower. After the Naval Air Rework Facility accomplished these changes, the T-28 was in outstanding mechanical condition. It made nearly 200 research flights from 1972 through 1976 in support of the National Hail Research Experiment (NHRE) without further modifications. Then, structural strengthening in the tail section was accomplished by the Naval Air Rework Facility in 1977 in response to another TO.

Two more successful field seasons, involving thunderstorm studies in Colorado, Florida, and Oklahoma, followed in 1978 and 1979 before a mishap on a slippery runway necessitated replacement of the engine and propeller in 1980. The replacement engine was identical to the damaged one. However, the replacement propeller was a shortened model used for carrier-based aircraft; this resulted in an estimated 15% increase in rate of fuel consumption with a corresponding decrease of ~15 min in flight duration but no significant loss in other performance characteristics.

The T-28 participated in summer field programs every year in the 1980's except for 1988. Overhauls of the last engine in 1981 and 1982 leave the T-28 in the early 1990's with a low-time engine (300 hours) having a life expectancy equivalent to more than a decade of field seasons. Another long-blade propeller was located in 1987 and has been installed on the aircraft to return its endurance to the former levels.

2. AIRCRAFT DESCRIPTION

The T-28 has been modified extensively from its original configuration. The leading edges of the wings and tail surfaces are covered with 2.29 mm (0.090 inch) 2024T4 heat-treated aluminum sheets formed to fit and bonded to the existing wing and tail surfaces. The tops of the wings are covered with 0.81 mm (0.032 inch) sheets of the same material. The leading edges of the cowling are covered with an additional sheet of fitted 3.18 mm (0.125 inch) aluminum. This armor plating adds about 318 kg (700 lb) to the aircraft weight.

The carburetor is protected from ingestion of large hailstones by the addition of a metal grate to the air intake to break up the hailstones prior to entry. A similar device was installed over the oil cooler intake to prevent damage to the relatively fragile oil radiator.

The canopy also required substantial modification since the standard plexiglass bubble canopy was much too weak to withstand encounters with large hail. The windshield was replaced with flat sheets of 1.91 cm (0.75 inch) stretched acrylic and the side panels were made of flat sections of 1.52 cm (0.60 inch) stretched acrylic. The windshield and the leading-edge armor were tested to withstand 7.6-cm diameter hail at penetration velocities by firing ice balls from a specially-built hail "cannon" at test sections of the aircraft.

The engine installed in 1972 required a new scheme for protecting it from hail damage since the cylinders and front of the engine were of a slightly different design than the engine originally installed on the aircraft. The push-rod housings and the ignition harness were protected with sections of electrical conduit formed to fit the respective areas. The propeller governor was protected with a shield of aluminum. The areas now most susceptible to damage on the entire aircraft are the baffles between the cylinders and the cooling fins on the cylinders themselves.

The T-28 is equipped with alcohol for anti-icing of the propeller and the carburetor, to permit the engine to develop full power in icing conditions. Since the aircraft is somewhat overpowered, it is able to carry a substantial load of ice on the airframe if the engine can develop full power.

The T-28 airframe is occasionally struck by lightning so lightning rods are placed on the aircraft extremities to attempt to reduce the lightning damage. The propeller is occasionally struck but usually sustains no physical damage other than small burned spots on its trailing edges. Significant burn marks on some of the airframe trailing edges resulted from lightning strikes in Oklahoma during SESAME '79 (Musil and Prodan, 1980). During the 1986 COHMEX field season in Alabama, a lightning strike to the propeller disabled the alcohol anti-icing system, but it was repaired after the season ended.

Since the distinct possibility exists that the entire electrical system could be disabled by a lightning strike or an unintentional overload, precautions are taken to minimize damage under such conditions. The aircraft has a 300 A 28 VDC generator used to power the sensing, recording, and de-icing equipment. To protect the system from damage due to equipment failures, double circuit breakers are placed on all high-power equipment and the switches are made easily accessible to the pilot. The pilot can thus turn off any or all scientific equipment in the event of an electrical problem. Since a primary flight attitude reference panel is not considered adequate for continued flight in the severe environment of a thunderstorm, the T-28 is equipped with dual artificial horizons, one electrical and the other vacuum driven, to enable continued safe flight in the event of a complete electrical failure.

The breathing oxygen system was completely overhauled and updated by the Naval Air Rework Facility during the extensive rework in 1972. This system can provide safe, reliable operation to well above the T-28 service ceiling.

3. INSTRUMENTATION DESCRIPTION

The basic requirement of the instrumentation system is that it must reliably measure and record the selected quantities with minimum attention during flight, since the aircraft is flown solo. Limited capability for monitoring the data system in flight is available. There is also an ability to telemeter some data to the ground for examination. The system is designed to be remotely controlled from the front cockpit with a minimum requirement for in-flight checks. Johnson and Smith (1980) provide a basic description of much of the T-28 instrumentation system, although the recent replacement of the data acquisition system and other equipment additions render some of this description obsolete.

The data collection system is normally activated on the ground prior to each research flight, although it can be started and re-started in flight. The pilot can monitor certain aspects of data system operation in flight through a programmable CRT display. During flight, he has displays of time and liquid water concentration from the Johnson-Williams device.

3.1 State Variables

Because of the importance of the static pressure and temperature measurements within and around storm clouds, these variables are measured redundantly. The static pressure instrument, the Rosemount 1301-A-4-B, has a basic accuracy of 0.1% and response time of a few tens of milliseconds. Two of these units are now carried on the aircraft. A Ball EX-210-B pressure sensor available as a backup is accurate to within 1% and has similar response time. The resolution of the 16-bit analog-to-digital converter in the data recording system is 0.0000152, so the realized resolution of incremental pressure measurements with the Rosemount instrument is about 0.0015 kPa.

Reliable temperature measurements outside the clouds are obtained from both a Rosemount and an NCAR reverse-flow sensor (Rodi and Spyers-Duran, 1972). In-cloud temperatures cannot be measured as reliably because of wetting of the sensing elements (Heymsfield *et al.*, 1979; Lawson and Cooper, 1990). The NCAR reverse-flow thermometer has a basic accuracy similar to that of the Rosemount device (±0.5°C) but a slower response, with the Rosemount time constant being ~1 s and the reverse-flow time constant ~3 s. Usually the NCAR device is used for in-cloud measurements because of its superior wetting resistance, but it may not be possible to provide reliable in-cloud temperature measurements under all conditions.

The T-28 system does not include a humidity sensor. The emphasis of research involving T-28 observations is usually on the interior characteristics of storms, and we have yet to find a generally suitable instrument for measuring humidity in clouds.

3.2 Kinematic Measurements

Horizontal winds can be obtained by subtracting aircraft movement relative to the air, based on measured heading and true airspeed, from the aircraft ground track obtained from an on-board Global Positioning System (GPS). Winds obtained in this way are comparable in accuracy with winds obtained by INS-equipped aircraft.

Updraft measurements can be derived from aircraft rate-of-climb values obtained by differentiating the static pressure (altitude) values or from direct rate-of-climb measurements made with a Ball variometer. The altitude differentiation approach is normally used to get the rate-of-climb values. The variometer is not used as the primary sensor because it has a limited range (±30 m s^{-1}) and becomes nonlinear near the ends of this range. It also has an inaccuracy near the zero point which results in a reading of -3 m s^{-1} when the actual value is between ±3 m s^{-1}. If the rate-of-climb is outside the ±3 m s^{-1} range and within the ±30 m/s limit, the instrument functions properly and the data can be used for backup purposes.

The simplest approach to updraft calculation is an expansion of the concept used by Auer and Sand (1966); some of the aircraft-induced vertical motions are removed during computer processing of the data by correcting the rate-of-climb values for the effects of airspeed and engine power variations. An additional term based on energy conservation considerations (Dye and Toutenhoofd, 1973; Cooper, 1978) can be applied to correct further for pilot-induced effects. In this manner, the larger-scale updrafts can be measured with an estimated accuracy of better than ±3 m/s or 10%, whichever is larger. Small-scale motions (i.e., gusts) with horizontal dimensions smaller than 0.5 km or so are below the sensitivity of this relatively simple system.

An improved method of calculating updraft speeds from the T-28 measurements has been developed by Kopp (1985) based on earlier work by Lenschow (1976). It uses the aircraft equations of motion to obtain a better correction for the aircraft-induced motions. The required measurements are static pressure, dynamic pressure, and pitch angle. Estimated accuracy is ±3 m s^{-1} and spatial resolution is ~0.5 km.

Redundancy is an important feature of the T-28 instrumentation system. Only a few storms a year can be studied in detail and the data are sufficiently important to warrant the added expense of backup instrumentation. For determinations of vertical air motion, for example, the variometer (rate-of-climb indicator) output is used in the event of a malfunction of the Rosemount pressure sensors. If both pressure instruments and the variometer should fail, the accelerometer data could be integrated to determine rate of climb.

3.3 Hydrometeor Measurements

One unique feature of the T-28 instrumentation system is its ability to measure the numbers and sizes of hydrometeors over almost the entire size spectrum present within a storm. The particles may range from cloud droplets a few micrometers in diameter to hailstones several centimeters in diameter. Various sensors cover different portions of the size range in an overlapping fashion. Somewhat comparable measurements can be obtained for each subrange from two different sensors, again affording a useful degree of redundancy.

The sensors applicable to each particle size category are listed below. The values in parentheses indicate the approximate sampling volume per unit distance along the flight path for each instrument; the sampling volume per unit time can be estimated by multiplying by the nominal T-28 true airspeed of 0.1 km s^{-1}.

1) Cloud droplets, up to about 30 μm in diameter: J-W cloud liquid water concentration sensor; Particle Measuring Systems Forward Scattering Spectrometer Probe (FSSP) (3×10^{-4} m^3 km^{-1}).

2) Intermediate or "embryo" size particles, 30 to more than 1000 μm: Particle Measuring Systems (PMS) two-dimensional optical array spectrometer (0.1 m^3 km^{-1}); particle camera (up to 2.6 m^3 km^{-1}).

3) Raindrops, graupel, and snowflakes, from about 1 mm up to 5 mm or larger: Continuous hydrometeor sampler (foil impactor; 1.4 m^3 km^{-1}); particle camera.

4) Hailstones, from 4 mm to more than 5 cm: Hail spectrometer (100 m^3 km^{-1}); foil impactor.

The instrument sampling volumes tend to be larger for larger particles to compensate for the smaller concentrations of such particles. The particle camera and hail spectrometer cannot be carried simultaneously because both require the same mounting points under the left wing of the aircraft.

The above allocation of instruments to particle size categories is arbitrary to some extent. For example, the two-dimensional probe (2D-C) provides partial images of particles considerably larger than 1000 μm, while the particle camera can photograph centimeter-size hailstones. However, the instrument sampling volumes can impose serious limitations on the representativeness of the data. It is also generally recognized that all of the available instruments are deficient in the 50-150 μm size range.

Our data system can accept data from a PMS 2D-P probe (covering the size range from ~200 μm to ~6.4 mm) and the T-28 has, in fact, carried a 2D-P on occasion. As currently configured, however, it can carry only one imaging probe at a time. Normally no 2D-P is available for use on the T-28, but one can sometimes be borrowed on a project-by-project basis.

A variety of computer techniques can be used to process the two-dimensional image data to determine particle sizes and crystal habits. A capability to automate the processing of foil impactor data has recently been developed. Information about particle size distributions can be obtained from the PMS probes, the particle camera, the foil impactor, and the hail spectrometer. Particle phases (ice or water) can be determined unequivocally from the particle camera data and frequently can be identified from the PMS two-dimensional images as well. (Early attempts to identify phases from the foil impactor data were shown to be suspect by Knight *et al.*, 1977.) Particles larger than 5 mm, which are measured mainly by the foil impactor and hail spectrometer, are normally assumed to be ice because raindrops of these sizes break up very quickly in nature due to dynamic instabilities.

The hailstone spectrometer, developed at the South Dakota School of Mines and Technology, operates on a "shadowgraph" principle similar to that employed in the PMS probes. It uses 128 phototransistors spaced at 0.9 mm intervals in a linear array to count, size, and image hailstones as they pass through a planar beam of laser light perpendicular to the flight path. Shadows smaller than about 4.5 mm are not counted, and the data are usually analyzed with the assumption that all particles larger than this are hail.

A device has been developed by NCAR scientists to capture hailstone samples inside the thunderstorm. Frozen particles are decelerated and captured in a chilled receptacle for later analysis in the laboratory.

3.4 Electric Field Measurements

Holes and mounting hardware are in place to carry up to four cylindrical rotating-shutter electric field mills. The locations are (1) the upper rear canopy facing upward; (2) the lower fuselage baggage-bay door facing downward; and (3) and (4) the wing tips facing outward. The existing hardware is designed to hold mills made at New Mexico Institute of Mining and Technology (NMIMT), although arrangements can be made to carry other mills as long as the external diameter does not exceed ~4 inches (a constraint imposed by the thickness of the wing tips). As of spring 1991, the T-28 facility is negotiating to acquire two, or possibly three, mills of its own. Additional mills must be borrowed when needed.

Experience and in-flight intercomparisons with other aircraft using the four existing mill locations have shown that reliable estimates of the electric field components in the vertical and transverse directions can be obtained in clear air and in the presence of light precipitation. It is also possible to derive an estimate of charge on the aircraft using mill readings or an instrumented discharge wick on the lower fuselage. More work is required to provide reliable interpretations of observations obtained during penetrations of severe storm interiors when the aircraft becomes highly charged (see, e.g., Jones, 1990). It is likely that a fifth field-mill mounting location will need to be developed to allow determination of the field component along the aircraft fuselage.

3.5 Navigation and Performance Variables

The aircraft currently carries a GPS/LORAN navigation system as well as a VOR/DME system including two DME's. There is no on-board radar. The aircraft navigation equipment is used by the pilot to arrive at the desired initial point for a cloud penetration, but instructions relating to penetration headings are transmitted from ground radar. The equipment on board is not considered sufficient for precise navigation in regions of mature storms where heavy precipitation zones and strong up- and downdrafts can have sharp boundaries which don't always correspond to visible features. Real-time tracking on the ground coordinated with a research-grade meteorological radar display, with aircraft position data based on the GPS system, FAA surveillance radar, or other precision ground-based radar or radio-direction finding systems, is therefore required for operations in mature storms. Telemetry of the position data from the T-28 to the ground is available to assist in this process (see Sec. 4). The position data are also recorded on the aircraft data system for use in later analyses.

A gyro-stabilized platform and accelerometer system is available to provide aircaft pitch and roll data as well as vertical accelerations. No angle-of-attack or yaw data are available with the present system configuration.

Dynamic pressure (indicated airspeed) and aircraft heading data are recorded routinely, the former redundantly. A real-time true airspeed computer supplies data to timers in instruments requiring this synchronization, such as the PMS imaging probe or the particle camera. Post-hoc true airspeed calculations can be made to determine the exact sampling volumes of other instruments. As indicated in Sec. 3.2, the rate-of-climb data serve mainly a backup function.

3.6 User-supplied Instrumentation

The facility can accommodate user-supplied instrumentation. Currently, space in the rear cockpit is available, as well as various hard points and pylons on each wing. The aircraft normally flies near its maximum allowed gross weight and can only carry an additional load of 70 kg (about 150 lbs); however, further capacity to carry user-supplied instrumentation can be made available if some of the standard instrumentation is removed. About 500 W of 28V DC and 700 VA of 115 VAC (400 Hz) power are available above the requirements of the standard instrumentation and other aircraft systems. Users should be aware that the instrument operating environment will be unheated, unpressurized, and likely subject to significant levels of shock and vibration.

The T-28 has carried more than a dozen different precipitation, cloud, and aerosol particle samplers over the years, in addition to the current suite of instrumentation described above. It also carried an SF_6 analyzer during two recent field campaigns in which tracer techniques were used to study cloud circulations and precipitation development.

4. DATA ACQUISITION SYSTEM

The current data acquisition system was installed in 1989. Its core is an IBM PC-AT-compatible industrial-grade microcomputer. It has 32 analog input channels and uses 16-bit analog-to-digital converters. There are also interfaces to accept digital data from our hail spectrometer, one PMS FSSP or 1D probe, and one PMS 2D imaging probe. Data are stored on a 40-MB streaming tape cartridge. Most data are sampled once per second, but some variables (e.g., electric fields) are sampled at rates up to 20 per second. The pilot can enter event codes and has the ability to re-boot the data system in flight should a failure occur. He also has a display screen in the cockpit to allow him to monitor critical data.

A small audio stereo recorder is carried to record pilot comments on one track and the sounds of hailstone impacts on the windscreen of the aircraft on the other track. The volume swept out by the windscreen is about the same as the sampling volume of the hail spectrometer, so two somewhat comparable modes of hail detection are available. A filter is inserted in the hail impact channel to reduce the masking effects of the engine noise. This recorder has proven to be extremely valuable in providing supporting qualitative data for the other instruments. It also allows the pilot to concentrate on flying the aircraft and making subjective observations without the burden of taking notes during the penetrations. This is part of the general system design philosophy of keeping the requirements for in-flight performance monitoring and adjustment to a minimum.

An air-to-ground telemetry system is also carried. The current model is a Data Radio G5S1SSSG system including a 2 W transmitter operating on 418 MHz, a receiver, and a PC for display of telemetered data on the ground. It can transmit digital data to the ground at 4800 baud using a network protocol that allows several telemetry systems to share the same frequency. Our standard frequency is one also used by the NCAR "NATS" telemetry system. Other frequencies could be used, if necessary, but this would require shipping the unit back to Data Radio for modification.

Capability exists for quick-look data reduction on the ground after a flight. Data can be listed or plotted within roughly two hours of landing.

5. OUTLINE OF OPERATIONAL PROCEDURES

5.1 Flight Operations

The general objective of most T-28 projects in the past has been to obtain data within and in the immediate vicinity of thunderstorms and hailstorms. The main emphasis of the research has been on the study of mature hailstorms. A typical scientific objective of the mature storm studies is to locate and characterize the hail growth regions for different types of storms. This involves determining the hydrometeor types and size distributions in various parts of the storm at various stages of storm development. A combination of aircraft, radar, and other data has also been used to estimate hailstone growth trajectories.

For these investigations, a variety of flight patterns for penetrating mature storms has evolved over the years. The basic procedure is that a qualified meteorologist with access to a quantitative weather radar system and real-time aircraft flight track data is in charge of vectoring the aircraft into desired areas of a storm. The vector selected normally permits penetration of a high radar reflectivity zone as well as an updraft region at aircraft altitude. Penetration of adjacent feeder clouds or other regions of the storm may also be important in some cases. A penetration is normally made at a constant heading until clear air is encountered or the T-28 is well clear of any radar echoes. The aircraft then reverses course in preparation for another penetration.

A limit is normally imposed on the maximum radar reflectivity factor permitted for penetration. This reflectivity limit is based on coordinated analysis of the experience from past penetrations along with radar reflectivity data and hailstones collected at the ground. The normal limit is 55 dBz along the penetration path at or above the altitude of penetration. This criterion was selected to permit the aircraft to encounter hail, but to avoid hail of destructively large sizes which would tend to damage the instruments and thus prevent the collection of the desired data. The maximum hailstone size encountered using this limit has normally been about 2.5 cm, but larger particles are sometimes found.

A normal flight consists of from three to six storm penetrations, although more than 10 have been made on some flights. This is limited mainly by the fuel supply (about 2 hrs with reserves). In the early years, the normal operational procedure in hail research programs was to begin penetration at 7.3 or 6.7 km MSL (24,000 or 22,000 ft MSL) and proceed downward at 0.6 km (2,000 ft) intervals on successive penetrations until 4.9 km (16,000 ft) was reached. This routine was interrupted on occasions when airframe ice built up to a point where the pilot considered another penetration unwise. Further penetrations were then delayed until a descent was made to melt the accumulated ice.

The pattern involving successive penetrations at progressively lower altitudes used in the early studies (e.g., Sand and Schleusener, 1974) was abandoned because of the difficulty of sorting out temporal from spatial (vertical) differences found in the data. More recent projects have generally involved making repeated penetrations at a single level for each storm, usually in the temperature range from -5° to -15°C where ice processes are believed to become operative in the storms. This indicates the evolution of each storm at the chosen level, and by studying other similar storms at different levels inferences can be drawn about the vertical structures. When additional observations are available from other aircraft penetrating the clouds at other altitudes, or operating below cloud base, information about the vertical structure is more readily obtained. Scientific questions about coalescence and recirculation processes have suggested greater emphasis on storm penetrations near the 0°C level, and the most recent projects have included some penetrations at that level.

The T-28 typically operates in projects involving other aircraft and often becomes involved in simultaneous penetrations of the same storm by two or more aircraft. This type of study has proven highly successful. Due to the workload in the T-28 cockpit, overall coordination of multiple aircraft missions must be carried out from the ground or from another aircraft with sufficient crew.

The problems of greatest concern during penetrations are the intense turbulence encountered in some storms and the occasional occurrence of extremely rapid ice accumulation on the airframe (sometimes at an observed rate of 2.5 cm min^{-1}). The latter has the effect of rapidly increasing the weight and changing the aerodynamics of the T-28. When the air intakes to the carburetor and oil cooler are constricted by ice accumulation in such icing situations, a loss of power and high oil temperatures also result. The carburetor intake is protected from large hail ingestion by the grate described earlier, and this grate provides a surface area for heavy ice accumulation in regions of the cloud with high supercooled liquid water concentrations. Limited airflow to the carburetor can be partially restored with the addition of carburetor heat; this procedure uses air from inside the cowling, but cannot restore full engine power. Even so, the engine has occasionally stopped running due to excessive ingestion of ice and water. Fortunately, engine restarts can be accomplished and there has been no loss of data continuity in such cases.

It takes about 20 min to climb to, or descend from, the normal T-28 operating altitudes (~18,000 ft MSL), leaving typically 80 min on-station time. This is less than the lifetimes of many thunderstorms, so judicious timing of the initiation of T-28 flights is important. Data tapes cannot be changed in flight, but total data storage capacity is ~40 MB on our current data system. Typically, only ~20 MB is used even on our longest flights, so this is not a limiting factor.

5.2 Ground Operations

Because of the adverse conditions in which the aircraft operates and the comparatively abusive treatment that results, high quality maintenance is imperative. This is provided by the employment of a mechanic whose primary responsibility is the meticulous care of the T-28. Normal maintenance includes a very detailed inspection before and after each research flight by both the pilot and the mechanic. The engine is checked at regular intervals to detect any possible damage from rapid heating and cooling during penetrations. An oil sample is subjected to spectrometric analysis for metals at regular intervals to check for any abnormal internal wear. Only knowledgeable and qualified personnel are allowed to work around the aircraft and all work is checked and double checked. All modifications on this restricted-category aircraft are approved by the Federal Aviation Administration. The mechanic also conducts a regular program of progressive inspections to comply with FAA mandates concerning airworthiness.

For field operations, the T-28 facility requires hangar space with sufficient power (about 20 A at 110 V) to run the aircraft electrical systems (using our own 28 V power supply). The height clearance and floor space required are approximately 13.5 ft x 40 ft x 40 ft. Space required for tools and materials for in-field maintenance is an additional 20 ft x 20 ft. Separate space is generally required for the quick-look data reduction activities.

Minimum runway length is 4,000 ft. One hundred octane aviation gasoline should be available. Arrangements for deicing alcohol, engine oil, and breathing oxygen are also needed; the facility can supply the first two of these items, if necessary.

The aircraft's VHF radios cover the band from 118.0 to 135.975 MHz. Arrangements should be made for a dedicated project frequency for use between a meteorologist on the ground and the aircraft in flight, in addition to the frequencies normally used for conversations with FAA Air Traffic Controllers. The facility can furnish a transceiver for the ground station, if needed, but users must provide sufficient notice to permit arrangements for licensing and the procurement of any necessary crystals.

6. EXAMPLES OF RESEARCH RESULTS

The T-28 has now accomplished more than 750 storm penetrations in a series of research projects dating back to 1970. Those projects have involved investigations of convective storm processes in Alabama, Alberta, Colorado, Florida, Montana, New Mexico, Oklahoma, North Dakota, South Dakota, and Switzerland. In most cases, the emphasis has been on studies of hail development, for which the T-28 with its ability to penetrate storms containing hail up to more than 5 cm in diameter is uniquely suited. The TRIP project in Florida (1978) had as its major focus the relationship between precipitation development and charge separation in convective clouds. The COHMEX project in Alabama (1986) was concerned with precipitation development, cloud electrical processes and the development of downbursts. Recent work in North Dakota has involved investigations of transport and dispersion in convective clouds using gaseous tracer techniques.

T-28 data have been employed in various studies of thunderstorm processes. In each case, the interpretation of the T-28 observations has been greatly facilitated by the availability of good aircraft tracks, supporting radar data (both conventional and Doppler), and observations from other research aircraft, as well as other comprehensive meteorological surface and upper air data. Much of this research has been undertaken jointly by scientists from the South Dakota School of Mines and Technology (SDSM&T) and other organizations, including NCAR and various universities. Important contributions have been made to the resolution of major questions about the development of hail in thunderstorms. For example, it was established that there are no accumulations of high concentrations of supercooled raindrops, like those envisioned in the Soviet model of hail development, in Colorado or Swiss thunderstorms (Musil *et al.*, 1973, 1976b; Sand, 1976; Knight *et al.*, 1982; Waldvogel *et al.*, 1987). Accumulations of this sort have been found in storms in the southeastern U.S., but rapid freezing and natural "beneficial competition" appear to prevent the development of large hailstones (Musil and Smith, 1989).

Mechanisms of hail development involving recirculation of ice particles (Musil *et al.*, 1976a) or the transfer into the main storm of ice particles developed to embryo sizes in feeder cloud regions (Heymsfield and Musil, 1982; Heymsfield, 1983; Foote, 1984) have been established as important processes in the development of hail in at least some Colorado storms. Evidence was found in Oklahoma storms of mixed-phase precipitation processes with recirculation within the main storm likely being important (Heymsfield and Hjelmfelt, 1984). Analysis of T-28 data from SESAME 1979 and CCOPE (1981) showed that shedding of drops from graupel or hail undergoing wet growth or melting may produce enough supercooled raindrops in Oklahoma and Montana storms to account for the observed incidence of frozen-drop embryos (Heymsfield and Hjelmfelt, 1984; Rasmussen and Heymsfield, 1987).

The T-28 observations of the microphysical and updraft structure of high-reflectivity regions of thunderstorms have served to characterize the types and concentrations of particles in those regions, identify the types that may serve as hail embryos, and define the growth environment for those particles. They have revealed that supercooled cloud liquid water is often depleted by ice particle growth in the primary hail growth regions around the edges of the major storm updrafts as well as by entrainment. Updraft cores may be relatively undiluted in large High Plains thunderstorms; a study of a supercell storm investigated during CCOPE provides one example in which a huge updraft core (maximum updraft speed about 50 m s^{-1}) was relatively free of entrainment effects (Musil et al., 1986).

In 1987, and again in 1989, the T-28 was employed in studies of transport, dispersion, and precipitation initiation in developing cumulus. It was equipped with an SF_6 analyzer in addition to its normal suite of microphysical instruments. Seeding agents and SF_6 released into the base of cumuli tagged the inflow air. Upper cloud regions were then probed by the T-28 and other aircraft for evidence of the tracer gas and developing ice (Stith et al., 1990).

In 1986 and 1989, the aircraft carried field mills during penetrations of large storms. Results from one of these flights discussed in Detwiler et al. (1990) show the presence of horizontally extensive charge accumulation regions downshear of relatively narrow updraft regions in which charge separation appears to be taking place.

These studies provide examples of the ways in which T-28 data can be used in investigations of cloud physics processes. Coupling of the aircaft data with radar and other related observations in a framework incorporating numerical cloud models (e.g., Kubesh et al., 1988; Huston et al., 1991) can enhance the scientific value of the aircraft data.

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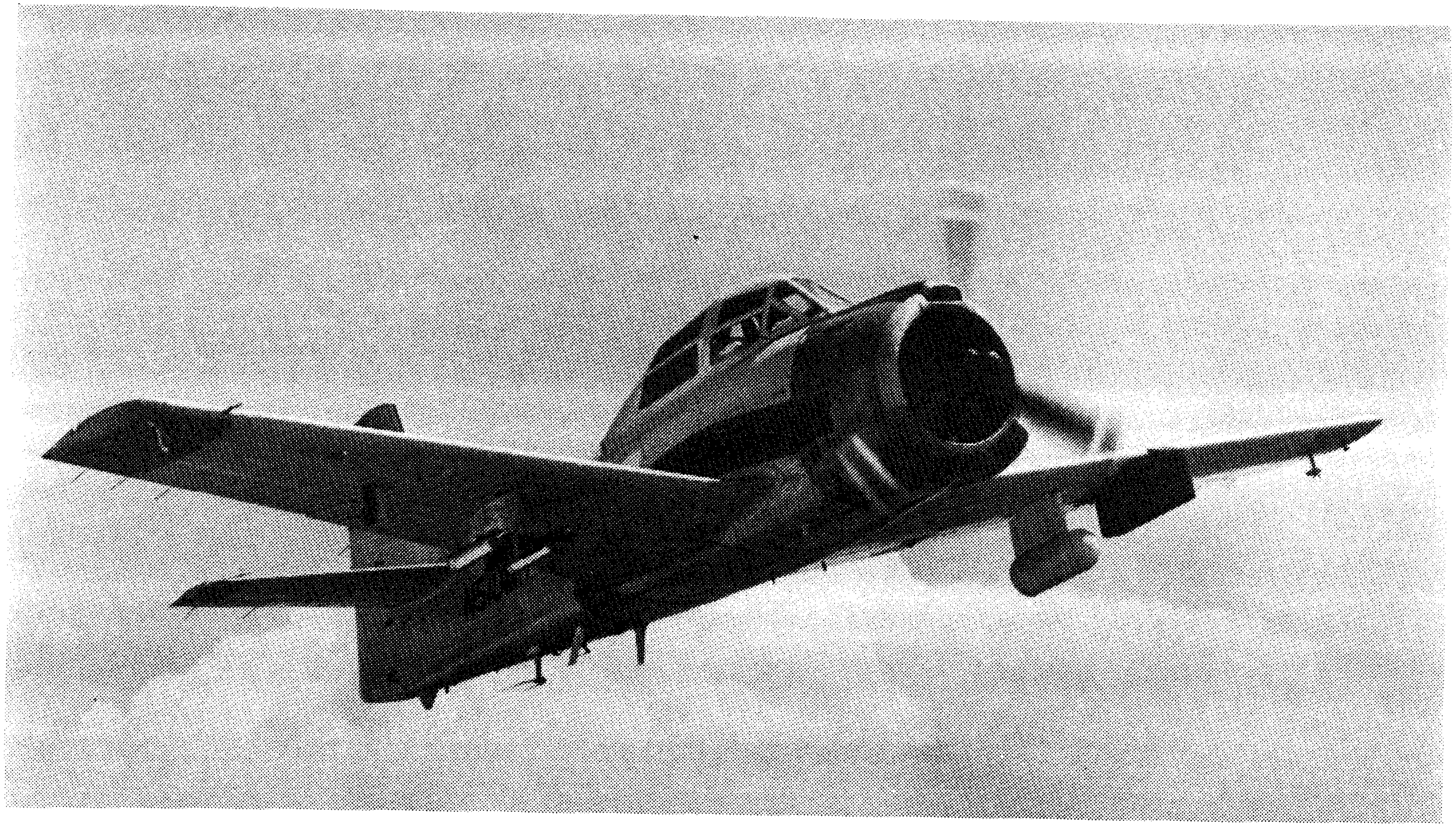
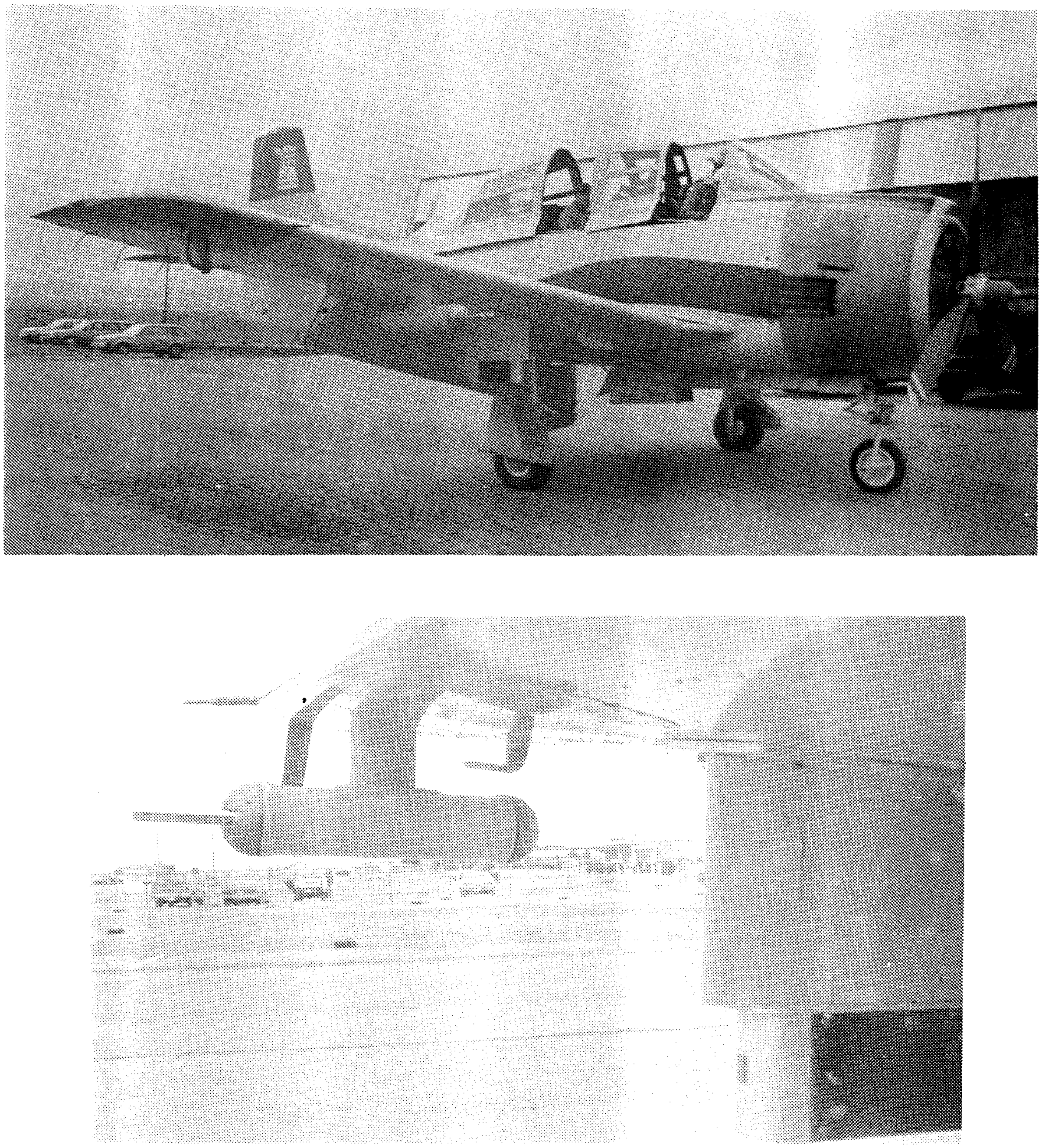
VARIABLE	INSTRUMENT	RANGE	ACCURACY	RESOLUTION (as recorded)	NOTES
STATIC PRESSURE	ROSEMOUNT 1301-A-4B	0-15 psi (0-103 kPa)	±0.015 psi (±0.1 kPa)	0.0002 psi (0.002 kPa)	• Bench calibration, 3/89
	ROSEMOUNT 1301-A-4B	5-15 psi (35-103 kPa)	±0.015 psi (±0.1 kPa)	0.0002 psi (0.002 kPa)	• Bench calibration, 3/89
TOTAL TEMPERATURE	ROSEMOUNT 102AU2AP	-30 - +30°C	±0.5°C	0.001°C	• Platinum wire • ~2 sec time constant
	NCAR REVERSE FLOW	-30 - +30°C	±0.5°C	0.001°C	• Diode • Several sec time constant • Bench calibration, 3/89 • Recovery factor adjusted, 5/89
CLOUD WATER AND CLOUD DROPLETS	JOHNSON-WILLIAMS LIQUID WATER CONCENTRATION	0 - 6 g/m^3	±20%	0.0001 g/m^3	• Accurate if all droplets have d <30 μm
	PARTICLE MEASURING SYSTEMS, INC. FORWARD SCATTERING SPECTROMETER PROBE	Size ~1 < 57 μm Concentration 0 - ~2000 droplets/cm^3	±1 size channel in size and ±1% in concentrations 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 ~±20%. Depends on processing.
PRECIPITATION PARTICLE SIZES AND CONCENTRATIONS	WILLIAMSON FOIL IMPACTOR	1 - 20 mm	0.2 mm	0.2 mm	• Sampling rate 1.4 m^3/km
	PARTICLE MEASURING SYSTEMS, INC. 2D Cloud Probe	Size 25 - 800 μm	±25 μm	25 μm	• Computed ice and water concentration can vary ±50% with processing technique • Sampling rate: 0.1 m^3/km; DAS can accept ~250 particles/sec (2500/km)
	HAIL SPECTROMETER	Size 4.5 mm - 5.4 cm Concentration 0 - 100/m^3	±1 size class	1 size class	• 14 size classes • Sampling rate 100 m^3/km • Alternates with particle camera
	NCAR PARTICLE SAMPLER				• A batch sampler, primarily for hailstones • Sampling rate 2.6 m^3/km
	CANNON PARTICLE CAMERA	Size >50 μm	50 μm	50 μm	• Sampling rate <2 m^3/km • Alternates with hail spectrometer
AIRCRAFT MOTION	NCAR TRUE AIRSPEED COMPUTER	0 - 250 kts (0 - 130 m/s)	±3 kts (±1.5 m/s)	0.125 kt (0.07 m/s)	• True airspeed
	HUMPHREY SSA09-00101-1 VERTICALLY STABILIZED ACCELEROMETER	-1 to +3 g's pitch -50° to +50° roll -50° to +50°	0.004 g 0.2° 0.2°	0.00006 g 0.002° 0.002°	
	ROSEMOUNT 1301-0-1B DYNAMIC PRESSURE	-3 to +3 psi (-20 to +20 kPa)	±0.1%	0.0001 psi (0.0006 kPa)	• Indicated airspeed • Bench calibration, 3/89
	ROSEMOUNT 1221-F-2A DYNAMIC PRESSURE	-2.5 to +2.5 psi (-18 to +18 kPa)	±0.1%	0.0001 psi (0.0006 kPa)	• Indicated airspeed • Bench calibration, 3/89
	GIANNINI 45218YE MANIFOLD PRESSURE	0 to 50 in Hg (0 to 169 kPa)	±2%	0.0008 in Hg (0.003 kPa)	• Used in one vertical veolocity calculation • Bench calibration, 3/89
	BALL ENGINEERING 101A VARIOMETER	-6000 to +6000 ft/min (-30 to +30 m/sec)	±200 ft/min (±1 m/sec)	0.2 ft/min (0.001 m/sec)	
AIRCRAFT LOCATION	NARCO NAV-122 VOR	0 - 360°	±2°	0.005°	
	CESSNA 400 DME	0 - 100 nmi (0 - 185 km)	0.1 nmi (185 m)	0.002 nmi (3 m)	• Maximum 2 sec to lock on and acquire range
	TRIMBLE TNL3000 GPS/LORAN	(global)	30 m (GPS)		
ELECTRIC FIELD	NMIMT Model E-100 DC Electric Field Meter	~ ± 200 $\frac{kV}{m}$		0.01 $\frac{kV}{m}$	

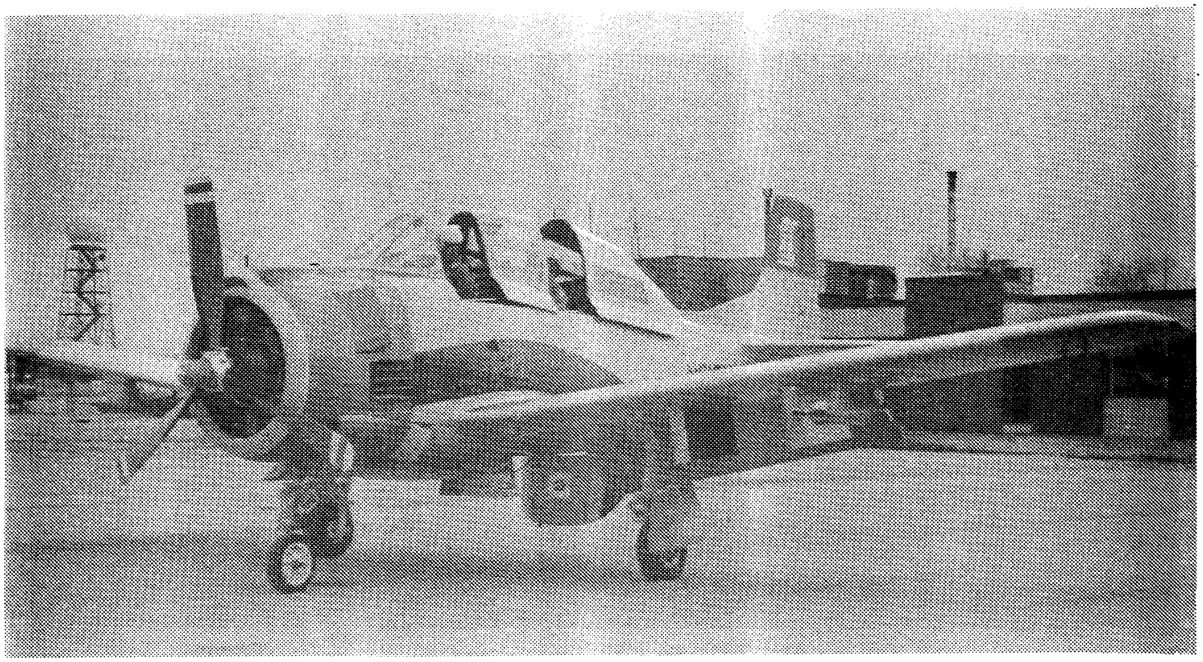
NOTE: Many of these instruments do not behave as ideal instruments. The use of one measure of accuracy over the entire range of measurement is, in many cases, questionable. An accuracy representative of the most useful part of the range is given here.

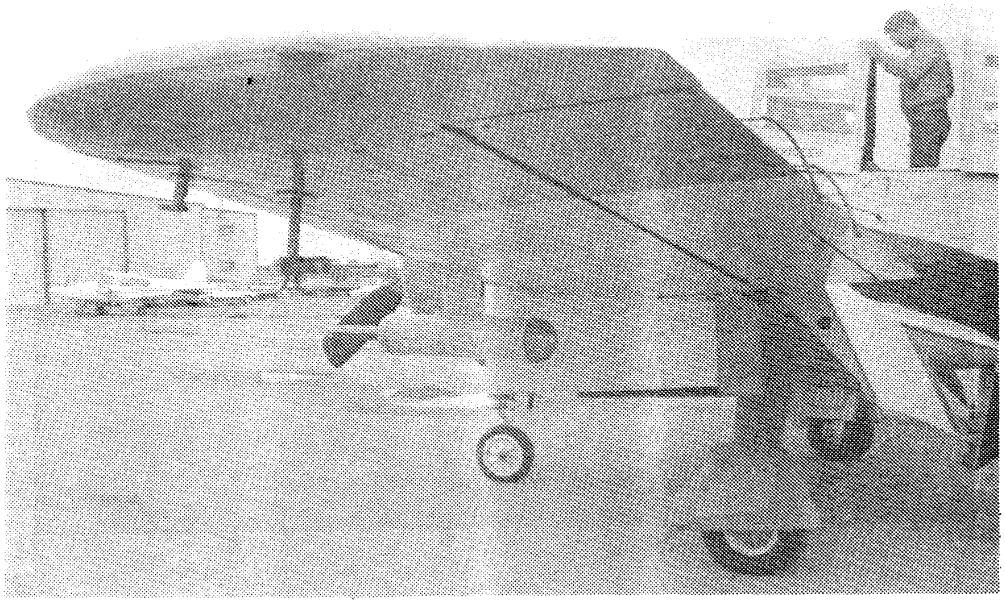


The T-28 is shown airborne over Florida in 1978. The two large packages under the left wing make up the Cannon particle camera. Two PMS probes and a foil impactor are mounted on a pylon under the opposite wing. An angle-of-attack vane mounted just outboard of the PMS probe pylon has not been used in recent years. The Johnson-Williams liquid water instrument rides under the right wing tip and two temperature probes hang under the left wing tip.



The T-28 is shown from its right side as it was configured in 1988. The instrumentation on its right wing includes, starting at the wing tip, a Johnson-Williams cloud water meter, the aircraft dynamic pressure probe (on the leading edge), the research dynamic pressure probe (aft of the leading edge, under the wing), a PMS 2D-C optical array probe, and a foil particle impactor.





The T-28 is shown from its left side. The instrumentation on its left reverse-flow temperature probe, a PMS Forward Scattering Spectrometer Probe, and a hail spectrometer. A rotating-vane electric field mill is visible on the baggage compartment door which is open and hanging below the fuselage just aft of the wing. [This photo does not show the wing-tip field mill which was installed later.]