Reprinted from the Preprint Volume, 6th Conference on
Aerospace & Aeronautical Meteorology, Nov. 12-15,1974
El Paso,Tex. Published by Amer. Meteor. Soc., Boston,MA.

OBSERVATIONS OF TURBULENCE AND ICING INSIDE THUNDERSTORMS

W. R. Sand, D. J. Musil, and T. G. Kyle*

Institute of Atmospheric Sciences
South Dakota School of Mines and Technology
Rapid City, South Dakota 57701

*National Hail Research Experiment
National Center for Atmospheric Research
Boulder, Colorado 80303

1. INTRODUCTION

The dangers of flying through thunderstorms have long been recognized and the point has been well made that, if possible, "Don't do it!" Most companies operating radar equipped aircraft have some sort of policy for avoiding thunderstorms (high reflectivity zones) by a specified distance and, in most cases, use their airborne radar primarily for flying around high reflectivity zones (Aarons, 1974). There is little question that these procedures have saved a lot of uncomfortable hours for passengers and, in some cases, may have saved some lives. However, it is of considerable scientific interest to know the thunderstorm composition and in what areas turbulence and icing are most severe. This information is also of interest to the operators of aircraft who at times are forced to fly in the immediate vicinity or through thunderstorms.

A North American T-28 aircraft has been heavily modified to fly through thunderstorms. It is currently being used by the South Dakota School of Mines and Technology as part of the overall National Hail Research Experiment (NHRE) to better understand thunderstorms.

The T-28 platform (Sand and Schleusener, 1974) was designed to repeatedly investigate the interior of thunderstorms with minimal aircraft damage. The overall objective of the research is to use the armored T-28 to obtain data within and in the immediate vicinity of hailstorms (Sand et al., 1972). The specific objectives are:

1. Obtaining measurements of updrafts in regions of hail formation and growth;

2. Determining the composition of high radar reflectivity zones; and

3. Studying ice-water budgets in hailstorms.

The T-28 made 83 thunderstorm penetrations during the 1972 field season. The penetrations were made between 5 and 7 km MSL corresponding to temperatures of -4 to -18C through thunderstorms with radar returns no greater than 55 dBz† at the altitude of penetration.

The pilot made both turbulence and icing observations during the penetrations using common nomenclature for such phenomenon. These subjective estimates of turbulence were supplemented by a more objective method utilizing a definition of turbulence based on airspeed fluctuations for a more definitive measure of turbulence. The turbulence parameter $\varepsilon^{1/3}$ was also calculated based on airspeed fluctuations. All of these turbulence measures are compared and presented to give a representation of turbulence inside a thunderstorm.

Icing observations, on the other hand, are limited to the pilot's subjective observations of icing rates and depth of ice actually accumulated on the airframe during a penetration. These observations give an indication of where the icing is encountered in a thunderstorm and how much adheres to the aircraft.

Updrafts, Johnson-Williams liquid water content, and altitude data are combined with observations of icing and turbulence to give a representation of the conditions encountered by the T-28 during these thunderstorm penetrations. Radar data gathered by the NHRE CPR-2 radar are computer processed into vertical sections along the T-28 track and Constant Altitude Plan Position Indicator (CAPPI) displays to give a detailed radar picture of the cloud during the penetration. These data are all combined to give a composite representation of three of the thunderstorms penetrated by the T-28. This representation enables the location of the most severe turbulence and icing at the penetration level to be determined relative to the high radar reflectivity zones.

†Reflectivity factor in dBz = 10 log $[Z/(1\ mm^6\ m^{-3})]$.

2. DATA

2.1 Turbulence

Observations of turbulence made by the T-28 pilot in real time and recorded on an onboard voice recorder were based on the following definitions of turbulence taken from Aerographers Mate 1 & C (1969), (Navy training manual).

Light: A turbulent condition during which occupants may be required to use seat belts, but objects in the aircraft remain at rest.

Moderate: A turbulent condition in which occupants require seat belts and occasionally are thrown against the belt. Unsecured objects in the aircraft move about.

Severe: A turbulent condition in which the aircraft momentarily may be out of control. Occupants are thrown violently against the belt and back into the seat. Objects not secured in the aircraft are tossed about.

Extreme: A rarely encountered turbulent condition in which the aircraft is violently tossed about, and is practically impossible to control. May cause structural damage.

Since the pilot was quite busy with other duties while penetrating a thunderstorm, these turbulence observations were oftentimes very infrequent. It was, therefore, decided to use airspeed fluctuations as a source of turbulence measurement. A turbulence definition based on airspeed fluctuations can also be found in Aerographers Mate 1 & C (1969), (Navy training manual).

Light: 2.4-7.5 m sec^{-1} (5-15 knots)

Moderate: 7.5-12.5 m sec^{-1} (15-25 knots)

Severe: More than 12.5 m sec^{-1} (25 knots)

Extreme: Rapid fluctuations in excess of 12.5 m sec^{-1} (25 knots)

Based on these definitions of turbulence a transparent template was made to permit more objective estimates of turbulence to be made from analog traces of indicated airspeed fluctuations. The template was made so that the airspeed block examined was 20 seconds long, therefore the maximum airspeed fluctuation had to be within this 20 second period to qualify for the turbulence classification as listed above. Indicated airspeed data during each penetration were examined with this device and moderate turbulence or greater was noted on the upper parts of Figs. 1A, 2A, and 3A.

Since the rapid fluctuations of airspeed in excess of 12.5 m sec^{-1} (25 knots) used as the definition for extreme turbulence were never noted, the only values noted in Figs. 1A, 2A, and 3A are moderate and severe, designated by M and S respectively along the top of each figure.

In almost all cases these values of turbulence matched quite well with the turbulence values noted in real time by the pilot so the infrequent turbulence observations made by the pilot were not included on the figures.

Steiner and Rhyne (1962) calculated some turbulence characteristics based on data gathered above 7 km MSL by penetrating aircraft. They measured short wavelength vertical gust velocities as high as 63 m sec^{-1}. These data do not compare with the longer wavelength updraft data discussed here (maximum less than 20 m sec^{-1}) since the T-28 system only responds to "updrafts" to which the aircraft itself responds. The turbulence discussed here is based on airspeed data recorded every 0.67 sec (approximately every 67 m).

Turbulence can be measured quite accurately using the parameter ε (a dissipation rate of turbulent energy) derived from the power spectrum of the airspeed fluctuations (MacCready, 1964). This more sophisticated method of deriving turbulence was employed as part of this study and is included as the parameter $\varepsilon^{1/3}$ in the lower part of Figs. 1A, 2A, and 3A. MacCready relates $\varepsilon^{1/3}$ values at 200 mph (the approximate penetration speed of the T-28) to levels of turbulence as follows:

Light:	$1.0 < \varepsilon^{1/3} < 2.0$
Moderate:	$2.0 < \varepsilon^{1/3} < 5.3$
Severe:	$5.3 < \varepsilon^{1/3} < 12.5$
Extreme:	$12.5 < \varepsilon^{1/3} < 22.0$

2.2 Icing

All icing data portrayed as part of Figs. 1A, 2A, and 3A were taken from the pilot's observations made in real time. The icing rates were merely subjective estimates of how fast the ice was accumulating on the airframe. These observations were supplemented with the aid of two homemade visual aids to help gage the ice depth on the aircraft. One of these aids can be seen in Fig. 4. It consisted of a small airfoil mounted on the side of the T-28 canopy within easy view of the pilot. The airfoil had a graduated rod protruding from its leading edge so that the ice depth on the leading edge of the airfoil could be accurately determined at any time. This device permitted determination of the ice depth on the airfoil at any time and by simple subtraction the ice accumulated during any specific time period or in any specific section of the cloud can be determined.

The second aid was a pattern of squares painted along the top leading edge of one of the wings, again in easy view of the pilot. This pattern of squares helped confirm the ice depth on the airframe. The number of squares covered with ice would tell the pilot how far the ice had progressed aft of the leading edge of the wing.

The icing observations are included in Figs. 1A, 2A, and 3A along the 10 km elevation line and are coded as LICE, MICE, and SICE to correspond to light, moderate, and severe icing respectively. At the extreme right along the

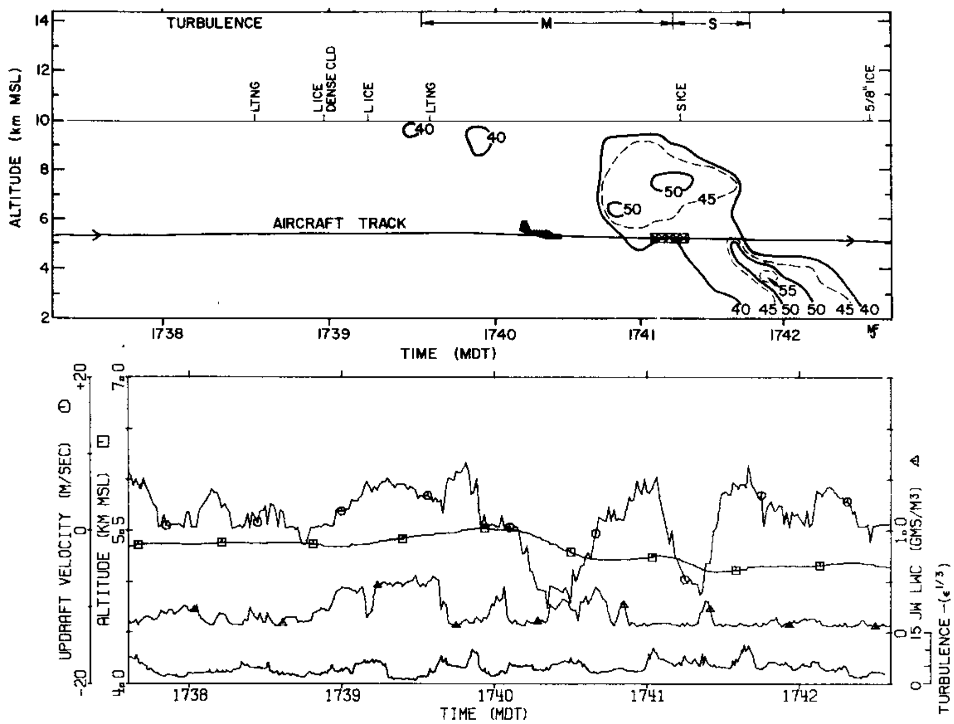

Fig. 1A. 21 June-Penetration 2. Vertical section, aircraft data and pilot's observations.

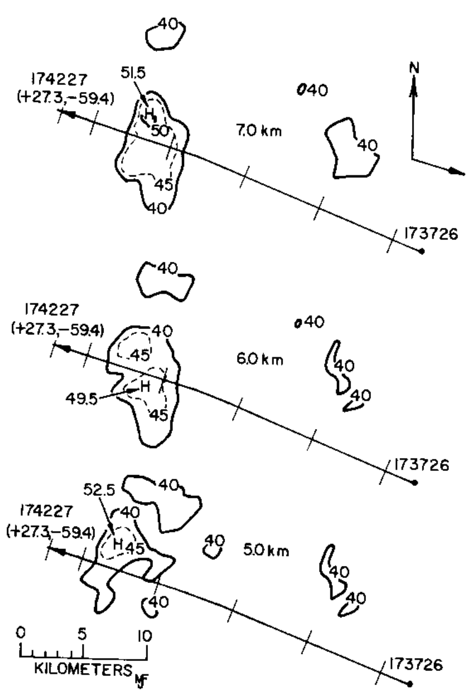

Fig. 1B. 21 June-Penetration 2. CAPPI displays at 5, 6, and 7 km MSL along T-28 track.

<u>NOTE to Figs. 1A, 2A, and 3A</u>: The vertical sections are hand contoured at 5 dBz intervals from computer generated reflectivity arrays. The outer contour represents 40 dBz. The vertical section is taken along the aircraft track as derived from an M-33 track radar. The altitude of the aircraft path in the vertical plane is given. LICE, MICE, and SICE represent observations by the pilot of light, moderate, and severe icing respectively. The total airframe ice accumulated (in inches) during a penetration is given at the far right along the 10 km elevation line. The airspeed fluctuation deduced turbulence is given along the top of the figure as M and S denoting moderate and severe turbulence respectively. Hail encounters are indicated along the aircraft track by a hatched area. The lower part of each figure represents data recorded onboard the aircraft and was computer plotted. Traces of updraft velocity (m sec^{-1}), altitude (km), Johnson-Williams liquid water content (g m^{-3}), and turbulence ($\varepsilon^{1/3}$) are indicated by circles, squares, triangles, and a plane line respectively. The abscissa of the lower part of each figure is representative of distance. An average aircraft velocity of 100 m sec^{-1} was assumed such that each minute represents 6 km distance. The abscissa of the upper part of each figure used the actual aircraft groundspeed as determined by the M-33 radar to relate distance to time. Therefore, a slight discrepancy will be noted between the abscissa of the upper and lower parts of each figure.

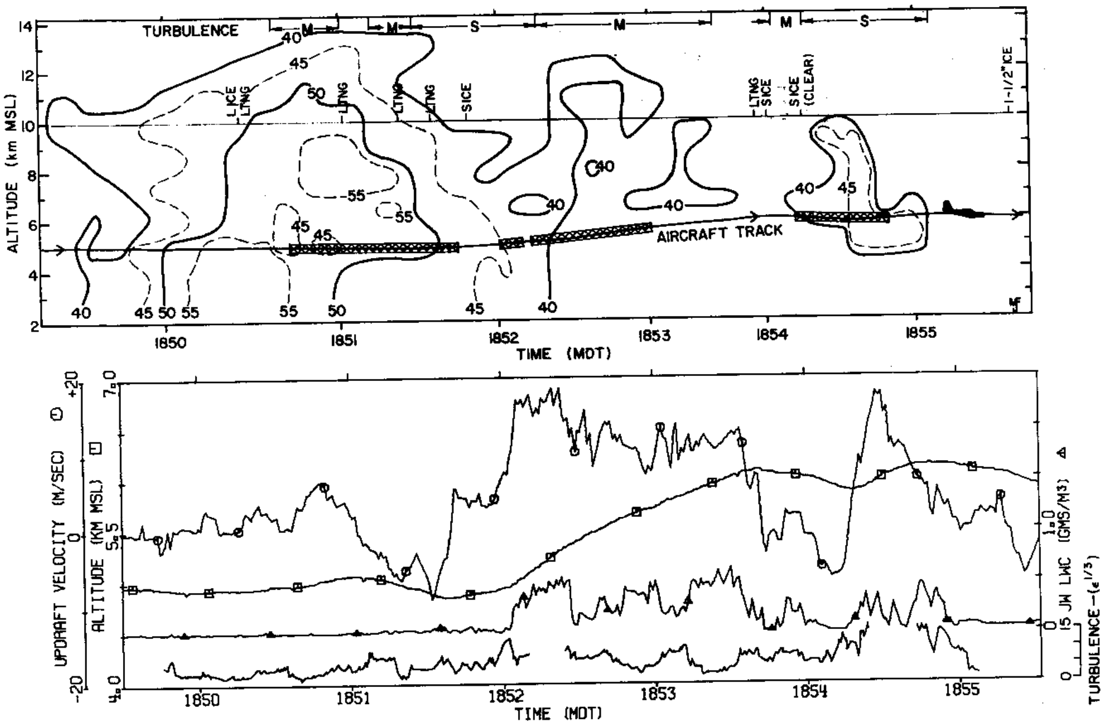

Fig. 2A. 7 July-Penetration 4. Vertical section, aircraft data, and pilot's observations.

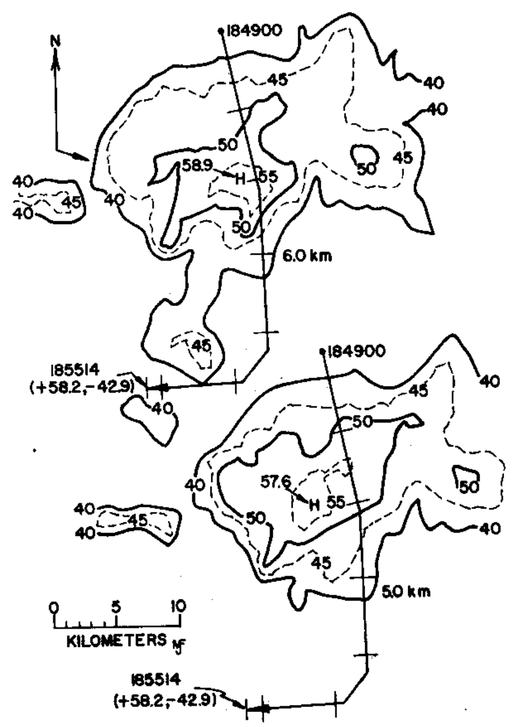

Fig. 2B. 7 July-Penetration 4. CAPPI displays at 5 and 6 km MSL along T-28 track.

NOTE to Figs. 1B, 2B, and 3B: CAPPI's are machine contoured at 5 dBz intervals with the outer contour representing 40 dBz. Computer derived points of maximum reflectivity are noted with an "H". CAPPI's are given for whole km altitudes MSL such that they bracket the altitude of T-28 penetration. The T-28 track through the storm is given on each CAPPI. The times of two known locations are given to the second and tick marks are placed along each track representing whole minutes. A reference point on the track is given relative to the Grover CPR-2 radar site with +X representing east and +Y representing true north. Direction of storm motion is given by the arrow at the base of the true north arrow.

10 km elevation line the total ice accumulated during the penetration is given.

3. DISCUSSION OF RESULTS

Notice by comparing Figs. 1A and 1B that light icing was encountered southeast of the high reflectivity zone downwind from the cell. Figures 2A and 2B show severe icing and turbulence being encountered on the southeast corner of the cell penetrated in the area of what could be construed to be a hook echo on the 6 km elevation CAPPI. Note also that during this penetration 1½ inches of clear ice was accumulated on the aircraft and that almost all of it was collected in the vicinity of the hook echo on the southeast corner of the storm. Using an airborne weather radar

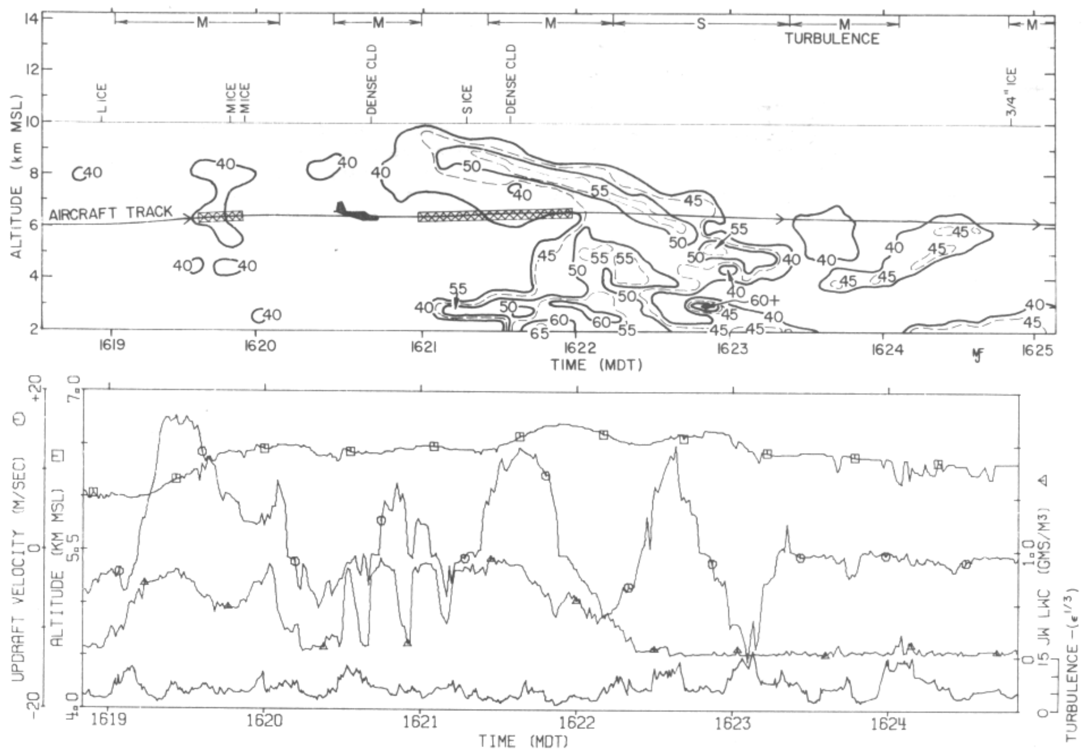

Fig. 3A. 22 July-Penetration 2. Vertical section, aircraft data, and pilot's observations.

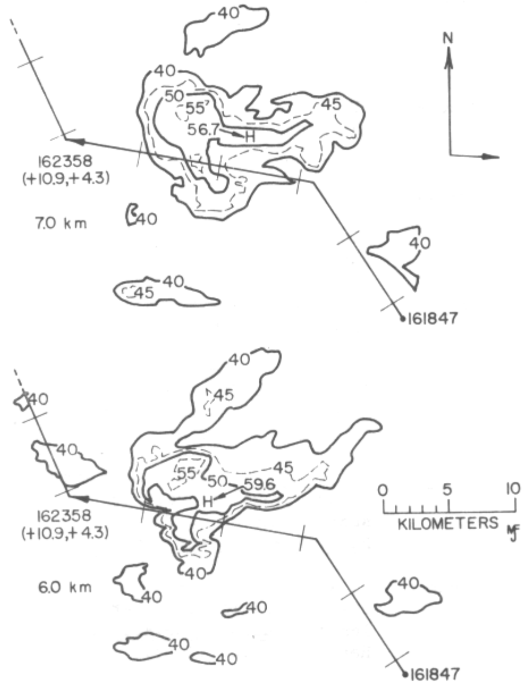

Fig. 3B. 22 July-Penetration 2. CAPPI displays at 6 and 7 km MSL along T-28 track.

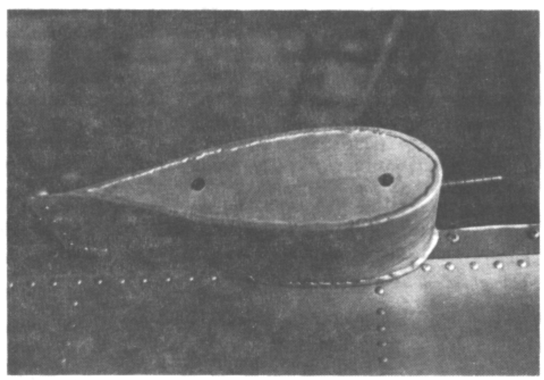

Fig. 4. Passive ice depth probe.

with no antenna tilt at 5 km or less one would be tempted to duck around the south edge of this storm only to meet some very formidable resistance anywhere within about 10 km. Figures 3A and 3B show moderate icing about 12 km from the 40 dBz contour at 6 km elevation. Note also the U-shaped area (Fig. 3B) encountered between 1621 and 1622 on the 6 km elevation CAPPI where severe icing and hail were encountered.

Icing could be determined in a more quantitative manner with more sophisticated instrumentation. This was attempted during the

1973 season and is the subject of a paper by Musil and Sand (1974). They describe a Rosemount icing rate probe installed after the 1972 season and find that it only gives the character of the icing and not a very quantitative icing rate in the severe icing conditions encountered in most thunderstorms. The important thing in this study is that there is substantial airframe icing potential present in updraft areas and these areas are not giving a significant radar return. The strong updrafts associated with the often severe icing and low radar reflectivities (less than 40 dBz) could give an unsuspecting pilot some moments of grave concern. The advice at this point would be not to fly in the close proximity of strong radar echoes, especially on the downwind side (or the side on which the strong inflow is occurring). This would correspond to the area adjacent to the hook, the U-shaped areas or scalloped areas, of the radar echoes (Aarons, 1974).

It should also be noted that frequently the supercooled water encountered was partially in the form of slush. This part ice, part water substance was quite effective in adhering to the aircraft to give a very dense form of aircraft ice, something between clear ice and rime ice.

In all cases, severe turbulence was associated with the high reflectivity zones. The turbulence observations made by the pilot correlated well with the turbulence values based on the airspeed fluctuation. The airspeed fluctuation turbulence values were based on a 20 second time period. The $\varepsilon^{1/3}$ turbulence values represent a 10 second average of $\varepsilon^{1/3}$ turbulence values based on indicated airspeed data taken every 0.67 sec.

With the three different methods of determining turbulence there seems to be little doubt that in any case the turbulence occurs in the same general area of the cloud, even though there is some disagreement on just how severe the turbulence really is. The most severe turbulence seems to be associated with the strongest radar return so, of course, the most obvious course of action to avoid the most severe turbulence is to avoid the strong radar returns. This agrees well with work reported by Burnham and Lee (1969) where penetrations were made between 7 and 11 km MSL.

4. SUMMARY AND CONCLUSIONS

It should be noted that the results of this study are based on thunderstorm penetrations made between 5 and 7 km MSL corresponding to air temperatures of -4 to -18C.

1. The most severe turbulence encountered during penetrations through thunderstorms was consistently found to be associated with the strongest radar reflectivity. Therefore to avoid the most severe turbulence in, and in the immediate vicinity of a thunderstorm, one should avoid the areas of strongest radar return.

2. The most severe icing is found in the area of the strong updrafts, downwind from the strong radar reflectivity areas. These inflow areas can be several km away from the high radar reflectivity zones in areas with relatively low radar reflectivities. It is very difficult to avoid these areas when trying to avoid thunderstorms using airborne radar since they do have relatively low radar reflectivities and look quite tempting compared to the adjacent high reflectivity areas. The familiar hook echo and U-shaped echo will be the best clue that these strong inflow areas are present and that severe icing and hail may be found in the immediate vicinity and some several km from these types of radar returns.

Acknowledgment. This research was supported under NSF Prime Contract No. C-460, NCAR Subcontract No. 182-71 as part of the National Hail Research Experiment, sponsored by the Weather Modification Program, RANN, National Science Foundation.

Acknowledgment is also made to the National Center for Atmospheric Research, which is sponsored by the National Science Foundation, for computer time used during this research.

REFERENCES

Aarons, R. N., 1974: Using weather radar. Business and Commercial Aviation, July 1974, 35-39.

Aerographer's Mate 1 and C, 1969: Bureau of Naval Personnel, Rate Training Manual. NAVPERS 10362-A. Stock Ordering No. 0500-112-0050, 819, p. 380.

Burnham, J., and J. T. Lee, 1969: Thunderstorm turbulence and its relation to weather radar echoes. J. Aircraft, 6, 5, 438-445.

MacCready, P. B., Jr., 1964: Standardization of gustiness values from aircraft. J. Appl. Meteor., 3, 439-449.

Musil, D. J., and W. R. Sand, 1974: Use of the Rosemount icing rate probe in thunderstorm penetrations. Accepted for publication in Atmos. Tech., (June 1974).

Sand, W. R., R. A. Schleusener, and D. J. Musil, 1972: Final report of the T-28 armored aircraft during the period 1 May 1971-1 May 1972. Report 72-17, Institute of Atmospheric Sciences, South Dakota School of Mines and Technology, Rapid City, South Dakota, 55 pp.

________, and ________, 1974: Development of an armored T-28 aircraft for probing hailstorms. Accepted for publication in Bull. Amer. Meteor. Soc., (Sept. 1974).

Steiner, R., and R. H. Rhyne, 1962: Some measured characteristics of severe storm turbulence. National Severe Storms Project, Report No. 10, 17 pp.