A. I. A. PC 338-1 PROJECT

INVESTIGATION OF ENGINE POWER LOSS AND INSTABILITY IN INCLEMENT WEATHER

SUB-COMMITTEE - OPERATIONAL FACTORS AND PROCEDURES FOR HIGH BYPASS ENGINES

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INTRODUCTION

1.0

INTRODUCTION

The information contained in this document has been prepared under the direction of the Aerospace Industries Association (AIA) PC 338-1 Project "INVESTIGATION OF ENGINE POWER LOSS AND INSTABILITY IN INCLEMENT WEATHER."

The objectives of PC 338-1 Project were as follows:

1. "Examine the historical record related to single and multiple engine power loss events in flight on transport type aircraft in inclement weather."

2. "Develop processes and/or operating procedures that will minimize the possibilities that the first exposure of such problems will be in airline revenue service. FAR 33.77C will be reviewed to determine whether revision is required and/or the need for an Advisory Circular addressing test technique."

The PC 338-1 Project directive also requested that a study be accomplished which would include an in-service history survey as follows:

1. "Conduct an in-service history survey of all turbine powered fixed wing transport type aircraft to expose for analysis all single and multiple engine power loss events (flameout, run down, shut down, stall/surge which required power reduction to prevent engine damage) solely as the result of flight in inclement weather (rain, freezing rain, hail, snow, sleet, icing conditions, volcanic ash, and/or turbulence including lightning)."

A review of service experience indicates that most of the power loss events have occurred during operation in heavy rain/hail, or in icing condition, or in turbulence, or with a combination of these conditions. The study also shows that for turbofan engines the problem is mostly limited to high by-pass ratio engines with only a few events reported on low by-pass engines.

Due to the limited data available on low by-pass engine events, the information in this report will address only high by-pass engine operation.

Of the four primary weather factors involved during power loss events, (rain, hail, icing and turbulence) only operation in heavy rain and/or hail will be discussed in this report. AIA Project PC 337-1, Natural Ice Effect on High By-pass Ratio Installations, revealed an operational problem in icing conditions, which is being addressed in AIA PC 338-1 study. Airplane Operations Manuals currently provide procedures for engine operation in icing conditions, therefore, this will not be addressed herein. Most of the power loss events in turbulence were limited to one engine manufacturer with the cause understood and corrective action has been taken to eliminate the problem. For this reason, power loss events due to turbulence will not be covered in this report.

Operation in volcanic ash is not considered in this study for the following reasons. Volcanic ash encounters are very improbable, only three reported for all commercial jet operations to date. Additionally, procedures are available to flight crews in their Operations Manuals should they inadvertently encounter volcanic ash. AVOIDANCE is strongly recommended. Also a review of current procedures, as they relate to previous volcanic ash encounters, did not indicate a requirement to publish new or revised operating instructions.

The information contained herein was compiled by the Aerospace Industries Association (A.I.A.) PC 338-1 project subcommittee for Operational Factors and Procedures for High Bypass Engines. It is intended that the material presented will be used by regulatory, airplane manufacturers and airline personnel to develop flight crew training programs and operating procedures for airplane operations in inclement weather. The material presented, for the most part, is general in nature and applicable to all models of airplanes equipped with high by-pass turbine powered engines.

DEFINITIONS

Terms "Aircraft" and "Airplane" are used interchangeably throughout this document and refer only to turbine powered fixed wing transport type aircraft.

The Terms spool down, run down, spin down, roll back are considered to have the same meaning and are used to indicate an engine thrust loss without complete loss of combustion within the engine.

The term "flameout" is used to indicate complete loss of combustion within the engine.

ENGINE POWER LOSS IN INCLEMENT WEATHER

2.0

ENGINE POWER LOSS IN INCLEMENT WEATHER

A review of service experience for high by-pass ratio engines during operation in inclement weather, where a power loss or instability occurred, has been accomplished. Events of most interest to the flight crews are engine shutdowns (rundown, flameout) with no crew action. During the study, data for the following airplanes and engines were examined.

Airplanes: A300, A310, A320, DC8-70, DC10, L1011, B737-300, B757, B767 and B747

Engines: JT9D, CF6, CFM56, RB211, PW2000, PW4000, V2500

During the period from January 1, 1980, through December 31, 1989, there were 57.8 million engine departures accumulating 171.2 million engine hours. During this same period, 101 inflight power loss events occurred with 85 of the events resulting in engine shutdown (rundown, flameout). Figure 1 shows the weather factors involved in aircraft inflight shutdown events since January 1, 1980. The majority of inflight shutdowns in cruise occurred with turbulence as the only weather factor involved. However during descent, approach and hold, most of the inflight shutdowns involved more than one weather factor.

FIGURE 1

WEATHER FACTORS INVOLVED IN AIRCRAFT EVENTS SINCE 1/1/80

INFLIGHT SHUTDOWN

EVENTS	T/O, CLB	TOC	CRU	TOD	DES, APP, HOLD	UNK	TOTAL	% OF EVENTS
	11	1	36	3	28	6	85	
RAIN	4		2		16		22	(25.9%)
HAIL					4		4	(4.7%)
SNOW					2		2	(2.4%)
TURBULENCE	4	1	31	3	7	4	50	(58.8%)
LIGHTNING	4		1		3		8	(9.4%)
ICE			2		10	2	14	(16.5%)
CLOUDS	1		1		3		5	(5.9%)
STORMY	2		1	1	2		6	(7.1%)
WINDSHEAR	1						1	(1.2%)
VOLCANIC ASH	1		2				3	(3.5%)

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Figure 2 shows the distribution for these inflight shutdown events. Power loss events in turbulence which resulted in engine surge or stall and where the engine was shutdown by the crew are not included.

The engine power loss events shown on Figure 2 during descent are approximately equally divided between the three major engine manufacturers. Most of the events during descent occurred in rain, hail and/or in icing conditions with the thrust levers at or near idle where the engine flamed out or ran down without any crew action .

Figure 3 shows a more detailed break down of flame out and rundown events since January 1, 1980.

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DISTRIBUTION OF AIRCRAFT EVENTS BY FLIGHT PHASE
ALL REVENUE SERVICE IN-AIR SHUTDOWNS SINCE 1/1/80
(NOT INCLUDING TURBULENCE ONLY EVENTS)

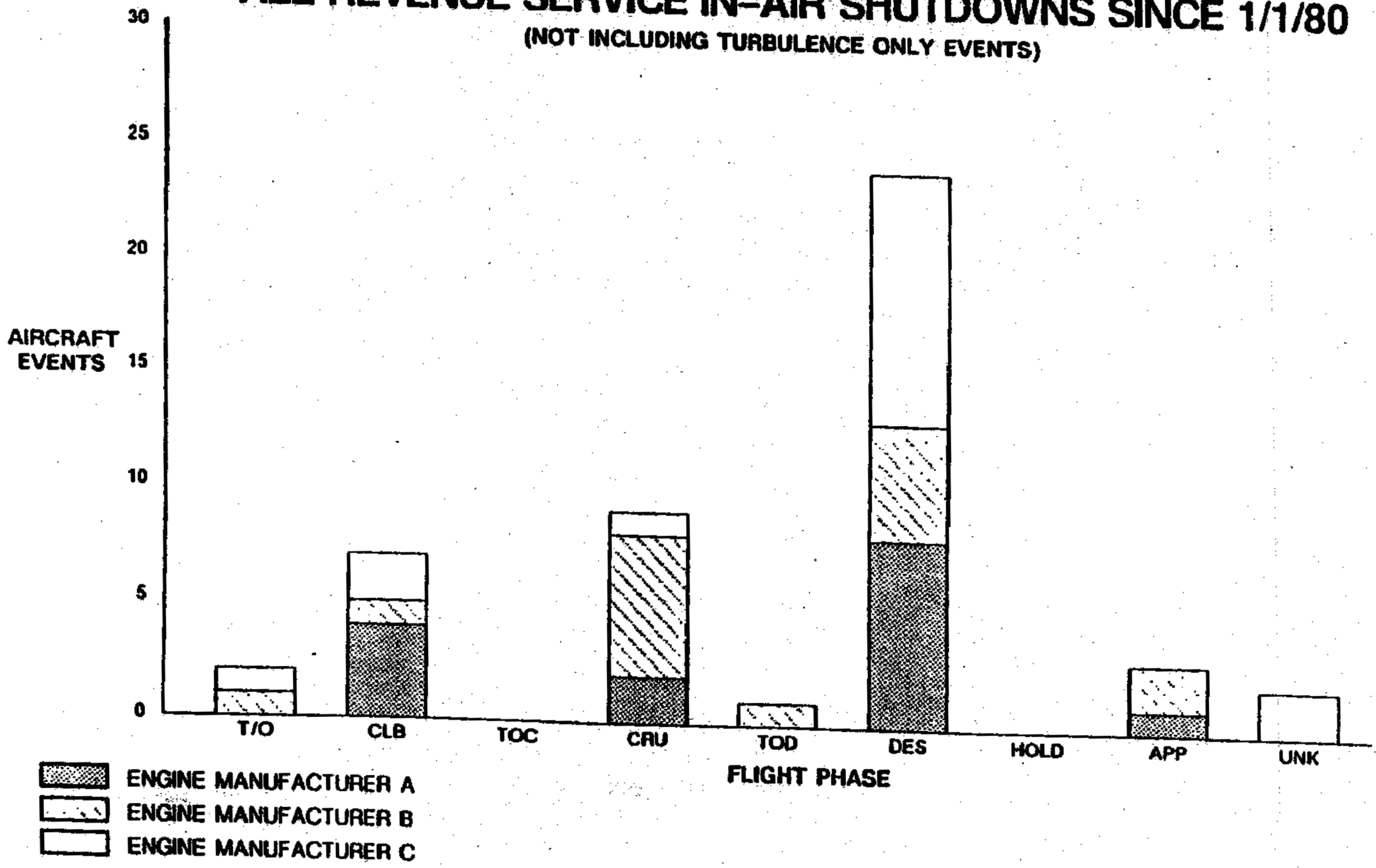

FIGURE 2

FIGURE 3

FLAMEOUTS & RUNDOWNS DURING DESCENT AND APPROACH

AIRPLANE EVENTS OCCURRING SINCE JANUARY 1, 1980, THAT RESULTED IN AN ENGINE SHUTDOWN.

- 28 AIRPLANE EVENTS
  - 19 OF 28 INVOLVED SINGLE ENGINES
  - 9 OF 28 INVOLVED MULTIPLE ENGINES
- RESTARTING
  - 16 EVENTS RESTARTED AND RAN OK
  - 1 EVENT RESTARTED AND WAS SHUT DOWN AGAIN
  - 1 EVENT NO ATTEMPT TO RESTART
  - 3 EVENTS RESTART NOT SUCCESSFUL
  - 7 NO INFORMATION
- 3 AIRPLANE MANUFACTURERS INVOLVED
- 3 ENGINE MANUFACTURERS INVOLVED
- 24 OF 28 EVENTS INVOLVED RAIN, HAIL AND/OR ICING
- THRUST LEVEL
  - 18 AT LOW POWER
  - 10 NO INFORMATION

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In summary, engine power loss events occurring since January 1, 1980, that were shutdown without crew action (e.g., rundown or flameout) during descent, hold and approach appear to affect various engine models and manufacturers (See Figure 4)

FIGURE 4

<u>DESCENT, APPROACH AND HOLD</u>

AIRCRAFT INFLIGHT REVENUE SERVICE EVENTS OCCURRING SINCE 1/1/80 THAT RESULTED IN AN ENGINE SHUTDOWN

OBSERVATIONS

- THIS IS THE MOST SIGNIFICANT FLIGHT PHASE FOR POWER LOSS EVENTS
- VARIOUS ENGINE MANUFACTURERS AND MODELS INVOLVED
- APPEARS TO OCCUR DURING LOW POWER SETTINGS OR AT CONDITIONS WHICH WOULD BE INFERRED TO BE AT REDUCED POWER
- EVENT RATES
  - ONE AIRCRAFT EVENT PER 7.3 X 10-5 AIRCRAFT DEPARTURES

    OR

    13.7 X 10-7 AIRCRAFT EVENTS PER AIRCRAFT DEPARTURE
  - ONE MULTIPLE ENGINE AIRCRAFT EVENT PER 2.3 X 10-6 AIRCRAFT DEPARTURES

    OR

    4.39 X 10-7 MULTIPLE ENGINE AIRCRAFT EVENTS PER AIRCRAFT DEPARTURE

HISTORY OF SELECTED INCIDENTS

3.0

HISTORY OF SELECTED INCIDENTS

A brief summary of selected inflight thrust loss (rundown, flameout) incidents during operations in rain and/or hail and/or icing is presented in this section to give flight crews better understanding of the conditions which can result in a thrust loss. A study of these incidents will help flight crews to avoid similar conditions that can result in a thrust loss or if such conditions cannot be avoided, then apply appropriate operating procedures.

HISTORY OF SELECTED INCIDENTS

A 737-300 airplane, equipped with CFM56-3 engines, experienced a two engine flameout during descent in rain, heavy hail, and moderate turbulence.

The flameout occurred when the airplane was descending through 8,900 feet, airspeed 289 KIAS, TAT +15 degrees C, left ignition on "Continuous," engine anti-ice off, thrust levers idle, left engine N1=33 percent and right engine N1=35 percent. Both engine generators were lost at flameout, and the crew reverted to standby instrumentation.

Number 2 engine was quickly relit, using a rapid relight procedure, bringing the generator on line and restoring normal instrumentation. The number 1 engine was restarted using the normal inflight start procedure and its generator brought on line.

An uneventful landing followed a visual approach. No visible damage to either engine was detected during a post flight inspection, which included a borescope inspection, nor was there any damage to the inlets or nacelles. There was hail damage to the stabilizer leading edge. Subsequent testing of the number 1 engine, by CFMI, did not reveal any abnormalities which could have caused a flameout. It is suspected that the ingestion of intense rain and hail was the cause of the flameout.

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HISTORY OF SELECTED INCIDENTS

An operator reported loss of thrust on both engines of a 737-300 airplane, which was descending between 15,000 and 10,000 feet in moderate turbulence, hail and heavy rain. The airspeed was 267 knots and TAT -2 degrees C. The thrust levers were at or near idle when both engines flamed out. Emergency electrical power was established and the APU was started. Attempts to restart engines were unsuccessful. An unpowered emergency landing was made on a grass strip next to a waterway.

There were no reports of injuries as a result of the incident. There was no damage to the airplane except hail dents in horizontal stabilizer leading edge, paint chips from the radome, and over temperature damage to the right engine turbine section. At the time of engine flameouts, anti-ice was on, boost pumps were on and continuous ignition was on.

The airplane was flown out of the same grass field after replacing the right engine.

HISTORY OF SELECTED INCIDENTS

A 747 airplane, equipped with RB211 engines, was at 19,000 feet on descent into Jakarta when it encountered extremely heavy rain and hail in cumulonimbus cloud. TAT of 14.2°C dropped quickly to +3°C and IAS rose from 280 kts to 298 kts in 3 seconds when Numbers 1 and 4 engines decelerated to a sub idle condition. Thrust levers were advanced and engine anti-ice switched on. Engines 2 and 3 responded immediately and engine 4 followed after a short pause. From the DFDR data it appeared that the Number 1 engine had just commenced to accelerate when the flight crew cut the fuel, believing the engine to have stagnated. The subsequent relight at FL120 was normal and the flight landed at Jakarta without further incident.

HISTORY OF SELECTED INCIDENTS

A DC-9-31 aircraft was on a scheduled domestic passenger flight from Huntsville to Atlanta.

During descent for Atlanta, the aircraft entered a small but intense precipitation area at about 15,000 feet. This small area was part of a much larger area of lesser intensity. In the area of intense rain and hail, both engines flamed out and the windshield was crazed or shattered, engine inlet fairings, wings and empennage leading edges also suffered hail impact damage. The pilot radioed ground control requesting vector to the nearest airport. During the glide the aircraft lost electrical power for about 2 1/2 minutes. Unable to reach an airport, the pilot elected to land on a narrow road.

Initial contact came with the wings clipping trees and poles on both sides of the road. The fuselage contacted the road, impacting cars and a country store, breaking up and burning. Some survivors were thrown free during fuselage breakup.

During the glide, the flight crew had tried to restart engines without success.

PROBABLE CAUSE - ESTABLISHED BY NTSB:

Weather: Ingestion of massive amounts of water and hail, which in combination with thrust lever movement, induced severe stalling and major damage to engine compressors.

Note: Although this event occurred on an airplane equipped with low bypass engines, it has been included in the history of Selected Incidents due to the general knowledge of this accident in the aviation community.

HISTORY OF SELECTED INCIDENTS

A L1011 airplane, equipped with RB-211-22B engines, inbound to JFK from LAX experienced a rundown of engines 1 and 2 about 50 miles northeast of JFK VOR while descending from FL200 to FL170. Both engines were later shutdown and restarted and the airplane landed normally a short time later.

Weather: Heavy rain showers, large thunderstorm buildups in the area, TAT 0°C.

The flight was on vectors with instructions to slow from 250 KIAS to 220 KIAS. Throttles were at idle. During the descent, the crew reported a turbulence spike which the flight recorder later revealed to be 1.6g. The autopilot was in turbulence mode, engine anti-ice and engine ignitions were on. All three engine fuel heat lights were out. During the brief encounter, the crew reported the sound of heavy rain on the fuselage. About 30 seconds later, when throttles were advanced for level off, engines 1 and 2 did not respond, and the crew reported that they had flamed out. Number 3 engine continued to operate normally. The APU was started and the ram air turbine was deployed to provide systems back-up for number 3 engine. The crew declared an emergency and received vectors direct to JFK.

Initial attempts to restart the engines in flight start mode were unsuccessful. The crew then switched to ground start and were successful. The airline later stated that the windmilling engine RPM and airspeed combination were out of the air start envelope.

No cause has been determined for the event, but the airline suspects that the combination of idle RPM, rain and turbulence probably accounted for the flameouts.

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HISTORY OF SELECTED INCIDENTS

A L1011 airplane, equipped with RB-211-22B engines, experienced a #2 engine flameout descending through FL160 to FL140 northeast bound into Gander. The engine was restarted later and a normal landing was accomplished.

Weather: Extremely heavy rain described by veteran Captain as "the heaviest he had ever seen." He also initially believed hail was included because of the intense noise. However, the post flight inspection revealed no evidence of hail. There were imbedded thunderstorms with unknown tops because the flight was in continuous clouds. TAT about +6 C.

The descending airplane was initially on autopilot with idle thrust and autothrottles off. Continuous ignition and engine anti-ice were both on. Initial speed was 300 IAS slowing to about 260 when the flameout was discovered. The radar was on 50 mile scale set on contour mode for the most part. There was considerable ground clutter but the crew felt they had avoided the storm contour areas. Turbulence was moderate. The airplane had just ridden out a significant updraft (nose down - airplane climbing) when the #2 generator light was discovered on. This led to flameout recognition a few seconds later. The thrust levers may have been moved out of idle just before, or coinciding with the generator light on discovery.

After exiting the heavy rain the engine restarted normally using an assisted start procedure.

A post flight inspection revealed no aircraft or engine damage.

HISTORY OF SELECTED INCIDENTS

On March 16, 1971, a 747 airplane equipped with JT9D engines, experienced a thrust loss and nonrecoverable stall on three engines while descending into Seattle.

At approximately 16.000 feet the airplane entered clouds. Approximately 2 minutes later, the engine anti-ice was turned on with the thrust levers at idle. The airplane unexpectedly entered extremely heavy precipitation of an ice/freezing rain mixture. Over the next few minutes, engines 2, 3, and 4 experienced severe engine icing. The thrust levers were advanced slightly, resulting in EGT increase with no N2 increase which necessitated shutdown and subsequent restart of these engines.

It has been concluded that the thrust loss experienced was probably caused by a rapid accumulation of ice which severely reduced low compressor flow capacity, thereby suppressing rotor speeds to a level from which engine acceleration was not possible. Operation in accordance with the Airplane Flight Manual procedures for icing conditions would preclude the rapid accumulation of ice and subsequent thrust loss described above.

HISTORY OF SELECTED INCIDENTS

On May 21, 1978 a 747 equipped with JT9D engines encountered a thrust loss on three engines during descent in clouds with visible ice crystals.

The lack of engine response on Engines 1, 2, and 4 occurred during descent into Honolulu. The descent was initiated at 37.000 feet with power reduction to idle. Fuel heat and nacelle anti-ice had been applied for two minutes prior to the descent. In the vicinity of 27.000 feet, the thrust levers were moved forward to adjust the descent. The number 3 engine was the only engine responding. The airplane had entered clouds and the presence of visible ice crystals was reported. Anti-ice, fuel heat, and ignition were switched on. The airplane continued its descent to 5,000 feet with the crew unable to obtain response from Engines 1, 2, or 4.

As the airplane descended lower, the flight engineer requested permission to shut down and restart number 2 engine. The captain concurred and number 2 engine was shut down and restarted. Initially the flight crew had difficulty starting number 2 engine because of low duct pressure. The engine was finally started and symmetrical thrust on engine 2 and 3 was regained at approximately 300 feet AFE.

As the airplane slowed on final approach, engines 1 and 4 began overtemping because of reduced airflow. It was decided to disregard the overtemping so that closer attention could be given to the two-engine approach and landing. After landing engines 1 and 4 were shut down.

Number 1 engine was changed after arrival because of turbine overheat damage, and number 4 engine was changed after two test flights. Maintenance could not find any reason for the malfunctions.

HISTORY OF SELECTED INCIDENTS

On June 7, 1980 a 747 airplane equipped with JT9D engines experienced a lack of thrust lever response on engines 1, 3, and 4 during a descent through cloud and rain into Toronto.

The crew reportedly attempted to advance thrust on all four engines at 9,000 feet when it was noted that the cabin pressurization altitude was climbing. Only the number 2 engine responded. The crew attempted to use a quick relight procedure but was unsuccessful. Each engine was shutdown and restarted in sequence. Thrust was restored on number 1 engine at 5,500 feet, number 3 engine at 5,000 feet and number 4 engine at 4,000 feet. AIDS data reportedly shows engine 1, 3, and 4 were in a state of stall starting at 19,000, 21,000 and 23,000 feet altitudes respectively. N1 speeds were 26 to 27 percent. The N1 speed on number 2 engine was 30 percent at this time. At no time did the engines flameout.

Operational procedures call for a minimum of 50 percent N1 above 10,000 feet in conditions where icing may be anticipated.

HISTORY OF SELECTED INCIDENTS

On April 12, 1982, during descent, a 747 airplane powered by CF6-50E2 engines experienced a four engine thrust loss. The engines flamed out at 26,000 feet in the following order: 2, 4, 1 and 3. The electrical generators tripped off. All engines were restarted and operated normally at 22,000 feet, approximately two minutes after the last engine had lost thrust. Engine restart was normal.

At the time of the incident, the airplane had penetrated cirrus stratus and cirrus clouds. OAT was minus 23 degrees C. There was no visible icing on the airplane. After engine restart at 22,000 feet, some light icing was detected, The airplane was returned to service and no subsequent difficulties have been reported.

Preliminary analysis of the flight recorder data revealed that thrust was reduced to idle for descent at 37,000 feet. Approximately 2 minutes after thrust reduction, a rapid rise in SAT from minus 42 degrees C. to minus 25 degrees C. occurred in 44 seconds. Approximately 2 minutes later, engines 2 and 4 flamed out. About 30 seconds later, engine 1 ran down and engine 3 flamed out. The transcription showed fuel flow to each engine was not interrupted prior to engine flameout and/or run down. All engine generated electrical power was lost. Engines were restarted and electrical power was restored within 80 seconds after electrical power was lost.

The four-engine flameout was concluded to be the result of ice shedding through the high pressure compressor and to the inlet of the combustor with all engines in a low idle setting.

HISTORY OF SELECTED INCIDENTS

On November 20, 1983 a 747 airplane with RB211-524 engines was descending through 25,000 feet in icing conditions when #3 and #4 engines ran down.

The flight crew reported that TAT dropped from plus 12 C to 0 C during descent. Before ignition and anti-ice were turned on, the number 4 engine ran down, followed by the number 3 engine. Multiple engine shutdown and restart procedures for these engines were completed satisfactorily. The descent continued through heavy rain and cumulo-nimbus activity with no further difficulties.

Ground checks of all suspect systems were satisfactory and the airplane was released. Late selection of anti-icing is suspected as the cause.

HISTORY OF SELECTED INCIDENTS

On September 29, 1989, a 737-300/CFM56-3B-2 operator encountered hail during descent in clouds while passing through 17,000 feet. The airplane experienced a brief two engine spooldown with both generators tripping off. It was reported that the airplane was in the green zone displayed on the weather radar and at least four miles from any indicated red zone. The engine ignition was on Continuous with the right ignitor selected and the anti-ice was off. Preliminary review of the Flight Data Recorder indicated N1 on both engines was at Low Idle (approximately 26 percent) when the hail was encountered.

After departing the hail area, both engines spooled up from sub-idle to normal operation without pilot action. The flight was completed with an uneventful landing. An inspection of the airplane and engines revealed no damage except for minor erosion on the radome.

WEATHER HAZARD/DEFINITION

4.0

WEATHER HAZARD/DEFINITION

INTRODUCTION

A number of different weather hazards associated with a variety of weather systems can be encountered while in flight. This section identifies and describes some common weather systems and the associated hazards inherent in each.

TYPES OF WEATHER SYSTEMS AND ASSOCIATED HAZARDS

Weather systems occur in nature over a wide variety of spatial and temporal scales. As a general rule the larger the horizontal extent of the system, the longer lifetime it is likely to have. Table I below identifies the scales of interest for this discussion.

---Table I---

Scale	Horizontal extent	Temporal extent
Convective	tens of miles	to ~1 hour
Mesoscale	tens to a few hundred miles	~1 - 10 hrs
Synoptic	a few hundred to a few thousand miles	~10 hrs - several days

AIR-MASS THUNDERSTORMS

These are convective-scale, isolated thunderstorm "cells" that often develop in the late afternoon, especially over land in the spring and summer months. They are also often seen to the west of frontal systems (see below) over the ocean. These cells generally do not pose as significant a threat as those found in larger mesoscale convective systems (see below), however they are capable of producing high wind shear, heavy rain and/or hail, and lightning. They will show up on radar as relatively small circular echoes and should be avoided.

MESOSCALE CONVECTIVE SYSTEMS (MCS)

An MCS is an organized system of convective thunderstorm cells. A familiar example of an MCS is a squall line; a line of convective cells. While the individual cells may have lifetimes as short as 15 to 20 minutes, the squall-line system may persist for several hours as new cells continually form out ahead of the leading edge of the storm. Other MCSs may appear less organized than a squall-line system, but both squall and non-squall systems will usually appear on a radar display screen as a region of contiguous echo with local reflectivity maxima embedded within the larger echo (see, for example, Figs. 1 through 3 in Section 5). The local reflectivity maxima are the individual thunderstorm cells, these regions should certainly be avoided at all costs, but in general the entire MCS should be avoided since new cells can develop as quickly as 10 minutes. Because of the more organized nature of MCSs, the individual cells are stronger, and can be more of a threat than, airmass thunderstorm cells. Heavy rain and/or hail, high wind shear and turbulence, strong vertical motions, and lightning can be produced by MCSs.

SUPERCELL THUNDERSTORMS

When certain atmospheric conditions are present, supercell thunderstorms can develop. A supercell storm is really an MCS that rather than having a multi-celluar structure, effectively acts as a single strong cell with a continuous updraft and downdraft. In multicellular MCSs, the individual cells are self-destructive in that the downdraft that eventually develops tends to cut off the inflow into the updraft, thereby killing off the supply of moisture and energy to the cell. Supercell storms on the other hand are characterized by an updraft-downdraft couplet that is non-interfering. As a consequence, the supercell thunderstorm can be very long-lived, with lifetimes often exceeding six hours. Supercells are the most severe storms that can be encountered. The largest hailstones and most tornadoes are spawned by supercell storms. Extreme hail and/or rain, strong wind shear and turbulence including tornadoes, strong vertical air motions (updraft can exceed 75 knots), and lightning are hazards that can be encountered in and around supercell storms. They frequently occur as isolated single-cell systems, but they can occur with ordinary cells in multi-celluar MCSs or even in a line. Fig. 1 shows typical radar horizontal cross-sections of a supercell at various altitudes and a vertical cross-section in the plane of storm motion. There often is a region of minimum reflectivity termed the bounded weak-echo region (BWER), like that shown in Fig. 1 at 4 and 7 km. The reflectivity pattern at 1 km is often referred to as a hook echo. The BWER and hook coincide with the strong updraft region. The BWER or hook will not always be present and therefore the reflectivity pattern can look similar to that of an ordinary thunderstorm cell.

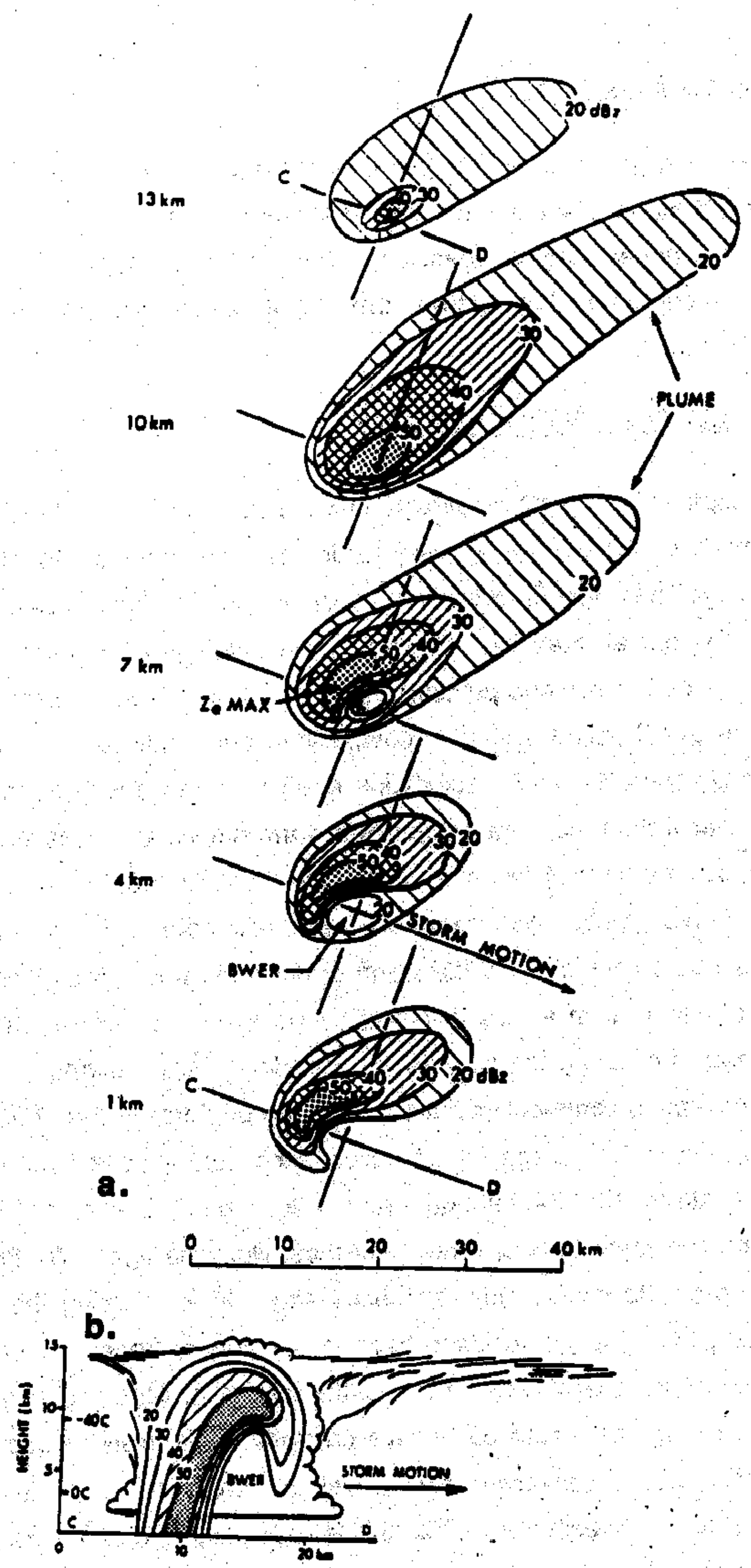

Fig. 1. a.) Schematic horizontal sections showing the radar structure of a supercell storm at altitudes of 1, 4, 7, 10 & 13 km above ground. Reflectivity contours are labeled in dBZ. Note the indentation on the right front quadrant of the storm at 1 km which appears as a bounded weak-echo region (BWER or "vault") at 4 & 7 km. On the left rear side of the vault is a reflectivity maximum extending from the top of the vault to the ground (see Fig. 1b). b.) Schematic vertical section through the plane of storm motion (along CD in Fig. 1a). Note the reflectivity maximum referred to elsewhere as the hail cascade, which is situated on the (left) rear flank of the BWER. (From Chisholm and Resnick, 1972)

HURRICANES AND TROPICAL STORMS

It is highly unlikely that a commercial airplane would have an inadvertent encounter with a hurricane or tropical storm since these storm systems are very long-lived and are well monitored by various meteorological agencies. Therefore, these types of storms will not be discussed here. Numerous publications on tropical storms exist and can easily be found in the meteorological literature.

EXTRATROPICAL CYCLONES (FRONTAL SYSTEMS)

These are the synoptic-scale weather systems that are tracked daily on weather maps. They are responsible for much of the day-to-day weather in the mid-latitudes. Most of the precipitation from extratropical cyclones occurs in the vicinity of "fronts", so named because they mark the boundary of two different air masses. There is a discontinuity of sorts in relative humidity, temperature, wind, and atmospheric pressure across a front. There are three basic types of fronts that occur in extratropical cyclones; cold, warm, and occluded[1]. The vertical air motions, liquid water contents, and precipitation rates associated with frontal systems are commonly much smaller than those associated with convective and mesoscale weather systems. There are, however, important exceptions to this rule. Squall lines can occur several miles ahead of or behind cold fronts. Significant convection also commonly occurs in conjunction with the cold front, and less commonly with the warm or occluded front. If a strong cold front moves through a region of warm moist air, as indicated by surface observations, then convection is likely to occur ahead of or along the cold frontal boundary. When extratropical cyclones are over the ocean, convection commonly occurs behind the cold front. Fig. 2 illustrates an extratropical cyclone in various stages of its development and indicates the locations of different fronts. In its initial stage (Fig. 2a), a cloud band will probably be present in conjunction with the stationary front, but precipitation, if any, will most likely be light. As the system begins to develop (Fig. 2b), precipitation intensity increases and a kink, marking the junction of the warm and cold front, forms along what had been the stationary front. Convective precipitation can start developing at this stage. Fig. 2c shows the mature cyclone with warm, cold, and occluded fronts. The regions where convective precipitation is likely to occur, if it develops, are indicated in the figure. If convection does develop, it presents the same hazards to aircraft as those associated with convection in MCSs, this is especially true of the convection that can occur ahead of and along the cold front

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[1] Actually, there is a fourth front, the stationary front, but it is simply a warm or cold front that isn't moving.

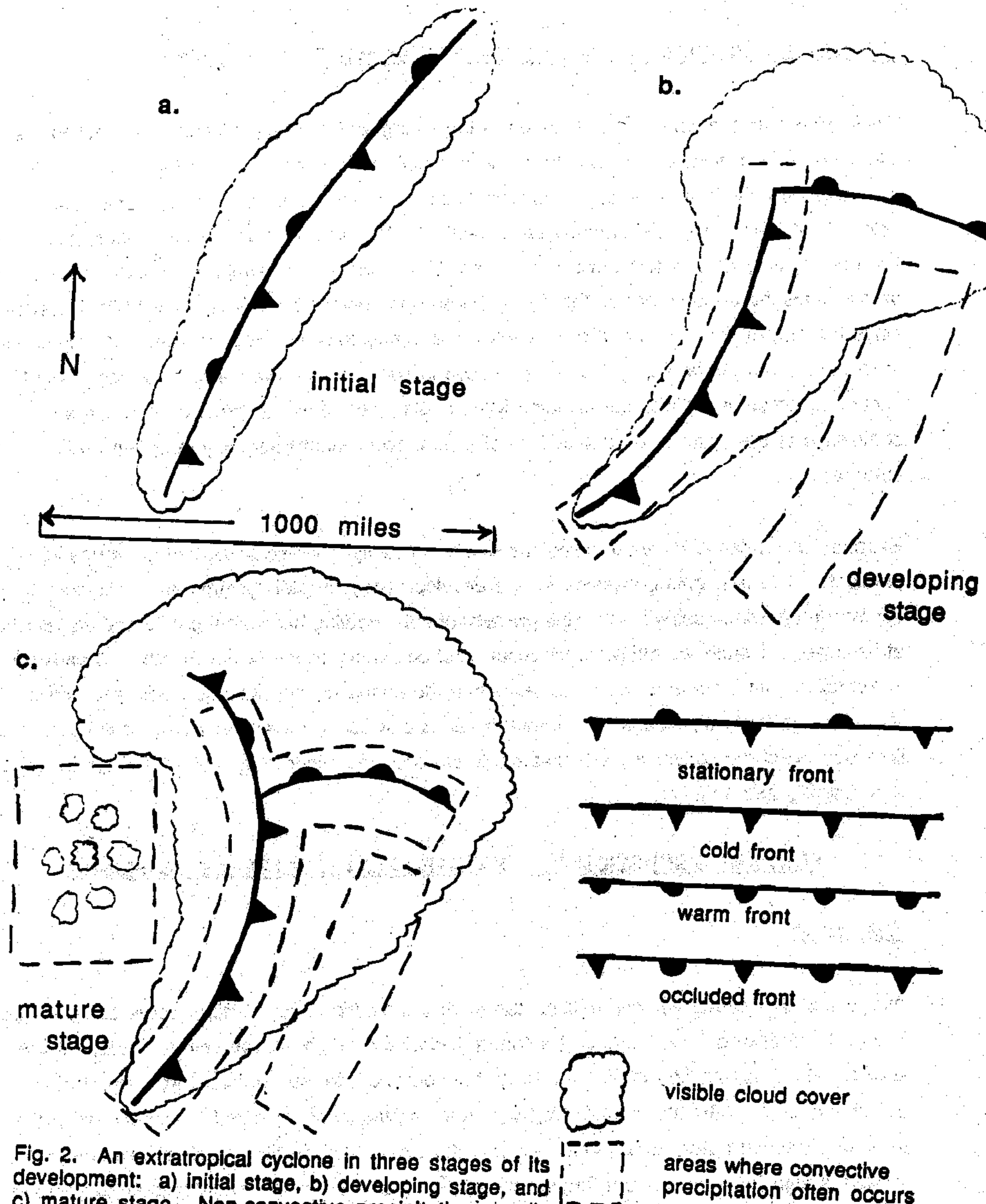


Fig. 2. An extratropical cyclone in three stages of its development: a) initial stage, b) developing stage, and c) mature stage. Non-convective precipitation usually occurs as rain or snow and can fall anywhere under the visible cloud cover, but is usually most intense in a broad region north of the warm front and in the vicinity of the cold front.

SEASONAL VARIATION IN THE OCCURRENCE OF WEATHER SYSTEMS

Convective precipitation is more common in the spring and summer months. Convection results when the vertical temperature profile of the atmosphere is unstable. In simple terms, this occurs when temperatures near the surface of the earth are warm and temperatures aloft are cold. During the spring and summer solar heating at the ground is strong and contributes towards creating an unstable atmosphere. In addition, there is a certain lag time in the heating of the atmosphere, such that as the spring season progresses atmospheric instability increases since the earth's surface warms quickly while the atmosphere is slower to warm. Consequently, in most areas of the world, spring is the season in which convective weather is most likely to occur. Since all of the weather systems listed above, except extratropical cyclones, are convective or are systems of convective cells, they occur most frequently in spring and summer.

Extratropical cyclones develop in regions of enhanced synoptic-scale horizontal temperature gradients. The gradients necessary for the development of frontal systems are most likely to develop in the winter season when the gradient of solar heating between the pole and equator is at its largest. Hence, frontal systems occur most commonly in the winter months. Convection in frontal systems, however, is more frequent in the spring for the reasons discussed above. It should be pointed out, though, that frontal systems can occur virtually any time of the year and likewise, any of the convective and mesoscale systems can occur in the fall and winter as well as in the spring and summer.

FURTHER DISCUSSION OF WEATHER-RELATED HAZARDS TO FLIGHT

WIND SHEAR

Wind shear and strong vertical motions can have a dramatic effect on flight paths as illustrated in Fig. 3. Expected flight paths and actual trajectories through a supercell thunderstorm are shown. The cross-section indicated is from the southwest to the northeast from left to right across the page. If the storm motion is towards the northeast as indicated, then because of the three-dimensional nature of supercell storms, the cruise altitude flight path shown would have to have a significant component through the page towards the south in order to fly first through the downdraft and then through the updraft. The glideslope flight path would be effected as indicated if it is actually along the page towards the southwest as it appears in the figure.

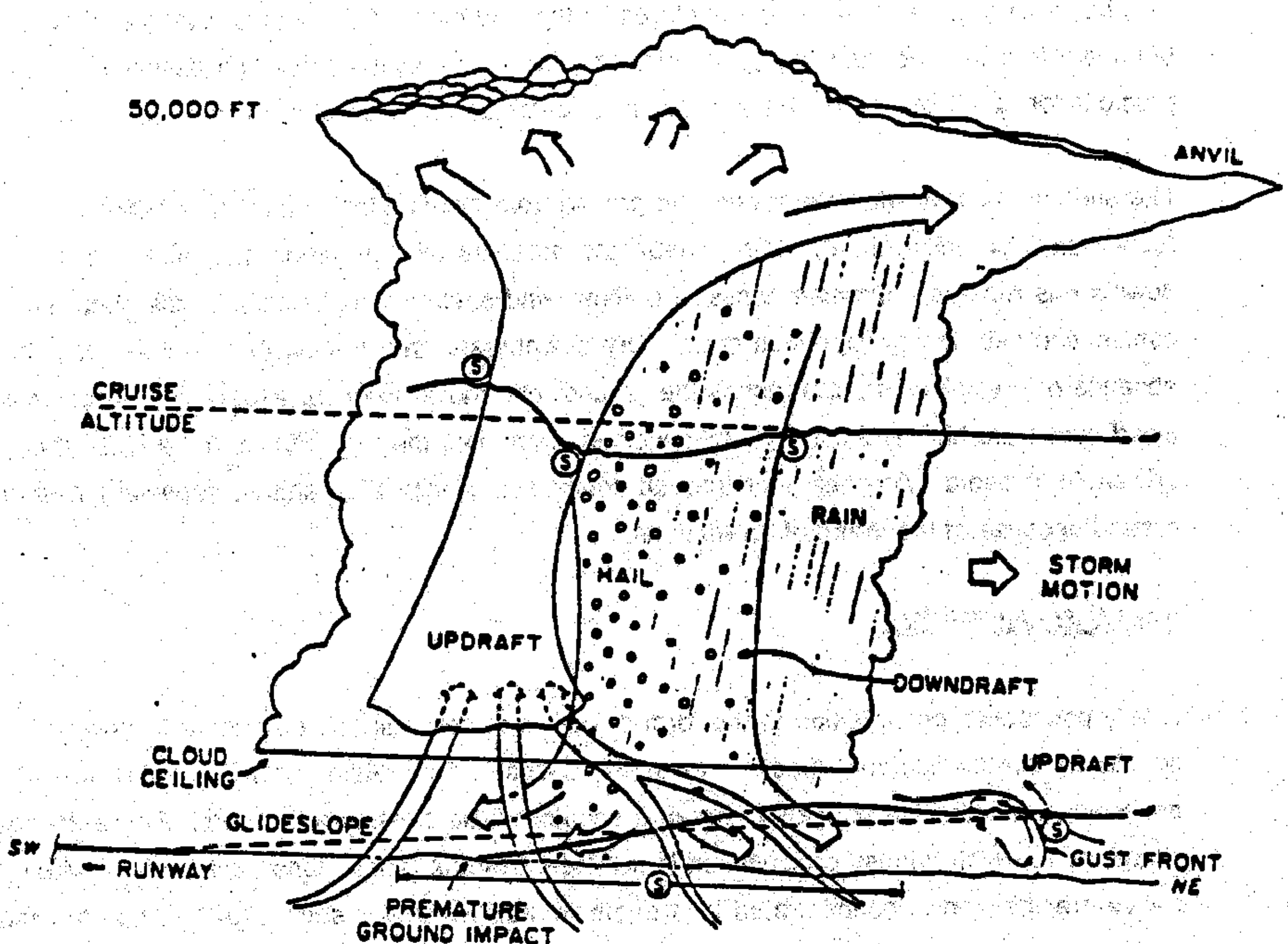


Fig. 3. Schematic showing the structure of a typical supercell thunderstorm and its effect on aircraft in cruise and landing flights. Dotted lines represent expected flight paths and solid lines are actual trajectories. S indicates the likely zones of wind shear and wavy segments of flight paths are caused by encounter with turbulence. In very severe storms, the updraft may also have a superimposed rotation, resulting in a helical air motion.

Fig. 3 shows that as an airplane enters the downdraft at cruise altitude it encounters shear and then is forced down out of its flight path, then at the interface of the up and downdrafts shear is again encountered and the airplane is forced back up to its flight path and beyond. Upon leaving the updraft, shear is again encountered and then finally the flight path is recovered. In the glideslope flight path, shear is encountered at the boundary of the thunderstorm outflow (this boundary is called the gust front). As indicated in the figure, the downdraft associated with the precipitation shaft can force the airplane into premature contact with the ground.

The sudden onset of wind shear near the ground from thunderstorm outflows is called a "downburst" or "microburst". Wind shear accompanies all thunderstorm outflows, but downbursts represent extreme cases of outflow wind shear. Usually downbursts occur in conjunction with the precipitation shaft. Dry downbursts, that is downbursts that occur in the absence of precipitation that reaches the ground, are known to occur especially in regions where cloud bases are high and the layer below cloud is dry, i.e., the High Plains in the U.S. It is advisable to avoid flying below or through convective precipitation shafts, especially near the ground because of the threat of downbursts.

RAIN AND HAIL THREAT

Heavy convective precipitation in the form of both rain and hail can contribute to engine spooldown and/or flameout (see, for example, Section 2.0). While radar is a valuable tool for assessing the inflight precipitation threat, it should not be considered perfect. There are many situations in which intense precipitation is not "seen" by the radar. One such case is when heavy precipitation is concentrated in a relatively narrow and/or short shaft. Since the radar beam spreads out with distance from the radar, a narrow precipitation shaft can be smaller than the resolution of the radar and therefore a "diluted" echo is returned. Another situation in which heavy precipitation can go undetected by the airplane radar occurs when a small "pocket" of intense precipitation exists above the radar beam. Fig. 4 illustrates this using actual radar returns from a convective storm in Alabama. In this particular example, an airplane probably would not fly through the cloud shown anyway because of the high reflectivity surrounding the more intense pocket, but it is easy to imagine similar situations in which an airplane would intercept an unseen pocket of intense precipitation. Attenuation of the radar beam by intervening precipitation is yet another way in which regions of intense precipitation can go unseen; this is discussed further in the next section.

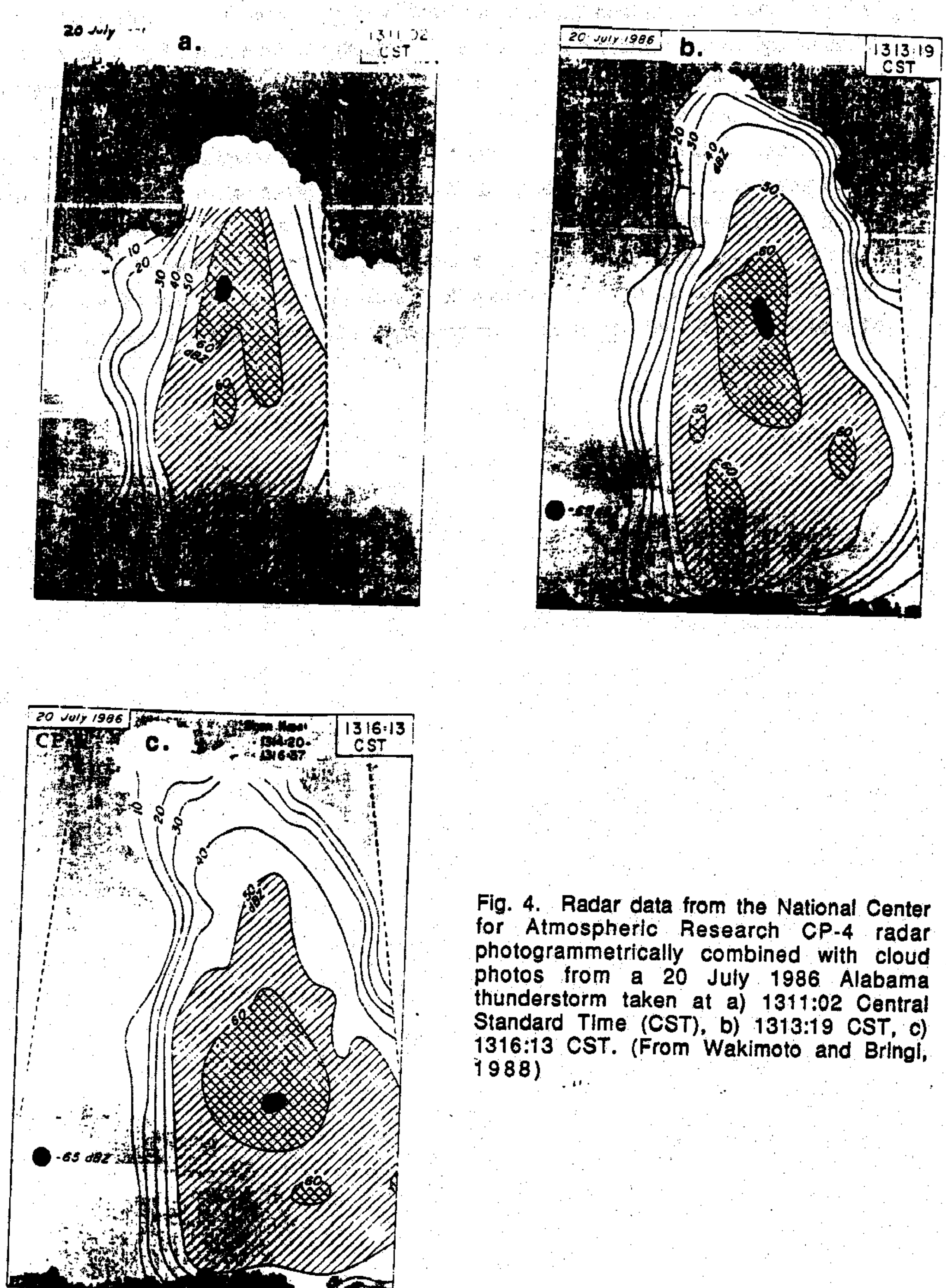


Fig. 4. Radar data from the National Center for Atmospheric Research CP-4 radar photogrammetrically combined with cloud photos from a 20 July 1986 Alabama thunderstorm taken at a) 1311:02 Central Standard Time (CST), b) 1313:19 CST, c) 1316:13 CST. (From Wakimoto and Bringi, 1988)

Perhaps of more concern than the threat imposed by heavy rain is that of intense hail. Unfortunately, on-board radar cannot reliably distinguish hail from rain. Fig. 5 shows the chance of hail being present versus radar reflectivity. In Fig. 5, it was assumed that magenta was used for reflectivity, but for many of the radar configurations magenta is used to indicate the presence of turbulence. The color ranges of a Collins 3-cm wavelength radar are indicated in the figure. There is no real threat of hail in the black or green return. The chance of hail in the yellow regions of the echo display varies from 0 to 22%. If the radar is set such that magenta is used as another reflectivity level then the chance of hail in the red return areas ranges from 22 to 65%. If magenta is used for turbulence, then all that can be inferred from a red echo return is that the chance of hail is greater than 22% and as high as 100%.

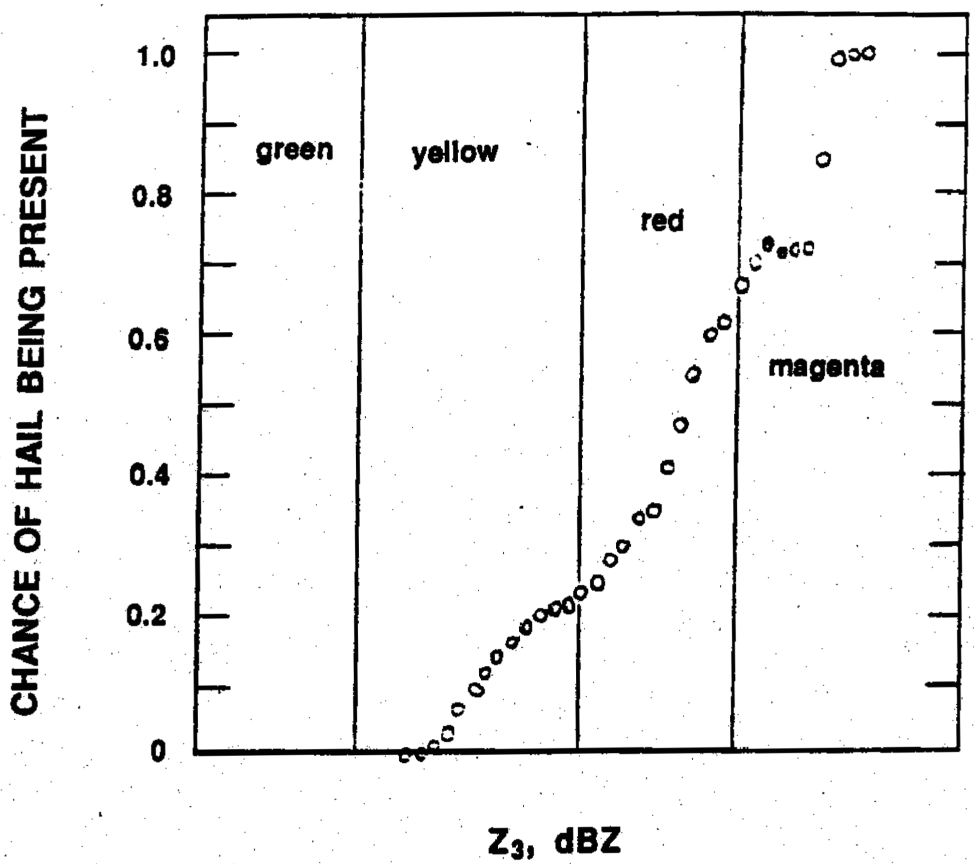


Fig. 5. Chance of hail being present in the various color ranges of a Collins 3-cm aircraft radar. The cross-overs from one color level to the next are marked by the solid vertical lines. (Adapted from Jameson and Heymsfield, 1980)

WEATHER AVOIDANCE

USE OF RADAR

5.0

WEATHER AVOIDANCE - USE OF RADAR

INTRODUCTION

ARINC 708 series radars, standard equipment on all new airplanes since 1980, are characterized by low power transmitters, flat plate antennas, digital processing, narrow beam width and color screen imagery. These new technology, solid state radars offer greater reliability and new turbulence detection methods, but also require new operating techniques and knowledge of system limitations. This section describes the new features of the 708 series radar and recommended operating techniques.

C-BAND TO X-BAND

With the advent of digital radar, most operators have made the switch from C-band (5400 MHZ) to X-band (9400 MHZ) in their new airplanes. Some basic properties of radar wave are:

-As frequency increases, reflectivity increases.
-As frequency increases, attenuation increases.
-As frequency increases, beam width decreases.

X-band scores high for total energy return, but due to its higher attenuation (signal weakening) rate, it loses ability to penetrate clouds with high levels of precipitation. Radar manufacturers have added features for displaying areas of probable attenuation.

Reduction in beam width is significant in improving target resolution and definition. The best return is generated where the target fills the radar beam. For a storm at 60-mile range to fill the beam of a C-band radar, it would have to be 5 1/2 miles in diameter; while to fill the beam of an X-band radar, it would only have to be 3 miles in diameter.

POWER OUTPUT

Previous generation radars, the monochrome or green screen sets, used high power (60 KW) transmitters. By comparison, the new radar has a power output of about 125 watts. This large reduction in transmitter power has been made possible by improved receiver technology, such that the ability of the new radar to paint returns at any given range is comparable to the old high power radar. Aside from the obvious benefit of reduced load on the airplane electrical system, the most important benefit from this reduction in power output is the ability to accurately control frequency, which allows implementation of turbulence detection, ground clutter suppression and reduction in interference.

DISPLAY, CALIBRATION AND RESOLUTION

The colors represent variations in rainfall rate and are easier to interpret than the older monochrome sets. The color-rainfall calibrations below are rounded numbers encompassing slight variations among manufacturers. The precipitation rates are valid only in Auto Gain mode and for typical size droplets. Be aware that Red and Magenta can have significantly different meanings depending upon the manufacturer, customer options, and number of colors displayed.

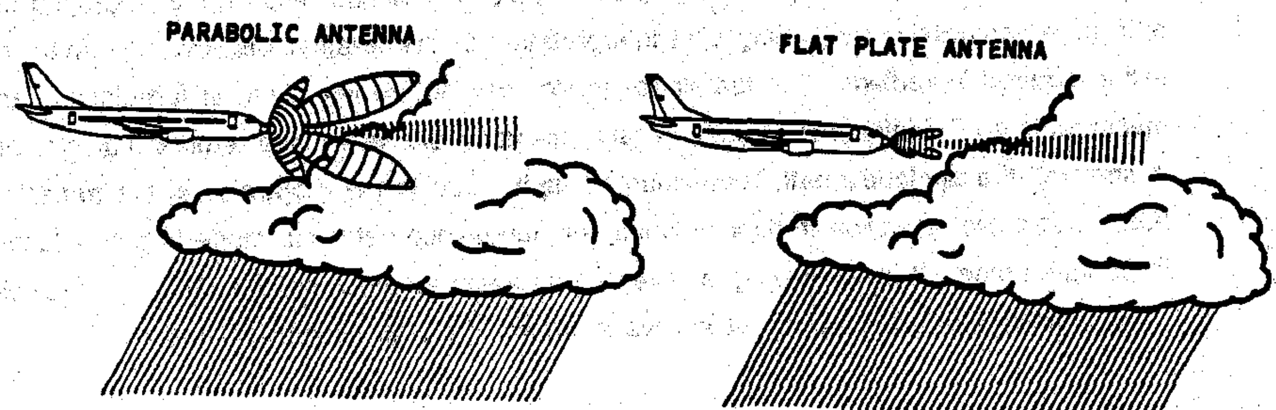
		RAINFALL RATE
BLACK	VERY LIGHT OR NO RETURN	Less than I mm/hr
GREEN	LIGHT	I-4 mm/hr
YELLOW	MEDIUM RETURN	4-12 mm/hr
RED (Monochrome Contour)	STRONG RETURN	Greater than 12 mm/hr
RED (Bendix with Magenta)	STRONG RETURN	12-25 mm/hr
RED (Collins, Honeywell with Magenta)	STRONG RETURN	12-50 mm/hr
MAGENTA (Bendix)	VERY STRONG RETURN	Greater than 25 mm/hr
MAGENTA (Collins, Honeywell)	VERY STRONG RETURN	Greater than 50 mm/hr and/or Turbulence > 5mm/sec
WHITE (Honeywell)		Turbulence> 5 mm/sec

Another significant difference is the way the picture is painted on the screen. In the old analog models, new returns were added by each sweep of the antenna, and the old returns gradually bled away depending on the level of persistence selected. The new radar display is generated in the same way as a TV screen; each new sweep is a totally new picture - the old picture is completely erased. Thus, there can be more abrupt changes in the picture from one sweep to another. Color changes can occur quickly if a return is close to the threshold between rainfall rate categories. A calibrated radar is one that accurately displays the true intensity of a storm regardless of its range. The new digital radars incorporate hypersensitive receivers and sophisticated sensitivity time control (STC) circuitry to present a true or calibrated image within a range of approximately 60 miles. Therefore, a yellow storm return at 60 miles will still be yellow at 10 miles. The calibration accuracy is based on gain control being set at the automatic, preset, or calibrated position.

Resolution characteristics are improved with flat plate antennas and narrow beams. Transmitted pulse width varies with the range selected, and thus two targets at short range would only have to be one-half mile apart to appear as separate returns, while at longer ranges, one and one-half mile longitudinal separation would be required to break out two targets. In azimuth, the resolution qualities are a function of beam width - but the same principle applies - the closer the target, the better the resolution qualities. A 3-degree beam can break out two targets with one and one-half mile separation at 30 mile range; at 100 mile range, 5 mile separation would be required.

FLAT PLATE ANTENNA

Some energy from the older parabolic antenna was lost in the side lobes resulting in more ground clutter at low altitudes and more close-range weather returns around the periphery of the main beam. The flat plate antenna transmits a narrow focus long-range beam greatly reducing the side lobes and focusing much more energy into the main lobe. With loss of the side lobes, tilt control becomes more critical. As you approach storms or reduce the range, the tilt must be adjusted downward to avoid overscanning significant returns.



MAP MODE

In the old generation radar, the map mode generated a fan-shaped beam that was effective over wide areas from low or intermediate altitudes. This fan beam was not useful at normal cruise altitudes due to the energy loss associated with the wider beam; so the narrow pencil beam used in the weather mode was usually used for mapping at high altitude. Now, with the new generation radar, the fan beam has been eliminated, but all that was really lost is the low altitude, short-range wide area mapping capability. Improvements in airborne and ground based navigation aids over the years have made this map mode a secondary function in most areas of the world. The mapping function from high altitude is quite effective if, as in weather avoidance, the tilt control is understood and used properly. For instance, at FL330 with 5 degrees of down tilt, the beam sweeps a 140-mile swath of ground from 50 to 190 miles in front of the airplane, whereas with 10 degrees of down tilt, the beam sweeps only a 15-mile swath of ground from 26 to 41 miles in front of the airplane. Adjustment to the gain is necessary to "break out" terrain features. Too much gain blots the landscape, paints returns between targets and obscures landmarks. Since the STC circuit is deactivated in the map mode, gain will have to be reduced for closer range targets. Good practice in radar mapping can be had on clear days when mountains, coast lines, cities, rivers, etc., can be seen visually and compared to radar screen images.

TURBULENCE DETECTION (OPTIONAL FEATURE)

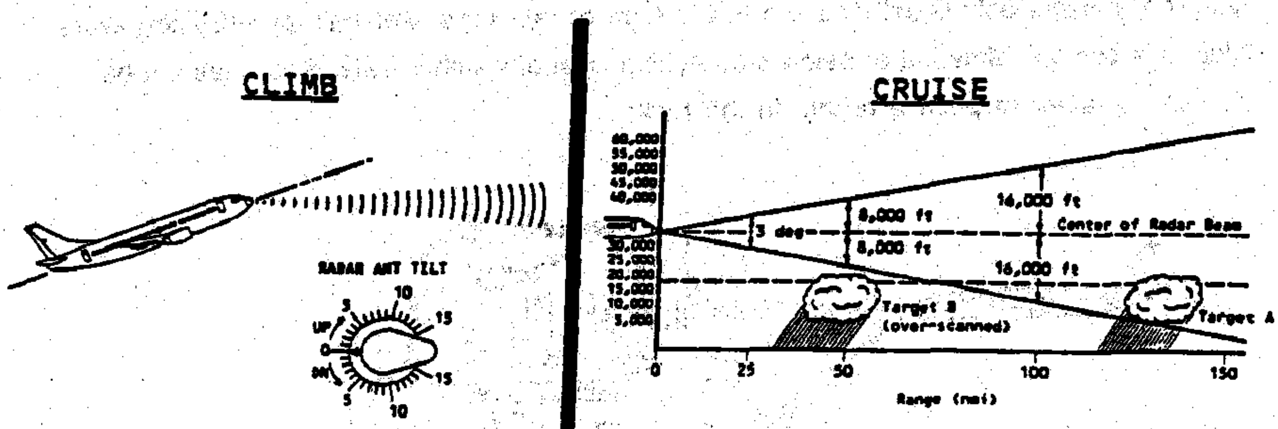
With the introduction of doppler techniques in radar, turbulence detection is displayed directly and more accurately, eliminating pilot interpretation of the weather display. However, rain is still a required ingredient. The turbulence mode does not display clear air turbulence. By measurement of longitudinal velocity of rain, the radar displays those returns that are moving in line with the airplane's path faster than 11 mph. Due to the properties of the transmitted beam and pulse repetition frequency limits, this turbulence detection mode is only effective out to 50-mile range. It is interesting to note that turbulent areas sometime show up in areas of light precipitation (green) and not always in areas of moderate (yellow) returns.

GROUND CLUTTER SUPPRESSION (OPTIONAL FEATURE)

Ground Clutter Supression (GCS) uses doppler frequency shift as does the turbulence mode. Here, however, any target that exhibits less than 2 mph longitudinal movement is considered a ground return and eliminated. Targets with speeds of 2-11 mph are considered precipitation returns and those over 11 mph as turbulent precipitation returns. Tilt angles of no more than minus 5 degrees suppress ground returns well, but steeper tilt angles result in inadequate suppression of ground clutter. Since GCS "identifies" ground returns as anything that moves slower than 3 mph, it is possible that slow moving weather returns may also be filtered out. Thus GCS should not be left on continuously, but rather used in quick analysis of returns, then turned off.

FLIGHT PROCEDURES

Takeoff and Climb - Prior to takeoff, it is desirable to tilt the antenna up to scan for weather along the departure path. During initial climb, the antenna should remain tilted up to avoid ground clutter and to coincide with the airplane's climb angle. The antenna stabilization, controlled by the airplane gyro or IRU, is referenced to the horizon, not to the longitudinal axis of the airplane.



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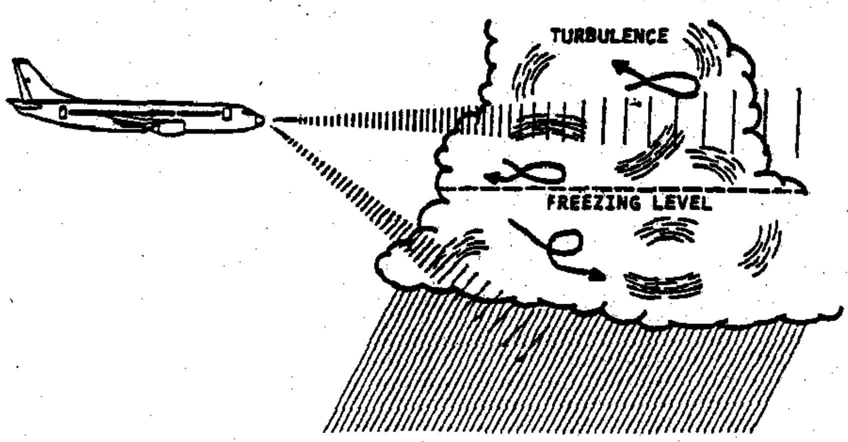
Range selection should be appropriate for airplane speed and location of weather returns. As the airplane continues climbing, the tilt should be gradually decreased to aim at the regions of maximum precipitation while avoiding ground clutter. Tilt angles below approximately plus 4 degrees will pick up some ground clutter below 5,000 feet AGL.

Cruise - For cruise, recommended tilt settings vary from one manufacturer to another, but generally speaking, the tilt should be adjusted so that ground returns are barely visible at the outer edge of the screen. Ground returns are displayed in arcs parallel to range marks. They merge together as the tilt is brought down and cause shadowing behind prominent features. They are generally smaller, sharper, and more angular than weather returns. The tilt will have to be adjusted more frequently as storms are approached or range is changed to avoid overscanning. Having once adjusted the tilt setting, the flight crew should not be content with just an occasional glance at the screen. Failure to periodically down tilt leads to "disappearing" targets. The narrow beam width of the radar presents only a two-dimensional cross section of the storm. To adequately analyze a storm front, the pilot should vary the tilt and try to construct a three-dimensional "picture" of what lies ahead. Also, since the power output of the transmitter is changed significantly as range is switched, the antenna must be re-aimed with each range switch. For normal cruise altitudes, it will be more difficult to detect cells lower than the cruise altitude inside of 40-mile range due to ground clutter, particularly over land. For this reason, a diversion route should be initiated before the target is inside of 40 miles.

Setting the tilt near zero at cruise altitude can degrade the usefulness of the radar significantly. This radar detects only liquid moisture in the form of raindrops, wet hail, or wet snowflakes. Unless the beam is aimed at or below the freezing level of weather cells, there may not be sufficient moisture to paint a return on the radar.



The National Severe Storm Laboratory in Oklahoma City advises that thunderstorms to 60,000 feet show little variation in turbulence intensity with altitude. Further, they state that strong vertical drafts and large hail exists to within several thousand feet of the tops of these storms. If you can visually confirm that you will top a storm, conservative philosophy says you should top it by 1,000 feet per 10 knots of wind at altitude. Since every degree of tilt moves the beam center vertically (in feet), an amount equal to 100 times the targets range, you may be able to determine your vertical clearance over a storm. Applying this rule, if you picked up a return at minus 3 degree tilt and 50-mile range, its liquid top would be 15,000 feet below you.

Any storm return with more than one color is bound to have turbulence, even in the green area. Steep gradients, that is, thin lines of color, are areas of greatest turbulence. A return that is changing shape or size over a short period of time is potentially very turbulent. The other prime indicators of severe activity and hail such as fingers, hooks, scalloped edges and horseshoe shapes require avoidance, and should not be ignored even if they are green in color. Tornadoes frequently have very little moisture and paint as green narrow curved fingers or figure 6's. Shape is just as important as color in determining the intensity and turbulence of a storm.

<u>Descent</u> - Antenna tilt will have to be raised approximately one degree per 10,000 feet of descent down to 15,000 feet, then one degree per 5,000 feet below 15,000 feet. Range should be adjusted as necessary to scan the arrival route adequately. In heavy weather, the longest appropriate range should be used to plan a safe storm avoidance route; then selection of shorter ranges will show greater detail as you enter the affected area. Remember that more tilt adjustment will be required each time the range is switched.

REFLECTIVITY

Radar reflectivity, Z, is a measure of the power returned to the radar by precipitation, usually expressed in decibel form, dBZ (= 10 log Z).

Airplane radar will not display clouds, only the raindrops within. The size of the particles are more important than the actual liquid water content. A visible cloud in mist or ice crystal form may not show up on radar in Auto Gain. Ice crystals and other small frozen precipitation particles do not reflect as well as raindrops of the same size. Any hail of significant size will show up on radar, and when coated with water will become highly reflective.

Figs. 1, 2, and 3 are severe storm PPI displays for S-, C-, and X-band (10, 5, and 3 cm) weather radars, respectively. The series illustrates a fundamental limit to the performance of aircraft radars as severe storm liquid water content (LWC) sensors.

Precipitation elements attenuate as well as backscatter radar energy, and this attenuation limits the "depth" to which a given radar can "peer into" a storm. The shorter the wavelength, the greater the attenuation and the shallower the radar penetration depth. Many of the airplane radars correct for the effects of attenuation. Ultimately, though, heavy precipitation can attenuate the beam to the degree that the power returned to the radar is so low that it becomes indistinguishable from noise. Precipitation beyond the range where this occurs cannot be seen by the radar. Figs. 1-3 illustrate the effects of attenuation on the radar display. Three radars, S-, C-, and X-band (Figs. 1, 2, and 3, respectively), scanned the same convective storm system simultaneously and at the same elevation angle. In this example none of the three had a built in correction for attenuation, but note that even if the X-band radar had corrected for attenuation it still would not have been able to "see" many regions of the storm. The region bounded by azimuths 0 to 90° and the ranges 100 to 200 km was not seen by the X-band radar (Fig. 3) because the beam had been attenuated completely in the first 100 km. As can be seen in the S-band display (Fig. 1), there are several areas in this region where the reflectivity exceeds 40 dBZ (red on aircraft displays). The C-band radar (Fig. 2) is also affected by attenuation, but not nearly to the extent of the X-band.

Most weather radars in the commercial airplane fleet are X-band. The implication of these last three figures is thus that, though extremely valuable, use of such radars for hazardous weather avoidance is by no means sure-fire.

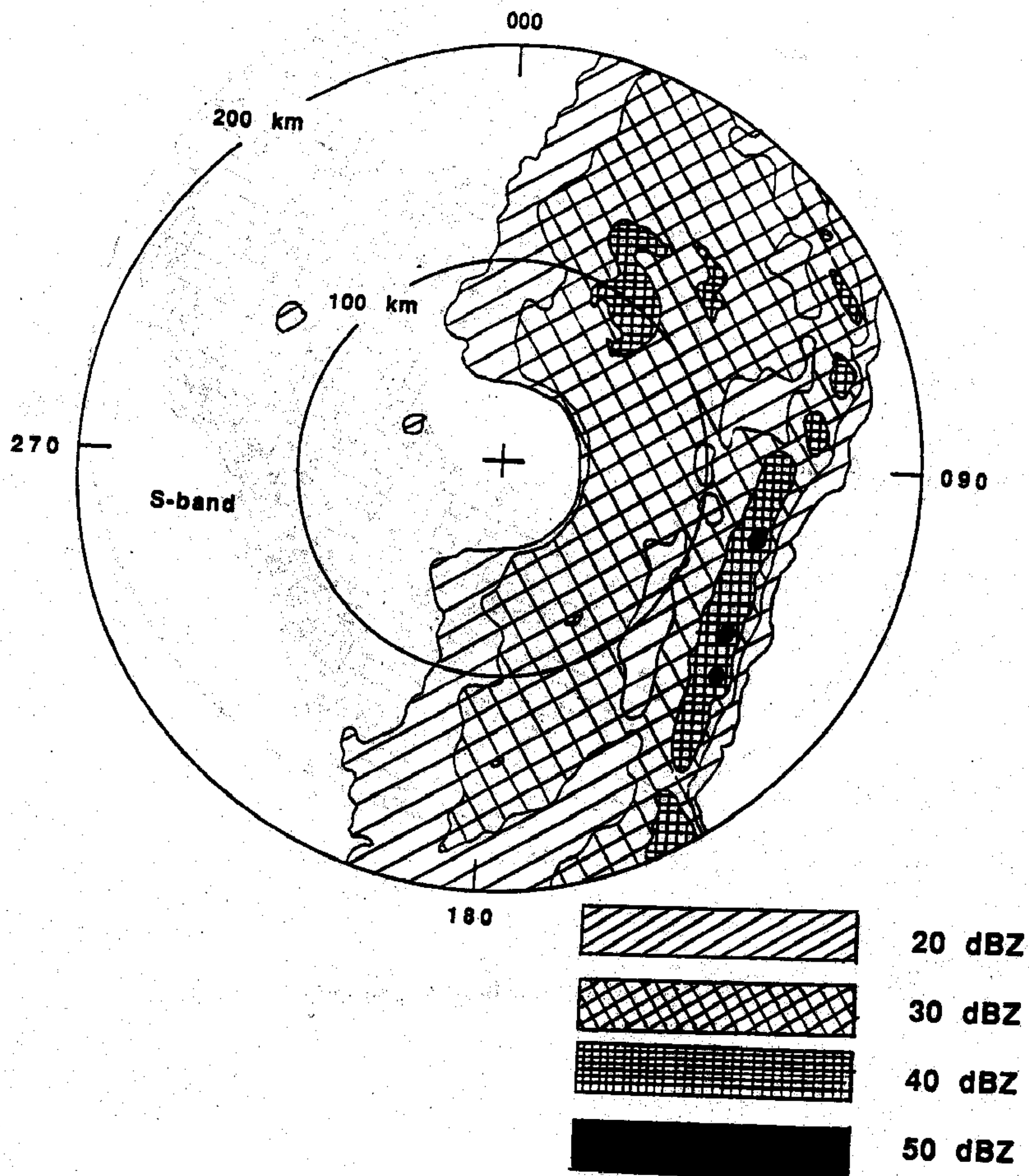


Fig. 1 PPI scan of a Midwestern United States storm system as seen by an S-band (10CM) radar. Range ring intervals are 100 km. Figs. 1-3 are simultaneous and at the same elevation angle.

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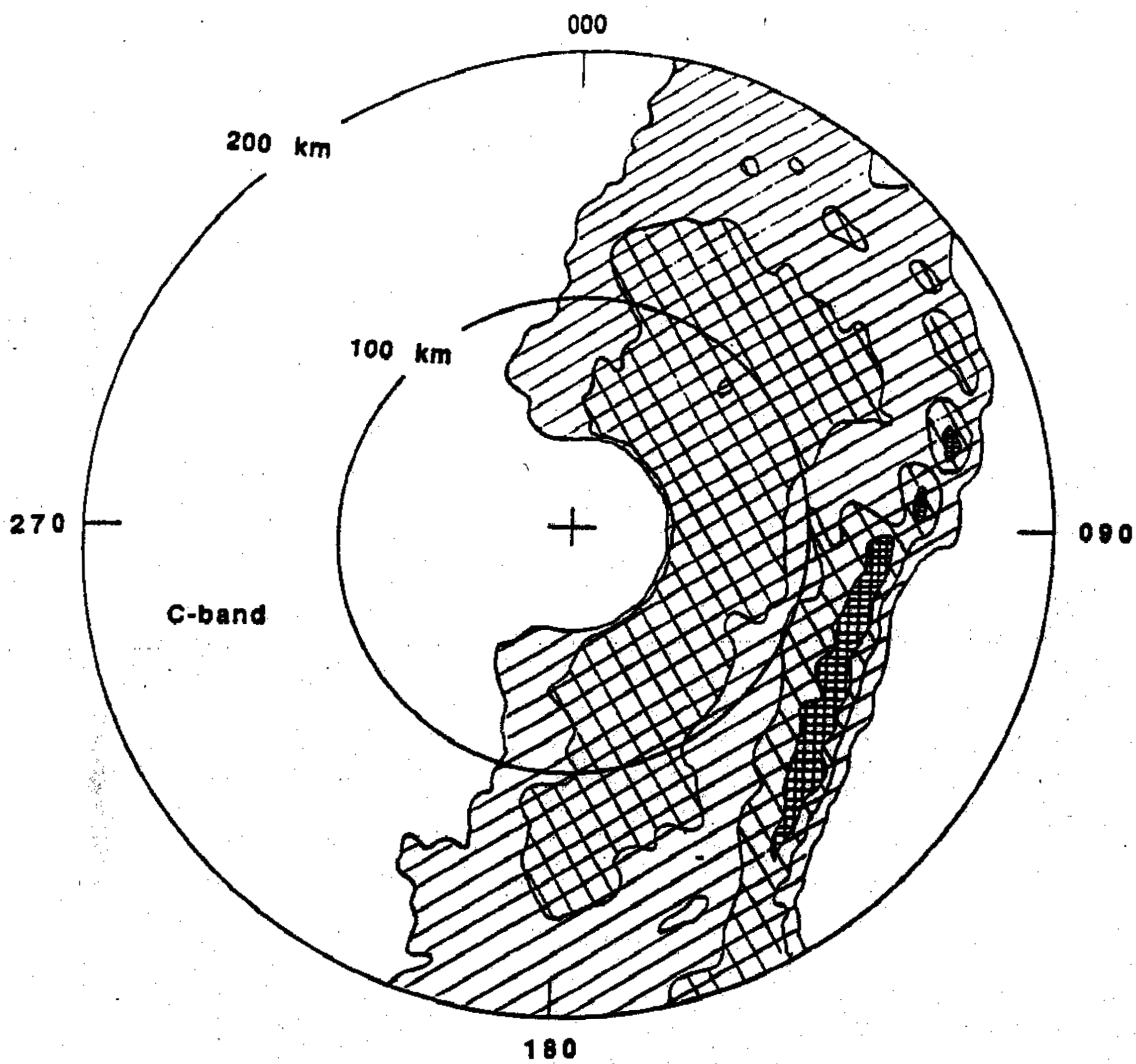

Fig. 2. As in Fig. 1 except from a C-band (5 cm) radar.

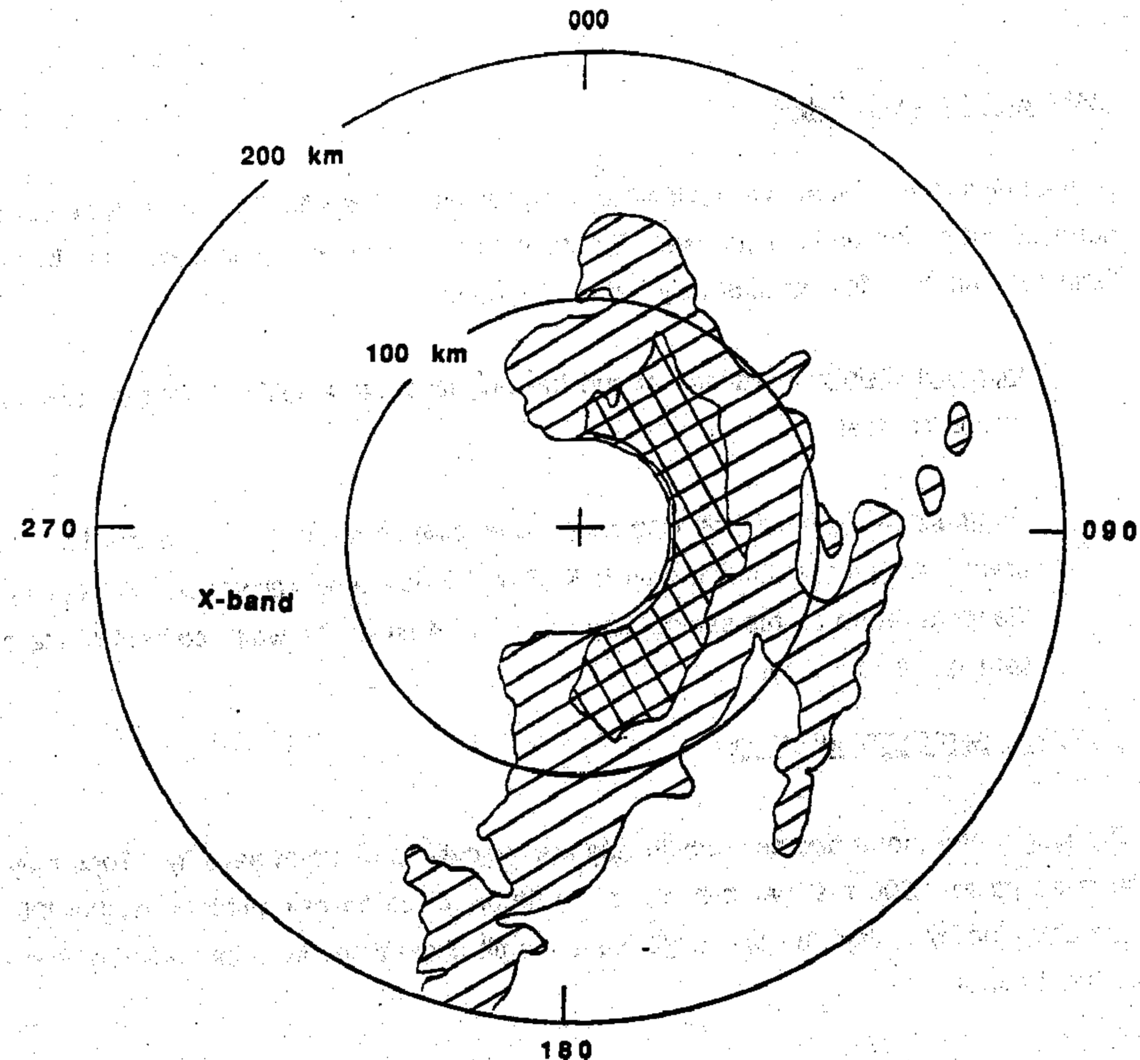

Fig. 3. As in Fig. 1 except from an X-band (3 cm) radar. X-band is used in most commercial aircraft.

MANUAL GAIN - WEATHER

Manual Gain control may be provided for weather use. It is effective for analysis but should normally not be left on continuously. The increment of adjustable gain above and below Auto Gain calibration varies considerably between models.

Increase Gain when aimed at sub freezing levels to amplify returns for potential hail, ice clouds or sleet.

Decrease Gain periodically on heavy precipitation return to interrogate for most severe areas. A typical minimum gain is 10-15 dBZ below auto calibration. A Contour, Red, or Magenta return at this setting may have 3 to 4 times the water content of the calibrated setting - a real threat.

CLOUD HEIGHT DETERMINATION

The height of a storm and cell growth rate are indications of storm severity. Tops may swell up at rates up to 7,000 feet per minute. An estimate of storm cell altitudes (within 100 miles) can be made by multiplying the range times the tilt angle times 100. Increased gain may help locate the tops.

Example
Tops identified at range 30 NM
Tilt angle + 10 degrees
Height = 30 x 10 x 100 = 30,000 ft

ATTENUATION OR SHADOW

Extremely heavy rainfall can reduce the ability of the radar waves to penetrate and present a full picture of the weather area. This condition is referred to as "attenuation." The condition can generally be identified by a complete blackout or "shadow" behind a weather cell. Sometimes ground returns can be helpful in analyzing the weather situation. Tilt the antenna down and observe the ground returns around the radar echo. With very heavy intervening rain, the ground returns behind the echo will not be present but rather will appear as a shadow. This may indicate a larger area of precipitation than appears on the indicator.

CAUTION: **AVOID AND NEVER PENETRATE A SHADOWED AREA**

EFFECT OF WATER INGESTION ON TURBINE ENGINES

6.0

EFFECT OF WATER INGESTION ON TURBINE ENGINES

INTRODUCTION

There have been several known events in which engines have experienced complete thrust loss during an encounter with heavy rain and hail. In most cases, the thrust losses occurred as the airplane encountered heavy precipitation and moderate turbulence during descent. Engine thrust was most likely near or at idle setting; however, thrust lever excursions may have been made during the event. In one case, an airplane experienced a thrust loss event when heavy precipitation was encountered during cruise flight. Whereas engines are most susceptible to rain ingestion at the lower thrust levels associated with descent and approach, it is believed for the cruise flight event that the turbulence caused an autothrottle command for thrust reduction, thereby putting the engine near or at idle setting. Experience is mixed as to whether the thrust losses have been the result of engine surge, flameout or rundown.

The complicated and varied interactions that determine the effects of water ingestion on turbine engine operation preclude quantitative engine module by module analysis. The magnitude of the shifts in gas generator performance will vary depending upon the particular circumstances. The general effect, however, is that if sufficient water is ingested, compressor surge, rundown or engine flameout may occur. The purpose of this discussion is to examine the various aspects of engine instability due to rain, hail and/or sleet ingestion in order to achieve a better understanding of the phenomenon. The term "water" will be used hereafter in place of rain, hail and/or sleet.

LOSS OF SURGE MARGIN FROM COMPRESSOR REMATCH

Ingestion of water in liquid or solid form will affect engine operation because of the higher specific heat of water and the latent heat associated with evaporation. To better understand how this applies, a brief explanation of the complex process of compressor matching would be helpful.

A high bypass turbofan engine consists of two or three independent rotors. The speeds at which each rotor operates are intended to provide an uninterrupted flow of air through the engine and the appropriate pressure rise across each compressor. The parameters having the primary influence on the operation of each compressor are air flow, rotor speed, gaspath pressure and gaspath temperature. The thermodynamic interrelationship between the compressors and their respective turbines is referred to as matching.

The ingestion of heavy amounts of water in the gaspath causes the compressors to assume new operating conditions. The reason for this compressor rematching is that when the water is vaporized within the engine, it absorbs about 1000 BTU per pound of evaporated water from the air passing through the engine, effectively reducing the air temperature in the downstream stages of the compressor and in the combustion chamber. The ingestion of ice can further increase the cooling in the compressors as it absorbs heat if it melts into water and then more heat if this water evaporates. The degree of compressor rematch is, of course, a function of the water/air ratio and the compressor design. The compressor rematch moves the high pressure compressor operating line toward the surge line, as illustrated in Figure 1, thus causing the compressor to be more susceptible to surge.

HIGH PRESSURE COMPRESSOR

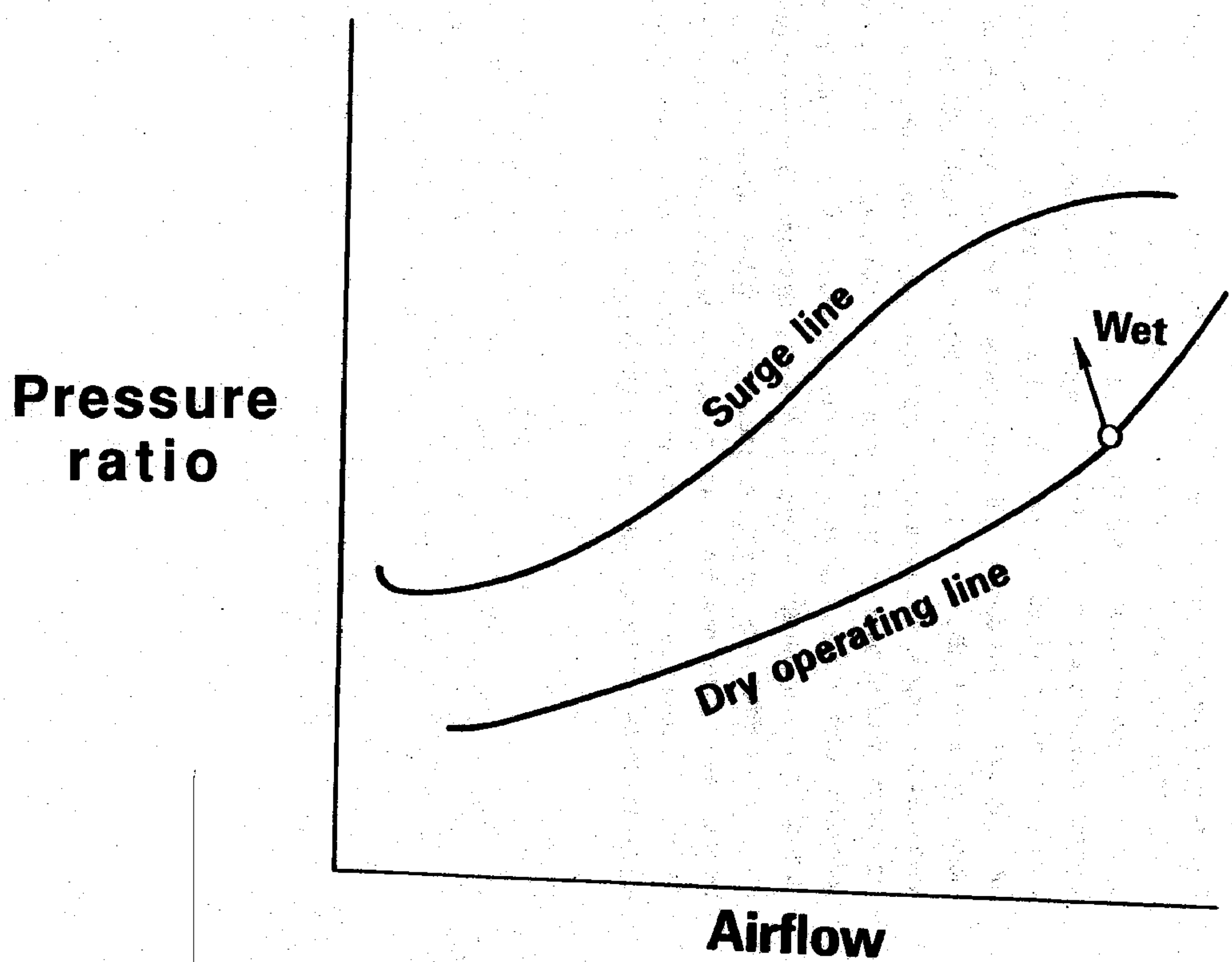

Figure 1

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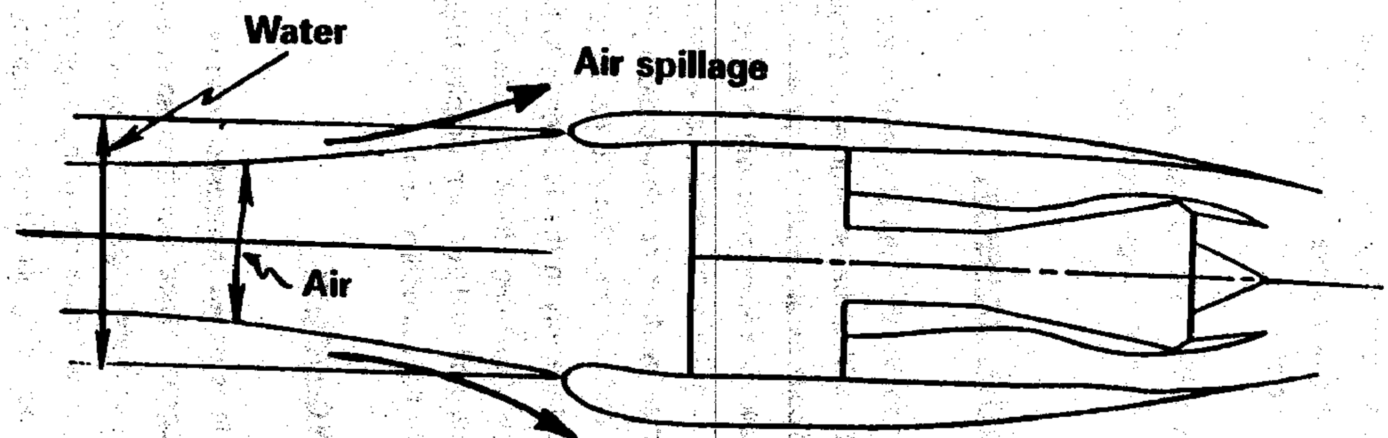
INGESTION RATE INFLUENCED BY ENGINE THRUST AND AIRSPEED

The amount of water that is ingested by the core of the engine is influenced by the scooping effect of the engine inlet and by the centrifuging effect of the fan.

The column of air in front of the engine is captured to a greater or lesser extent by the inlet for use by the engine. When flying in rain, this column is, in effect, two columns; one of air particles and the other of water particles. The amount of air ingested by the engine depends on airplane and engine speed. At high airplane speeds and low engine RPM, more air is intercepted by the inlet than the engine requires. Thus air is spilled around the inlet, effectively reducing the cross section of the column of air being ingested. The water droplets, having greater momentum, are not spilled around the inlet and the column of water particles thus remains essentially the same size as the inlet projected frontal area. This "scoop factor" can increase the water/air ratio by as much as 200 percent at the inlet plane. A further increase in water/air ratio can occur at the engine core entry plane downstream of the fan as air is further displaced into the bypan duct at low power operating conditions. Increasing engine RPM increases the airflow requirement, thus reducing the spillage, while maintaining the same capture area for water ingestion. Reducing airplane speed will also reduce air spillage around the inlet. The combined action of increasing thrust and decreasing airspeed can significantly reduce the ingested water/air ratio as illustrated in Figure 2.

SCOOP FACTOR

Inlet air spillage at low engine rpm/high aircraft speed increases engine face water/air ratio



High engine rpm/low aircraft speed decreases engine face water/air ratio by reducing air spillage

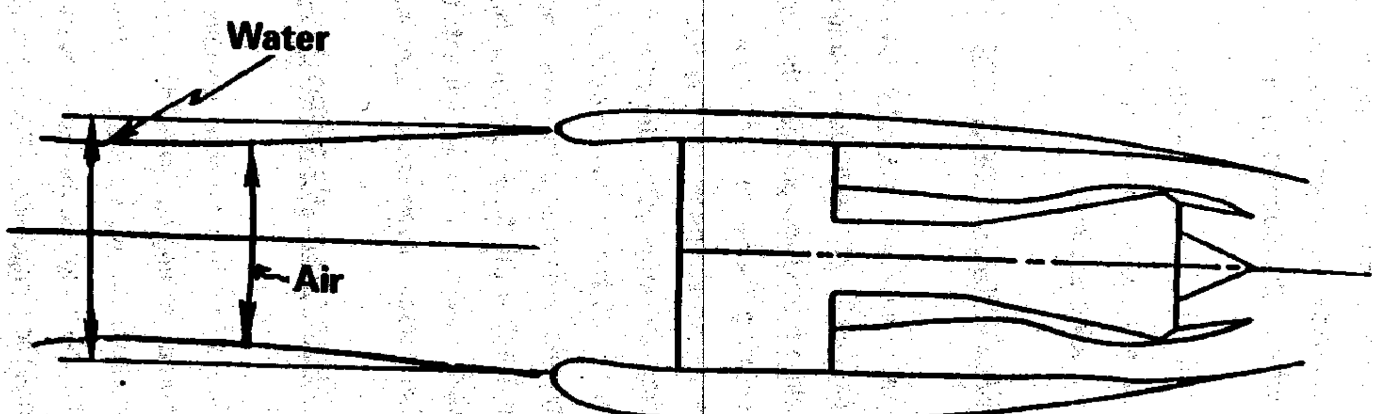


Figure 2

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Airspeed and engine speed also are factors in determining how many water droplets, which are in line with the core of the engine, are centrifuged by the fan into the fan exhaust duct. A water droplet approaching the fan at a high velocity has a better chance of passing through the fan without making contact with a blade than would a droplet travelling at a lower velocity. Likewise, a fan operating at a high rotational speed presents a more solid front to an approaching water droplet than does a fan operating at a slower speed and is more likely to provide the desired centrifuging of this water droplet.

The scoop factor of the inlet and the centrifuging of the fan are separate effects, but as they both have a direct bearing on the ingested water/air ratio in the engine core they are to be considered as being additive.

HAIL/LARGE RAIN DROPLETS MORE READILY ENTERS COMPRESSOR

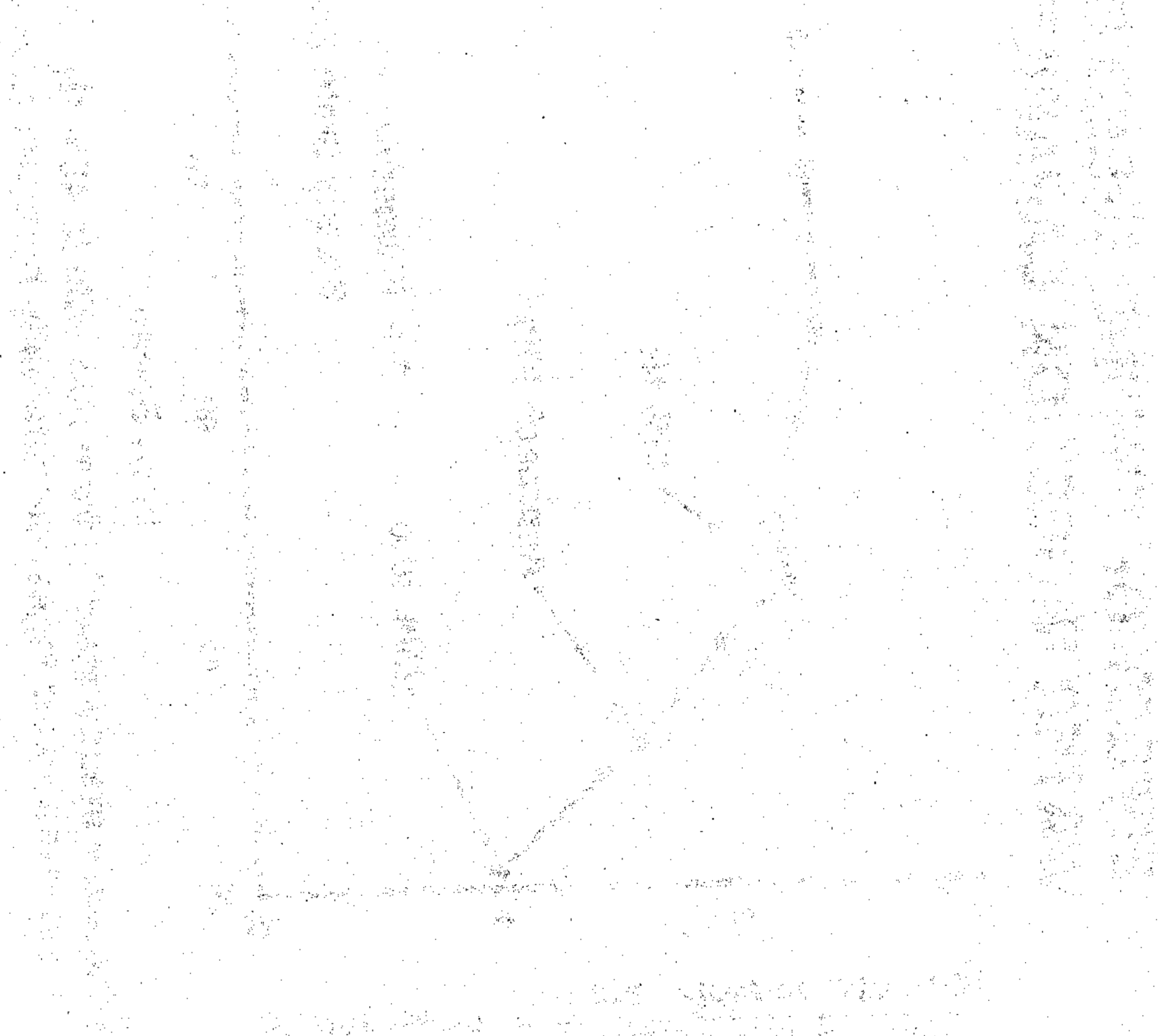
Air is usually ingested by the engine at a lower velocity than the airspeed of the airplane, especially at low thrust conditions. It has been verified that smaller water particles in the air stream tend to approach the fan at the same velocity as air; both air and water particles thereby entering the fan blades at the same angle of attack. Water particles which impact on the blade surfaces are centrifuged radially outward away from the compressor inlet as described above. Hail and larger diameter rain droplets, on the other hand, do not decelerate significantly. They enter the fan blades at essentially flight velocity and are more likely to pass through the fan blades directly into the compressor. Also, hail's trajectory in the inlet tends to be straight and not follow the flow field, thereby, allowing a larger percentage to be captured by the core/fan duct splitter. It is significant, therefore, that the hail or large rain droplet trajectory through fan blades allows more water into the compressor than does light rain.

EFFECT OF ENGINE SPEED ON WATER INGESTION CAPABILITY

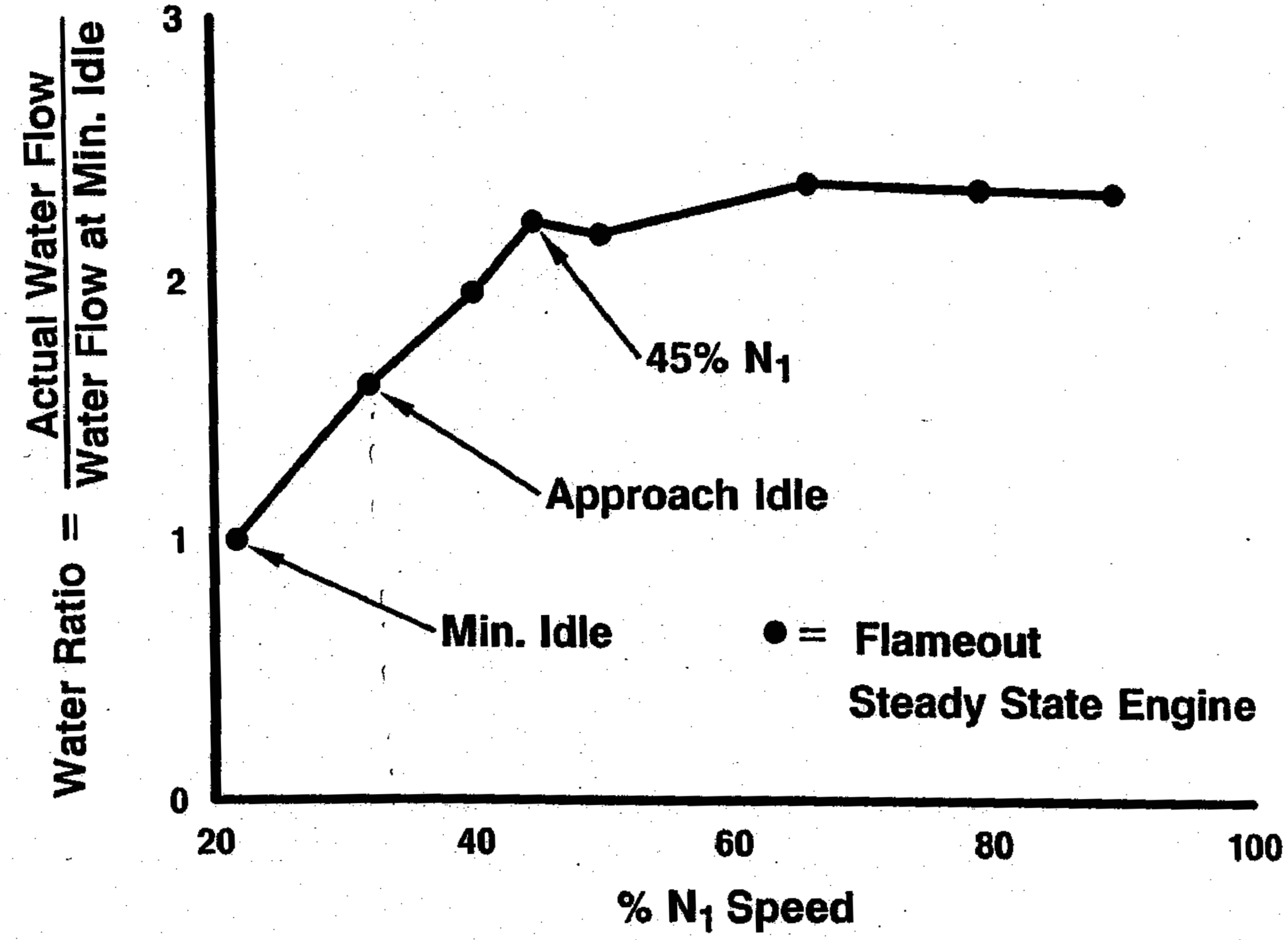
The above two sections discuss the beneficial effects on water ingestion rate resulting from increasing engine speed and decreasing aircraft speed. Since aircraft speed in a storm environment would likely be fixed at turbulence penetration speed, engine RPM is, therefore, the most significant factor available to the flight crew for improving the engines' water ingestion capability. Testing has confirmed that increasing N1 above the minimum idle setting significantly increases the capability of the engine to ingest water without experiencing flameout or engine rundown.

Figure 3 illustrates this effect. The test first determined the amount of water ingestion required to make the engine rundown or flameout at the minimum idle setting. The process was then repeated at several increasing N1 settings. In this test, the water ingestion capability was improved at each successive N1 setting and reached the optimum condition at 45% N1. At that point the capability had improved by a factor greater than two.

Note that the optimum value of 45% N1 mentioned above pertains to a particular engine model. Refer to Section 7 for recommended operating procedures.



EFFECT OF ENGINE SPEED ON WATER INGESTION CAPABILITY



- Increase steady state N_1 from min. idle to 45% N_1
  - Improves water ingestion capability by factor greater than 2

Figure 3

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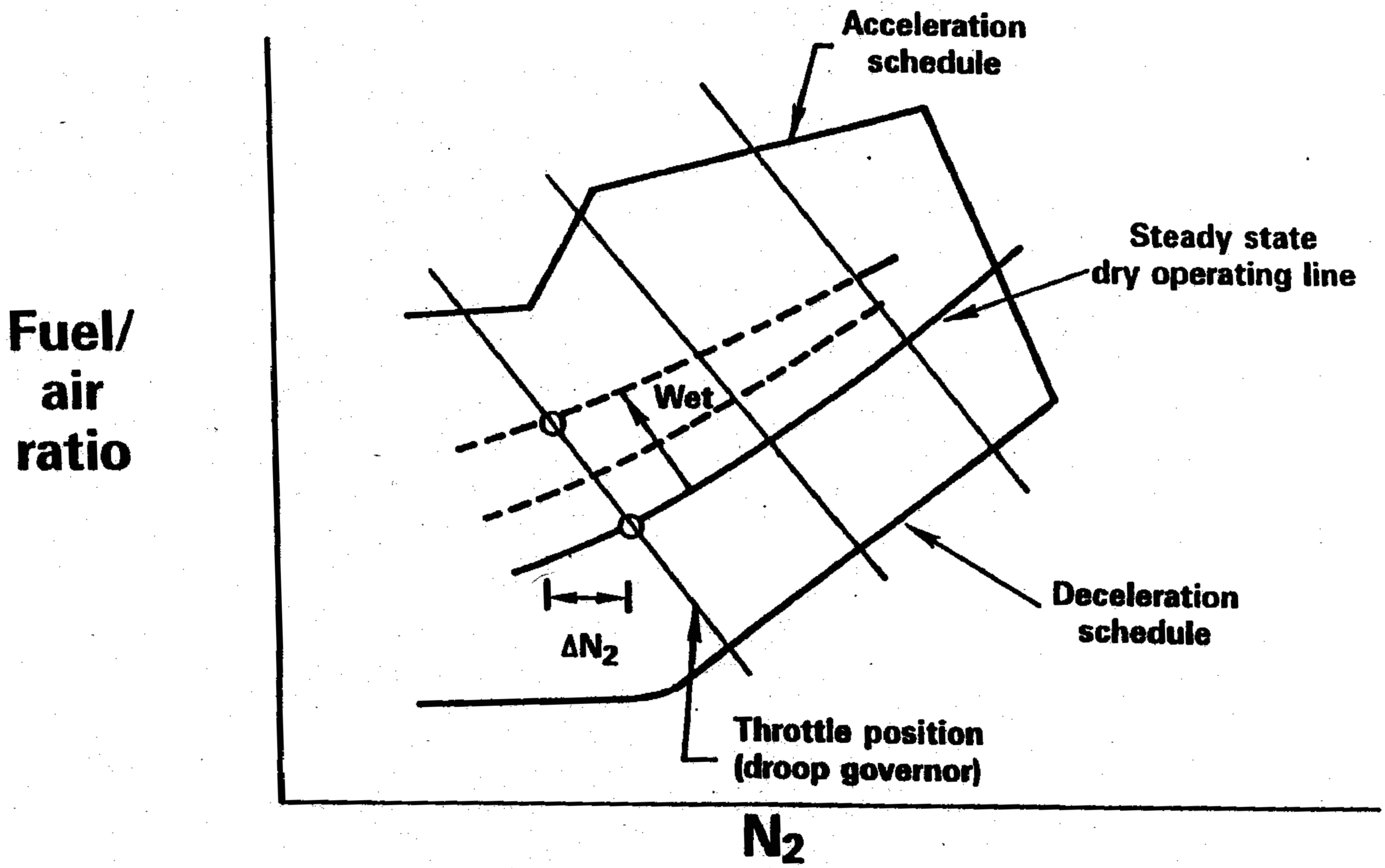
REACTION OF THE ENGINE TO WATER INGESTION

Figure 4 illustrates the effect of water ingestion on the controlled engine response for engines which use droop governing controls. The dashed lines represent fuel required (operating) lines for various rates of water ingestion. As the water/air ratio is increased, the operating line moves upwards toward the acceleration schedule. The higher the operating line, the more fuel is required to run steady-state. The slope of the lines of constant throttle position on the diagram describe the basic characteristic of a droop governing control. From this, it is apparent that a rise in the operating line results in a loss in high pressure compressor speed (N2 for two-spool and N3 for three-spool engines) when throttle position remains fixed. The acceleration schedule represents the maximum fuel/air ratio available to the engine. As the operating line rises, it can, under the most severe situation, reach the acceleration schedule, at which point the fuel control would be unable to deliver additional fuel to accommodate the increasing water ingestion. Under this condition, the engine will rundown to the point where the maximum fuel flow available is insufficient to operate the engine steady-state. This could, depending on the amount of water being ingested, result in rundown below idle, loss of throttle response and loss of electrical power if the generator drops off line. As the aircraft leaves the area of heavy precipitation, the water/air ratio will decrease and the fuel required line may return to it's normal setting, thus allowing the engine to re-accelerate to the original set speed.

TYPICAL ENGINE CONTROL CHARACTERISTICS



N_2 decay due to water ingestion at constant throttle position

Figure 4

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The engine is most susceptible to flameout or compressor surge when it has entered a sub-idle operating condition. The above mentioned self-recovery, when exiting the rain encounter, is, of course, predicated on the engine not having experienced flameout or other non recoverable operating condition during the rundown event. Experience has also shown that an engine may hang in a sub-idle operating condition and not recover as mentioned above. In that case, the engine must be shut down and restarted by the flight crew in order to return to normal operation. For engine controls which use constant speed governing, the engine response will be similar to the above except that the rotor speed will not change at constant throttle as water ingestion is increased until the limiting acceleration fuel schedule is reached. At this point the engine will rapidly rundown

The above discussion pertains to engines equipped with hydromechanical controls. Engines equipped with supervisory electronic controls react to water ingestion in the same manner as hydromechanical controls.

Most latest technology engines are equipped with full authority digital electronic controls (FADEC) which schedule fuel as a function of rate of change of compressor speed. A significant difference is that the speed derivative control mode provides consistent acceleration and deceleration thrust response as water ingestion causes the operating line to rise. A maximum fuel/air ratio limit (fuel flow topping) is sometimes used with the speed derivative control. This can have the same rundown effects with rain ingestion as does the acceleration schedule previously discussed, however the FADEC maximum fuel/air ratio limit is significantly higher than a comparable acceleration schedule. Therefore, engines controlled using a speed derivative control mode are more tolerant to water ingestion because they can ingest significantly more water before rundown is encountered..

ENGINE RESPONSE TO THROTTLE MOVEMENT WITH WATER INGESTION

The engine response to throttle movement varies depending on the direction the throttle is moved.

Throttle Advance

As the fuel control operating line rises due to the increasing water ingestion, the margin between the operating line and the acceleration schedule is reduced. For heavy water ingestion, the engine will respond more slowly to an acceleration command from the throttle because of the reduced acceleration margin.

Throttle Retard

As the fuel control operating line rises, the margin between the operating line and the deceleration schedule is increased and the engine response to a deceleration command is more rapid than normal. This could enhance the probability of encountering a sub-idle condition or engine flameout.

This operating characteristic is prevalent in most high by-pass engines. There are some engines, however, which respond to a deceleration command in a near normal manner in a water ingestion event.

EFFECT OF AIR BLEED EXTRACTION DURING WATER INGESTION

The use of engine and wing anti-ice during a water ingestion encounter affects engine operation in the following manner:

Advantages

The extraction of bleed air typically provides an improvement in surge margin. by lowering the compressor operating line.

Depending on the location of the anti-ice bleed air ports, the use of anti-ice may result in some of the water draining from the compressor.

Disadvantages

For engines not equipped with a bleed bias control function, the operating line, as described in the fuel control section above, moves upward toward the acceleration schedule as a result of the need for additional fuel to compress the air that is eventually extracted from the compressor. This effect, which increases the engine susceptibility to rundown, is additive to the operating line shift described above.

The net effect of the use of anti-ice is greatly dependent on the magnitude of the individual effects which, in turn, are dependent on the type of engine being considered. In general, however, air bleed has the effect of increasing surge margin and decreasing flameout margin. Operating experience has shown that sub-idle rundown and flameout are more predominant problems in water ingestion conditions than is engine surge. For this reason, if anti-ice air bleed is not needed for ambient operating conditions and if the engine is at idle speed, it is suggested that anti-ice air bleed be turned off.

ENGINE DAMAGE CAN RESULT FROM WATER INGESTION RELATED SURGE

Engines typically are not damaged during a heavy rain encounter. Usually the most severe situation is to experience multiple engine flameout or surge with a subsequent pilot initiated engine shutdown. In one case, however, multiple engines were severly damaged while operating in an unusually heavy rain storm. The accident investigation found that the engines probably surged as a result of throttle movement during the period of reduced surge margin as described above. The surges, coupled with the presence of massive amounts of water and hail, caused severe compressor blade damage. Continued operation of the engines with damaged compressors caused severe overtemperature in the turbines resulting in subsequent complete loss of engine thrust.

In another case, an engine overtemperature occurred while operating in a sub-idle condition after a water encounter. The flight crew did not recognize the engine overtemperature condition for several minutes before corrective action was taken. Inspection of the engine after landing revealed substantial damage had occurred to the low pressure turbine.

EFFECT OF WATER INGESTION ON STARTING

Tests have been conducted to determine the effect that water ingestion has on engine starting characteristics. The results are as follows:

Time from lightoff to idle	Increased
Surge margin in the start regime	Negligible differences
Combustion efficiency	Decreased

The probability of achieving a satisfactory start is greatly reduced in water ingestion conditions. Start attempts will most likely result in no lightoff or in hung starts. Also, it should be noted that, under these conditions, the slow acceleration to idle of a satisfactory start can be quite similar in appearance to a hung start.

HAIL INGESTION CERTIFICATON TESTS

The fact that engines are certified to operate safely in hail of specified dimensions should not be confused with the hazards associated with the ingestion of hail as discussed above. The tests which engine manufacturers conduct are to demonstrate that the damage to the engine from the impact of ice particles is within prescribed limits. The effect of ingesting these ice particles on engine operability is not a primary factor in the certification testing.

SUMMARY

The ingestion of water by a turbine engine may result in the following:

- Reduced surge margin and flameout margin
- Possible engine rundown to sub-idle
- Reduced acceleration capability from sub-idle
- Slower response to throttle advance
- Rapid response to throttle retard
- Reduced inflight start capability

NORMAL RAIN INGESTION, BY ITSELF, IS NOT LIKELY TO CAUSE AN ENGINE TO RUNDOWN OR FLAMEOUT OR SURGE. UNUSUALLY HEAVY RAIN, TYPICALLY REFERRED TO AS "A WALL OF WATER," OR RAIN PLUS AN ADDITIONAL INFLUENCE SUCH AS HAIL OR A THROTTLE TRANSIENT IS PROBABLY REQUIRED TO CAUSE AN ENGINE TO RUNDOWN OR FLAMEOUT OR SURGE.

OPERATING PROCEDURES

7.0

OPERATING PROCEDURES

Based on analysis of engine operation in inclement weather, it is concluded that high by-pass turbine engines have a much greater tolerance to rain, hail and sleet when operated at thrust settings above minimum or low idle. (See Figure 3 in Section 6). Therefore, if moderate and/or heavy rain, hail or sleet cannot be avoided, the minimum thrust settings recommended by the engine and airplane manufacturers for operation in such conditions, or greater, should be maintained to minimize engine spooldown or flameout

The information presented in this section is a summary of key items which can be used to develop specific airplane/engine operating procedures for operations in rain, hail or sleet.

OPERATING PROCEDURES

WHEN TO APPLY

The following can be used as a guide as to when to apply recommended operating procedures to minimize possible engine rundown and/or flameout when moderate to heavy rain, hail or sleet are encountered or anticipated and is especially applicable to any low thrust operation.

Operation in hurricanes and tropical storms.

Normally commercial airplanes do not operate in this type of weather conditions, however if they are inadvertently encountered it is essential that at least the minimum recommended thrust settings be maintained. Extremely heavy precipitation can be encountered in hurricanes and tropical storms.

Operation in or near thunderstorms.

Well developed thunderstorms can produce sudden heavy rain and hail (wall of water) which can result in engine rundown and/or flameout. Due to the inability of airplane radar to "see" small "pockets" of heavy precipitation, moderate to heavy rain and/or hail can be encountered even in the green area on the radar display. It is also possible to encounter hail while flying in the clear (out of clouds) when passing on the downwind side of a thunderstorm. The recommended minimum thrust settings or higher should be maintained anytime the airplane is within 20 miles of a thunderstorm.

Operation in or near cold fronts.

Moderate to heavy precipitation can occur in a broad region ahead of the warm front and in the vicinity of the cold front. Convective type precipitation can occur in a squall line which can form ahead of a fast moving cold front.

Recommended operating procedures to minimize possible engine rundown or flameout should be followed when operating in or near convective type weather conditions where moderate to heavy rain, hail or sleet could be encountered.

OPERATING PROCEDURES

ENGINE OPERATION IN MODERATE TO HEAVY RAIN, HAIL OR SLEET

Flight should be conducted to avoid thunderstorm activity. To the maximum extent possible, moderate to heavy rain/hail should also be avoided. Ground based radar reports, weather radar, pilot reports and flight crew observations may be used by the flight crew to determine when rain, hail or sleet is anticipated. When operating in or near moderate and heavy rain, hail or sleet, accomplish the following:

IGNITION

Ignition should be ON during flight through moderate and heavy rain, hail or sleet. The ignition system offering maximum flameout protection and restart capability should be used in case of generator power loss.

ANTI-ICE

Engine Anti-Ice should be ON if icing conditions exist, otherwise engine Anti-Ice should be OFF if it has been determined to improve engine acceleration.

THRUST LEVERS

Autothrottles/Autothrust should be DISENGAGED.

Do not make rapid thrust lever movements in heavy precipitation unless excessive airspeed variations occur. If thrust changes are necessary, move the thrust lever very slowly. Avoid changing thrust lever direction until engines have stabilized at a selected setting.

Do not make thrust lever movements to correct for fluctuations in engine parameters. Engine parameters will return to normal immediately upon leaving the area of heavy precipitation.

MINIMUM ENGINE N1

Maintain recommended N1 as follows to improve engine tolerance to water ingestion:

Airplanes which have a specific water ingestion minimum N1 recommended by the engine manufacturer, maintain at least that N1.

Airplanes which do not have a specific water ingestion minimum N1 recommended by the engine manufacturer, maintain at least 15% N1 greater than minimum flight idle.

Example: Minimum flight idle 30% N1 plus 15 percent equals 45% N1.

Note: Some engine models have demonstrated satisfactory operation in rain/hail at high (flight) idle and/or at thrust settings normally used for engine anti-ice and a further increase in thrust above these settings is not necessary for these engines.

APU

APU (if available,) START.

The APU can be used to power the electrical system and to provide a pneumatic air source for improved engine starting in the event of a multiple engine thrust loss.

In heavy precipitation conditions, it is possible there may be fluctuations in engine parameters, particularly a noticeable drop in EGT. It is not necessary to adjust thrust settings as there is no thrust loss during these conditions. Engine parameters will return to normal immediately upon leaving the area of heavy precipitation.

If a dual or multiple engine thrust loss is experienced, accomplish the RAPID RELIGHT procedure as described on pages 7.4.1 through 7.4.4. For a single engine thrust loss, accomplish the normal ENGINE FAILURE AND SHUTDOWN checklist followed by the INFLIGHT ENGINE START checklist.

OPERATING PROCEDURES

RECOGNITION OF THRUST LOSS

During low thrust operation in a descent with the thrust levers at idle, engine thrust loss or flameout events (except airplanes with engine failure message/light installed.) are not immediately recognized. Engine rundown or flameout during descent may be first indicated by illumination of the generator off message/light or the low oil pressure message/light or blink of CRT's as appropriate. If the generator is off with the thrust lever at idle, advance the thrust lever and check N2/N3 and EGT to verify engine operation.

NOTE: During flight crew simulator training, engine flameout during descent should be part of the curriculum to enhance engine failure recognition at low thrust settings.

Engine thrust loss or flameout during operations at high thrust settings (takeoff, climb, cruise or go-around) are usually immediately recognized by the flight crew. Engine thrust loss or flameout during high thrust operations is easily recognized by:

1. Engine failure message/light (if installed).

2. Decrease in engine noise.

3. Thrust asymmetry which results in airplane yaw/roll.

4. Control wheel position as autopilot attempts to hold heading.

5. Loss of airplane performance, indicated by flight instruments.

6. Vibration and/or surging from the affected engine.

OPERATING PROCEDURES

INFLIGHT ENGINE RESTART - RAPID RELIGHT

Starting a turbofan engine requires the right combination of fuel and air, and an ignition source. Today's high bypass ratio engines utilize sophisticated sub-systems to ensure reliable starts with minimum exposure to potential problems which could cause expensive damage to various engine components.

The typical ground start procedure uses an air driven starter to rotate the high pressure (N2 or N3) rotor. When the start valve is opened, the starter drives the high pressure rotor through a shaft/gear mechanism. When the rotor reaches a specific minimum speed, the fuel control lever/switch is raised to the "engine operating" position, initiating fuel flow into the combustor, and "firing" the ignitor(s). Ignition takes place and the engine accelerates. At starter cutout speed, the starter disengages and the engine continues to accelerate. As rotor speed nears idle, the EGT and fuel flow will normally peak, then decrease as the engine stabilizes at idle.

During the start sequence, unless the engine is equipped with an automatic starting feature, the crew must monitor engine parameters and starter cutout for any indication of a problem, and take appropriate action if necessary. The start EGT limit is chosen to prevent turbine damage during start. It is considerably lower than the takeoff EGT limit.

During the ground start, the starter turns the N2 or N3 rotor until maximum motoring or the minimum RPM is obtained before fuel and ignition are introduced. Engine "light off" and initial acceleration occurs at very low N1 RPM which significantly affects the flow of cooling air through the engine, thus the lower EGT limit for starting. During takeoff with maximum airflow through the engine, a higher EGT limit is allowed.

For an inflight start, the physics surrounding the start process are significantly different. Depending on flight conditions such as airspeed, altitude and time since shutdown, N2 RPM may or may not be sufficient for a windmill inflight start. If N2 RPM is sufficient, a windmill inflight start should be successful. Depending on whether the need is to start one or several engines, the crew will need to decide between the normal Inflight Engine Start or a more expeditious Rapid Relight procedure.

Crews should be aware that the Inflight Restart Envelope has been defined by very conservative criteria and does not represent limits to the conditions under which a successful inflight start can be achieved.

1. The Inflight Restart Envelope defines altitudes and airspeeds that will assure an inflight start. (certification proving starts were 100% successful).

2. For the Inflight Restart Envelope certification test points, the engine was stabilized in the windmilling condition prior to the inflight start attempt.

3. The Inflight Restart Envelope was defined on the basis of successful engine inflight starts accomplished with only one ignitor operational.

Since the Inflight Restart Envelope is very conservative, an immediate start attempt should be made if a multiple engine thrust loss occurs, even if engine parameters are outside the normal start envelope.

SINGLE ENGINE INFLIGHT START

In a situation where one engine is to be restarted, the Inflight Engine Start procedure is to be used. The single engine inoperative case should be considered a non-normal flight condition, not an emergency. Methodically perform the inflight start procedure according to the checklist.

MULTIPLE ENGINE INFLIGHT START - RAPID RELIGHT

A multiple engine inoperative event is an emergency situation which demands prompt action regardless of altitude or airspeed. The inflight start attempt should take advantage of the inertia of the engines as they are spooling down if possible (Rapid Relight). There is a higher probability that a windmill start will succeed if the restart attempt is made before the N2 RPM has decreased to too low a level. Perform the procedure in a methodical manner. DO NOT RUSH. In the case of a four engined airplane, where the need is to start at least two engines, ensure that the engines to be restarted are POSITIVELY IDENTIFIED.

The "Rapid Relight" attempt includes:

- Ignition ON
- Thrust Lever IDLE

- EGT CHECK

  If EGT normal advance thrust lever and check increase in thrust.
  If EGT rising rapidly or above limit,
  Cycle fuel control lever/switch to CUTOFF (OFF) and then to IDLE/RUN (ON).
  Leave start lever in CUTOFF (OFF) until a decrease in EGT is observed before moving to IDLE/RUN (ON).
  This action will clear the engine in the event of a non-recoverable surge or sub-idle condition.

- Do not allow the EGT to exceed the takeoff EGT limit.

  The takeoff EGT limit may be used in place of the ground start EGT limit on most engines as long as the RPM is increasing.

- APU (If Available) START AND ON BUS.

  Do not await successful engine start(s) prior to starting the APU. If the APU is available and previous start attempts have been unsuccessful, the APU can be used to power the electrical system and to provide a pneumatic air source to restart engines using starter assist.

The above procedure should enable the engine to relight and accelerate to idle. It is likely that the EGT may approach or even exceed the normal engine start EGT limits. However, when attempting a Rapid Relight, it is permissible to allow EGT to approach the takeoff EGT limit if RPM is increasing before the restart should be aborted and re-attempted. EGT's in excess of the takeoff limit may cause mechanical damage which will make it impossible to start the engine on successive attempts.

Since water ingestion has been shown to degrade starting performance, repeated inflight start attempts may be necessary to restore engine thrust. Start attempts should be initiated immediately. In moderate to heavy rain, the engines may be slow to start and it may take up to 3 minutes to accelerate to idle. In some cases, it may not be possible to start engines until exiting areas of heavy rain, hail or sleet.

When multiple engine inflight starts are necessary, the Rapid Relight procedure should be initiated promptly. Such attempt (or attempts) should simultaneously include all non-operating engines, and should be repeated, until at least one engine is operating for twin-jet airplanes. For a four engine aircraft, the Rapid Relight attempt(s) should be made simultaneously on all engines until at least two engines are operating. If the Rapid Relight is not successful and the windmilling RPM has stabilized and a bleed air source (APU or engine) is available, use the normal inflight starter assist Engine Start procedure. With no bleed available, increasing the airspeed and decreasing the altitude, if possible, will enhance the windmill starting capability of the engines. When the minimum number of engines required to maintain safe flight are operating, use the normal Inflight Engine Start procedure to start the remaining engine(s).