

Engine Power Loss in Ice Crystal Conditions

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High-altitude ice crystals in convective weather are now recognized as a cause of engine damage and engine power loss that affects multiple models of commercial airplanes and engines. These events typically have occurred in conditions that appear benign to pilots, including an absence of airframe icing and only light turbulence. The engines in all events have recovered to normal thrust response quickly. Research is being conducted to further understand these events. Normal thunderstorm avoidance procedures may help pilots avoid regions of high ice crystal content.

ICE CRYSTAL ICING CAN OCCUR DEEP IN THE ENGINE, WHERE SURFACES ARE WARMER THAN FREEZING.

Since 1990, there have been at least 100 jet engine power-loss events on both commuter and large transport airplanes, mostly at altitudes higher than 22,000 feet, the highest altitude where airframe icing is expected to exist. "Power loss" is defined as engine instability such as a surge, stall, flame-out, or rollback that results in a sub-idle operating condition. High-altitude ice crystals are believed to have caused most or all of these events.

This article explains the ice crystal phenomenon, how ice crystals cause power loss, the types of power-loss events, where and when engine power-loss events have occurred, conditions associated with ice crystal formation, and recommendations

for flight near convective weather. It also discusses the importance of pilot reporting of ice crystal power-loss events.

HIGH-ALTITUDE ICE CRYSTAL ICING

Several engine power-loss and damage events have occurred in convective weather above the altitudes typically associated with icing conditions. Research has shown that strong convective weather (thunderstorm activity) can lift high concentrations of moisture to high altitudes where it can freeze into very small ice crystals, perhaps

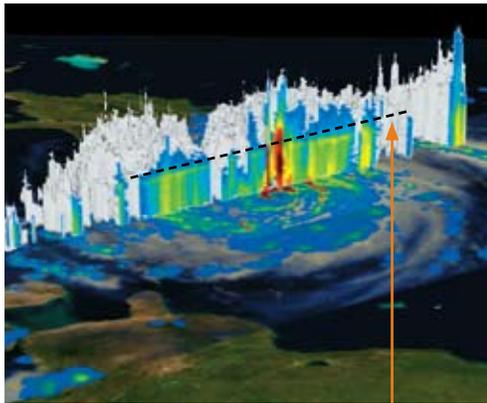


Photo Credit: NASA TRMM
image by Hal Pierce (SSAI/GSFC)

Freezing Level

SATELLITE/RADAR IMAGE OF A HURRICANE CONVECTIVE STORM

Figure 1

This NASA Tropical Rainfall Measurement Mission (TRMM) combined satellite radar image shows a vertical cross-section of a convective storm. The image shows the freezing level clearly by the “bright band” where ice particles become coated with melted water and are excellent reflectors of radar energy. Below the freezing level, liquid water is highly reflective. Above the freezing level, while the concentration of moisture may still be high, the cloud is mostly composed of frozen ice particles with radar reflectivity below 20dBZ (units of radar energy). Small ice crystals are irregular in shape and poor reflectors of radar energy. These small ice crystals are believed to be associated with engine power-loss events.

as small as 40 microns (the size of flour grains). These are the crystals that can affect an engine when flying through convective weather. The industry is using the phrase “ice crystal icing” to describe these icing conditions, and to differentiate it from icing conditions due to supercooled liquid.

Ice crystals do not adhere to cold airframe surfaces because the ice crystals bounce off. However, the crystals can partially melt and stick to relatively warm engine surfaces.

“Glaciated conditions” refers to atmospheric conditions containing only ice crystals and no supercooled liquid. “Mixed phase conditions” refers to atmospheric conditions containing both ice crystals and supercooled liquid. Both glaciated and mixed phase conditions occur in convective clouds and have been present during engine power-loss and damage events.

On-board weather radar can detect large particles such as hail, rain, and large ice crystal masses (snowflakes). Small particles, such as ice crystals in high concentrations near thunderstorms, are invisible to on-board weather radar, even though they may comprise the majority of the total mass of a cloud (see fig. 1).

Sophisticated satellite radar technology has been used to detect crystals smaller than the lower limit of on-board weather radar. Above the freezing level, where icing can occur in a deep convective cloud, satellite radar has confirmed that large particles, which can be detected by on-board weather radar, are only found near the convective precipitation core. Away from the convective precipitation core, satellite radar has confirmed that small ice crystals, which are invisible to on-board weather radar, exist.

For this reason, flight in visible moisture near deep convective weather, even without radar returns, and at temperatures below freezing, is very likely to be in ice crystal conditions.

Ice building up on the inlet, fan, or spinner would likely shed outward into the fan bypass duct without causing a power loss. Therefore, in these power-loss events, it is reasonable to conclude that ice must have been building up in the engine core.

It is now believed that ice crystal icing can occur deep in the engine where surfaces are warmer than freezing (see fig. 2). Both older generation jet engines and the new generation of jet engines (high bypass ratio engines with electronic engine controls) can be affected by ice crystal icing.

TYPES OF POWER-LOSS EVENTS

The actual mechanism for ice crystal-related engine power loss takes many forms, depending on the design characteristics of each particular engine type (see table below).

WHERE AND WHEN ICE CRYSTAL POWER-LOSS EVENTS HAVE OCCURRED

About 60 percent of recorded ice crystal power-loss events have occurred in Asia. Researchers speculate that this may be due to the fact that the highest sea surface temperatures are also found

POWER-LOSS TYPE	DESCRIPTION	EFFECT	RECOVERY
Surge/Stall*	Ice shed into compressor drives engine to surge, then stall causes rotor speeds to decay, and reducing airflow while combustor remains lit.	Thrust loss and high exhaust gas temperature.	Throttle to idle. Cycling of the fuel switch may be required to clear some stalls.
Flameout*	Ice shed into the combustor quenches the flame.	Thrust loss and all parameters dropping.	Ignition. Many events self-recover due to auto-relight or having the ignition already on.
Engine Damage	Engine blades become damaged as shed ice impacts them.	Typically no effect at time of initial damage, but damaged blades may fail later causing vibration or engine stall.	As appropriate — refer to Quick Reference Handbook.

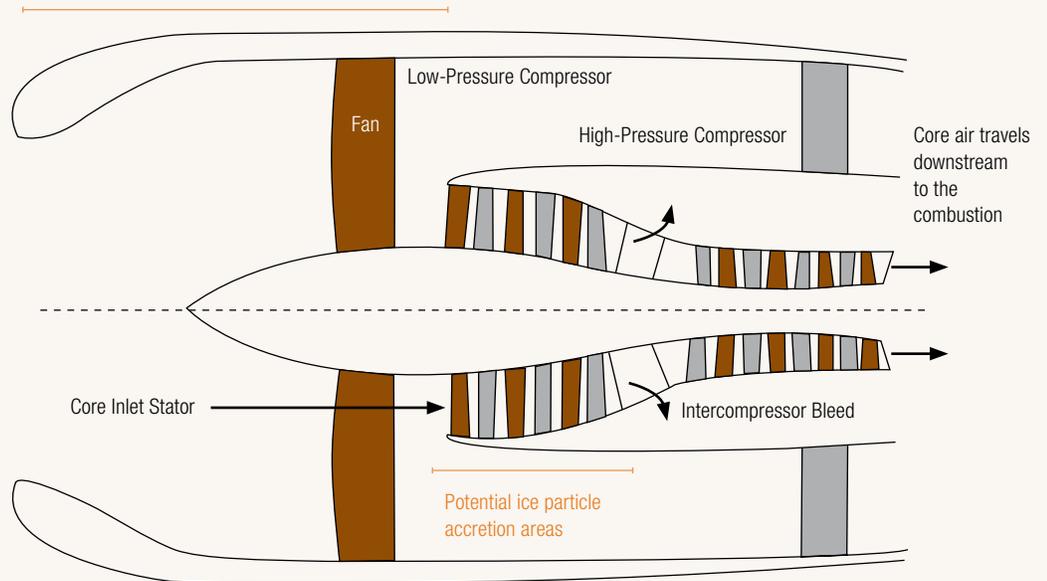
*In every large transport power-loss event occurring due to stall and flameout that has been tracked to date, the engines were successfully restarted.

HOW ICE CRYSTALS ACCRETE IN A JET ENGINE

Figure 2

Researchers hypothesize that ice particles enter the engine and bounce off surfaces colder than freezing (inlet, fan, and spinner). Once reaching surfaces warmer than freezing in the core, some of the small particles can melt and create a film of water on the surface to which additional incoming ice crystals can stick. This process gradually reduces the temperature of the surface until ice can begin to build up.

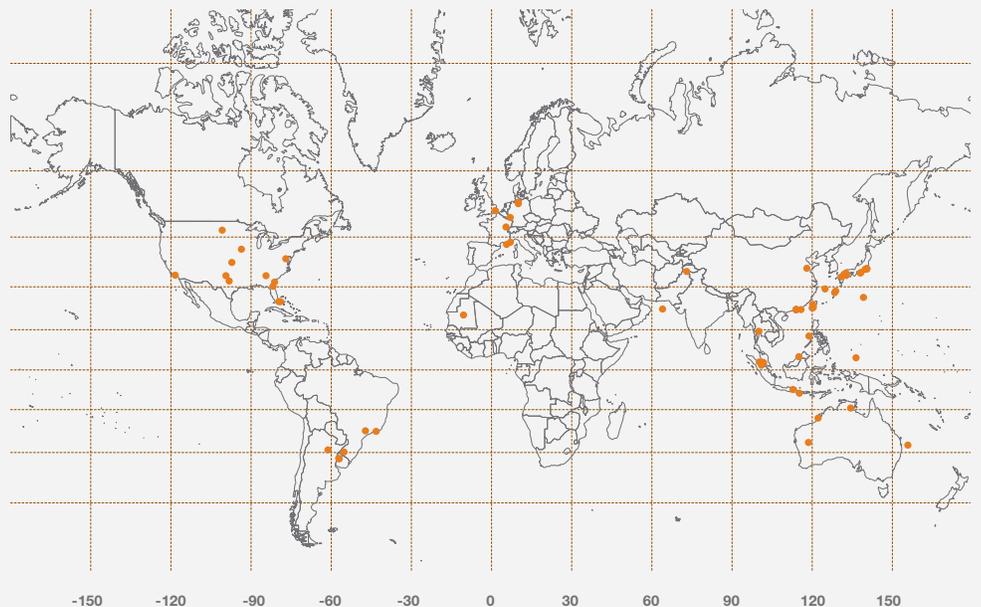
Supercooled liquid water accretion areas (inlet, spinner, fan, and first stages of the core)



LOCATIONS OF ICE CRYSTAL POWER-LOSS EVENTS

Figure 3

While most ice crystal power-loss events that have been studied to date have occurred in Asia, events have been noted in most parts of the world. Note: Latitude and longitude information is not available for all 100 events. This chart actually shows 67 events, some of which are overlaid. Not all events are Boeing airplanes.

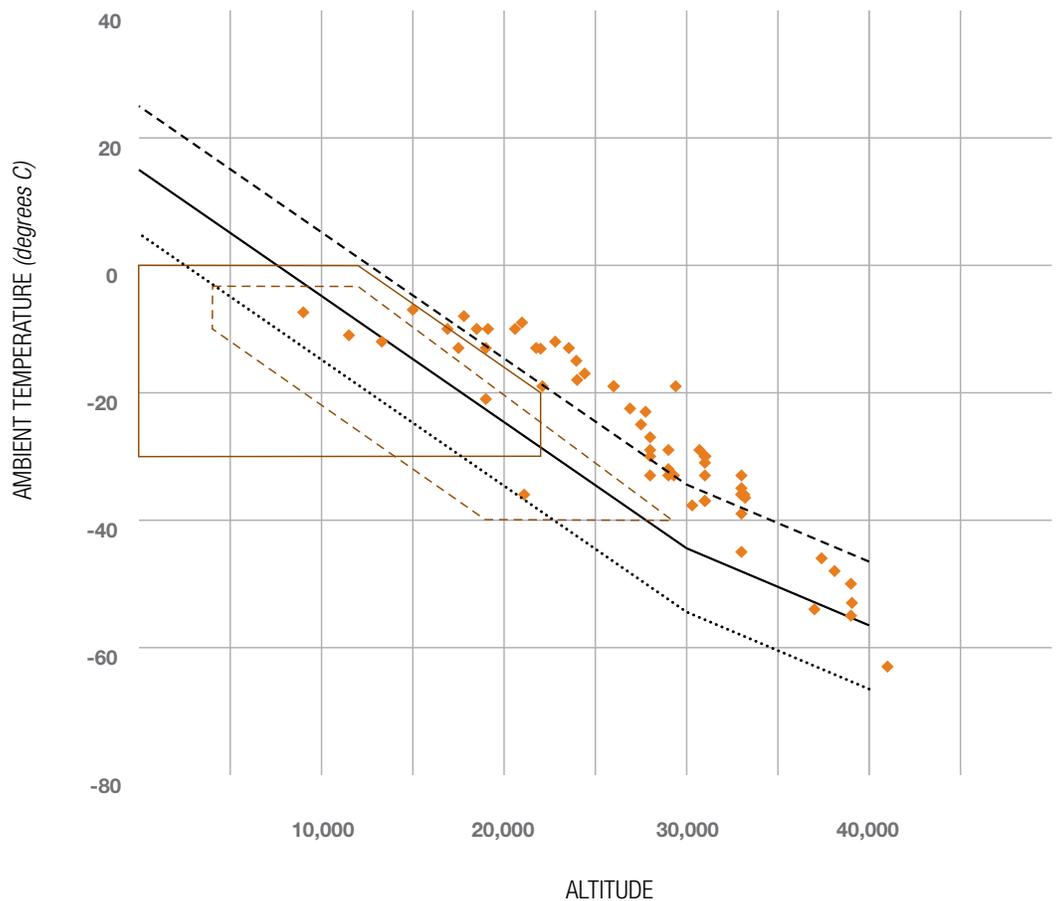


ALTITUDE AND TEMPERATURE OCCURRENCE OF ENGINE POWER LOSS

Figure 4

Temperatures for the majority of the events for which data is available are significantly warmer than standard day temperatures, and also fall outside of the current icing design envelopes for supercooled liquid water.

- ◆ = Power-Loss Event
- = Standard Atmosphere
- = Standard Atmosphere +10C
- ... = Standard Atmosphere -10C
- = Continuous Maximum — Stratiform Clouds
- - - = Intermittent Maximum — Cumuliform Clouds



RECOGNIZING HIGH ICE CRYSTAL CONDITIONS

in this region. Higher temperature air can hold more water. There is a heavy concentration of ice crystal power-loss events between 20 and 40 degrees north latitude with a few events farther than 45 degrees from the equator (see fig. 3).

Engine power-loss events have occurred in three phases of flight: climb, cruise, and descent. However, most events occur during the descent phase, most likely because of a combination of two factors. First, for icing to occur, the ambient temperature must be below the freezing level, and therefore icing tends to occur at the higher altitude associated with the descent phase. Second, the engine is least tolerant to ice shedding at idle power, which occurs in the descent phase. Icing at high power and high altitude is possible due to the existence of high concentrations of ice crystals for long distances, such as in the anvil of a large convective storm, and the fact that ice can build up on warm engine surfaces.

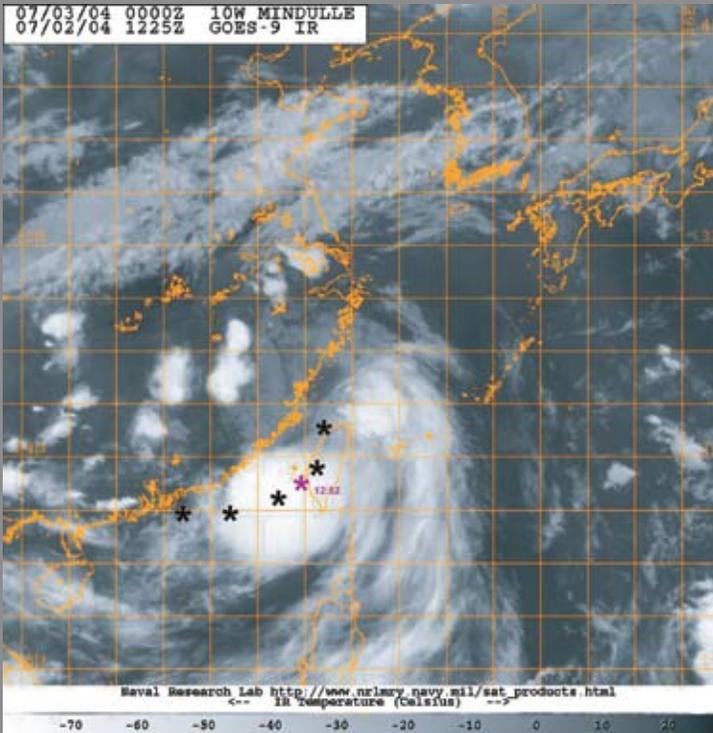
Researchers have identified several conditions that are connected to engine ice crystal icing events. The most important factors are:

- *High altitudes and cold temperatures.* Commercial airplane power-loss events associated with ice crystals have occurred at altitudes of 9,000 to 39,000 feet, with a median of 26,800 feet, and at ambient temperatures of -5 to -55 degrees C with a median of -27 degrees C. The engine power-loss events generally occur on days when the ambient temperature is warmer than the standard atmosphere (see fig. 4).
- *The presence of convective clouds.* Convective weather of all sizes, from isolated cumulonimbus or thunderstorms to squall lines and tropical storms, can contain ice crystals. Convective clouds can contain deep updraft cores that can lift high concentrations of water thousands of feet into the atmosphere, during which water vapor is continually condensed and frozen as the temperature drops. In doing so, these updraft cores may produce localized regions of high ice water content which spread downwind. Researchers believe these clouds

can contain up to 8 grams per cubic meter of ice water content; by contrast, the design standard for supercooled liquid water for engines is 2 grams per cubic meter.

- *Areas of visible moisture above the altitudes typically associated with icing conditions.* This is indicated by an absence of significant airframe icing and the ice detector (when installed) not detecting ice, due to its ability to detect only supercooled liquid, not ice crystals.
- These additional conditions are also typically found during engine ice crystal power-loss events.
- No pilot reports of weather radar returns at the event location.
 - Temperature significantly warmer than standard atmosphere.
 - Light-to-moderate turbulence.
 - Areas of heavy rain below the freezing level.
 - The appearance of precipitation on heated windshield, often reported as rain, due to tiny ice crystals melting.
 - Airplane total air temperature (TAT) anomaly-reading zero, or in error, due to ice crystal buildup at the sensing element (see case study on following page).
 - Lack of observations of significant airframe icing.

AN ICE CRYSTAL POWER-LOSS EVENT CASE STUDY



INFRARED IMAGE WITH AIRPLANE TRACK

In this infrared satellite image from about the time of an engine event, bright white indicates colder cloud, and therefore at high altitude. The airplane penetrated the upper altitudes of a fully developed typhoon, yet the pilot did not see any flight level radar returns.

The asterisks represent the aircraft path from left to right on descent into Taipei, with the event noted in purple.

- A commercial airplane on descent, flying in convection conditions, experienced a TAT anomaly. (The anomaly is due to ice crystals building up in the area in which the sensing element resides, where they are partly melted by the heater, causing a 0 degrees C reading. In some cases, TAT has stabilized at 0 degrees C during a descent, and may be noticeable to pilots. In other cases, the error is more subtle, and not a reliable-enough indicator to provide early warning to pilots of high concentrations of ice crystals.)
- At 38,000 feet (-42 degrees C), the pilot encountered moderate turbulence and noted some lightning in the vicinity.
- A brief power-loss event occurred at 30,000 feet — the engines restarted quickly.
- There were no radar echoes at the altitude and location of the airplane.
- An absence of a response from the ice detector indicated that no supercooled liquid was present.
- The pilot reported heavy rain at -25 degrees C.
- Initial report of rain on the windscreen was later determined to be ice crystals, and confirmed by the pilot to have a unique sound.

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Pilots are advised to familiarize themselves with the conditions under which ice crystal icing typically occurs and follow the recommendations in related technical bulletins.

RECOMMENDATIONS FOR FLIGHT NEAR CONVECTION

Even when there are no radar returns, there may be significant moisture in the form of ice crystals at high altitudes. These are not visible to airborne radar. As a result, it is not possible to avoid all ice crystal conditions. However, normal thunderstorm avoidance procedures may help pilots avoid regions of high ice crystal content.

These avoidance procedures include:

- Avoiding flying in visible moisture over storm cells. Visible moisture at high altitude must be considered a threat since intense storm cells may produce high concentrations of ice crystals at cruise altitude.
- Flying upwind of storms when possible.
- Using the radar antenna tilt function to scan the reflectivity of storms ahead. Assess the height of the storms. Recognize that heavy rain below the freezing level typically indicates high concentrations of ice crystals above.
- Avoiding storm reflectivity by 20 nautical miles has been commonly used as a recommended distance from convection. This may not be sufficient for avoidance of high concentrations of ice crystals, as they are not visible on airborne radar.

These recommendations are included in flight operations technical bulletins Nos. 707-06-1, 727-06-1, 737-06-1, 747-15, 747-400-55, 757-75, 767-75, 777-21, 787-1 issued by Boeing on August 1, 2006: *Convective Weather Containing Ice Crystals Associated with Engine Power Loss and Damage*.

FURTHER RESEARCH

Today, knowledge of the nature of convective weather and the exact mechanism of ice crystal buildup and shedding in the engine is limited. A research program is being developed by an industry icing group to address these needs. It involves flights into convective clouds to measure their properties, as well as ground-based engine testing.

Most of what is currently understood about the environment associated with engine events is based on pilot reports and flight data. Additional pilot reports of high-altitude ice crystal encounters (with or without engine events) will help researchers understand the conditions associated with engine events, ensure that the flight program is directed into the appropriate flight conditions, and help develop cues for these flight conditions.

Pilots encountering conditions such as those described in this article are encouraged to provide as many details about the conditions as possible to their airlines for subsequent use by researchers.

SUMMARY

Ice crystal icing conditions have been recognized as a hazard to turbofan engines. Ice can build up deep in the engine core.

Pilots are advised to familiarize themselves with the conditions under which ice crystal icing typically occurs and follow the recommendations in related technical bulletins.

Airline awareness of the potential for ice crystal icing on all engine models/airplane types may provide additional information that will help Boeing and the industry better understand this phenomenon.

For more information, please contact Jeanne Mason at jeanne.g.mason@boeing.com. **A**

Material for this article has been drawn from AIAA 2006-0206 "Ice Particle Threat to Engines in Flight," Mason, Strapp and Chow.