Low fuel temperatures

Basics, principles of operations and a new software tool for operational predictions

With the operation of the very long range A340-500 and -600 on polar routings, the exposure of Airbus aircraft to low fuel temperature issues has increased. This article summarizes some basics regarding the minimum fuel temperature that can be tolerated, reviews the principles of the FUEL LO TEMP procedures on the Electronic Centralized Aircraft Monitor (ECAM) and in Flight Crew Operating Manual (FCOM) 3.02.28 and describes new software now available to operators to predict fuel temperatures for a given flight at the time of dispatch.

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Minimum allowed fuel temperature

Operating the aircraft within the certified environmental envelope is not sufficient to prevent issues with cold fuel. Indeed, safe engine operation leads to two engine-specific limitations: the minimum inlet temperature and the fuel heat management system limitation. More information on fuel characteristics is given in the *'Getting to Grips with Cold Weather Operations'* brochure available from Airbus.

FUEL FREEZING POINT

The fuel characteristic that best describes the lower limit in temperature for use in aircraft operations is not actually the fuel freezing point, but the pumpability limit. This limit is very close to the pour point, a temperature at which the fuel, cooled without stirring, will only just still pour from a standard glass cylinder. However, since the pour point is difficult to determine accurately, the fuel freezing point continues to be used as a reference for low-temperature characteristics.

Fuel is a mixture of different hydrocarbons that do not all solidify at the same temperature. When fuel is cooled, an increasing proportion of wax crystals form in the fuel. The wax crystals can block fuel lines and filters, thus causing engine instability, power loss and eventually flameout, and their formation should therefore be avoided.

The fuel freezing point is commonly measured with the ASTM automated optical test method D5901-03. ASTM International is an organization which develops standards, amongst which are the fuel freezing point tests. This test method is based on the observation of wax crystals completely disappearing from a warmed fuel sample that was previously frozen. The method is used widely except for Russian and other Eastern-European fuels, for which the GOST (Russian state standard) method gives the temperature at which solid particles first appear during the cooling process. The ASTM method therefore affords higher margins.

The specification fuel freezing point depends directly on the level of distillation aimed for in its production. The higher the distillation grade, the lower the yield of fuel from the crude oil. Fuel of different specifications is found in different parts of the world, each with a different specification fuel freezing point. The main focus is on JetA1, primarily available everywhere except the United States of America, and on JetA, which is used there (see left-hand table).

Fuel freezing point

JetA	-10°C
JP5	-46°C
JetA1/JP8	-47°C
RT/TS-1	-50°C
JetB	-50°C
TH	-53°C
JP4	-58°C

FUEL MIXTURES

When flying between areas where different fuel types are available, mixtures of fuel with different specification fuel freezing points will occur in the tanks. Experimental evidence has shown that fuel mixtures do not behave as ideal fluids and that the resulting fuel freezing point is commonly adversely affected. Airbus recommends avoiding mixtures in the outer, most exposed tanks. JetA1 can be considered as having unaltered freezing characteristics up to a content of 10% of JetA, above that fraction results become unpredictable and the fuel freezing point should be considered to be that of JetA fuel.

ACTUAL FUEL FREEZING POINT

When known, the actual fuel freezing point of the fuel carried onboard the aircraft may be retained as a criterion for cold fuel management in flight, if a monitoring process, including maintenance, dispatch, and crew procedures, has been set up in a way that is acceptable to local authorities. The process involves the retrieval of samples from the tanks through the drain holes after the refueling is completed. These are then put through jet fuel quality analysers, results can be radioed to the crew if not available before takeoff. Based on a fuel freezing point measurement survey conducted by a company involved in research in cold temperature behaviour of petroleum products at major US airports, a typical benefit of at least 3°C and up to 18°C can be expected from the implementation of such a monitoring process.

MINIMUM INLET TEMPERATURE

Engines have an oil cooling system at their inlet, which uses the arriving fuel as a heat sink, thus warming it. Various system architectures and hardware leads to a varying specification of the minimum temperature that a given engine type can cope with. The minimum temperature is expressed as a margin versus fuel freezing point - the minimum engine inlet temperature is the actual fuel freezing point with the manufacturers margin added to it (see right-hand table).

FUEL HEAT MANAGEMENT SYSTEM LIMITATION

During flight, the fuel temperature quickly drops below the freezing point of water, of which a certain proportion is always contained in aviation fuels. This water can then form ice crystals, which could travel to the engine inlet filters and clog them. To avoid this, the fuel is warmed in the oil cooling system. For some engine types, a minimum fuel temperature below which takeoff and/or flight is not permitted therefore results from the engine capability to warm up a water-saturated fuel flow, unless an anti-ice additive is used.

Minimum inlet temperature

Pratt & Whitney	0°C
GE	0°C
Rolls-Royce	3°C
International Aero Engines	4°C
CFM A320F	4°C
CFM A340	5°C

Operational procedures

GROUND PROCEDURES

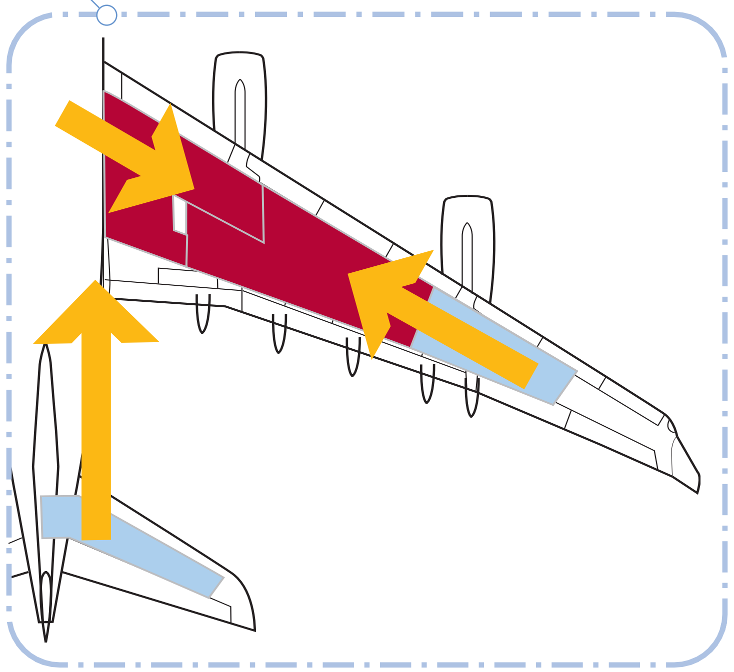
Special attention should be paid to the fuel contained in the outer tanks before a flight through forecast cold atmosphere is commenced. These tanks may remain completely or partially filled with the cold reserve fuel from the previous flight. This may have an unrelated, but undesirable, effect of leading to wing surface icing after landing in a humid environment. More importantly, if partially filled, it may lead to high-proportion mixtures of different fuel types. Both can be avoided by performing a manual transfer of the outer tank fuel inboard during the taxi-in. If the outer tanks remain full with fuel of a lower

freezing temperature than fuel locally available, it may be advantageous to keep that fuel there, since experience shows that a higher initial fuel temperature only has a delaying effect on the cooling process, but usually does not affect the minimum temperature observed in-flight. The benefit of the lower freezing point prevails in such a case.

IN-FLIGHT PROCEDURES

On aircraft equipped with a fuel temperature measurement system, an ECAM warning is triggered when the fuel temperature drops below the minimum acceptable temperature in that tank. The minimum acceptable temperature is not the same for all tanks. The temperature in the feed tanks (typically, but not exclusively, the inner tanks) may not drop below the minimum acceptable temperature limited by the engine inlet and the heat management system limitation, while the fuel in the remaining tanks may be allowed to reach the freezing point. The ECAM warnings are calibrated to the specification values of JetA and JetA1 fuel and request manual fuel transfers. The crew may delay the application of the procedures appropriately, if the actual fuel freezing point of the fuel carried is known.

Tank transfer schematic



The figure 'tank transfer schematic' shows an example for the A340-500 and -600, the FCOM 3.02.28 FUEL LO TEMP procedures request manual transfers:

- From outers to inners, when the fuel freezing point is reached in the outers
- Forward from the trim tank, when the fuel freezing point is reached in the trim tank
- From center to inner, when the minimum acceptable temperature is reached in the inners

TAT INCREASE

In addition to manual transfers, the procedure also recommends to increase the TAT (Total Air Temperature), which is the temperature measured on the structure of the aircraft. The TAT is derived from the outside or Static Air Temperature (SAT) and depends on the Mach (Ma) number:

$$TAT = SAT \times (1 + 0.2 \times Ma^2)$$

There are two means of increasing the TAT: increasing speed to increase aerodynamic warming, and reducing altitude to fly in warmer air. The TAT formula highlights that speed increase only has a marginal effect, while the exchange rate SAT to TAT is one to one.

To give an impression of the effect in time, both means are shown in separate variations from a basic scenario, which considers an A340-600 taking off at Maximum Take Off Weight (MTOW) flying from the US East Coast to East Asia on a great circle routing at Long Range Cruise (LRC) speed and on an optimum altitude profile. The aircraft is using JetA fuel with a specification fuel freezing point of -40°C. A statistical outside temperature profile is considered for this example, based on a 95% reliability for January, meaning that at any point during an actual flight in that month, there is only a 5% chance of encountering lower temperatures.

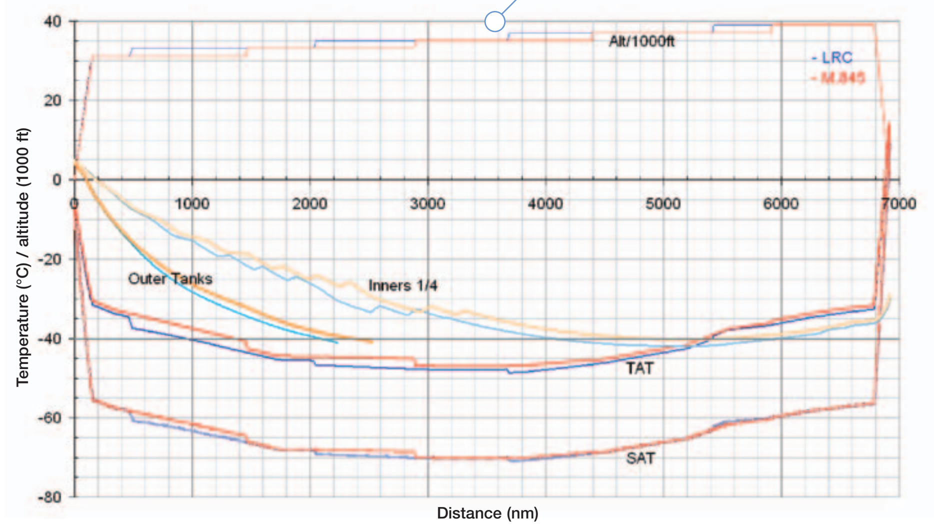
LOW FUEL TEMPERATURES - BASICS, PRINCIPLES OF OPERATIONS AND A NEW SOFTWARE TOOL FOR OPERATIONAL PREDICTIONS

The first variation consists in flying at maximum managed speed (Ma 0.845 for this type) on a fuel-optimized profile. The figure "fly faster" shows the relevant parameters plotted against the ground distance, the basic scenario always shown in shades of blue and the variation case in shades of red/orange. The speed increase leads to a shift in the optimum profile, which is mirrored by the SAT profile, but even where the aircraft flies at the same altitude, a small increase in TAT can be observed. This increase delays the moment when the temperature drops below freezing point in the outer tanks by some 300 nautical miles (nm), but does not avoid the need for the manual transfer procedure from the outers to the inners. It does, however, succeed in maintaining the inner tanks temperature above or at the freezing temperature, which is sufficient for the Rolls Royce Trent 500 engines that equip this aircraft type. This comes at a cost: fuel burn at identical takeoff weight is increased by 7.9 tonne (t).

The second variation considers flying the whole distance at Flight Level (FL) 290. The figure 'fly lower' shows the large increase in SAT, which is mirrored by the TAT. The lower flight level succeeds in delaying the manual transfer by 800 nm and subsequently maintaining a comfortable margin of the fuel freezing point in the inner tanks. The cost of this variation is a fuel burn increase by 5.5t.

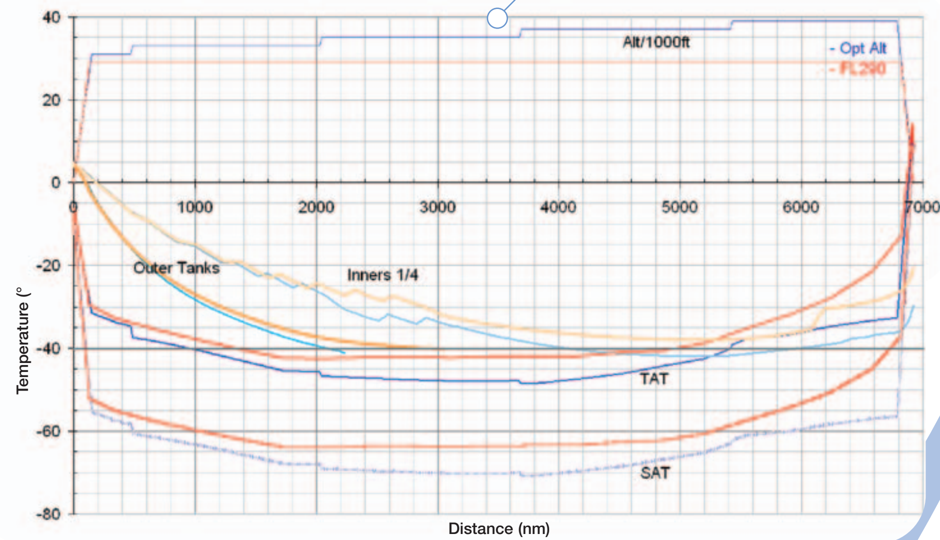
TAT increase - 'fly faster'

Comparison of fuel temperatures in outer and inner 1/4 tanks for two speeds



TAT increase - 'fly lower'

Comparison of fuel temperatures in outer and inner 1/4 tanks for two altitude profiles



LOW FUEL TEMPERATURES - BASICS, PRINCIPLES OF OPERATIONS AND A NEW SOFTWARE TOOL FOR OPERATIONAL PREDICTIONS

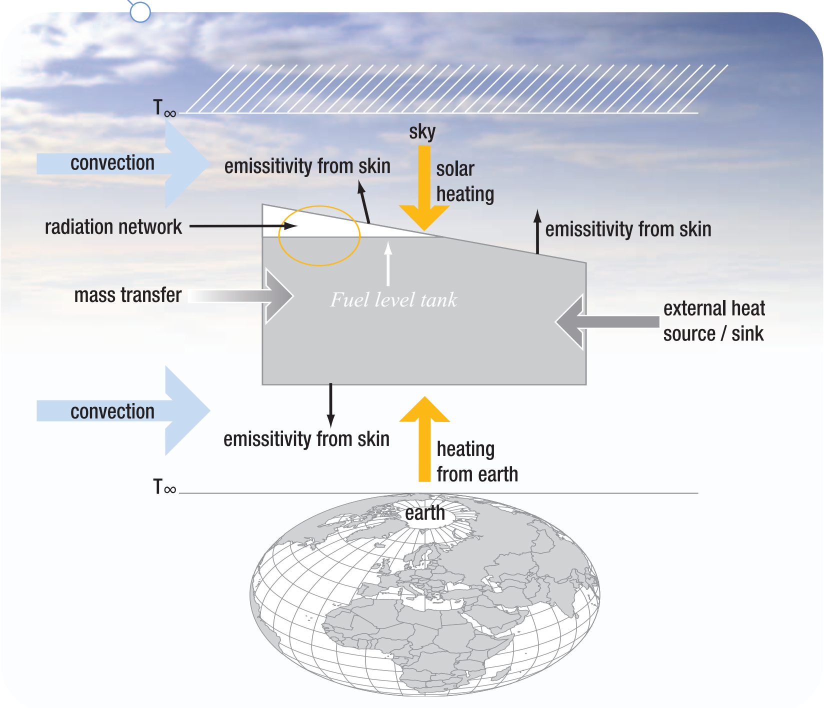
Fuel temperature prediction software

As described in the previous section, while it is possible to manage cold fuel issues once in flight, an un-forecasted occurrence can lead to over-consumption and even diversion. In order to give airlines the ability to analyse a flight for its exposure to fuel freezing before it is flown, Airbus has designed the Fuel Temperature Prediction (FTP) software.

PRINCIPLES

The FTP software relies on external data sources to obtain:
- Navigation data (waypoints, distance, time)
- Weather data (temperatures)
- Performance data (altitude, speed, fuel on board)

Schematic of heat exchange mechanisms



From this data, it determines the nominal fuel distribution and movement during the flight and simulates the effect of the various heat exchange processes, like convection, radiation, external heat sources and mass transfer. The result is a detailed output of the fuel temperatures in each tank at each waypoint, a summary that indicates whether the flight can be dispatched under the given conditions, whether any manual transfers were triggered during the simulation, and what the lowest temperature forecast in each tank is. This information allows the dispatcher to decide in an informed manner, which areas may have to be avoided on a critical flight.

OPERATING MODES

The FTP can be used in two ways depending on the original source of the navigation, weather and performance data: the Flight Plan Analysis and the Sector Analysis.

FLIGHT PLAN ANALYSIS

The Flight Plan Analysis uses an airline operational flight plan (or pilot log) as a basis for the computation. Operational flight plans are generated with Computerized Flight Planning (CFP) systems available from a number of providers. They run on different hardware, like PCs, UNIX or mainframe computers, or even remotely over Internet or similar connections, and they produce a document, which is highly customized by the operators to their specific needs.

One of the design constraints for the FTP software was therefore its operability on a variety of platforms. At this time, stand-alone solutions are being developed for PC and UNIX under RS6000, in addition to the basic implementation, which is a complete solution included in the Performance Engineer's Programs (PEP) software suite.

An important aspect lies in the large variety of flight plans to be imported. This has been tackled in the PEP environment through the definition of a standard format, which uses XML (eXtensible Markup Language) and is a subset of the standard defined for the A380 Onboard Information System (OIS). The translation of the airline pilot log to XML requires the development of a customized tool. All the relevant information for this task is provided in the Performance Programs Manual (PPM), but assistance and even the development of such a tool is available as an Airbus service.

SECTOR ANALYSIS

The Sector Analysis is designed to help assess the exposure of a city-pair to cold fuel issues on a statistical basis. For this task, some simplifications are made. The routing is assumed to be a Great Circle one; the performance on the route is established with the Airbus Flight Planning (FLIP) software, which is also part of the PEP.

For the statistical weather data, a connection has been built to the NOAA GUACA (National Oceanic and Atmospheric Administration - Global Upper Air Climatic Atlas), which was compiled from data obtained in the 80's and 90's from the ECMRWF (European Centre for Medium Range Weather Forecasts). This database needs to be installed specifically to allow extraction of statistical data for monthly or seasonal exposure analysis.

Information and the database are available from the NOAA website: http://navy.ncdc.noaa.gov/products/compactdisk/guaca.html.

The FLIP computation results in a specific output, which can be directly imported into the FTP PEP user interface, through which the same type of analysis can be obtained as for a Flight Plan Analysis.

APPLICABILITY

The FTP software is available for all A330/A340 Family aircraft and will be released for entry into service of the A380 and the A350.

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Conclusion

For some years monitoring of fuel temperatures for flights in cold atmospheres, such as trans-polar flights, has been normal and operational procedures to deal with this have been put in place. With the very long range A340-500 and A340-600, Airbus considered the increased exposure of these aircraft to low temperatures should be addressed at an earlier stage in the process than through the existing in-flight management procedures detailed in the FCOM and triggered by ECAM warnings.

This led to a review and from this came Airbus' recommendation that operators implement a fuel quality monitoring programme for exposed flights from airports where only high freezing temperature fuel is available and the creation of the Fuel Temperature Prediction (FTP) programme. The FTP enables the prediction and avoidance of cold fuel issues at the time of aircraft dispatch and is recommended for operators to support their operations on routes where such issues can arise.