Greening Aviation:

Hydrogen & Decarbonisation Scenarios

Contrails

What can be expected from H_2 fuelled aircraft?

Formation and mitigation

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ISABE 2022

Saturday 24 September 2022

Scope

- A brief introduction
- Climate effects
- Processes influencing contrail formation
- Prediction - Schmidt-Appleman criterion
- Mitigation strategies
- H_2 - what to expect

Contrails- Con*densation* trails

- Ice clouds (8-13 km)- Short lived(non persistent)/ Long lived (Persistent- WMO)
  - "Cooling" effects - scattering incoming shortwave solar radiation (RF_{SW}) with minimal atmospheric absorption
  - "Warming" effects- absorbing and re-emitting outgoing terrestrial radiation (RF_{LW})

Net radiative forcing (RF)

- Negative shortwave RF during the day
- Longwave-RF impacts of contrails during both day and night are positive

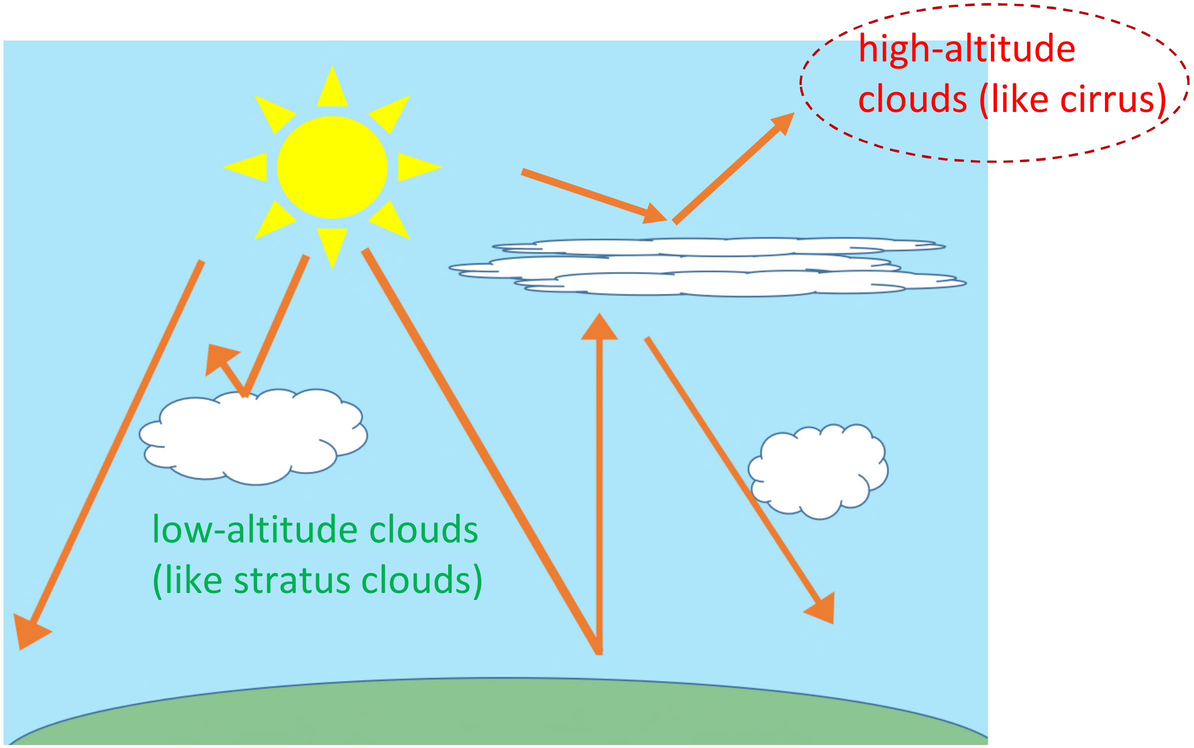
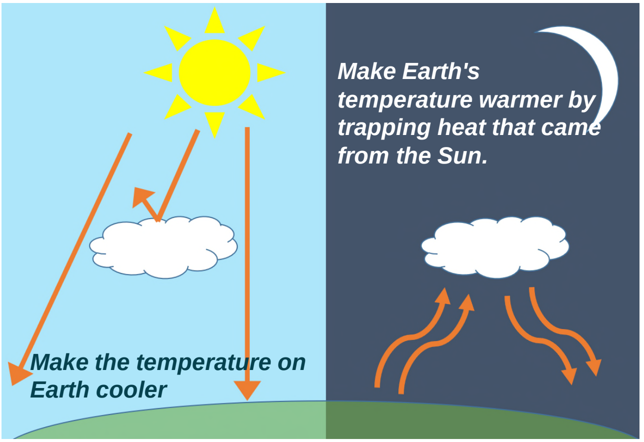


Image recreated from a NASA source

****Radiative forcing*** *is the change in energy flux in the atmosphere caused by natural or anthropogenic factors of climate change as measured by watts / metre*

Clouds affect earth's climate



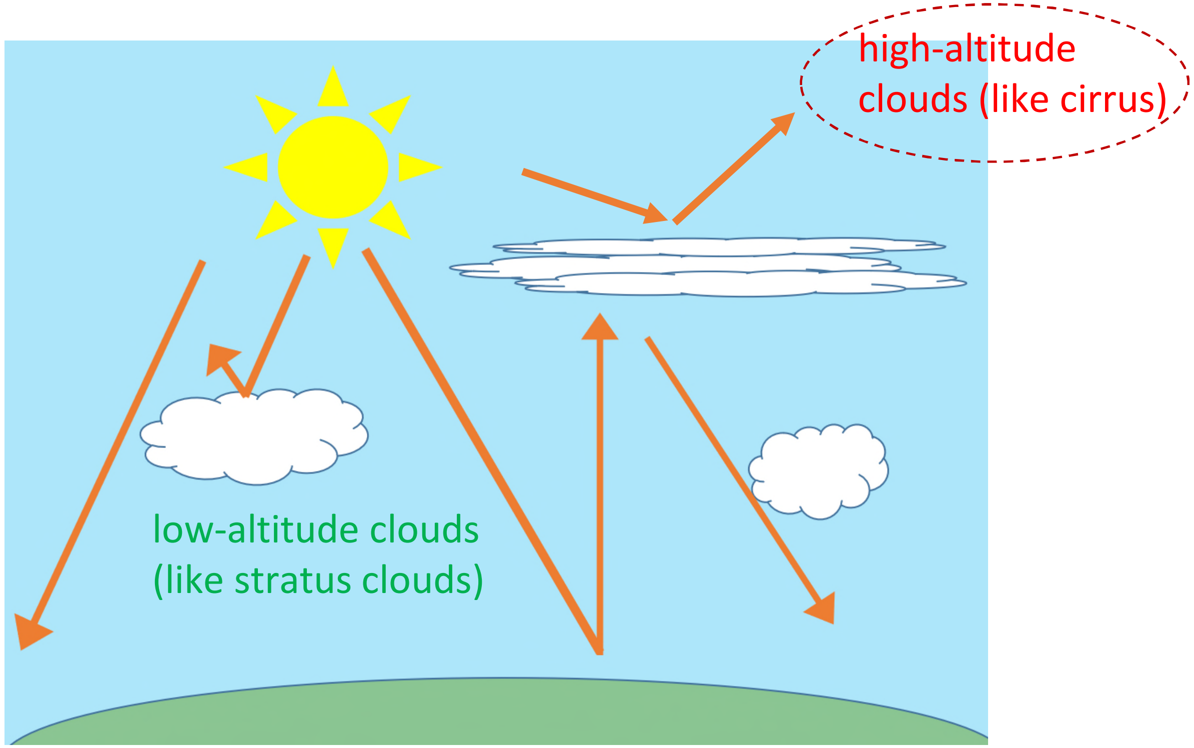
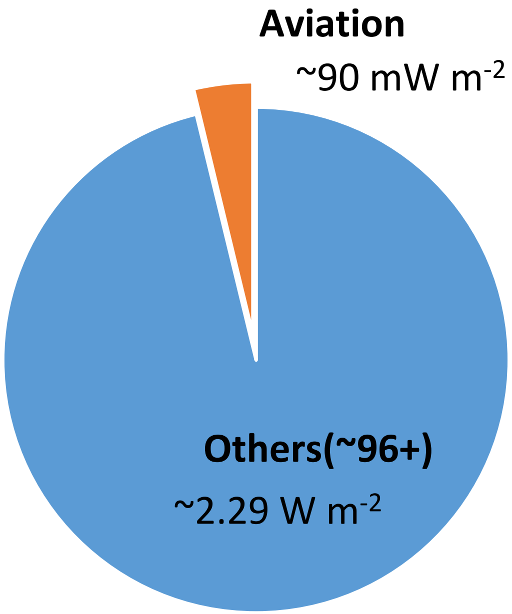


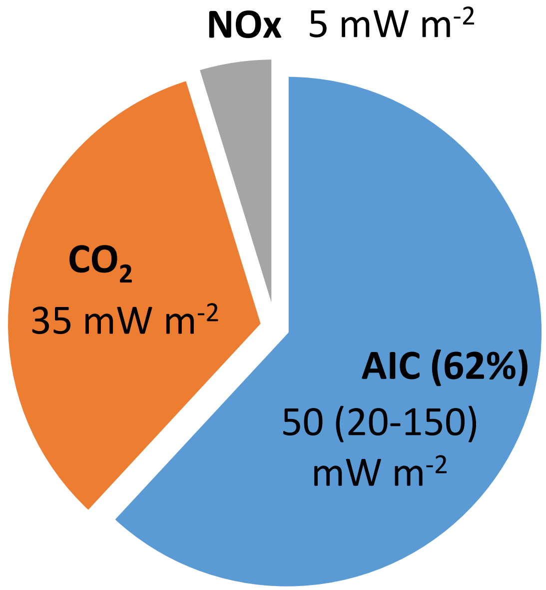
Image recreated from a NASA source

- Characteristics- Optical Thickness (how much light the cloud can intercept) and height
- Radiative "blanket" by absorbing the thermal infrared radiation
- Complicated predictions – net effect

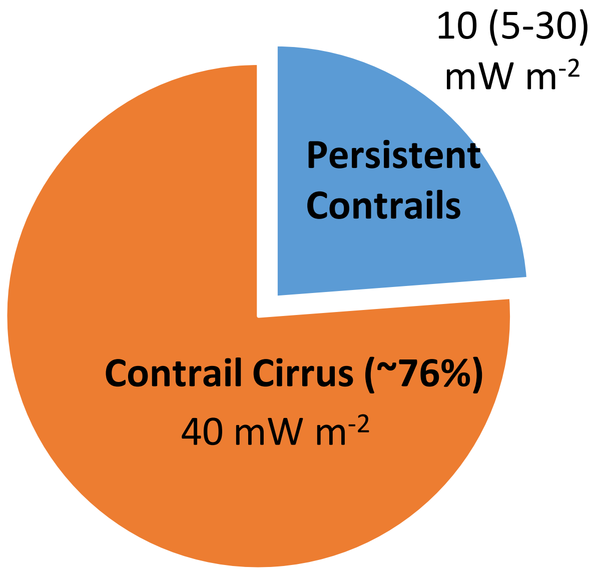
Climate effects



Anthropogenic RF



Aviation-derived RF

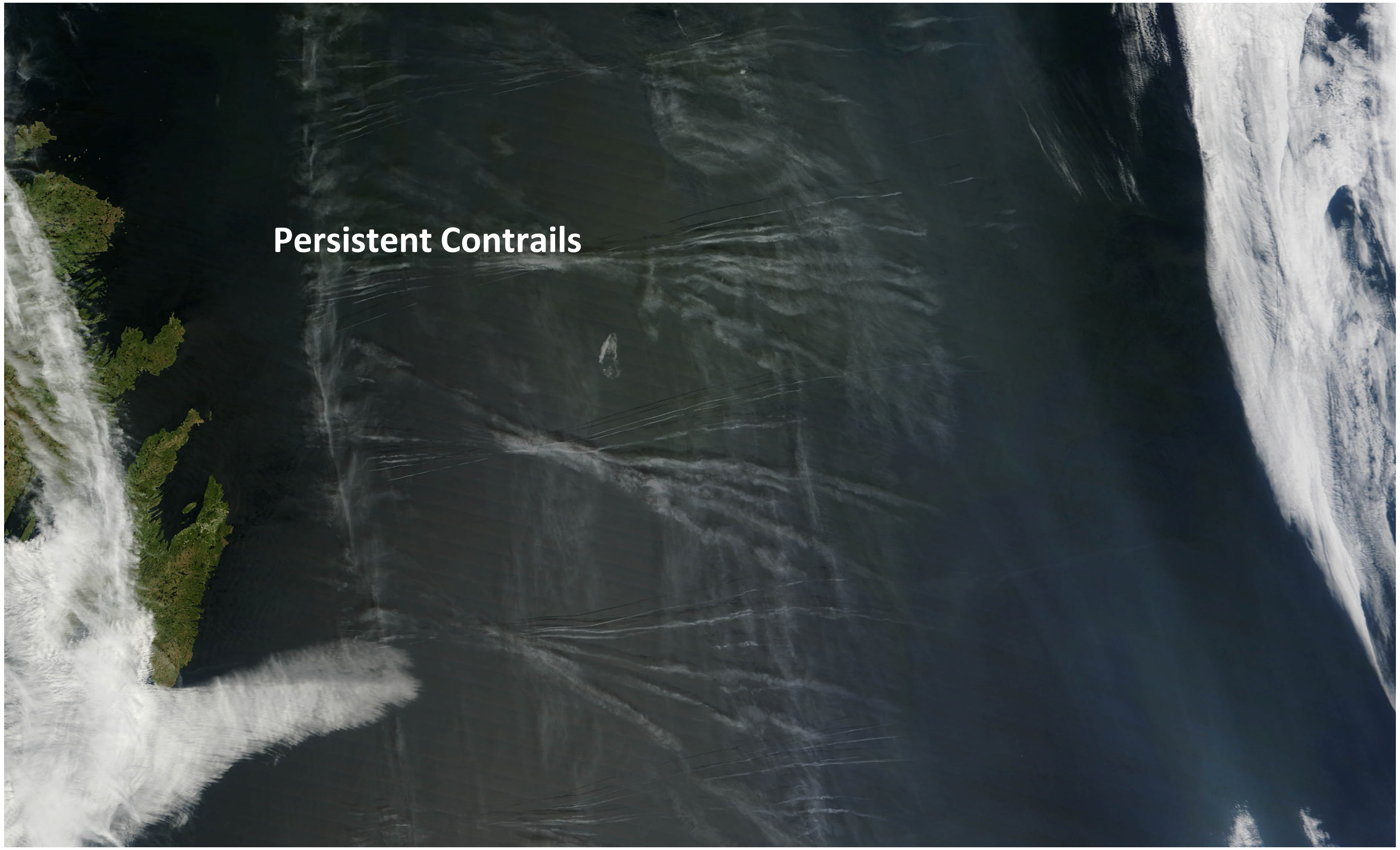


Aircraft-induced cloudiness RF

Recreated based on data presented in Kärcher, Bernd. (2018). Formation and Radiative Forcing of Contrail Cirrus. Nature Communications. 9. 10.1038/s41467-018-04068-0.

Contrail images

14:35 UTC- May 26, 2012
Multiple contrails off the coast of Newfoundland, Canada.
Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite



Source: NASA- https://earthobservatory.nasa.gov/images/78154/the-evolution-of-a-contrail

https://skyvector.com/

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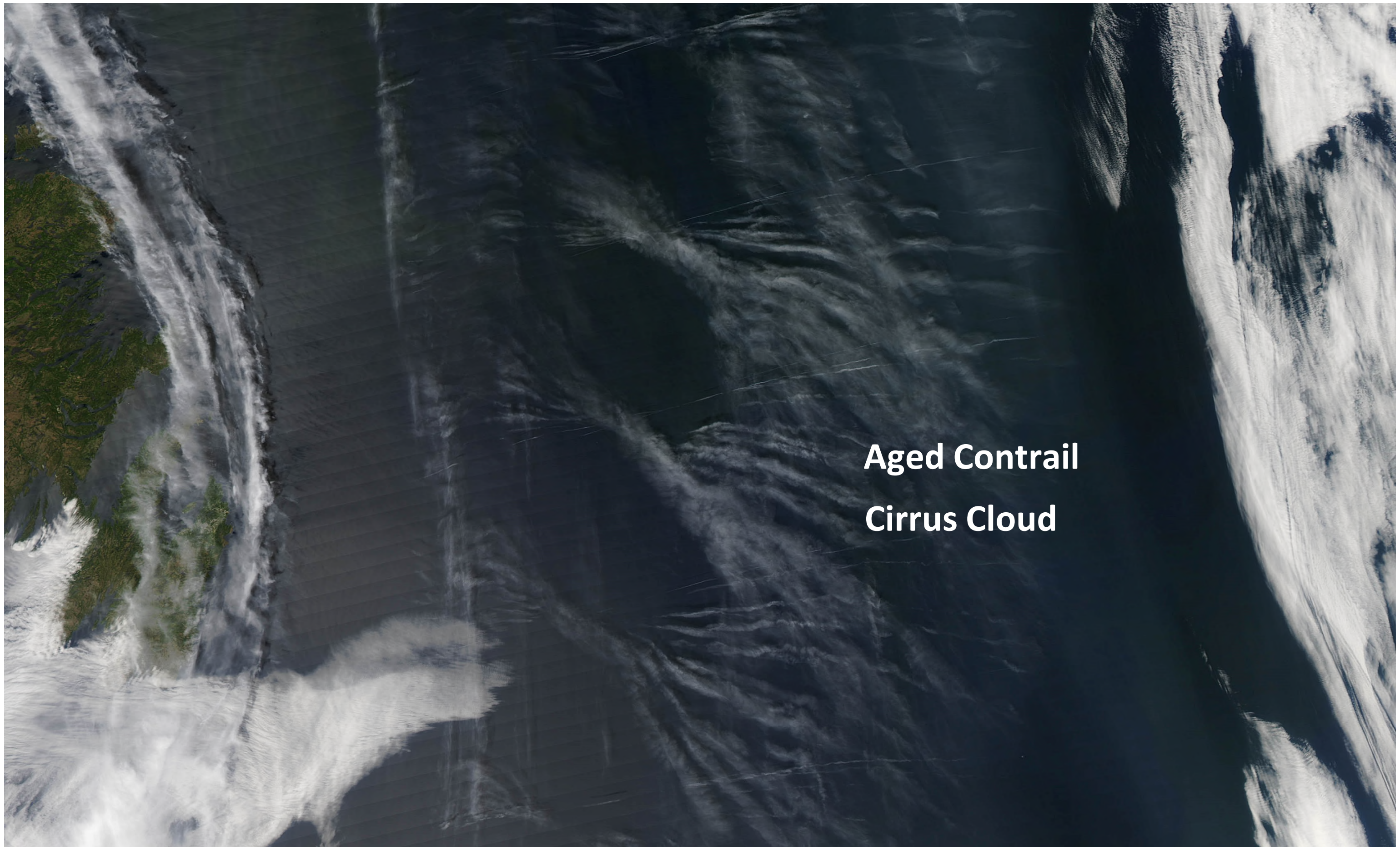

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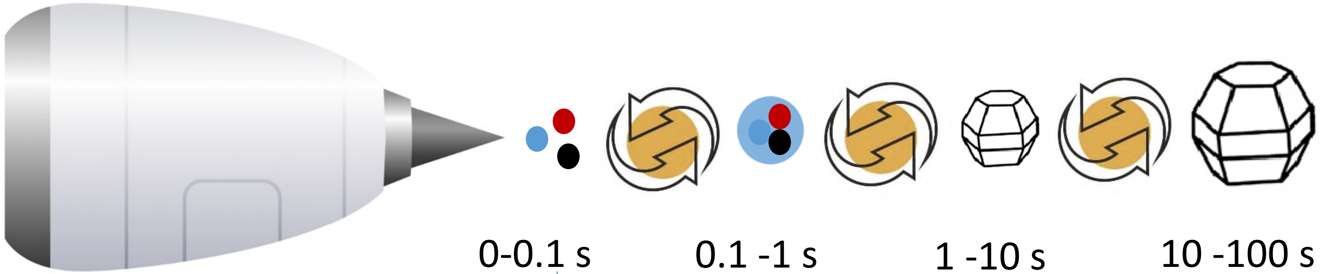
Processes influencing the contrail formation



0-0.1 s — Aerosol /soot *10 nm*

0.1 -1 s — Activation into water droplet *100 nm*

1 -10 s — Water droplets freeze and ice crystals grow *1000 nm*

10 -100 s — Ice crystal grow in upper wake and sublimate in lower wake

Jet regime (t = 0-10s)
Vortex roll-up; Jet vortex interaction

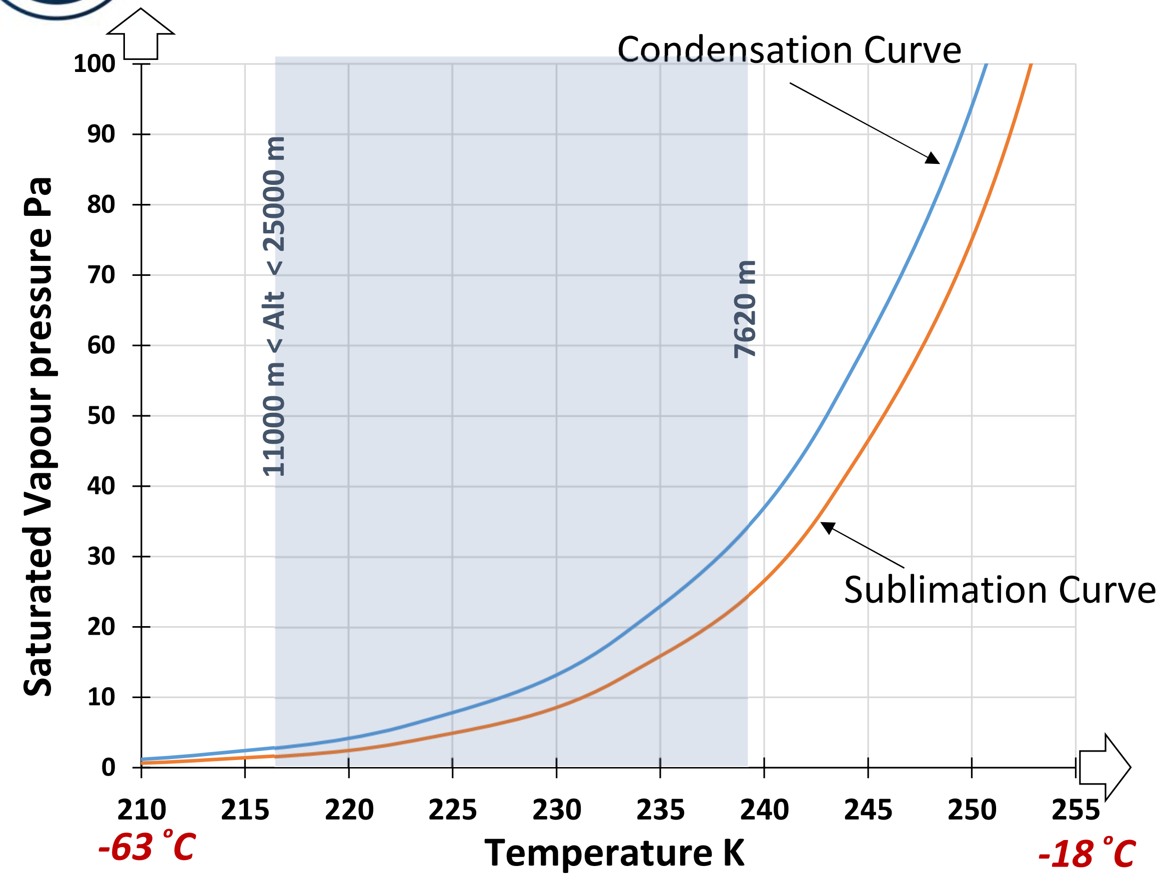
Vortex regime (t = 10-100s)
Vortex descent; Mutually induced downward vel.; secondary wake

Dissipation regime (t = 100-1000s)
Stratification; Vortex break-up

Diffusion regime (t = 1000s- few hours)
Atmospheric turbulence, particle sedimentation, radiative processes, wind shear

>10,000 /cm^3 small ice crystals need to form within a wingspan behind cruising aircraft to make contrails visible

Contrail assessments



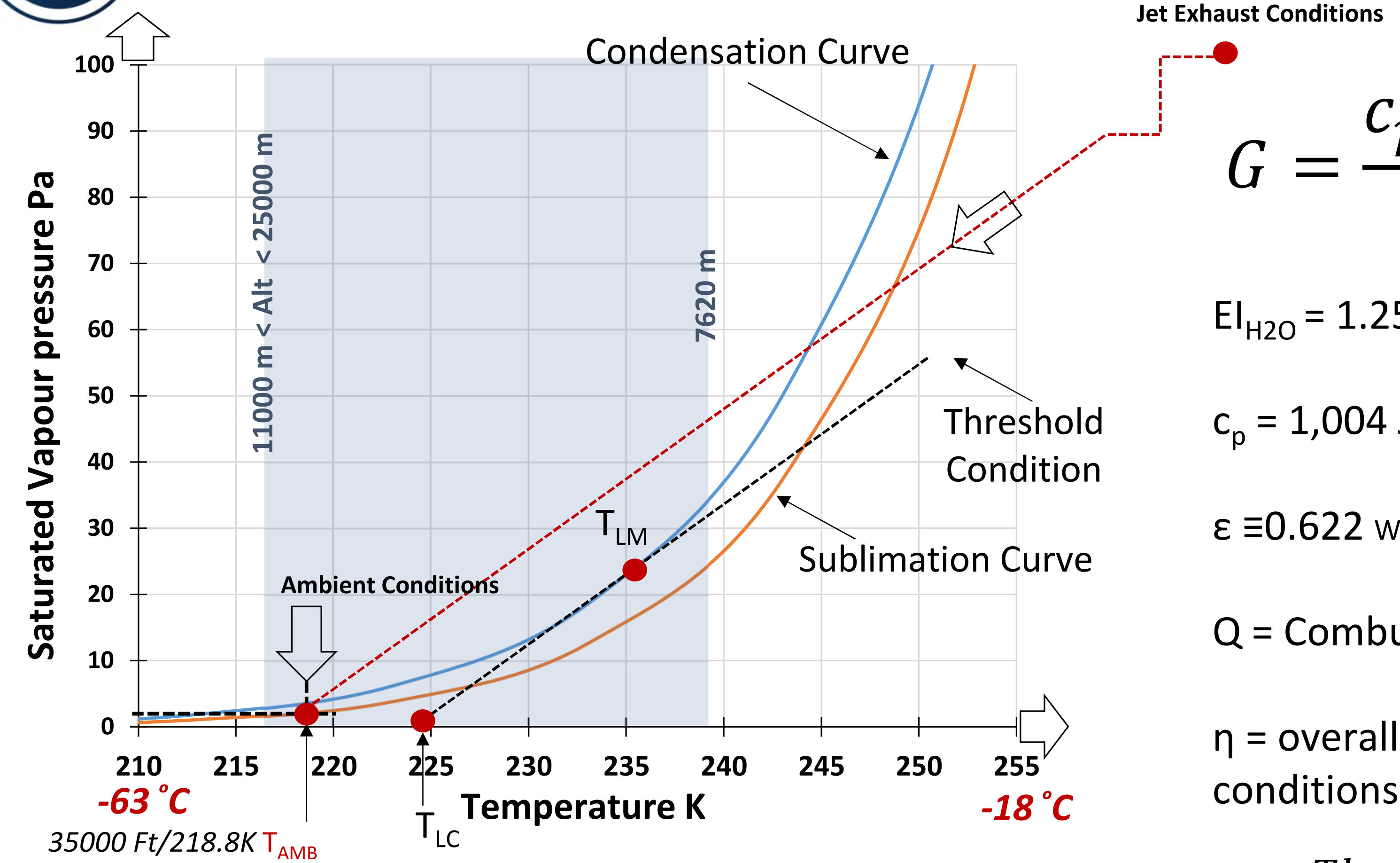
Clausius-Clapeyron equilibrium equation for a perfect gas

- **Thin linear ice particle clouds** - local liquid saturation, condensation of water on aerosols, and subsequent freezing
- **Ice-supersatured** air masses (ISSR)- contrails spread and grow by uptake of ambient water (several orders of magnitude larger)
- **Threshold temperature-** temperature below which liquid saturation conditions are reached in the young plume behind the aircraft

The Schmidt-Appleman criterion

Analytical method based mainly on engines efficiency, exhaust temperature, water vapor emission index, ambient temperature and ambient humidity. It provides the temperature threshold of contrails formation

Contrail assessments



Clausius-Clapeyron equilibrium equation for a perfect gas

$$G = \frac{c_p\, p}{\epsilon} \frac{EI_{H_2O}}{(1-\eta)Q}$$

EI_{H2O} = 1.25 (water vapour emission index)

c_p = 1,004 J kg^{-1} K^{-1} (heat capacity of air)

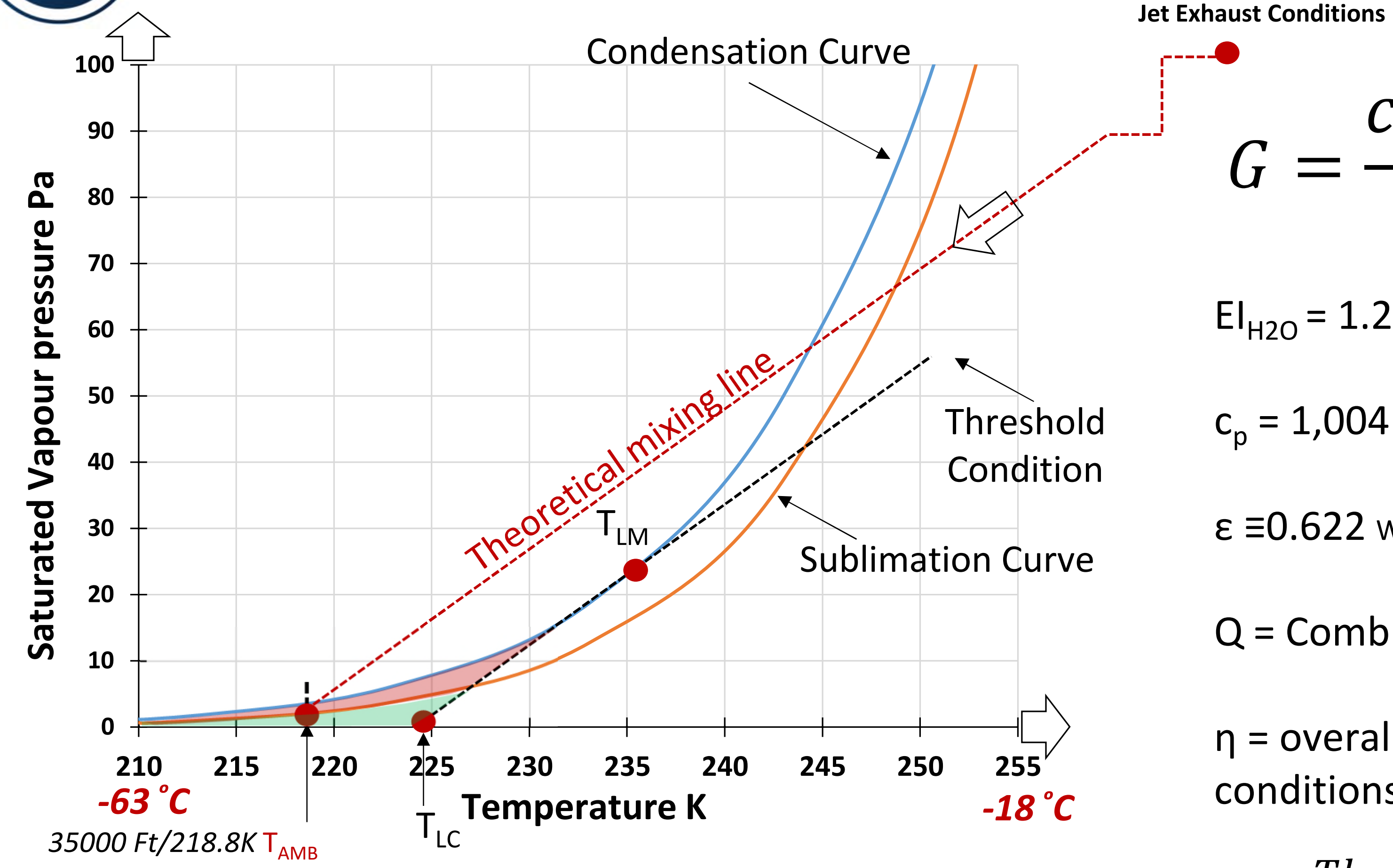
ε ≡0.622 W_{H2O}/W_{air} (molar mass ratio- vapour to air)

Q = Combustion heat per mass of fuel J/kg

η = overall engine efficiency in cruise conditions

$$\eta = \frac{Thrust * V_{TAS}}{FF * LHV}$$

Contrail assessments



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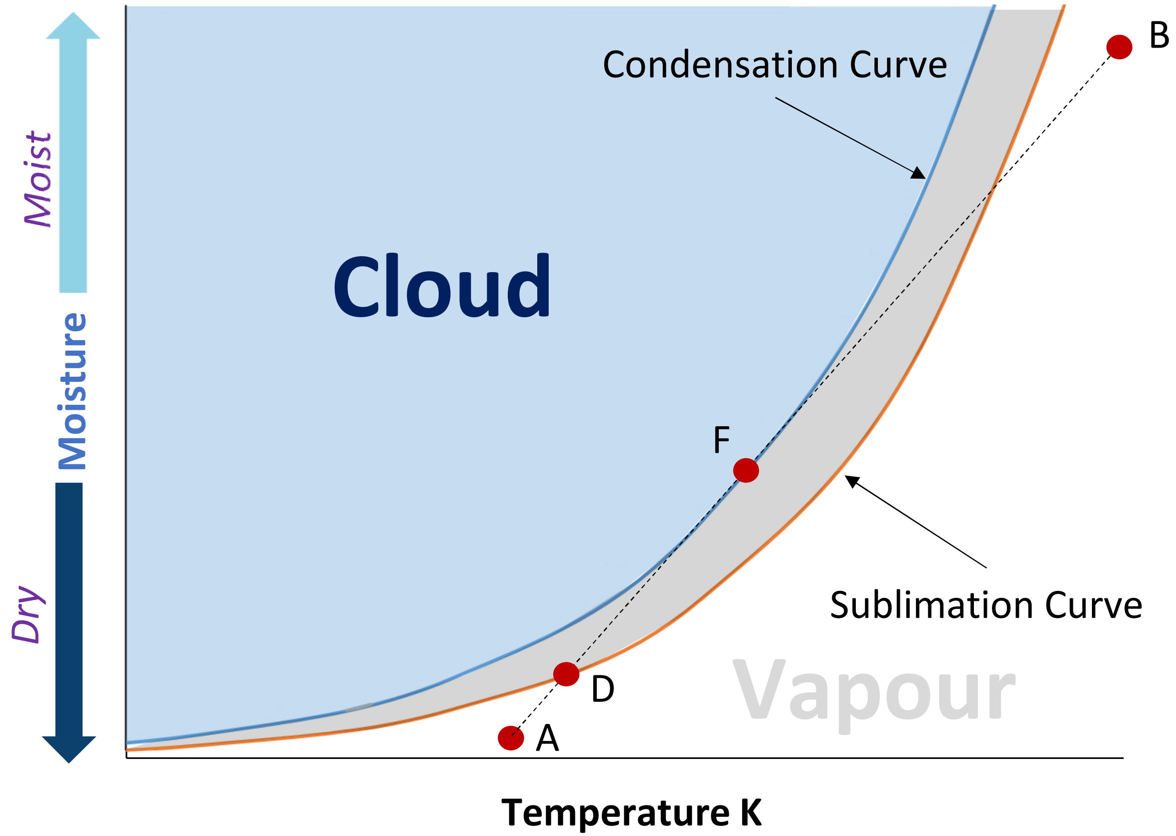
Predicting contrails

Types

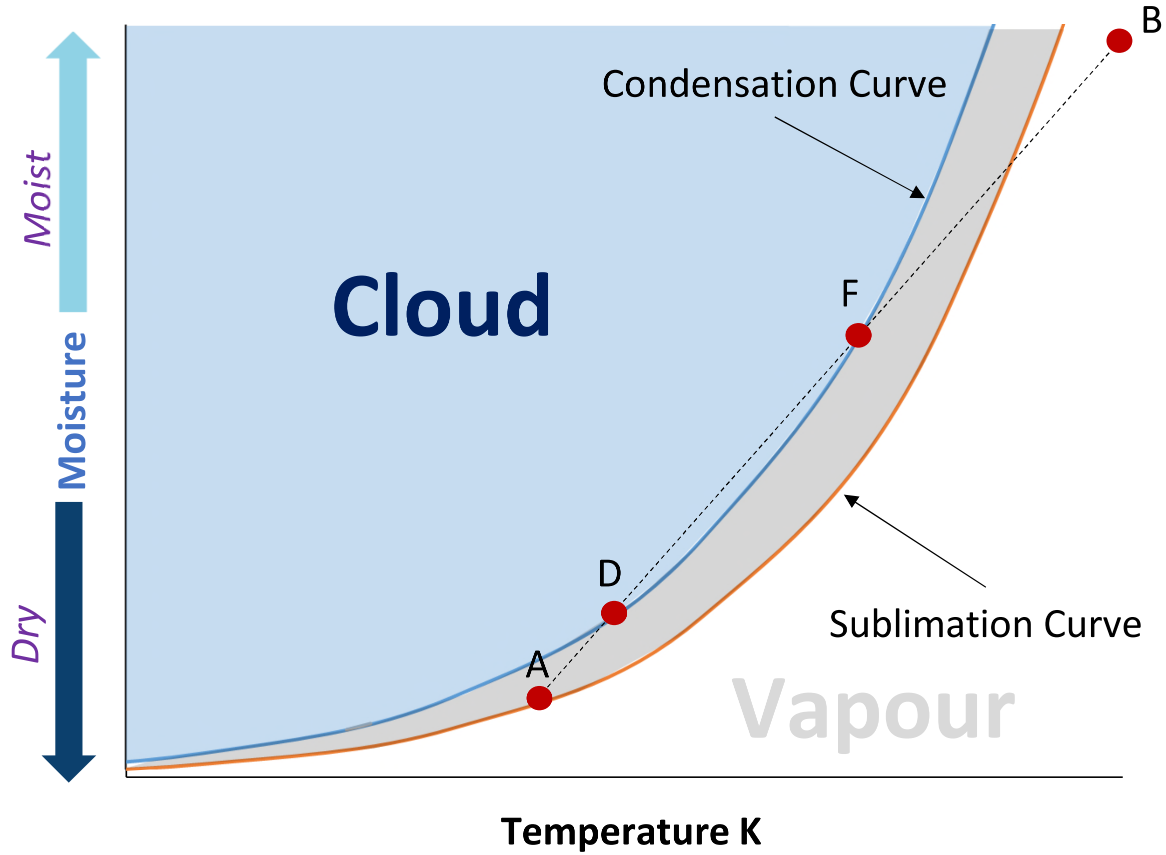


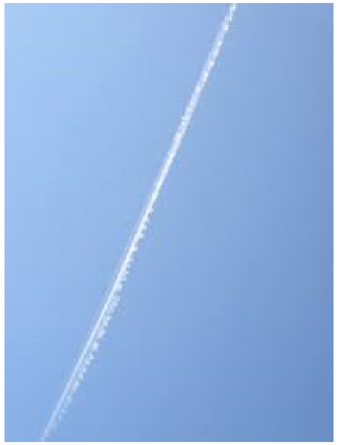
Short Lived Contrail (Dry upper atmosphere)

Image source: https://science-edu.larc.nasa.gov/contrail-edu

Predicting contrails

Types



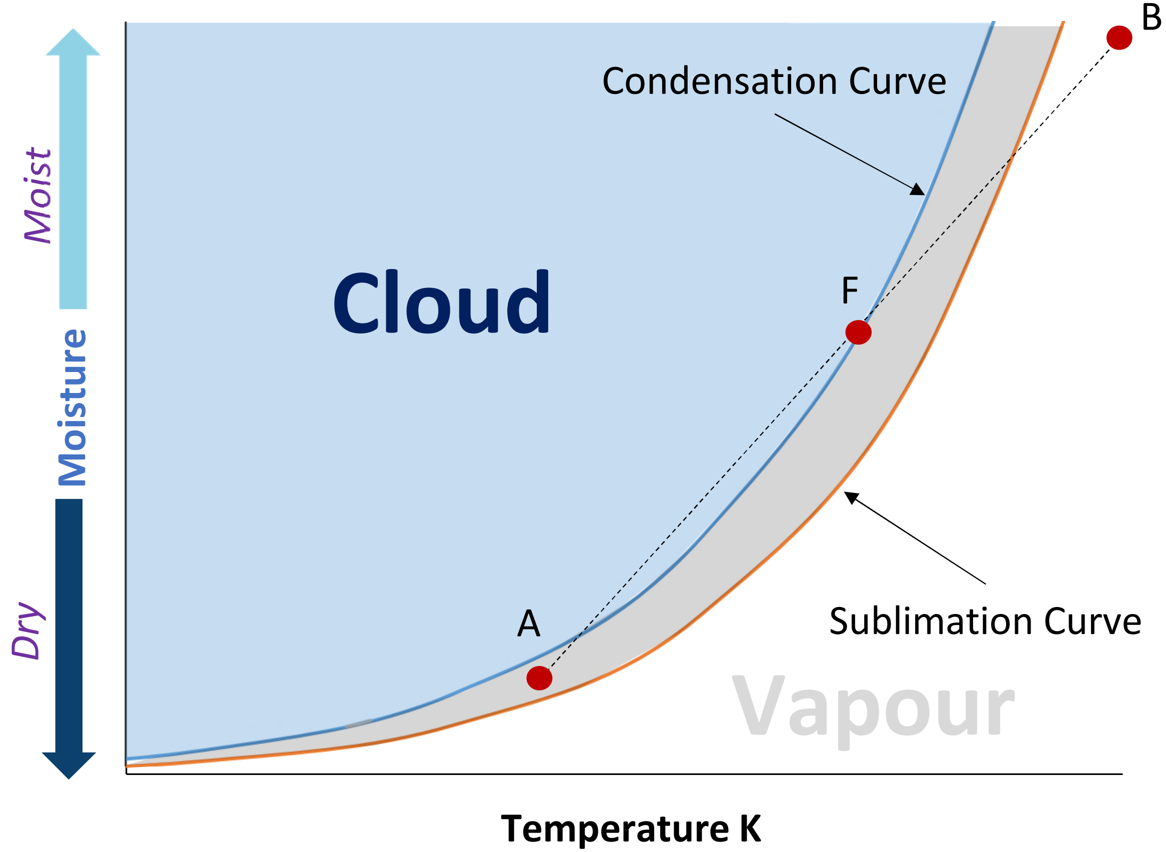


Persistent Contrail (Moister upper atmosphere)

Image source: https://science-edu.larc.nasa.gov/contrail-edu

Predicting contrails

Types



In summary

- If the mixing line crosses the condensation line, a contrail will begin to form at point F.
- The location of point A determines what type of contrail will result.

Persistent Spreading(Moister upper atmosphere)

Image source: https://science-edu.larc.nasa.gov/contrail-edu

Contrail Mitigation Strategies

Contrail Mitigation Strategies

$$G = \frac{c_p\, p}{\epsilon} \frac{EI_{H_2O}}{(1-\eta)Q}$$

EI_{H2O} = 1.25 (water vapour emission index)

c_p = 1,004 J Kg^{-1} K^{-1} (heat capacity of air)

ε ≡0.622 W_{H2O}/W_{air} (molar mass ratio- vapour to air)

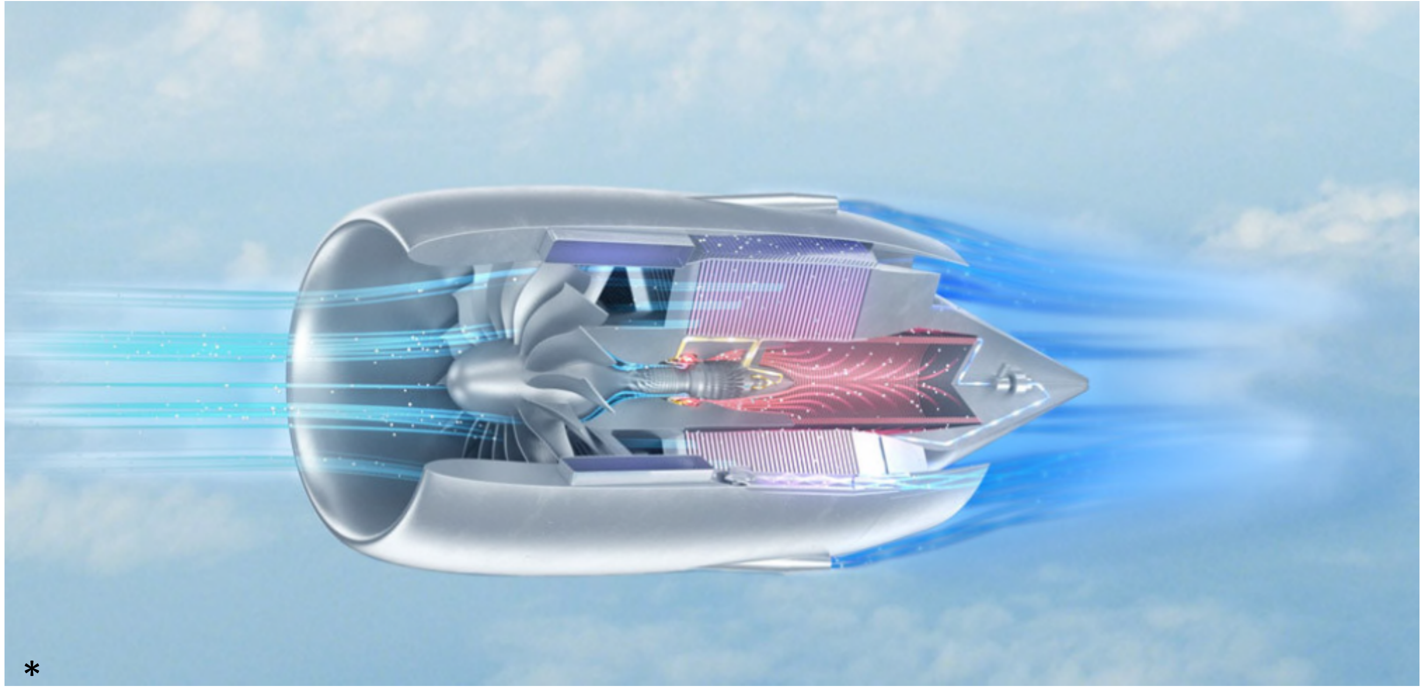
Q = Combustion heat per mass of fuel (Ker- 42 MJ/kg)

η = overall engine efficiency in cruise conditions

$$\eta = \frac{Thrust * V_{TAS}}{FF * LHV}$$

Water extraction from exhaust

WET (Water-Enhanced Turbofan) Engine Concept- MTU

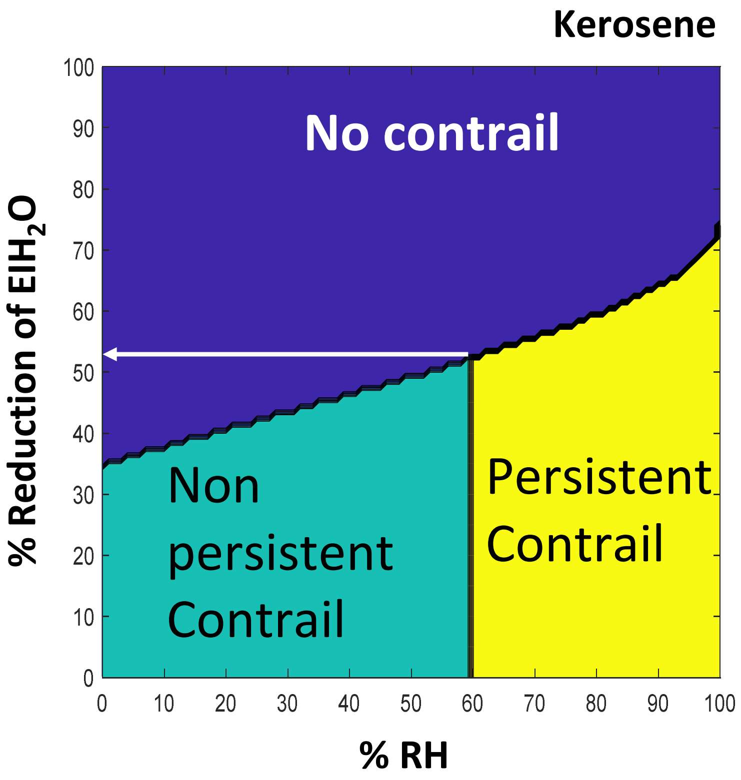


Proposed reduction in climate impact- 80% (in comparison to EIS2000 technology)

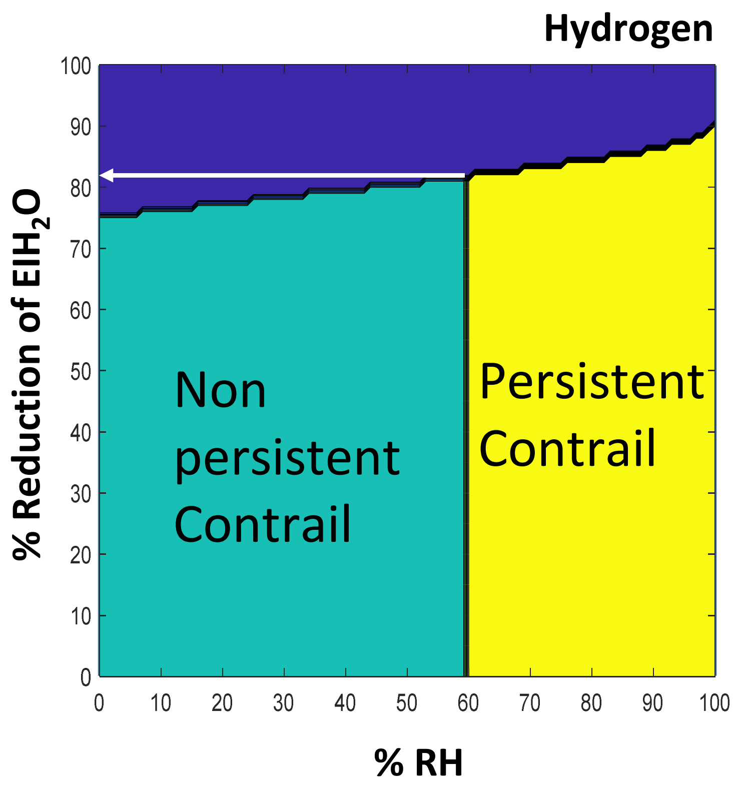
*https://aeroreport.de/en/good-to-know/a-brief-guide-how-the-wet-concept-works

Sensitivity analysis: EIH_2O and Relative Humidity

Aircraft cruising at 35000 ft



Minimum 53-75% removal depending on the ambient condition



Minimum 82-91% removal depending on the ambient condition

Trajectory alteration - Case Study

A320-100/ CFM56-5B

LGW **LONDON, UNITED KINGDOM**

RAK **MARRAKECH, MOROCCO**

Distance
2435 km / 1315 nm

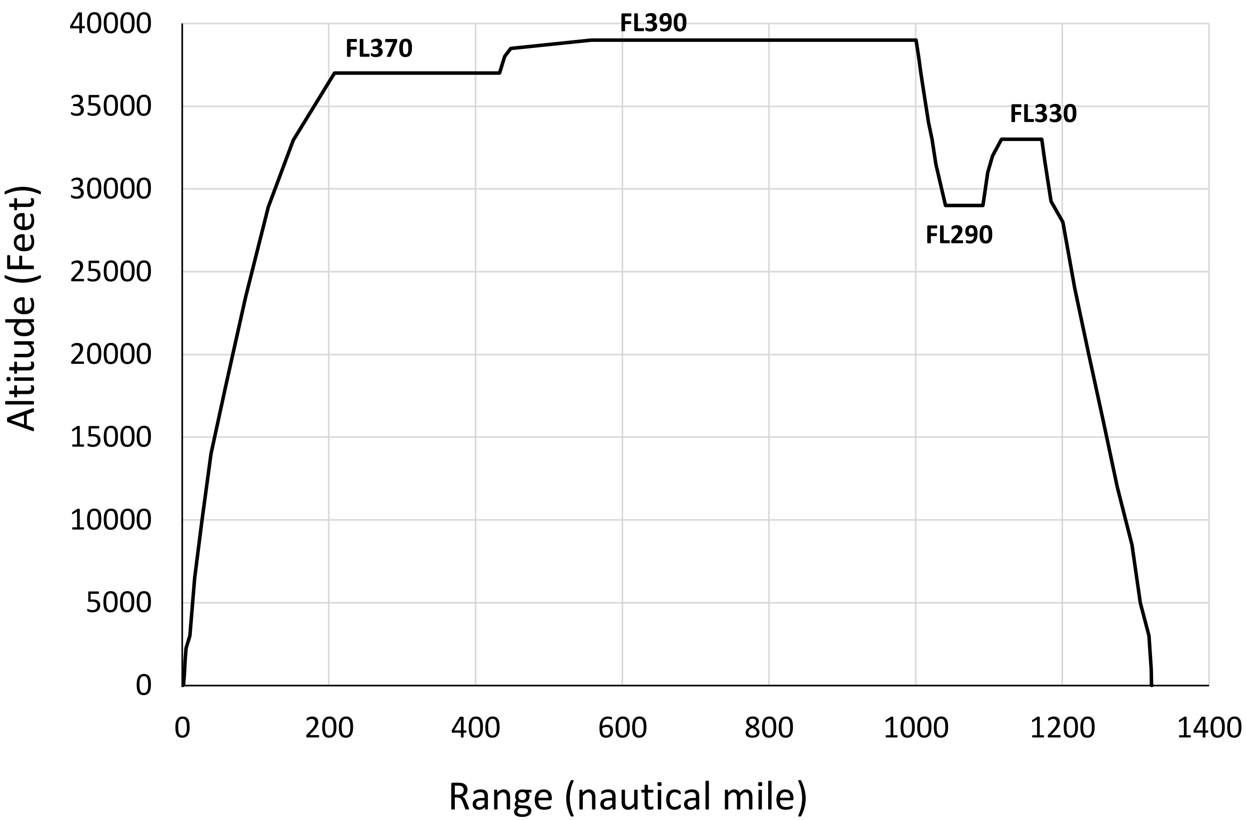
Mission Performance
Cruise : FL370 / M 0.77
Payload: 13000 kg
Load factor : 65.5% (118 pax with 110 kg PL)

Data
TOW: 63.42 tons
FOB: 9.85 tons
Mission time: 3.18 hrs

https://uk.flightaware.com/live/flight/EZY8893/history/20180626/0450Z/EGKK/GMMX/tracklog

Trajectory alteration - Case Study

Simulated SMR aircraft



LGW **LONDON, UNITED KINGDOM**

RAK **MARRAKECH, MOROCCO**

Distance
2435 km / 1315 nm

Simulated SMR aircraft*

Mission Performance

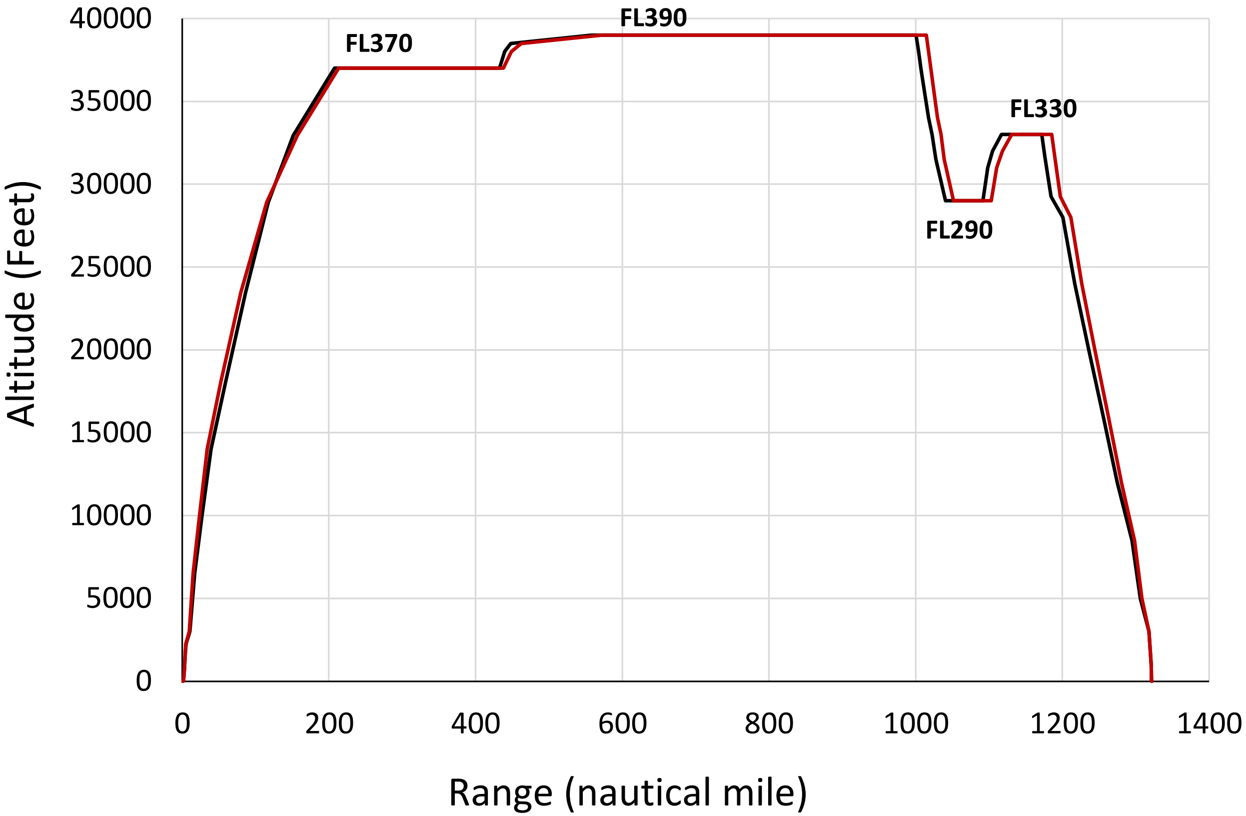
Cruise : FL390 / M 0.77
Payload: 13000 kg

TOW: 65488 kg
FOB: 9888 kg
Block fuel: 8362 kg
Mission time: 3 hrs 23 min

*Based on an A320-100 aircraft with two CFM56 powerplants

Trajectory alteration - Case Study

Simulated SMR aircraft



LGW **LONDON, UNITED KINGDOM**

RAK **MARRAKECH, MOROCCO**

Distance
2435 km / 1315 nm

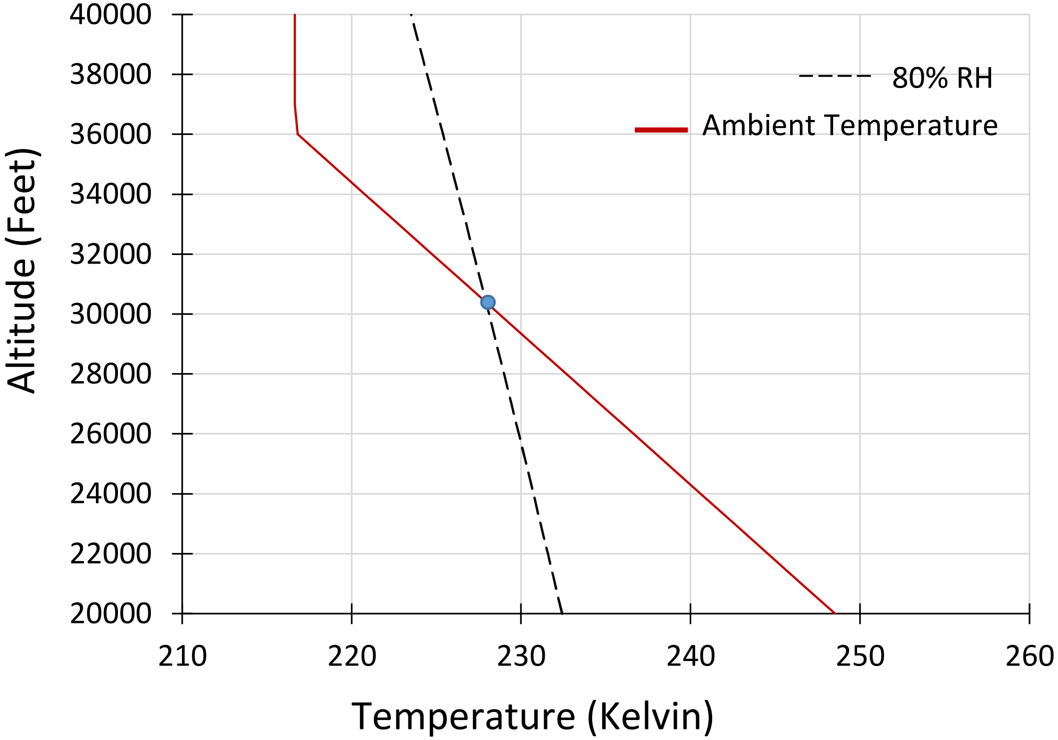
Simulated SMR aircraft*	**Improved SMR aircraft#**
Mission Performance	**Mission Performance**
Cruise : FL390 / M 0.77	Cruise : FL390 / M 0.77
Payload: 13000 kg	Payload: 13000 kg
TOW: 65488 kg	TOW: 65730 kg
FOB: 9888 kg	FOB: 8430 kg
Block fuel: 8362 kg	Block fuel: 7183 kg
Mission time: 3 hrs 23 min	Mission time: 3 hrs 22 min

Mission fuel burn reduction – 14.1%

*Based on an A320-100 aircraft with two CFM56 powerplants
Based on an A320 NEO aircraft with two LEAP -1A powerplants

Trajectory alteration - Case Study

Simulated SMR aircraft



Trajectory alteration - Case Study

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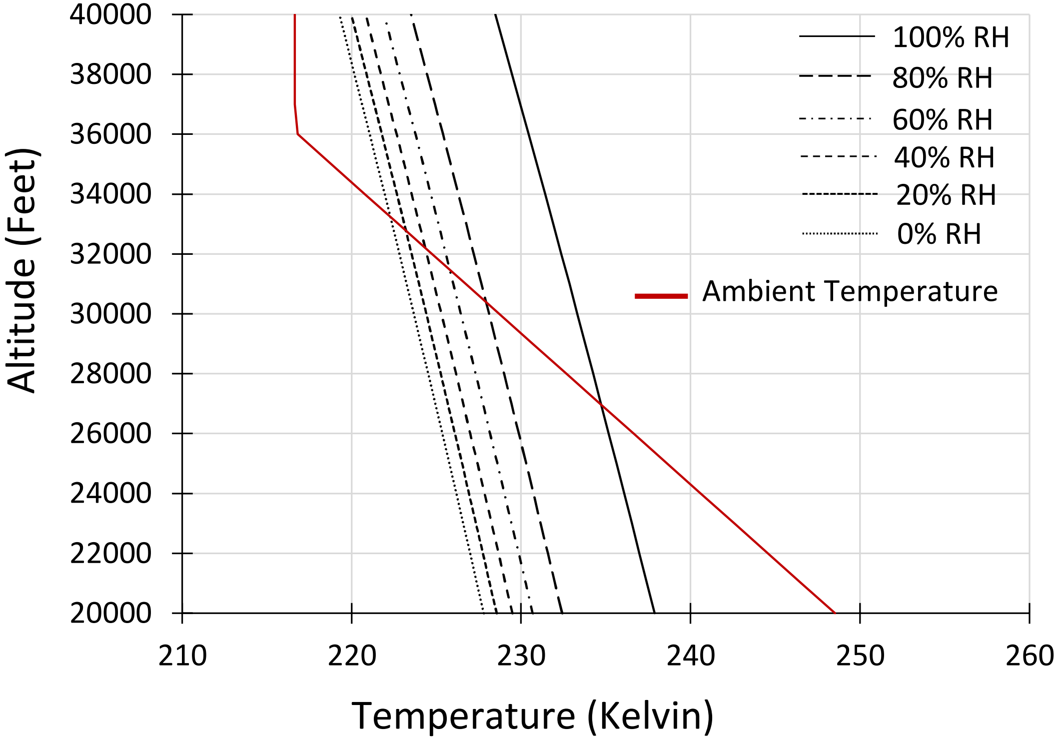

Trajectory alteration - Case Study

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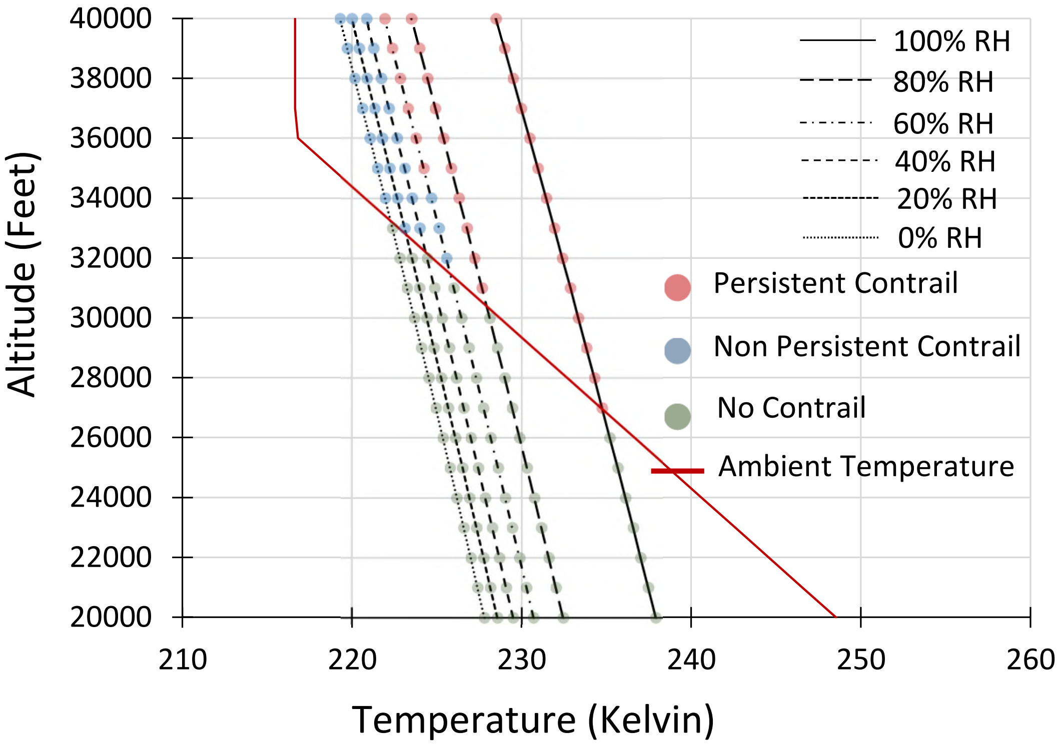

Trajectory alteration - Case Study

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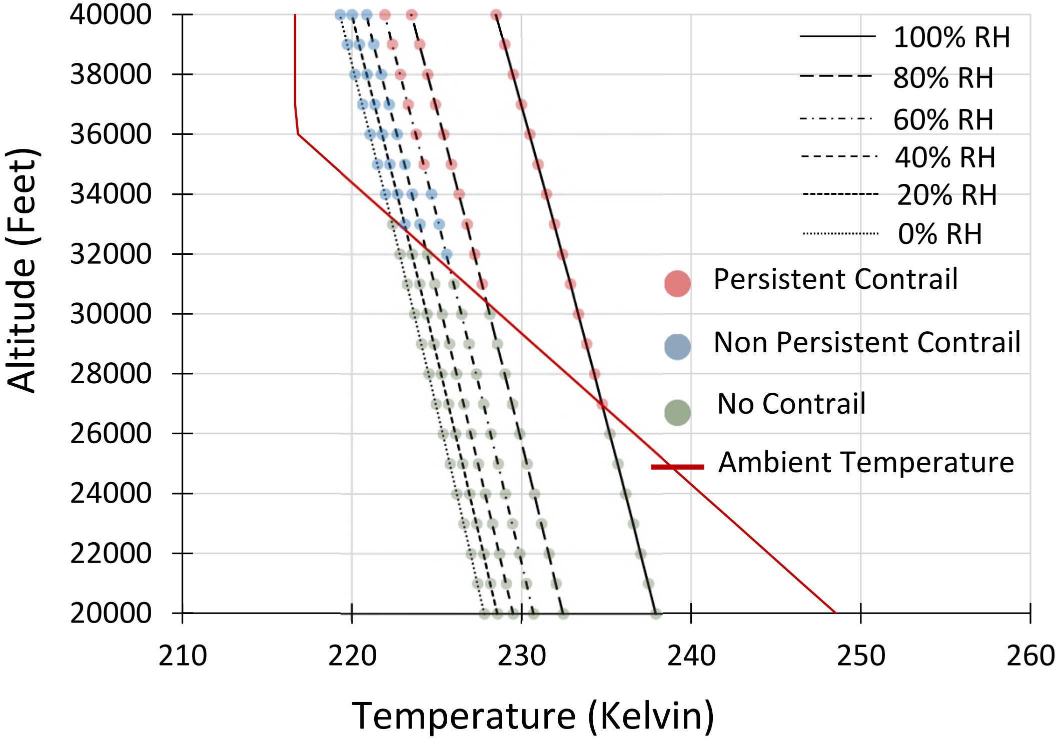

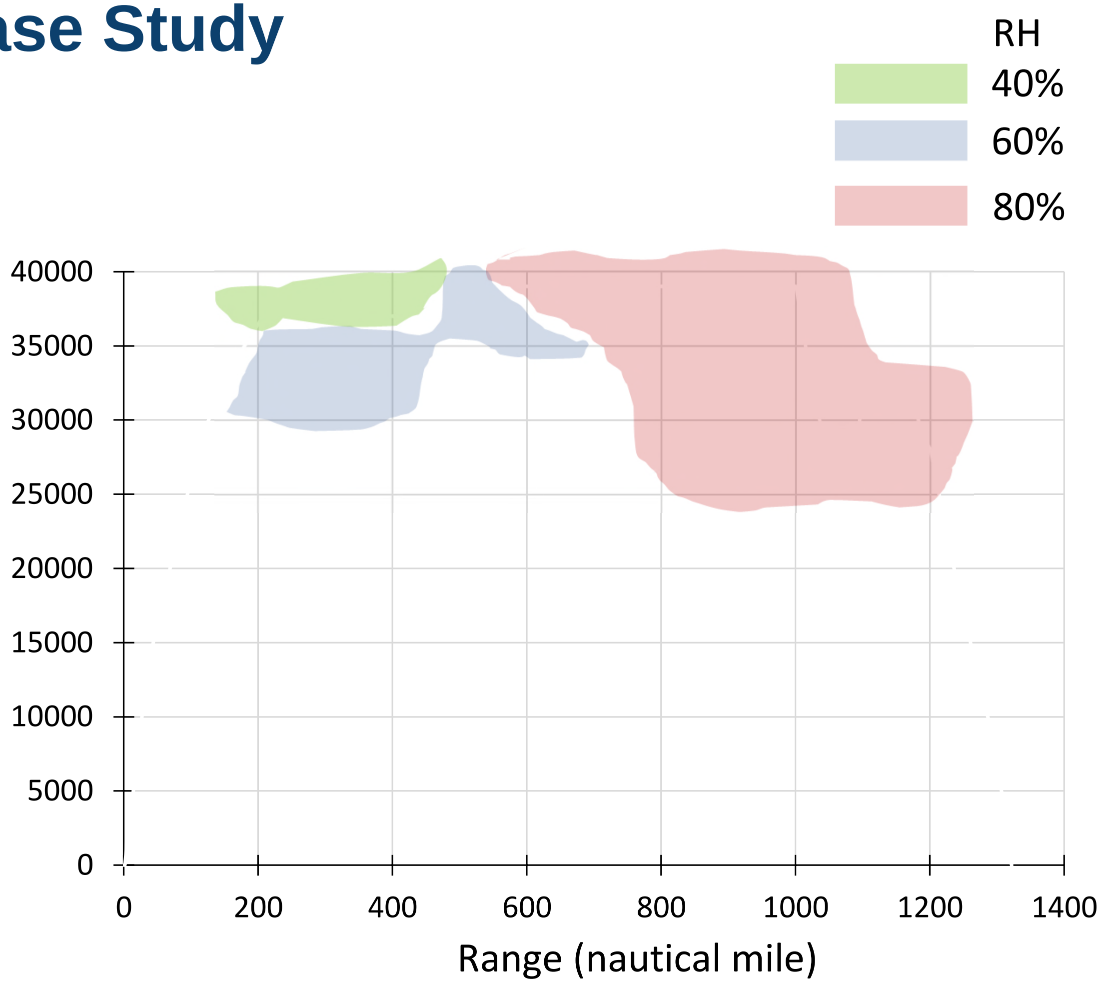

Trajectory alteration - Case Study

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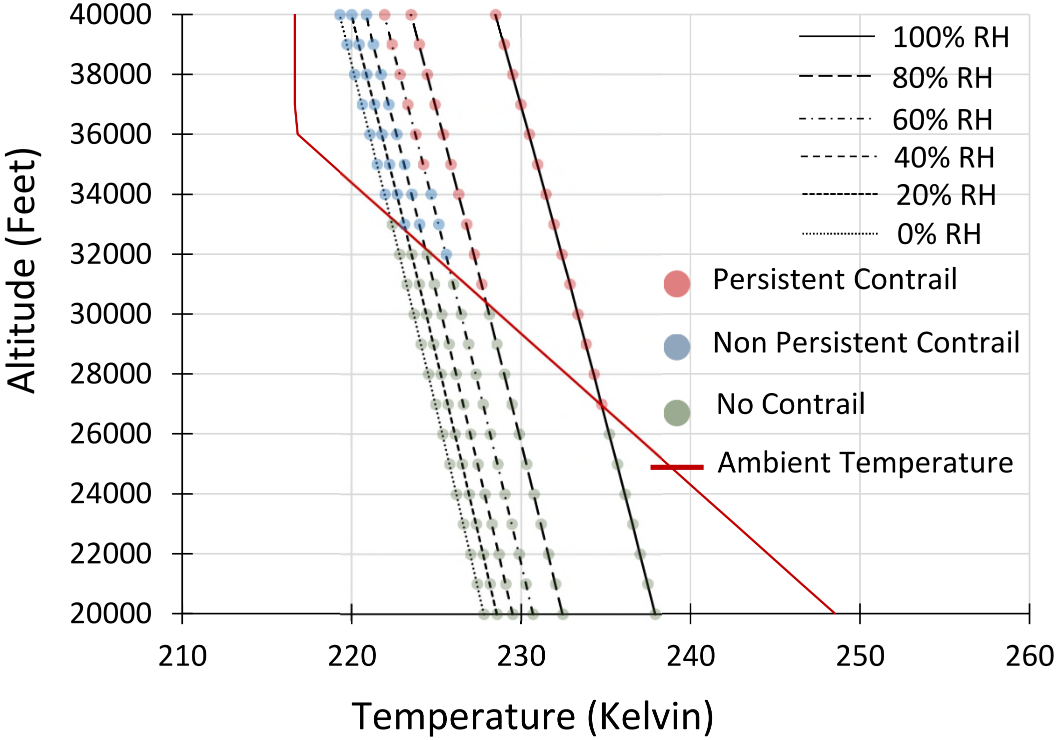

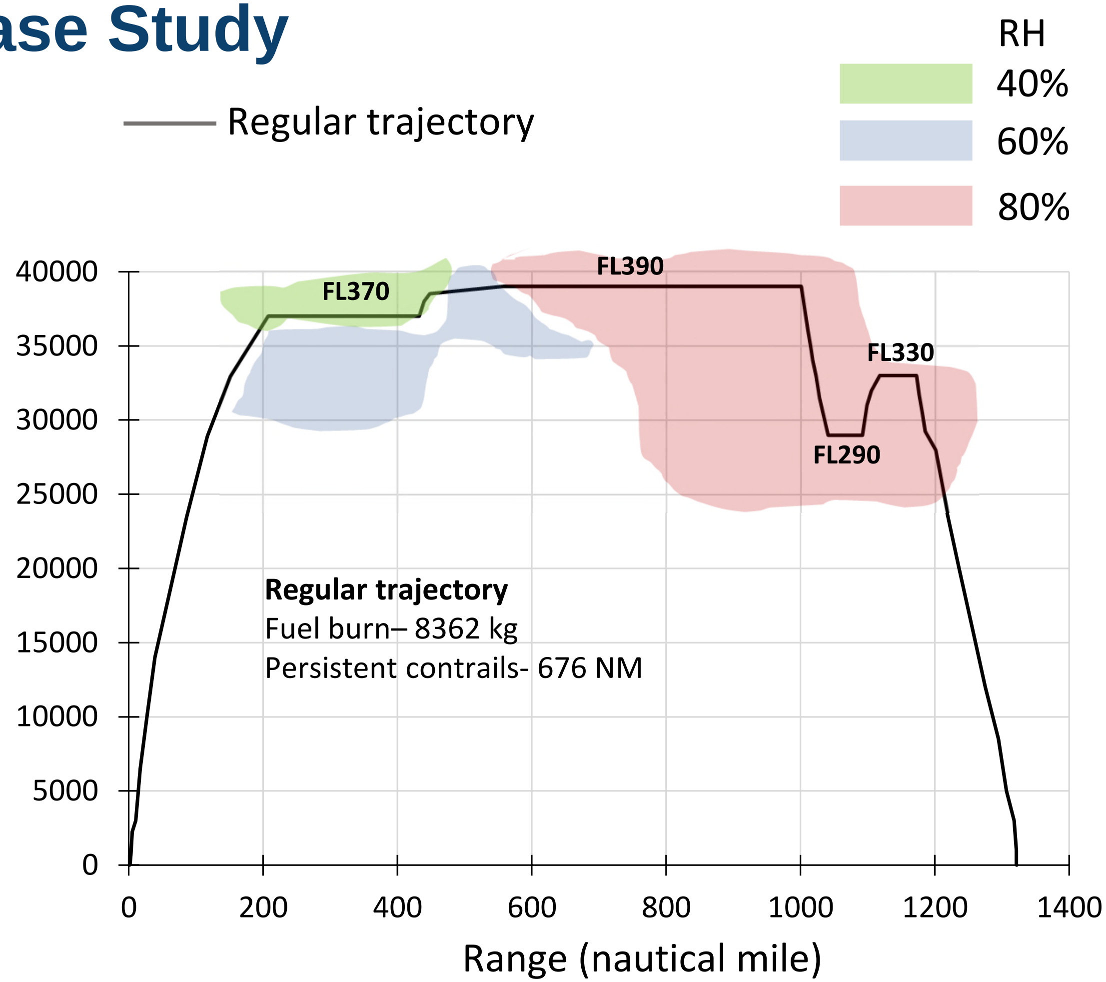

Trajectory alteration - Case Study

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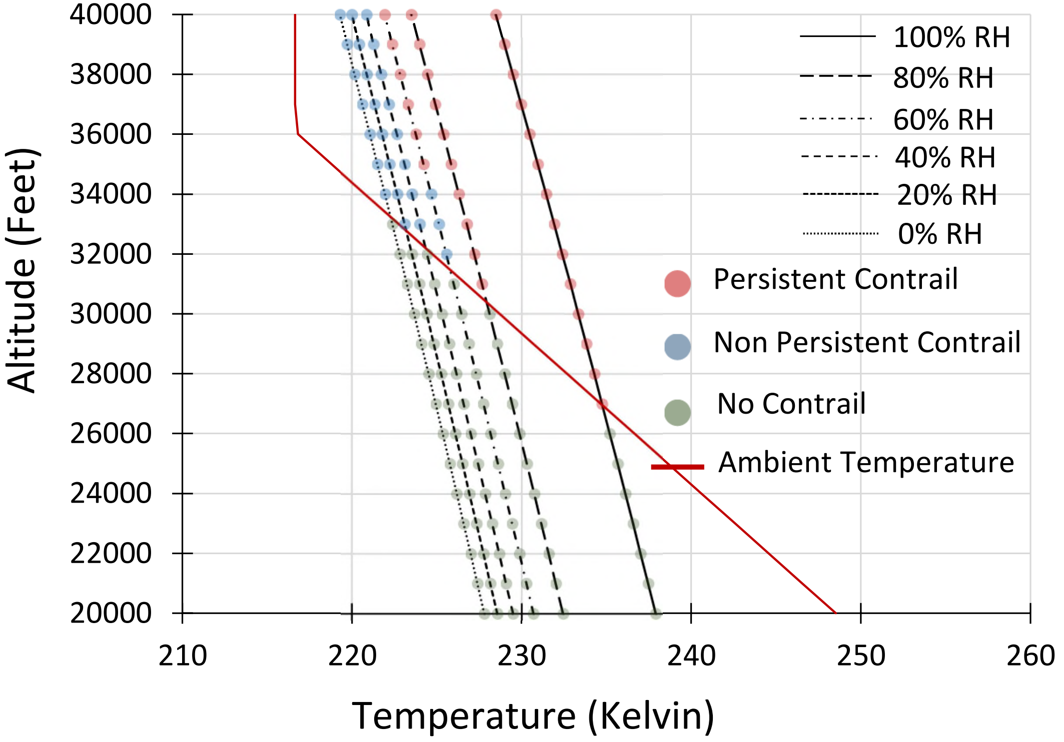
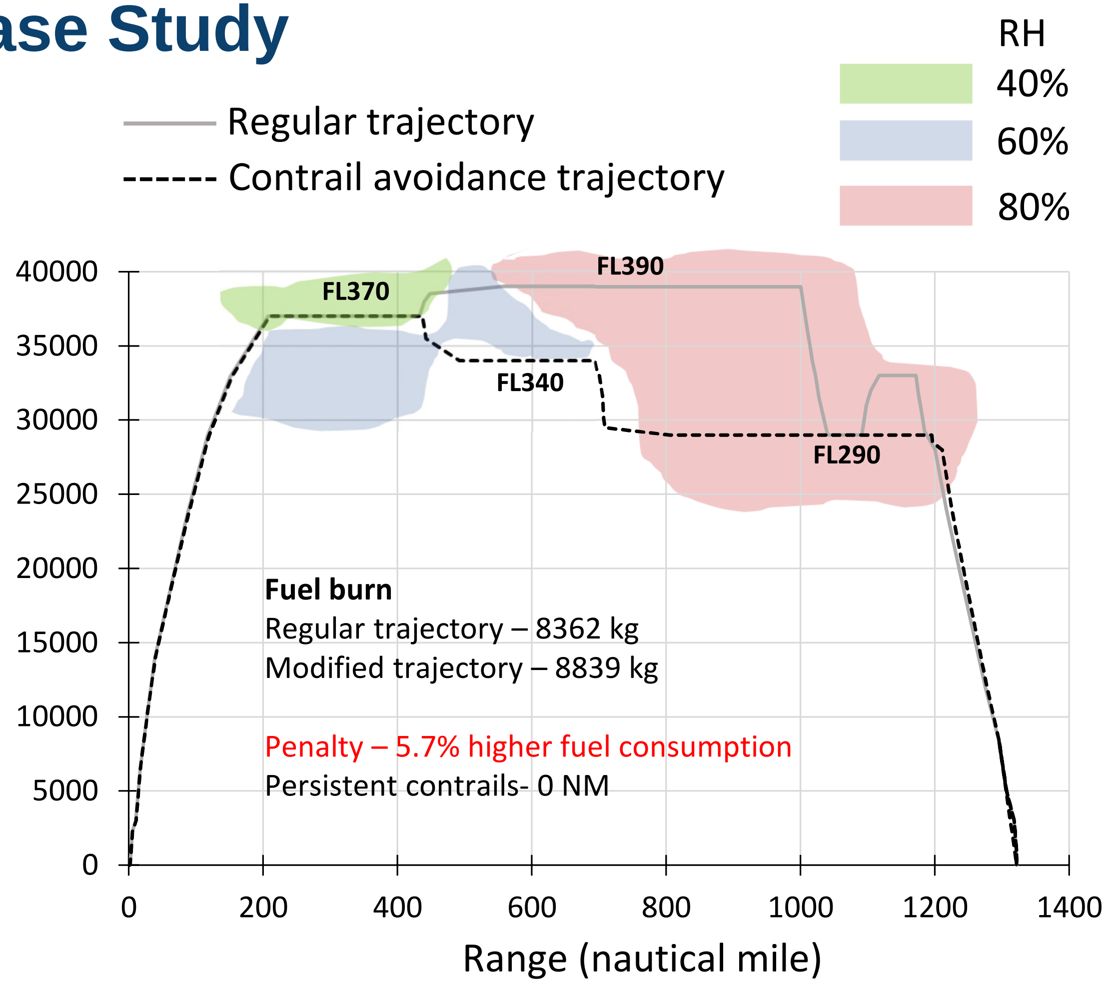




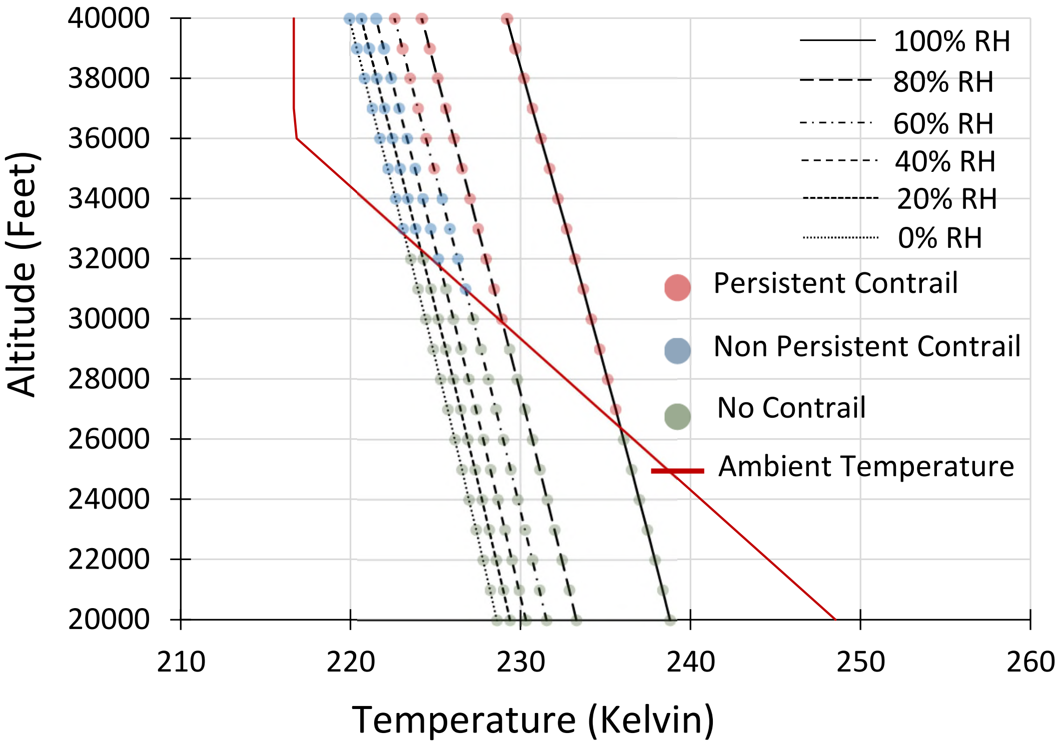
Fuel burn
Regular trajectory – 8362 kg
Modified trajectory – 8839 kg

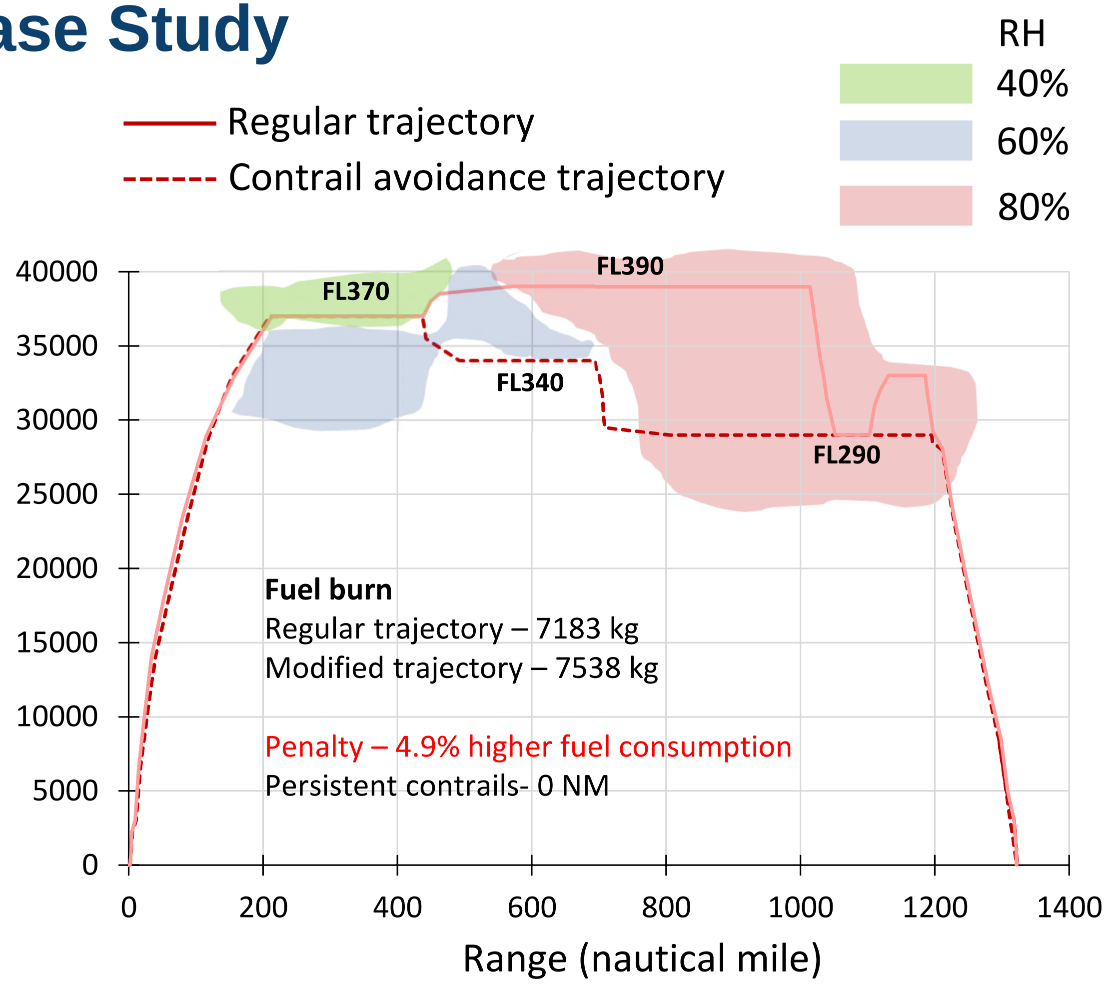
Penalty – 5.7% higher fuel consumption
Persistent contrails- 0 NM

*Based on an A320-100 aircraft with two CFM56 powerplants

Trajectory alteration - Case Study

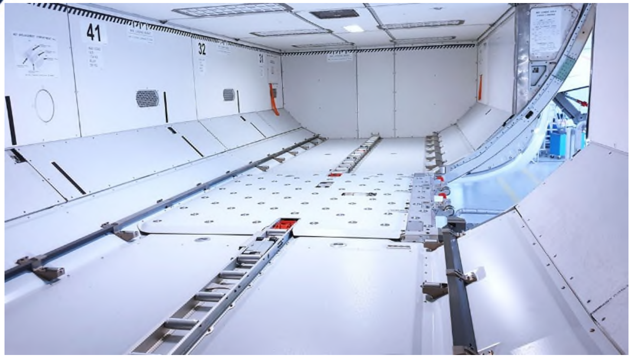
Improved SMR aircraft



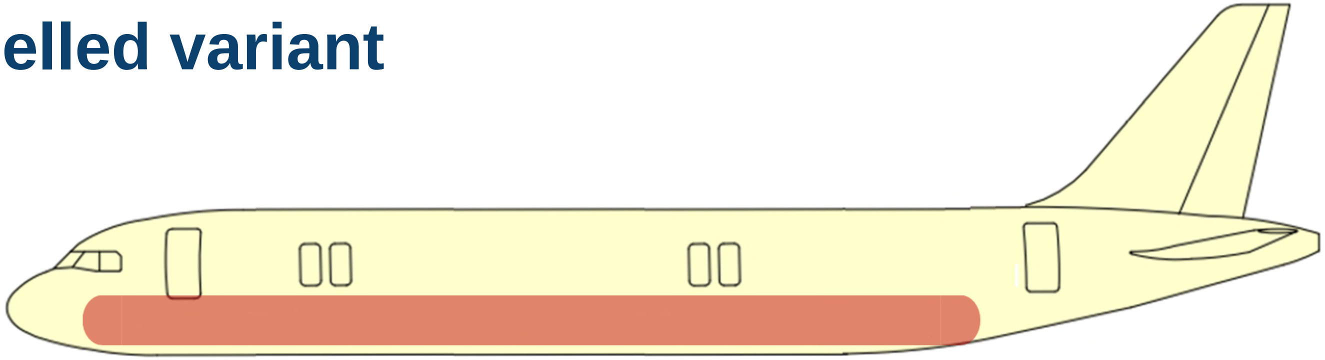


Based on an A320 NEO aircraft with two LEAP-1A powerplants

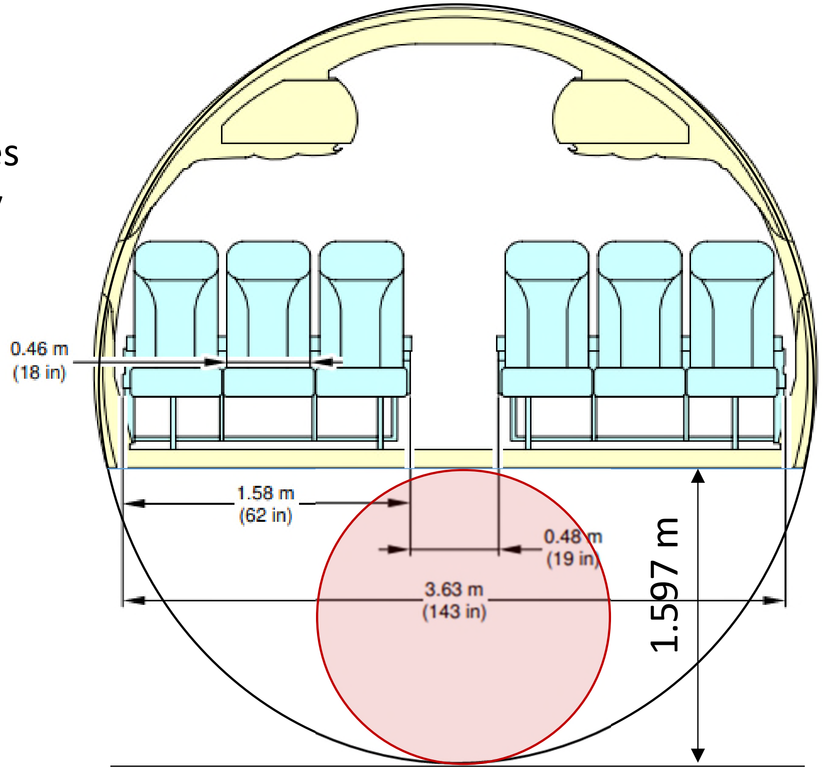
SMR aircraft - H_2 fuelled variant

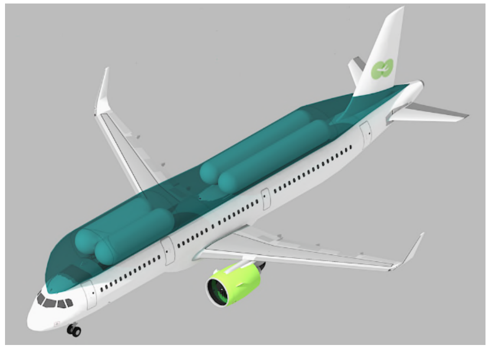


Img1: https://telair.com/a320_lower_deck_air_cargo_modcar/



- Based on and A320 Neo with LEAP 1-A engines
- Single tank (foam insulated) assumed to carry cryogenic fuel
  - Maximum Take off Weight= 79000 kg
  - Mass of fuel= 3300 kg
  - Maximum diameter of tank = 1.6 m
  - Length of tank= 25.9 m
  - Mass of tank= 1259.4 kg



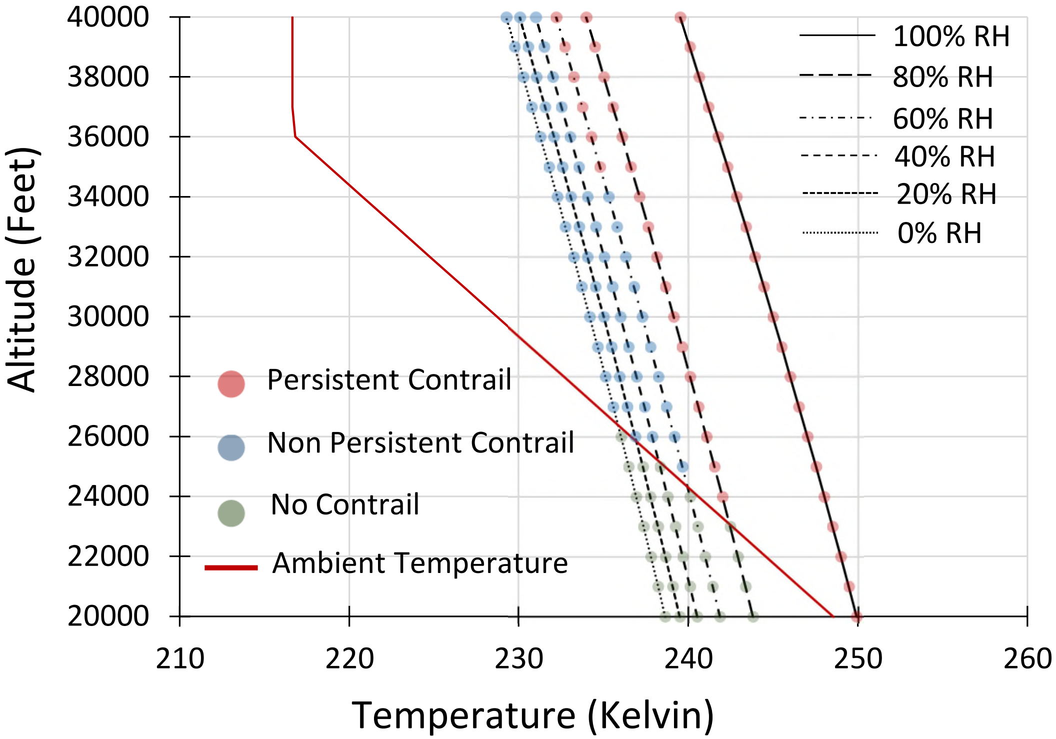


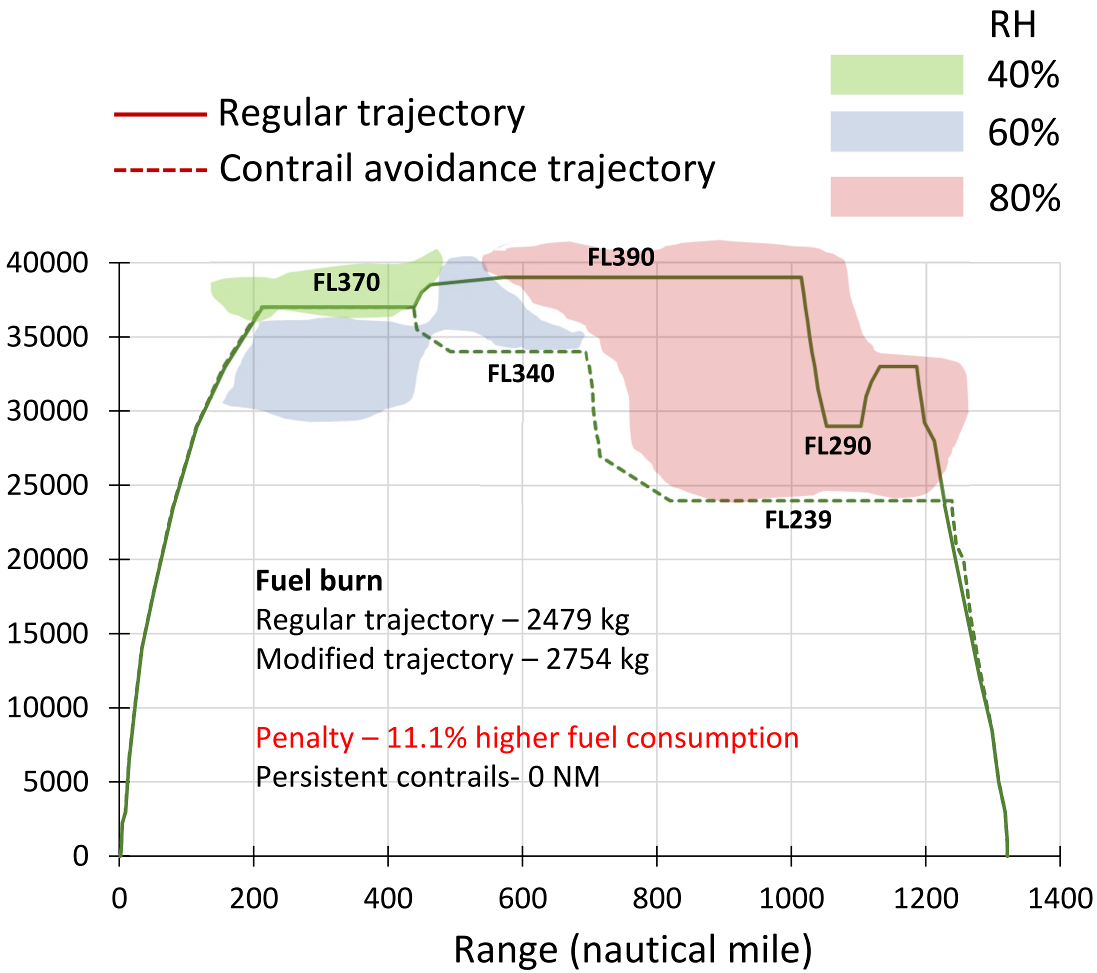
https://www.enableh2.eu/

Case Study

Hydrogen fuelled aircraft

Improved SMR aircraft – H_2 fuelled





[#] Based on an A320 NEO aircraft with two LEAP-1A powerplants

Case Study

Hydrogen fuelled aircraft

– The aircraft performance simulation indicated the aircraft would produce over 675 NM of persistent contrails which would be 51% of the range flown

Contrail avoidance

– On a regular trajectory – **Hydrogen variant 4.4% more energy efficient**

– On a contrail avoidance trajectory -**Hydrogen variant consumes 1.25% higher energy**

–Most importantly no mission-level CO_2!!

Contrail mitigation strategy- what's the best way then?

- Navigational avoidance- effectiveness and extent?

- Water extraction devices

- Technology adoption-
  - Lean combustion and DACs
  - Pure synthetic and biofuels- next to no sulphur and aromatics
  - Kerosene- biofuel blends- reduce soot particles moderately
- Change of fuel

Transition to alternative fuels

Voight C et.al (2021) Cleaner burning aviation fuels can reduce contrail cloudiness
Nature Communications Earth and Environment

Recent work by DLR

- five different fuels
- including two traditional, petroleum-based Jet A-1 fuels
- Three blends of Jet A-1 with synthetic jet fuel or bio-based alternative jet fuel.

– The contrail ice size distribution -40% larger

– Effect of Hydrogen content of the semisynthetic fuel blend on the ice crystal size

– The increase in crystal size - larger ice crystals sediment and sublimate faster

– *Contrail ice water content-*

– Initial ice number concentrations - optical thickness: 1 min-old SSF1 contrail is ~30% reduced with respect to the Jet A-1 contrail

– 50–90% reduced ice number concentrations -reduction in the radiative forcing from contrail cirrus by 20–70%

Contrails from Hydrogen fuelled engines

- Significant quantities water vapour in the exhaust - contrails can be expected to form at typically 10 K higher temperatures
- Could spread to larger areas before evaporating
- Burning of liquid hydrogen -of soot and sulphur emissions- Aerosols in the atmosphere still present
- Smaller number of particles lead to larger droplets and ice particles - expected to exhibit a smaller optical thickness in spite of larger water content
- Given larger size of ice particles would sediment earlier
- This suggests that aircraft burning liquid hydrogen may cause more persistent contrails, but with much shorter life spans and possibly lesser climate impact than kerosene
- Water extraction- a remote possibility

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Conclusions

- Climate impact of contrails
- Necessary conditions to produce of contrails
- Prediction models to predict contrail formation
- Mitigation strategies

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Some of the information included in this presentation has been adapted from research undertaken within project ENABLEH2.
This project has received funding from the EU Horizon 2020 research and innovation programme under GA no. 769241

ENABLE·H2