Contrails: An introduction

Gas Turbine Combustors Short Course (21-24 Sep 2022)

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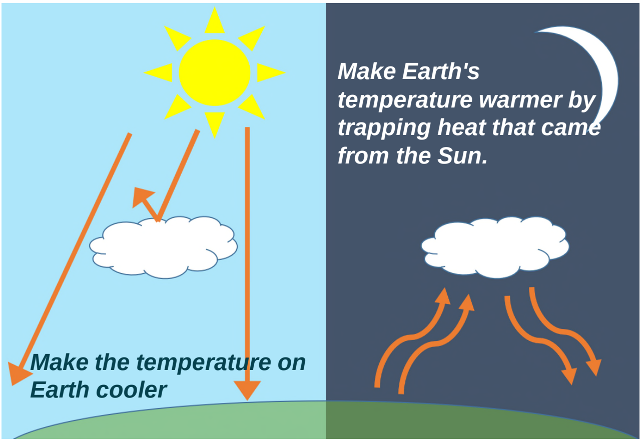
Propulsion and Thermal Power Engineering Centre

Intended learning outcomes

- Understand the climate impact of contrails
- Identify the necessary conditions to produce of contrails
- Apply qualitative prediction models to predict contrail formation
- Analyse mitigation strategies through case studies

Clouds affect earth’s climate



- Characteristics- Optical Thickness (how much light the cloud can intercept) and height

- Radiative “blanket” by absorbing the thermal infrared radiation

- Complicated predictions – net effect

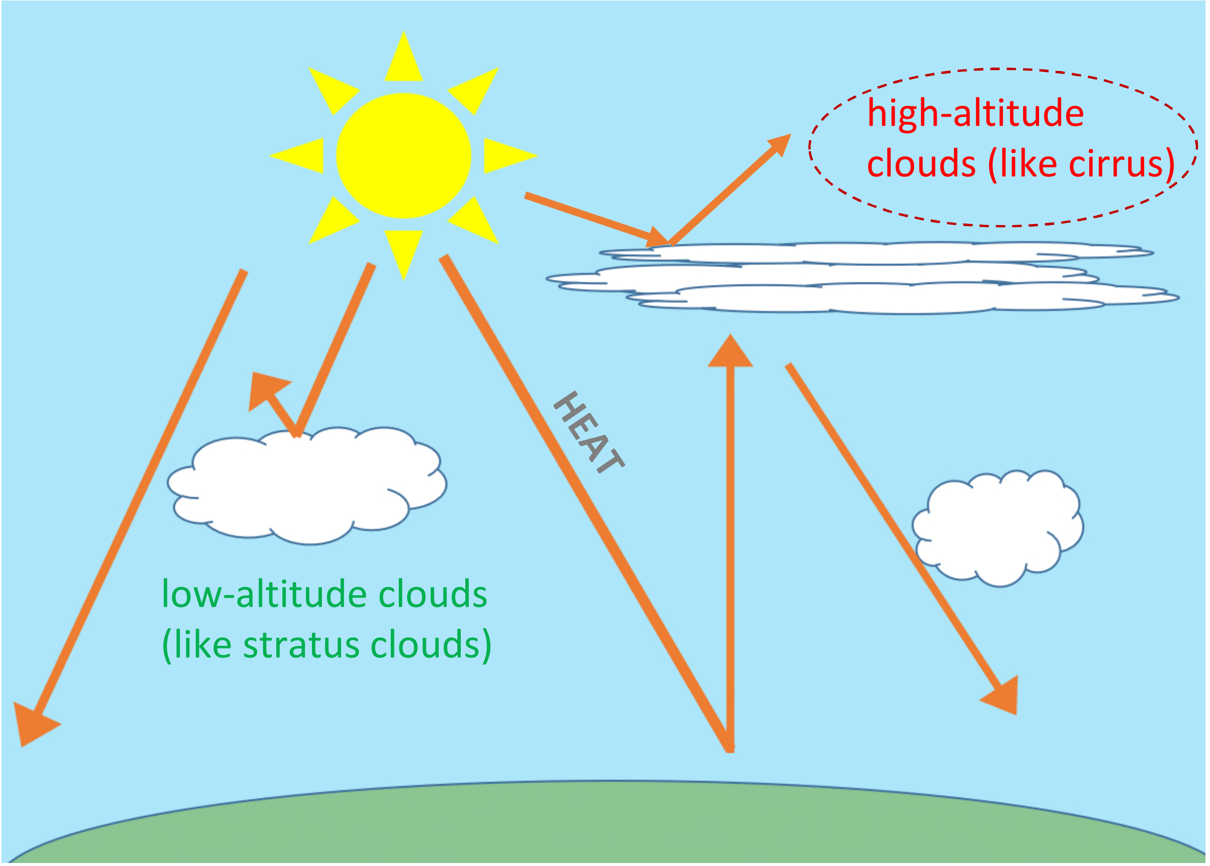
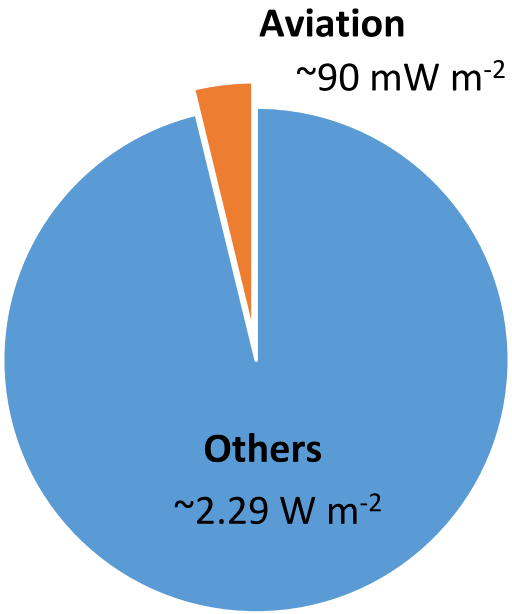


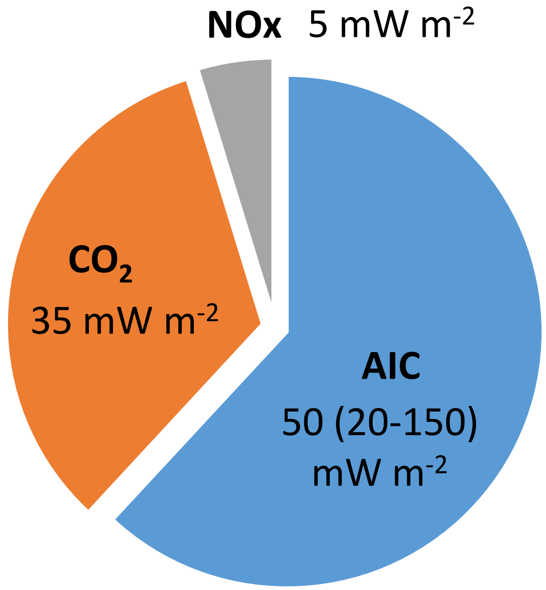
Image recreated from a NASA source

Climate effects

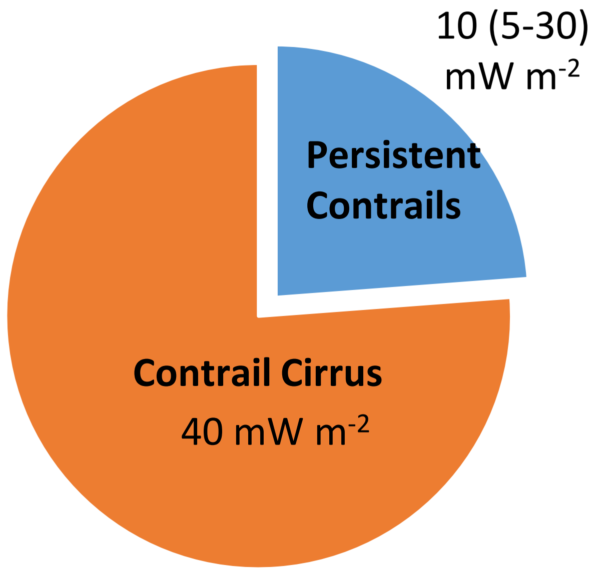
- 8-13km
- Line shaped ice clouds
- AIC
- Short/ Long lived



Anthropogenic RF



Aviation-derived RF

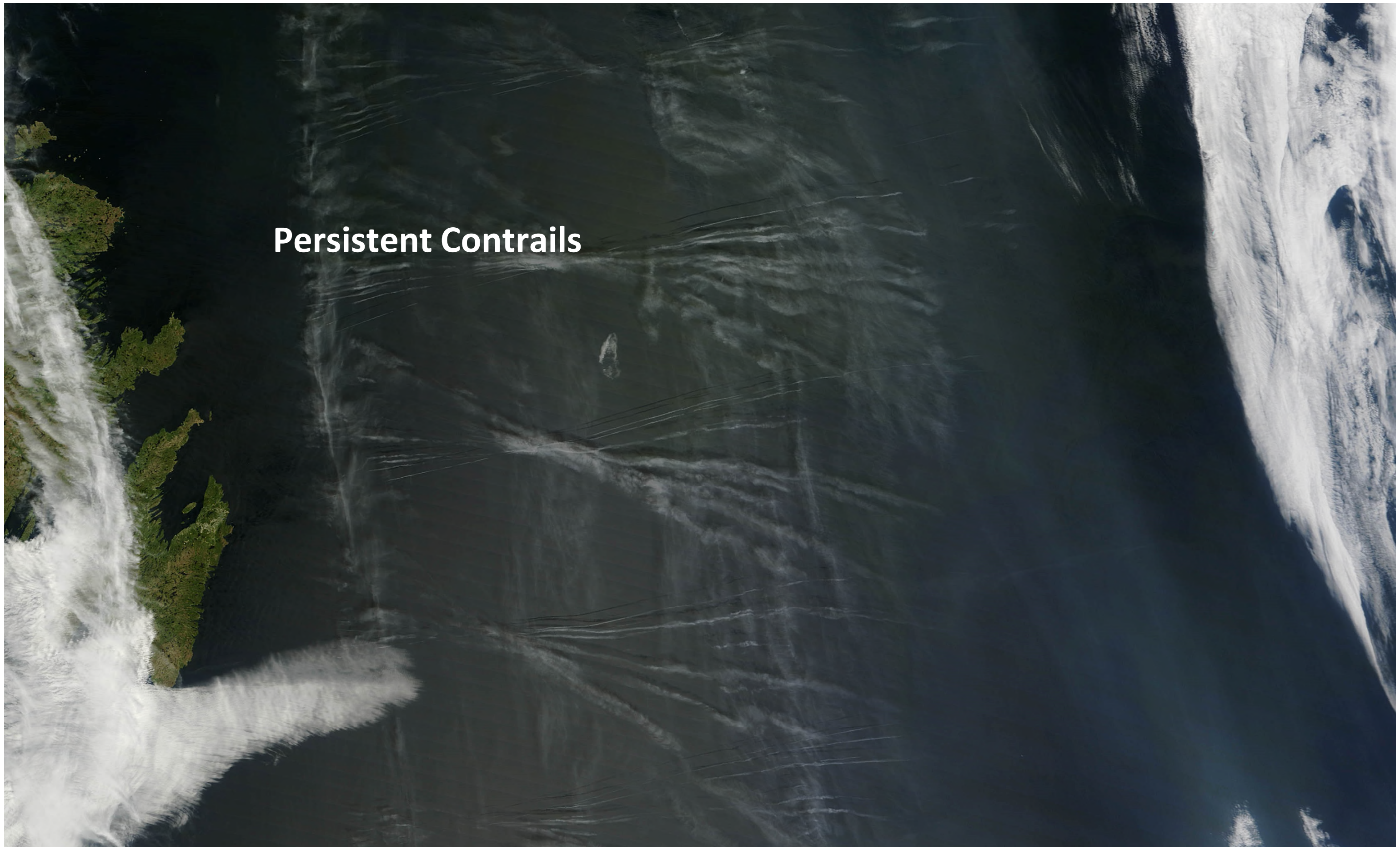


Aircraft-induced cloudiness RF

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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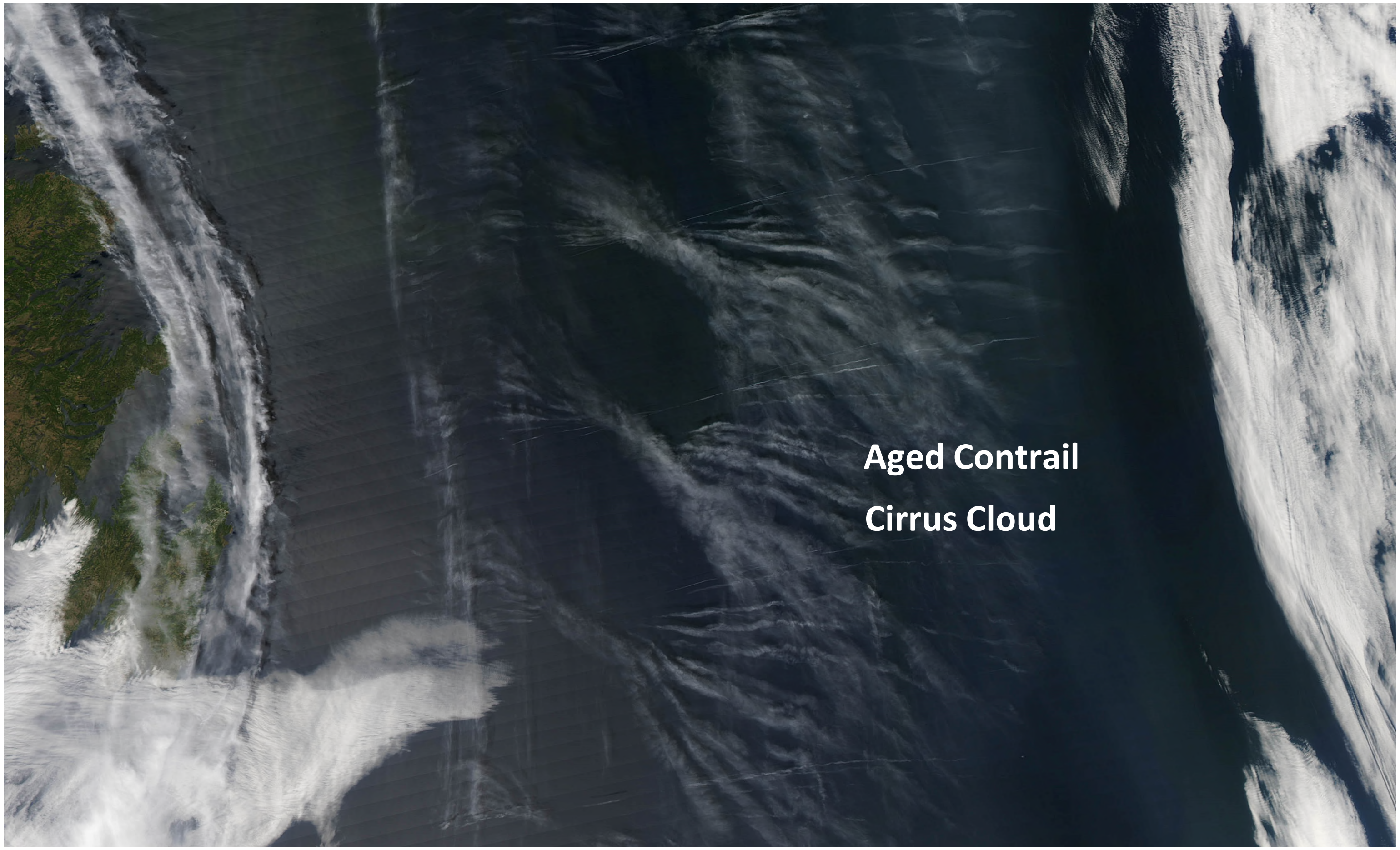

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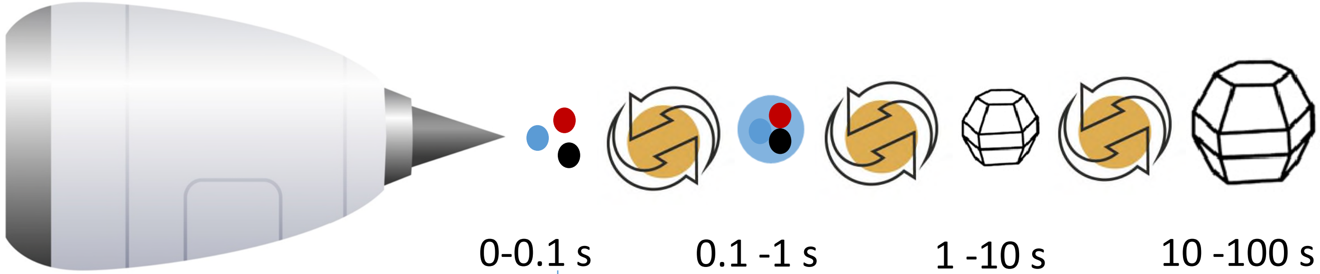
Processes influencing the contrail formation

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

Vortex regime (t = 10-100s)
Vortex descent; Crow instability

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

Diffusion regime (t = 1000s- few hours)



0-0.1 s
Aerosol /soot
10 nm

0.1 -1 s
Activation into water droplet
100 nm

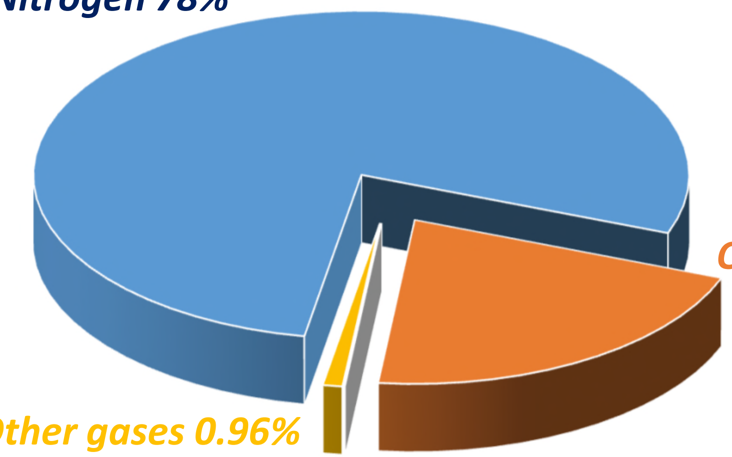
1 -10 s
Water droplets freeze and ice crystals grow
1000 nm

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

The basics- a short recap

“The total pressure of a gas is equal to the sum of the different gases’ partial pressures” ***Daltons Law***

Vapour pressure of water is the pressure exerted by molecules of water vapor in gaseous form



100 kPa = 78 kPa + 21 kPa + 0.5kPa + 0.5kPa

Air — Nitrogen — Oxygen — Water — Others

The water vapour concentration in the atmosphere varies from about 0.01% to 4.24% (lower troposphere, areas near the tropics)

The composition of dry air by mass it is roughly 75.46% N2, 23.20% O2, 1.28% Ar and 0.06% CO2.

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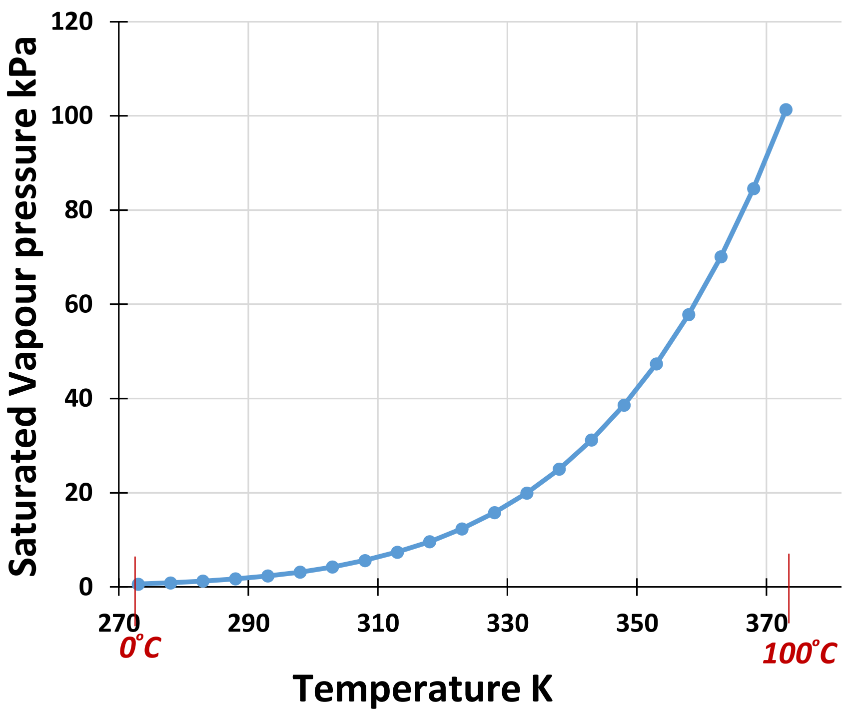

Saturation vapour pressure

- Pressure at which water vapour is in thermodynamic equilibrium with its condensed state.
- At pressures higher than vapour pressure, water would condense, whilst at lower pressures it would evaporate or sublimate.

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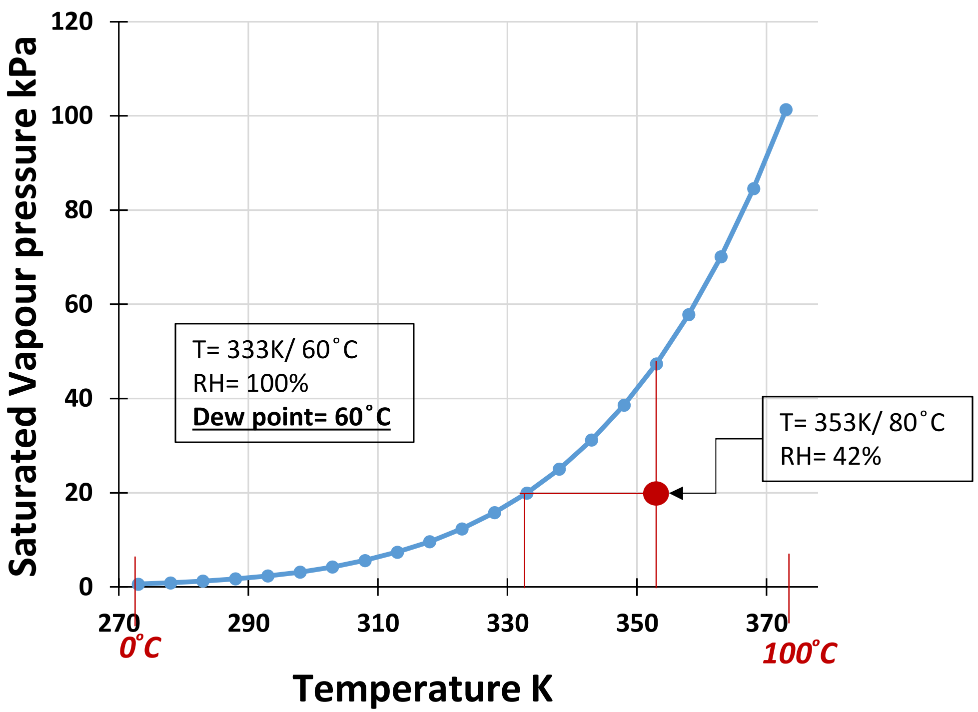

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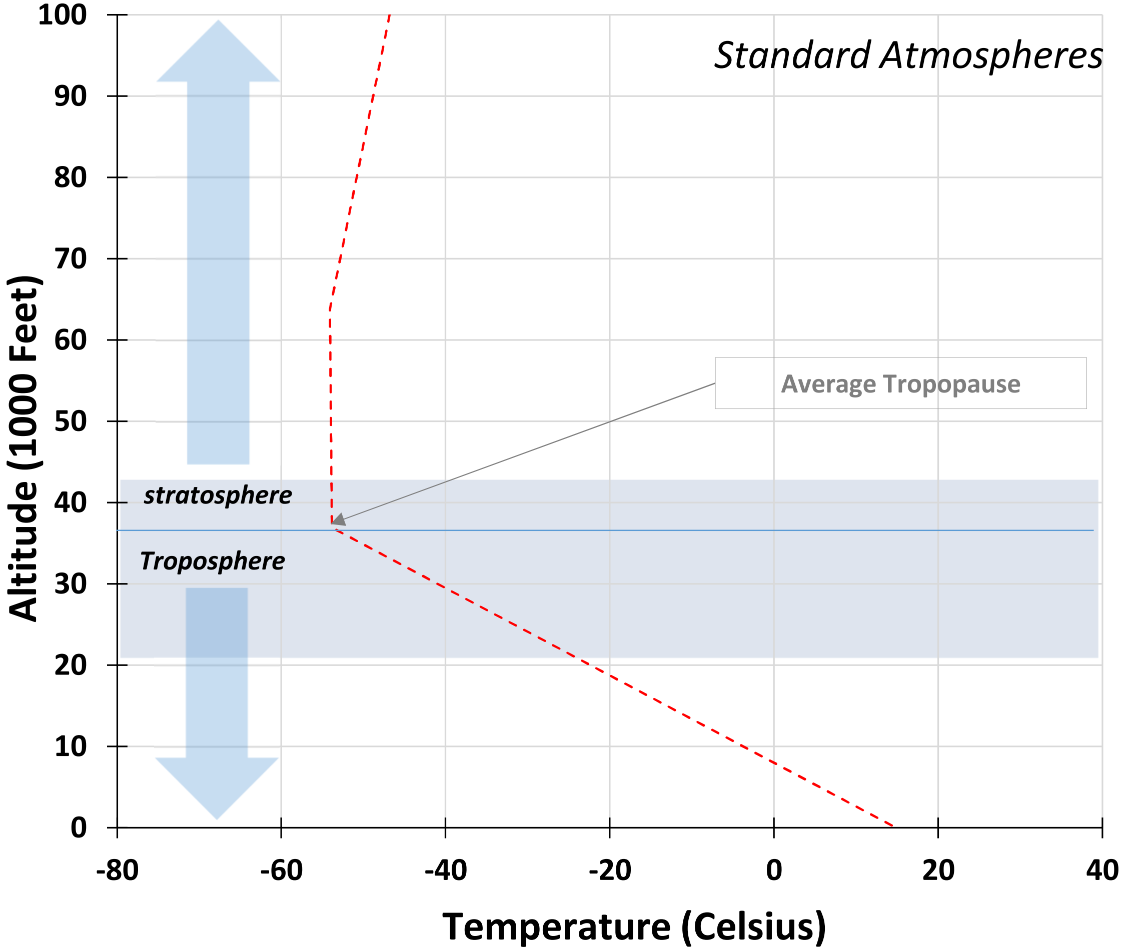
Relative humidity : Partial water vapor pressure in relation to the saturation pressure (expressed in per cent)

Dewpoint : Temperature at which condensation begins, or where the relative humidity would be 100% if the air was cooled.

Temperature variation with altitude



Weather for Aircrews, Air Force Handbook (AFH) 11-203, Volume 1, 1 March 1997, Department of the Air Force

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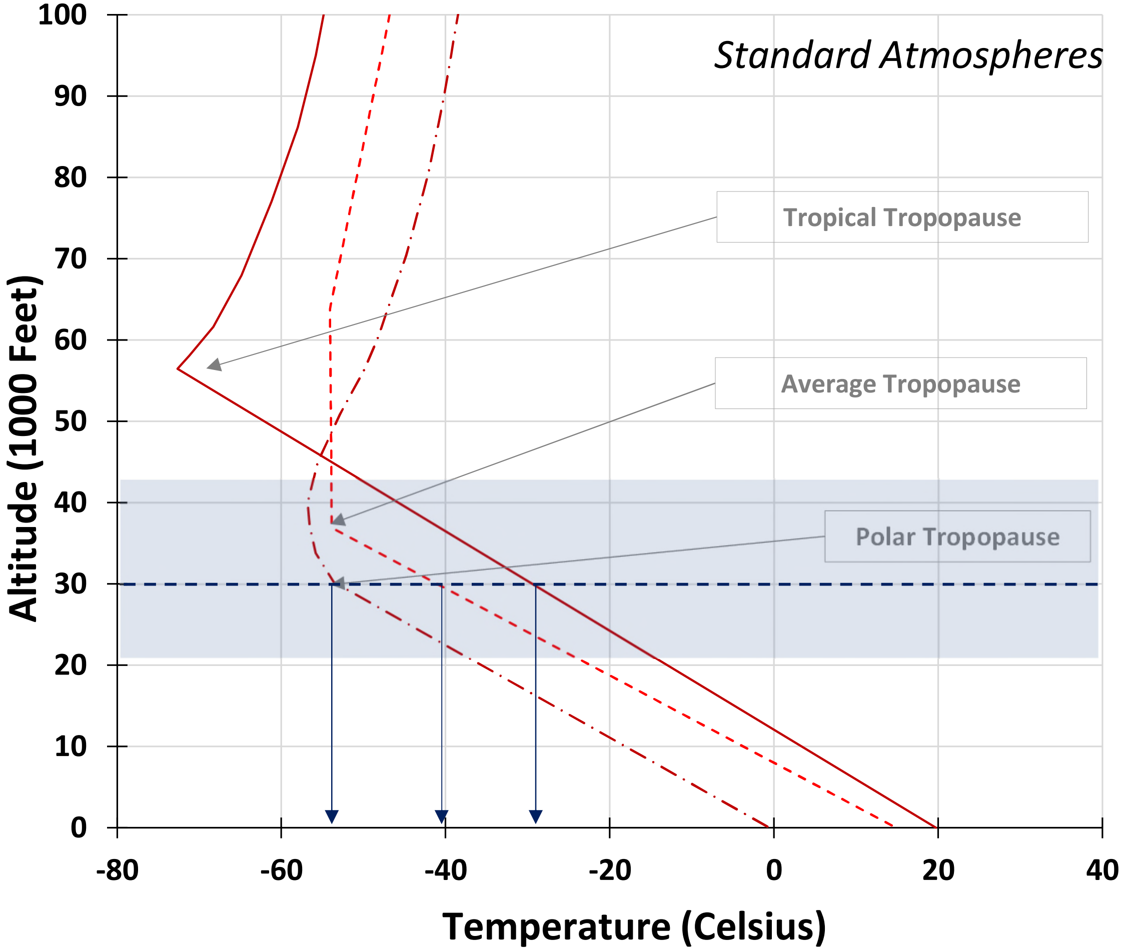

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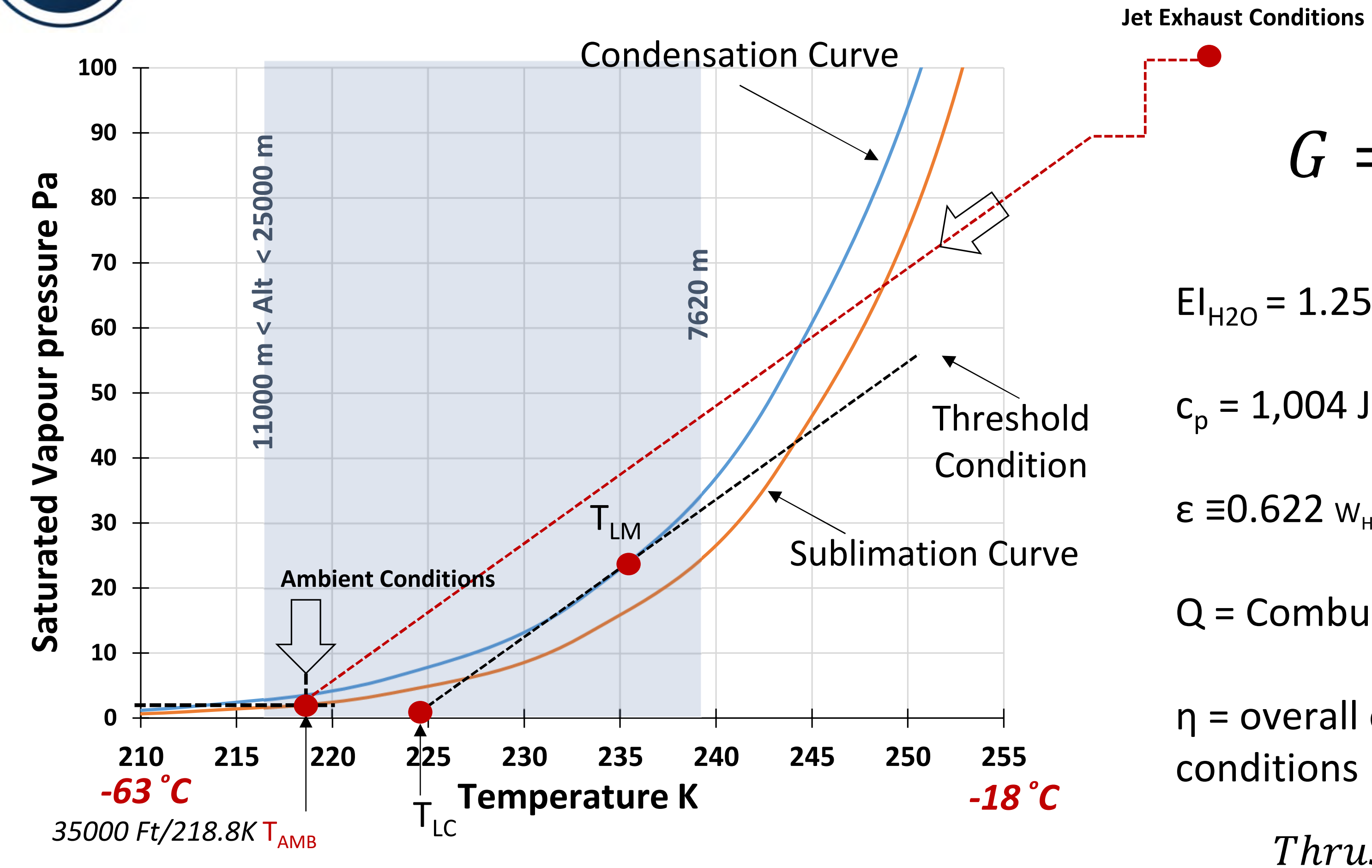
Contrail assessments



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

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)

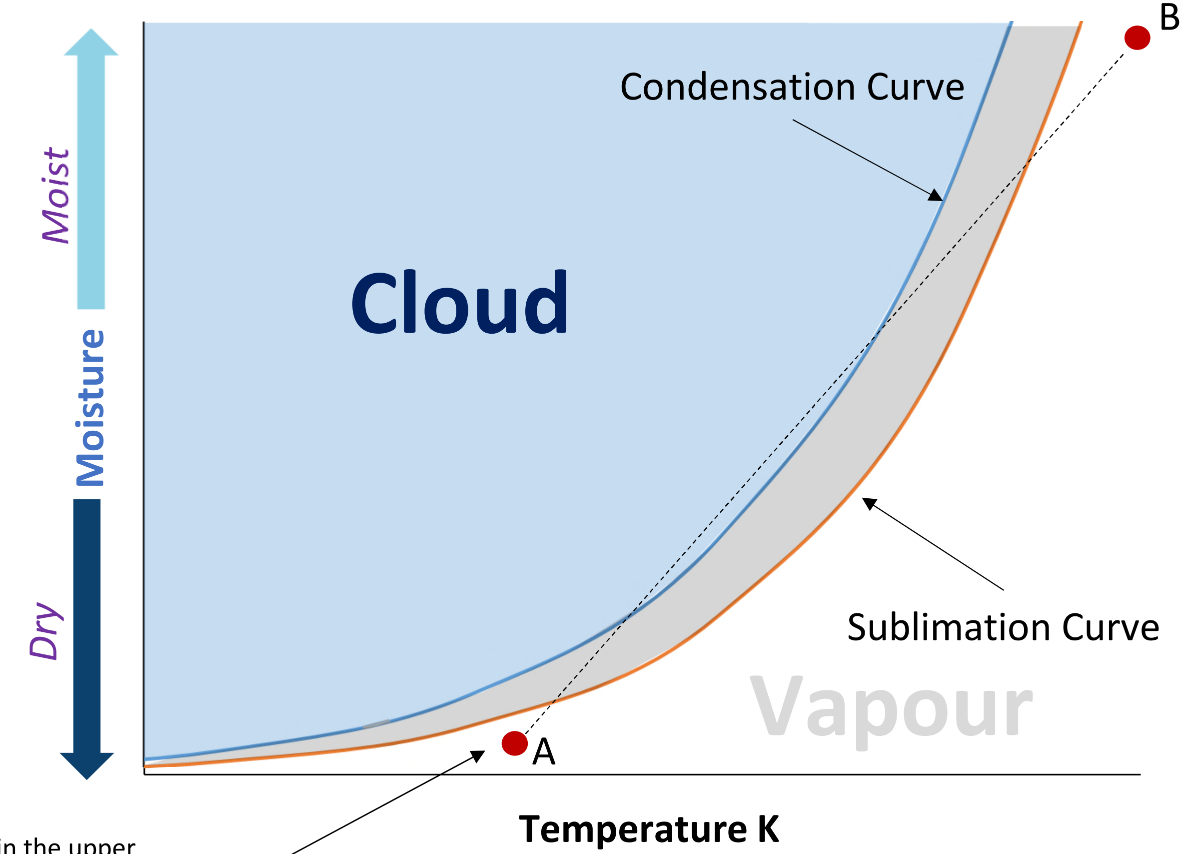
Q = Combustion heat per mass of fuel J/kg

η = overall engine efficiency in cruise conditions

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

Clausius-Clapeyron equilibrium equation for a perfect gas

Predicting contrails



Typical conditions in the upper troposphere - absence of clouds and relatively dry

Water vapour partial pressure (Pv or e) as a function of temperature T

Pv ≡ X H_2O*P (where X H_2O is the vapour mole fraction)

Saturation curves for liquid water and ice - $P_{liq\_vsat}(T)$ and $P_{ice\_vsat}(T)$,

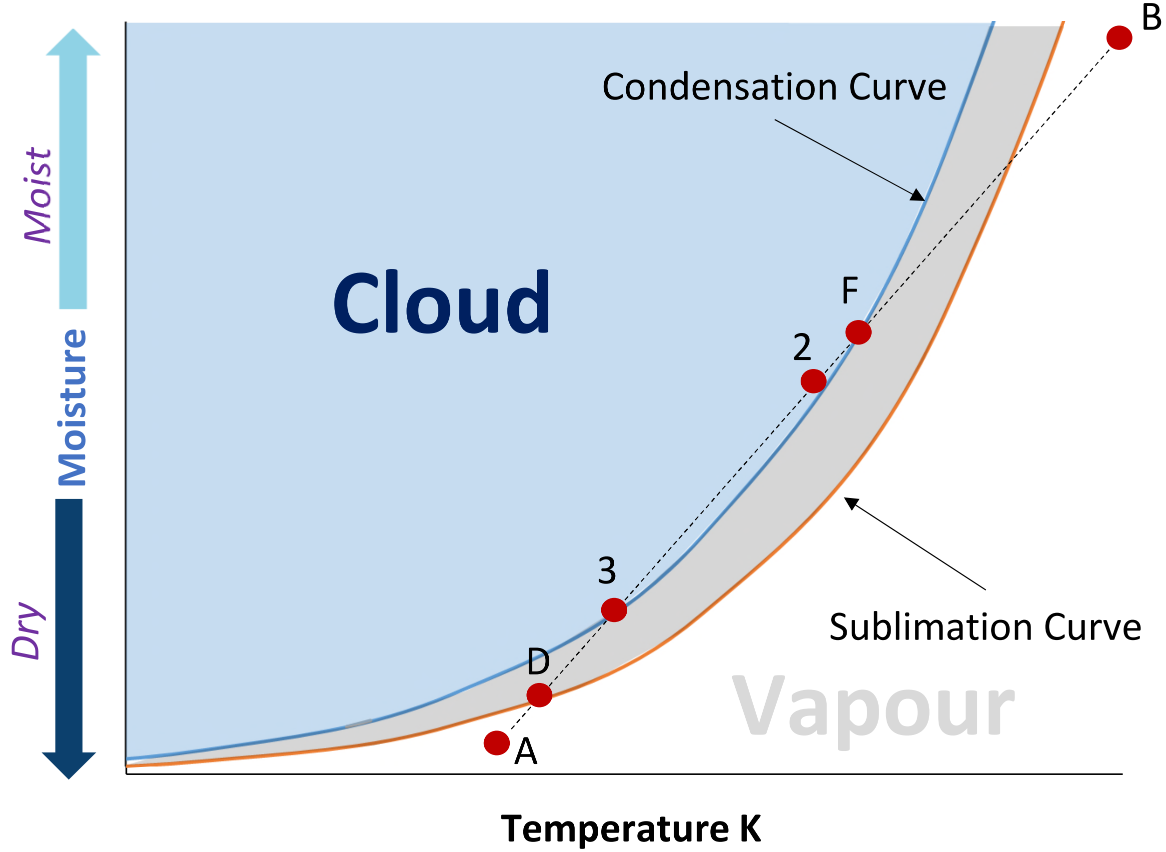
Derived from the ***Clausius-Clapeyron equilibrium equations*** for a perfect gas

$$\frac{d\ln P_{v_{sat}}^{liq}}{dT} = \frac{L_{liq}(T)}{RT^2} \quad \text{and} \quad \frac{d\ln P_{v_{sat}}^{ice}}{dT} = \frac{L_{ice}(T)}{RT^2}$$

$L_{liq}(T)$ =latent heat of evaporation
$L_{ice}(T)$ =latent heat of sublimation,
R = 8.31 J mol^{-1} K^{-1} molar gas constant

The Mixing Process

Predicting contrails



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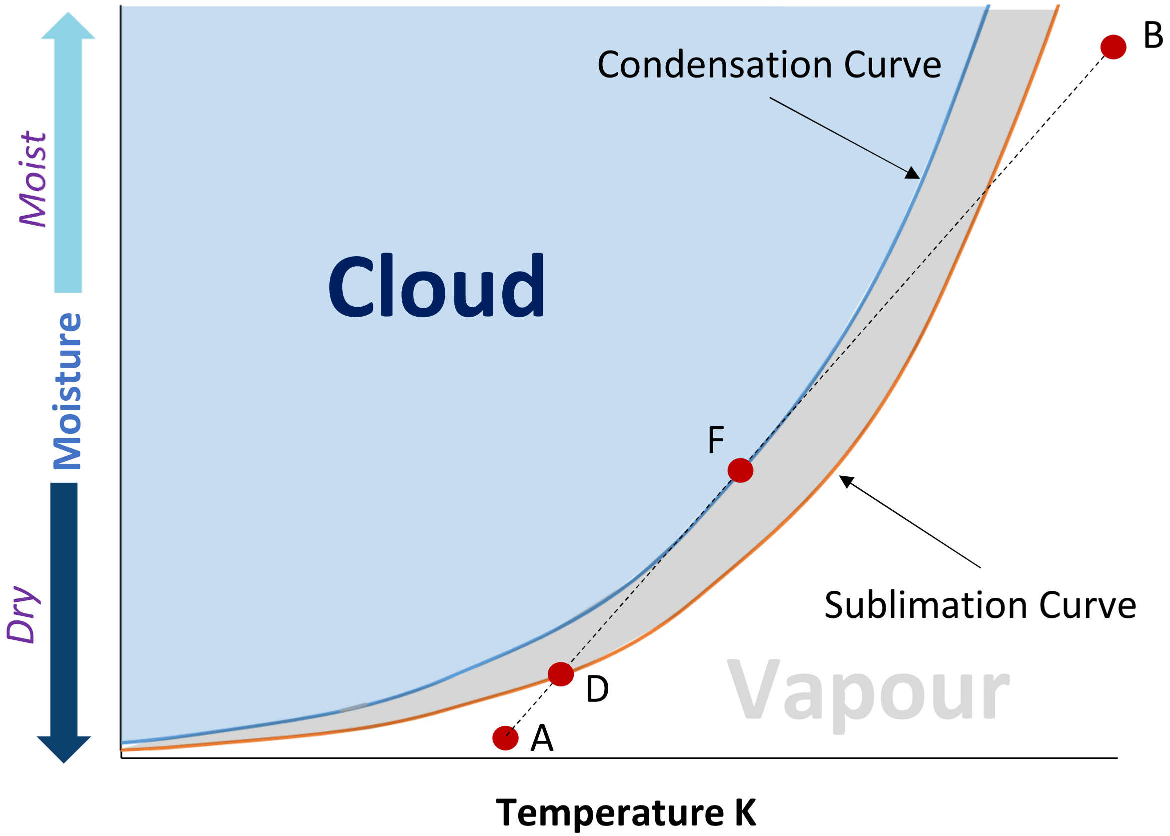
Predicting contrails

Types

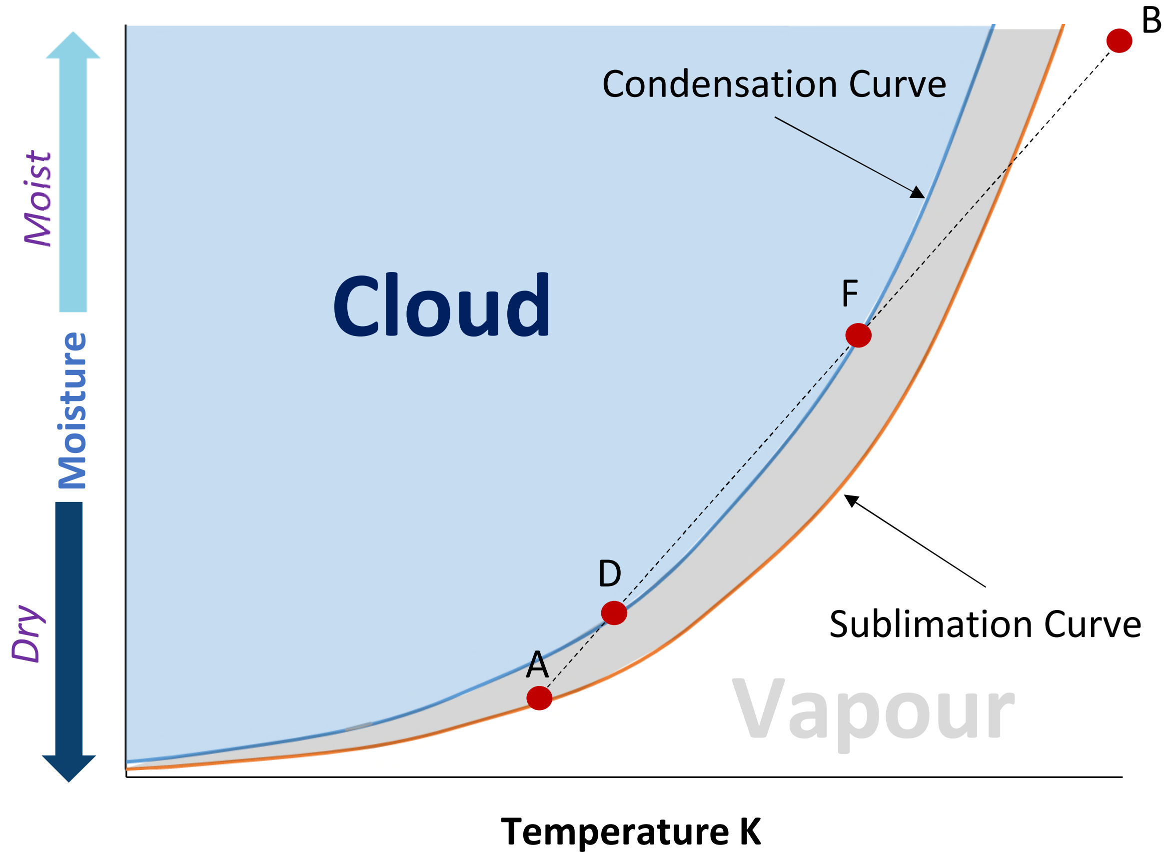


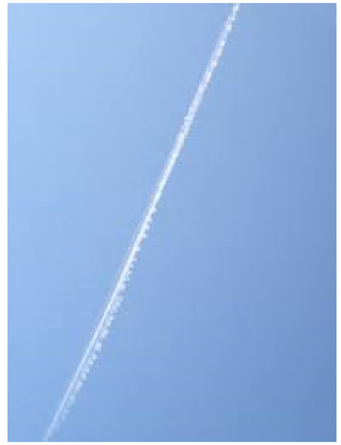
Short Lived Contrail (Dry upper atmosphere)

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

Predicting contrails

Types



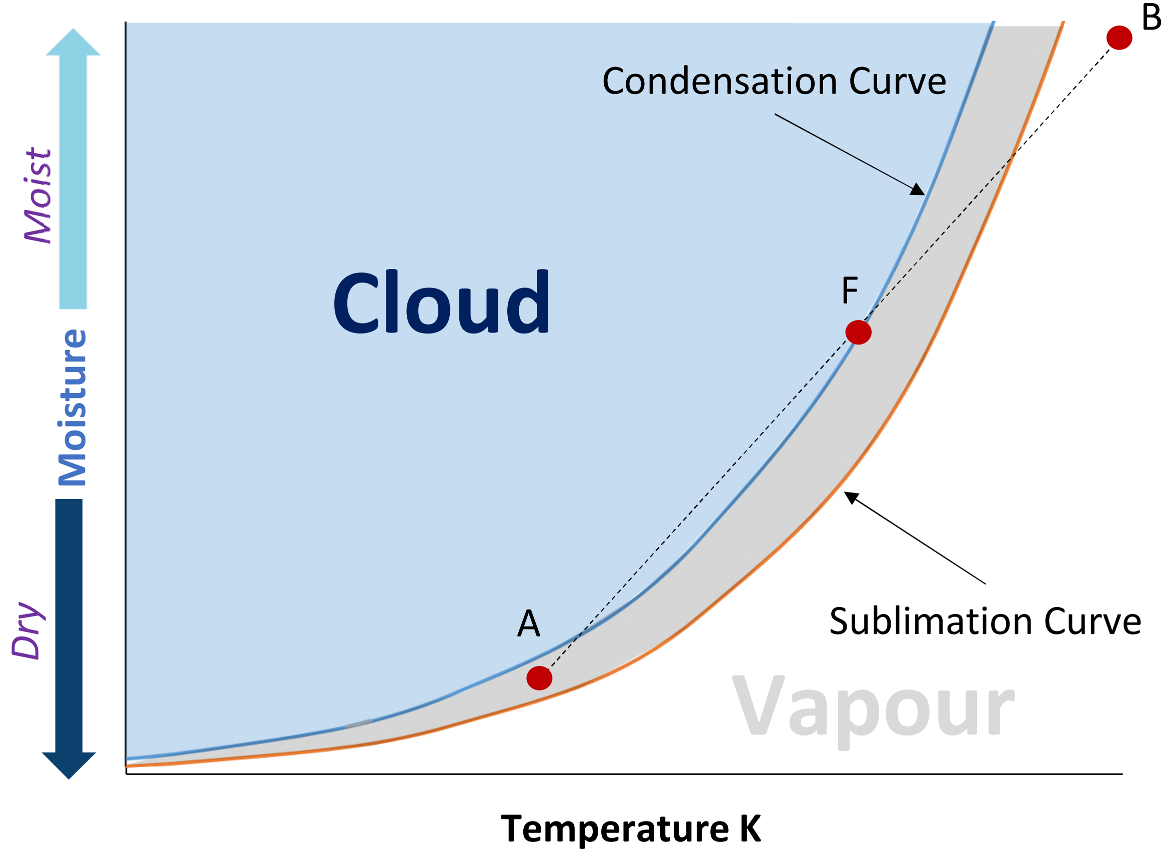


Persistent Contrail (Moister upper atmosphere)

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

Predicting contrails

Types



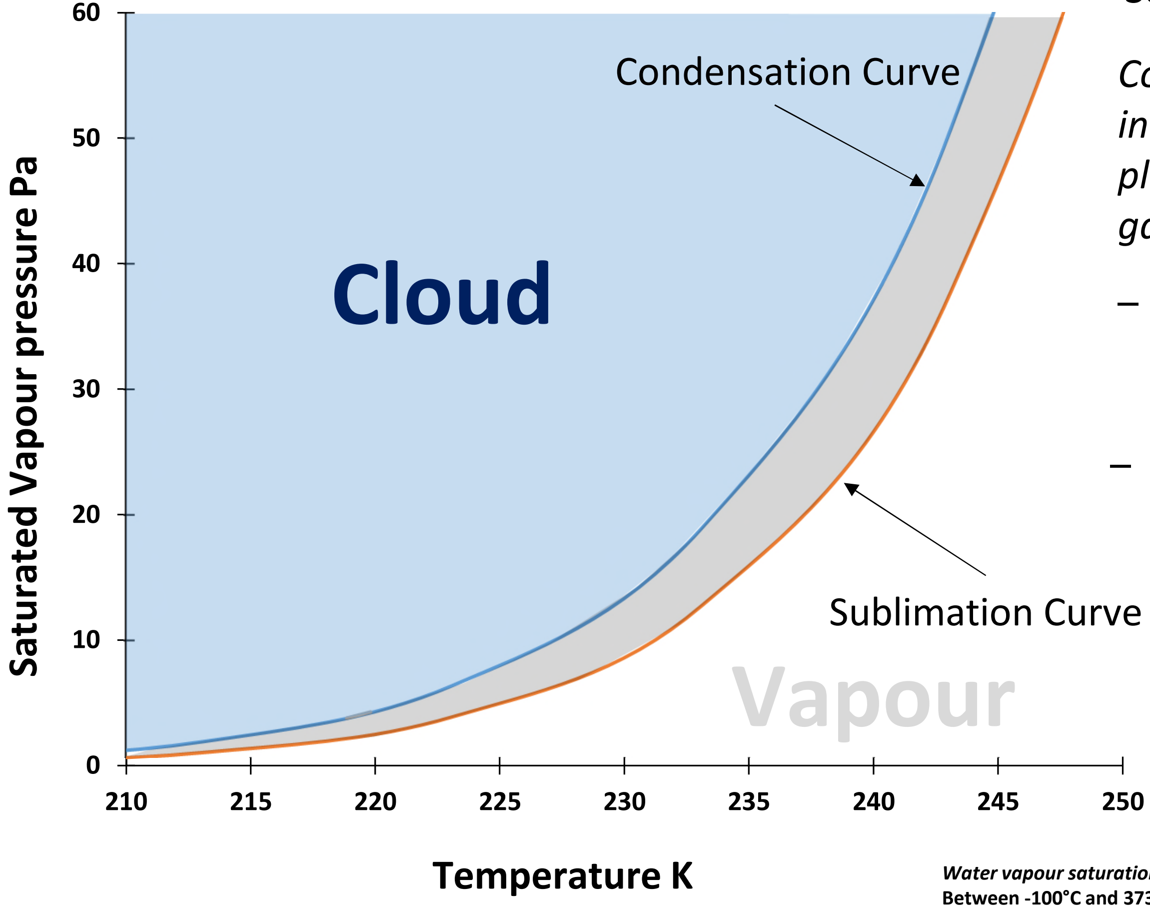
In summary

- 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

Predicting contrails



Schmidt-Appleman criterion

(Schmidt 1941, Appleman 1953)

Contrail formation is explained by the increase in relative humidity that occurs in the jet plume as moist but unsaturated hot exhaust gases mix with cold ambient air.

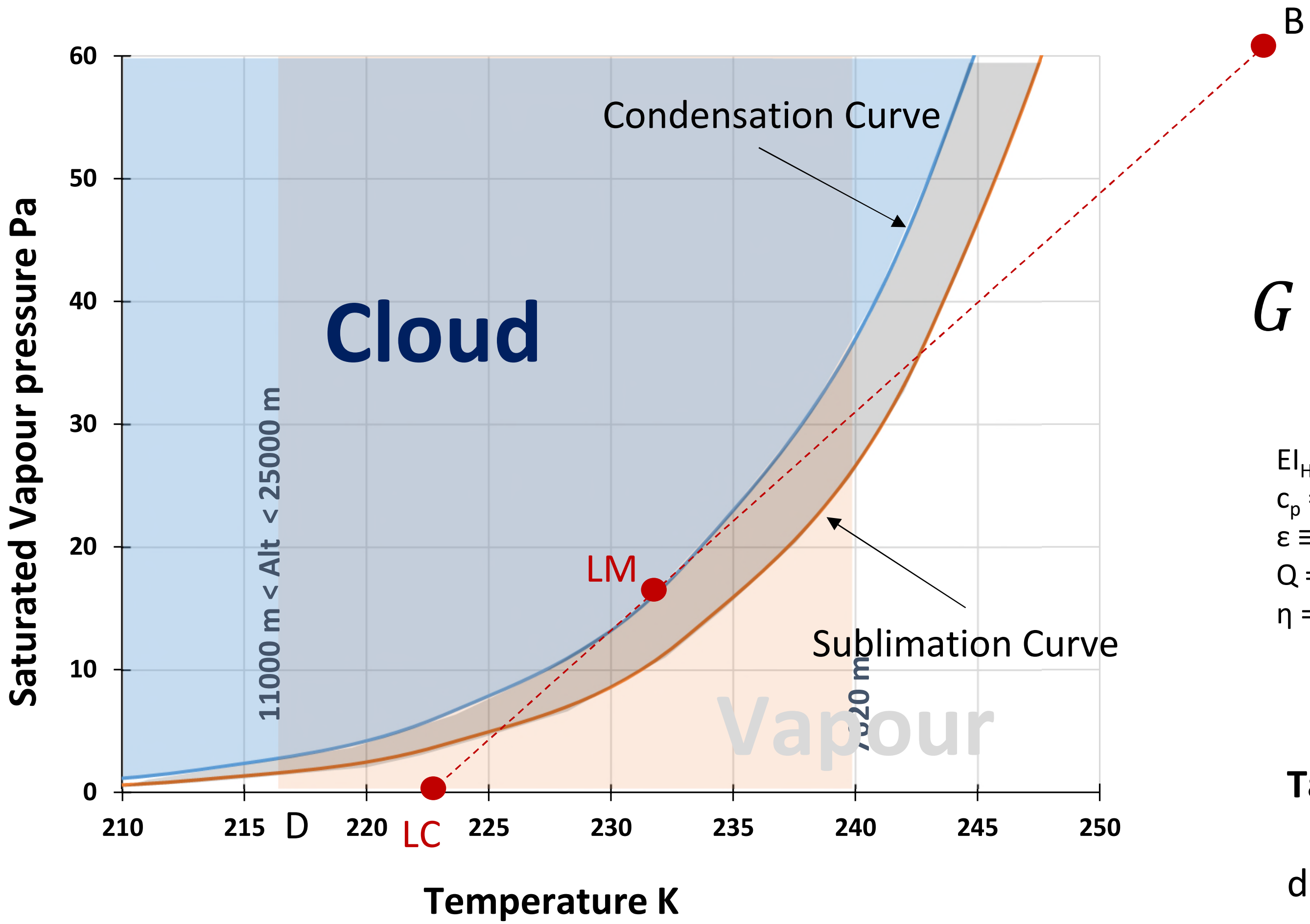
- Mixing represented by a straight line connecting the points corresponding to engine exit conditions
- Assumes -process adiabatic and vapour conserving, and that vapour and heat diffuse at the same rate

….So how is contrail formation predicted ?

Water vapour saturation pressure vs temperature

Between -100°C and 373°C : W. Wagner and A. Pruß:" The IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use ", Journal of Physical and Chemical Reference Data, June 2002,Volume 31, Issue 2, pp. 387535

Predicting contrails



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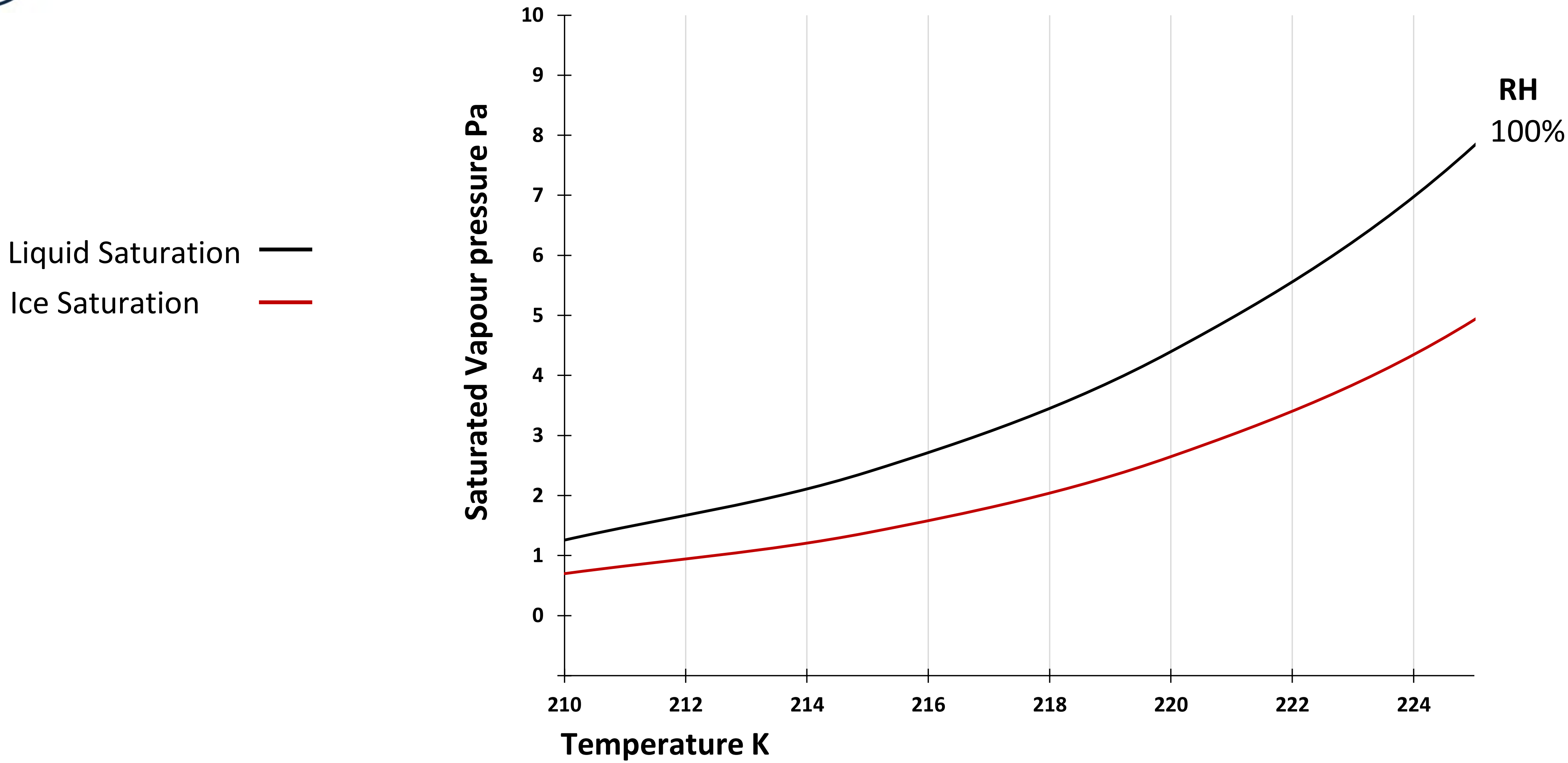
Tangency condition

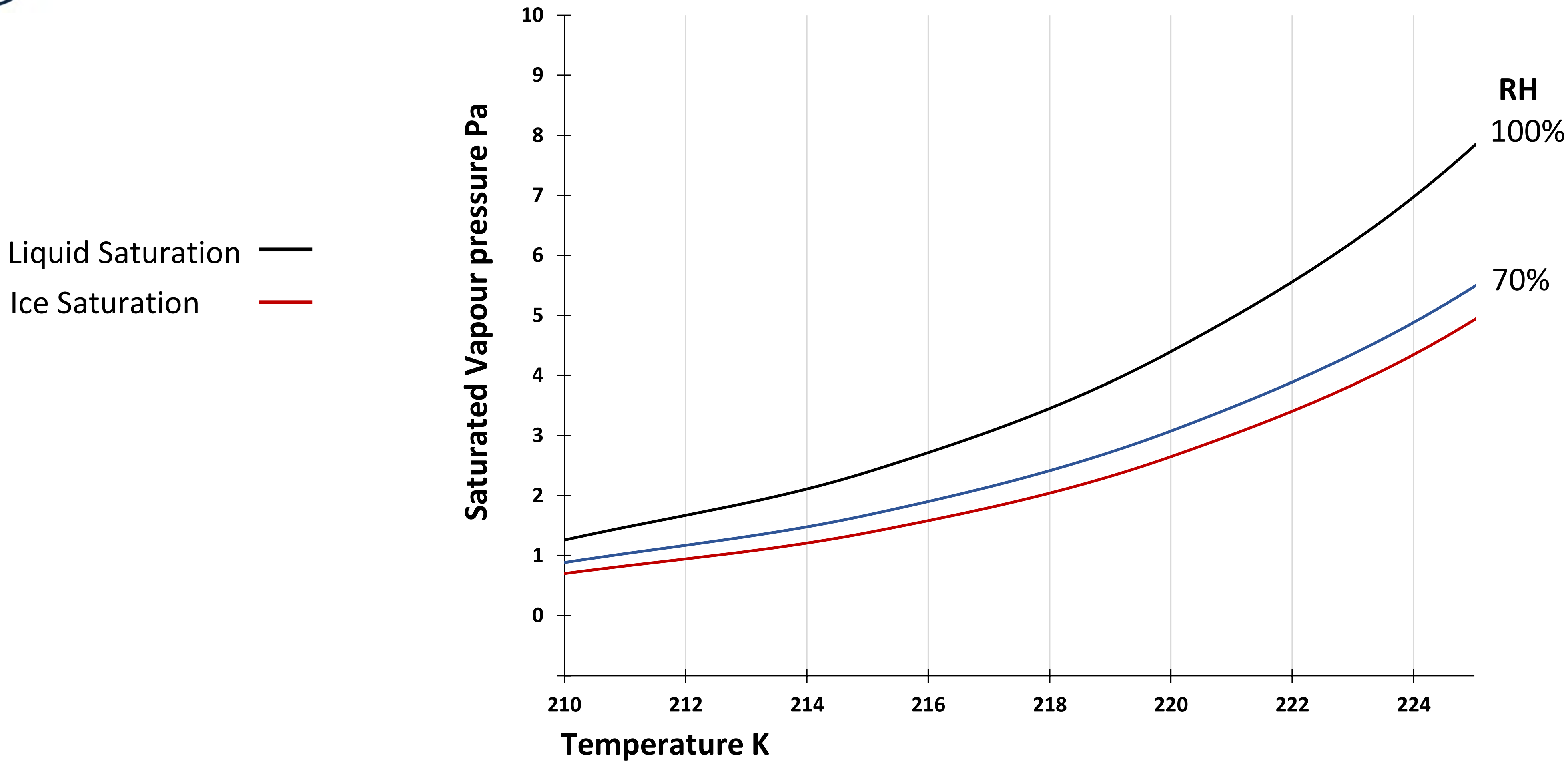
$dP_{liq\ vsat}/dT = G$

RH curves

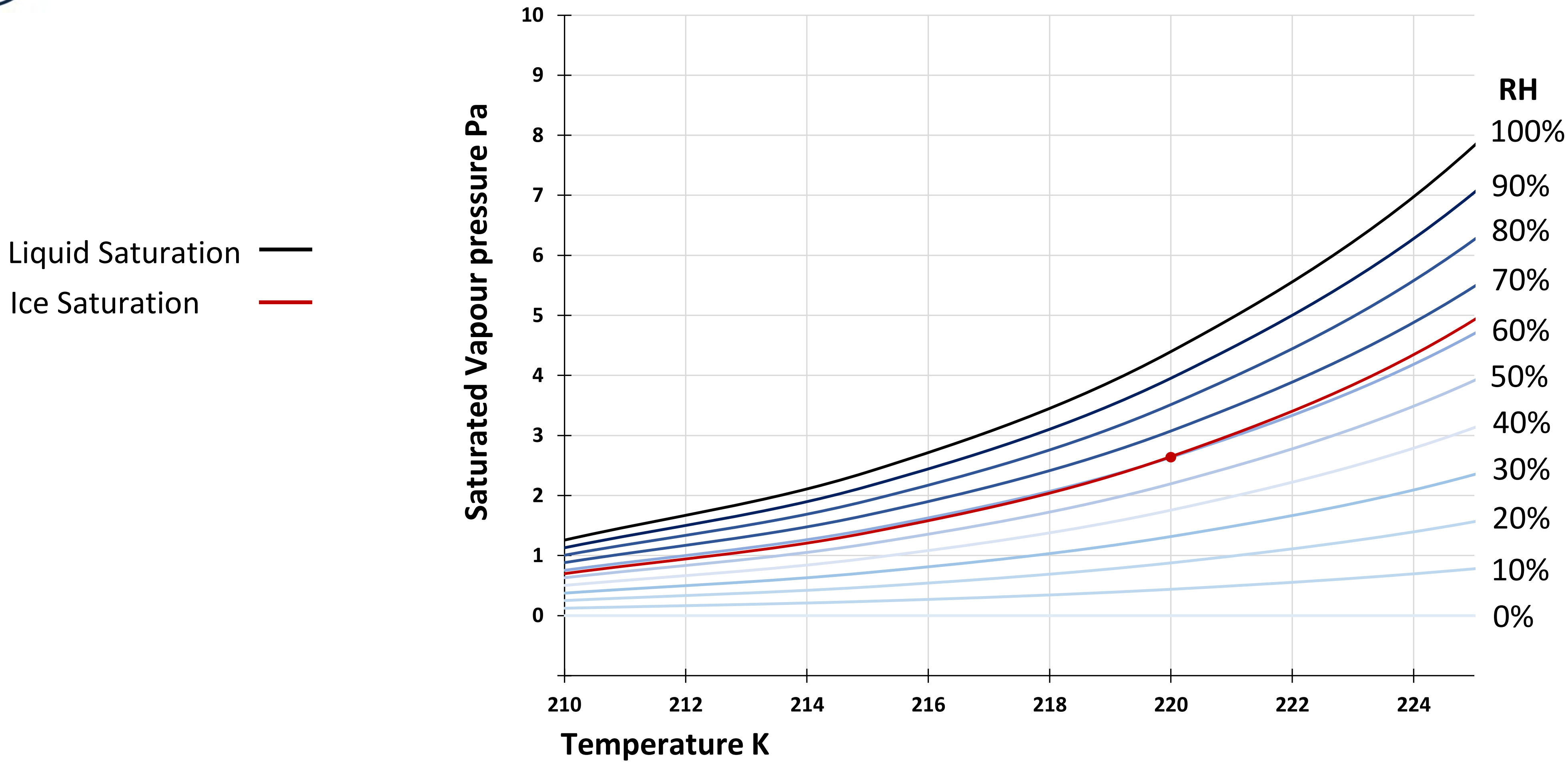


Liquid Saturation
Ice Saturation
Saturated Vapour pressure Pa
10
9
8
7
6
5
4
3
2
1
0
210
212
214
216
218
220
222
224
Temperature K
RH
100%

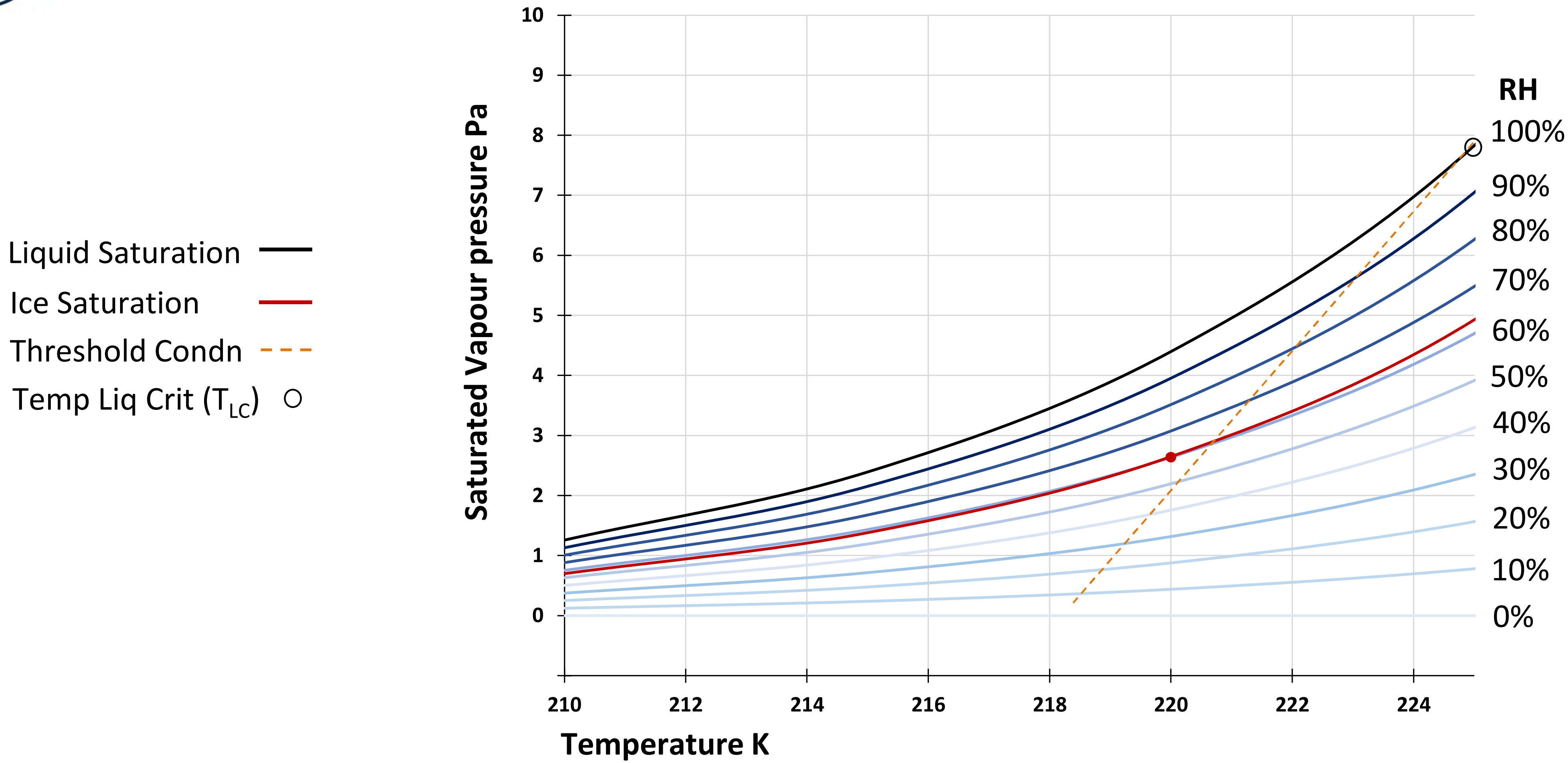
RH curves


Liquid Saturation
Ice Saturation
Saturated Vapour pressure Pa
10
9
8
7
6
5
4
3
2
1
0
210
212
214
216
218
220
222
224
Temperature K
RH
100%
70%

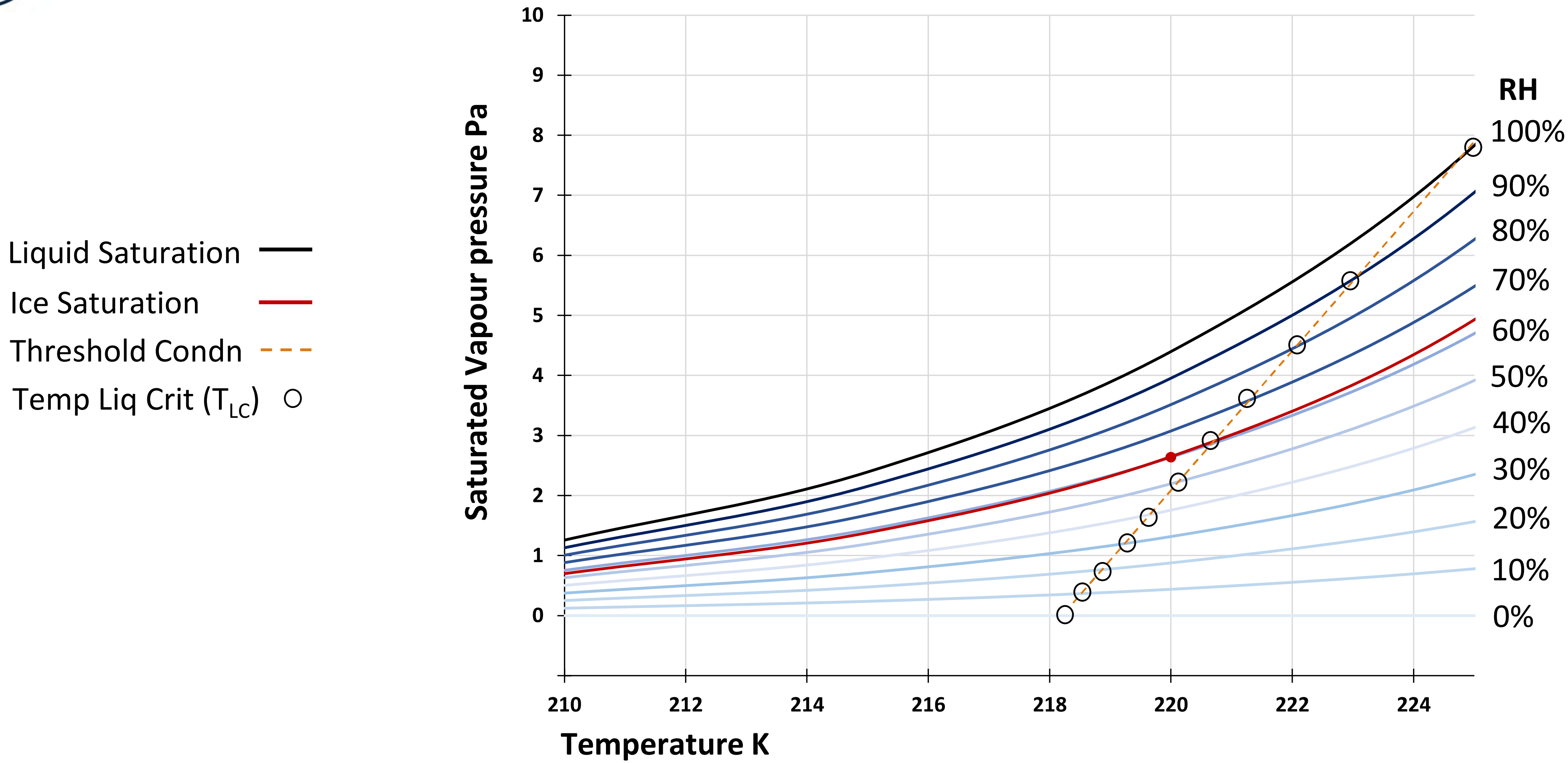
RH curves


Liquid Saturation
Ice Saturation
Saturated Vapour pressure Pa
10
9
8
7
6
5
4
3
2
1
0
210
212
214
216
218
220
222
224
Temperature K
RH
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%

RH curves


Liquid Saturation
Ice Saturation
Threshold Condn
Temp Liq Crit (T_{LC})
Saturated Vapour pressure Pa
10
9
8
7
6
5
4
3
2
1
0
210
212
214
216
218
220
222
224
Temperature K
RH
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%

RH curves


Liquid Saturation
Ice Saturation
Threshold Condn
Temp Liq Crit (T_{LC})
Saturated Vapour pressure Pa
10
9
8
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216
218
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Temperature K
RH
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90%
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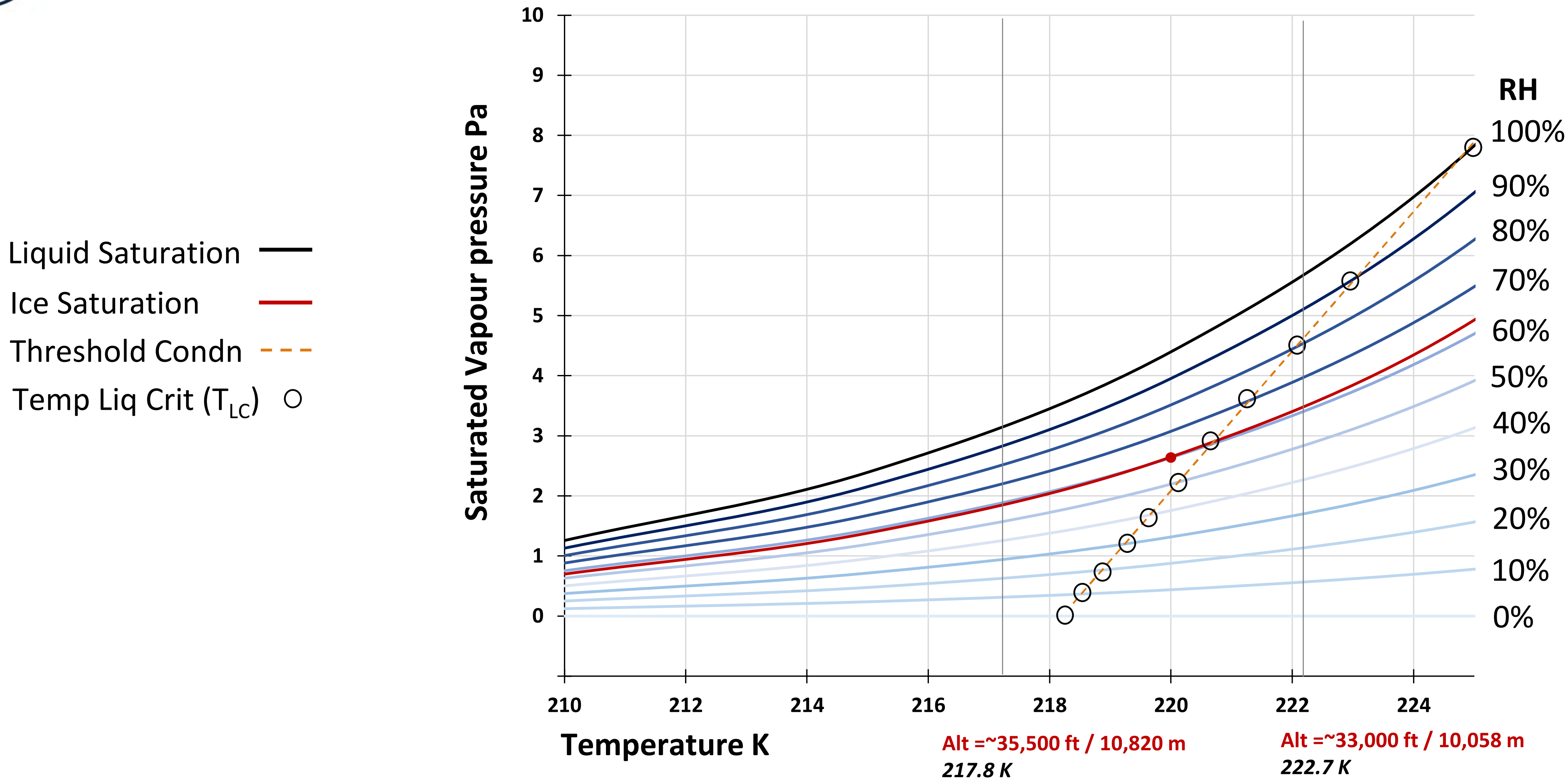
30%
20%
10%
0%

RH curves


Liquid Saturation
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Threshold Condn
Temp Liq Crit (T_{LC})
Saturated Vapour pressure Pa
10
9
8
7
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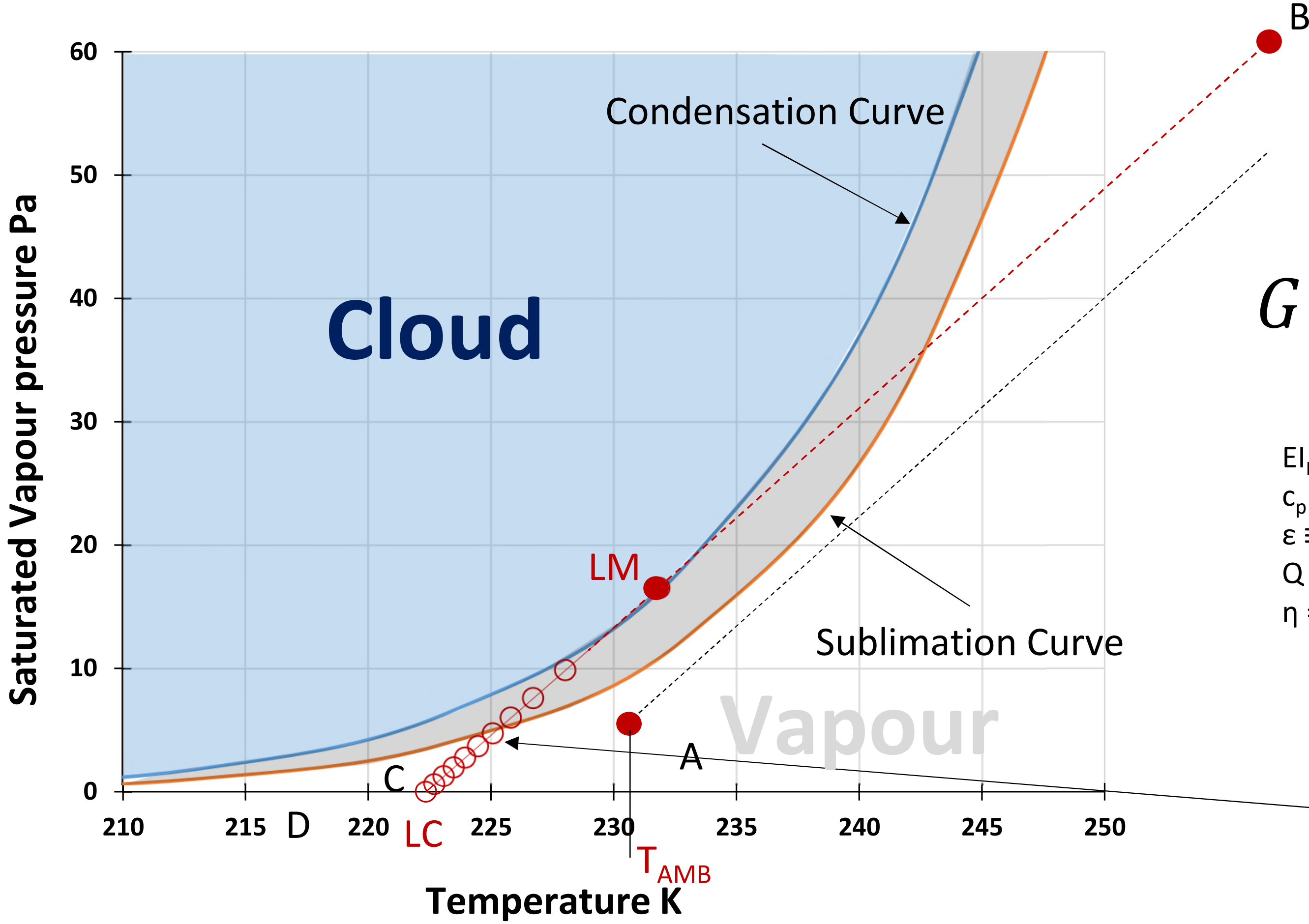
4
3
2
1
0
210
212
214
216
218
220
222
224
Temperature K
RH
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Alt =~35,500 ft / 10,820 m
217.8 K
Alt =~33,000 ft / 10,058 m
222.7 K

Predicting contrails



Slope G of the mixing line - expressed in terms of atmospheric conditions and the propulsive characteristics of the engine

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Q = combustion heat per mass of fuel
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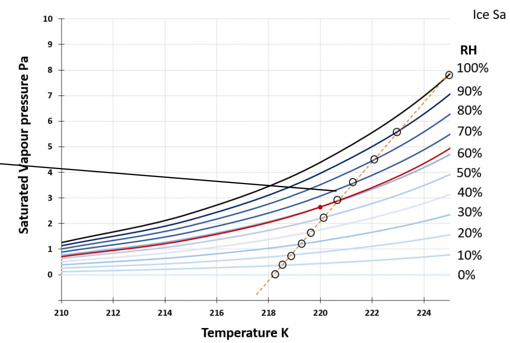

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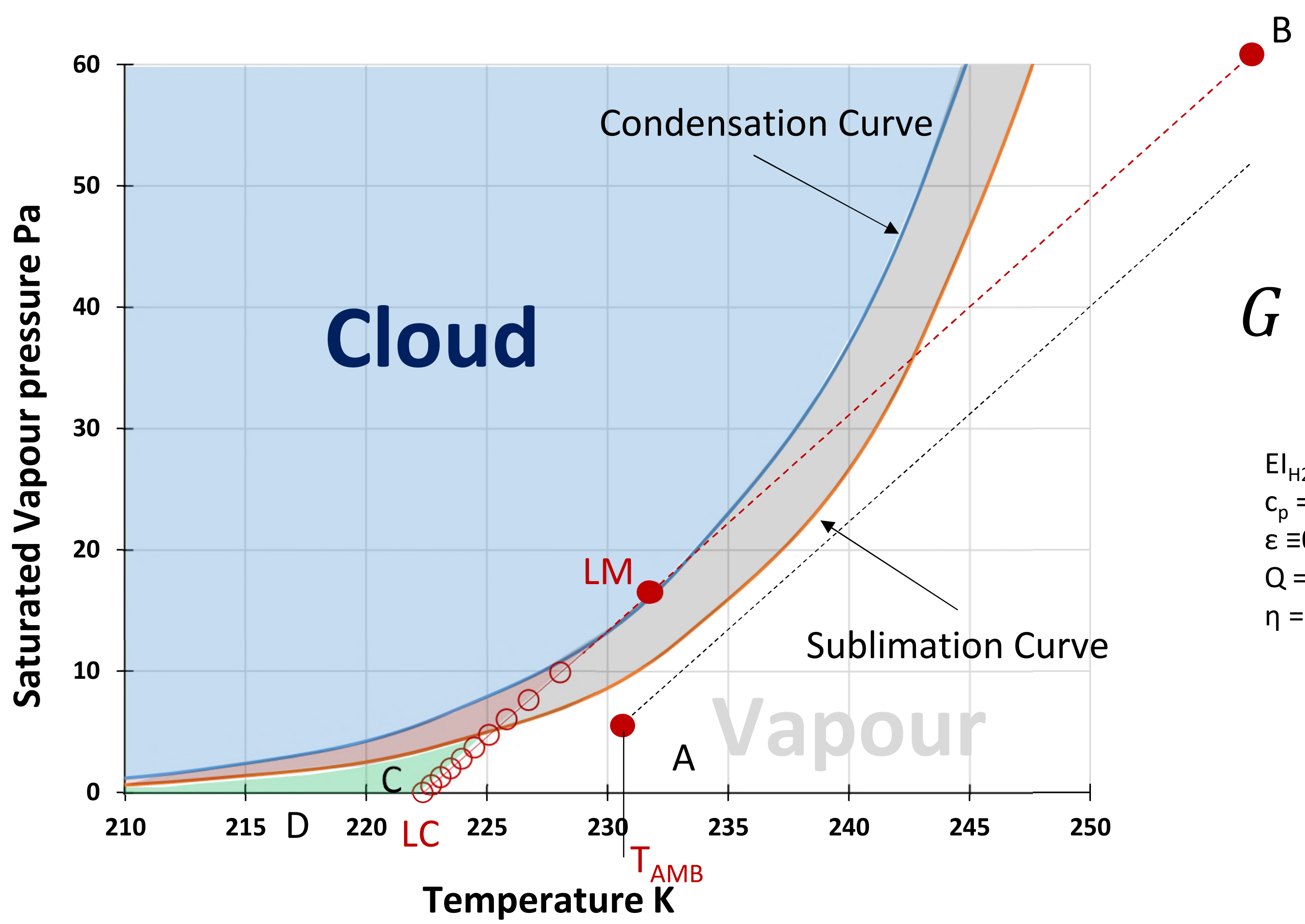

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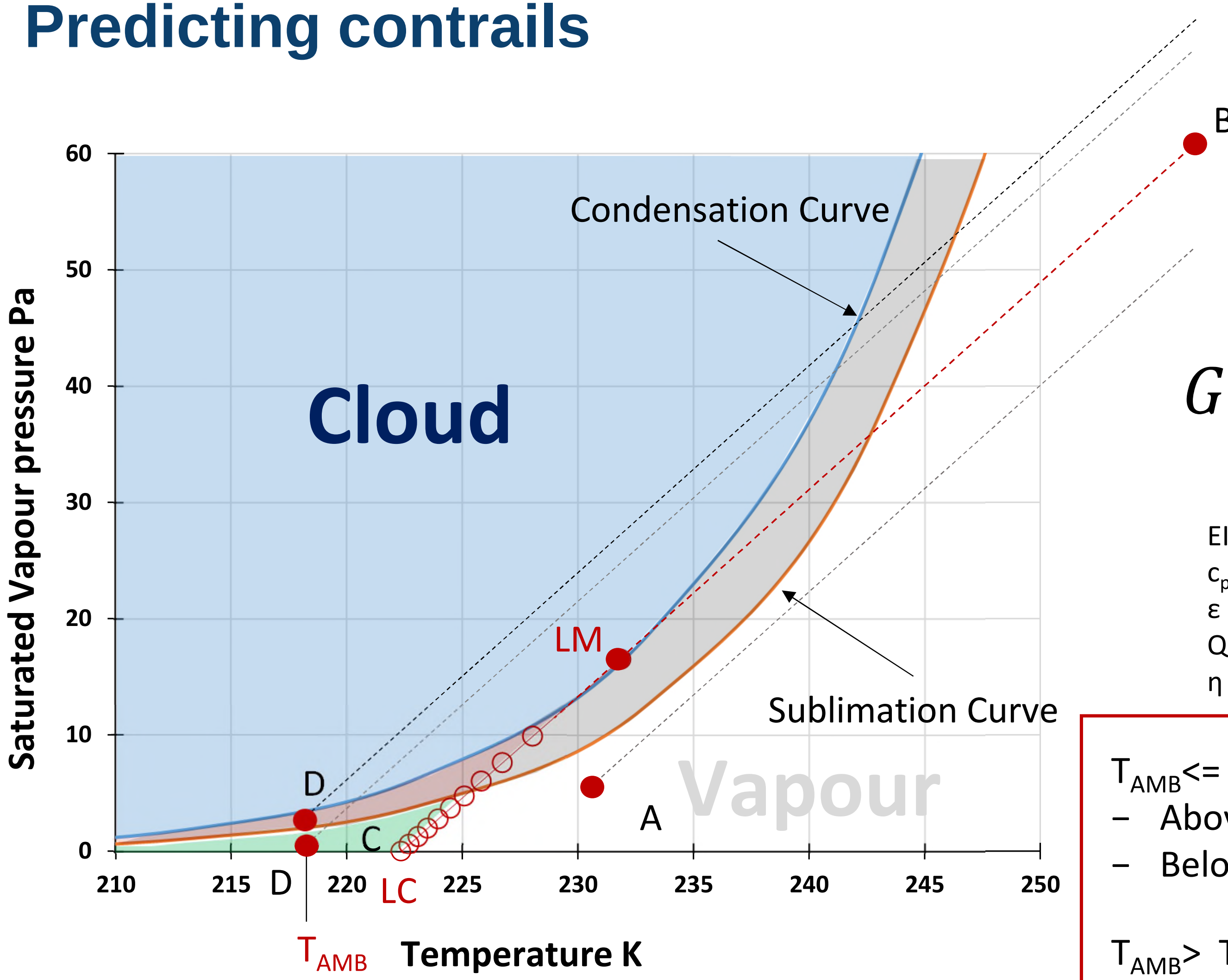

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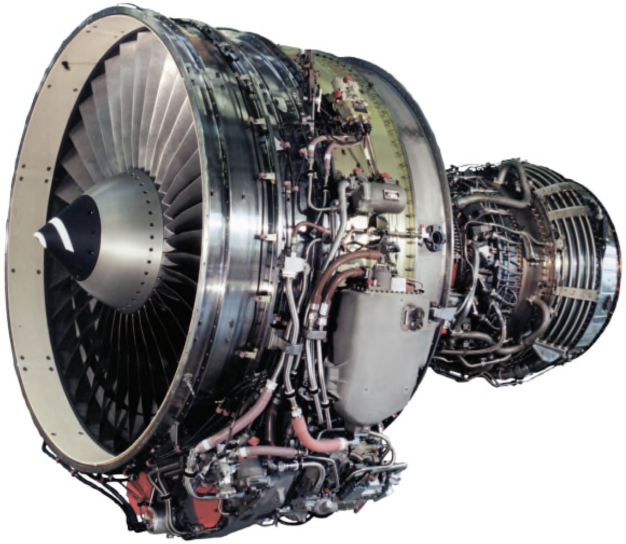
T_{AMB}<= T_{LC} Contrail will form

- Above the Sub curve – Persistent (ISSR)
- Below the Sub curve – Non persistent

T_{AMB}> T_{LC} Contrail will **NOT** form

Case Study - η and fuel effects



CFM56-5B (Kerosene)

- Aircraft : A320 CEO family
- T/O thrust: 33000 lbf
- BPR: 5.1
- Fan diameter: 68.3 inches

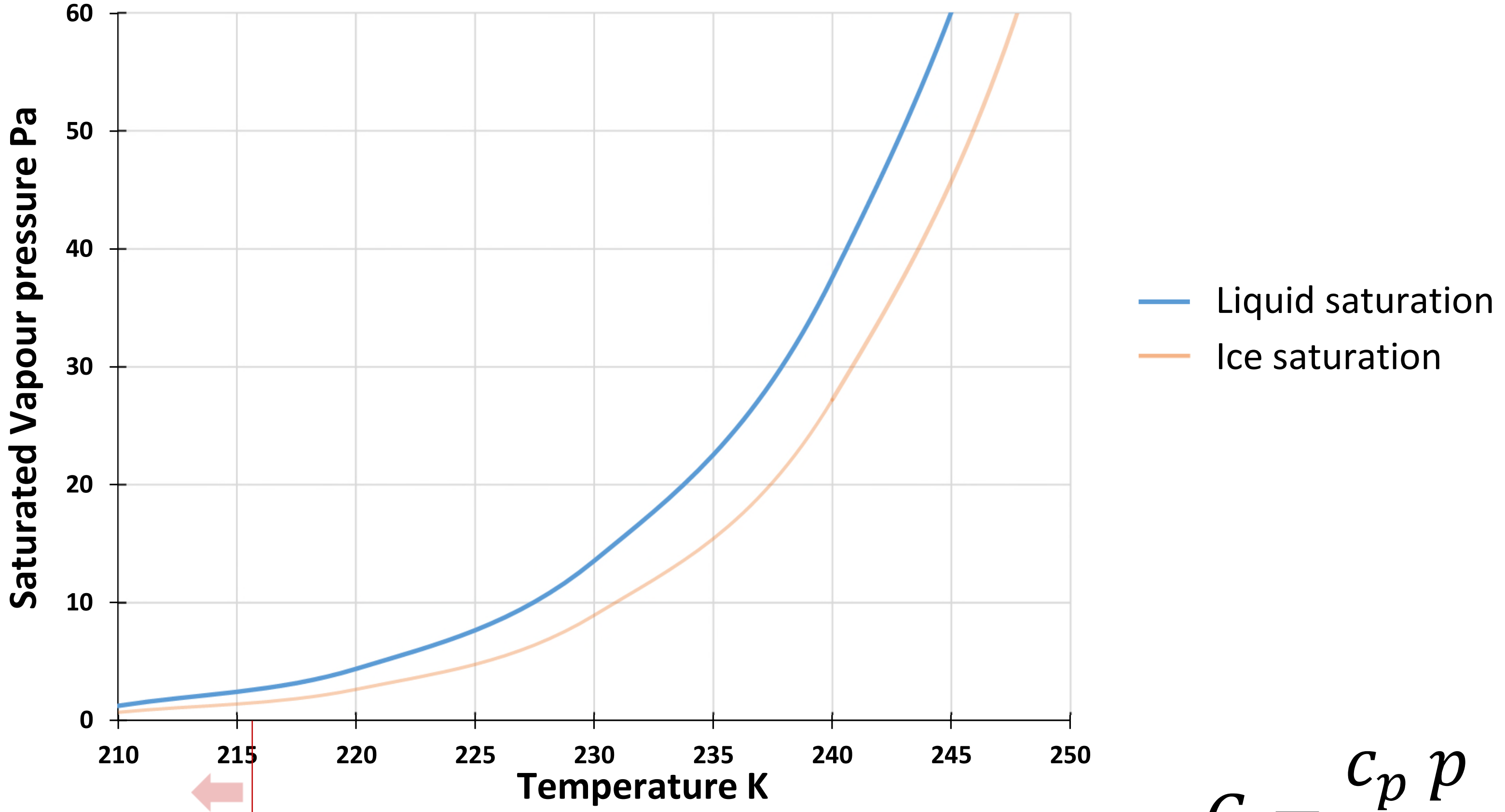
Leap-1A (Kerosene)

- Aircraft : A320 NEO family
- T/O thrust: 35000 lbf
- BPR: 10.6-11
- Fan diameter: 78 inches

https://www.cfmaeroengines.com/wp-content/uploads/2017/08/FICHES_CFM56_170x260H-v8.pdf

https://www.safran-group.com/products-services/leap-1a-new-generation-engine-single-aisle-commercial-jets

Case Study - η and fuel effects

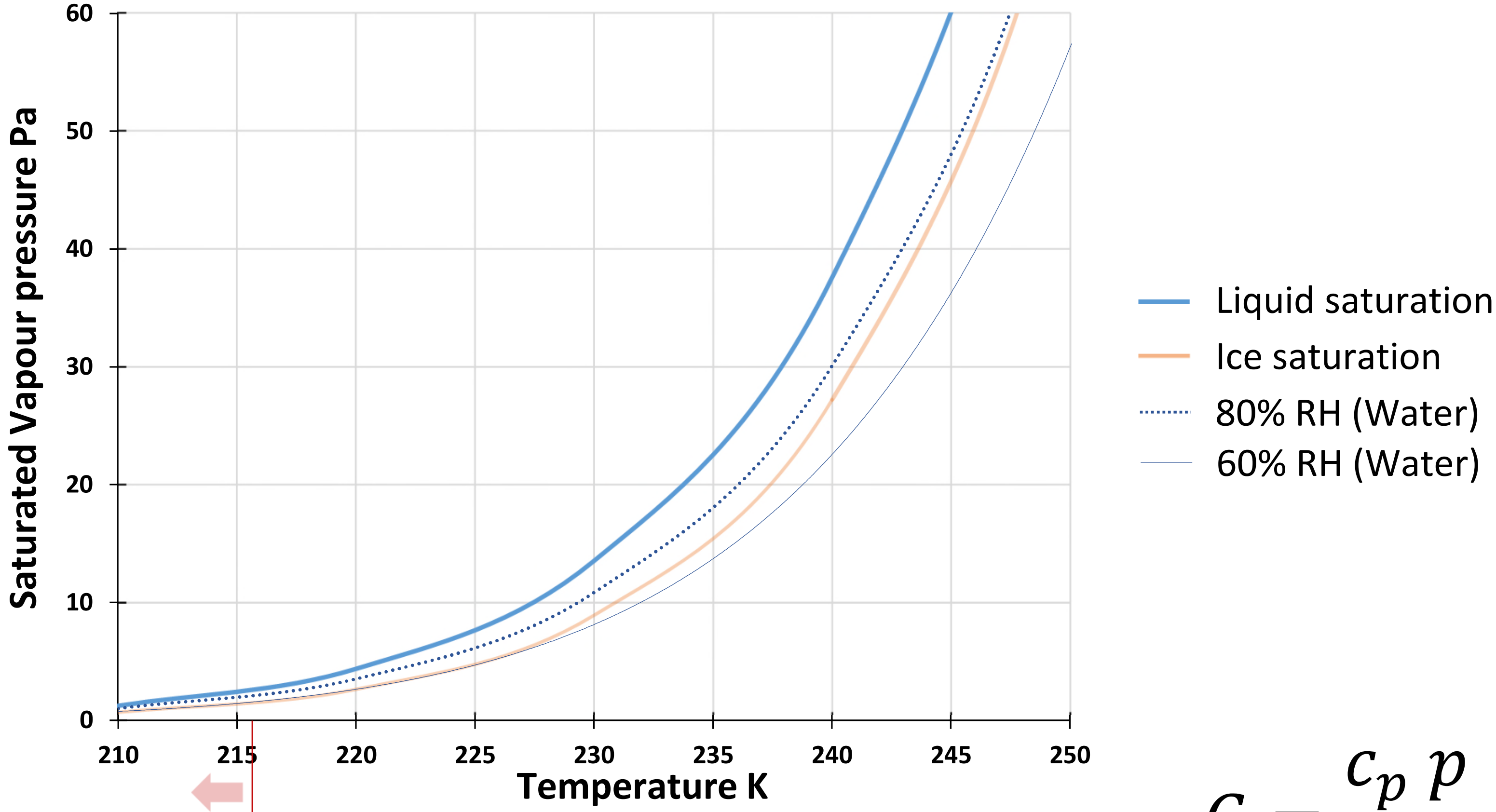


Alt >=~36,100 ft / 11,003 m
Alt <=~65,616 ft / 20,000 m
216.6 K / -56.5˚C/-69.69˚F

Alt =~19,258 ft / 5,870 m
250 K / -23.15˚C/-9.67˚F

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

Case Study - η and fuel effects



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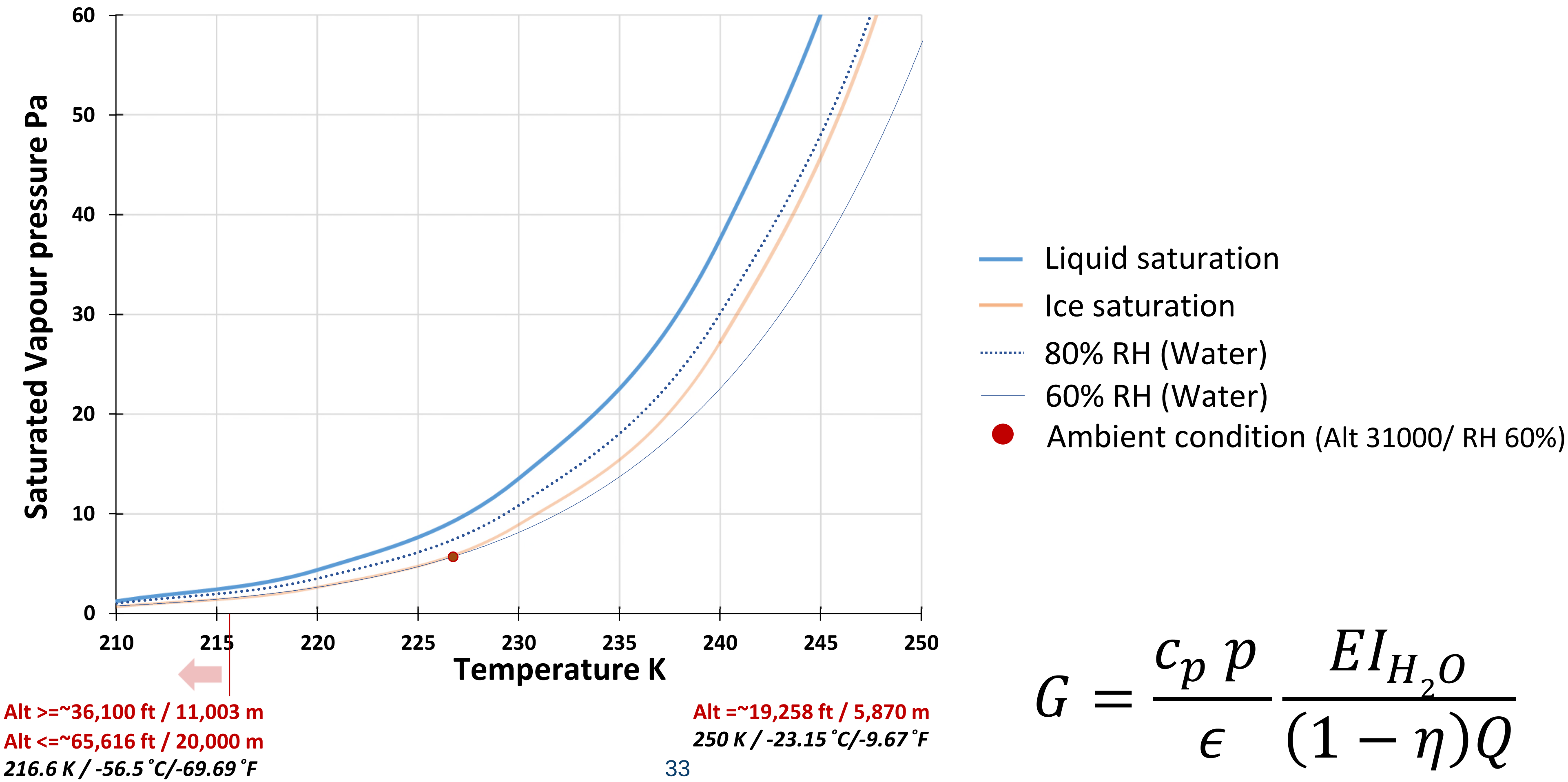
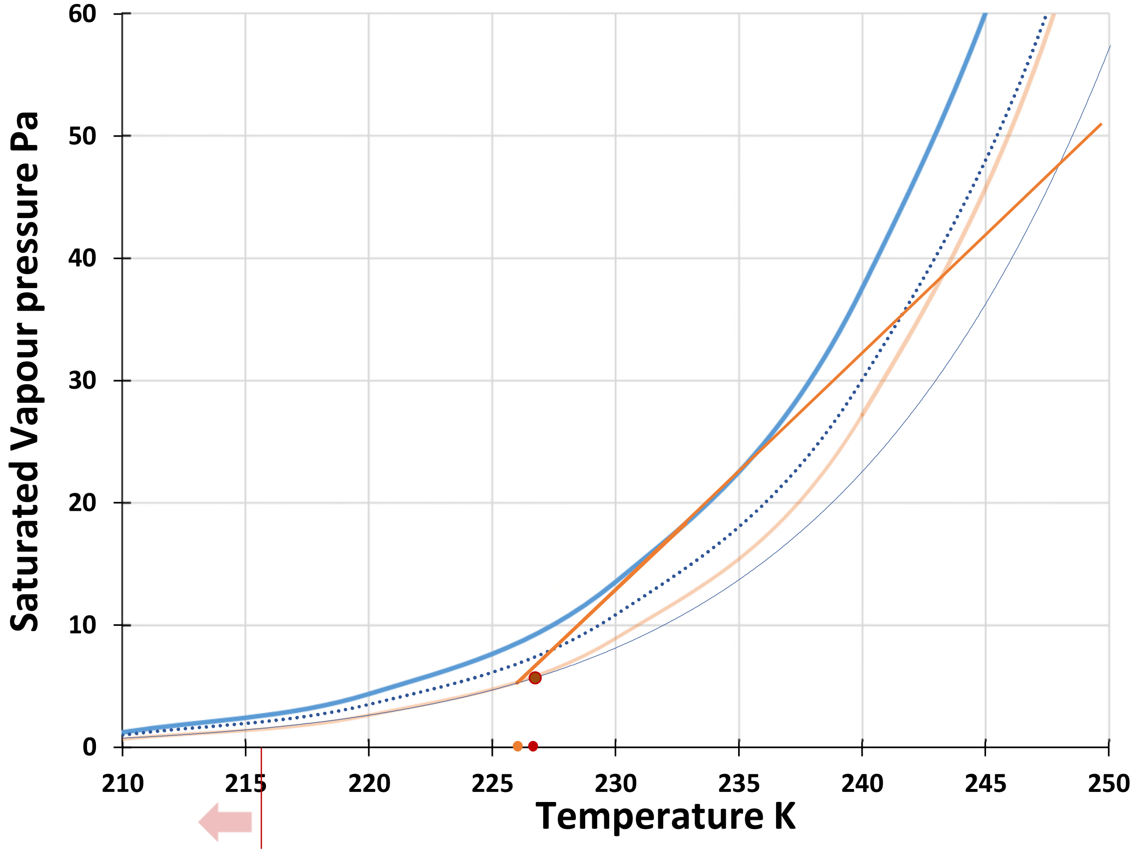


$$G = \frac{c_p\, p}{\epsilon} \frac{EI_{H_2O}}{(1-\eta)Q}$$

Case Study - η and fuel effects

Test case
Engine : CFM 56
EI H_2O = 1.26
Q= 43.2 MJ/kg
T_{LC} = 226
T_{AMB} = 226.73
G= 1.906



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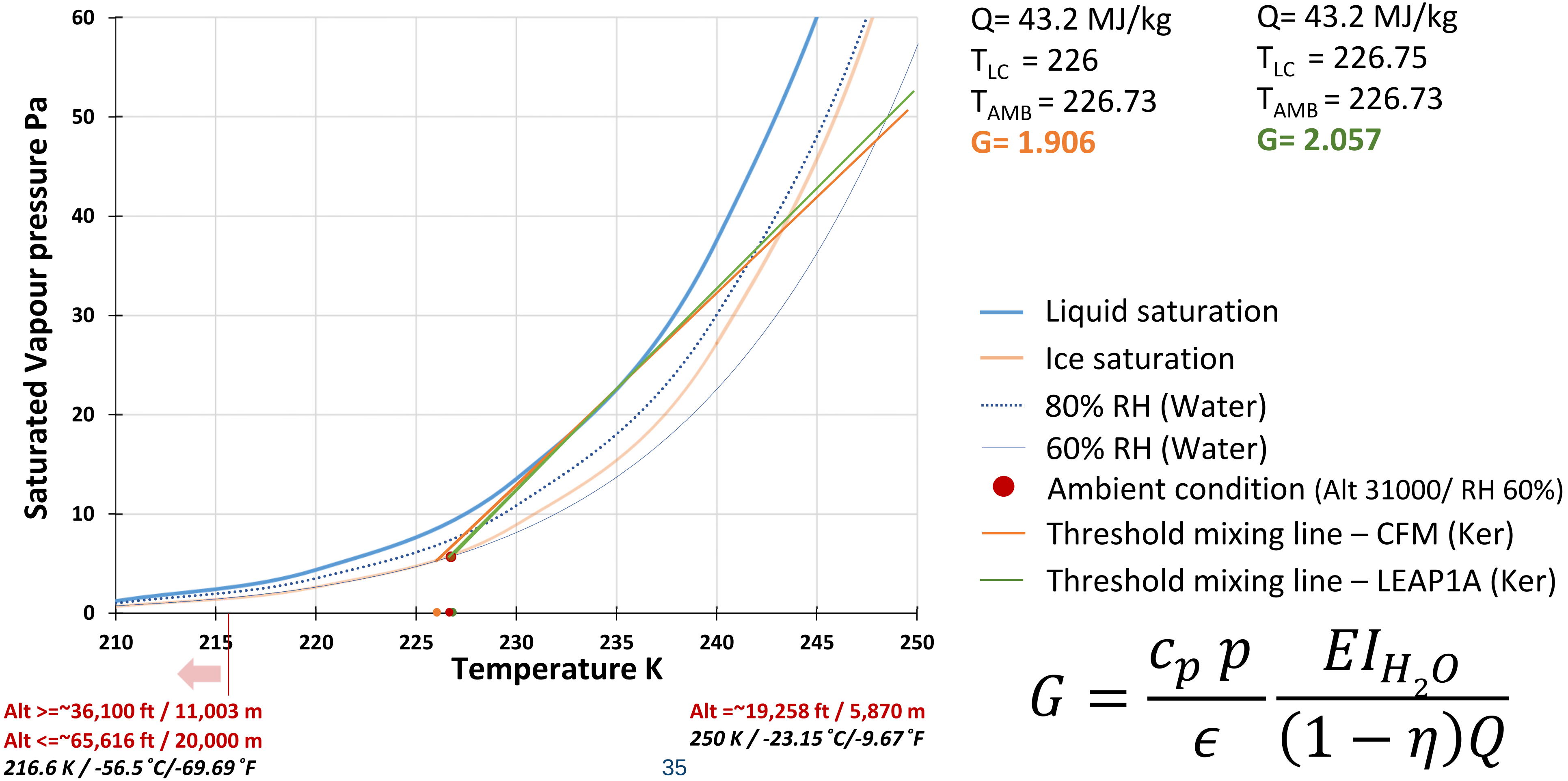
Case Study - η and fuel effects



Test case

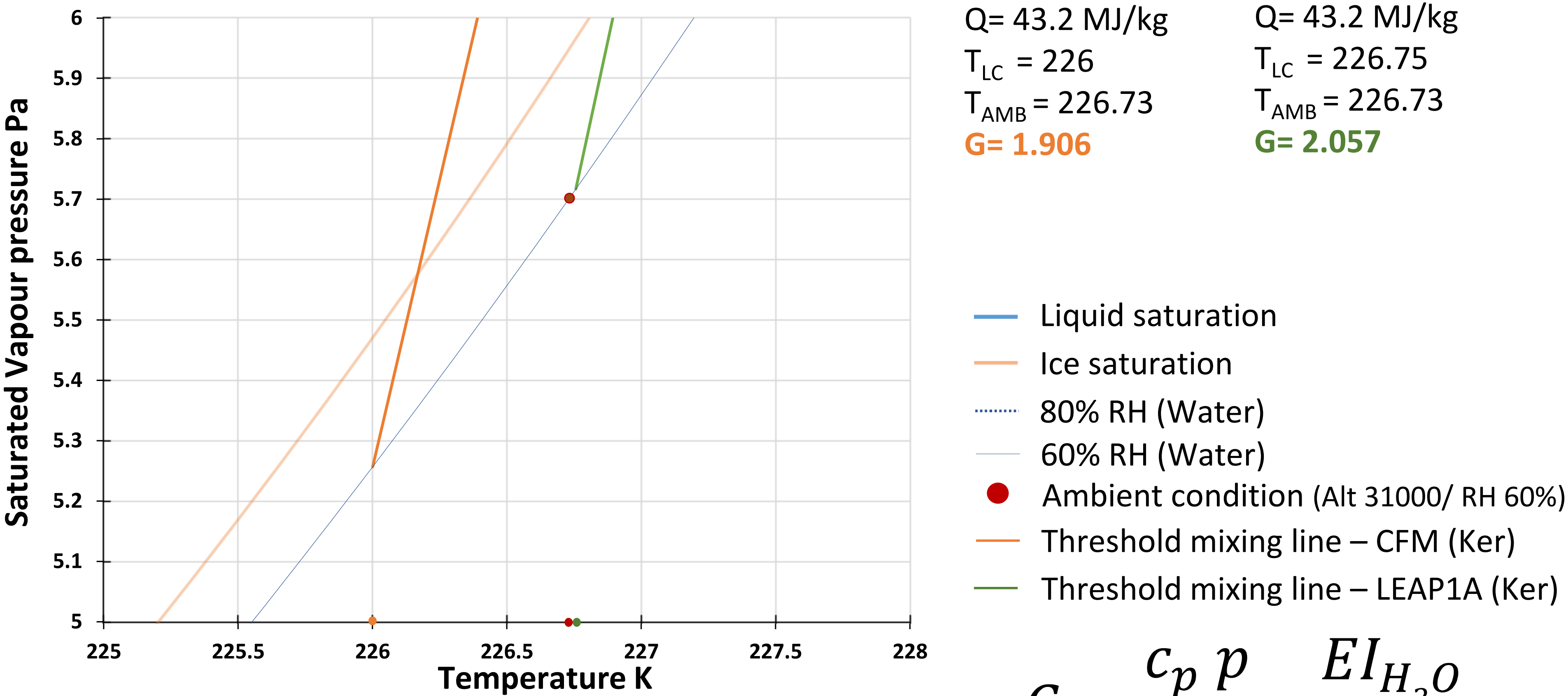
Engine : CFM 56	Engine : LEAP-1A
EI H_2O = 1.26	EI H_2O = 1.26
Q= 43.2 MJ/kg	Q= 43.2 MJ/kg
T_{LC} = 226	T_{LC} = 226.75
T_{AMB} = 226.73	T_{AMB} = 226.73
G= 1.906	**G= 2.057**

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

Case Study - η and fuel effects

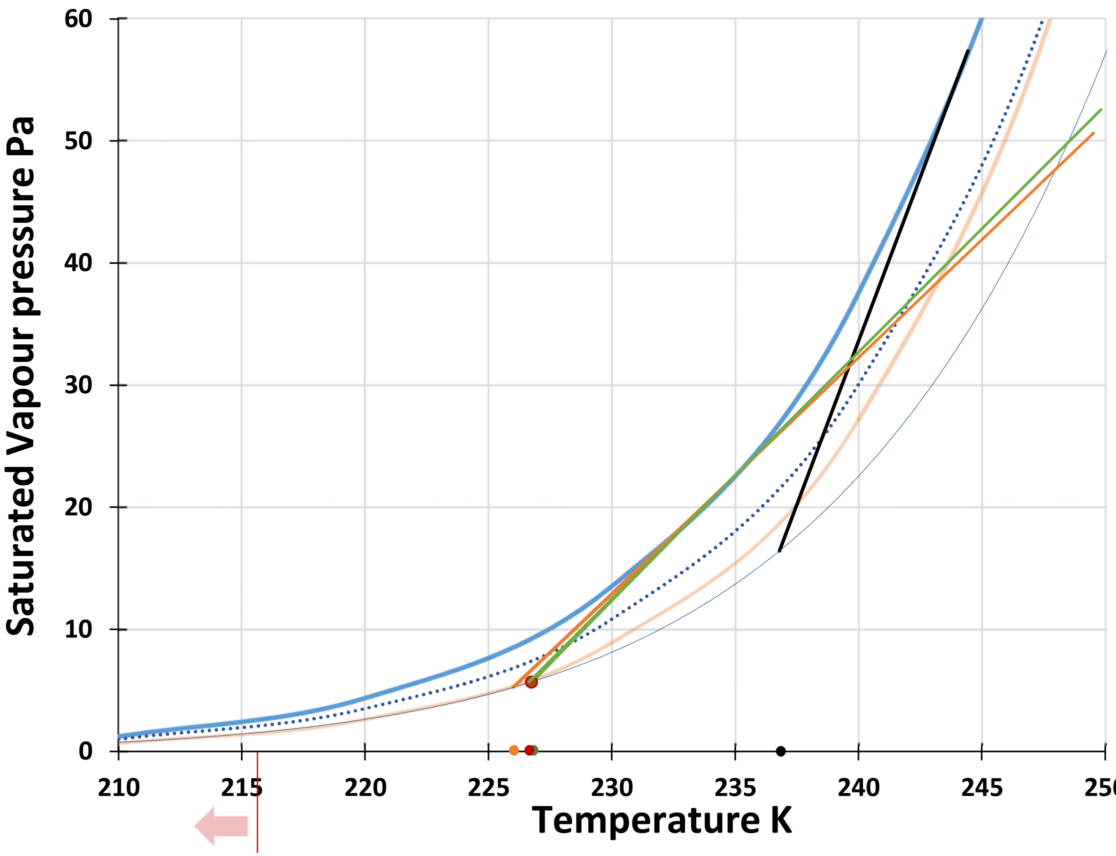
Test case

Engine : CFM 56	Engine : LEAP-1A
EI H_2O = 1.26	EI H_2O = 1.26
Q= 43.2 MJ/kg	Q= 43.2 MJ/kg
T_{LC} = 226	T_{LC} = 226.75
T_{AMB} = 226.73	T_{AMB} = 226.73
G= 1.906	**G= 2.057**



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

Case Study - η and fuel effects



Alt >=~36,100 ft / 11,003 m
Alt <=~65,616 ft / 20,000 m
216.6 K / -56.5˚C/-69.69˚F

Alt =~19,258 ft / 5,870 m
250 K / -23.15˚C/-9.67˚F

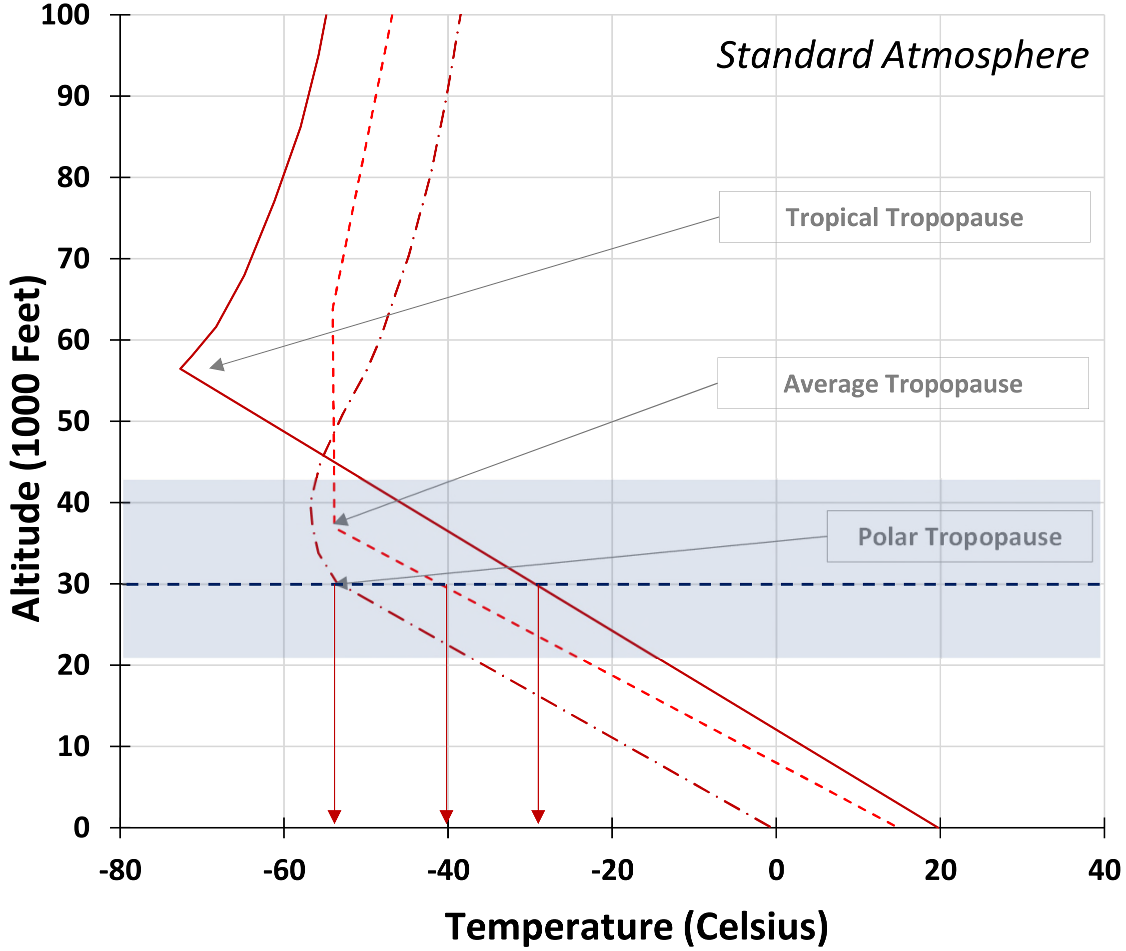
Test case

Engine : LEAP-1A (KE)	Engine : LEAP-1A (H_2)
EI H_2O = 1.26	EI H_2O = 9
Q= 43.2 MJ/kg	Q= 120 MJ/kg
T_{LC} = 226.75	T_{LC} = 236.78
T_{AMB} = 226.73	T_{AMB} = 226.73
G= 2.057	**G= 5.35**

- Liquid saturation
- Ice saturation
- 80% RH (Water)
- 60% RH (Water)
- Ambient condition (Alt 31000/ RH 60%)
- Threshold mixing line – CFM (Ker)
- Threshold mixing line – LEAP-1A (Ker)
- Threshold mixing line – LEAP-1A (H_2)

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

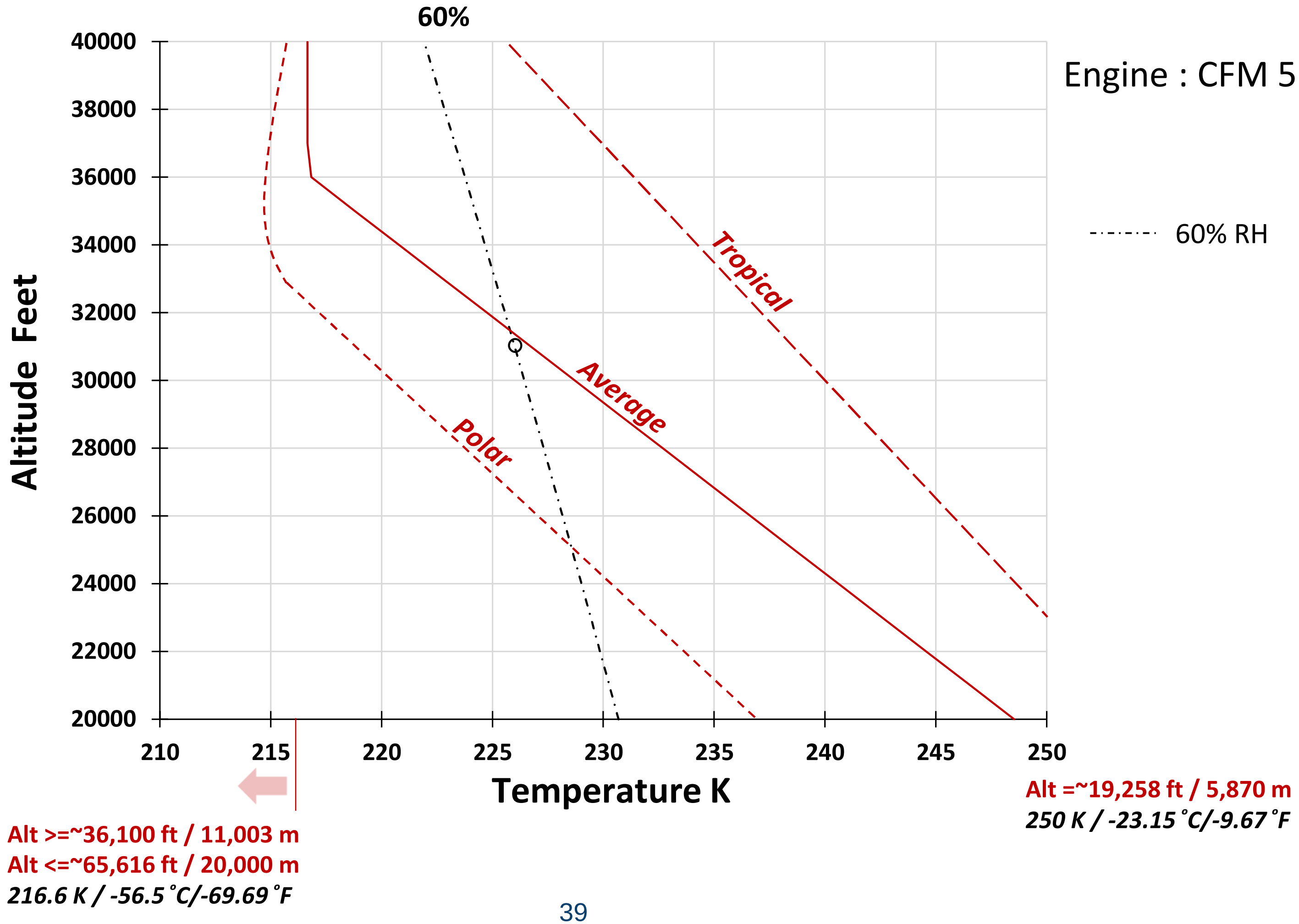
Temperature variation with altitude



Weather for Aircrews, Air Force Handbook (AFH) 11-203, Volume 1, 1 March 1997, Department of the Air Force

Case Study - η and fuel effects

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



Case Study - η and fuel effects

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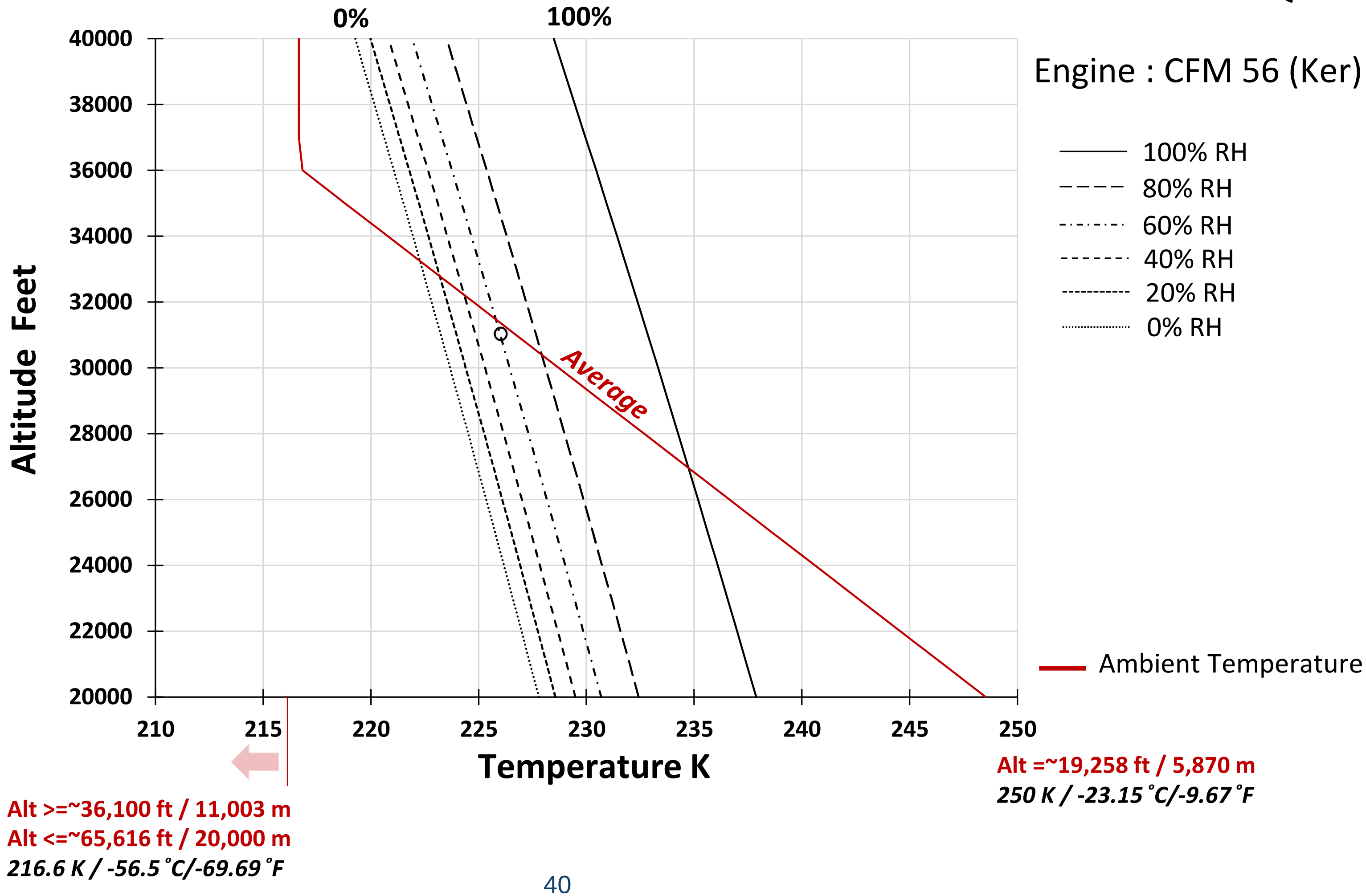

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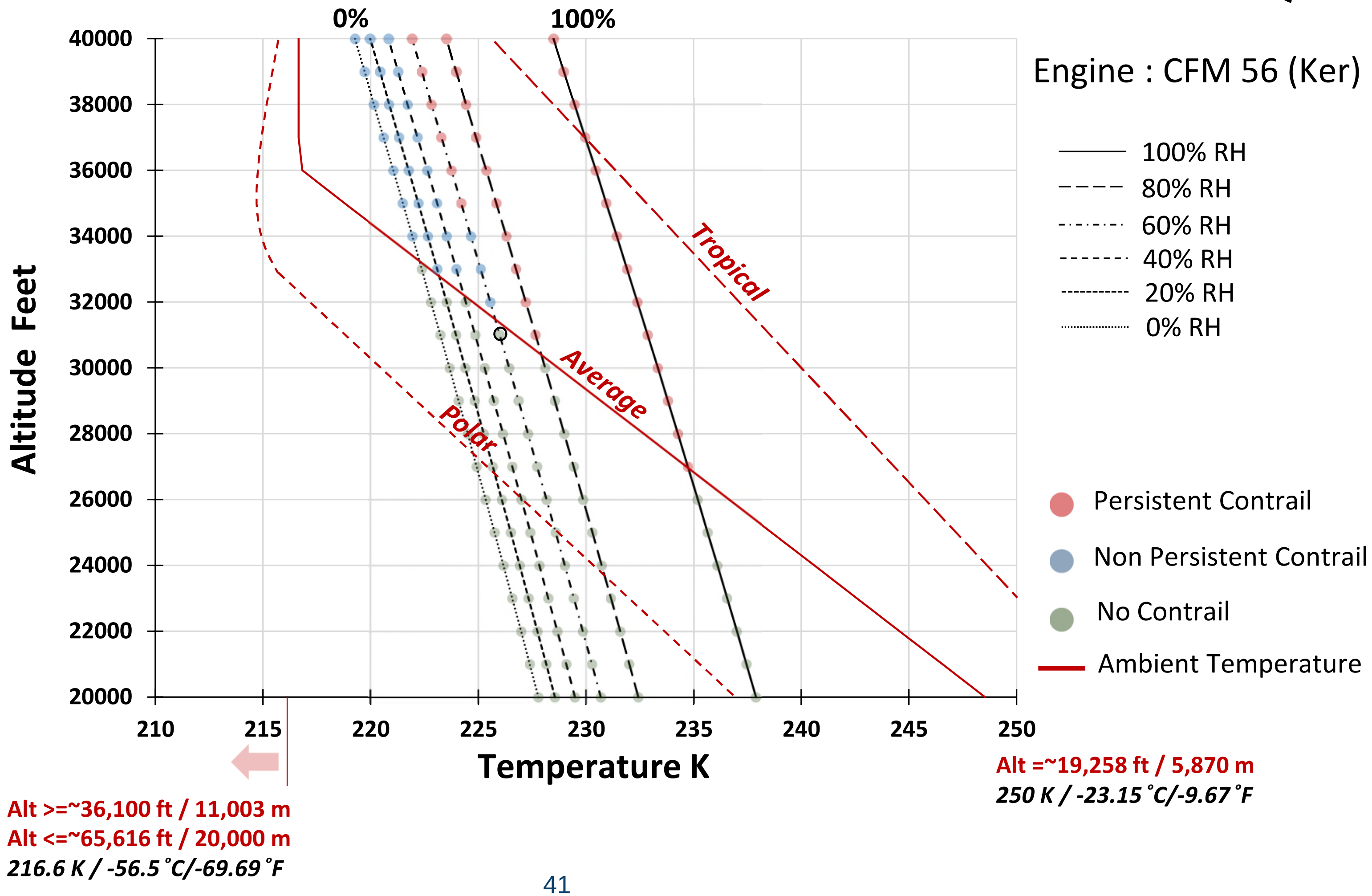

Case Study - η and fuel effects

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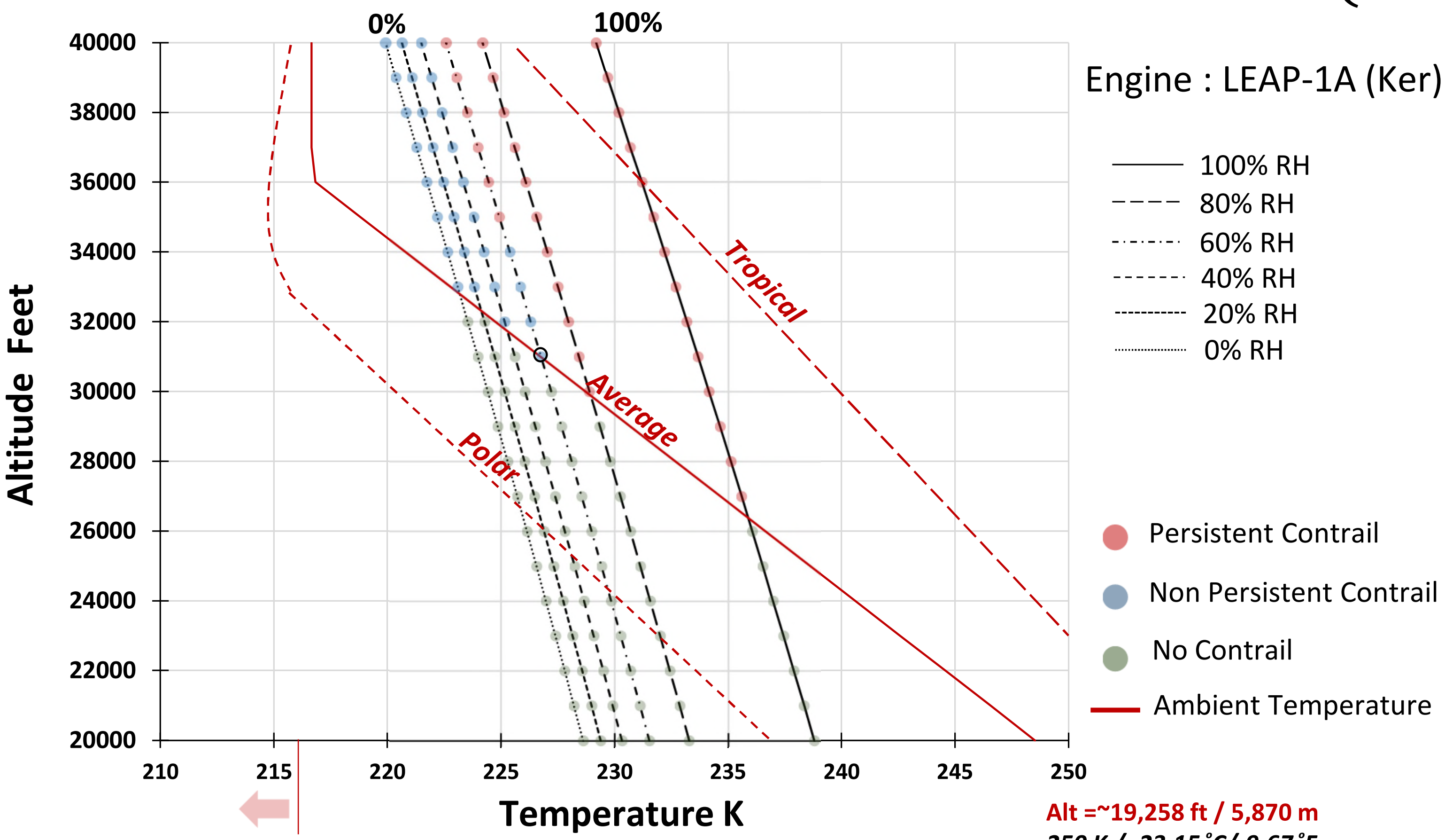

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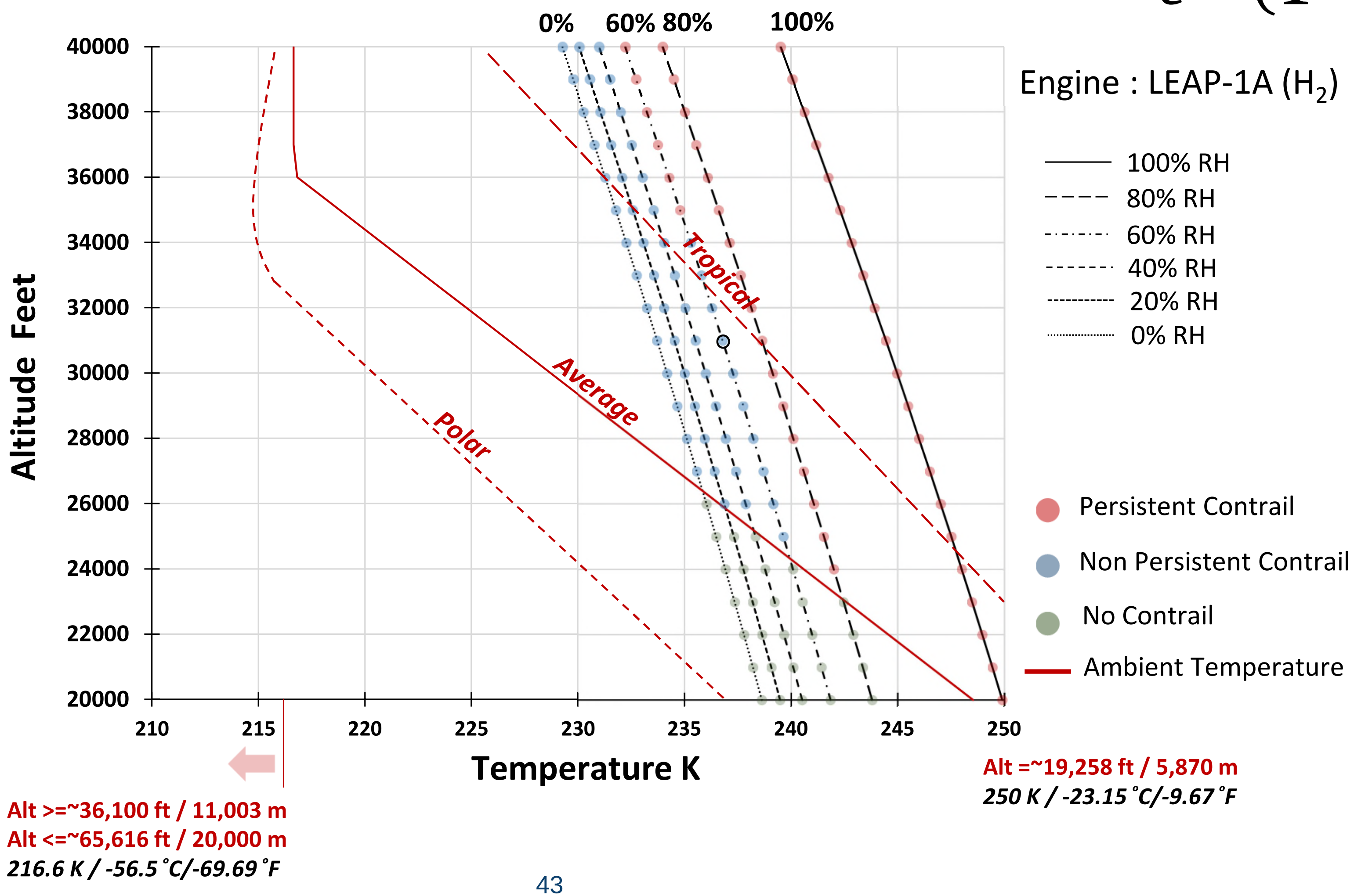
Case Study - η and fuel effects

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



Contrail Mitigation Strategies

Contrail Mitigation Strategies

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

EI_{H2O} = 1.25 or 9 (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)

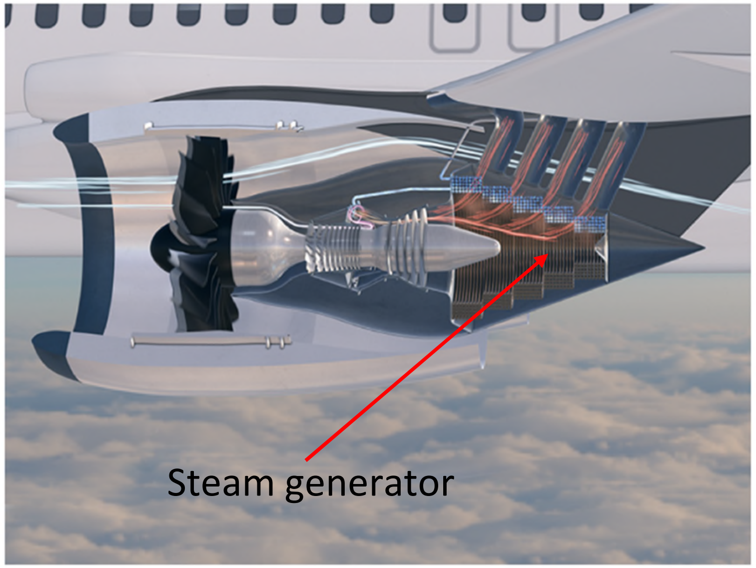
Q = Combustion heat per mass of fuel (42 or 120 MJ/kg)

η = overall engine efficiency in cruise conditions

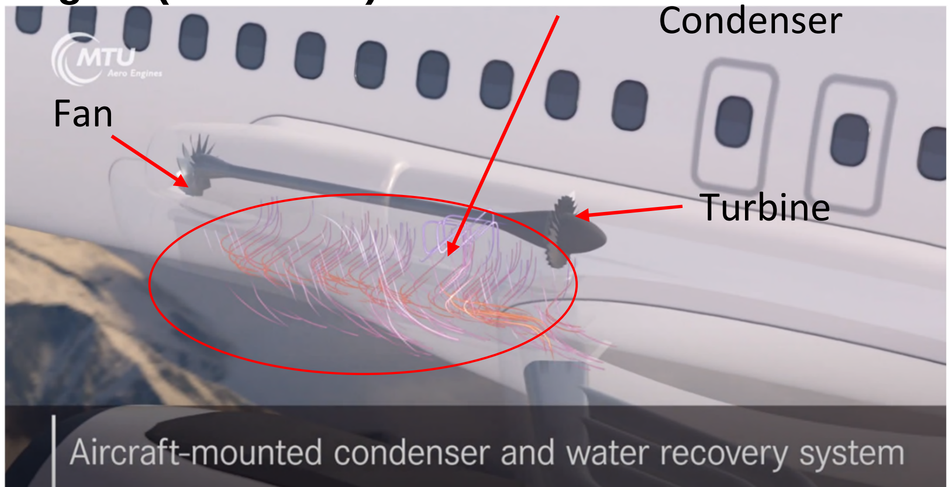
$$\eta = \frac{Thrust * V_{TAS}}{FF * LHV}$$

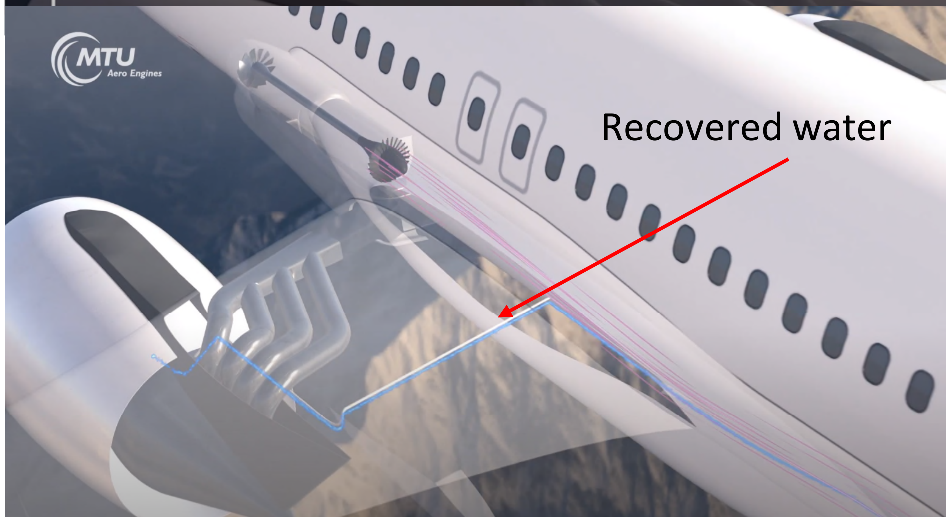
Water extraction from exhaust

The Steam Injecting and Recovering Aero Engine (MTU 2020)



https://www.youtube.com/watch?v=pMg_PWK6C-s





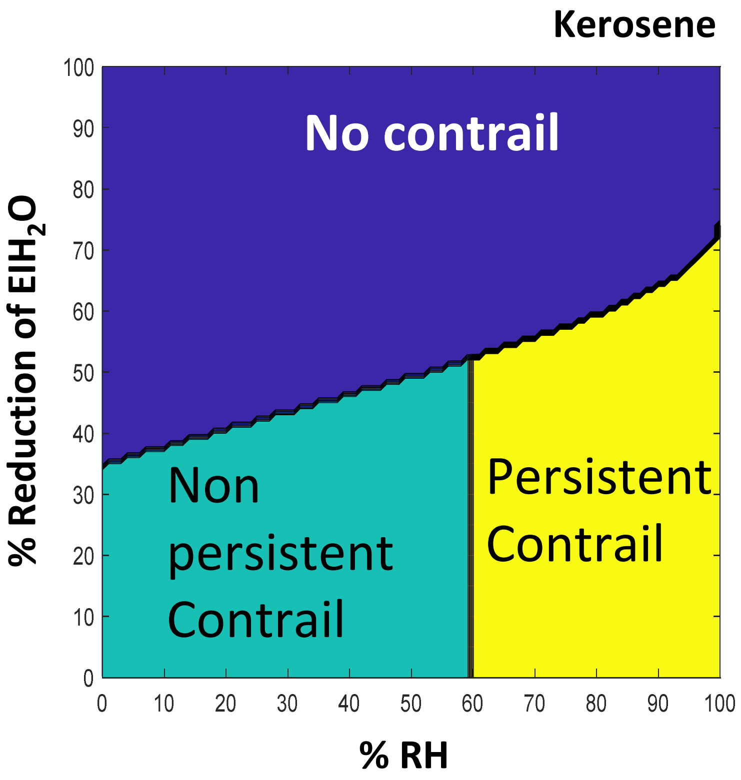
Fuel consumption: -15%

CO_2 emission: -15%

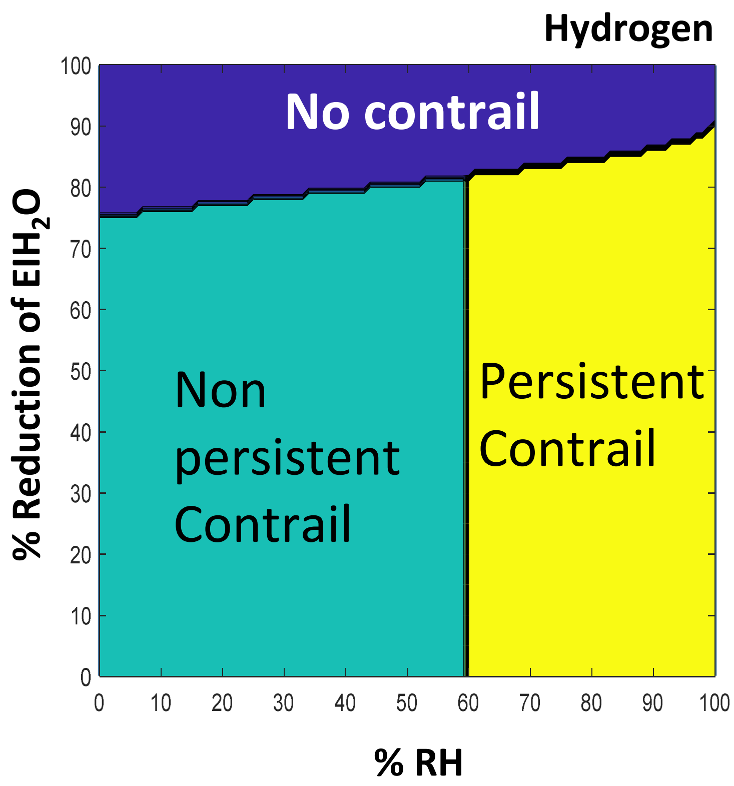
Water recovery > 40%

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

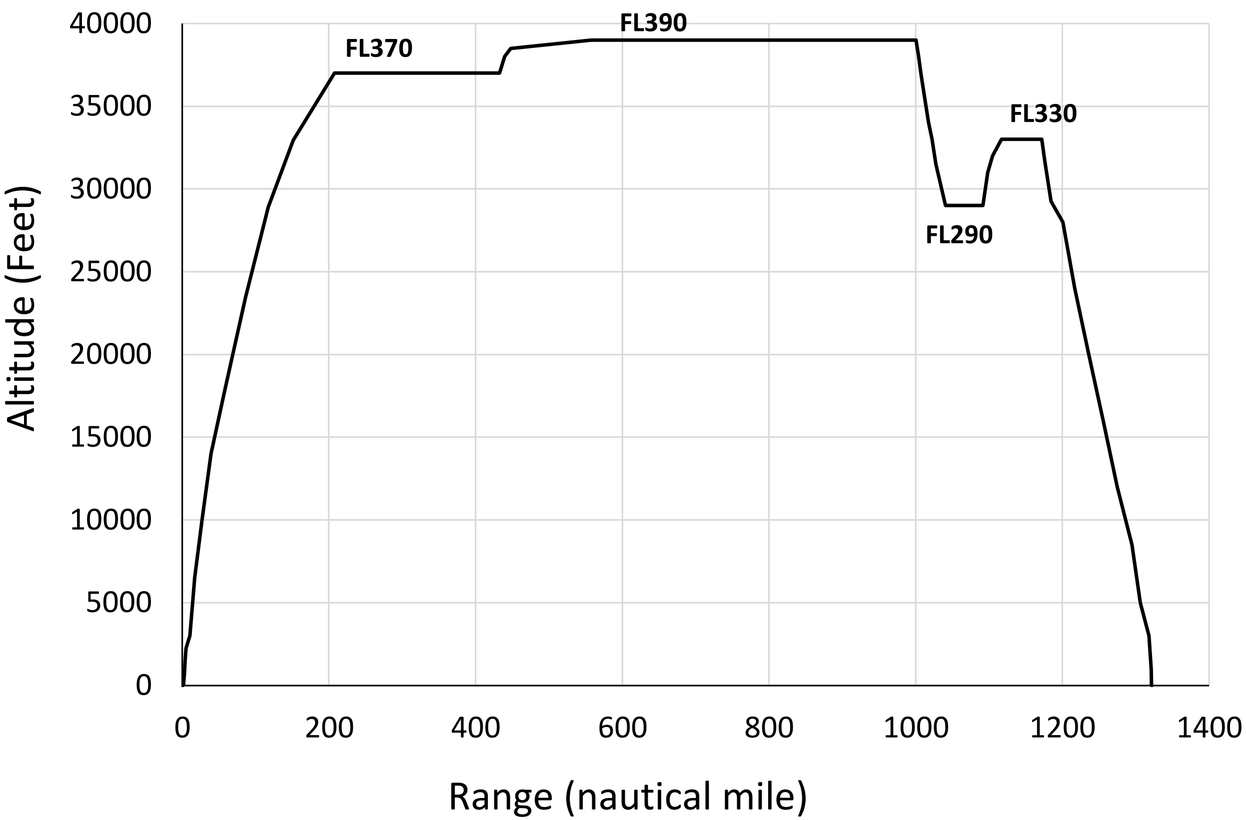
Mission Performance
Cruise : FL370 / M 0.77
Payload: 13000 kg
Load factor : 65.5% (118 pax with 110 kg PL)

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

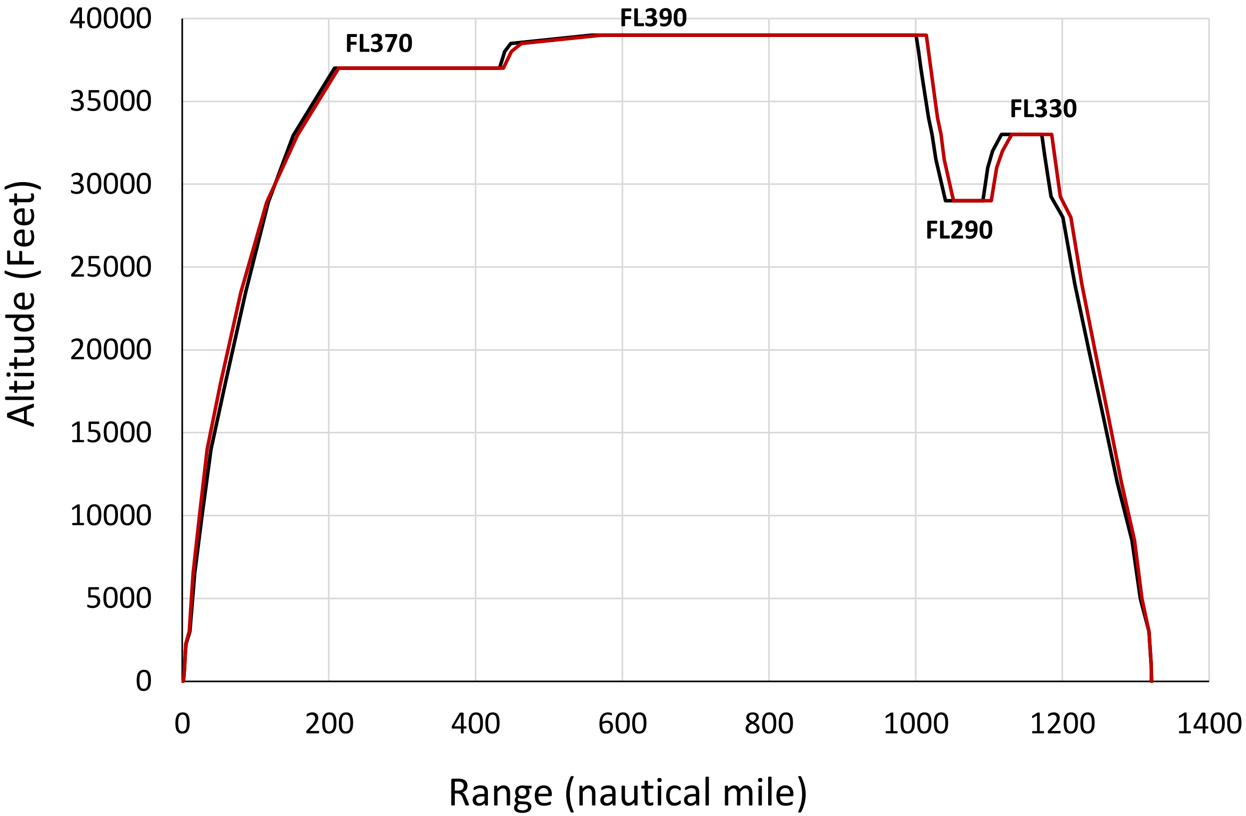
Cruise : FL390 / M 0.77
Payload: 13000 kg

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**

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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

Improved SMR aircraft#

Mission Performance

Cruise : FL390 / M 0.77
Payload: 13000 kg

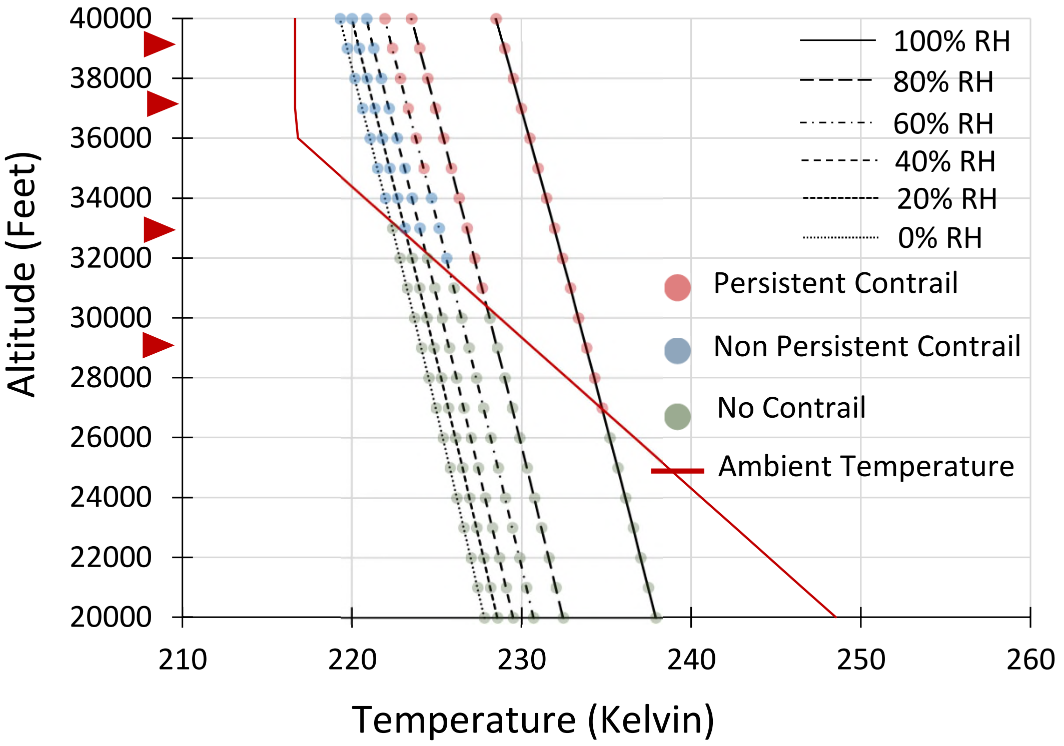
TOW: 65730 kg
FOB: 8430 kg
Block fuel: 7183 kg
Mission time: 3 hrs 22 min

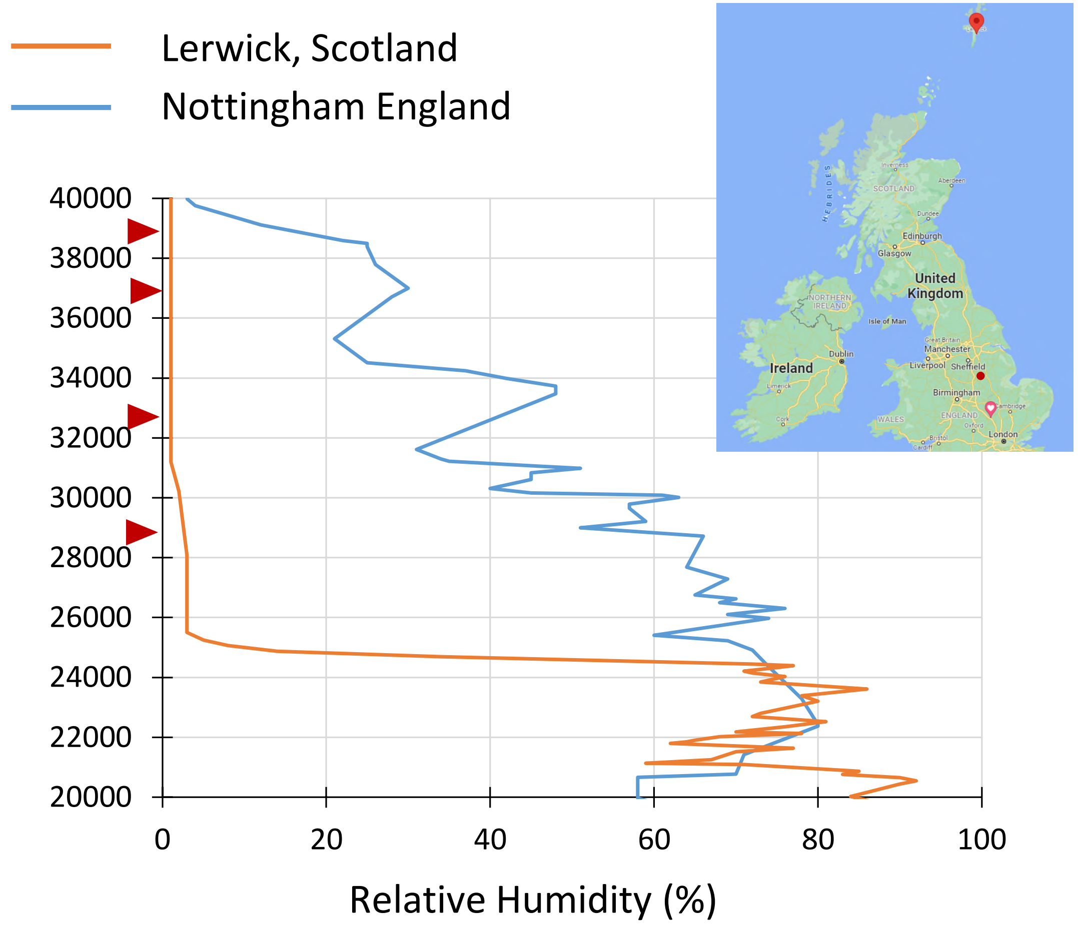
Mission fuel burn reduction – 14.1%

*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

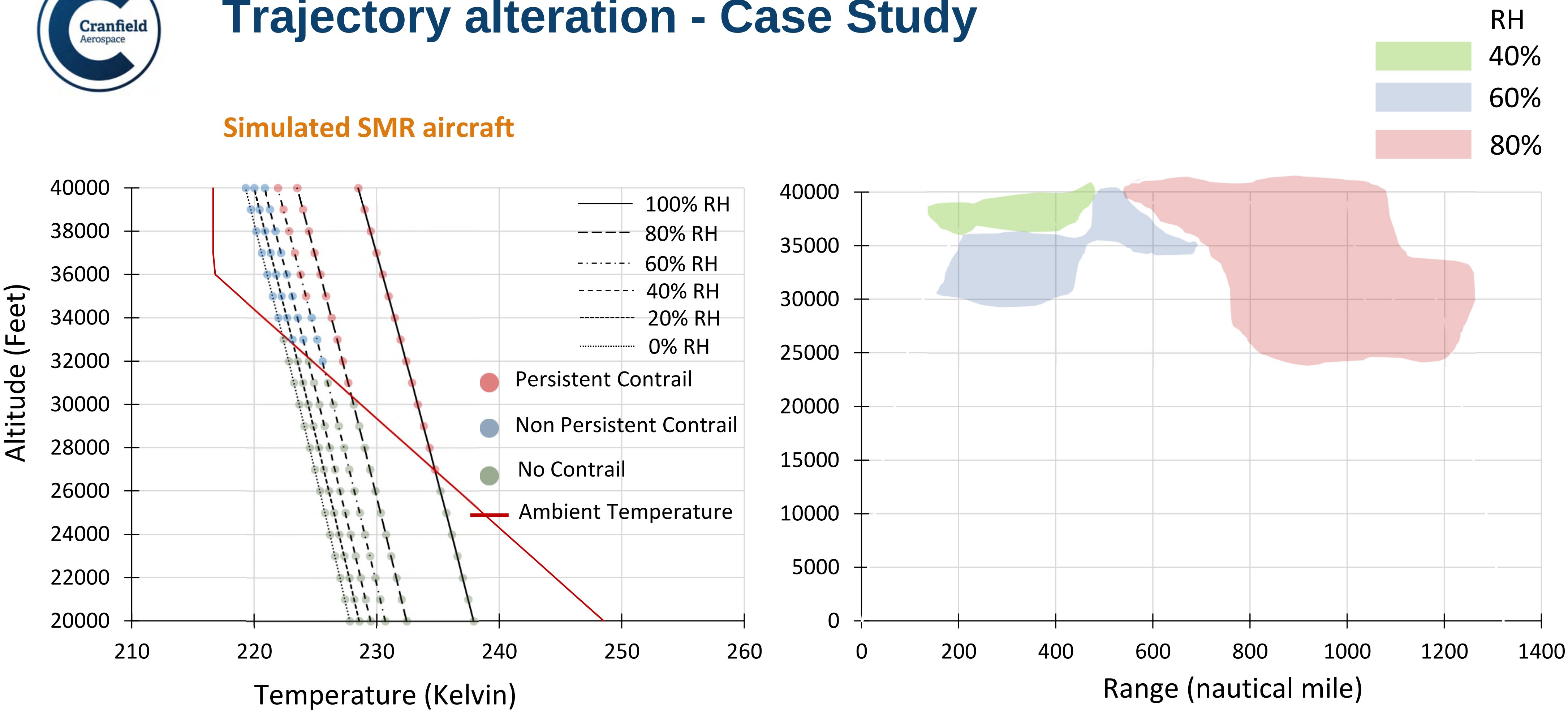




http://weather.uwyo.edu/upperair/sounding.html

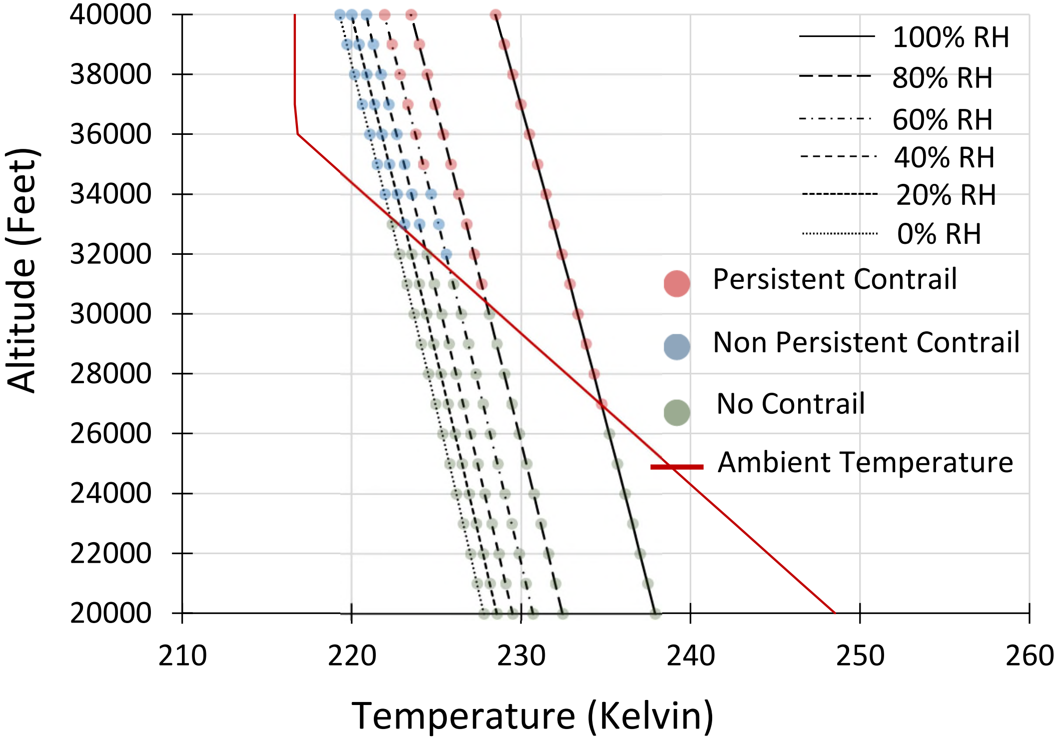
Trajectory alteration - Case Study

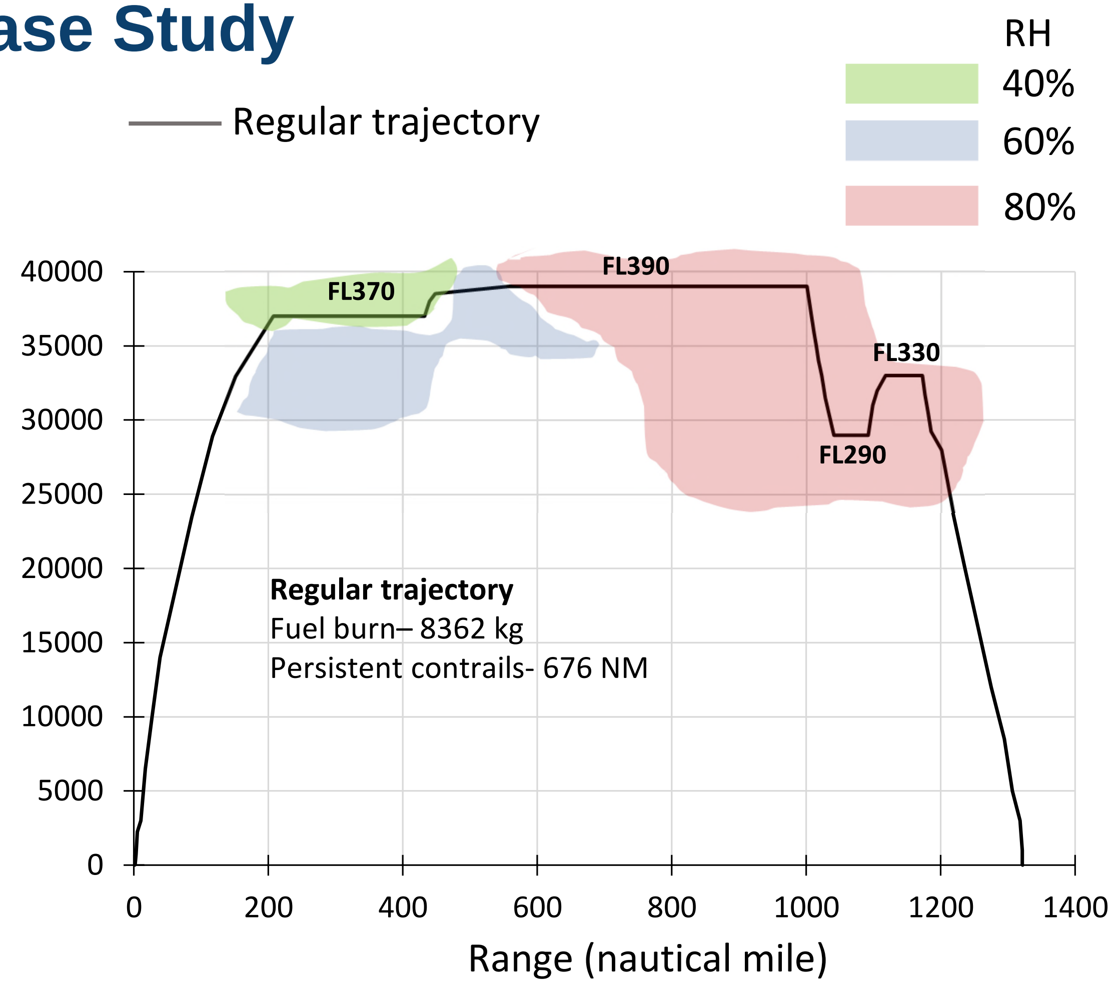
Simulated SMR aircraft



Trajectory alteration - Case Study

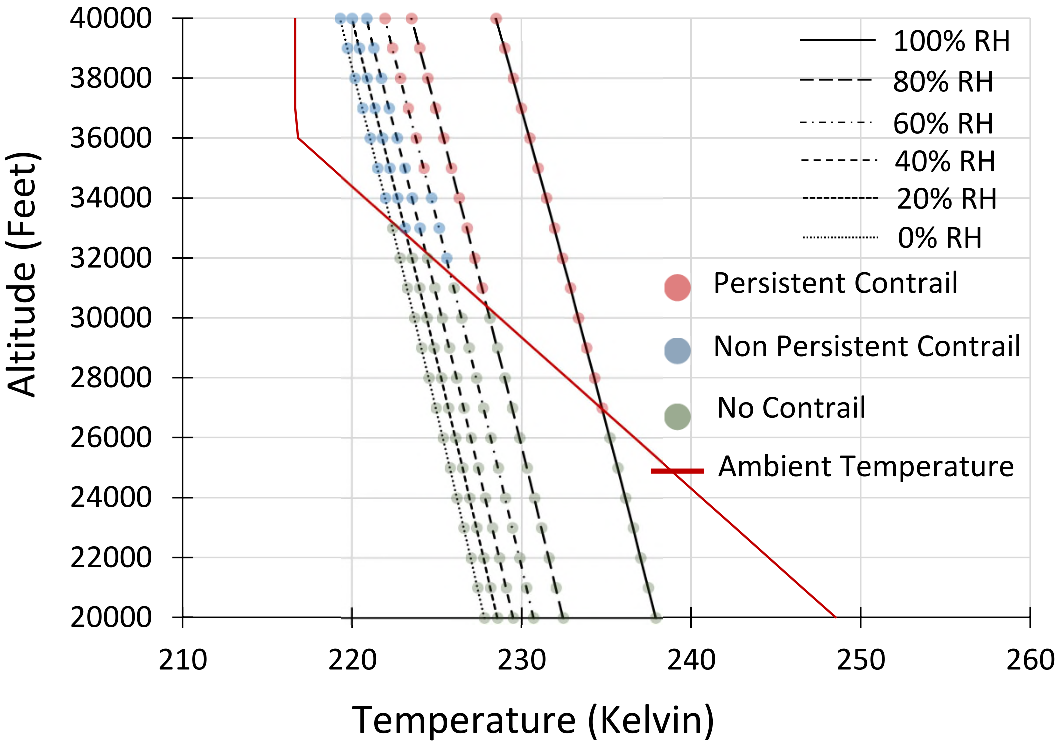
Simulated SMR aircraft

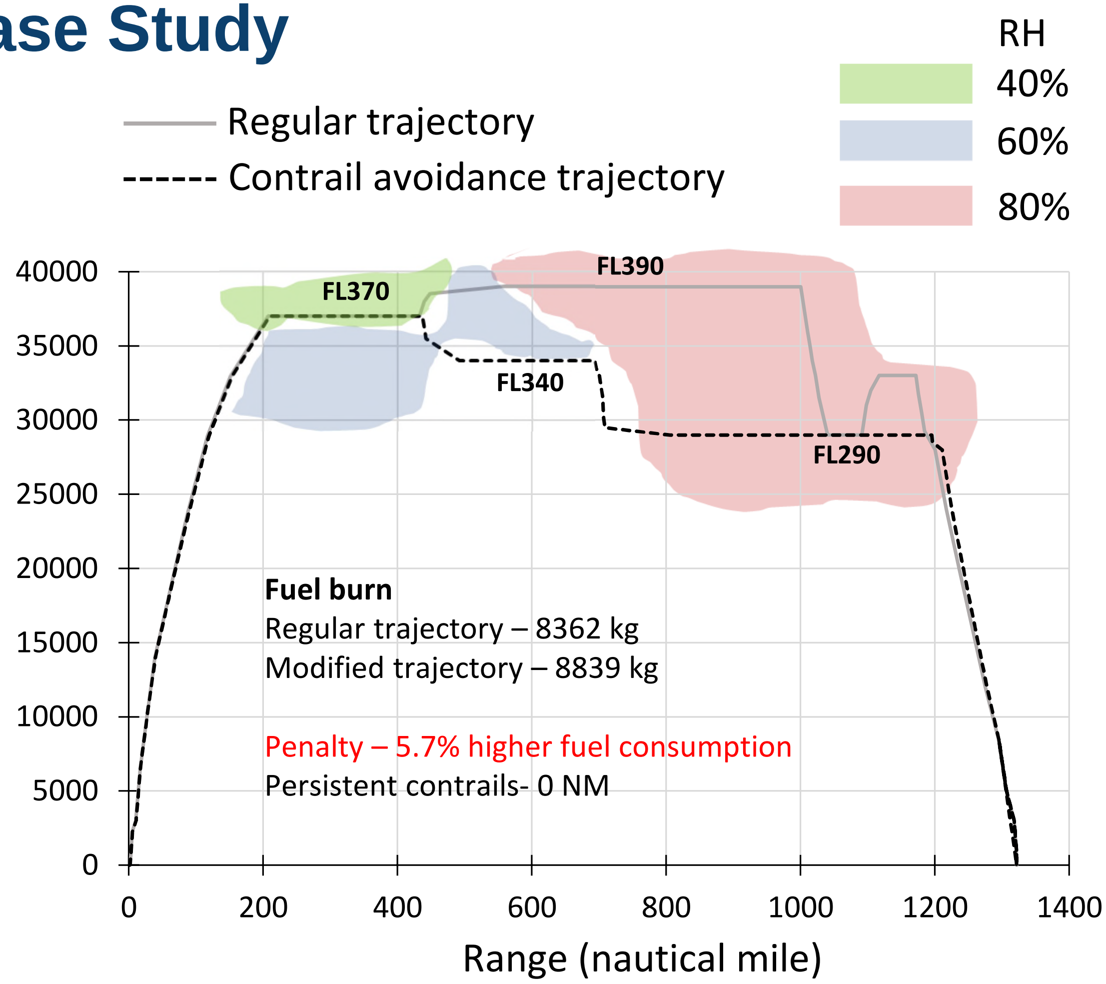




Trajectory alteration - Case Study

Simulated SMR aircraft

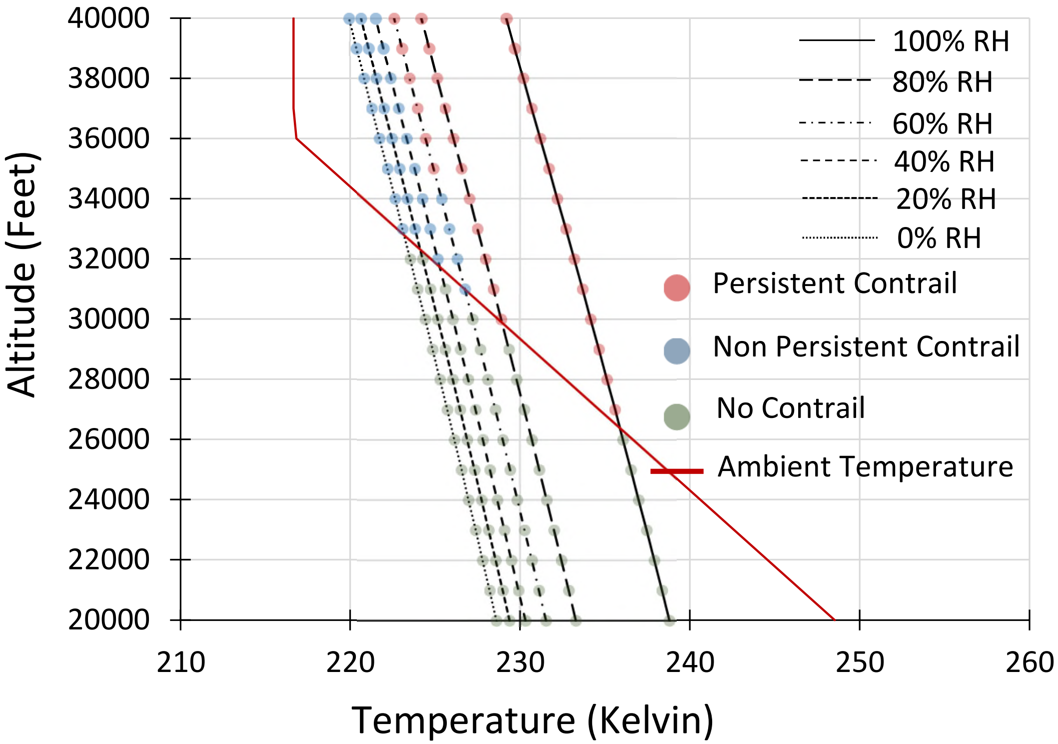


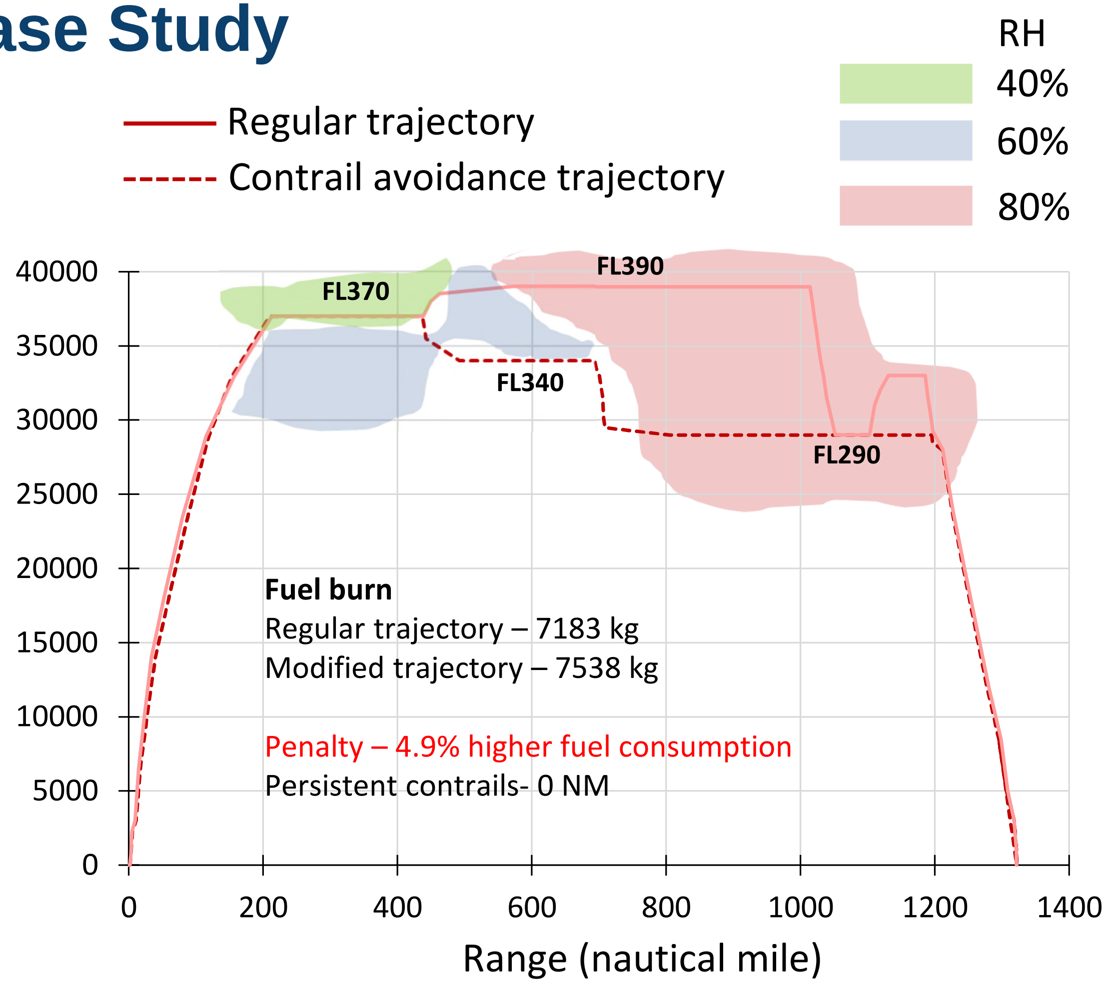


*Based on an A320-100 aircraft with two CFM56 powerplants

Trajectory alteration - Case Study

Improved SMR aircraft





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

Trajectory alteration - Case Study

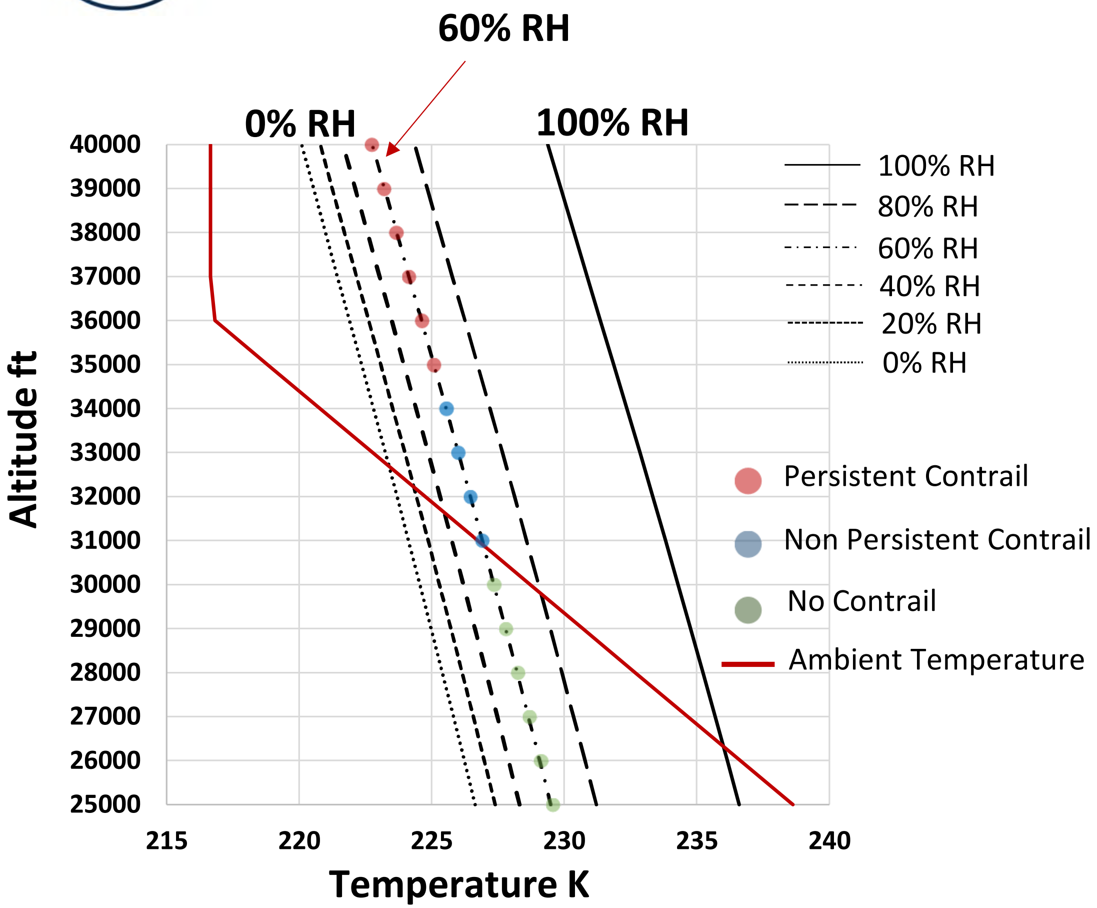
Kerosene fuelled aircraft

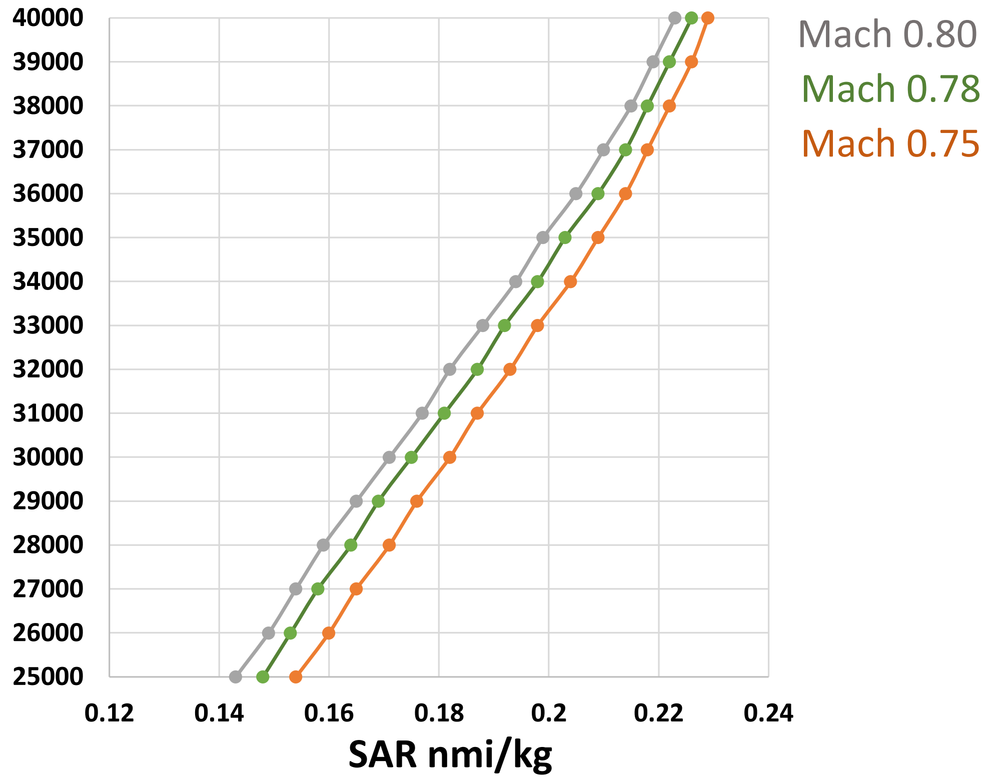
- Upgraded propulsion system enables **14.1%** improvement in fuel burn (kerosene)
- The aircraft performance simulation indicated the aircraft would produce over 675 NM of persistent contrails which would be 51% of the range flown

Contrail avoidance

  - Conventional propulsion system flown on non optimal mission – 5.7% higher fuel consumption
  - Upgraded propulsion system flown on non optimal mission – 4.9 % higher fuel consumption
  - Conventional propulsion system flown on regular mission but upgraded propulsion system flown on non optimal mission **9.9 % improvement in fuel consumption**

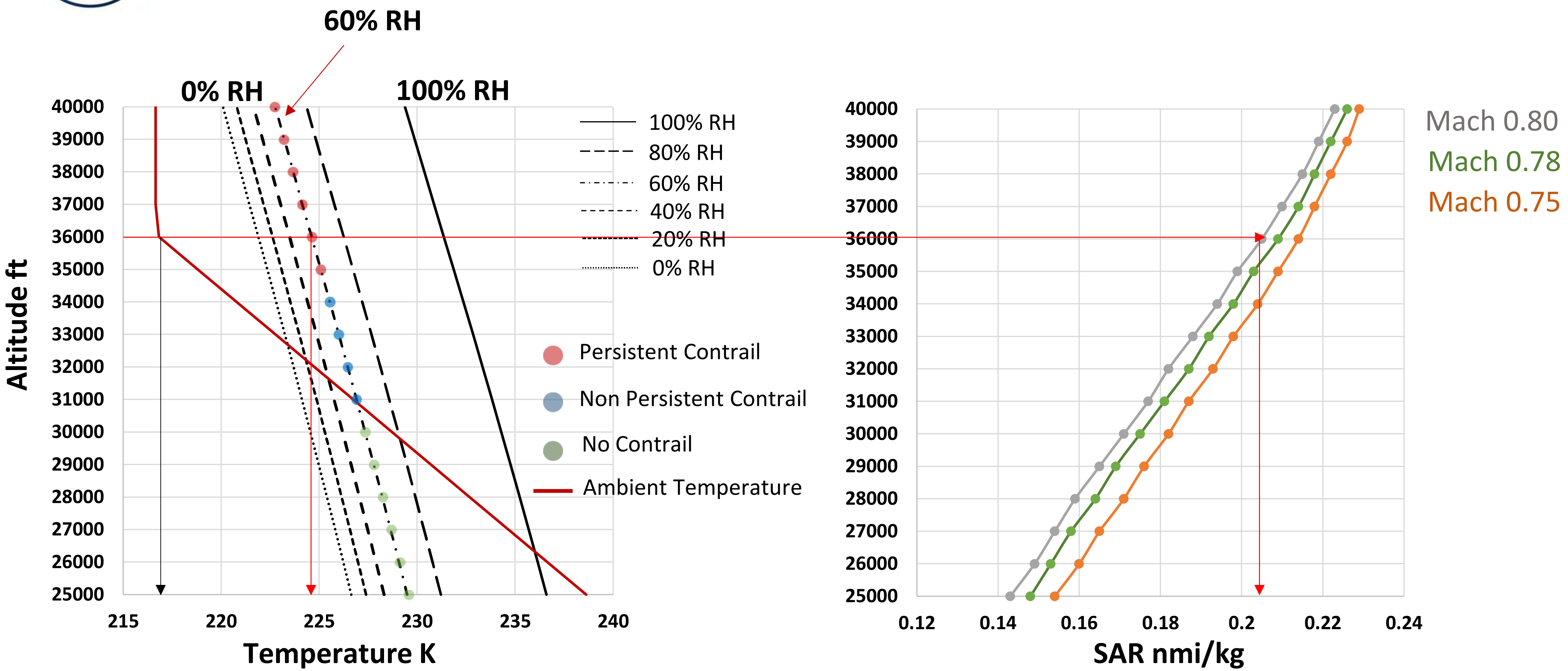
Fuel burn penalty- SAR Analysis





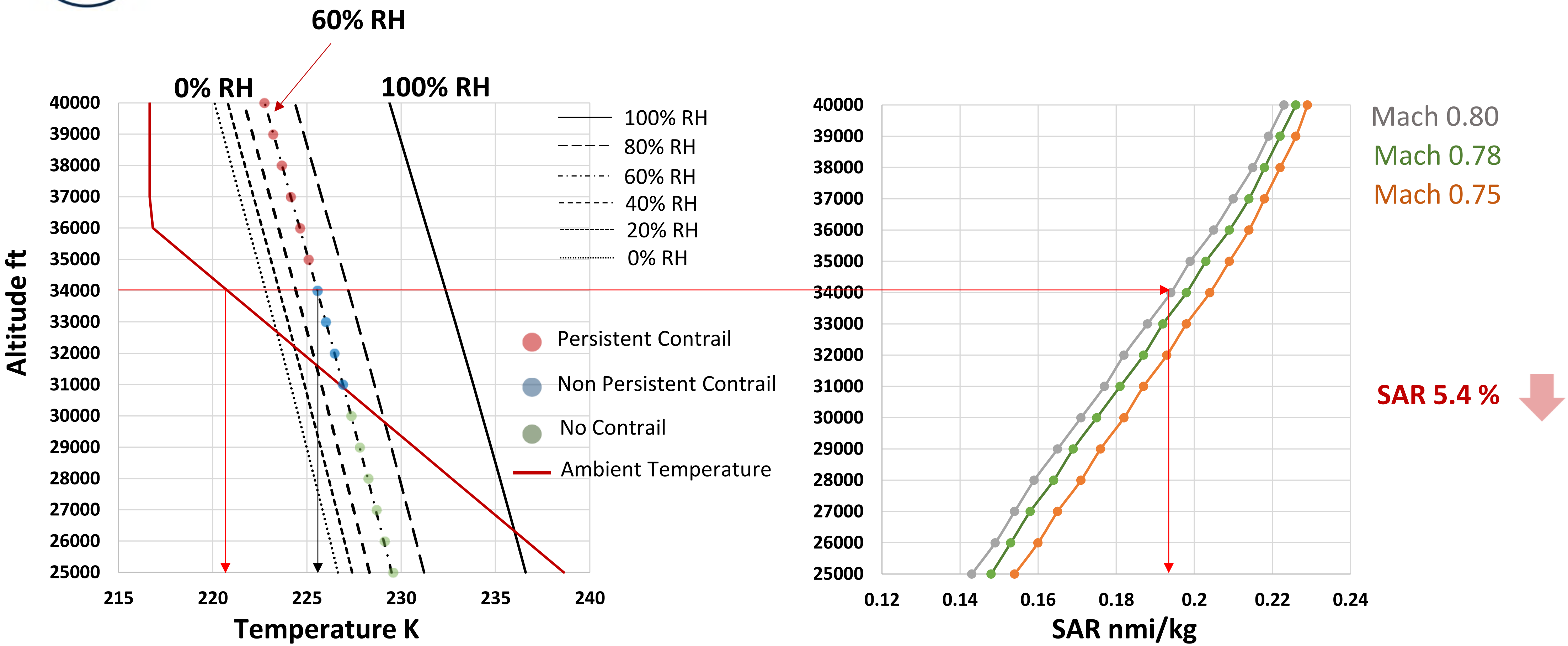
$$SAR = \frac{distance\ flown\ in\ cruise\ (nmi)}{fuel\ burnt\ in\ cruise\ (kg)}$$

Fuel burn penalty- SAR Analysis



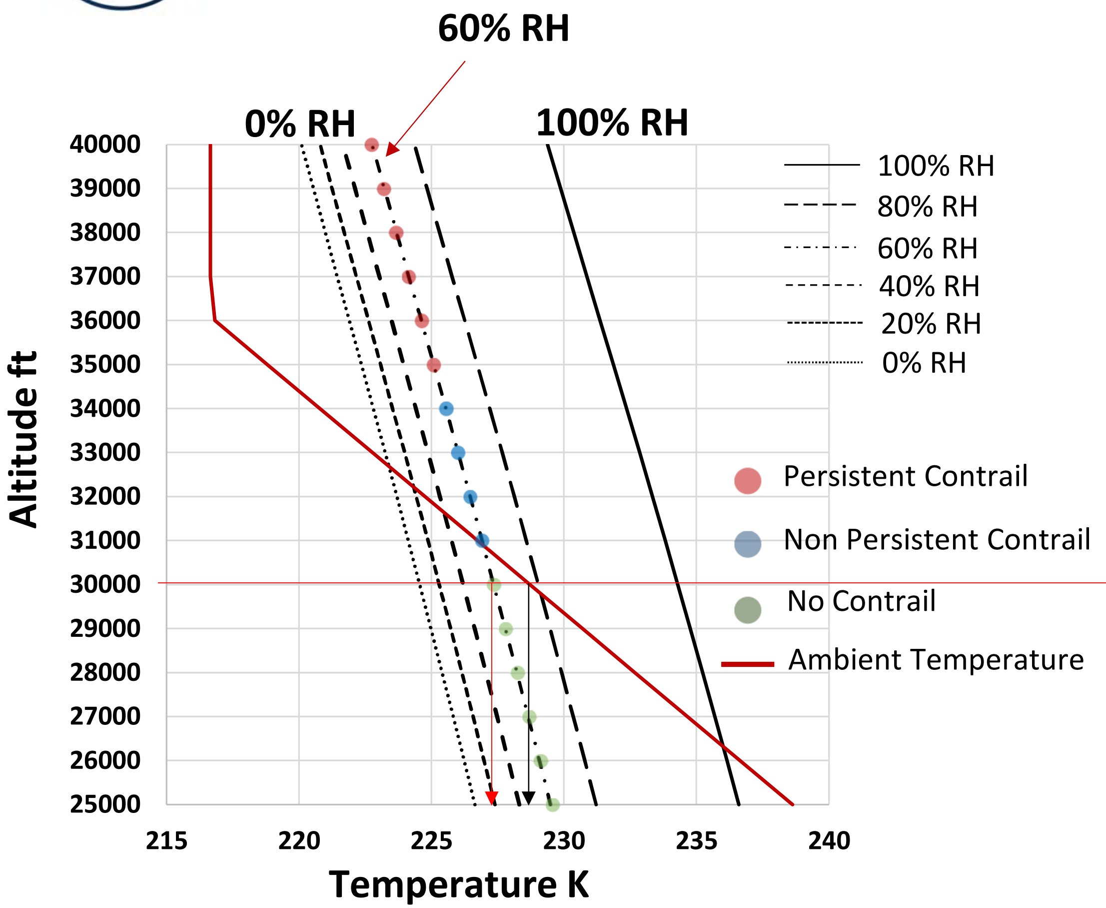
Aircraft flying at FL360/ M0.8 – P Contrails will form (Amb T< TLC) - SAR 0.205

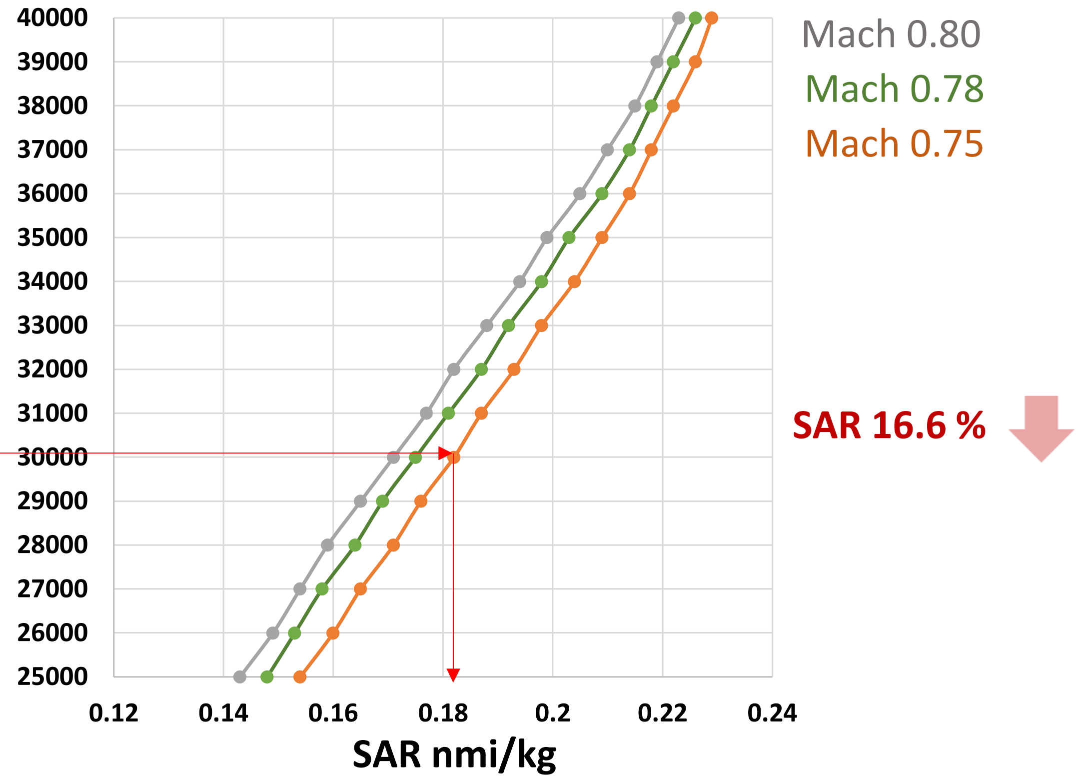
Fuel burn penalty- SAR Analysis



Aircraft flying at FL340/ M0.80 –Non Pers Contrails will form (Amb T< TLC) - SAR 0.194

Fuel burn penalty- SAR Analysis





Aircraft flying at FL300/ M0.80 – No Contrails will form (Amb T> TLC) - SAR 0.171

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

- Trajectory modification and route diversion- effectiveness
- Technology adoption- Water extraction device
- 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%

Conclusions

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

Cranfield
Aerospace

www.cranfield.ac.uk

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