Development and Application of a Fluid-Based Nacelle Ice Protection System

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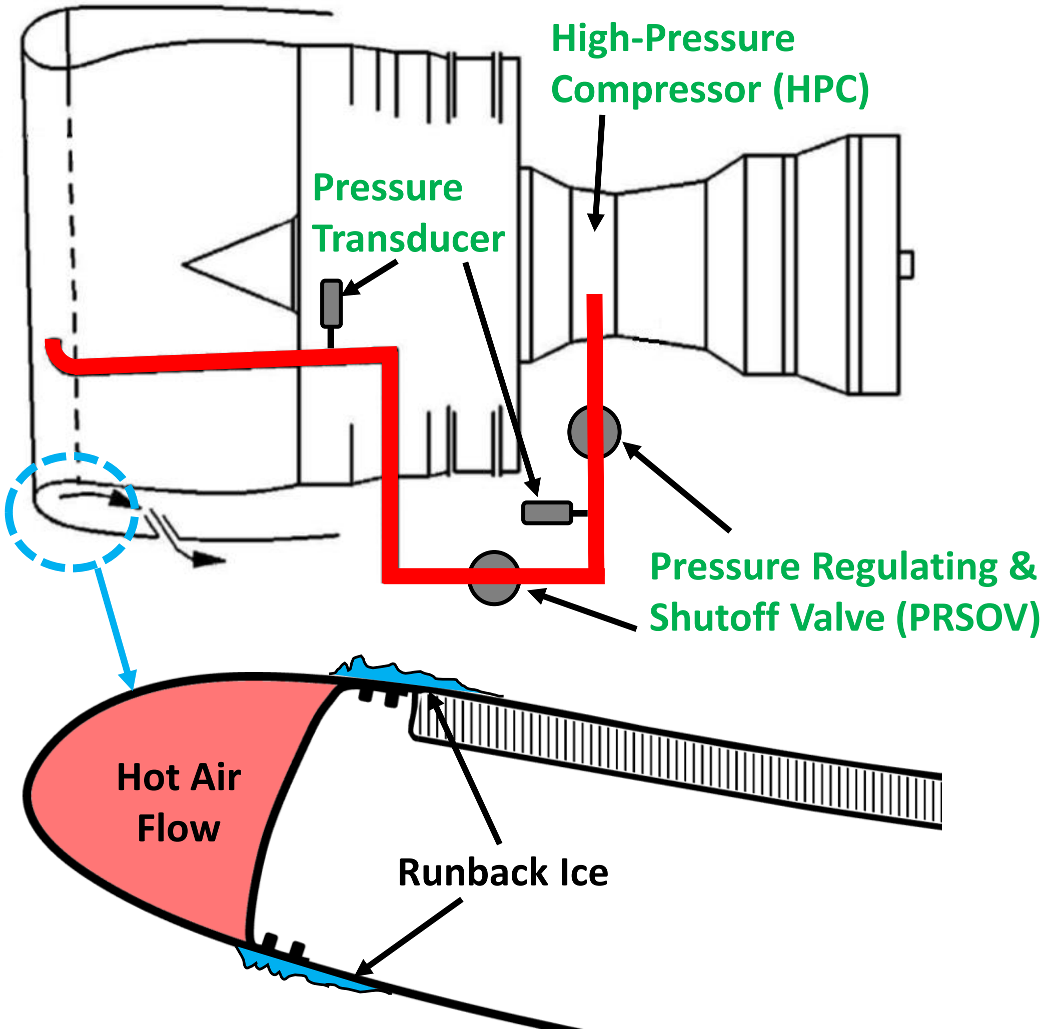
Icing on Nacelle Inlet

- **Ice on nacelle inlet surface**
  - Reduces engine operating performance due to the adverse effect on air flow into the engine
  - Damages fan blades and engine core components if it sheds.

Current Nacelle Anti Ice Protection System

- **Most aircraft with turbofan engines are protected with a hot bleed air Nacelle Anti-Ice System.**
- **Disadvantages**
    - High power consumption,
    - High complexity,
    - Undesirable impact on the engine performance due to operational coupling.
    - Can generate runback ice
    - As hybrid or fully electric aircraft are developed, unlikely hot bleed air or surplus electrical power will be available for the NAIS.



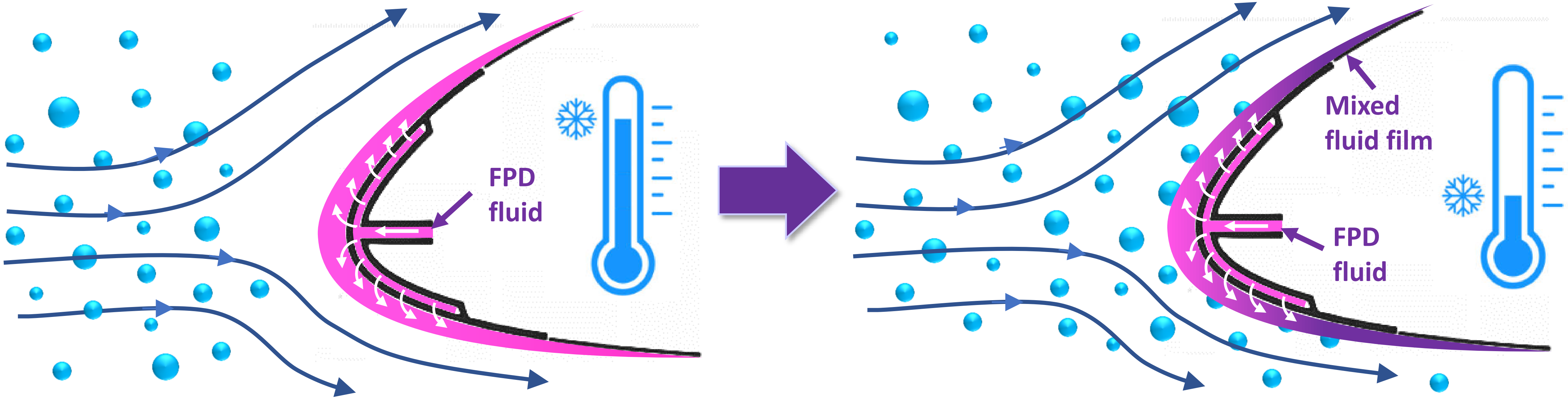
Is there an alternative solution for the future?

TKS Ice Protection System

- A fluid-based anti-ice & de-ice system using a freezing point depressant (FPD) delivered to leading edges of the surfaces requiring ice protection.

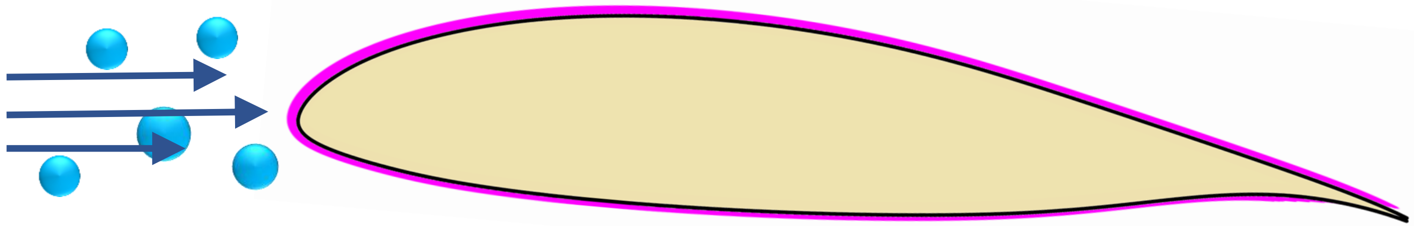
TKS Ice Protection System

- FPD fluid reduces the freezing point of impinging supercooled water to prevent ice formation.

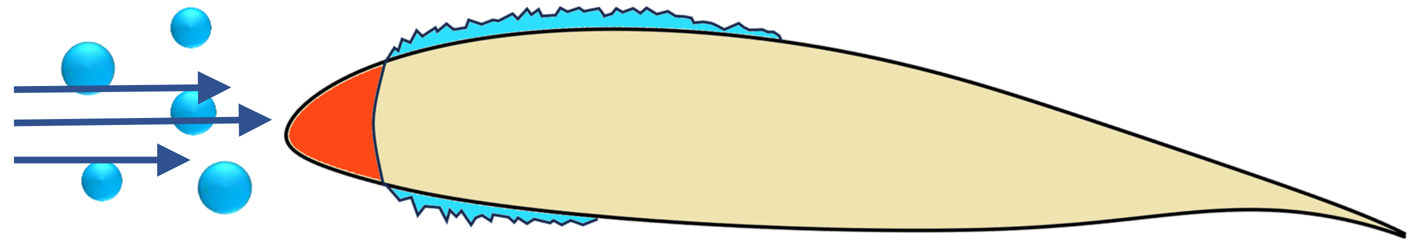


TKS Ice Protection System

- Effective in all icing conditions.
- Protect wing/tail surface from LE to TE
- Enables anti-ice performance in SLD icing condition
- Negligible impact on aerodynamics.



TKS System in SLD condition

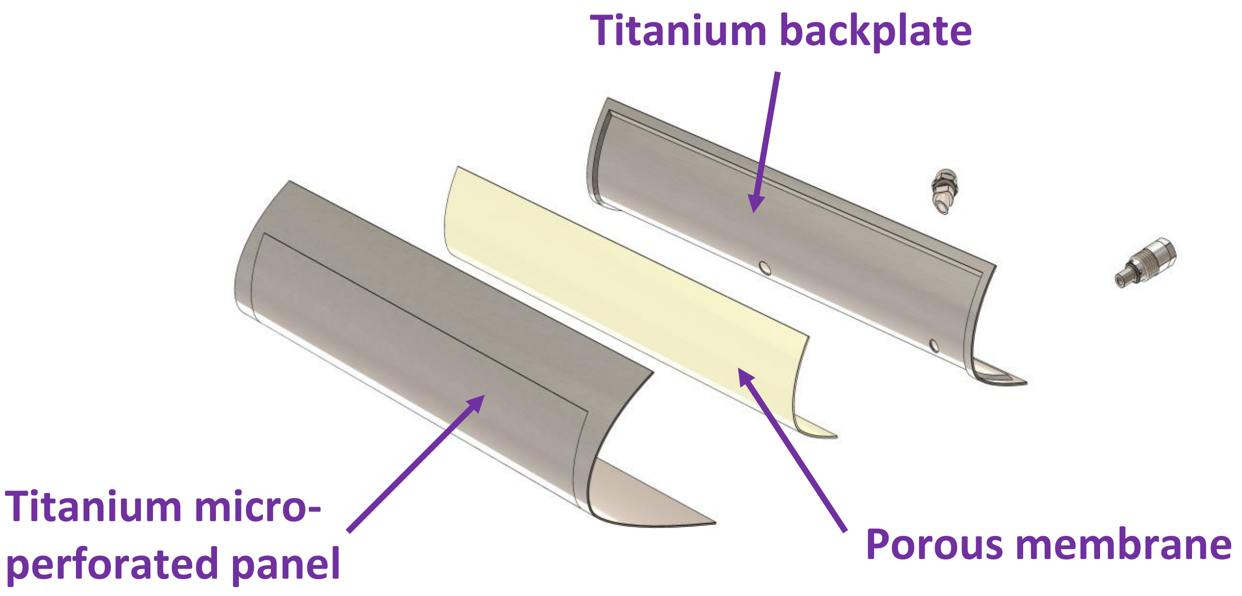


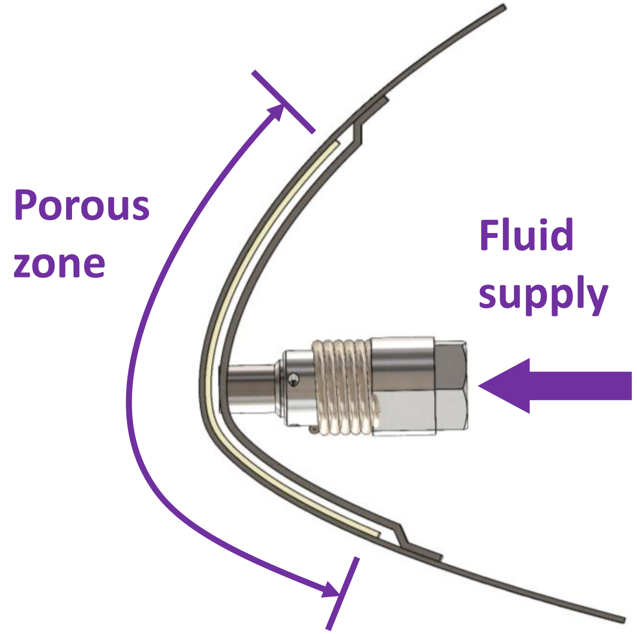
Other system in SLD condition

TKS system in action

TKS Ice Protection System

- Requires only a small footprint <1% chord (TKS) vs 10 to 15% chord (bleed air)
- Requires very low power (100 ~ 200 Watts)
- Reliable and low maintenance



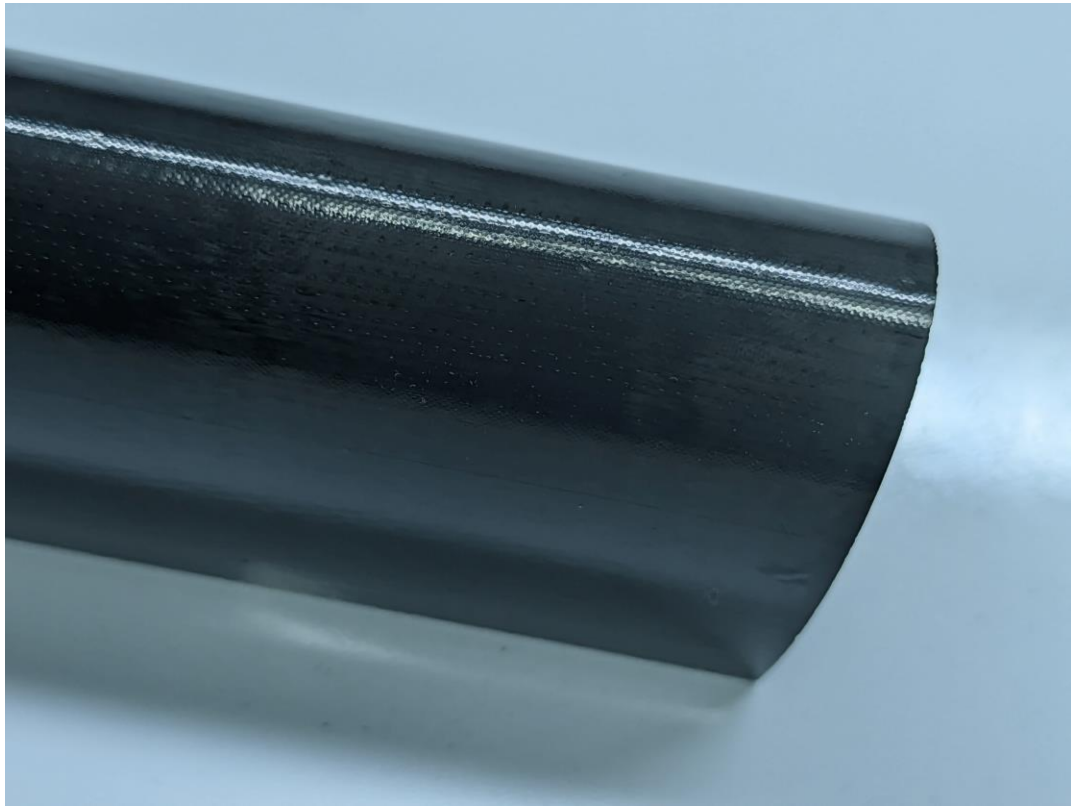


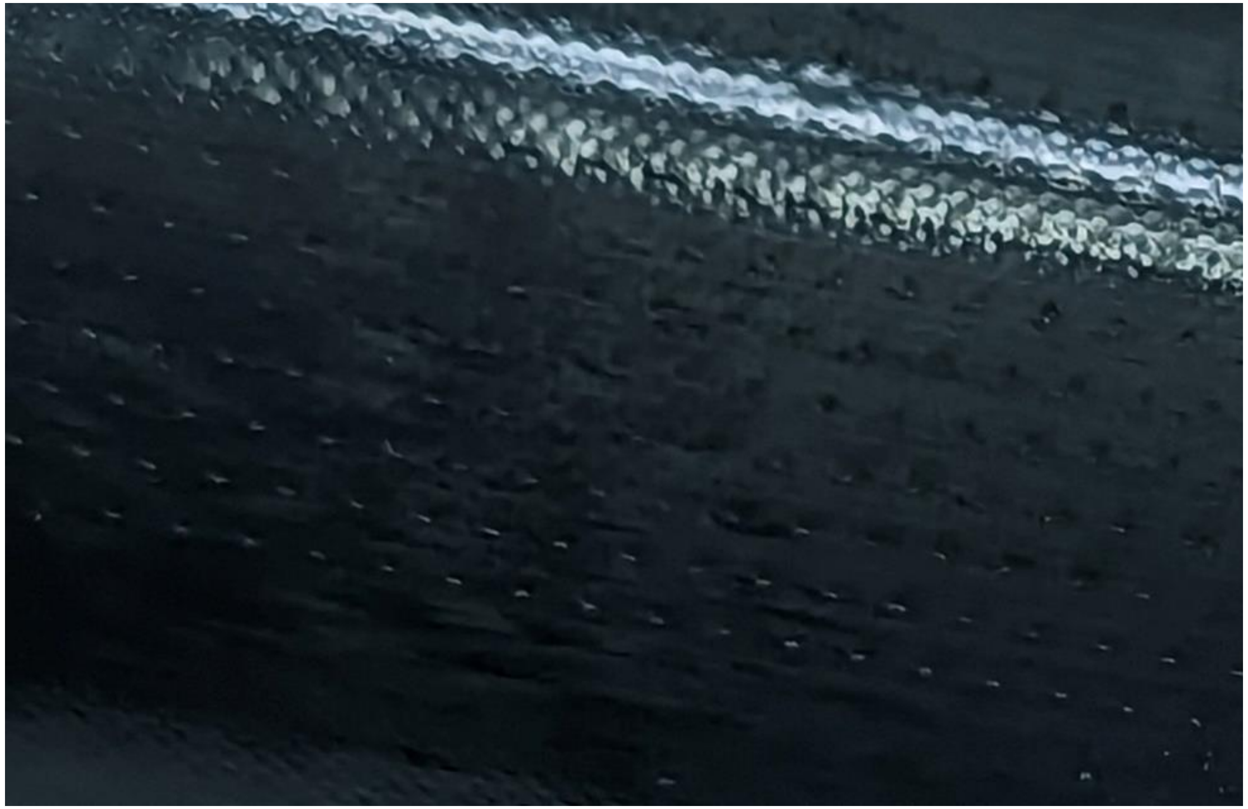
TKS Ice Protection System

- Over 10,000 systems in operation worldwide.
- Over 80 years of experience in ice protection.

TKS Ice Protection System

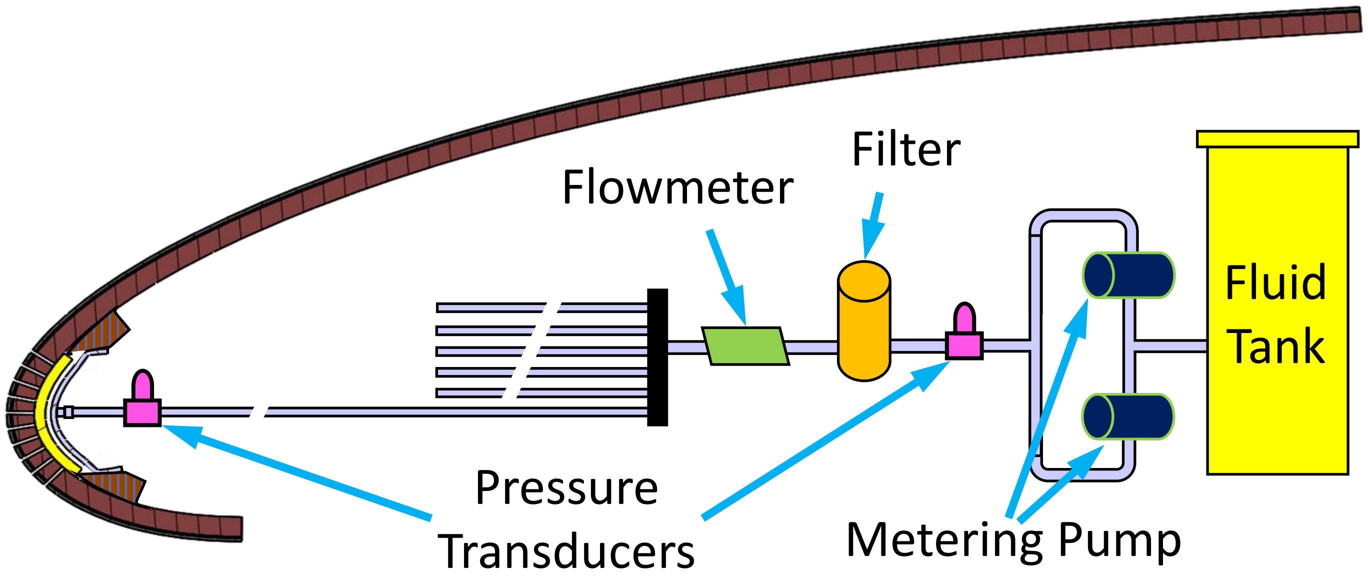
- **Technological advancement enables the production of TKS leading edge panels from carbon fiber reinforced polymer (CFRP) composite materials with complex geometries.**

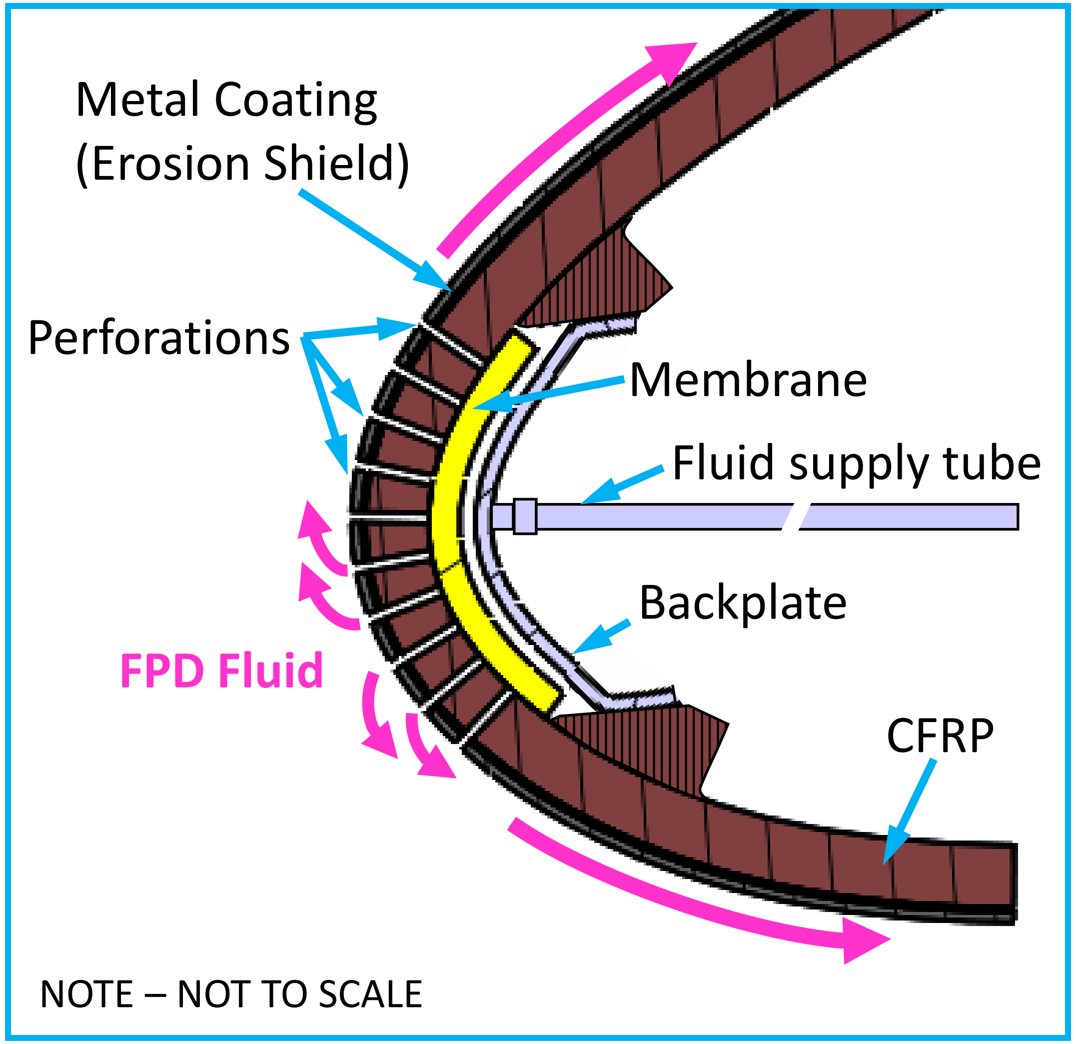




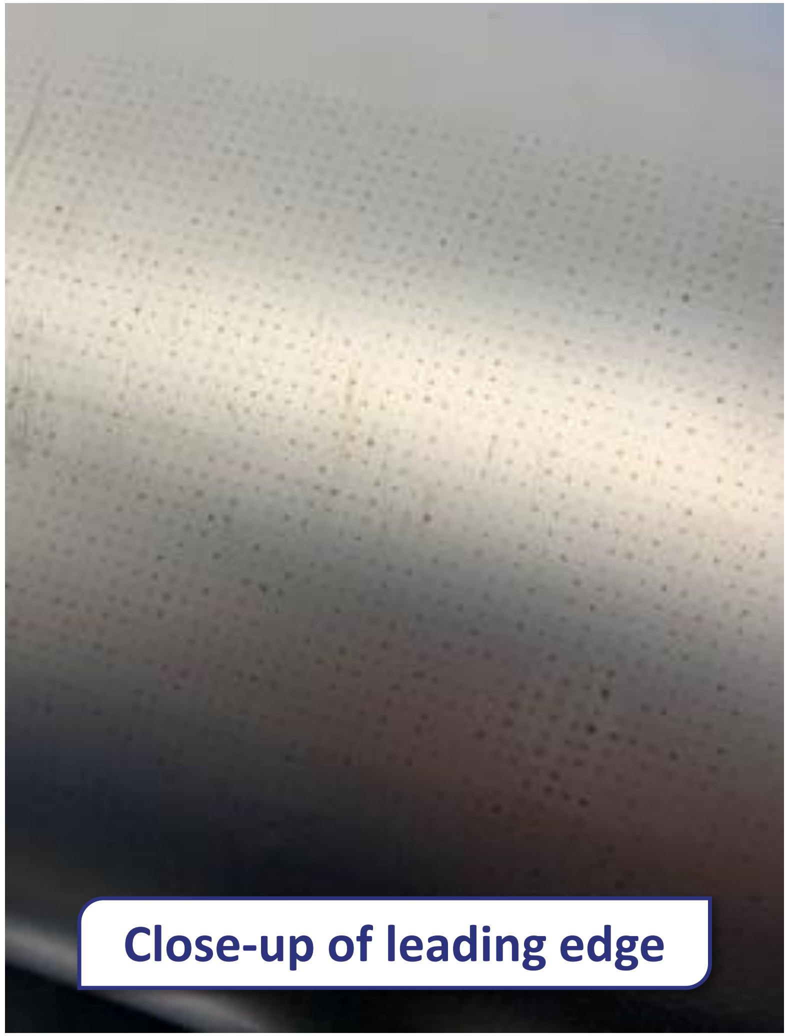
TKS Ice Protection System on Nacelle Inlet

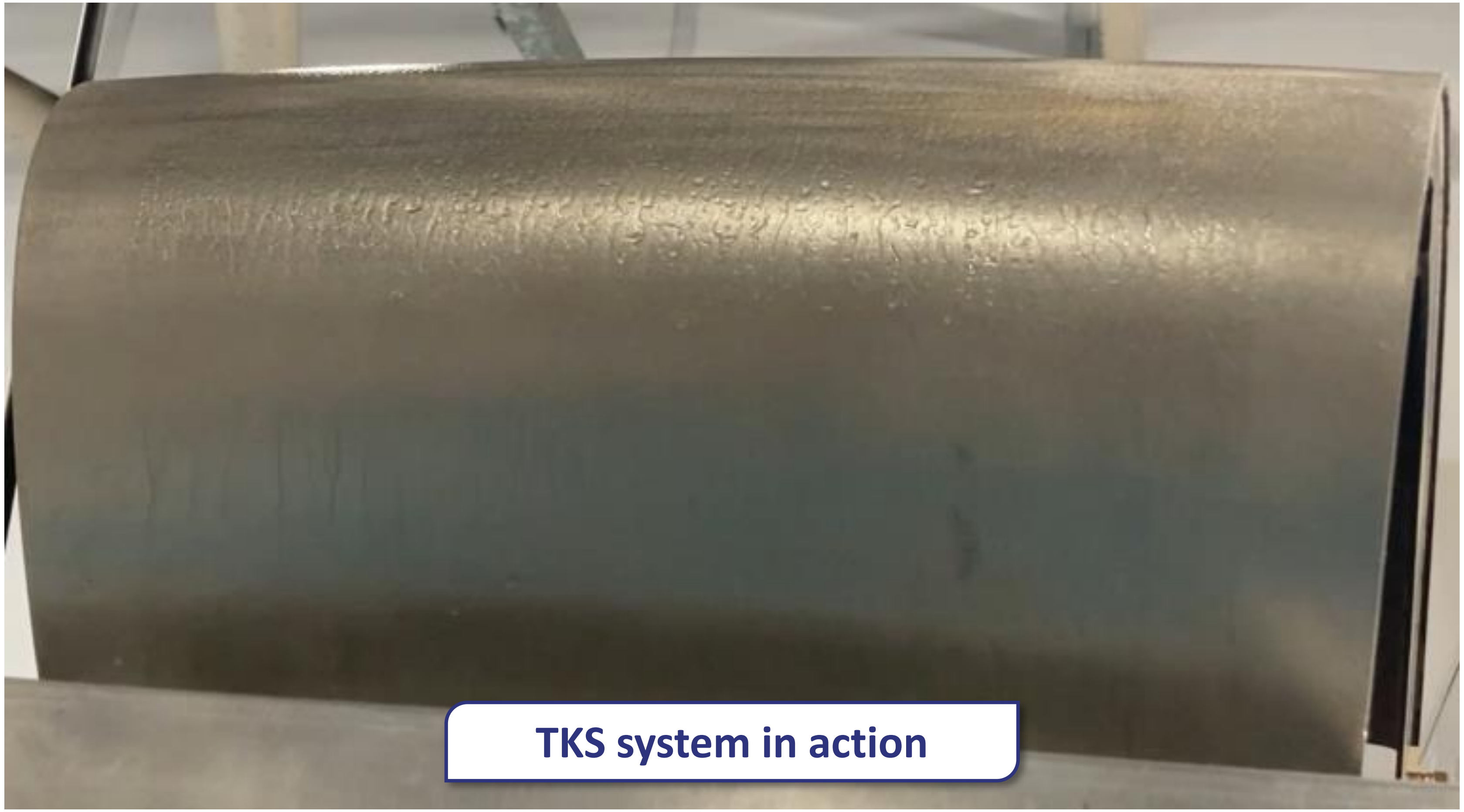
- **The system operates at ambient temperatures which enables the use of CFRP materials on lipskin for weight reduction and improved manufacturability.**
- **The external surface of the composite lipskin has an electroplated metallic coating providing an erosion shield that protects the composite skin from leading edge damage.**





TKS Ice Protection System on Nacelle Inlet





TKS Ice Protection System on Nacelle Inlet

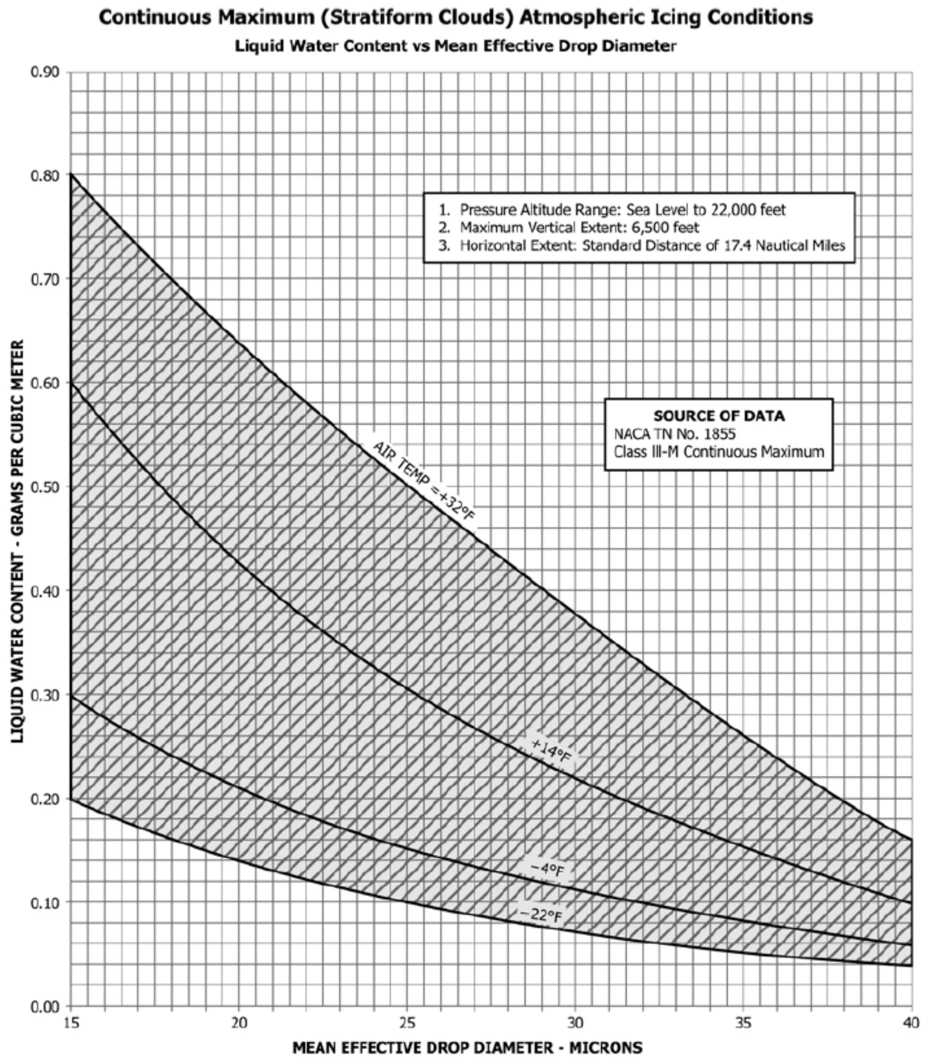
- **A nacelle for a engine powering a Boeing 767-400ER-size aircraft was modelled**

Parameter	Values
Fan Diameter	100 inches (254 cm)
Takeoff Thrust	62,000 lbf (276 kN)
Compressor	1 fan, 3-stage LP, 10-stage HP
Bypass Ratio	11
Overall Pressure Ratio	45:1
NAI Bleed Air Source	7th stage HPC
Available NAI Beed Air Mass flow (%W26)	≤1%

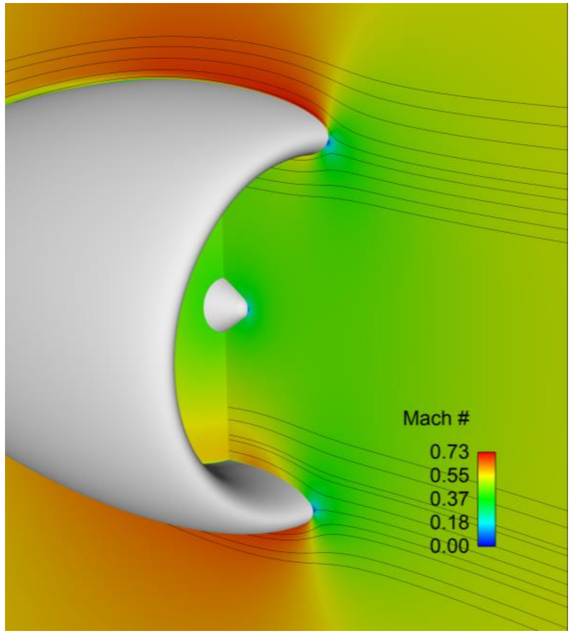
Flight and Icing Conditions

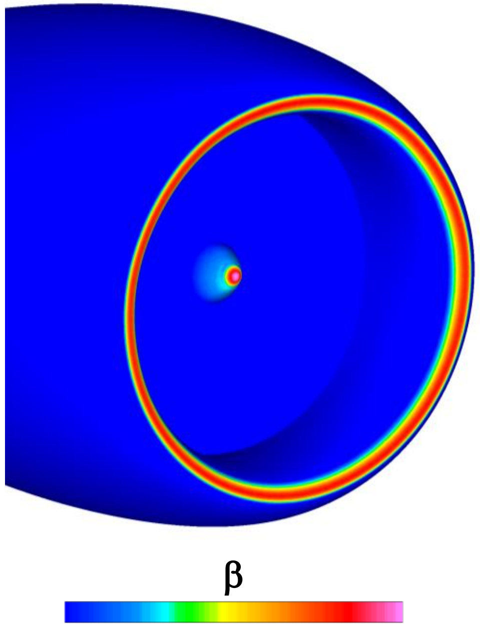
- **Following conditions were considered for design and modelling TKS and Bleed Air IPS for comparison.**

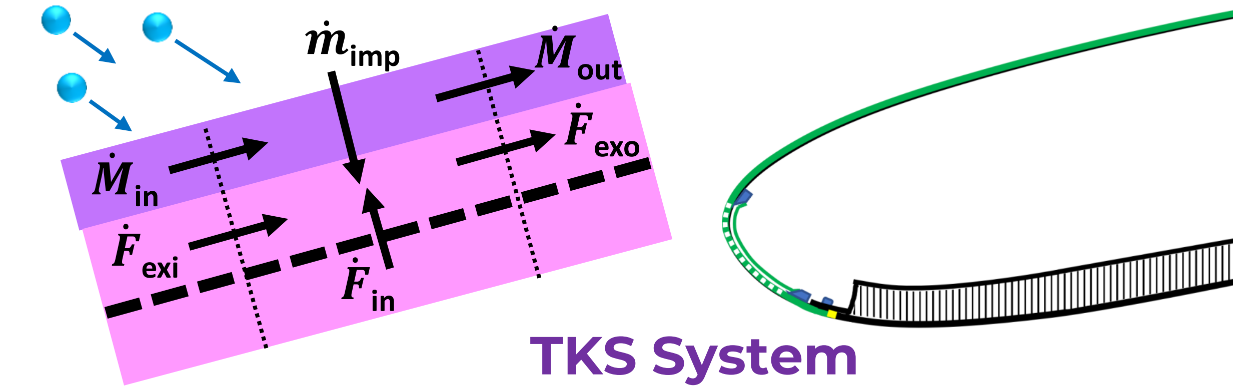
Flight Phase	Altitude	Mach	Corrected Inlet Airflow	Inlet AoA (wrt engine centerline)
	ft		lb/sec	deg
MCL	5000	0.42	2060	4.5
MCL	15000	0.56	2200	3.0
Descent	5000	0.41	915	5.0
Descent	15000	0.50	1150	5.0
Heavy Hold	15000	0.48	1670	7.0

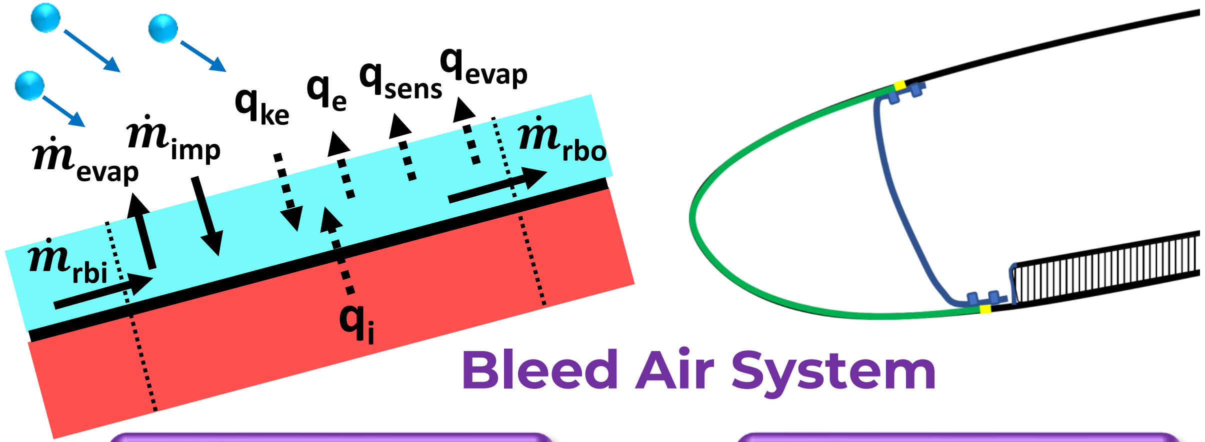


Modeling TKS and Bleed-Air IPS on Nacelle Inlet









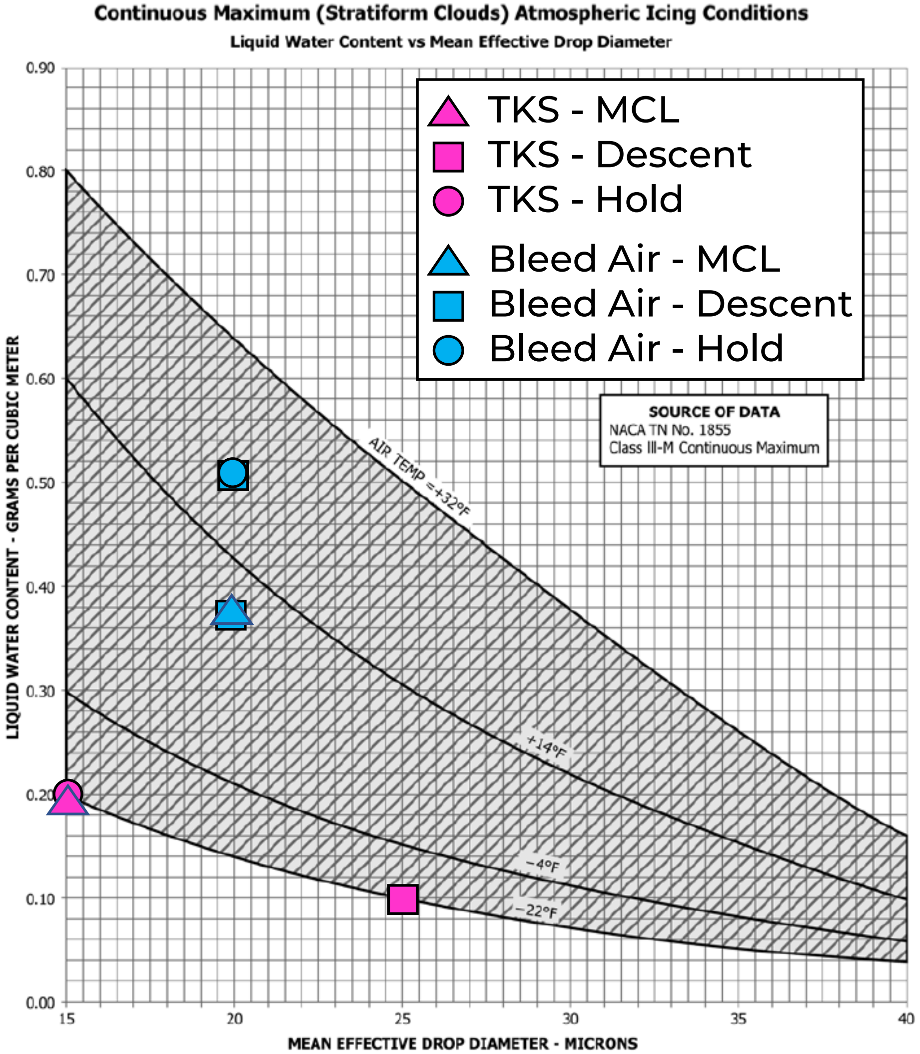
Aerodynamics Analysis → Icing Analysis → Heat/Fluid Requirement → IPS Design

Performance over Severe Icing Conditions

Critical Icing Conditions for TKS and Bleed Air IPS

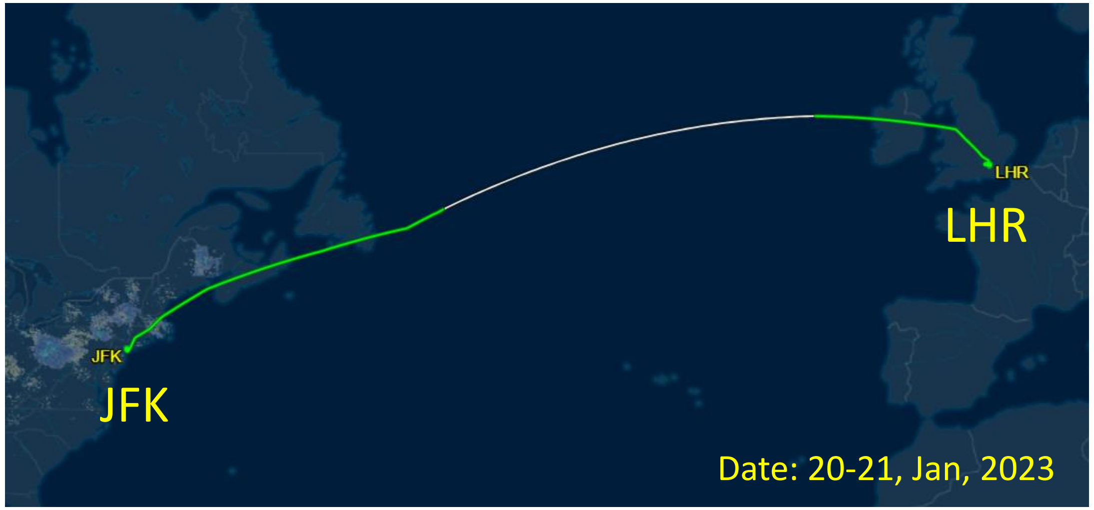
						TKS IPS	Bleed Air IPS	
Flight Phase	Altitude (ft)	Mach	LWC (g/m³)	MVD (μm)	Temp (°C)	Fluid Required (mL/min)	Ave. Heat Available (kW/m²)	Ave. Heat Required (kW/m²)
MCL	15,000	0.56	0.20	15	-30.0	654.3	15.3	4.6
Descent	15,000	0.50	0.10	25	-30.0	627.8	8.0	5.6
Hold	15,000	0.48	0.20	15	-30.0	537.4	10.3	3.6
MCL	15,000	0.56	0.38	20	-11	623.1	16.2	19.6
Descent	15,000	0.50	0.38	20	-11	556.4	7.4	14.7
Descent	5,000	0.41	0.51	20	-6.1	399.1	8.6	11.4
Hold	15,000	0.48	0.51	20	-6.1	480.9	10.5	16.7

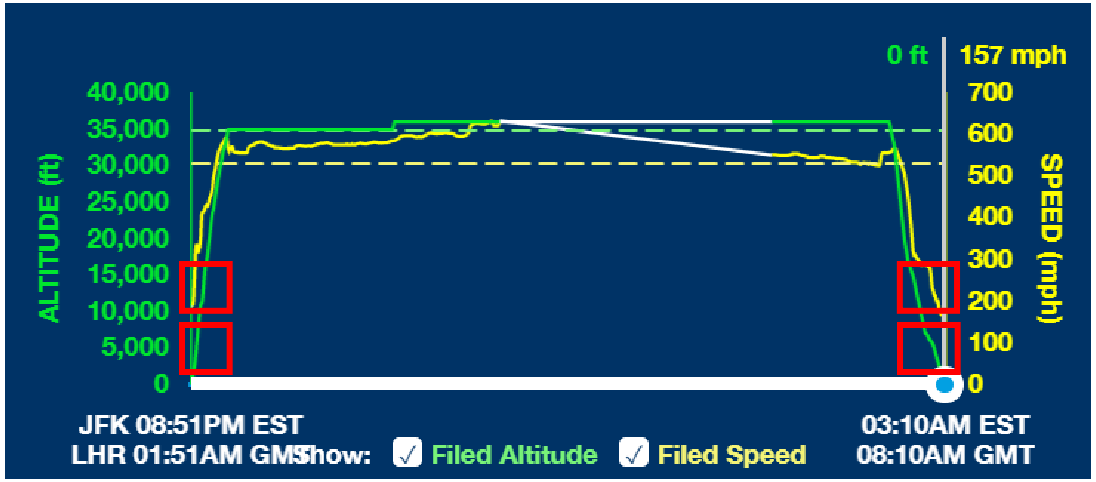
- **TKS IPS can protect all the icing conditions with sufficient fluid.**
- **Bleed air IPS is not able to perform fully evaporative anti-ice for some severe icing conditions due to insufficient heat from engine.**



Annual Fuel (Bleed Air) and FPD Fluid (TKS) Consumption

- Daily flight between New York and London.
- 3 trips (one way) per day → 1,080 trips per year.
- Assumption:
  - 10% of flights encounter icing conditions.
  - Two icing encounters on climb.
    - 2,000 ft to 8,000 ft
    - 10,000 ft to 16,000 ft
  - Two icing encounters on descent.
    - 16,000 ft to 10,000 ft
    - 8,000 ft to 2,000 ft
  - All encounters are a 50th percentile LWC CM icing with 15-μm MVD for the horizontal extent of a standard 14 CFR Part 25 Appendix C cloud [1].
- Flight airspeeds and icing encounter times were derived from actual flight data of 767-400ER [2].





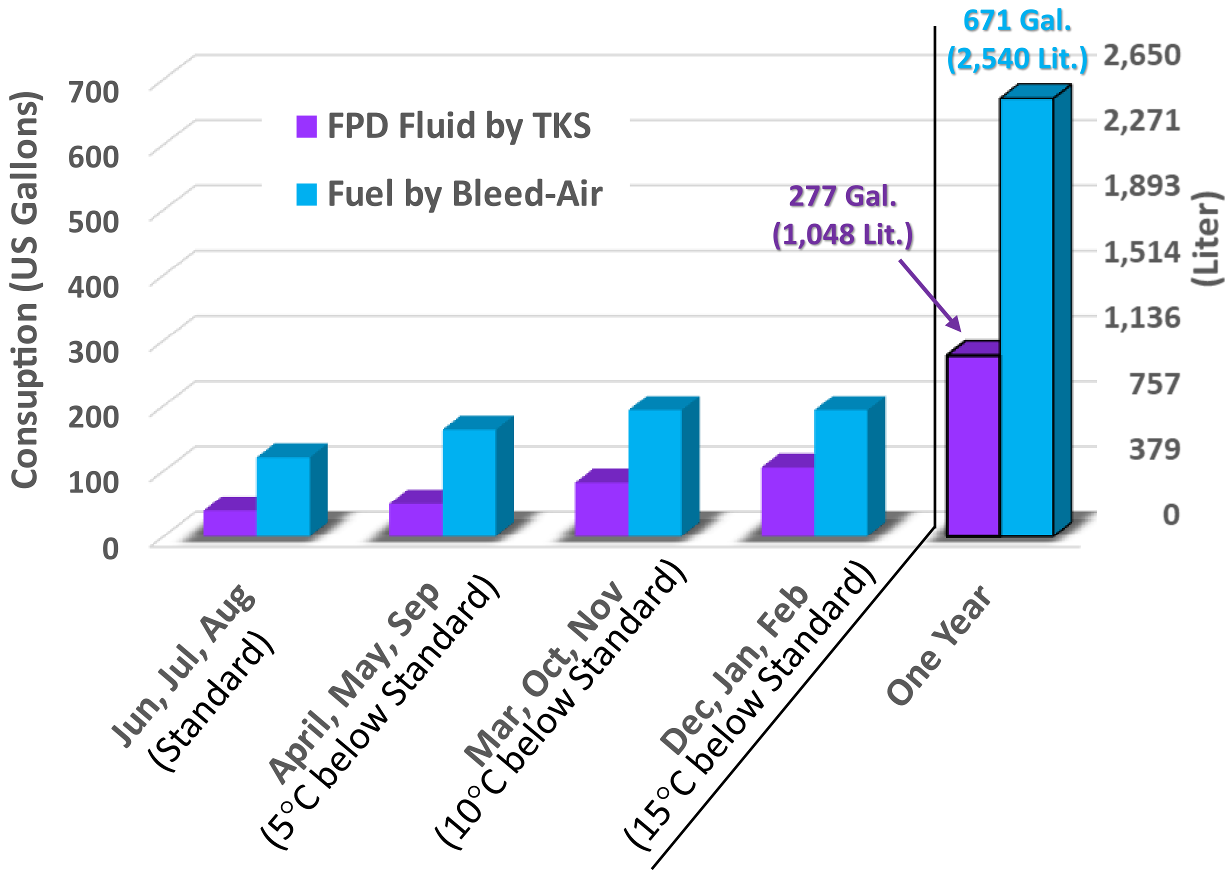
Ref 1: R. K. Jeck, "Advances in the Characterization of Supercooled Clouds for Aircraft Icing Applications," FAA Technical Report DOT/FAA/AR-07/4, 2008.

Ref 2: https://flightaware.com/live/flight/DAL1/history/20230121/0110Z/KJFK/EGLL

Annual Fuel (Bleed Air) and FPD Fluid (TKS) Consumption

Flight Phase	Altitude (ft)	Ave. Airspeed (KTAS)	Ave. Duration (minutes)
Climb	2,000 to 8,000	257	4
Climb	10,000 to 16,000	377	4
Descent	10,000 to 16,000	307	7
Descent	2,000 to 8000	215	11

- FPD fluid usage was based on a "SMART SYSTEM" usage
- The SMART SYSTEM algorithm has been produced by CAV Design
- This algorithm utilizes current aircraft databus parameters plus LWC supplied by LWC sensor



Note: The values are for 2 nacelles (engines)

TKS IPS reduces carbon footprints by reducing fuel consumption of bleed air system

FPD Fluid Tank Sizing

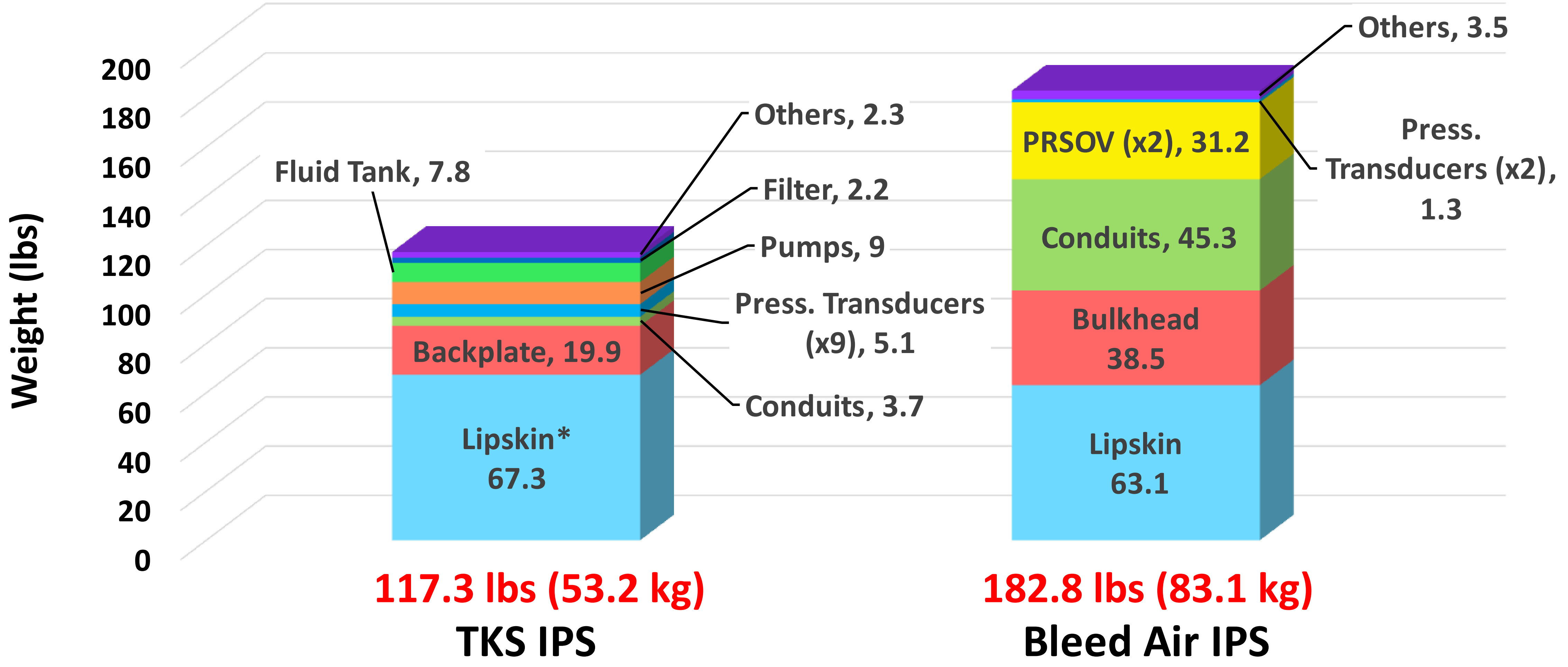
- 8 US Gallons for minimum dispatch quantity
  - Meets 90 minutes in CM icing condition [3].
  - Covers most transatlantic flights (7 to 10 hours)
  - Meets the 45 minute hold requirement in CM icing conditions [3].
- 16 US Gallons for fluid tank
  - Usage per month varies from 7 to 18 US Gallons required for icing events
  - Fluid reservoir service requires once or twice depending on fluid usage each month

Airplane Type	Minimum Fluid Capacity is the greater of:
Turbojet powered airplanes Turbopropeller airplanes with maximum operating altitude above 30,000 feet	90 minutes or 15 percent of the maximum endurance based on the flow rate required in continuous maximum icing conditions

Ref 3: FAA AC 23.1419-2D & DOT/FAA/CT-TN86/11

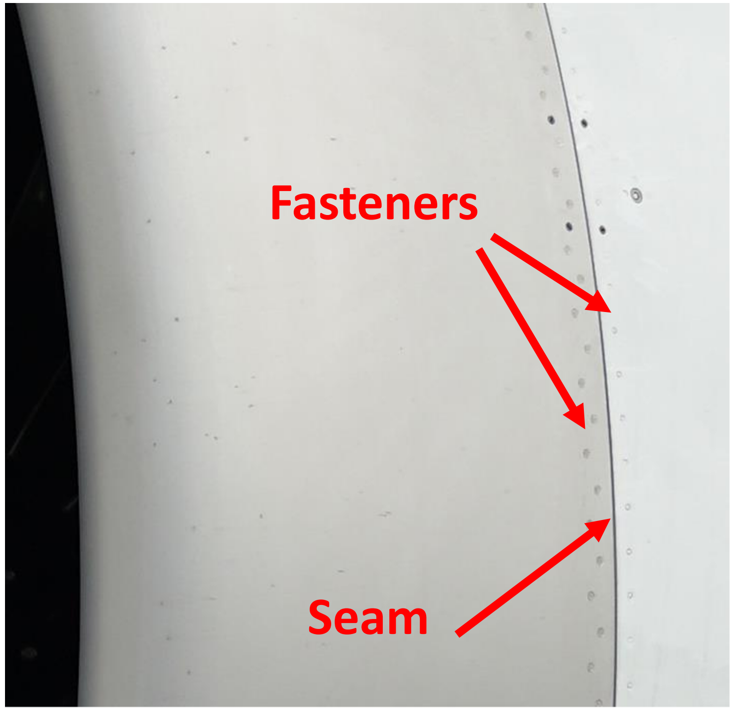
	Fluid Consumption per Nacelle (US Gallons)			
Trip from JFK to LHR	June July August	April May Sept	March Oct Nov	Dec Jan Feb
Per Month	7	8	14	18
Per Trip	1	1	2	2
Per Trip plus ETOPS	2	2	3	3
Per Trip plus 45 min. Hold	7	7	8	8

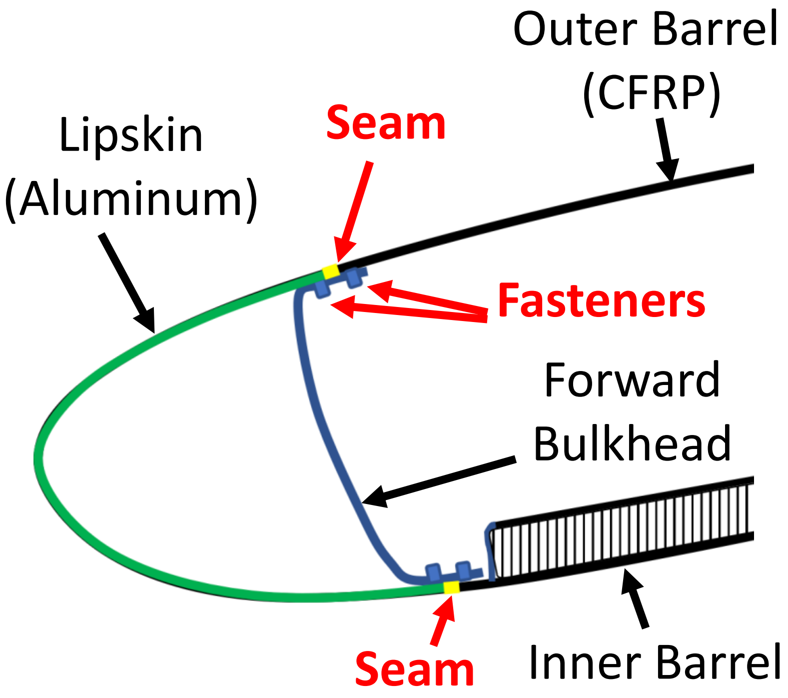
Dry Weight Comparison



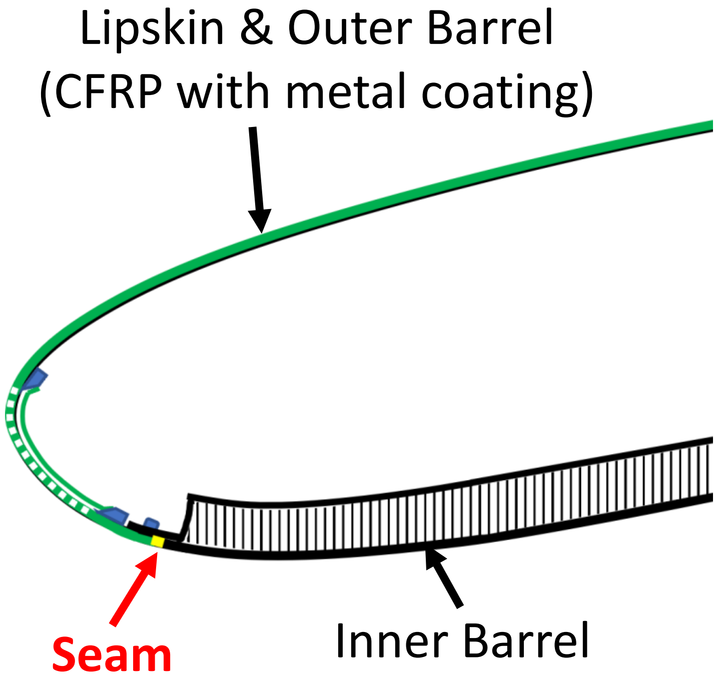
*Note: Metal coating thickness may be reduced for weight reduction.

Seamless Inlet Cowl





Inlet Cowl with Hot Bleed Air IPS

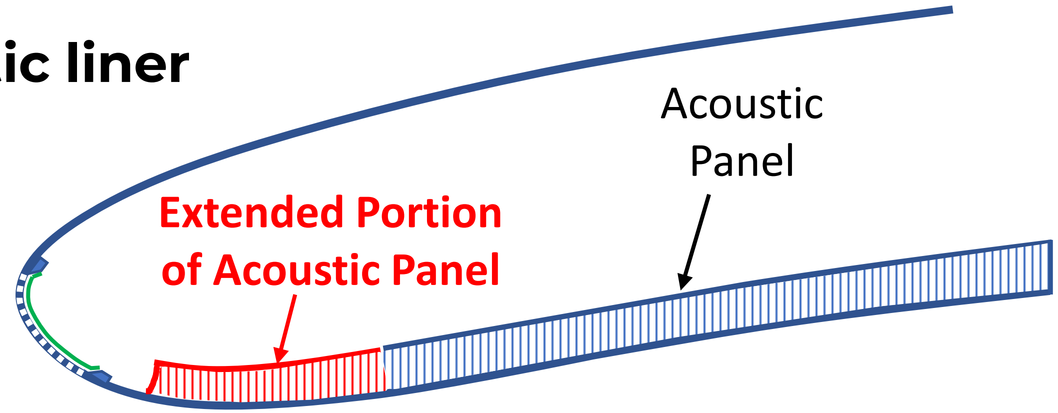


Inlet Cowl with TKS IPS

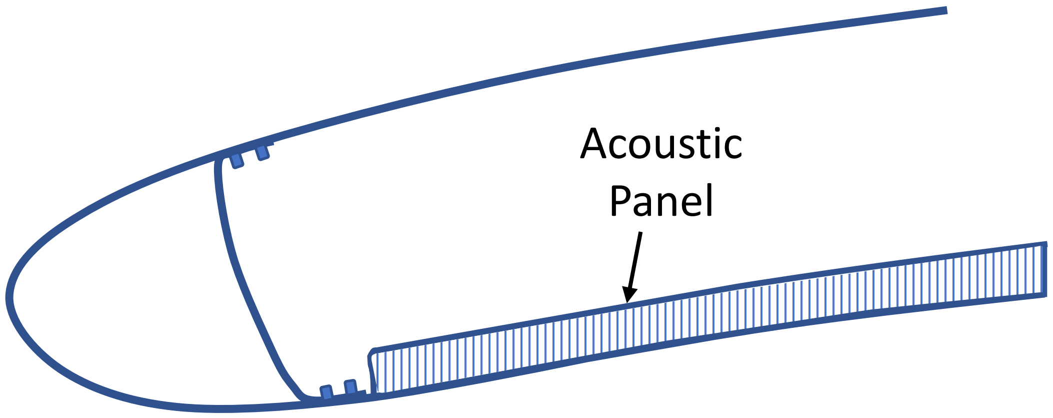
Inlet with TKS IPS improves aerodynamics performance for better fuel efficiency

Acoustic Treatment Area Comparison

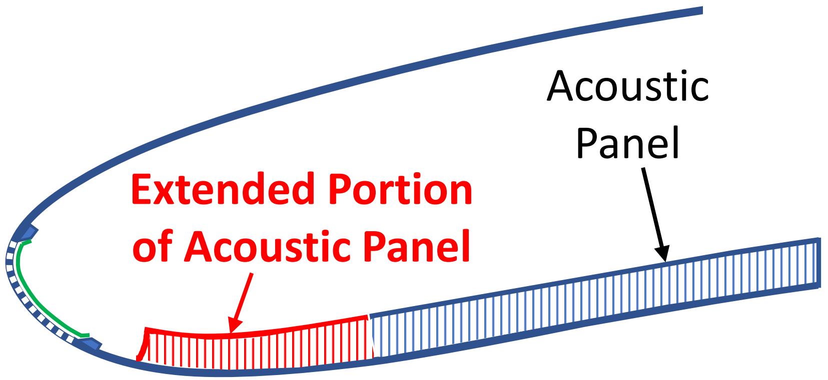
- **TKS IPS can accommodate a larger acoustic liner**
  - 20 to 35% larger acoustic panel than a conventional inlet cowl.
  - Maintains similar acoustic performance to the conventional inlet for a shorter inlet while reducing nacelle weight and drag.



Inlet Cowl with TKS IPS and Extended Acoustic Panel



Conventional Inlet Cowl with Hot Bleed Air IPS



<u>Short</u> Inlet Cowl with TKS IPS and Extended Acoustic Panel

Conclusion

- **TKS IPS can provide a reliable and low-energy ice protection solution for nacelles while improving both engine and IPS performance.**
  - Reduces carbon footprints.
  - Eliminates IPS coupling to engine allowing anti-icing through entire flight and icing envelope.
  - Enables CFRP construction improving production of natural laminar flow nacelles and reducing drag through removal of seams and fasteners.
  - Small footprint allows a short nacelle inlet to mitigate loss of the acoustic treatment area.
  - Bleed air reduction enables smaller core and higher bypass ratio

Technology Demonstrator

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