Cooling of Electric Motors Used for Propulsion on SCEPTOR

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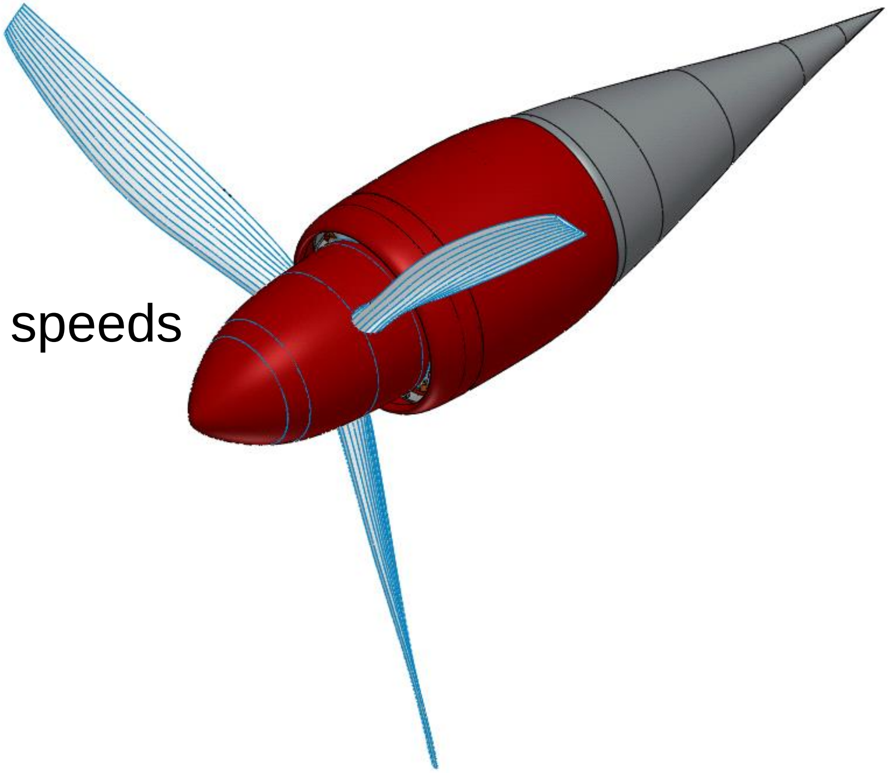
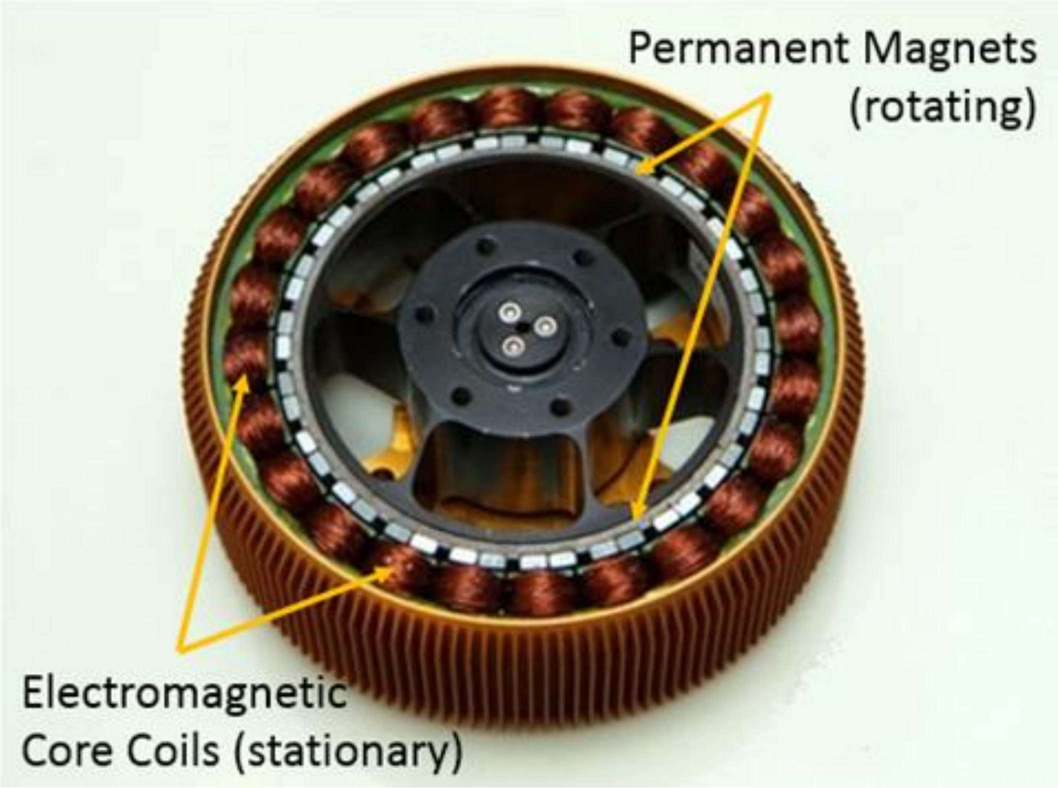
- Benefits of Electric Power
  - ✓ Reduced energy consumption
  - ✓ Lower emissions
  - ✓ Less noise

SCEPTOR
Scalable Convergent Electric Propulsion
Technology Operations Research

- Traction motors
  - ✓ Permanent magnet
  - ✓ Synchronous
  - ✓ High torque at low rotational speeds
  - ✓ High power density
    - High concentration of heat

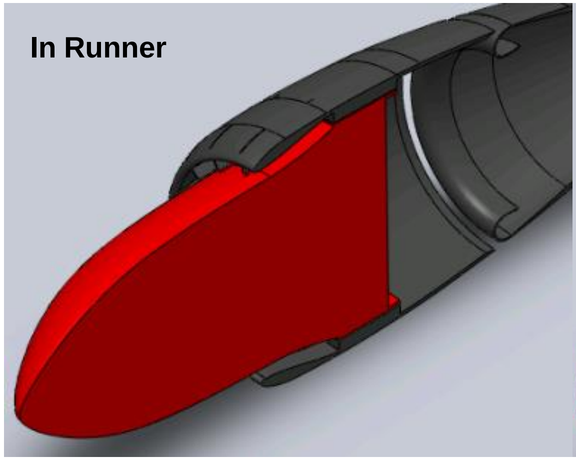


SCEPTOR Cruise Motor

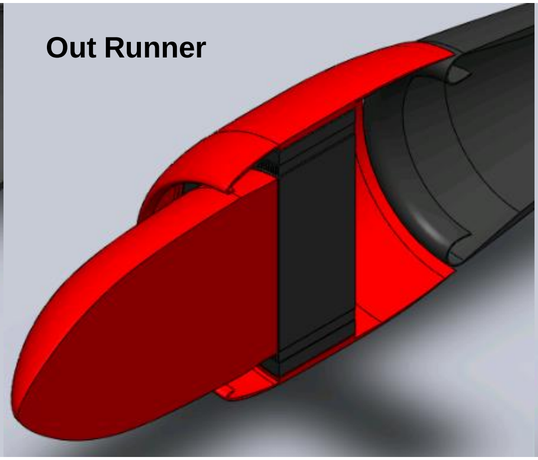


Typical permanent magnet synchronous motor

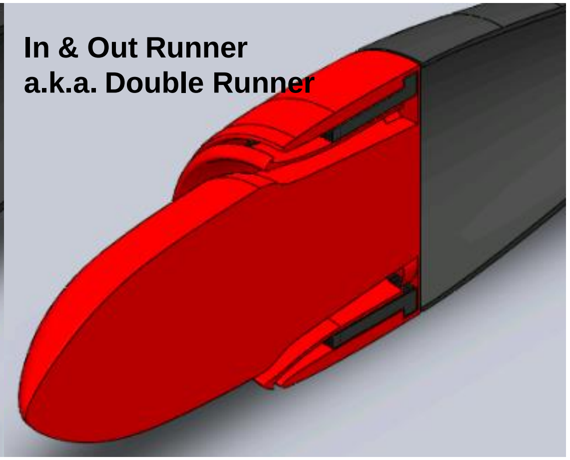
In-Runner is shown but final design is an Out-Runner



In Runner



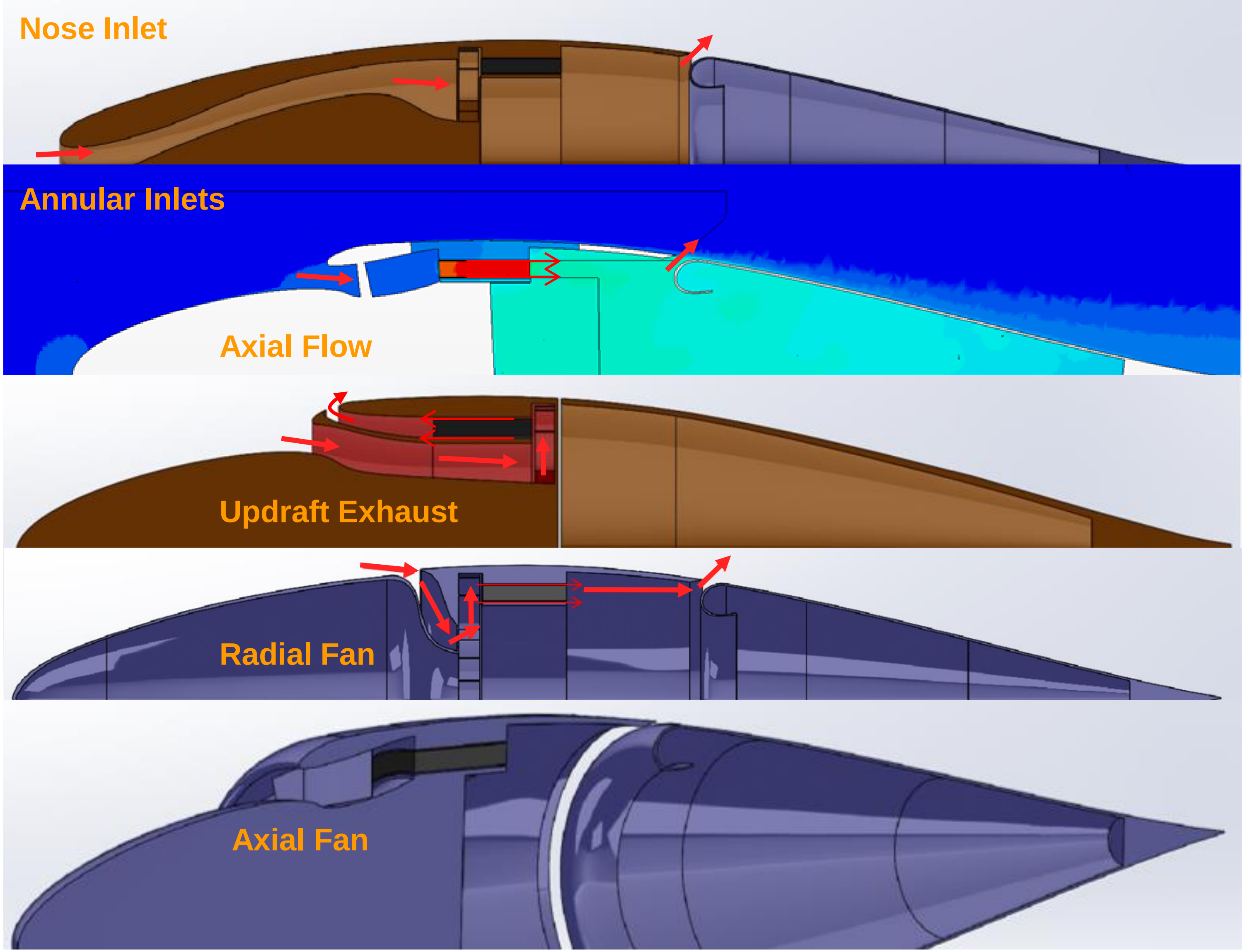
Out Runner

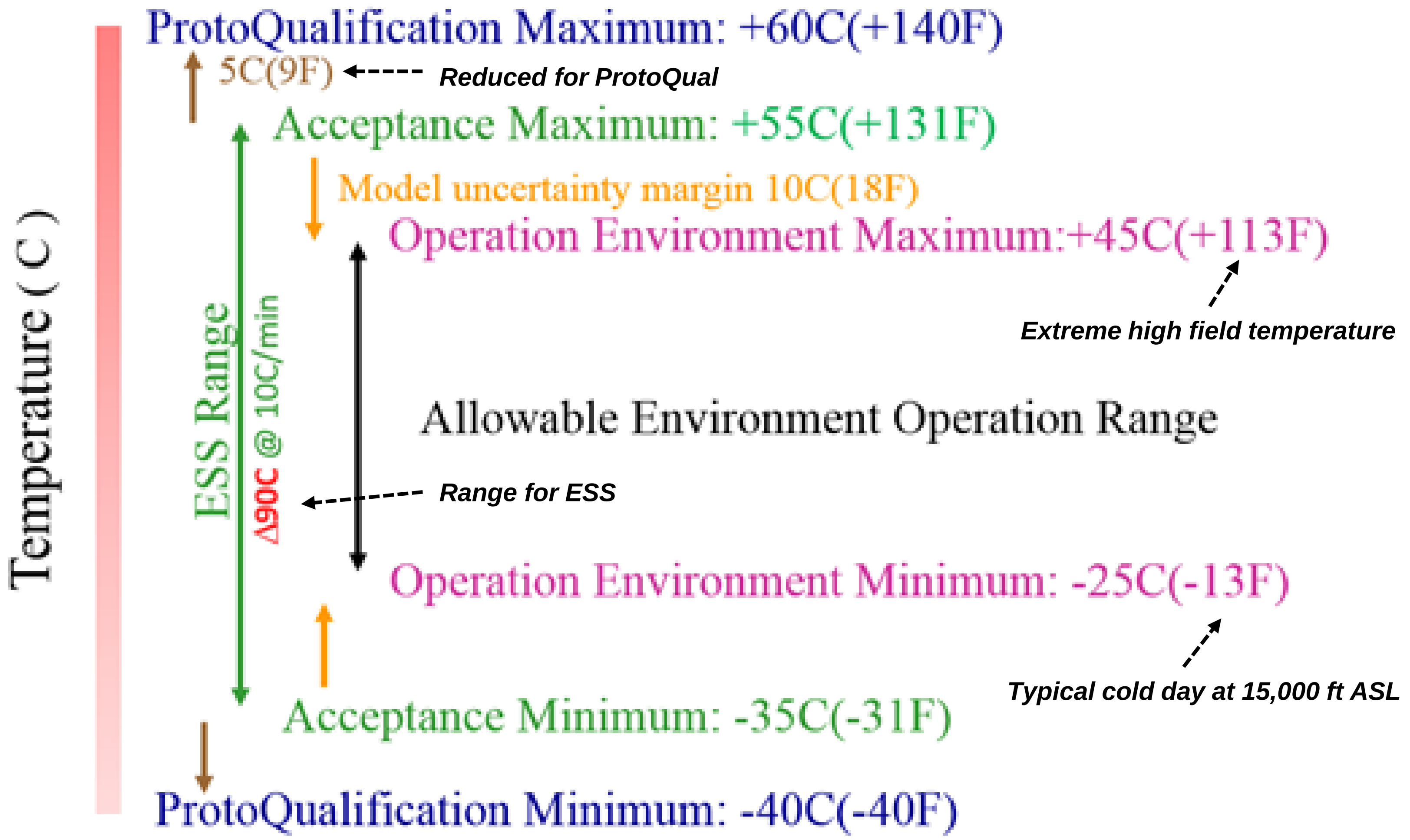


In & Out Runner
a.k.a. Double Runner

Motor Configurations

- Annular inlet
    - ➢ Very compatible with PM motors
        - ✓ Provides cooling where needed
        - ✓ No need for complicated ducting
        - ✓ Leads to a larger motor diameter which is beneficial for motor torque


Nose Inlet
Annular Inlets
Axial Flow
Updraft Exhaust
Radial Fan
Axial Fan



ProtoQualification Maximum: +60C(+140F)

5C(9F) ← Reduced for ProtoQual

Acceptance Maximum: +55C(+131F)

Model uncertainty margin 10C(18F)

Operation Environment Maximum:+45C(+113F)

Extreme high field temperature

Temperature (C)

ESS Range

Δ90C @ 10C/min

Allowable Environment Operation Range

Range for ESS

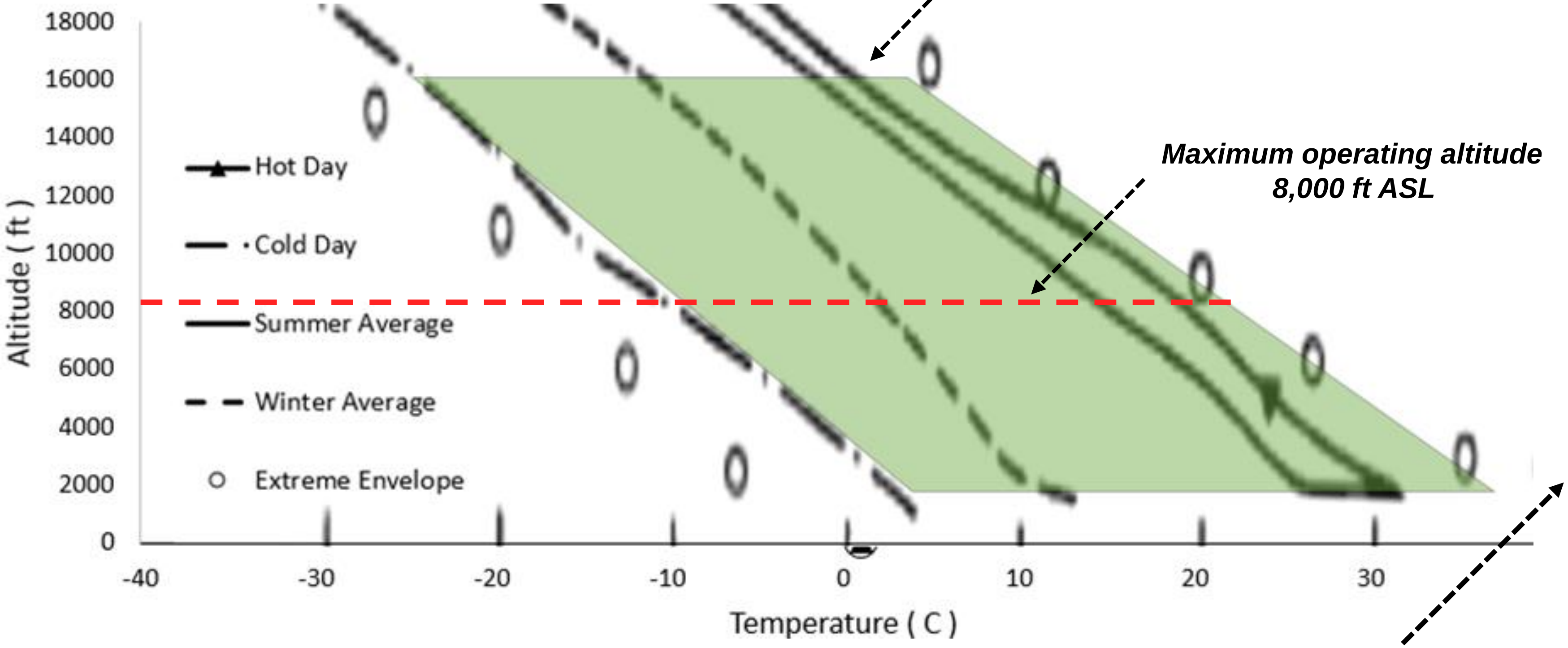
Operation Environment Minimum: -25C(-13F)

Typical cold day at 15,000 ft ASL

Acceptance Minimum: -35C(-31F)

ProtoQualification Minimum: -40C(-40F)

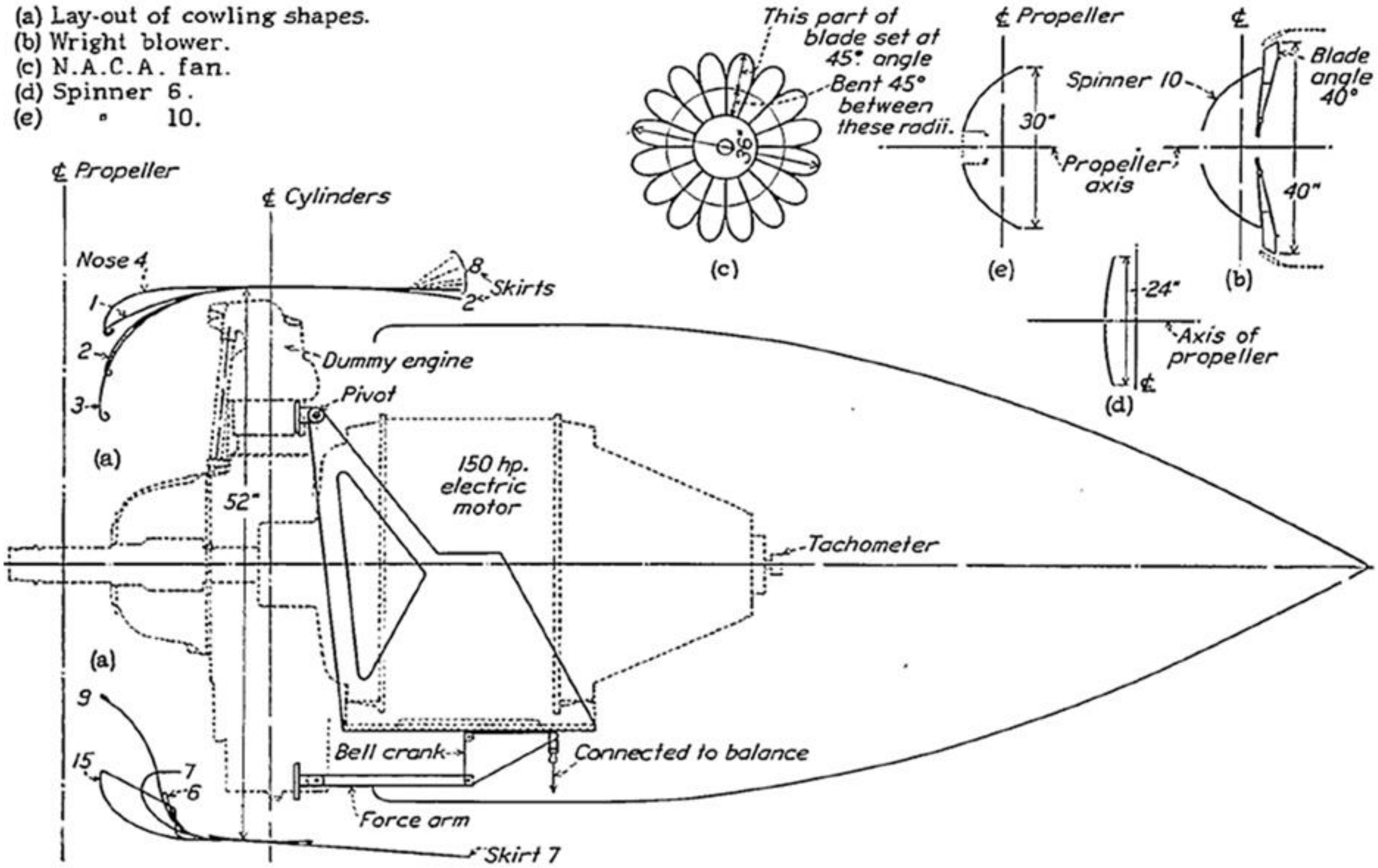
Designing for 15,000 ft ASL
per DO-160G Category A-1



Maximum operating altitude
8,000 ft ASL

At surface use +45^{o}C (113^{o}F)

SCEPTOR Environment Temperature Operating Range at Altitude superimposed on measured temperatures at EAFB

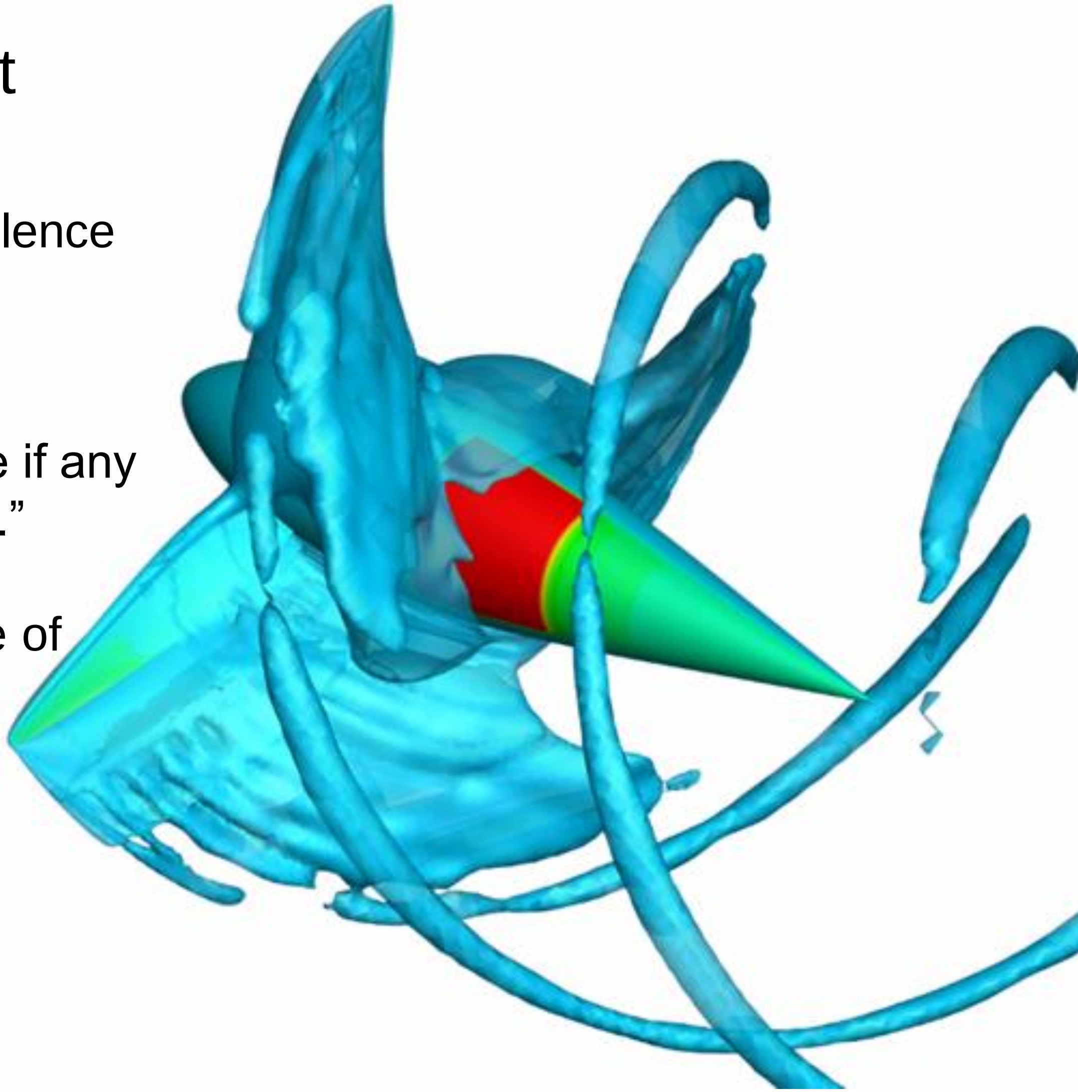


Hardware Configurations for Full-Scale Test of NACA Cowlings

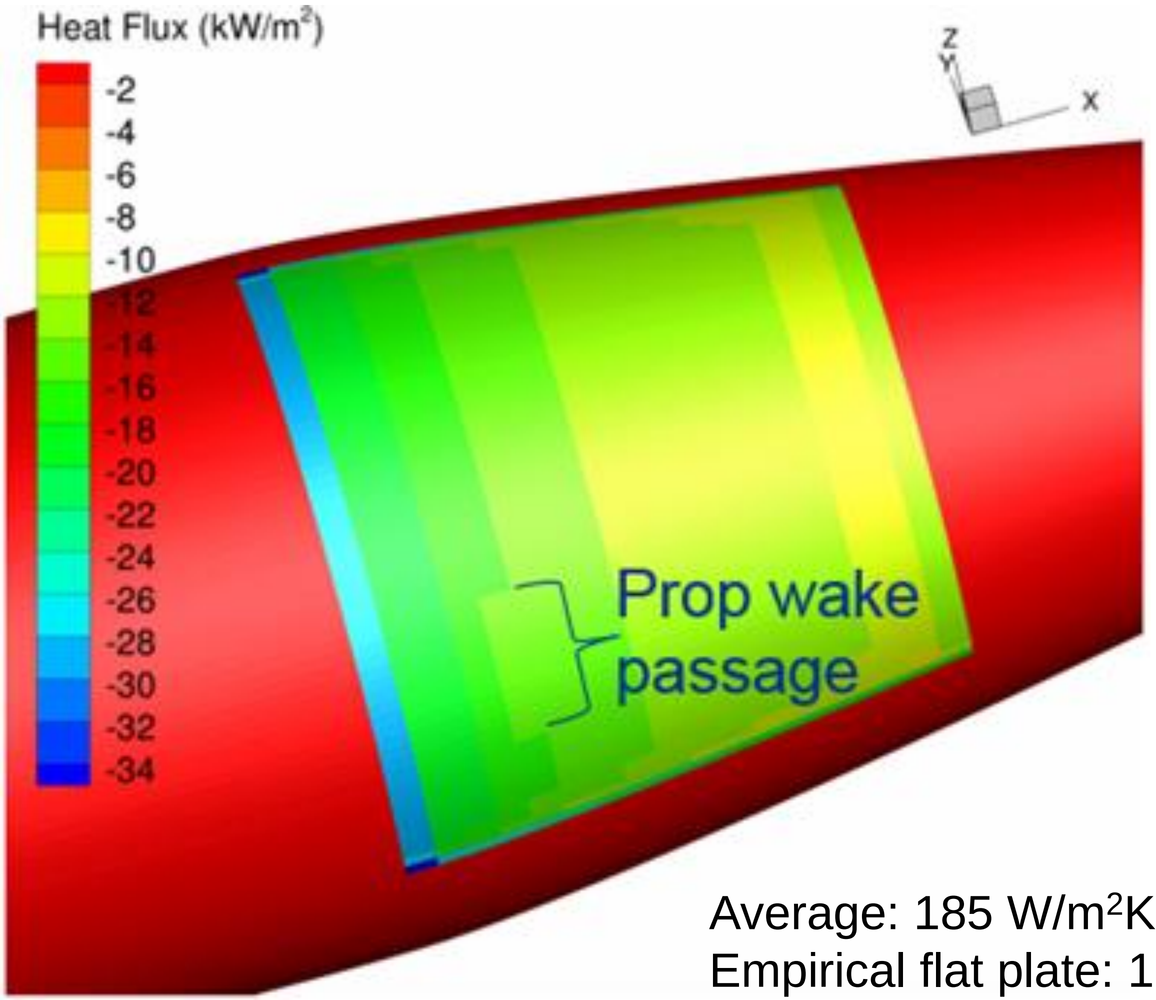
Lessons learned from NACA

- ✓ Shape #7 with spinner #10 was preferred
- ✓ Small diameter inlets, #3 & #9, were not acceptable
  - reduced turbulence on the front face of the engine
- ✓ Preferred nose shapes can be found in NACA report 662
- ✓ Because the flow velocity is so low inside of the cowling, the geometry of the internal flow path is not significant
  - True when motor has a high (3X) flow conductance relative to the inlet and outlet. This is not currently the case for SCEPTOR
- ✓ Fans/blowers provide little benefit for in flight cooling
- ✓ Propeller slip stream in only beneficial on the ground
- ✓ Variable geometry skirts proved to be inefficient
- ✓ Cooling drag is not just related to the geometry change: It includes the work done to pump the air through the motor, i.e. it's a function of flow rate

Effect of prop wash on heat transfer coefficients



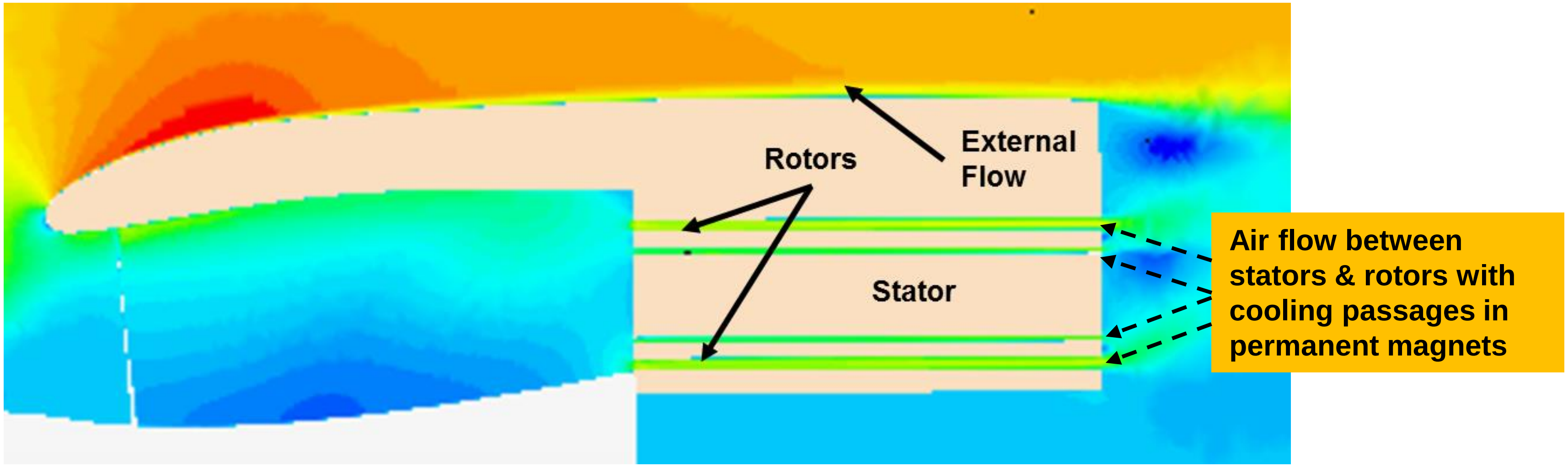
- ✓ Assumed propeller induced turbulence would increase heat transfer coefficients
- ✓ Holmes, Obara & Yip reported "propeller slipstream showed little if any apparent effect of the slip stream."
- ✓ Derlaga @ LaRC also found little change in heat transfer in the wake of the propeller



Average: 185 W/m^2K

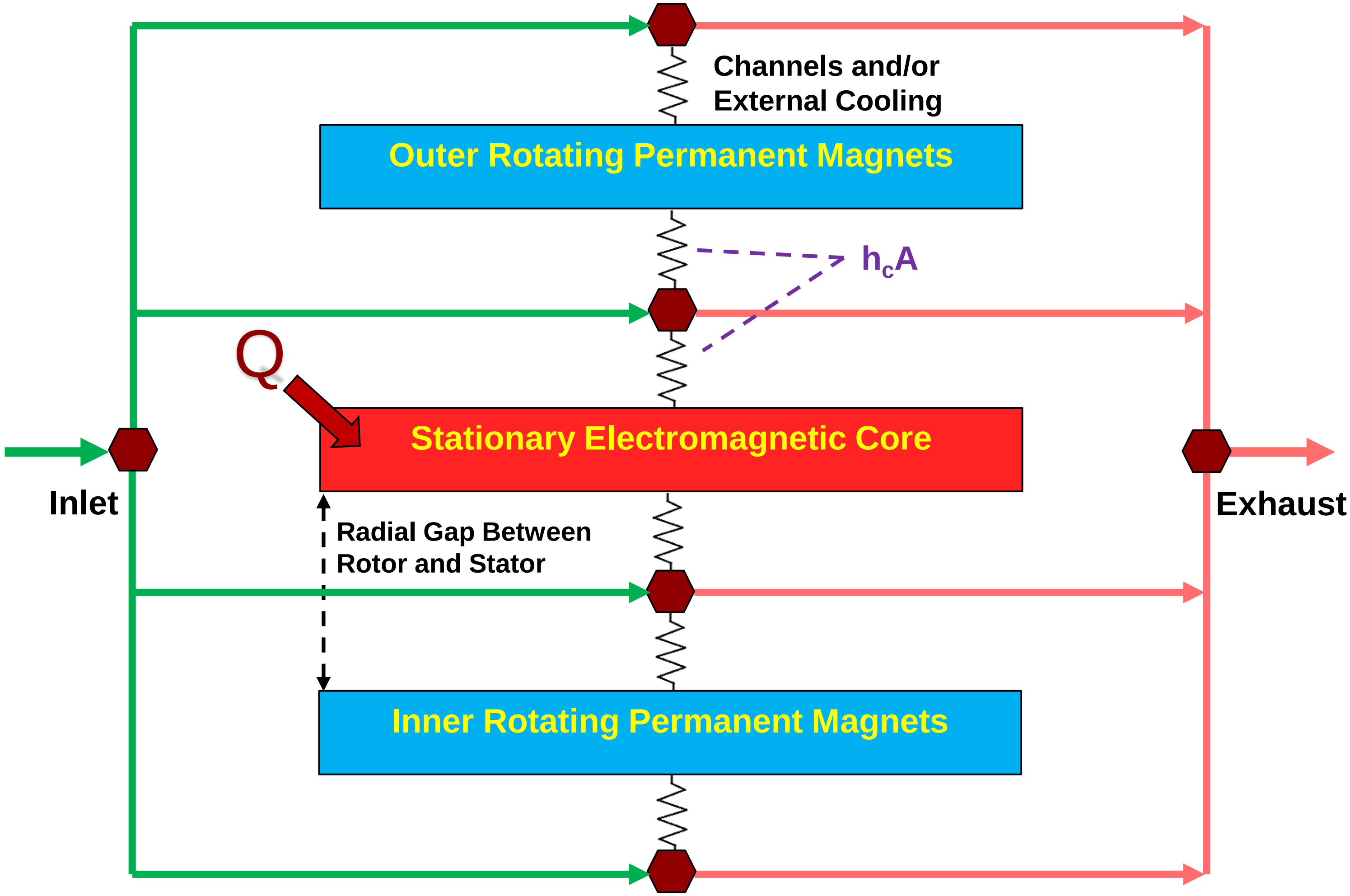
Empirical flat plate: 135 W/m^2K

- ❑ Lumped Parameter Model
- ✓ Spreadsheet to perform quick parametric studies
- ✓ Empirical equations for heat transfer coefficients
- ✓ 'Goal seek' method to find solution to simultaneous equations
- ✓ Correlated with conjugated heat transfer & CFD model
- ✓ Parameters varied to see effect on core coil temperature, a.k.a. stator



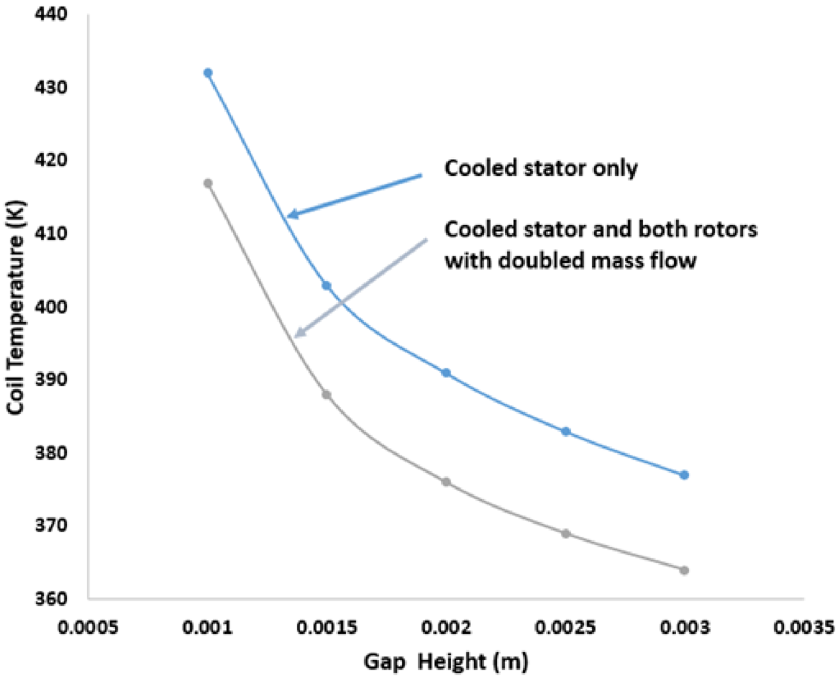
Air flow between stators & rotors with cooling passages in permanent magnets

Early 'In and Out Runner' Configuration

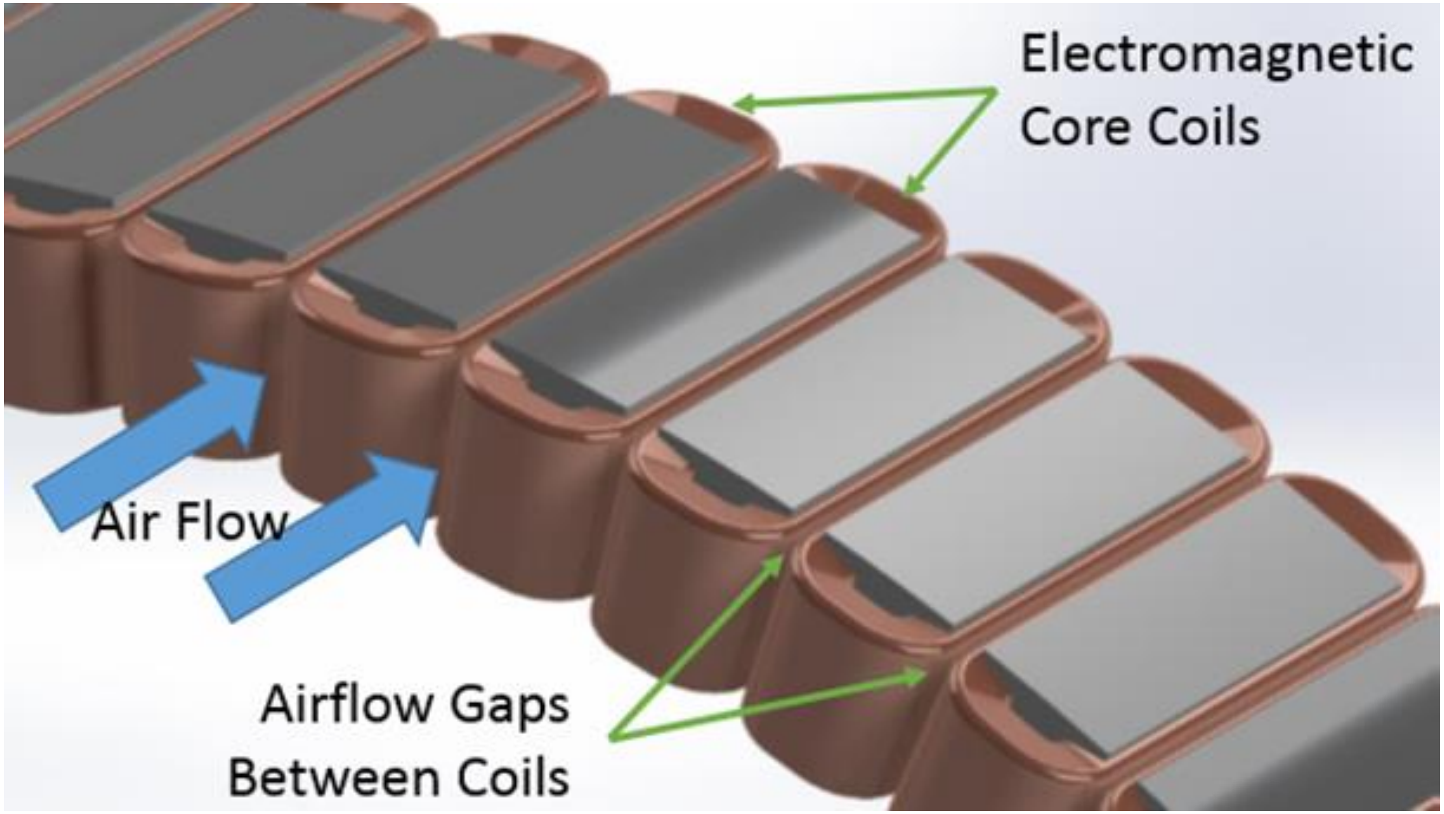


Lumped Parameter Model
‘In & Out Runner’ Configuration

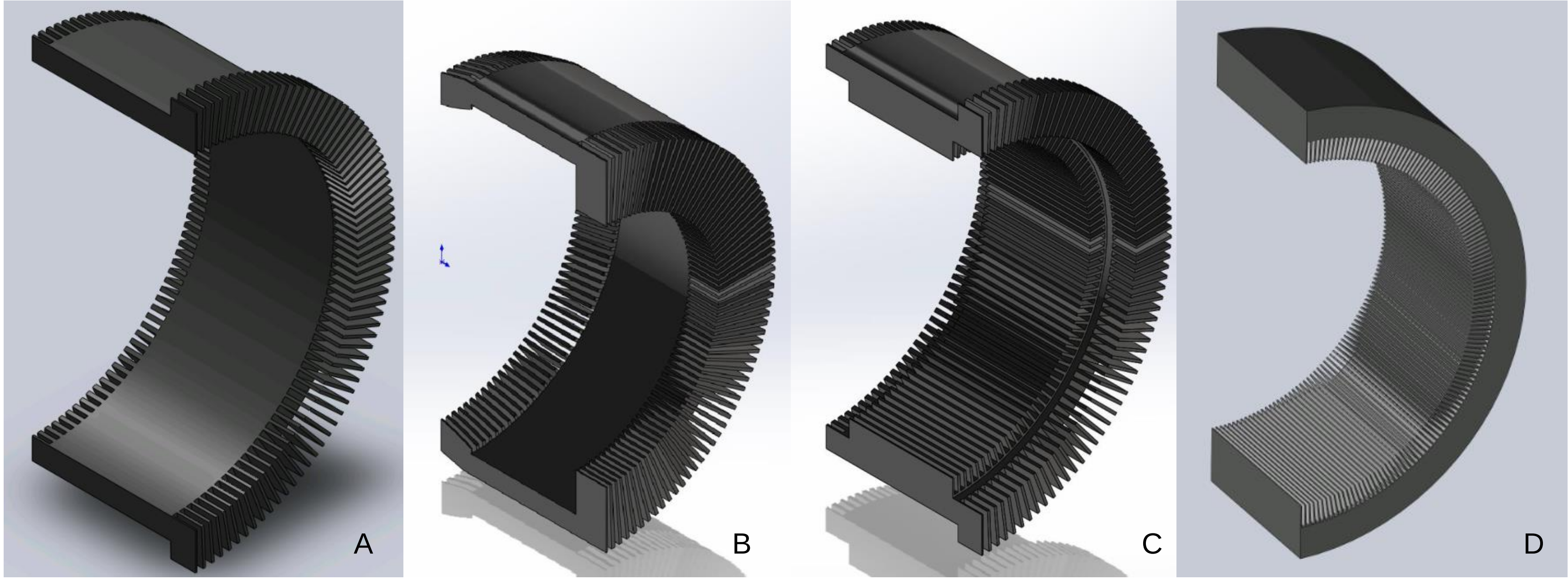
Lumped Parameter Model Results



- ✓ Increasing pressure head using fans or up-draft had little benefit
- ✓ Adding cooling area was most effective *(shown in plot)*
- ✓ Analysis of radial gap height showed 0.002m was desirable *(shown in plot)*
- ✓ Air flow gap between coils should be at least 0.001m wide
- ✓ Provided independent validation & verification and helped substantiate that the proper geometric dimensions, boundary conditions, and power levels were being used



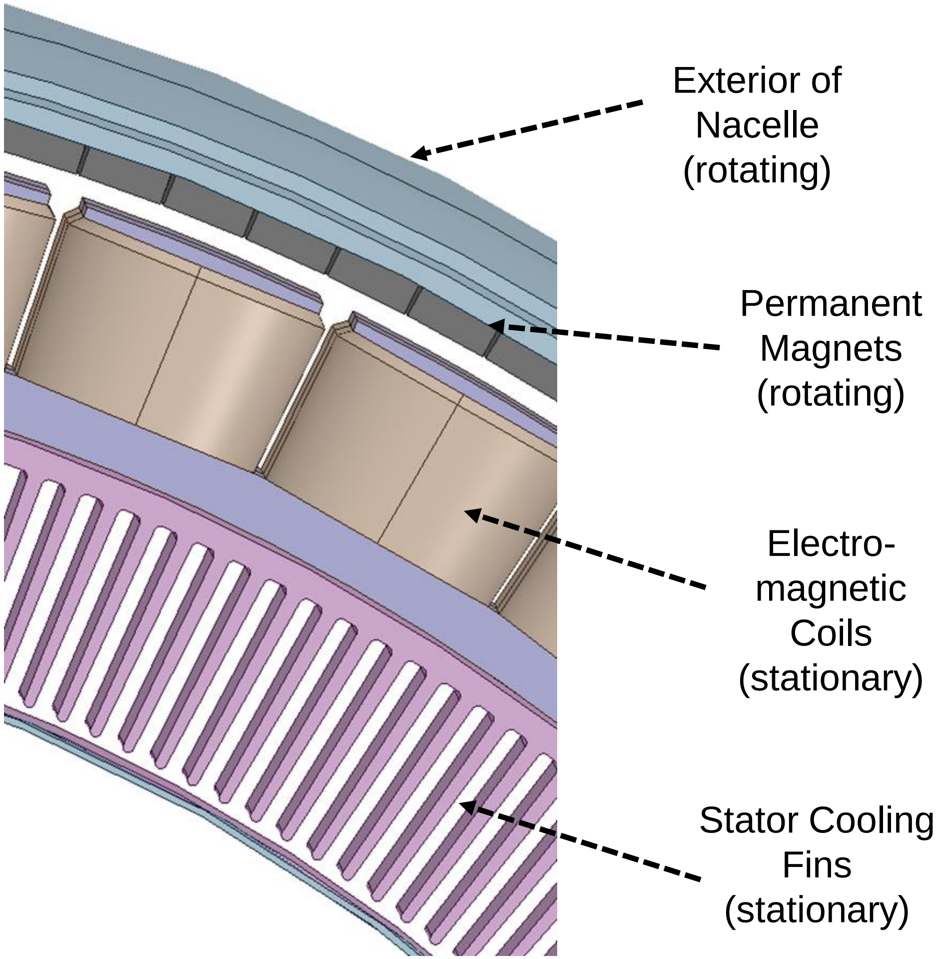
Intra-Coil Core Cooling



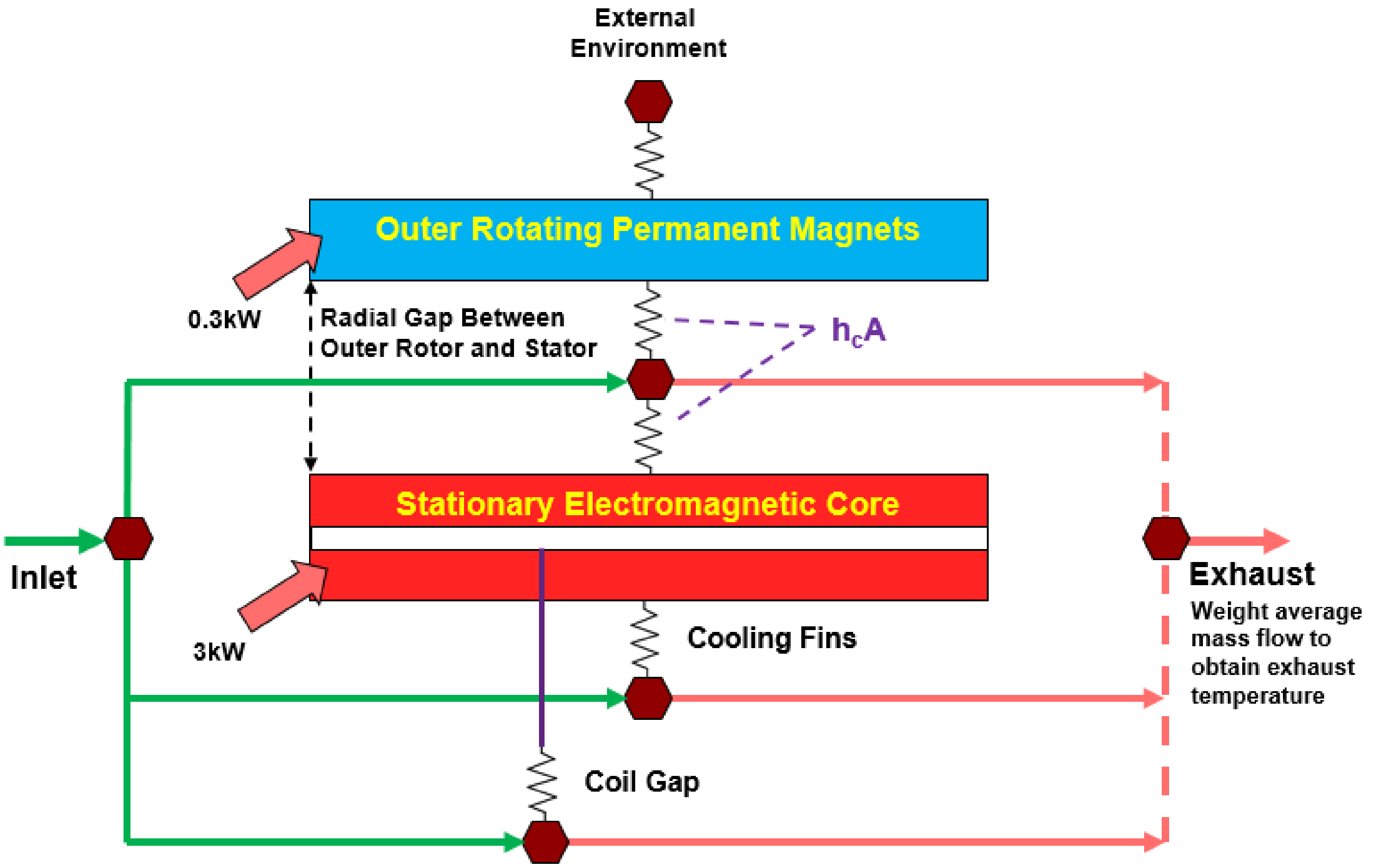
Stator Cooling Fin Concepts

Passage	% of Air Flow
Rotor/Stator Gap	17%
Stator Fins	75%
Coil Gaps	3%
Fin Tip Gap	4%

Passage	% of Cooling
Rotor/Stator Gap	31%
Stator Fins	48%
Coil Gaps	8%
Fin Tip Gap	-
External	14%



Out Runner Motor Cooling

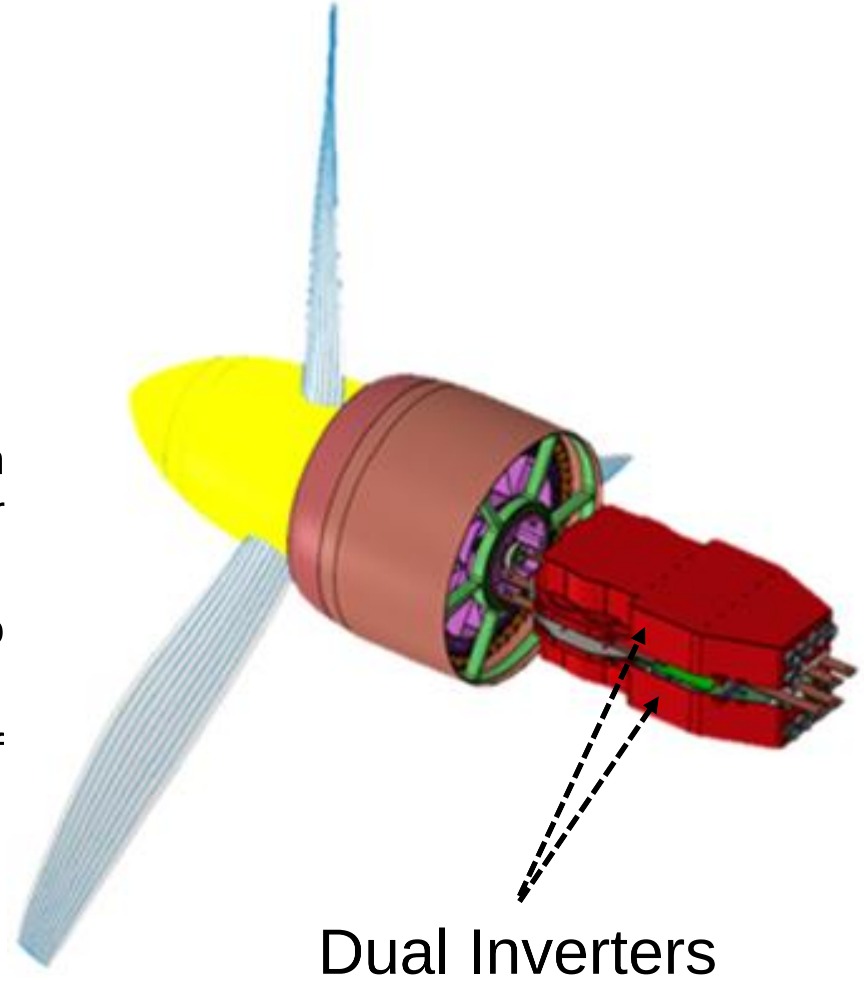


Lumped Parameter Model
'Out Runner' Configuration

Out-Runner Motor-Cooling

Observations:

- ✓ Adding fins to the ID of stator greatly increased the cooling area and air flow
- ✓ The fins provide 48% of the cooling
- ✓ The fins have an excess of air flow
  - ➢ Causes lower exit temperatures, which allow the exit air to be used for inverter cooling
  - ➢ Makes design robust, i.e. insensitive to moderate changes in airflow
- ➢ Pressure drop at inlet and outlet are of same magnitude as across the motor



Dual Inverters

Conclusions:

- ✓ Motor is adequately cooled for inflight operations
- ✓ A finned heat sink on the electromagnetic core is the most effective method to achieve adequate cooling
- ✓ The design is robust: Moderate changes in airflow will have minor effect on cooling
- ✓ Simple 1D models are very valuable
  - Provide insight into the what changes are most influential
  - Quickly do parametric studies
  - Perform independent verification
  - Discover errors or misunderstandings
- ➢ Details about the current design and a more in depth analysis will be presented by Arthur Dubois of Joby Aviation