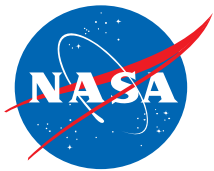


# Design Study of Double-Sided Axial-Flux Magnetically Geared Motors for Electric Aircraft Applications

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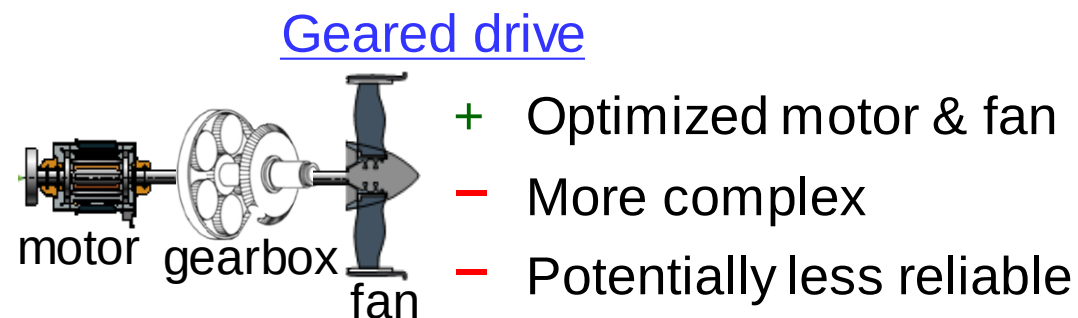
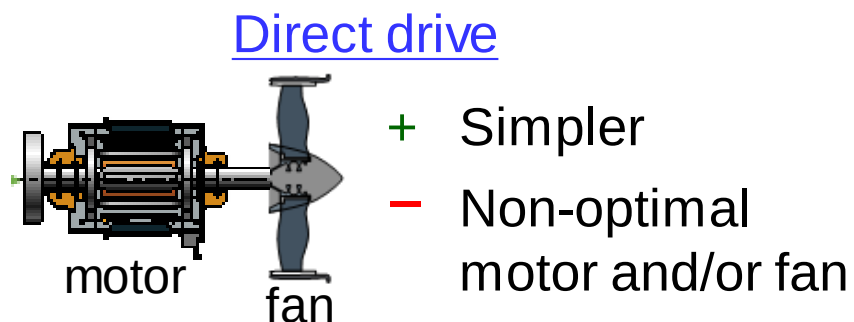
<sup>2</sup> Propulsion Division, Thermal Systems and Transport Processes Branch

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- The success of electrified aircraft depends on high performance electrified drivetrains

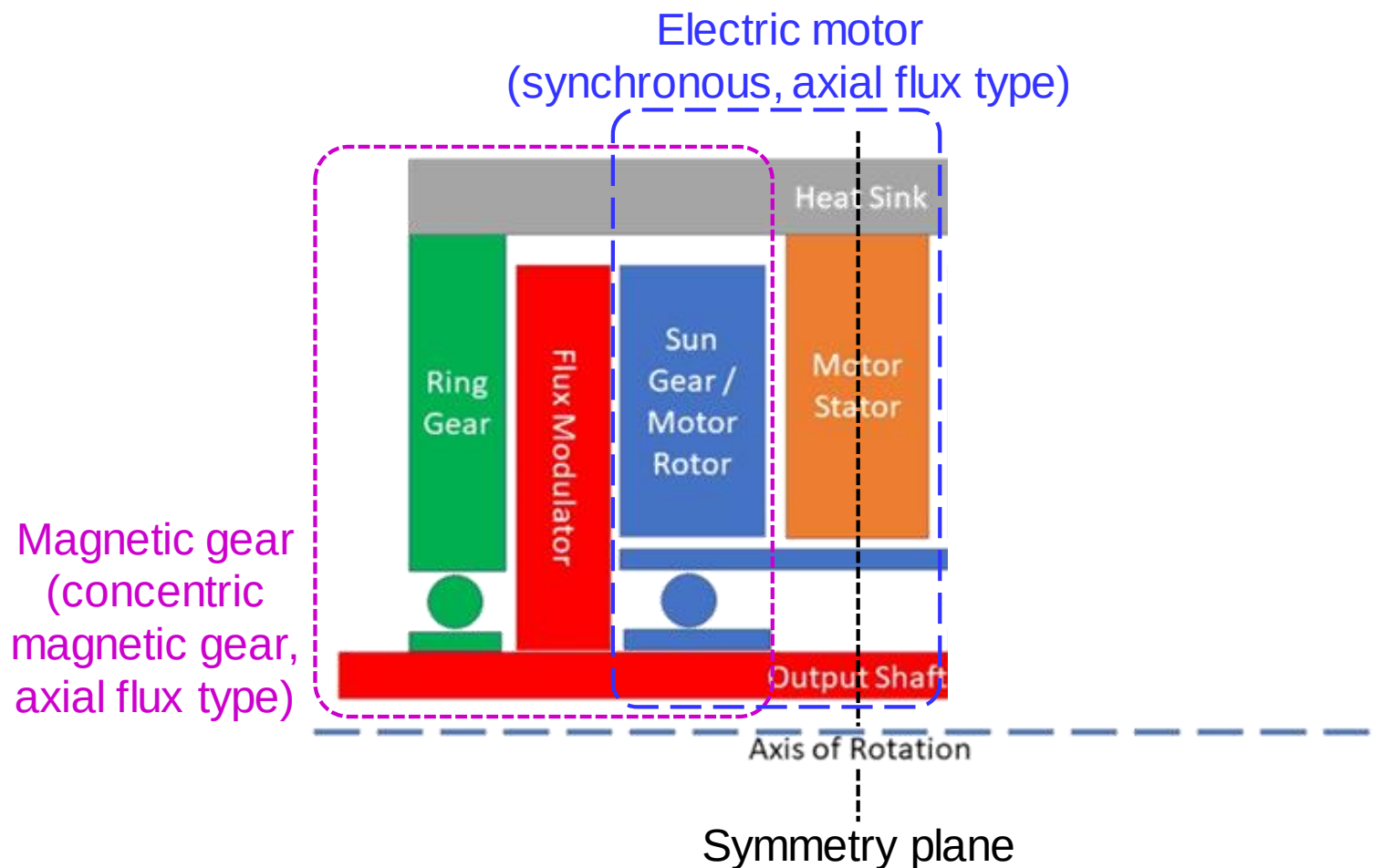


- Mechanical gears introduce several contact-related wear and failure modes (maintenance, reliability concerns) & lubrication requirements (system complexity, reliability)
- Magnetic gears are non-contact (apart from their bearings) & can share magnetic components with an electric motor
- Prior work demonstrated the feasibility of magnetic gears and magnetically-geared motors for electrified aircraft applications



# Overview of Axial-Flux Magnetically-Geared Motors

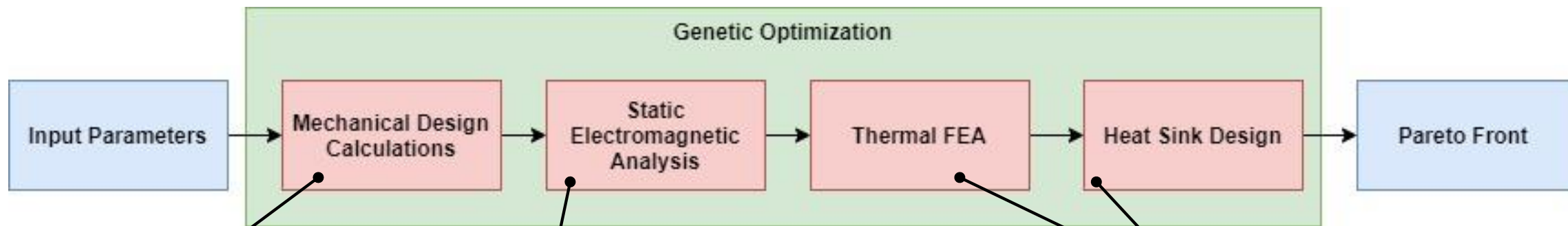
- Magnetically-geared motor = conventional electric motor merged with a magnetic gear
- Concentric magnetic gear has 3 magnetic bodies:  
2 permanent magnet rotors [sun gear, ring gear] & 1 soft magnetic (iron) rotor [flux modulator]





# Design Tool for DSAMGM: Overview

- Genetic optimization of specific torque and efficiency over 13 independent variables
  - Loss includes: eddy current, proximity, conduction, bearing, windage, coolant pumping
  - Mass includes: electromagnetic (magnets, iron, copper), structure (est.), bearings, HX
- See paper for all assumptions & fixed parameters



## Key assumptions

- No propeller loads
- Bearing life: 10,000 hr @ 99% reliability

## Key assumptions

- 3 phase synchronous, inverter-fed
- Electrical frequency  $\leq 1,000$  Hz
- Iron core stator
- Magnet layout: Halbach (in ring), N-S (in sun)
- Magnets: SmCo at 200 °C, laminated 1 mm

## Key assumptions

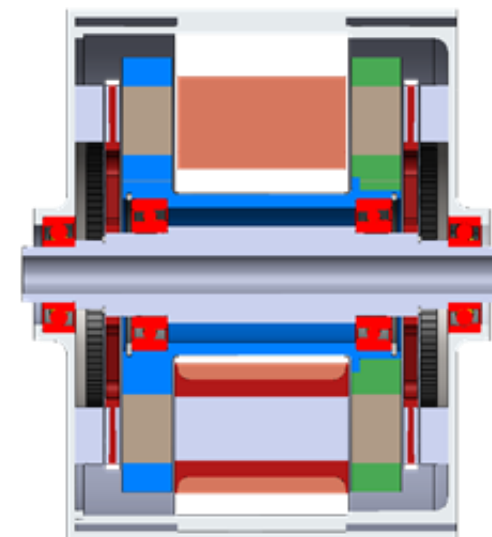
- Oil cooled via HX on outer diameter
- Max. winding temperature  $\leq 220$  °C



# Design Tool for DSAMGM

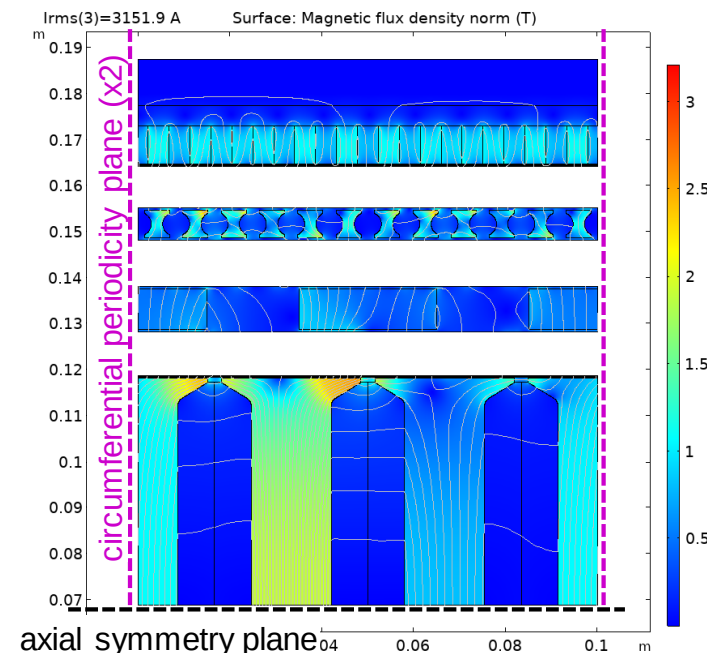
## Mechanical analysis

- Structure approximated by simplified geometry
- Loads considered: magnetic, gyroscopic (aircraft maneuvers), rotor imbalance
- Materials: steel (shaft), alumina (structure), aluminum (housing, HX), carbon fiber (containment hoops)
- Selected 4 identical bearings that meet required life with minimal diameter
  - Goal: minimize/eliminate eddy current loss in bearings



## 2D static electromagnetic analysis

- Nonlinear iron; linear permanent magnets
- Integer gear ratio to enable circumferential periodicity
- Circumferential slice at radial midplane of magnetic components
- 20% margin on torque

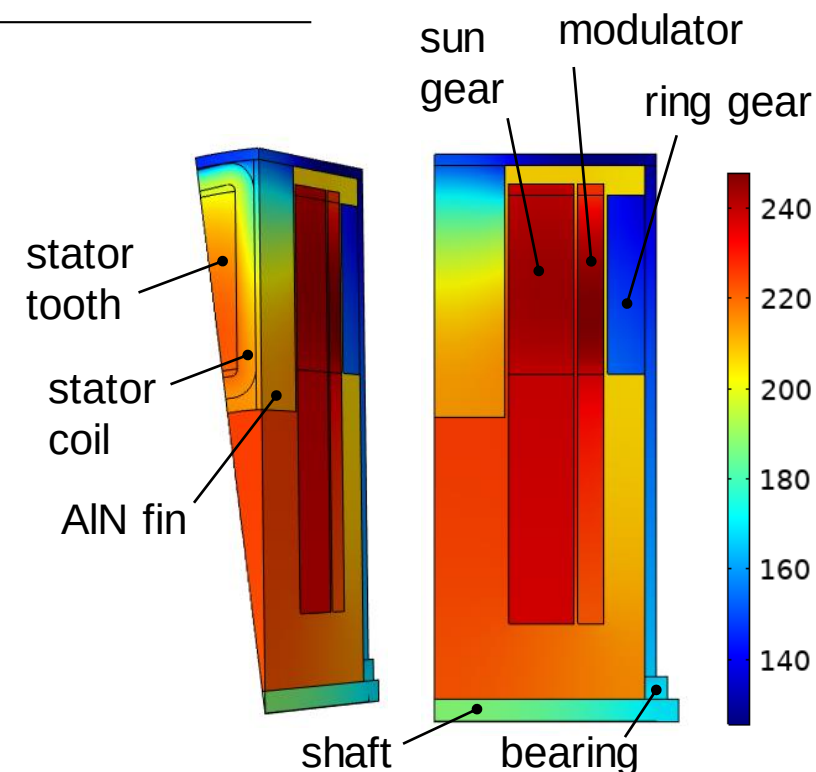


## Thermal analysis

- 3D wedge simulated (axial symmetry & circumferential periodicity)
- Air approximated as high conductivity solid
- Convective heat transfer approximated as thermal contact resistance between air & solid components
- Extracted peak winding temperature versus external convection coefficient
- Temperature of magnets and bearings not utilized in design tool

## Heat sink design

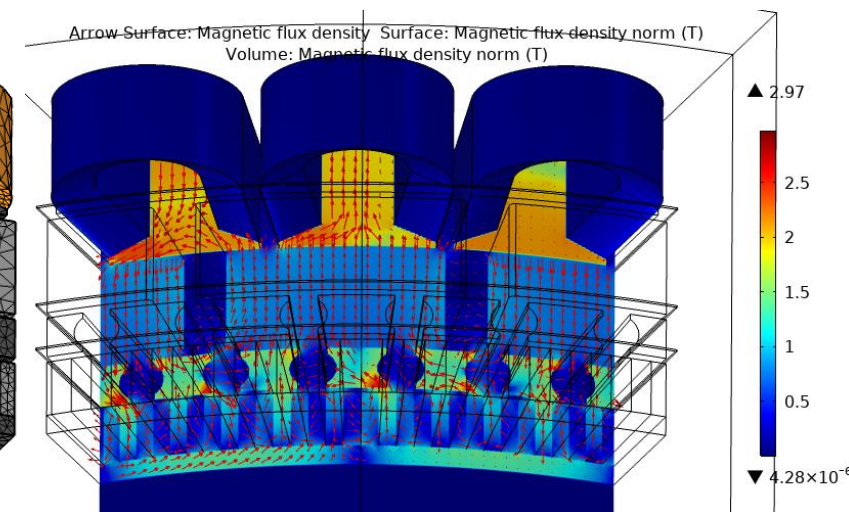
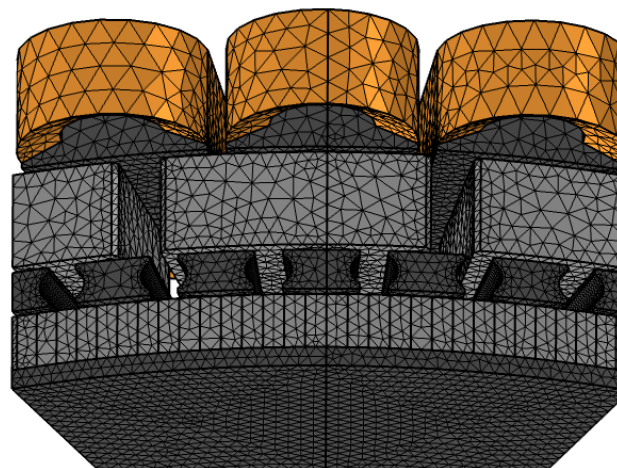
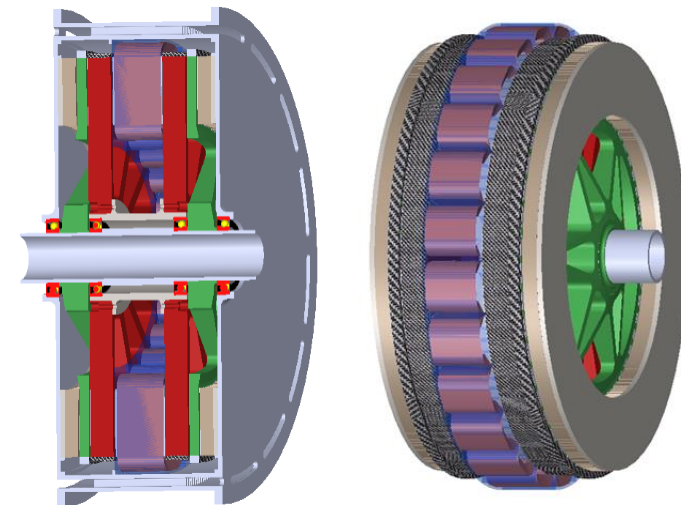
- Design variables: number, geometry of fins ▪ number of flow channels ▪ coolant temperature rise
- Convection coefficient & pumping loss calculated using common analytical expressions



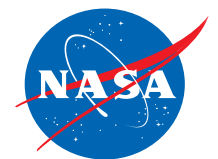


# High Fidelity 100 kW Design: 3D Electromagnetic Analysis

- Objective: assess suitability of design tool's 20% torque margin on 2D simulation results
- Approach: 3D electromagnetic FEA
  - Same assumptions as 2D simulation (nonlinear iron; linear permanent magnets)
- Results:
  - Required stator current 8.4% greater than design tool's prediction
  - Gear torque 100.1% of design tool's prediction

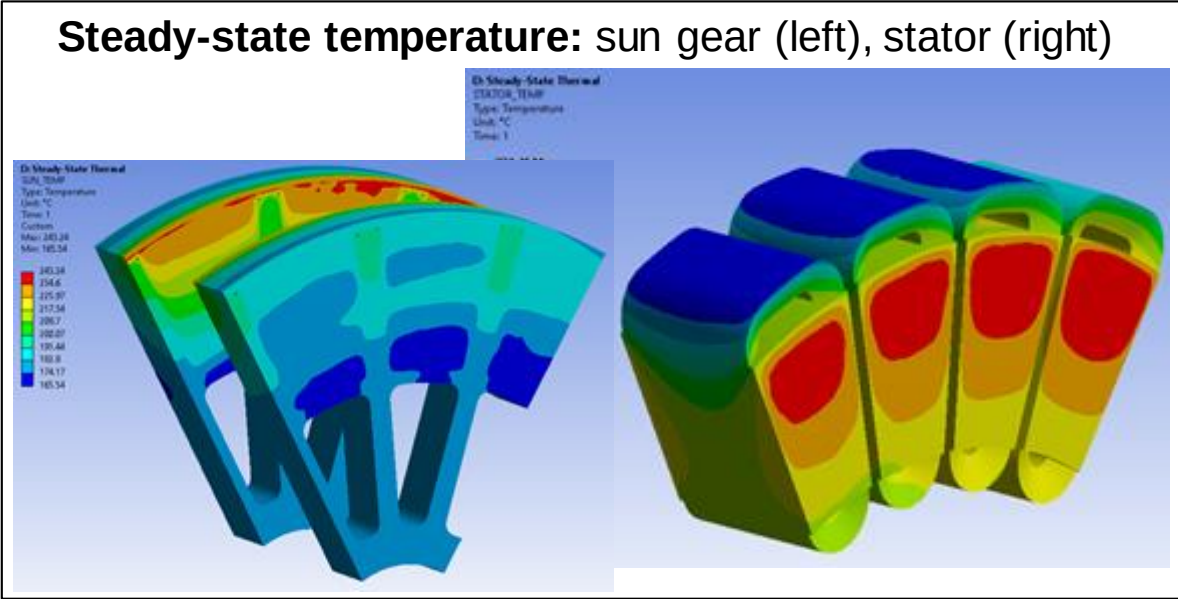


**Conclusions:** Added 10% margin to design tool's motor torque prediction (improves efficiency estimate)  
Design tool's margin on gear torque increased by 20% (ensures margin for over torque)



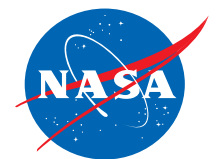
# High Fidelity 100 kW Design: Thermal Analysis

- **Objective:** Assess the accuracy of the design tool's convection coefficients and stationary air approach
- **Approach:** (a) 3D CFD (moving-boundary RANS) to calculate convection coefficients & near-wall air temperatures, followed by (b) 3D heat transfer model with no air
- **Results:**
  - Good agreement with design tool in component of interest (stator winding)
  - Design tool under predicts flow velocity in ring-modulator air gap



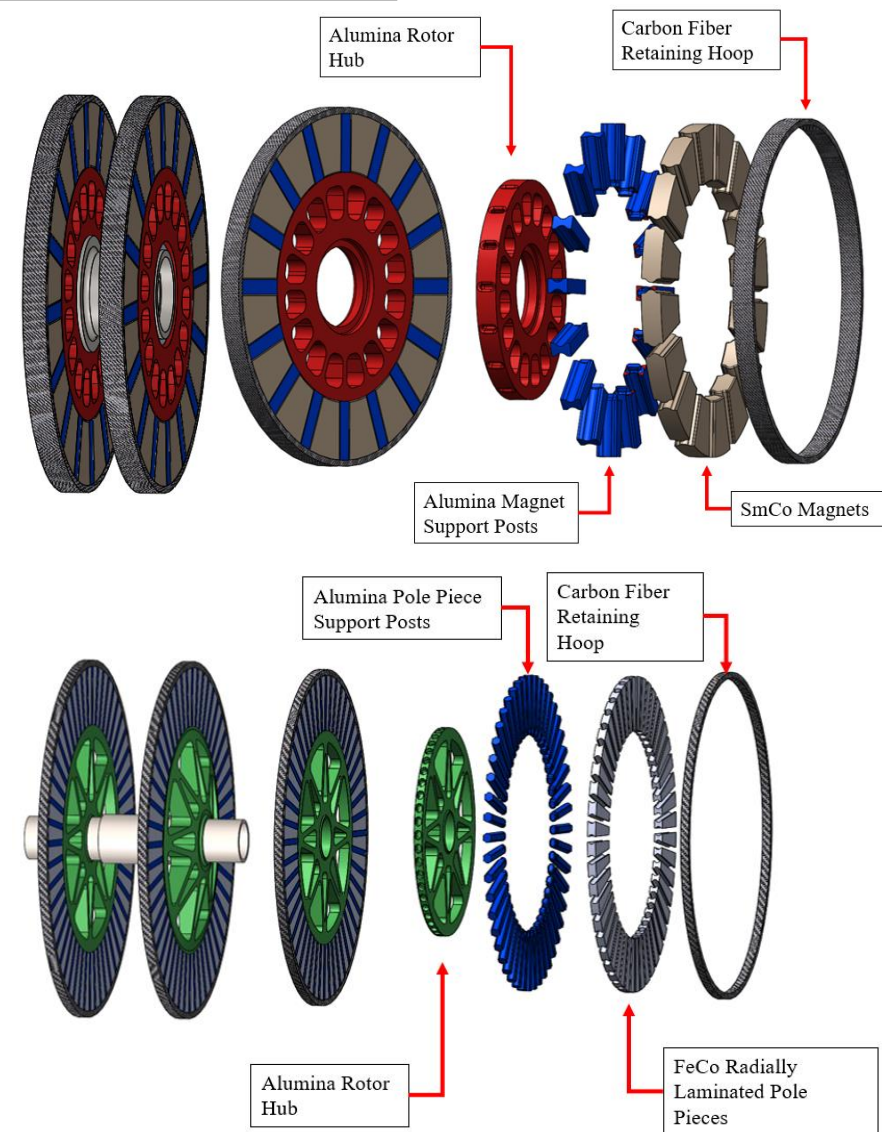
| Component             | Peak temperature, °C |                     |
|-----------------------|----------------------|---------------------|
|                       | Design tool          | High fidelity model |
| Stator windings       | ~220                 | 211                 |
| Sun magnets           | ~240                 | 243                 |
| Modulator pole pieces | ~245                 | 161                 |
| Ring magnets          | ~150                 | 155                 |

**Conclusion:** No corrections to the design tool needed

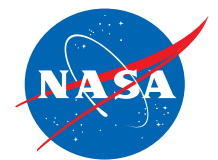


# High Fidelity 100 kW Design: Structural Analysis

- **Objective:** Assess the design tool's mass estimate and the safety factors on stress in its sun gear and flux modulator designs
- **Approach:** Preliminary design of critical components ▪ full CAD model ▪ 3D structural FEA for combined magnetic (torsional & axial), centrifugal, and thermal forces
- **Results:**
  - Peak stress in carbon fiber retaining hoops
  - Lowest strength components (magnets, iron, and alumina) are lightly stressed
  - Factors of safety  $\geq 1.5$
  - High fidelity design 6% (2.4 kg) heavier than that from design tool

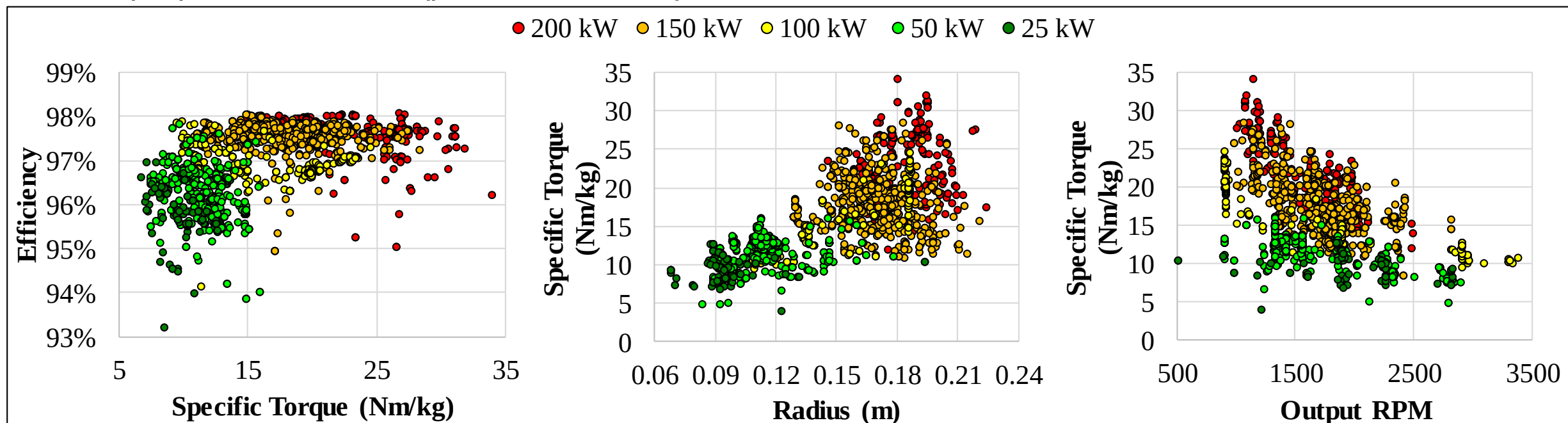


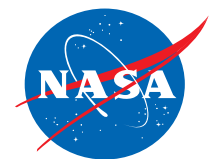
**Conclusion:** No corrections to the design tool implemented



# Genetic Optimization Results with Refined Design Tool

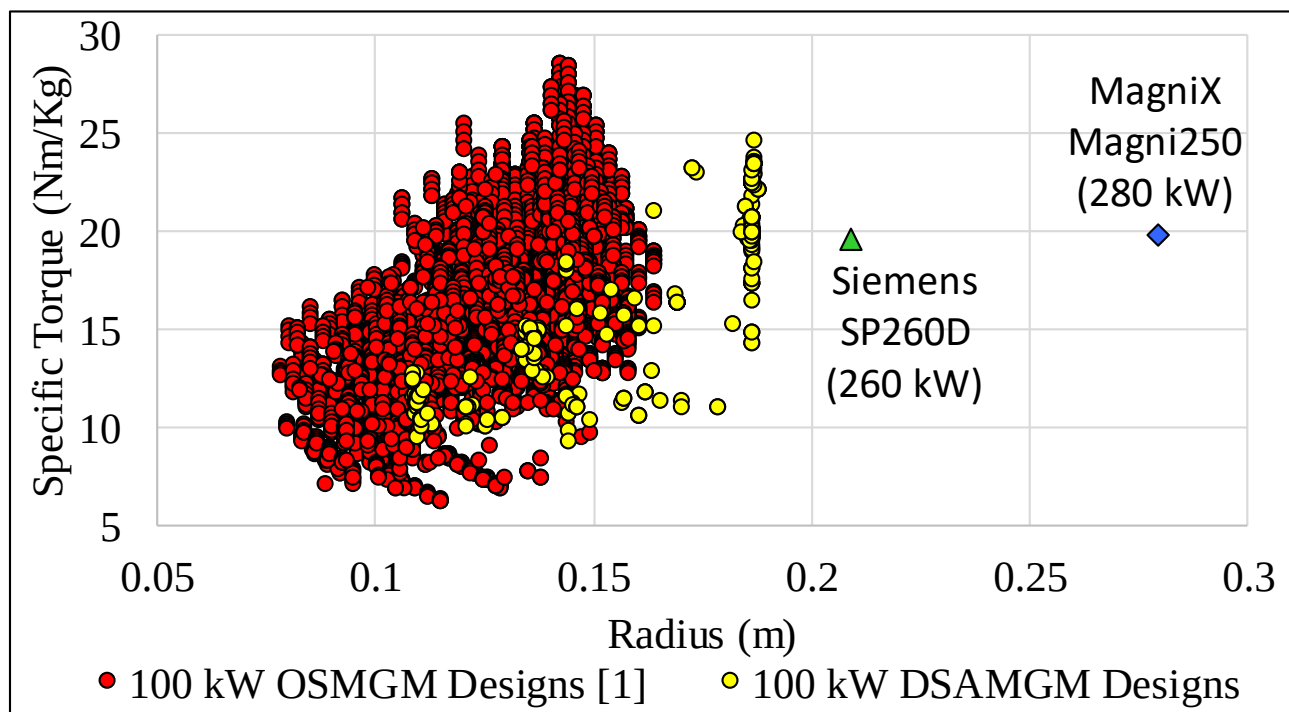
- Optimization run for power levels of 25 to 200 kW
- Achievable efficiency and specific torque increase with power level [*left plot*]
  - Results from larger radius, which provides direct benefit & permits better aspect ratio [*center plot*]
- Lower speed enables higher specific torque [*right plot*]
  - Primary cause: lower speed designs have higher torque, which allows larger radius
  - Secondary cause: # pole pairs lower at higher speed (electrical frequency limit)
  - Tip speed constraint (permitted radius) did not influence





# Genetic Optimization Results with Refined Design Tool

- DSAMGM compared to previously-studied [1] outer stator magnetically-geared motor (OSMGM)
  - At a given size, DSAMGM is heavier than the OSMGM
- Magnetically-geared machines (MGMs) predicted to have significant performance improvement over *higher power* state-of-the-art (SOA) aircraft motors
  - MGMs have higher specific torque in a more compact package
  - MGMs have higher efficiency (SOA are up to 93% and up to 95%)



1. T. F. Tallerico, Z. A. Cameron, J. J. Sheidler and H. Hasseeb, "Outer Stator Magnetically-Geared Motors for Electrified Urban Air Mobility Vehicles," in AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), Virtual, 2020.



# Conclusions

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- Evaluated potential of double-sided axial-flux magnetically-geared motors (DSAMGM) for electrified aircraft applications
- Developed a mechanical–electromagnetic–thermal design tool for DSAMGM
- Design tool verified & its accuracy refined using high fidelity, 3D electromagnetic, thermal, and structural FEA of an example output design
- Refined design tool used to explore performance limits of 25 kW to 200 kW DSAMGM
  - High efficiency (>97%) and high specific torque (>20 Nm/kg) achievable with 100+ kW DSAMGM
  - Predicted performance exceeds state-of-the-art direct drive motors in a more compact package
  - Outer stator magnetically-geared motor (OSMGM) outperforms the DSAMGM



# Acknowledgements

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# THANK YOU

