

Multidisciplinary Systems Analysis of a Six Passenger Quadrotor Urban Air Mobility Vehicle Powertrain

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Outline

- Introduction
- RVLT Quad6
- Architectures
- Architecture Trades
- Parameter Sensitivity Studies
- Initial TMS Modeling Work
- Conclusions

Introduction

- Electric variable takeoff and landing (eVTOL) vehicles seen as vital to urban air mobility (UAM)
 - eVTOL still developing research area
 - Few published systems studies with detailed power systems
- Difficult for program managers to drive research without data/trends
 - NPSS multidisciplinary modeling/analysis on NASA Revolutionary Vertical Lift Technology (RVLT) six passenger quadrotor (Quad6)
 - All-electric (DC), turboelectric (TE), and series hybrid
 - Sensitivity studies to highlight trends

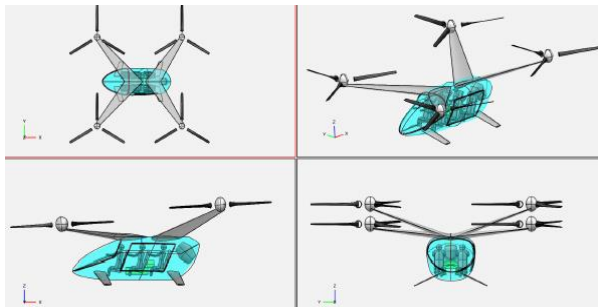


RVLT Quad6

➤ Set of NPSS models based on all-electric Quad6 propulsion system:

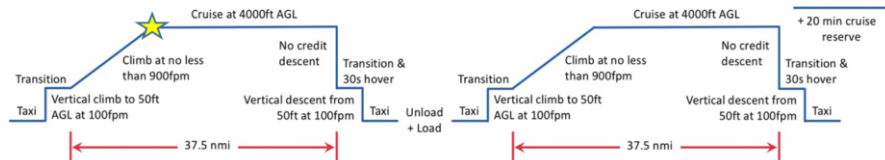
- Silva, C., Johnson, W., Antcliff, K. R., Patterson, M. D., "VTOL Urban Air Mobility Concept Vehicles for Technology Development," AIAA Aviation Forum, 2018 Aviation Technology, Integration, and Operations Conference, Atlanta, Georgia, USA. June 25-29

➤ Used same design mission, and kept as many parameters consistent as possible



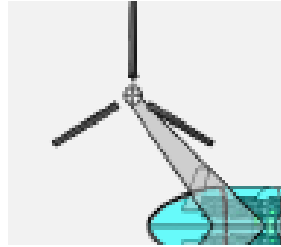
★ Top of climb design point (TOC)

Segment	1	2	3	4	5	6	7	8	9	10
Initial Alt. (MSL ISA)	6,000	6,000	6,050	6,050	10,000	6,050	6,050	6,050	6,000	10,000
Final Alt. (MSL ISA)	6,000	6,050	6,050	10,000	10,000	6,050	6,050	6,000	6,000	10,000
Time (sec)	15	30	10	t_{climb}	t_{cruise}	10	30	30	15	1200
Distance (nmi)	-	0	0	D_{climb}	$37.5 \cdot D_{climb}$	0	0	0	0	-
Speed	-	-	0	V_y	V_{br}	0	0	-	-	V_{br}
ROC (ft/min)	-	100	0	≥ 900	0	0	0	-100	-	0
Percent of Max Power	10%	100%	100%	P_{climb}	P_{cruise}	100%	100%	100%		



RVLT Quad6 – Modeling Assumptions

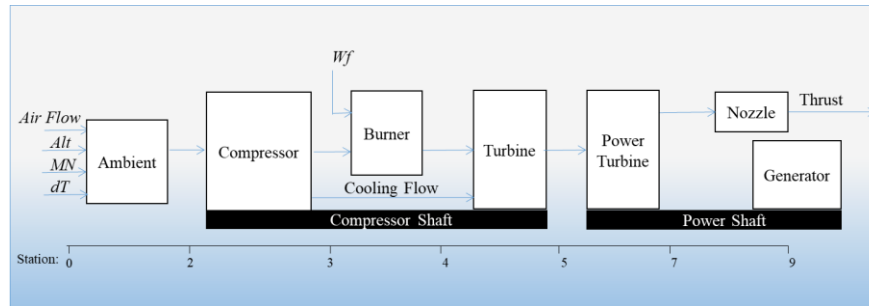
- Table of assumptions developed with available data and domain expertise
- Other assumptions
 - Powertrains are symmetric to all 4 rotors (duplicated)
 - Group components into load-side and source-side assemblies
 - Neglect thrust requirement going down as fuel burned over course of mission
 - Neglect weight of shafting, gearing



Technical Specifications	Quantity
Rotor Pylon Length (m) (i.e. cable length)	5
Hover Thrust (lbf)	1462
Climb Thrust (lbf)	1564
Design Thrust (lbf)	1564
Bus Frequency (Hz)	400
Battery Voltage (V_{dc})	1000
Battery Efficiency	0.944
Battery Specific Energy (Wh/kg)	400
Battery Hover Length (h)	1.50
Fuel Hover Length (h)	1.50
Generator Voltage (V_{ac})	1200
Electric Machine Specific Power (kW/kg)	13
Electric Machine Efficiency	0.96
Power Converter Specific Power (kW/kg)	9
Power Converter Efficiency	0.95
Breaker Specific Power (kW/kg)	250
Breaker Efficiency	0.995
DC Hybrid Design Battery Fraction	0.45

RVLT Quad6 – Engine Model

- NPSS developed turboshaft engine model, sized for TOC
- Sized differently for different models



Environmental Condition	Mach number	Altitude (ft)	Delta temperature (R)
	0.0	10,000	+27
Engine Performance	HPC pressure ratio radial compressor	T_4 (R)	
	8.5	2200	
Shaft	High Pressure Shaft Speed (rpm)	Power Turbine Shaft Speed (rpm)	Power Turbine Power Output (HP)
	50,000	19,680	592* / 329+

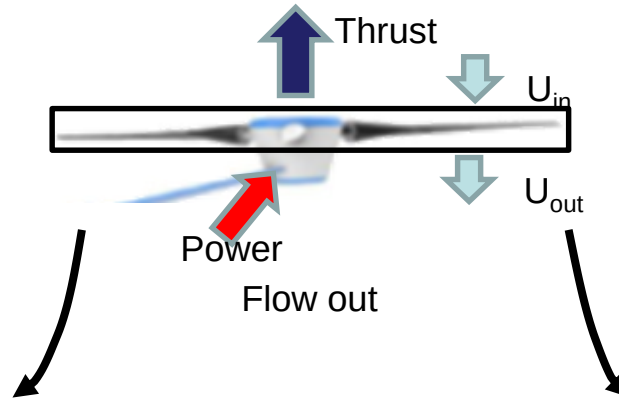
- Weight estimated with mass flow correlations developed from existing small engines

*Turboelectric, +Hybrid

RVLT Quad6 – Prop Model

- Propeller thrust calculated utilizing actuator disc theory

- Prop wash (flow out) used to drive TMS model



$$U_{disk} = \frac{U_{in} + U_{out}}{2}$$

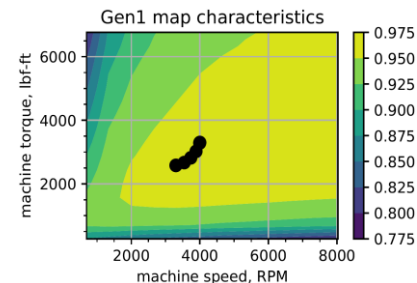
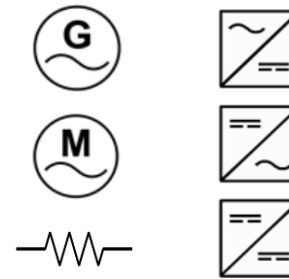
$$Thrust = \frac{Power}{U_{disk}} * \varepsilon$$

Where ε is an efficiency chosen to fit prop model to models from previous work

RVLT Quad6 – Power Model

- Open-source NPSS Power System Library components used
 - <https://github.com/nasa/NPSS-Power-System-Library>

Element	Modeling Assumptions
Cable	Sizes AWG to design point current (ampacity) drop tolerance (3%), and max paralleled conductors (4)... Cable resistance/inductance per foot from lookup table
Motor	Design efficiency at design point, runs efficiency map off-design, mass based on specific power
Generator	
Rectifier	
Inverter	
DC-DC converter	Design efficiency at design point, runs efficiency map off-design, mass based on specific power
Breaker	
Battery	

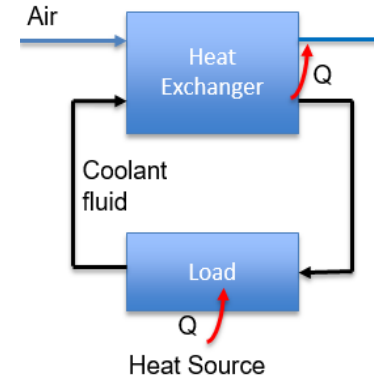


RVLT Quad6 – TMS Model

Thermal Management System (TMS): Methodology

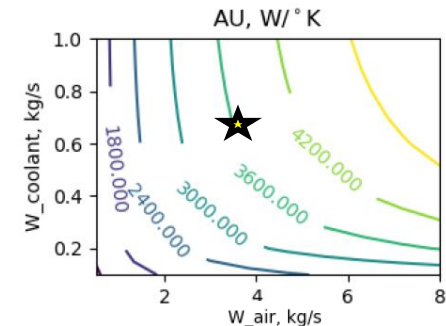
- Conventional pumped fluid loops utilizing air to coolant heat exchangers
- Heat Exchanger performance based on AU maps, scaled for required heat rejection
- Weight estimated utilizing sizing relations: relating rejected heat to mass

Example TMS architecture



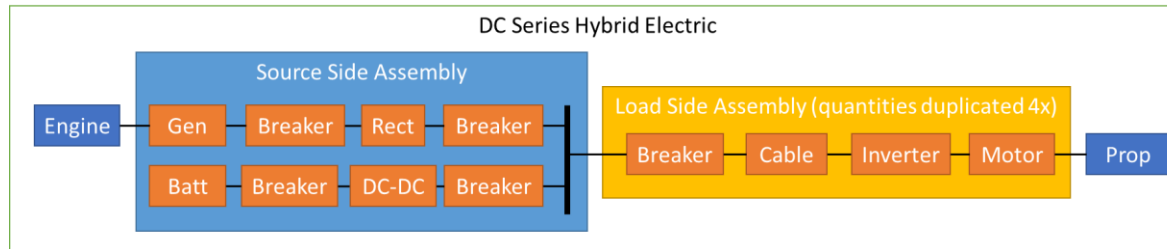
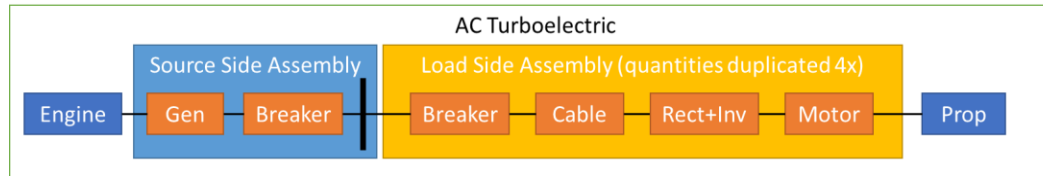
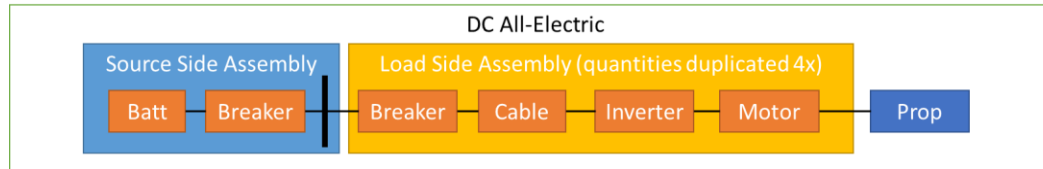
Example AU Map

- i.e., thermal transmittance times area



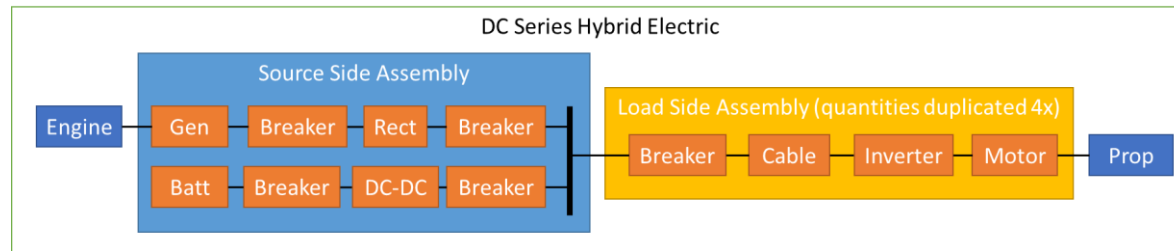
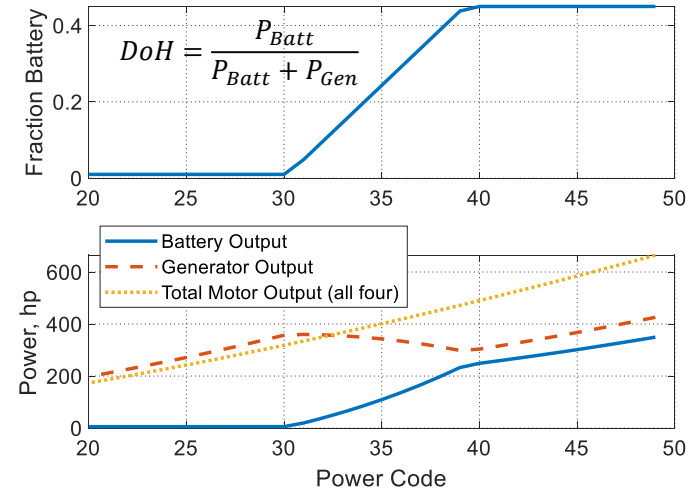
Architectures – DC vs TE vs Hybrid

- Power/propulsion architecture trades focus on power sources
 - Chose these b/c turboelectric and hybrid largely unexplored for this vehicle



Architectures – Details on Hybrid

- CONOPS for series hybrid
 - Engine sized for cruise power
 - Battery sized for addition power needed during hover/climb
 - Power split specified as “degree-of-hybridization” (DoH) w/ value selected for max range
 - Schedule and resulting power split shown
 - Battery fraction (dependent) controlled by solver by varying DC-DC voltage ratio (independent)
- Hybrid intended to have smaller engine, battery



Architecture Trades – Setup

- Compare architectures by running all at on-design case, sizing all powertrains to the same mass as all-electric reference Quad6 (2018 Aviation), tabulate output data, verify by running mission
 - For each, varied block fuel and/or battery block energy until mass target met (1211.5 kg)
 - Burned excess fuel/energy by changing length of cruise mission segment (range)

Architecture Trades – Results

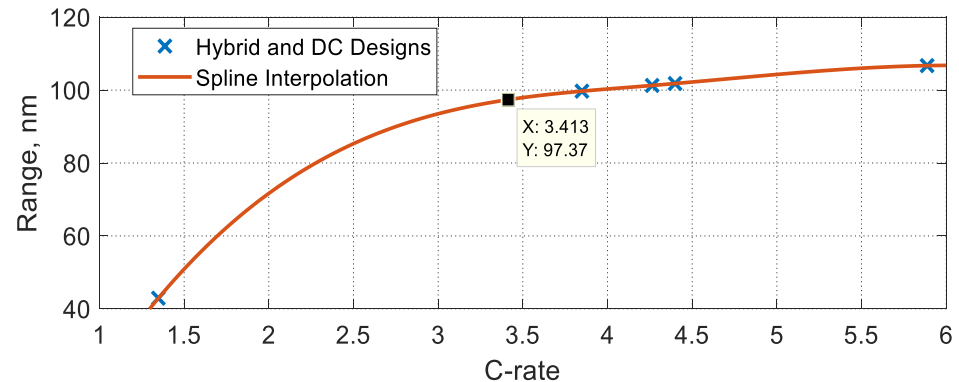
Metric Architecture	System Mass (kg)	Power System Mass (kg)	TMS Mass (kg)	Engine Mass (kg)	Fuel Mass (kg)	Battery Mass (kg)
DC	1211.5	117.14	39.286	0	0	1055.1
Hybrid	1211.5	205.78	41.430	128.43	721.17	114.69
Turboelectric	1211.5	219.35	35.901	165.60	790.64	0

Metric Architecture	Range (nm)	TOC Power System Losses (kW)	TOC Power System Efficiency	TOC (Design) Battery C-rate	Engine TOC PSFC (lbm/s/hp)	Engine Cruise PSFC (lbm/s/hp)
DC	42.899	90.937	0.9381	1.347	0	0
Hybrid	106.71	119.94	0.8867	5.887	0.626	0.642
Turboelectric	97.372	111.65	0.8918	0	0.611	0.690

- Range refers to range traveled during one of the two mission legs
 - Does not count reserves
- Data shows hybrid has the highest range followed by TE and DC
- Hybrid baseline design requires a very high design C-rate

Architecture Trades – Hybrid C-Rate

- Looking at Hybrid designs with different design power split (lower than baseline C-rate), and the DC design (lowest C-rate)
- Can see that C-rate must be higher than 3.41 for hybrid to exceed TE's range
- Therefore, hybrid needs batteries with high specific power and high specific energy



Parameter Sensitivity Study – Setup

- Observe parameter sensitivities by sweeping them, observing how output/performance parameters vary
- Varying engine, vehicle and power system variables, seeing how losses, mass and efficiency parameters vary

Design (Input) Parameters Swept		Output Parameters Observed	
Battery Voltage (V) 600-1200	Motor Specific Power (kW/kg) +/- 50%	Total Mass (kg)	Battery Mass (kg)
Generator Voltage (V) 600-1200	Motor Efficiency 93-99%	Total Power System Loss Power (kW)	Engine Mass (kg)
Generator Specific Power (kW/kg) +/- 50%	Thrust Requirement at TOC (lbf) +/-20%	Power System Mass (kg)	TMS Mass (kg)
Generator Efficiency 93-99%	Cable Length (m) +/-50%	Motor Losses (kW)	Design PSFC (lbm/s/hp)
Inverter Specific Power (kW/kg) +/- 50%	Battery Specific Energy (Wh/kg) 150-800	Inverter Losses (kW)	
Inverter Efficiency 93-99%	Battery Efficiency 93-99%		
DC-DC Specific Power (kW/kg) +/- 50%	Turbine Inlet Temp, T4 (°R) +/-20%		
DC-DC Efficiency 93-99%			

Parameter Sensitivity Study – Results

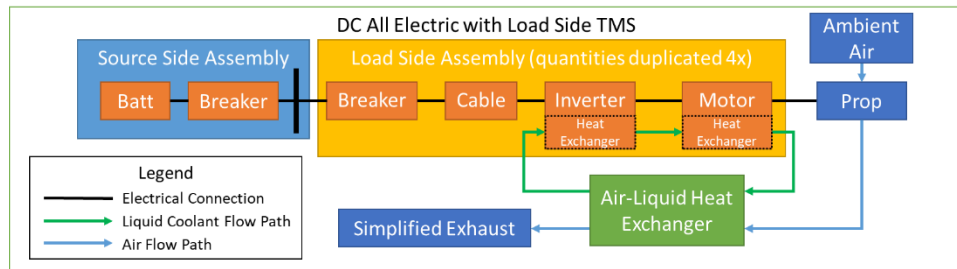
- Subset of sensitivity results presented

1% increase in machine/power electronics efficiency	→	1% system mass decrease
		2.5-7% system loss decrease
		2-4% TMS mass decrease
		1% power system mass decrease
1% increase in battery capacity	→	1.8% increase in cruise range for DC
1% increase in block fuel	→	2.1% increase in cruise range for TE and hybrid

- Increasing power device efficiency can result in significant benefits
 - Significant mass reduction from component and associated TMS mass decrease
 - E.g. Going from 95% to 97% efficient on all power electronics in TE means 4% system mass decrease (or about 48 kg)
 - Increasing fuel by 48 kg (about 6%) predicted to result in 12% range increase
- Other trends discussed further in the paper

TMS Study – Setup

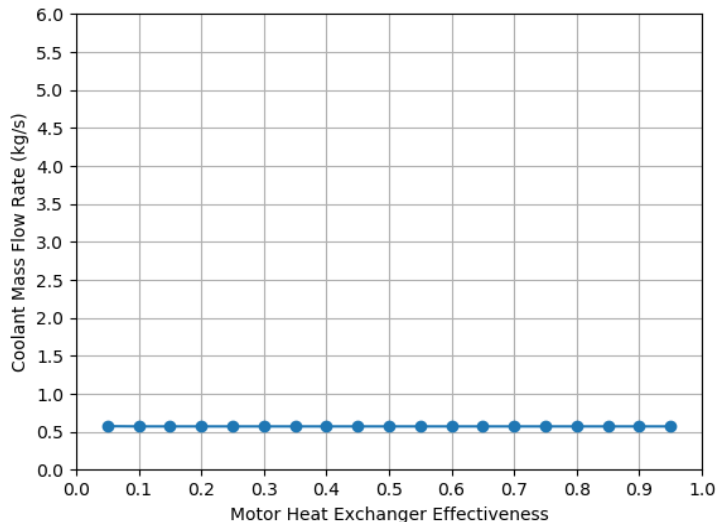
- Take DC model, add TMS (only cools load side components for now)
- Series loop
 - Motor max temp = 200 °C
 - Inverter max temp = 60 °C
- Inverter max temp much lower, so it drives design
- Vary inverter and motor heat exchanger effectiveness
- Observe how these changes effect the design



TMS Study – Setup

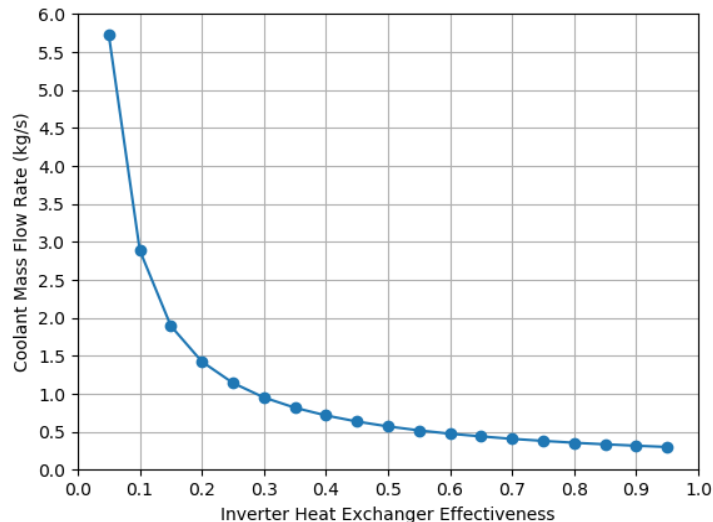
➤ Varying motor HX effectiveness

- Not hitting motor temp constraint, does not effect the series design significantly



➤ Varying inverter HX effectiveness

- To cool inverter to its temp constraint, requires higher (series) coolant flow rate as effectiveness goes down



Conclusions

- Three powertrain architectures explored for RVLT Quad6
 - Hybrid has best performance if a high C-rate is possible
 - Otherwise turboelectric performs best out of concepts studied
- Power, propulsion, and thermal design trends explored
 - Recommend investment in battery technology and device efficiency improvements
- Maturation of integrated NPSS multidisciplinary modeling and analysis capabilities shown

Future Work

- Investigate parallel hybrid and turboshaft (all-engine)
- See if hybrid can be made workable with smaller C-rate
- See if hybrid battery/supercap solution enables high C-rate
- Continue maturing NPSS multidisciplinary modeling tools,
 - Extend TMS model to cover entire powertrain
 - Improve component model fidelity
- Apply modeling tools/methods to other architectures (other eVTOLs, fixed wing, etc)
- Use data/trends from this work to inform future work

Acknowledgments

- Authors would like to thank NASA project support
 - **Susan Johnson**, *Revolutionary Vertical Lift Technologies (RVLT)*
 - **Sydney Schnulo**, *Hybrid Electric Analysis and Thermal Research (HEATHeR)*
- Check out other NASA RVLT/HEATHER talks including:
 - Session: EATS-28: Developments of the NASA High Efficiency Megawatt Motor
 - Sydney Schnulo- *Assessment of the Impact of an Advanced Power System on a Turboelectric Single-Aisle Concept Aircraft*
 - Session: EATS-15: Power Systems and Management
 - Jeffryes Chapman- *Thermal Management System Design for Electrified Aircraft Propulsion Concepts*
 - Session: EATS-29: Design and Modeling of Thermal Management Systems
 - Emre Sozer- *Computational Evaluation of an OML-based Heat Exchanger Concept for HEATHeR*
 - Session: EATS-23: Novel Thermal Management Integration Methods
 - Pat Hanlon- *Validation of Software Tools for the Analysis of Electrified Aircraft*
 - Session: EATS-04/GTE-22: Software Tools for Electrified Propulsion



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