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Design and Simulation of a Commercial Hybrid Electric Aircraft Thermal Management System

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The baseline design of the Thermal Management System (TMS) of a parallel, hybrid electric aircraft engine for a commercial, single aisle aircraft with batteries for energy storage has been completed. The Hybrid Electric Propulsion (HEP) system features a low spool motor to assist the propulsor, its attendant motor drive, propulsion batteries, and supplementary batteries to cover TMS electric loads during electric augmentation on takeoff and climb. The TMS further includes the heat loads sunk to engine oil including bearings, the fan drive system, and the accessory gearbox. The model was executed under hot day conditions (ISA + 15) over the mission sizing points when electric augmentation is active. REHEATS, a proprietary, object-oriented modeling tool created at the United Technologies Research Center, was used to model the TMS and find the solution with minimal fuel consumption. This study establishes a baseline for comparison of energy storage using batteries for future comparison. The results predict that the TMS of a HEP aircraft increases fuel consumption by 3.4% during takeoff, climb, and cruise.

I. Nomenclature

AOC	=	Air Oil Cooler
Bat	=	Batteries
Brg	=	Bearings
CP	=	Coolant Pump
ECS	=	Environmental Control System
ESC&D	=	Energy Storage, Conversion, and Distribution
Fan DS	=	Fan Drive System (gear train between LS and Fan)
FOC	=	Fuel Oil Cooler
FP	=	Fuel Pump
Gbx	=	Gearbox for accessories
HEP	=	Hybrid Electric Propulsion
HSSG	=	High Spool Starter Gen
LSMG	=	Low Spool Motor Gen
MD	=	Motor Drive
NPSS	=	Numerical Propulsion System Simulation
OP	=	Oil pump
RCC	=	Ram Coolant Cooler
TAT	=	Total Air Temperature
TAP	=	Total Air Pressure
TMS	=	Thermal Management System

II. Introduction

This NASA-funded effort investigates the impact of a commercial hybrid aircraft engine Thermal Management System (TMS) on vehicle weight and fuel consumption. The electric drive train or Energy Storage, Conversion and Distribution (ESC&D) system of a hybrid electric aircraft, even at high efficiency, rejects significant heat at relatively low temperature. Thus effective thermal management of the ESC&D system is critical to realizing the potential

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benefits of a hybrid electric aircraft as the TMS can add considerable weight (heat exchangers, pumps, batteries), impose high parasitic power loads (pumps, fans, bleed air), and cause drag (engine fan stream air and ram air).

A 5MW parallel hybrid configuration for a commercial, single aisle aircraft [1] provides a representative set of requirements for the development of TMS technology. The ESC&D system is integrated with a Geared Turbofan™ engine in which the electric motor assists the low pressure spool during takeoff and climb, thereby allowing the engine to be sized efficiently for cruise. The ESC&D system is deactivated during cruise, descent, approach, and taxi. The ESC&D system is comprised of a 1780 kW-hr battery system, 2 x 2.2 MW motor drives, 2 x 2.1 MW motors and the associated power panels and feeders [2].

An earlier NPSS HEP modeling effort of an electrically assisted turbofan provides input data for the TMS model created for steady state evaluation of the hybrid electric aircraft engine [3]. A previous investigation of energy storage concluded that batteries are generally heavier than a turbine-driven generator that burns Jet-A [4], however, for this study batteries are assumed to have competitive energy density in order to establish a baseline Hybrid Electric Propulsion (HEP) architecture for future comparison with other energy storage or conversion devices such as a turbogenerator powered by Jet-A fuel. The TMS cools batteries, however, at altitude when dormant they may need to be heated in order to avoid charge loss depending on their location in the aircraft (e.g. wings). This investigation focuses on cooling.

The object-oriented model created in the United Technologies Research Center's REHEATS MATLAB environment was executed optimizing against the user-specified objective function minimization of mission fuel consumption. This investigation provides details, results, and insights from the modeling of a hybrid electric aircraft TMS with battery storage.

III. Method

The steps in TMS analysis include defining the mission, calculating thermal loads, laying out the TMS, modeling performance over the design points of the mission, and finally visualizing results.

A. Mission Definition

A mission was defined consisting of taxi, sea level static, takeoff, several points of climb, cruise, two descent points, and approach. (See Table 1.) Although a full mission was defined, the model was executed over the sizing mission points: takeoff, climb, and cruise.

Electric fan-powered taxi was not considered in this study due to the large power required to run the Environmental Control System (ECS) electrically which translates in additional battery weight. In addition, a long period of taxi could detract from energy available for takeoff and climb.

This mission does not include any step climbs during cruise to take advantage of thinner air. The ECS&D system is not active during cruise, but it could assist with a step climb.

Last of all, during descent battery-charging was not simulated. The aircraft under consideration pressurizes its cabin pneumatically; it is unclear if the bleed air pressure would be sufficient to pressurize the cabin and to power the ECS during wind-milling of the fans. In addition, an AC-to-DC converter would be required, and it would have to be integrated into the TMS. A separate study is needed to determine feasibility.

Temperature and pressure data of heat sinks originate from a NPSS model of a HEP aircraft engine suitable for a single aisle aircraft. The NPSS model calculated thrust resulting from the addition of shaft power by an electric motor. Properties of ambient air, fan air, and fuel over the mission were harvested from the model results.

Ram air properties were calculated by adjusting ambient temperature and pressure for aircraft velocity (stagnation).

Fuel temperature and mass flow resulted from the NPSS model. Fuel pressure during the mission was estimated from the A320 fuel transfer pump product literature (Eaton Fuel Boost Pump Type 8410). Its pressure range is 25-45 psi with nominal 29 psi, so 29 psi was conservatively chosen for most mission points except for idle or near idle operation (e.g. taxi, descent) for which the minimum pressure was selected.

B. Thermal Loads

The following assumptions were made in determining the thermal loads:

- The TMS consists of numerous point heat loads including a High Spool Starter Generator (HSSG), a Low Spool Motor Generator (LSMG), Fan Drive System (DS), Motor Drive (MD), Batteries (Bat), Engine Bearings (Brg), and Accessory Gearbox (Gbx).
- Pneumatic loads (ECS) are sourced by the aircraft engine, not by the ECS&D system.
- Engine hot section thermal loads covered by engine air are not included in this analysis.
- Cooled cooling air, bleed air precooling, and inert gas cooling are not included in the HEP TMS.

Table 1. Mission Points and Data

Nr	Mission Point	Alti-tude	Mach	Length	Am-bient T	Am-bient P	Fan Air T	Fan Air P	TAT (Ram Air)	TAP (Ram air)	Fuel T	Fuel P	Fuel Mass Flow per Engine
		ft	-	min	°F	psia	°F	psia	°F	psi	°F	psi	pps
1	Ground Ops	0	0.00	10.0	103.0	14.7	106.7	14.9	103.0	14.7	103	25	0.01
2	Taxi	0	0.03	9	103.0	14.7	106.7	14.9	103.1	14.7	103	25	0.06
3	Sea Level Static	0	0.00	0.1	103.0	14.7	145.8	14.9	103.0	14.7	103	29	0.52
4	Takeoff	0	0.25	0.5	103.0	14.7	151.0	19.4	110.2	14.9	103	29	0.52
5	TO Climb	1500	0.39	1.3	97.2	13.9	152.6	19.2	114.0	14.3	103	29	0.52
6	Initial Climb	10000	0.45	2.8	63.9	10.1	123.1	14.5	85.3	10.5	103	29	0.35
7	Mid-Climb	20000	0.55	4.6	25.5	6.8	96.4	10.8	54.5	7.2	103	29	0.30
8	End Climb	37000	0.74	20.4	-43.6	2.9	52.9	5.5	1.9	3.2	103	29	0.18
9	End Cruise	37000	0.74	82.8	-43.6	2.9	41.0	5.1	1.9	3.2	74	29	0.15
10	Mid-Descent	20000	0.54	12.1	25.5	6.8	58.9	8.5	54.5	7.2	74	25	0.06
11	End Descent	1500	0.39	13.0	97.2	13.9	103.9	14.5	114.0	14.3	74	25	0.06
12	End Approach	0	0.00	4.8	103.0	14.7	118.7	15.3	103.0	14.7	74	25	0.15
13	End Taxi In	0	0.00	5	103.0	14.7	106.7	14.9	103.0	14.7	74	25	0.06

- Electric loads are sourced from batteries when the ECS&D system is active. The battery heat loads result from both propulsion and hotel loads such as avionics, lighting, passenger service, etc.
- The HSSG is not used for electric boost; only the LSMG assists the fan.
- The ECS&D system does not simultaneously add power to the low spool electrically and extract power from the high spool to make electricity. The HSSG stays off during electrically assisted operation.
- Hotel electric loads normally covered by the HSSG are covered by batteries during electric boost.
- No electric taxi (Pneumatic ECS requires large power)

Table 2 shows the hot day thermal loads per engine. Most heat loads were derived or calculated from a previous NPSS modeling effort of a hybrid electric aircraft engine that simulates the addition of shaft power to the low pressure spool by an electric motor [3]. The Low Spool Motor Generator (LSMG) was sized at max load during takeoff (2.1 MW). Its heat load was calculated, and then motor partial load performance data was used to calculate the motor heat loads at other mission points. Knowing the electric motor load allowed calculation of the MD and Bat heat loads by applying factors for efficiency: 96% and 95%, respectively. The Bat thermal load also includes the aircraft hotel loads adjusted by power factor (0.9) and divided by the number of engines. Both the Fan DS and Brg heat loads were extracted from NPSS results. The Brg loads are parasitic losses; we conservatively attributed all parasitic losses to them (no windage losses). Last of all, the accessory Gbx heat loads were estimated; the Gbx drives the hydraulic pump, fuel pump, oil pump, etc. The Gbx thermal loads and the hotel electric thermal loads from batteries were estimated on a standard day; the values were used in this hot day analysis. These loads are small relative to other loads, are not expected to vary greatly on a hot day, and are not expected to greatly influence the solution.

Brg is the largest TMS heat load. The mechanical fan DS also represents a large thermal load. Taken together, the ECS&D components (Bat, MD, and LSMG) constitute the majority of the thermal load.

C. TMS Architecture

The TMS was laid out by grouping heat loads at similar temperatures and locations on common cooling circuits. The TMS consists of two pumped liquid circuits that pick up numerous point heat loads and reject them to multiple heat exchangers. The coolant circuits are an oil loop for the higher temperature engine loads and a propylene glycol coolant loop for the lower temperature loads. Heat sinks include fuel, fan bypass air, and ram air.

Table 2. Hot Day Thermal Loads per Engine

Nr	Mission Point	HSSG	LSMG	Motor Drive	Bat	Fan DS	Brg	Gbx
		kW	kW	kW	kW	kW	kW	kW
1	Ground Ops	0.0	0	0	0	0.0	0.0	0.0
2	Taxi	16.0	0	0	0	2.1	60.3	2.7
3	Sea Level Static	0.0	45.7	89.5	119	72.0	162.7	3.5
4	Takeoff	0.0	45.7	89.5	119	72.0	162.7	3.5
5	TO Climb	0.0	47.2	87.4	117	72.0	163.8	2.7
6	Initial Climb	0.0	54.6	75.1	100	52.9	149.4	2.8
7	Mid-Climb	0.0	47.7	86.6	116	47.9	148.7	2.8
8	End Climb	0.0	56.0	32.1	44	30.6	137.8	2.8
9	End Cruise	30.9	0	0	0	22.5	123.3	3.1
10	Mid-Descent	17.8	0	0	0	4.9	70.0	2.1
11	End Descent	17.8	0	0	0	2.0	60.4	2.1
12	End Approach	13.5	0	0	0	15.0	95.2	2.0
13	End Taxi In	16.0	0	0	0	2.1	60.3	2.7

Figure 2 depicts the TMS layout. Heat loads are represented by red circles; pumps are green icons; and heat exchangers are purple rectangles. The conduits' color and width represent temperature and flow (Figure 1).

Oil Loop

The oil is a synthetic engine oil that meets military performance specification MIL-PRF-23699. The oil loop serves the higher temperature heat loads in engine including the HSSG, Gbx, Fan DS, Brg, and LSMG. Other components include the OP (Oil Pump), FP (Fuel Pump), AOC (Air Oil Cooler), and the FOC (Fuel Oil Cooler). The heat sinks for this loop are fuel and engine bypass air from the fan duct.

Coolant Loop

The coolant consists of a 50% mixture of propylene glycol and water. The coolant loop serves the lower temperature heat loads: Bat and MD that serves the LSMG. Other components are the electric ram fan, CP, and RCC (Ram Coolant Cooler). The heat sink is ram air. Ancillary components associated with the coolant loop are an air scoop and ram air fan. The scoop and fan combine to deliver cooling at sufficient pressure for the RCC.

D. TMS Model

The REHEATS environment enables multi-design point sizing and optimization of TMS components. REHEATS algorithms size heat exchangers and adjust component operation

The system was sized on a hot day (ISA+15) at several points: sea level static, takeoff, climb out, (takeoff climb), climb (numerous altitudes), top of climb, and cruise. Most design points use the electric augmentation system which must be transported during cruise.

Constraints

The below constraints were imposed explicitly:

- Fuel temperature $\leq$ 275°F
- Coolant temperature $\leq$ 135°F
- Oil temperature $\leq$ 300°F
- Oil flow rate $\geq$ 0.1 lbm/s
- Oil flow rate $\leq$ 20 lbm/s

Note that the fuel temperature limit is a projection of future capability of fuel to operate at elevated temperature without fuel deposit formation. The coolant temperature is chosen as not to overheat the batteries; typically lithium ion batteries should not exposed to this temperature due to capacity losses, but we assume that future battery chemistries will address this issue. The maximum oil flow constraint is included to avoid unrealistically high flow rates and small heat exchangers.

Objective Function

The objective function that best characterizes the impact of TMS weight, heat exchanger drag and power required for pumps and fans on the aircraft is minimization of fuel consumption. Fuel is consumed to transport weight, to power pumps and the ram fan motor, and to overcome aerodynamic drag from using ram air and engine fan air as heat sinks. The objective function considers operation of only one engine, so results must be adjusted for the number of engines.

The fuel penalties for pump power vary over the mission due to the varying cost of shaft power, however, pump powers are much, much smaller than other power loads so they were ignored. Battery weight for propulsion was not considered part of the TMS, however, the additional batteries to run the ram air fan motor and coolant pump were accounted for. Power loads covered by batteries incurred no generation penalty because the batteries are charged on the ground. Last of all, the benefit of sinking heat to fuel is not captured; this avoids burning some fuel that otherwise provides sensible heat and heat of vaporization of the fuel in the engine combustor. Rather, sinking heat to fuel is encouraged by penalizing the use of cooling flow in the AOC.

IV. Results

The REHEATS environment includes visualization capabilities that assist with the interpretation of results by mission point. The ensuing figures visually depict results from sea level static, takeoff, climb out, (takeoff climb), climb, top of climb, and cruise.

Each figure consists of two components: a layout of the system and a table of operational parameters by mission point. In the layout diagrams, the conduits that connect components are represented by lines with colors that indicate temperature as shown in Figure 1 below. The widths of lines indicate flow rate according to the legend. The tables have two sets of numbers: on the left colorful backgrounds indicate temperature of flows according to the legend in Figure 1 whereas black backgrounds represent components.

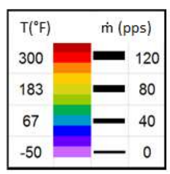


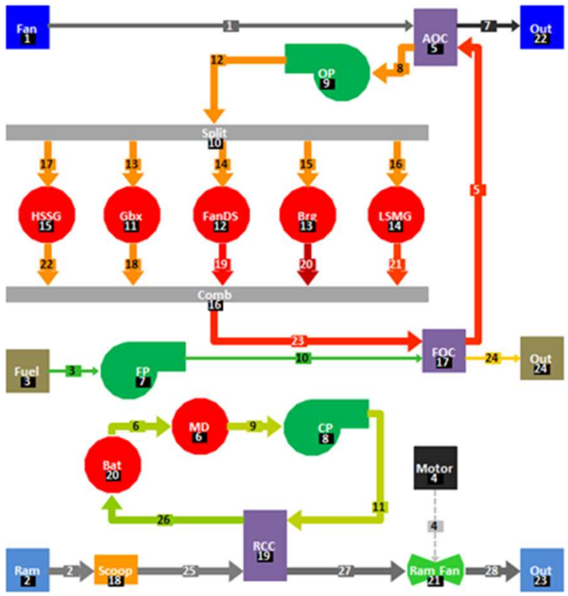
Figure 1. Legend for System Layout Figures.

The model optimized the TMS component sizes for minimal fuel consumption at several mission points resulting in a TMS with parameters that are provided in the ensuing figures. Some general observations of the TMS follow:

- The RCC is the largest heat exchanger by both volume and mass due to the low difference in temperature. Recalling that $Q = UA\Delta T$, low ΔT necessitates a large area.
- The oil temperature is high in order to maximize fuel temperature and to thereby avoid the penalty for fan air cooling flow in the AOC.
- The maximum oil temperature is at exit of largest heat load (Brg).
- The oil flow rates through heat load components vary
- When the aircraft is in motion, the ram air shows some temperature increase across the scoop due to as expected due to the conversion of kinetic energy to internal energy.
- The coolant temperature is typically 125 to 130°F prior to the battery heat load. The ΔT is thus small when cooling with ambient air.
- The AOC and FOC have negative values for heat transfer rates; this is only a matter of perspective in direction of heat transfer.

A. Sea Level Static

Figure 2 shows results at Sea Level Static conditions. Ram air shows no temperature change across the scoop as expected. The oil temperature nearly reaches its maximum at the Brg exit, however, the fuel temperature does not reach its maximum because it gets combined with other, cooler oil flows. The AOC has its maximum heat transfer during this mission point (sizing point) requiring the largest bypass fan flow (10.5 lbm/s).

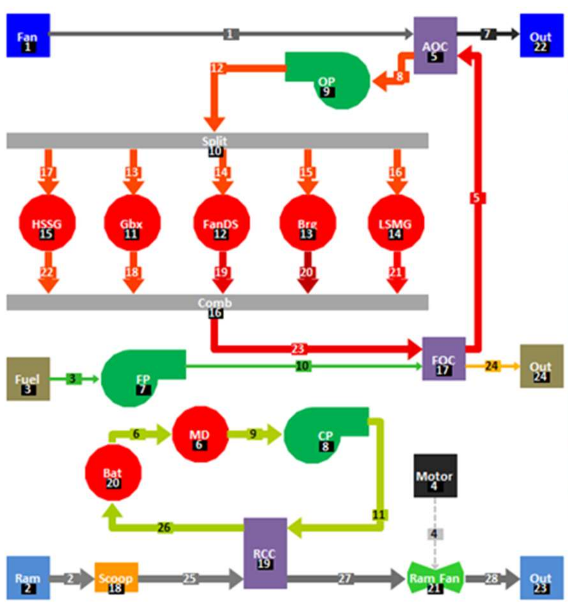


Tag	F	psia	pps	Type	Tag	kW	Eff	PR/CR	dP	in	in3	lbm	Matl
1	146	19	10.5	Air	1								
2	103	15	22.63	Air	2								
3	103	29	0.52	Fuel	3								
4				ShaftPower	4	30					2270	90.6	
5	252	100	18.05	oil23699	5	-261	0.9	0.28		5.2	1760	44.3	Al
6	135	100	10.67	Coolant	6								
7	242	15	10.5	Air	7	0	0.85		41				
8	225	49	18.05	oil23699	8	0	0.85		9				
9	144	100	10.67	Coolant	9	5	0.85		71				
10	103	70	0.52	Fuel	10								
11	144	109	10.67	Coolant	11								
12	225	120	18.05	oil23699	12								
13	225	120	3.35	oil23699	13								
14	225	120	3.61	oil23699	14								
15	225	120	4.12	oil23699	15								
16	225	120	3.61	oil23699	16								
17	225	120	3.35	oil23699	17	-26	0.61	0.03		2.9	130	11.4	In
18	227	120	3.35	oil23699	18								
19	263	120	3.61	oil23699	19	209	0.88	0.59		32.1	19320	357.9	Al
20	298	120	4.12	oil23699	20								
21	249	120	3.61	oil23699	21					14.2	5250	102.7	
22	225	120	3.35	oil23699	22								
23	255	120	18.05	oil23699	23								
24	196	70	0.52	Fuel	24								
25	103	15	22.63	Air									
26	123	100	10.67	Coolant									
27	139	15	22.63	Air									
28	143	15	22.63	Air									

Figure 2. TMS at Sea Level Static conditions.

B. Takeoff

At this mission point, ram air shows some temperature increase across the scoop as expected. The ram air flow is large: 32 pps. The oil temperature reaches its maximum at the Brg exit, however, the fuel temperature does not reach its maximum. The RCC has its maximum heat transfer duty at this mission point, as does the FOC (sizing point).

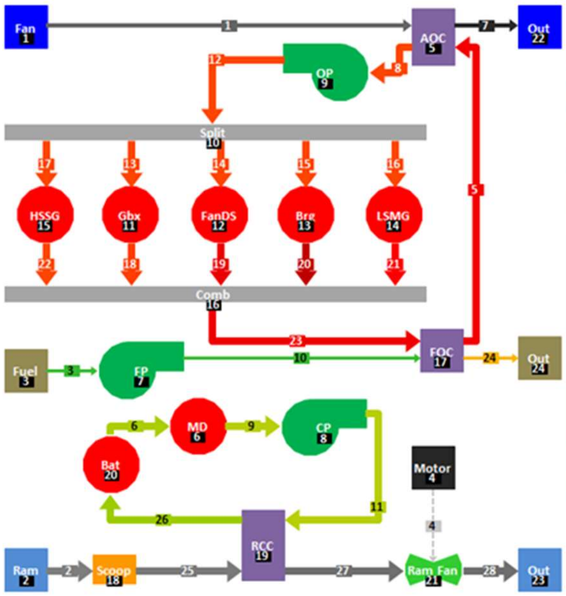


Tag	F	psia	pps	Type	Tag	kW	Eff	PR/CR	dP	in	in3	lbm	Matl
1	151	18	8.79	Air	1								
2	103	15	31.65	Air	2								
3	103	29	0.52	Fuel	3								
4				ShaftPower	4	24					2270	90.6	
5	272	100	18.65	oil23699	5	-257	0.94	0.23		5.2	1760	44.3	Al
6	135	100	40.14	Coolant	6								
7	264	15	8.79	Air	7	0	0.85		41				
8	246	50	18.65	oil23699	8	11	0.85		74				
9	137	100	40.14	Coolant	9	5	0.85		71				
10	103	70	0.52	Fuel	10								
11	137	174	40.14	Coolant	11								
12	246	121	18.65	oil23699	12								
13	246	121	2.29	oil23699	13								
14	246	121	4.26	oil23699	14								
15	246	121	5.57	oil23699	15								
16	246	121	4.26	oil23699	16								
17	246	121	2.29	oil23699	17	-30	0.61	0.03		2.9	130	11.4	In
18	249	121	2.29	oil23699	18								
19	278	121	4.26	oil23699	19	215	0.96	0.22		32.1	19320	357.9	Al
20	300	121	5.57	oil23699	20								
21	266	121	4.26	oil23699	21					14.2	5250	102.7	
22	246	121	2.29	oil23699	22								
23	275	121	18.65	oil23699	23								
24	207	70	0.52	Fuel	24								
25	110	15	31.65	Air									
26	132	100	40.14	Coolant									
27	136	15	31.65	Air									
28	137	15	31.65	Air									

Figure 3. TMS at Takeoff.

C. Takeoff Climb

At this mission point, the ram air flow rate reaches its largest value of 34 pps despite being slightly cooler. The oil temperature reaches its maximum at the Brg exit, however, the fuel temperature does not reach its maximum.

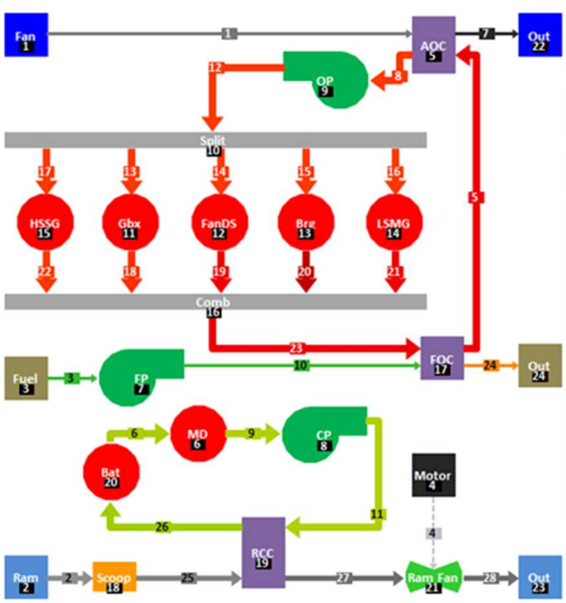


Tag	F	psia	pps	Type	Tag	kW	Eff	PR/CR	dP	in	in3	lbm	Matl
1	153	17	9.01	Air	1								
2	97	14	34.06	Air	2								
3	103	29	0.52	Fuel	3								
4				ShaftPower	4	20					2270	90.6	
5	271	100	19.24	oil23699	5	-259	0.94	0.22		5.2	1760	44.3	Al
6	135	100	16.48	Coolant	6								
7	264	14	9.01	Air	7	0	0.85		41				
8	247	47	19.24	oil23699	8	1	0.85		18				
9	141	100	16.48	Coolant	9	6	0.85		75				
10	103	70	0.52	Fuel	10								
11	141	118	16.48	Coolant	11								
12	247	122	19.24	oil23699	12								
13	247	122	2.46	oil23699	13								
14	247	122	4.35	oil23699	14								
15	247	122	5.64	oil23699	15								
16	247	122	4.35	oil23699	16								
17	247	122	2.45	oil23699	17	-29	0.61	0.03		2.9	130	11.4	In
18	249	122	2.46	oil23699	18								
19	277	122	4.35	oil23699	19	204	0.86	0.57		32.1	19320	357.9	Al
20	300	122	5.64	oil23699	20								
21	267	122	4.35	oil23699	21					14.2	5250	102.7	
22	247	122	2.45	oil23699	22								
23	274	122	19.24	oil23699	23								
24	207	70	0.52	Fuel	24								
25	114	14	34.06	Air									
26	127	100	16.48	Coolant									
27	137	14	34.06	Air									
28	138	14	34.06	Air									

Figure 4. TMS at Climb Out (Takeoff Climb).

D. Initial Climb (10,000 ft)

Despite the lower temperature of ram air, the ram fan motor increases its power due to the lower density of air at altitude. Once again, the oil that services the largest heat load, Brg, reaches the maximum temperature.

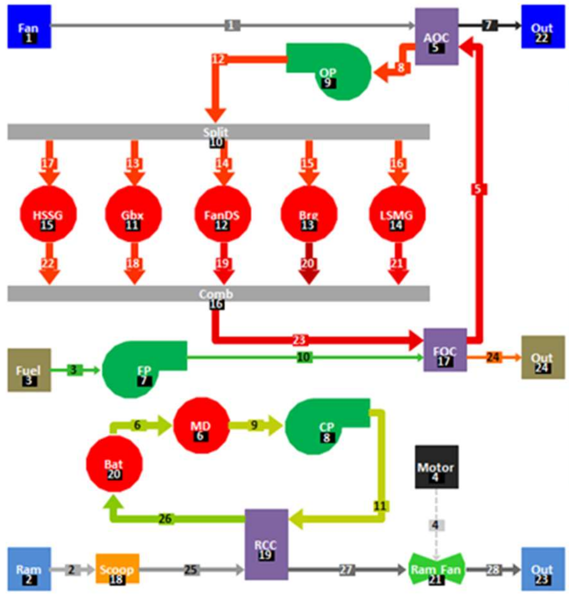


Tag	F	psia	pps	Type	Tag	kW	Eff	PR/CR	dP	in	in3	lbm	Matl
1	123	13	6.31	Air	1								
2	64	10	13.07	Air	2								
3	103	29	0.35	Fuel	3								
4				ShaftPower	4	24					2270	90.6	
5	274	100	18.06	oil23699	5	-238	0.97	0.17		5.2	1760	44.3	Al
6	135	100	19.64	Coolant	6								
7	269	10	6.31	Air	7	0	0.85		41				
8	250	53	18.06	oil23699	8	2	0.85		24				
9	139	100	19.64	Coolant	9	5	0.85		67				
10	103	70	0.35	Fuel	10								
11	139	124	19.64	Coolant	11								
12	250	119	18.06	oil23699	12								
13	250	119	2.12	oil23699	13								
14	250	119	4.17	oil23699	14								
15	250	119	5.5	oil23699	15								
16	250	119	4.17	oil23699	16								
17	250	119	2.12	oil23699	17	-25	0.73	0.02		2.9	130	11.4	In
18	253	119	2.12	oil23699	18								
19	274	119	4.17	oil23699	19	176	0.97	0.18		32.1	19320	357.9	Al
20	300	119	5.5	oil23699	20								
21	274	119	4.17	oil23699	21					14.2	5250	102.7	
22	250	119	2.12	oil23699	22								
23	277	119	18.06	oil23699	23								
24	230	70	0.35	Fuel	24								
25	85	10	13.07	Air									
26	130	100	19.64	Coolant									
27	137	10	13.07	Air									
28	140	10	13.07	Air									

Figure 5. TMS at Initial Climb (10,000 ft).

E. Mid-Climb (20,000 ft)

Oil reaches its maximum temperature at the exit of the Brg load. Fuel is at not at the maximum temperature. Ram fan motor power is less than in the previous mission point due to sub-freezing ram air temperature.

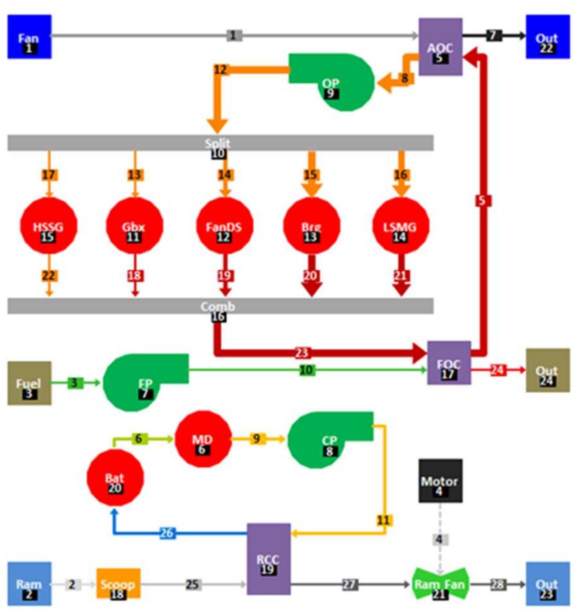


Tag	F	psia	pps	Type	Tag	kW	Eff	PR/CR	dP	in	in3	lbm	Matl
1	96	9	5.12	Air	1								
2	26	7	8.96	Air	2								
3	103	29	0.3	Fuel	3								
4				ShaftPower	4	14					2270	90.6	
5	274	100	17.44	oil23699	5	-227	0.97	0.14		5.2	1760	44.3	Al
6	135	100	9.26	Coolant	6								
7	268	7	5.12	Air	7	0	0.85		41				
8	250	55	17.44	oil23699	8	0	0.85		7				
9	145	100	9.26	Coolant	9	4	0.85		63				
10	103	70	0.3	Fuel	10								
11	145	107	9.26	Coolant	11								
12	250	118	17.44	oil23699	12								
13	250	118	1.93	oil23699	13								
14	250	118	4.08	oil23699	14								
15	250	118	5.43	oil23699	15								
16	250	118	4.08	oil23699	16								
17	250	118	1.93	oil23699	17	-22	0.78	0.02		2.9	130	11.4	In
18	253	118	1.93	oil23699	18								
19	272	118	4.08	oil23699	19	202	0.97	0.27		32.1	19320	357.9	Al
20	300	118	5.43	oil23699	20								
21	272	118	4.08	oil23699	21					14.2	5250	102.7	
22	250	118	1.93	oil23699	22								
23	276	118	17.44	oil23699	23								
24	237	70	0.3	Fuel	24								
25	54	7	8.96	Air									
26	122	100	9.26	Coolant									
27	142	7	8.96	Air									
28	144	7	8.96	Air									

Figure 6. TMS at Mid-Climb (20,000 ft).

F. End Climb (Top of Climb)

Oil reaches its maximum temperature at the exit of the Brg and LSMG loads. Fuel is at the maximum temperature. Ram fan motor power increases over the previous mission point due to lower air density.

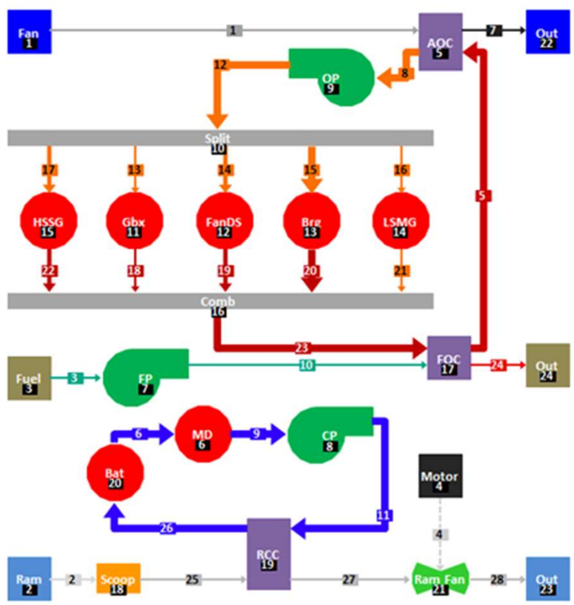


Tag	F	psia	pps	Type	Tag	kW	Eff	PR/CR	dP	in	in3	lbm	Matl
1	53	6	3.61	Air	1								
2	-44	3	1.85	Air	2								
3	103	29	0.18	Fuel	3								
4				ShaftPower	4	18					2270	90.6	
5	294	100	6.23	oil23699	5	-215	0.96	0.28		5.2	1760	44.3	Al
6	135	100	0.55	Coolant	6								
7	285	3	3.61	Air	7	0	0.85		41				
8	230	91	6.23	oil23699	8	0	0.85		0				
9	202	100	0.55	Coolant	9	0	0.85		12				
10	103	70	0.18	Fuel	10								
11	202	100	0.55	Coolant	11								
12	230	103	6.23	oil23699	12								
13	230	103	0.08	oil23699	13								
14	230	103	0.91	oil23699	14								
15	230	103	3.7	oil23699	15								
16	230	103	1.53	oil23699	16								
17	230	103	0	oil23699	17	-18	0.88	0.03		2.9	130	11.4	In
18	293	103	0.08	oil23699	18								
19	297	103	0.91	oil23699	19	79	0.82	0.95		32.1	19320	357.9	Al
20	300	103	3.7	oil23699	20								
21	300	103	1.53	oil23699	21					14.2	5250	102.7	
22	230	103	0	oil23699	22								
23	299	103	6.23	oil23699	23								
24	275	70	0.18	Fuel	24								
25	2	3	1.85	Air									
26	47	100	0.55	Coolant									
27	169	3	1.85	Air									
28	172	3	1.85	Air									

Figure 7. TMS at End Climb (37,000 ft).

G. End of Cruise

Cruise is a sizing point because although the ECS&D system is not active, transporting its weight for the longest duration mission point can affect the aircraft fuel consumption and thus influence TMS sizing. During cruise, the coolant decreases to low temperatures that would unacceptably cool the battery and potentially impact the ability to store charge. The coolant pump is active during cruise because the pump power, while small and not penalized in this analysis, still pumps sufficient coolant through the RCC to lower the temperature of the coolant below freezing. The fan motor operates at a minimum power setting, so some ram air flow is always passing through the RCC. Otherwise the TMS operates efficiently: oil reaches maximum temperature as does fuel.



Tag	F	psia	pps	Type	Tag	kW	Eff	PR/CR	dP	in	in3	lbm	Matl
1	41	5	2.64	Air	1								
2	-44	3	0.22	Air	2								
3	74	29	0.15	Fuel	3								
4				ShaftPower	4	11					2270	90.6	
5	294	100	5.26	oil23699	5	-166	0.97	0.24		5.2	1760	44.3	Al
6	2	100	3.16	Coolant	6								
7	286	3	2.64	Air	7	0	0.85		41				
8	236	93	5.26	oil23699	8	0	0.85		4				
9	2	100	3.16	Coolant	9	0	0.85		9				
10	74	70	0.15	Fuel	10								
11	2	104	3.16	Coolant	11								
12	236	103	5.26	oil23699	12								
13	236	103	0.09	oil23699	13								
14	236	103	0.7	oil23699	14								
15	236	103	3.59	oil23699	15								
16	236	103	0	oil23699	16								
17	236	103	0.89	oil23699	17	-17	0.89	0.03		2.9	130	11.4	In
18	300	103	0.09	oil23699	18								
19	300	103	0.7	oil23699	19	0	0.97	0.02		32.1	19320	357.9	Al
20	300	103	3.59	oil23699	20								
21	236	103	0	oil23699	21					14.2	5250	102.7	
22	300	103	0.89	oil23699	22								
23	300	103	5.26	oil23699	23								
24	275	70	0.15	Fuel	24								
25	2	3	0.22	Air									
26	2	100	3.16	Coolant									
27	2	3	0.22	Air									
28	3	3	0.22	Air									

Figure 8. TMS at End of Cruise.

V. Summary and Conclusions

The conceptual design of a baseline TMS has been completed. The solution predicts system weight at 697 lbm per engine with accessory battery weight for cooling circuit electric loads at 216 lbm per engine. The maximum ram air cooling flow rate is 34 lbm/s per engine during takeoff. The maximum bypass air cooling flow rate is 10.5 lbm/s per engine at sea level static. The fuel consumption impact of the TMS weight, power and drag for the design mission points plus cruise is 163 lbm per engine, or approximately 3.4% of total mission fuel burn. Including descent and approach in the analysis will increase the fuel consumption. It is projected that a parallel hybrid gas electric propulsion system could provide a 4 to 7% improvement in mission Jet-consumption, so the TMS erodes this benefit to 0.6 to 3.6%. Future work may involve researching and developing concepts for reducing the TMS impact including alternative power sources such as a turbine-driven generator operating on Jet-A fuel. In addition, future executions of the model will penalize the minute power consumption of the mechanically driven oil and fuel pumps as well as the electric coolant pump.

References

[1] Lents, C. E., Hardin, L.W., Rheaume, J.M, and Kohlman, L., "Parallel Hybrid Gas-Electric Geared Turbofan Engine Conceptual Design and Benefits Analysis," *52nd AIAA/SAE/ASEE Joint Propulsion Conference*, Salt Lake City, 2016, p. 4610.

[2] Lents, C. E., "Hybrid Electric Geared Turbofan Propulsion System Conceptual Design", Annual Interim Report Y1 Prepared for NASA Glenn Research Center under Contract NNC14CA32C, September 26, 2015.

[3] Lents, C. E., "Hybrid Electric Geared Turbofan Propulsion System Conceptual Design", Annual Interim Report Y2 Prepared for NASA Glenn Research Center under Contract NNC14CA32C, September 26, 2016.

[4] Rheaume, J. M., Lents, C. E., “Energy Storage for Commercial Hybrid Electric Aircraft”, No. 2016-01-2014, SAE Technical Paper, 2016.