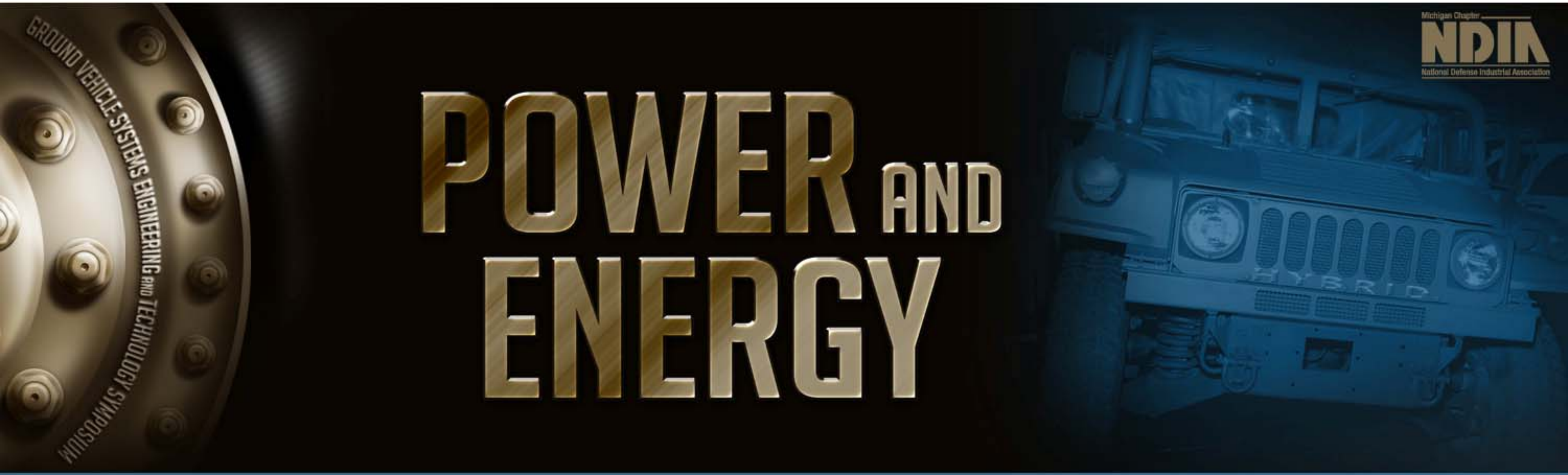

Developing a Methodology for the Evaluation of Hybrid Vehicle Thermal Management Systems

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Thermal Management System Evaluation

- How can we define a vehicle thermal management system (TMS) evaluation metric?
  - Performance
    - Does it meet the demand of maximum load at worst case boundary conditions?
    - Is the TMS operational power demand (hotel load) disproportionally large?
  - Size – is TMS disproportionally oversized in terms of:
    - Volume
    - Weight
- An evaluation metric structure could be developed that would -
  - Provide a means for comparison for and/or across classes of vehicles
  - Evaluate design maturity and point toward potential issues
  - Identify significant technological advancements

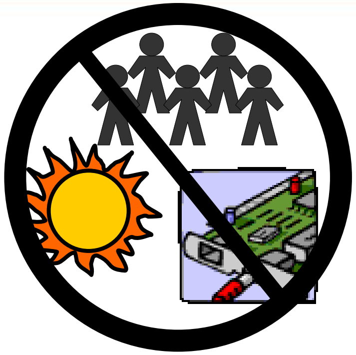
Vehicle TMS Definition?

- Vehicle Thermal Management System design requires intimate knowledge of vehicle:
  - Architecture – components and layout
  - Demand – component loading and boundary conditions
- Component-level cooling equipment needs to be included in estimates of component power density
  - Engine components: oil coolers and pumps, charge air coolers, water and fuel pumps, fuel coolers
  - Auxiliary components: closed loop specialized cooling equipment
  - Total volume must include ancillary non-system components like electrical wiring and connectors, plumbing fittings, etc. (i.e. not just shrink-wrapped volume)
- Vehicle packaging considerations may sometime make evaluation difficult
  - Component-level versus System-level thermal equipment
  - Plumbing considerations – valves, fittings, lines, etc.
- Specialized payloads and architectural outliers would need to be handled separately

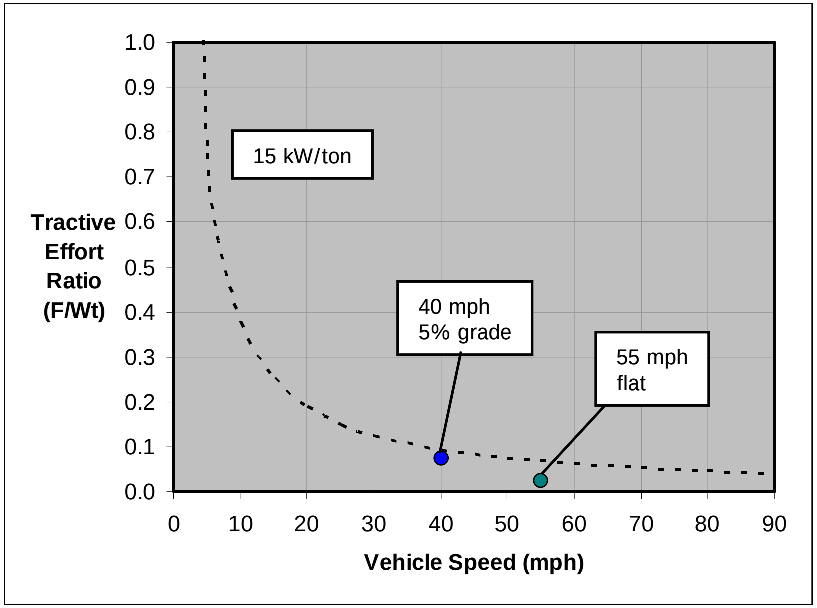
Procedural Example…

- Assumed baseline case demonstrates calculation of proposed metrics
  - Chosen climatic conditions: Category A1 – Hot Dry: 49°C ambient
  - Other climatic/operational conditions will yield metric values that can be tabulated
- Proposed metrics allow comparison/evaluation of competing vehicle TMS
- Other evaluation factors need to be considered for final judgment
  - Total cost: includes component and installation costs
  - Robustness: ease of/improvement in installation/operation
  - Readiness: maturity of component as well as availability

Baseline Case - Assumptions



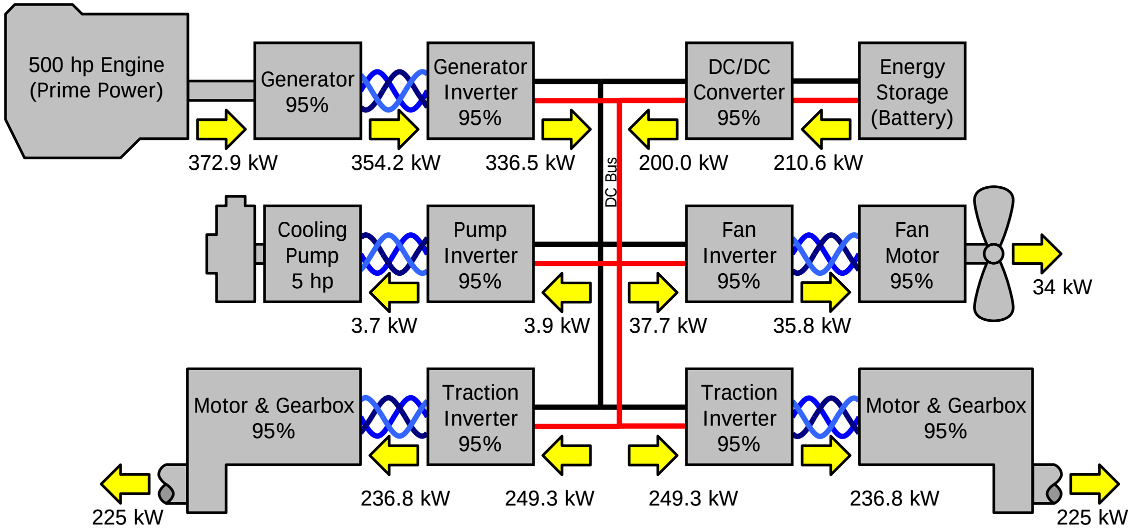
- Assume a generic layout of a 30-ton full hybrid electric vehicle
- Assume engine components are packaged to the engine block (oil pump, oil cooler, water pump, fuel cooler, etc)
- Assume engine operates on air-to-air charge air cooler and is considered "component-level" equipment
- Assume a sub-ambient cooling system is not required
- Consider mobility loads only – mission electronics, ambient solar, and human occupancy are considered negligible
- Packaging optimization is currently neglected
- Loading Condition (31 ton, 7 m^2 frontal area, C_D = 0.8, 35 lb/ton rolling resistance)
  - 40 mph continuous up a 5% grade (0.074 TE)
  - 55 mph continuous flat (0.026 TE)
  - Select vehicle tractive power ratio as 15 kW/ton
- Vehicle weight of 30 ton leads to tractive power of 450 kW (225 kW per side)



Baseline Case – Energy Balance

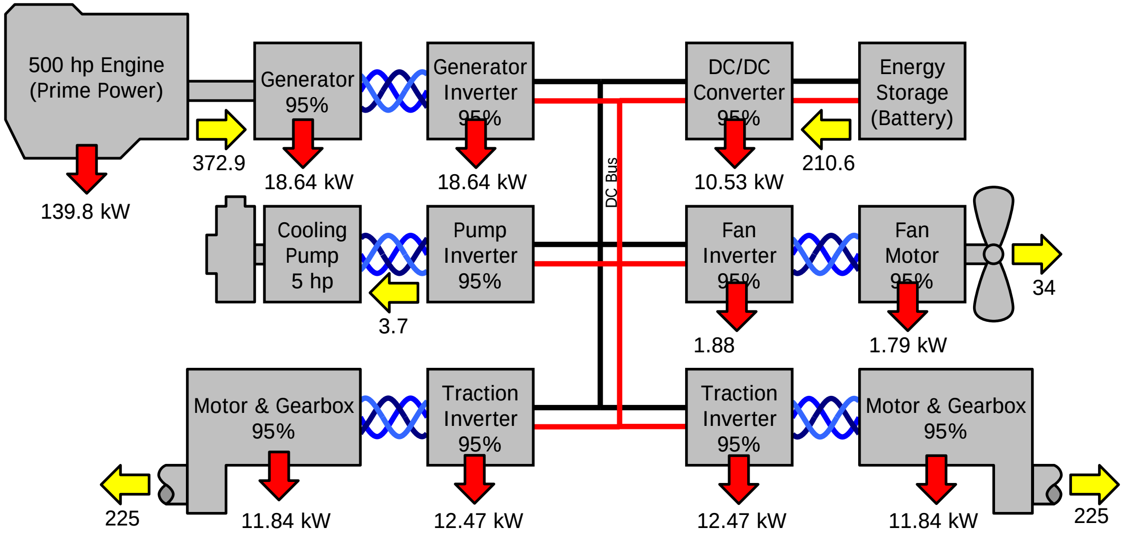
POWER AND ENERGY

- Assume a generic hybrid system
  - DC Bus distribution
  - Prime power generation: 500 hp
  - Energy storage system linked through DC/DC Converter
  - Tractive power (mechanical demand) of 225 kW per side
  - Auxiliary Cooling Pump (5 hp assumed)
  - Cooling Fan
  - 95% efficiency assumed for every component
- Solution Methodology
  - Fan power calculated 34 kW *[determination will be discussed in upcoming slide]*
  - Energy balance performed on DC Bus
  - Electronic component and motor thermal loads calculated



Baseline Case – Thermal Audit

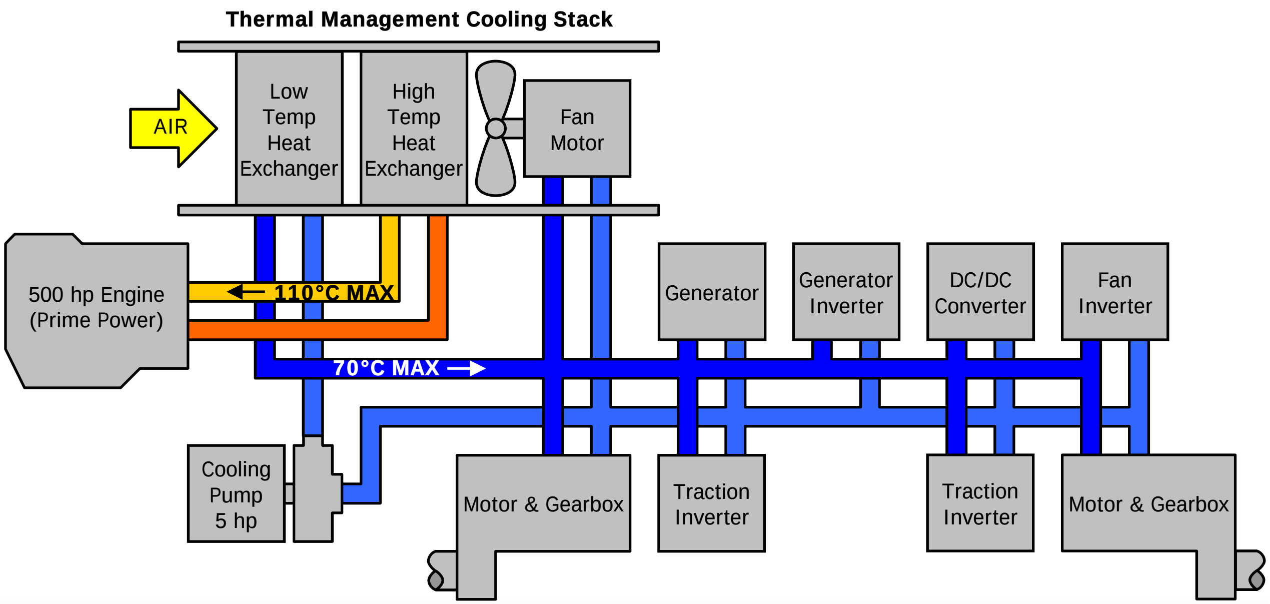
- Energy Balance gives loads for electronic components & motors
  - Cooling pump/inverter assumed air-cooled
  - Batteries assumed air-cooled
  - Electronics and motors assumed water-cooled (EGW/PGW)
- Representative engine loading to TMS
  - Engine block (86.2 kW)
  - Oil cooler (53.6 kW)
  - CAC assumed packaged with engine (air-to-air)
- Two cooling circuits
  - Low temperature circuit addresses electronics and motors (102.9 kW total)
  - High temperature circuit addresses engine needs (139.8 kW total)



Baseline Case – TMS Layout

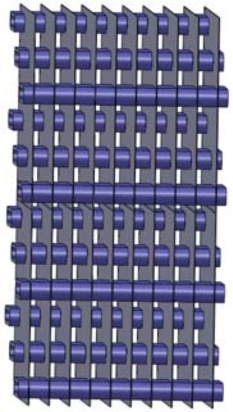
POWER AND ENERGY

- Two cooling circuits
  - Low temperature circuit addresses electronics and motors (102.9 kW total)
  - High temperature circuit addresses engine needs (139.8 kW total)
- All components on low temperature circuit plumbed in parallel with 70°C maximum allowable supply coolant temperature
- Low temperature coolant flow rate assumed to be 40 gpm
- High temperature coolant supplied by engine cooling pump (component-level thermal equipment)
- High temperature coolant flow rate assumed 80 gpm with 110°C maximum allowable supply temperature
- Heat exchangers assumed in series with respect to cooling air
- Climatic Conditions: Category A1 – Hot Dry: 49°C ambient

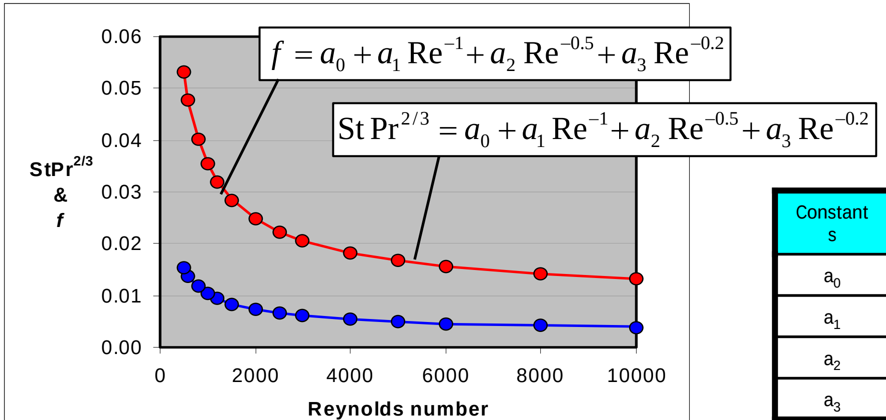


Baseline Case – TMS Sizing

- Determine heat exchanger stack size through knowledge of load and HX core performance
  - Stanton number correlation establishes heat transfer for a specific core geometry
  - Establishes core size (frontal area, depth and flow requirements)
- Establish expected air pathway pressure head loss
  - Friction factor correlation for HX core
  - Ducting pathway
  - Inlet/exhaust ballistic grill contributions
- Check pressure demand against fan performance curves
- Re-estimate fan power demand and check against energy balance calculations
- Iterate Steps 1-4 as necessary to generate convergence



Common Staggered Flattened Tube Extended Fin Core Arrangement



Finned Tube Surface 9.1-0.737S
<Compact Heat Exchangers - Kays & London, 1984>

Constants	f	$\mathrm{StPr}^{2/3}$
a_0	0.0096	0.0048
a_1	8.2596	1.0171
a_2	0.8230	0.3837
a_3	-0.0338	-0.0301

Friction Factor & Stanton Number Correlation Coefficients

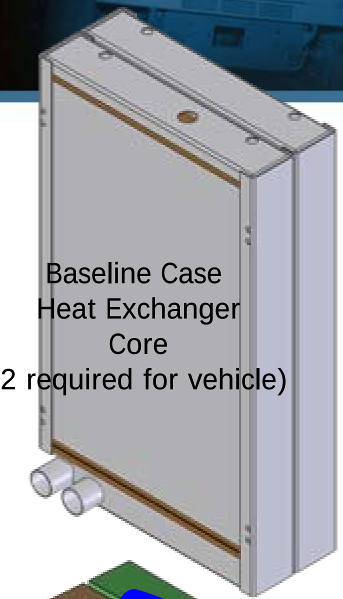
Surface Designation	Tube Arrangement	Fin Type	Tube Length (parallel to flow)		Tube Width (normal to flow)		Fins/in	Hydraulic Diameter		Fin Thickness		Free Flow/Frontal Area	Heat Transfer Area/Total Volume		Fin Area/ Total Area
			in	10^{-3}m	in	10^{-3}m		ft	10^{-3}m	ft	10^{-3}m		ft^2/ft^3	m^2/m^3	
9.1-0.737S	Staggered	Plain	0.737	18.7	0.100	2.5	9.1	0.01380	4.21	0.004	0.102	0.788	224	735	0.813

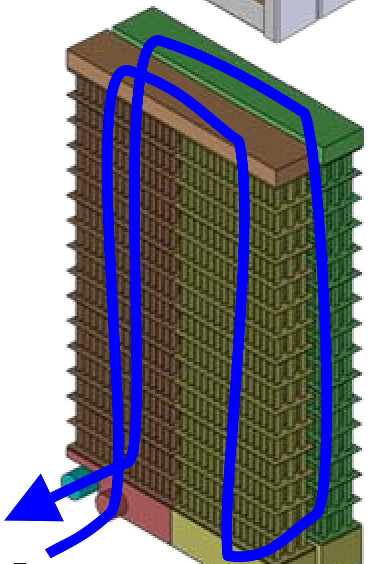
Baseline Heat Exchanger Geometrical Properties <*Compact Heat Exchangers* – Kays & London, 1984>

Baseline Case – Heat Exchanger Performance Evaluation

POWER AND ENERGY

- Heat exchanger performance evaluation based upon assumed packaging restrictions
  - Two heat exchangers in series with respect to air flow (i.e. – heat exchangers share common air flow)
  - Plumbing considerations impose a four-pass heat exchanger layout
- Assumed vehicle packaging considerations impose width restriction (mounted on vehicle sponson or similar)
- Analysis based upon core performance correlations (Stanton #) for baseline heat exchanger aspect ratio dictates:
  - Approximately 10,000 CFM airflow requirement to meet heat rejection needs
    - 49°C ambient dry air (no humidity corrections included)
    - Low temperature core heat rejection of 102.9 kW
    - High temperature core heat rejection of 139.8 kW
  - Air flow assumed uniform and well-mixed between heat exchanger core sections
  - Heat exchanger cores assumed clean (no internal/external fouling) and tube wall conduction resistance is negligible



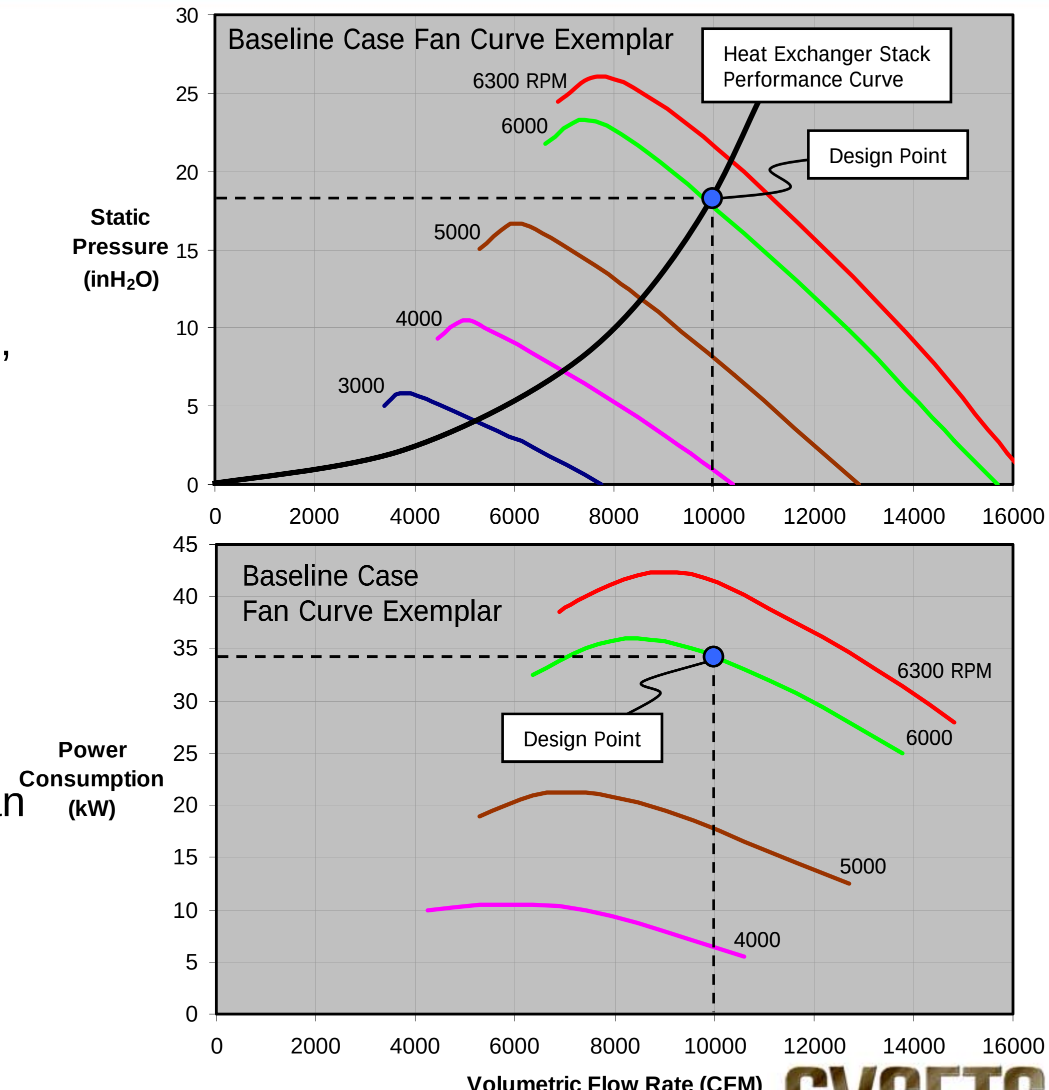


Four-pass coolant pathway

Baseline Case – TMS Design Point Operations

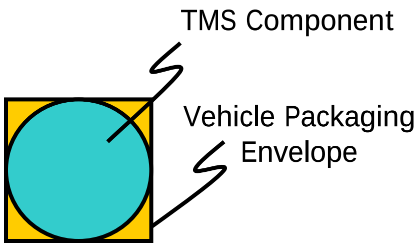
POWER AND ENERGY

- Heat exchanger core performance correlation (friction factor) establishes estimated pressure drop as a function of air flow
  - For 10,000 CFM each core loses approximately 6.5 inH_2O
- Airflow pathway may include ballistic grills, heat exchanger cores and flow routing ductwork
  - Actual performance would require detailed CFM analysis – for this case we've assumed a heat exchanger stack performance curve (shown on figure at right)
- Stack performance curve (pressure as a function of flow rate) is mapped against fan curve(s) to establish operational design point
  - 10,000 CFM flow rate
  - 6000 RPM fan speed
  - **34 kW fan power consumption**



Determining TMS Packaging Metric

- Identify component-level TMS equipment versus system-level equipment
- Evaluate packaging envelope as it impacts the vehicle
  - Includes overall vehicle size impact rather than just the volume of the component (not a shrink-wrapped solution)
  - 'Round component in a vehicle's square hole' effect
  - May become extremely significant when considering plumbing runs, fittings, valves etc.



- Components to be included in weight & volume estimates
  - TMS components to include heat exchangers, pumps, fans, controllers, reservoirs, plumbing, ductwork, grills, and coolant inventory
- Baseline system estimates:
  - TMS Volume 30 ft^3
  - TMS Weight 1100 lbs

Baseline Case with Proposed TMS Metrics

- **Packaging Metric** – Audit of TMS component size and weight
  - Compare cumulative TMS component size/weight to:
    - Vehicle mobility component size/weight audit
    - Overall vehicle size/weight

$$\textit{TMS Weight Metric} = \frac{\textit{TMS Weight}}{\textit{Vehicle Weight}} = \frac{(1100/2000)}{30\ ton} \times 100 = 1.8\%$$

- **Hotel Load Metric** – Audit of vehicle TMS comparing hotel load to deliverable vehicle tractive power
  - Baseline case – 3.7 kW pumping power, 34 kW fan power, 450 kW deliverable tractive

$$\textit{Hotel Load Metric} = \frac{\textit{Thermal Hotel Load}}{\textit{Tractive Power}} = \frac{(3.7+34)}{450} \times 100 = 8.4\%$$

- **Thermal Load Metric** – Audit of vehicle thermal load to deliverable tractive power
  - Baseline case: LT=102.9 kW, HT = 139.8 kW, 450 kW deliverable tractive

$$\textit{Thermal Load Metric} = \frac{\textit{Vehicle Thermal Load}}{\textit{Tractive Power}} = \frac{(102.9+139.8)}{450} \times 100 = 53.9\%$$

- **Operational Thermal Margin** – Comparison of maximum heat rejection capability to design point
  - Baseline Case – design point heat rejection 242.7 kW
  - Maximum Capability – estimated at 253 kW

$$\textit{Operational Thermal Margin} = \frac{\textit{Maximum - Design Point Load}}{\textit{TMS Maximum Capability}} = \frac{(253-242.7)}{253} \times 100 = 4.1\%$$

Proposed Vehicle TMS Metrics in Action…

- Proposed metrics result in quantitative descriptors for vehicle TMS
  - Other climatic conditions/operational points will yield different metric values
  - Comparison of metrics from other TMS designs generates quantitative comparison of systems
  - Component-level changes can be evaluated by comparing resulting system metrics (i.e. trade-offs)
- Operational margin allows fine-tuning
  - Large margin can be used to justify component-level changes to save cost/weight/volume at expense of TMS performance
  - Small margin signals requirement for improved component and system-level performance

Application of Vehicle TMS Performance Metrics

- **Conceptual Vehicles**
  - Packaging Metric
  - Hotel Load Metric
  - Thermal Load Metric
  - Operational Thermal Margin
- **Existing Vehicles**
  - Evaluate Packaging Metric
  - Hotel Load Metric
  - Thermal Load Metric
  - Establish performance limitations through operational data to evaluate operational thermal margin (if any) and/or performance deficits
- **Evaluating Component Alterations**
  - Easily identify packaging implications
  - Operational setpoint evaluations (e.g. – impact of higher operating temperature)
    - Needs model (as was developed for baseline case) to evaluate
    - May impose system layout changes (e.g. – series vs parallel)