14111

05MV-91

Combat Vehicle Engine Selection Methodology Based On Vehicle Integration Considerations

Charles Raffa, Ernest Schwarz and John Tasdemir
US Army RDECOM/TARDEC

ABSTRACT

Past experience has shown that the power density of an engine itself is not a sufficient guide to determine whether it will meet the power density needs of the intended combat vehicle application. The real need is for the complete propulsion system to be power dense. Here the definition of the propulsion system includes the engine, transmission, cooling system, air filtration system, intake and exhaust ducting, controls, accessories, batteries, fuel system and final drives. The power pack is a subset of the propulsion system and consists of that part of the propulsion system that would be lifted out of the vehicle for service or replacement and would typically consist of at least the engine, and transmission, cooling system, and power pack controls and ideally would also include the air filtration system and accessory drives.

Engine operating characteristics will directly impact power density for some propulsion system items. Engine air flow characteristics will impact air filtration and intake and exhaust space and weight claims, engine heat rejection and operating fluid temperatures will impact cooling system size and parasitic fan power required and engine fuel consumption characteristics will impact fuel system space for a given range or mission requirement. These characteristics as well as the physical nature, shape, and configuration of the engine will influence the power density of the overall propulsion system. The purpose of this paper will be to look at the issues of power density for combat vehicle propulsion and look at a methodology to evaluate engine candidates for such applications based on an overall propulsion system power density perspective.

INTRODUCTION

Twenty three years ago (1982), the U.S. Army TACOM embarked on a program to develop and demonstrate an advanced integrated propulsion system (AIPS) to increase propulsion system power density, improve fuel economy, and improve maintainability for a future main battle tank to replace the Abrams main battle tank. That program considered turbine and diesel engine candidates and ten years later demonstrated power densities of 6 sprocket horsepower per cubic foot of total propulsion system volume against the Abrams power density of 3.26 sprocket horsepower per cubic foot. To accomplish these power densities, both turbine and diesel AIPS efforts concentrated on high efficiency components, dense component packaging, reduction of parasitic losses throughout the system and engine technologies specific to the diesel or turbine engine types. Turbine AIPS efforts concentrated on higher turbine inlet temperatures, high recuperator effectiveness, and reduced pressure losses to accomplish reduced air consumption and improved fuel efficiency, especially at part power. Diesel AIPS efforts concentrated on improved engine power density, fuel consumption, and low heat rejection / higher coolant temperature technologies.

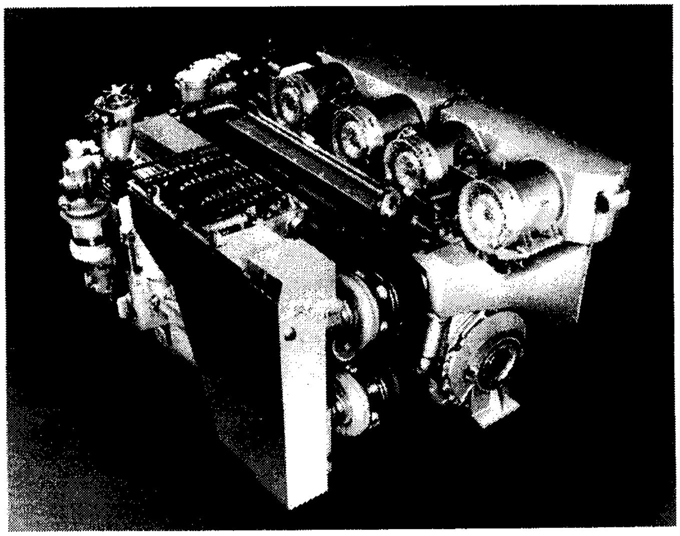

Figure 1: Advanced Integrated Propulsion System (AIPS) Power Pack

Figure 1 depicts the Diesel AIPS power pack, which includes a synthetic oil cooled 12 cylinder, 28 liter displacement diesel engine, a seven forward speed transmission, a self cleaning air filter, electronic power pack controls, cooling system with variable speed fan drive system, engine starter, vehicle alternator and turret hydraulic pump. The system design for the AIPS program began with a clean sheet of paper for the entire

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **01 JUN 2004**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Combat Vehicle Engine Selection Methodology Based On Vehicle Intergration Consideration**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Raffa, Charles; Schwarz, Ernest; Tasdemir, John**		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **USA TACOM 6501 E 11 Mile Road Warren, MI 48397-5008**		8. PERFORMING ORGANIZATION REPORT NUMBER **14111**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**
13. SUPPLEMENTARY NOTES **Presented at SAE 2005 World Congress**
14. ABSTRACT
15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**8**	

propulsion system so characteristics of the engine and transmission, cooling etc. were decided during design to maximize system power density. Very little turbocharger after cooling was done in the AIPS diesel which minimized heat rejection, allowed a single high temperature cooling loop and minimized plumbing complexity in the design. The congressional exclusion of combat vehicles from Environmental Protection Agency requirements also figured crucially in achieving these goals.

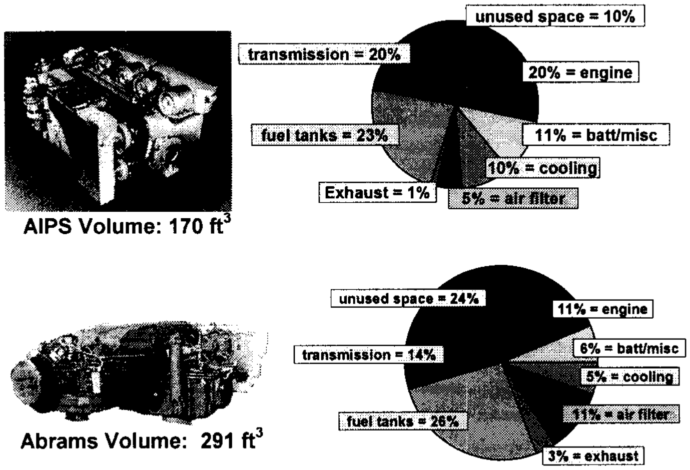

Figure 2: Volumetric Comparison of the AIPS vs. Current Abrams Propulsion Systems

Figure 2 compares the Abrams propulsion system versus the Diesel AIPS propulsion system volumes for the same vehicle range and similar sprocket power output. The principle differences in power density between these two propulsions systems might be summarized into five categories which could be labeled (1) density of packaging, (2) air consumption differences, (3) fuel consumption differences, (4) heat rejection differences and (5) parasitic loss differences. The impact of these five categories, three of which are engine characteristics and the remaining two installation or integration differences can explain the power density differences between these two systems. Items one and five are primarily in the control of the vehicle or propulsion integrator, but items two three and four are controlled by the engine developer. If the vehicle integrator and engine developer work closely together, the physical arrangement and the characteristics of the engine can often be modified to maximize the propulsion system power density, though often at some expense to engine power density.

During the time frame of the AIPS development effort, a new foreign engine development became known which was regarded as a potential competitor to the AIPS program. This new engine being developed for marine propulsion, rated 1500 horsepower at 1800 RPM, was a three stage turbocharged 2 stroke / cycle diesel engine, with only 3 cylinders and 7 liter displacement. The AIPS 4 stroke / cycle diesel engine, rated 1500 hp at 2600 rpm but with 12 cylinders and 28 liters displacement, was expected to be significantly larger dimensionally, so an analysis was structured to consider the size and power density potential of this new engine development compared to the AIPS effort being pursued. Engine characteristics for the new engine were not fully available but were estimated based on the information available. The analysis showed the larger diesel AIPS engine to be more power dense at the system level than the 7 liter 2 stroke / cycle potential competitor in spite of its anticipated substantially smaller engine size.

Several years ago, the U.S. Army TARDEC embarked on a program to develop and demonstrate high power density engines of a size and capability that would be suitable for the 20 ton class Future Combat Systems (FCS), manned ground vehicles. Because of high sustained cross country mobility requirements, high anticipated auxiliary loads (weapon systems, NBC, countermeasure armor, suspension, water generation, etc.) and space expected to be at a premium in a lightweight vehicle with such ambitious goals; a high power density engine solution was sought which would maximize the power density of the engine itself while minimizing the adverse impact on the remaining components, of the propulsion system. For the purposes of that effort the definition of the propulsion system was similar to the definition in the AIPS program. The objective in that program was to demonstrate the potential to double propulsion system power density from the typical level of 3 net horsepower per cubic foot found in current combat vehicles like Abrams and Bradley to 6 net horsepower per cubic foot.

In conjunction with the above program, a methodology was developed to assess the system power density potential, without firm knowledge of the specific vehicle requirements or reference to a particular vehicle design. This methodology included in the Appendix (Appendix was part of the TARDEC's FCS engine Request For Proposal (RFP) package) can also be used to evaluate advanced engine concepts to determine trends in overall propulsion system volumes and weight, if engine characteristics are known or can be estimated.

METHODOLOGY

The following is a description applied to the 28 liter AIPS diesel vs. the 7 liter Marine diesel. Table 1 compares the 28 liter AIPS diesel versus the 7 liter marine diesel using the FCS engine spreadsheet methodology somewhat modified for the tank application.

The engine characteristics entered in the "Engine Application Characteristics" section of table 1 are used later in the spreadsheet to assess the potential for installed power density. The two stroke / cycle engine had somewhat greater specific air consumption and specific fuel consumption and was calculated to have significantly higher specific heat rejection (due largely to three stages of turbocharger inter-cooling and after-cooling), but was expected to have considerably smaller physical size. The vehicle weight entry was taken as 60 tons to be consistent with the combat weight anticipated in the AIPS development effort for the then future tank.

Engine	Aips Diesel Hot Day 6 In Core	Aips Diesel Normal Day 6 In Core	7L 2 Stroke Hot Day 5.5 In Core	7L 2 Stroke Normal Day 5.5 In Core	7L 2 Stroke Hot Day 7.5 In Core	7L 2 Stroke Normal Day 7.5 In Core
Engine Application Characteristics						
Engine [hp]	1500	1500	1500	1500	1500	1500
Engine Dunk Volume [ft^3]	34	34	20	20	20	20
Engine Specific Heat Rejection [Btu / hp·min]	20	20	40.2	40.2	40.2	40.2
Engine Induction Air Flow [lbs / hr]	14400	14400	18500	18500	18500	18500
BSFC at Full Power [lbs / hp·hr]	0.37	0.37	0.39	0.39	0.39	0.39
Engine Heat Rejection [Btu / min]	30000	30000	60300	60300	60300	60300
Vehicle Weight [tons]	60	60	60	60	60	60
Cooling System Size / Parasitic (Fan) Power Sizing						
Heat Exchanger Type: Oil to Air or H_2O to Air	Oil to Air	Oil to Air	H2O to Air	H2O to Air	H2O to Air	H2O to Air
Core Thickness [in]	6	6	5.313	5.313	7.5	7.5
Fins / Inch	11	11	11	11	11	11
Atmospheric Pressure [in HgA]	29.696	29.696	29.696	29.696	29.696	29.696
Total heat rejection [Btu / min]	41426	41261	69489	70052	70353	70735
Core Area [ft^2]	8.6	8.6	21.8	21.8	19.3	19.3
Heat Exchanger Inlet Temp [° F]	340	275	230	195	230	195
Ambient Air [° F]	120	77	120	77	120	77
Air Density entering Radiator [lbs / ft^3]	0.0679	0.0733	0.0679	0.0733	0.0679	0.0733
Specific Heat Rejection [Btu / (min·ft^2·ITD·° F)]	21.90	24.23	28.98	27.23	33.14	31.06
Curve Fit Data NOT Valid Above [lbs / min-ft^2]	500	500	250	250	180	180
Required Air Mass Flow / ft^2 [lbs / min-ft^2]	152.4	185.8	225.0	208.2	179.7	166.7
Curve Fit Data NOT Valid Below [lbs / min-ft^2]	100	100	30	30	38	38
Radiator Delta P [in H_2O]	4.07	5.23	4.94	3.98	4.66	3.80
9.5 inches + Radiator Delta P [in H_2O]	13.57	14.73	14.44	13.48	14.16	13.30
Cooling Air Mass Flow [lbs / min]	1310.5	1597.7	4905.0	4539.6	3468.2	3217.1
Radiator Outlet Air Temp [° F]	250.1	183.3	178.3	140.5	203.5	167.5
Radiator Outlet Air Density [lbs / ft^3]	0.0549	0.0604	0.0609	0.0649	0.0587	0.0622
Fan Inlet Air Density [lbs / ft^3]	0.0536	0.0590	0.0595	0.0634	0.0573	0.0607
Fan Power (12 in + Rad delta P) @t 60% Efficiency HP	103.3	122.6	366.9	300.6	265.1	220.0
Radiator Core Volume [ft^3]	4.30	4.30	9.65	9.65	12.06	12.06
Transmission Input HP	1346.7	1327.4	1083.1	1149.4	1184.9	1230.0
Transmission Ouput HP @ 80% Efficiency	1077.4	1061.9	866.5	919.5	947.9	984.0
Transmission Heat Rejection [Btu / min]	11426	11261	9189	9752	10053	10435
Total Heat Rejection [Btu / min]	41426	41261	69489	70052	70353	70735
Power Pack Net Horsepower [hp]	1077	1062	867	920	948	984
Fan Power [hp]	103.3	122.6	366.9	300.6	265.1	220.0
Cooling System Volume [ft^3]	25.80	25.80	64.15	64.15	60.31	60.31
Inlet and Exhaust System Impact						
Air filter System Size [ft^3]	10.0	10.0	12.8	12.8	12.8	12.8
Inlet and Exhaust System Volume [ft^3]	2.06	2.06	2.64	2.64	2.64	2.64
Installation Loss (Intake and Exhaust Loss) [hp]	50	50	50	50	50	50
Mission Fuel Determination @ 60 Net hp*hr / ton						
BSFC at 10% Power	0.407	0.407	0.429	0.429	0.429	0.429
BSFC at 50% Power	0.333	0.333	0.351	0.351	0.351	0.351
BSFC at 100% Power	0.37	0.37	0.39	0.39	0.39	0.39
Gallons Fuel (for 60 net hp·hrs/ton) [gallons]	266.9	270.8	349.8	329.6	319.8	308.1
Weight of Fuel [lbs]	1780	1806	2333	2199	2133	2055
Volume of Fuel [ft^3]	35.7	36.2	46.8	44.1	42.7	41.2
Propulsion System Volume Estimate						
Engine Dunk Volume [ft^3]	34	34	20	20	20	20
Transmission Dunk Volume [ft^3]	34.9	34.9	34.9	34.9	34.9	34.9
Cooling System Volume (including fans) [ft^3]	29.29	29.67	75.93	74.38	68.97	67.89
Air filter System Size [ft^3]	10.0	10.0	12.8	12.8	12.8	12.8
Inlet and Exhaust System Volume [ft^3]	2.06	2.06	2.64	2.64	2.64	2.64
Control System Volume [ft^3]	1	1	1	1	1	1
Miscellaneous Volume [ft^3]	0	0	0	0	0	0
Batteries Volume [ft^3]	6	6	2	2	2	2
Wiring Harness Volume [ft^3]	1	1	1	1	1	1
Fuel Tanks and Plumbing @ 60 net hp*hr/ton [ft^3]	39.94	40.51	52.17	49.20	47.74	46.01
Final Drives Volume [ft^3]	3.9	3.9	3.9	3.9	3.9	3.9
Sum of Above Volumes [ft^3]	162.1	163.0	206.4	201.9	195.0	192.2
Clearance and Unusable Volume [ft^3]	15.2	15.3	17.8	17.6	17.2	17.0
Total Propulsion System Volume [ft^3]	177.3	178.3	224.2	219.5	212.2	209.2
Sprocket Power [hp]	1056	1041	849	901	929	964
Propulsion Power Density [sprocket hp / ft^3]	5.95	5.84	3.79	4.11	4.38	4.61

Table 1: Example Engine Density Calculations

COOLING SYSTEM AND PARASITIC FAN POWER SIZING

This section of table 1 sizes a cooling system and associated fan power using the guidelines of the Appendix but applied to the particular characteristics of these two engines. In this example, the cooling system volume and fan power, were calculated by taking the engine heat rejection numbers for the heat to the engine coolant, heat to engine oil, and heat from the induction air and adding these numbers together to come up with a single heat rejection number. This approach assumes that both the charge air and engine oil heat rejection ultimately go into a single water to air heat exchanger or oil to air heat exchanger which is the case for these two engines. Using this heat rejection number (which does not yet contain heat from the transmission) and the engine's maximum allowable coolant temperature, the heat is dumped into a single heat exchanger to reject the engine heat and calculate heat exchanger size, and fan power. This calculation provides the first estimate of fan power and transmission input power. Once the transmission power is estimated the transmission heat rejection (20% inefficiency per the Appendix) is added to the engine heat rejection and a final heat exchanger size, transmission input power, fan power, and net propulsion system power is determined by iteration in the spreadsheet.

The same heat exchanger technology should be used for each engine comparison to avoid biasing the outcome with differences in heat exchanger technologies. In this example, one engine is oil cooled and the other "water cooled" (actually water and glycol) so the heat exchangers aren't identical but were kept as nearly identical as available heat exchanger data would allow. So in this example, the oil to air heat exchanger was taken as a 6 inch thick core with 11 fins / inch, but data for a 6 inch core "water" to air heat exchanger was not available so the water cooled engine was calculated with a 5.31 inch thick core and 11 fins / inch then recalculated using a radiator 7.5 inches thick and 11 fins per inch to bracket the 6 inch core used for the oil cooled engine. Heat rejection and pressure drop characteristics for each heat exchanger are entered as curve fits. Heat rejection and pressure drop is entered as a function of air-flow per square foot of heat exchanger core. Heat exchanger face area is a variable that is selected to maximize the system power density. Particular care has to be taken with the oil cooler calculations because oil cooler heat rejection is much more sensitive to the fluid flow per square foot than is radiator performance.

A heat exchanger size and fan power is calculated first for the hot 120° F day and then for the 77° F day condition using fluid temperatures considered acceptable for each ambient temperature and engine control strategy or thermostat settings.

INLET AND EXHAUST SYSTEM IMPACT

The inlet and exhaust impact section of table 1 again uses the guidelines of the Appendix. The very tightly packaged AIPS diesel engine hardware experienced 50 horsepower of inlet and exhaust system losses from gross engine power in the installed condition so 50 horsepower of losses was entered for the AIPS and for the 7 liter competitor. Size was scaled as a function of airflow per the Appendix for both engines.

MISSION FUEL DETERMINATION

This section of table 1 was estimated using the mission profile of the Appendix but a value of 60 instead of 80 net hp hours per ton was used to better reflect the main battle tank Abrams / AIPS fuel on board requirements rather than the Appendix guide lines to better compare the resulting output with actual AIPS hardware numbers.

PROPULSION SYSTEM VOLUME ESTIMATES

ENGINE DUNK VOLUME

For the 28 liter AIPS diesel the contractor had estimated its dunk volume at 34 cubic feet and the 7 liter engine with its three series turbochargers was estimated to be 20 cubic feet.

TRANSMISSION DUNK VOLUME

This number would be chosen based on information available for the particular application. In cases where that information is not available experience shows that for tracked combat vehicles transmission volume is roughly linear with vehicle mass for vehicles with the same top speed. So in this example as in the Appendix, transmission dunk volume was calculated based only on vehicle mass by multiplying 0.65 cubic feet times the proposed vehicle gross weight in tons.

COOLING SYSTEM VOLUME

Cooling system volume here is estimated per the Appendix by multiplying the core face area by the arbitrary flow path length of 3 feet. The flow path length of 3 feet in the Appendix was originally chosen to yield a cooling system estimated size that would approximate real combat vehicle application experience.

AIR FILTER SYSTEM VOLUME

Air filter volume was determined using the Appendix factor of 2.5 cubic feet of air cleaner size for every pound per second of induction air flow. The engine's air-flow at rated power is used to determining air filter volume by multiplying engine airflow by a constant. This system can be used for both piston and turbine engines with appropriate consideration of expected pressure drop effects on power and fuel economy.

INLET AND EXHAUST SYSTEM VOLUME

If engines of like kind are being compared, Inlet and Exhaust system volumes can be estimated by a constant multiplied by the engine induction airflow. If different types of engines like turbines and diesels for instance, are being compared, then more care must be taken to get accurate input data for the comparisons relative to duct size and corresponding power loss numbers used for the analysis.

CONTROL SYSTEM VOLUME

Unless there is a noticeable difference between engines being compared, a constant number is often used for all engines, for example a value of 1 cubic foot for complete engine and power pack controls was used in the Appendix and also in the table 1 example.

MISCELLANEOUS VOLUME

This volume was taken as zero for both of these engines in the example but this category is a place holder for information that might be available. Items that fit this category are special accessories or items not covered in any other category. In the Diesel AIPS power pack the vehicle alternator, turret hydraulic pump and power pack mounts are included in this category.

BATTERY VOLUME

This example used 6 cubic feet for the AIPS engine (to be consistent with the Army standard of two 12 volt batteries to get 24 volts then multiples of two to achieve the required power) and 2 cubic feet for the much smaller 7 liter engine per the Appendix guidelines.

WIRING HARNESS VOLUME

Again similar type engines can be assumed to have similar requirements unless specific information is available to justify different numbers. In this example a constant of 1 cubic foot for wiring harness volume was used. This category could of course be more consequential if comparisons were being made with hybrid versus non-hybrid systems.

FUEL TANKS AND PLUMBING VOLUME

This example looked at a net stored energy of 60 sprocket horsepower hours per ton of vehicle weight instead of the 80 used in the Appendix to better match with the fuel storage requirement of the main battle tank that these engines were candidates to power. As the Appendix, this example calculated the fuel system volume based on three different engine power levels, one at full engine power and two others at part power. The engine fuel map data is used if that information is available. Otherwise knowledge of characteristics applicable to the type of engine being compared can be used to gain the required insight. Specific knowledge of the mission profile for the particular vehicle would be used here if that information is available.

FINAL DRIVES VOLUME

Based on tracked combat vehicle final drive experience, final drive volume was taken as a constant multiplied by gross vehicle weight in tons to estimate volume per the Appendix. Final drives are sized by the large torques required to meet the high tractive effort requirements common to combat vehicles. Typical combat vehicle specifications include requirements to be able to generate tractive forces in the extreme case equal to 1 to 1.2 times the vehicle combat weight and consequently the size is determined much more by torque issues than by power transmitted. Final drive size tends to be linear with vehicle weight within the range of weights found in tracked combat vehicles.

UNUSABLE VOLUME

Unusable volume is an estimate of space that cannot be utilized in the various nooks and cranny's of the power pack and always exists in every installation. This example generally followed the Appendix procedure.

CLEARANCE VOLUME

Clearance volume is the total space represented in the required clearance, typically one inch, between power pack components and the hull walls, floor, and top deck of the armored vehicle. In this example per the Appendix all the other volumes are added and the result considered a cube. Two inches were then added to the length width height dimension of the cube to figure the new cube volume then subtracting the old cube volume to calculate a number for the clearance volume.

POWER DENSITY DETERMINATION

The power density is calculated for the 120° F and 77° F conditions and divided by the sum of the 12 volumes listed above to obtain an estimate of the installed power density per the Appendix for each engine.

DISCUSSION

The above methodology uses engine characteristics like air flow, fuel consumption and heat rejection / fluid temperature characteristics to assess the potential for installed power density, but does not address the dense packaging or minimizing parasitic loss aspects which are so important to achieving a high power density propulsion system. To realize this potential the vehicle integrator must do his part to minimize parasitic losses in the system and arrange for the most compact physical arrangement of the propulsion components that is practical with other concerns like service access, fire hazard / extinguishing system, component accessibility, lifting points etc. Minimizing parasitic losses involves things like selecting a high efficiency transmission with suitable ratio coverage well matched to the engine, minimizing flow turning losses in the cooling air flow, minimizing fan power by selecting efficient fans and fan drives, good power pack control schemes, minimized accessory drive losses, and cooling system designs that take advantage of allowable fluid temperatures for different components to minimize fan power. Ultimately all these competing concerns will be compromises so the diligence of the vehicle integrator is crucial to program success.

A reviewer of table 1 may be shocked at some of the numbers indicated therein. Cooling fan power for instance may look extremely high to those not familiar with combat vehicle problems but the original Crusader program that was cancelled had a hot day fan power of 323 horsepower and was still shy of its cooling and vehicle performance requirements. That program was a good example of why an analysis of this type can be valuable before major component decisions like engines and transmissions are made.

CONCLUSION

As was seen in the AIPS diesel versus Abrams propulsion systems comparison or in the sample methodology given above, the most power dense engine doesn't always provide the most power dense system. Too often Military programs, do not sufficiently consider the system impacts of engine choices. Widely different power systems like turbine or diesel engines, fuel cells, or alternative fuel engines, can be compared on a system to system basis to obtain realistic information for vehicle improvement using relatively simple methods.

If the space claim within a vehicle is well defined, more rigorous approaches can be taken whereby components can be sized and installed virtually in the vehicle via sophisticated software programs and modeling tools and more direct comparisons made for the various engine types under investigation.

This paper primarily considered volume impacts, but similar approaches could be used to address other concerns like weight or affordability arising from the choice of major vehicle propulsion components.

ADDITIONAL SOURCES

Engineering Design Handbook: Military Vehicle Power Plant Cooling, U.S. Army Tank Automotive Research, Development & Engineering Center, May 1998.

APPENDIX

PROPULSION SYSTEM VOLUME ESTIMATES

The following exercise is required to provide the evaluators an estimate of the total cubed volume of your propulsion system. These numbers are estimates for evaluation purposes only. Any engine produced will not be required to be built, inspected, or tested to these numbers unless this information is specifically required in any resulting agreement. You are required to calculate and provide an estimated volume for each of the items listed below; however, in the event that your proposed engine design varies from the component descriptions below (either your design will not require one of the components or your design has a different type of component for that function), please indicate that you have an alternate propulsion system design and provide the information (calculations and volume) for your design in addition to the calculations below.

Provide a propulsion system volume estimate for each engine proposed.

For manufacturers who are proposing to up-rate an existing engine provide a propulsion system volume estimate for the standard existing engine in addition to the proposed up-rated engine. Provide the calculations for your answers to each of the numbered items below.

To make a crude estimate of propulsion system power density potential, without knowledge of, or reference to a particular vehicle design, follow the guidelines below. Show all calculations and list any assumptions that you made that are not listed in the following guide.

DEFINITIONS

Dunk volume is the volume of water that would be displaced by an object if its openings were taped shut and the object was dunked into a water tank.

Box volume is the volume estimated by representing the object as one or two simple boxes and calculating the length times width times height volumes of the box(s). Show the objects and the boxes used to approximate them.

For each engine you are proposing for an FCS ground vehicle, specify the engine power at 29.31 inches mercury absolute (HgA), at 77° F and 120° F. Specify the maximum FCS vehicle weight class your proposed engine is expected to serve. Gross horsepower (ghp) is defined as uninstalled engine shaft or flywheel horsepower.

Engine Power at 77° F __________ ghp

Engine Power at 120° F _________ ghp

Max. FCS vehicle weight ________ lbs

1. Engine Volume: Provide picture(s) and drawings, if available, of the proposed engine. Calculate both the engine's box volume and estimate the engine's dunk volume. Calculate the difference between engine's box volume and the dunk volume and record that volume as the "Unusable Volume" below. Record the engine box volume and engine dunk below.

Engine Box Volume ___________ ft^3

Engine Dunk Volume __________ ft^3

Engine Unusable Volume _______ ft^3

2. Transmission Volume: Scale the transmission volume linearly with the FCS vehicle weight class recorded at Maximum FCS vehicle weight above. Assume the transmission has a fixed volume of 13 cubic feet for a vehicle weighing 20 tons. Record your transmission volume as dunk volume below.

Transmission Dunk Volume ________ ft^3

3. Cooling System Volume: For cooling system volume select heat exchangers sized for each fluid that needs to be cooled. Select heat exchangers large enough to cool your proposed engine and the dummy transmission assuming the ambient air temperature is 120° F. Select a fan or fans large enough to deliver the required cooling airflow against the pressure loss of the heat exchangers selected plus 9.5 inches of water pressure loss for the inlet ballistic grills, and compartment pressure losses and 2.5 inches of water loss after the fan (total fan head equals 12 inches H_2O plus the heat exchanger delta p). Assume the fan(s) are suction fans located downstream from the heat exchangers. Assume the transmission is 80% efficient, is oil cooled and has a maximum allowable oil out temperature of 260° F. Assume the power handled by the transmission (at 80% efficiency) is the engine power minus the installation losses and fan(s) power. Assume the transmission oil flow is linear with input speed and is 10 gallons per minute per 100 horsepower of transmission rated horsepower (i.e. a 500 hp transmission would have 50 gallons per minute maximum oil flow). Estimate cooling system volume by adding the box volumes of all selected heat exchangers plus fan(s) "box" volume(s) and a cooling air flow path volume. Estimate cooling air flow path volume to equal the frontal core area of all heat exchangers exposed to the 120° F cooling inlet air times a flow path length of 3 feet. If you have heat exchangers in series, use only the frontal area exposed to the 120° F cooling air. Estimate the cooling fan(s) power based on the above and save this data for later. Assume the fan(s) drive(s) is (are) variable ratio, 100% efficient and take no space claim. List all assumptions and provide vendor names, model numbers, drawings, and complete performance maps for all fan(s), and heat exchangers utilized. Provide a system diagram showing airflow and fluid flow, temperatures, and pressures, and heat transfer quantities, throughout the cooling system for the 120° F day. Record your cooling system volume below.

Cooling System Volume __________ ft^3

Weight of Cooling System ____________ lbs

Weight of Cooling Heat Exchangers & Fans _______ lbs

4. Air Filtration System Volume: To estimate the volume of the air filter system; select a two stage, self cleaning barrier air filter system capable of 200 hour life at zero visibility dust (0.025 grams per cubic foot) dust sized for your engines air flow and pressure loss constraints. Assess the power loss for your engine based on the air filter selected assuming an additional 10 inches of water of additional restriction and save this data for later. Calculate the box volume and estimate the dunk volume of the air filter system. Calculate the difference between the box volume and the dunk volume and record as unusable volume below. Provide vendor names, model numbers, drawings, and performance descriptions of the two stage air filter system including scavenge fans and scavenge power requirements for the system selected. Assume that the scavenge fan drive is electric powered at 100% efficiency and that the fan drive has no space claim. List scavenge fan efficiency and other assumptions in estimating the volumes. Record your air filtration volumes below.

Air Filtration System Box Volume ___________ ft^3

Air Filtration System Dunk Volume __________ ft^3

Air Filtration System Unusable Volume _______ ft^3

Scavenge Fan _________ hp

Weight of Air Filtration System _________ lbs

5. Inlet and Exhaust System Volume: Estimate the inlet and exhaust system volumes by assuming the induction air flow path length and exhaust system path length are each 4 feet long with an area you select for an acceptable engine pressure drop. Estimate the induction and exhaust system volumes based on your induction and exhaust pipe areas times the 4 foot length and calculate the power loss on the engine from these pressure losses and save this data for later. You can assume the pipes are straight for this exercise. Record your inlet and exhaust system volume and power loss horsepower below.

Inlet and Exhaust System Volume __________ ft^3

Power Loss _________ hp

6. Propulsion Control System Volume: Show a picture of your proposed propulsion control system, if available. Calculate the box volumes and estimate the dunk volume. Calculate the difference in the box versus dunk volume and record those numbers below.

Propulsion Control System Box Volume ___________ ft^3

Propulsion Control System Dunk Volume __________ ft^3

Propulsion Control System Unusable Volume ______ ft^3

7. Miscellaneous Volume: State proposed component parts of your engine and list any items not included in other measurements required in the volume estimates. If any, describe and estimate their volume below.

Miscellaneous Volume __________ ft^3

8. Batteries Volume: For starting assume a minus -32° F day without external aids and estimate the number of 6TN lead acid 100 amp hour batteries needed at 85% charge to accomplish an engine start. Assume each battery installed is 1 cubic foot (ft^3).

Volume of Batteries _____________ ft^3

9. Wiring harnesses Volume: Assume wiring harness volume is equal to 1 ft^3.

Wiring Harnesses Volume = 1 ft^3

10. Fuel tanks and plumbing (sized for mission) Volume: Assume for the FCS mission that 1600 net (repeat: net) horsepower hours of work is required before refueling for a 20 ton vehicle. Scale on-board fuel linearly with vehicle weight. Assume 80% transmission efficiency and assume your engine will be at peak power 40% of the time, half power 50% of the time and 10 % power 10 % of the time. Estimate the fuel required based on the above and assume JP-8 at 6.67 pounds per US gallon (231 cubic inches) and 183,00 British thermal unit (Btu) per pound heating value. Assume a single tank in the shape of a cube with 8% more internal volume (for ullage and expansion space) than the required fuel volume and wall thickness of 0.25 inches.

Record your fuel system volume below.

Gallons of fuel required __________ gal

Fuel System Volume _________ ft^3

Estimated fuel weight _________ lbs

11. Final drives Volume: Assume final drives are linear with vehicle weight and are 1.3 cubic feet for a 20 ton vehicle. Record your final drive volume below.

Final Drives Volume __________ ft^3

12. Clearance and Unusable Volume: For the unusable volume add all the unused volumes estimated in items 1, 4, and 6. To estimate the clearance volume; take the sum of the unusable volume and the volumes of items 1 through 11. Take the cube root of this volume to come up with a length, then add two inches to this length and cube this new dimension. The clearance volume is the difference in this volume and the volume obtained before the 2 inches were added. Record your unusable and clearance volumes below. Add your unusable and clearance volume and record them below.

Unusable Volume (from Items 1+4+6) ________ ft^3

Clearance Volume ________ ft^3

Unusable Plus Clearance Volume ___________ ft^3

13. To estimate the net power available for the 120° F day subtract from the uninstalled engine power at 120° F, the engine losses estimated in items 4 and 5. Subtract the fan horsepower calculated for the 120° F day and multiply this number by 80% for the transmission efficiency. This is the estimated net power for the 120° F day. Show your calculations and record your net power below.

Net Power (120 F Day) __________ net hp

14. Referring back to item 3 above, recalculate the fan power required for a 77° F day using the heat exchangers and fan systems selected for the 120° F day. Assume a variable ratio fan drive. List all the fluid temperatures and pressure drops and heat transferred as before. Provide a system diagram showing airflow and fluid flows, temperatures, pressures, and heat transfer quantities, throughout the cooling system for the 77° F day. Calculate the fan power required for the 77° F

day and determine the estimated net engine power for the 77° F day. Use the same procedure as given in item 13. Show your calculations and record your net power below.

Net Power (77 F Day) ____________ net hp

15. Calculate the total Propulsion System Volume from above items 1- 12. (Engine dunk + transmission dunk + cooling system + air filtration dunk + inlet and exhaust + propulsion control system + miscellaneous + batteries + wiring harness + fuel system + final drives + unusable plus clearance). Record your Total Propulsion System Volume below.

Total Propulsion System Volume _____________ ft^3

16. Calculate the Net Power per Total Propulsion System Volume for 120° F and 77° F days. Show your calculations and record your net horsepower below.

Net hp / ft^3 on 120° F Day (Item 13/Item15) __________

Net hp / ft^3 on 77° F Day (Item 14/Item 15) __________