

## Power Supply and Integration in Future Combat Vehicles

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### ABSTRACT

*Future combat vehicles will require higher agility and unconventional weapons and armor systems such as Electromagnetic (EM) or Electro-Thermal Chemical (ETC) Guns, Electro-Magnetic (EM) Armor and Directed energy Weapons (DEW). To meet these requirements, hybrid electric power system has been identified as the best alternative to support the demand for propulsion, continuous auxiliary power demand and pulsed power demand for weapons and armor. Although the development of these weapons and Armor technologies are progressing at a fast rate and can be demonstrated at a smaller scale today, the power supply needed to be integrated in the vehicles to support these systems present a great challenge to technology developers and vehicle integrators. This paper will explore the power supply requirements for the continuous and pulsed power loads and will discuss their integration challenges in a 20-ton class hybrid electric combat vehicle.*

### 1.0 INTRODUCTION

In a Combat hybrid vehicle platform, power supply will mainly consist of two sources of energy, a prime power source driving an AC generator such as a heat engine and an energy storage system consisting of advanced batteries, ultra capacitors and flywheels or a combination of these three devices. Currently and in the near term the prime power will be either a diesel engine or a turbine, and in the far term fuel cells may become viable options once their power density reaches the required level.

The power supply has to meet the demand of mobility, lethality, survivability and some additional users such as C4ISR, and NBC systems. The demand for electric power becomes even more challenging during silent watch where the power draw must be provided solely from energy storage for extended periods of times (4 to 8 hours). Power supply must be delivered in two forms, continuous and pulsed. For a vehicle weighing about 20 tons, the continuous power, in most cases, ranges from 400 to 500 kW which is supplied from the main prime mover supplemented by 25-30 kW-hr of energy from storage system. Pulsed Power however, ranges from Megawatts to Gigawatts depending on the loads and rep rate. This will require a range of 100 kiloJoules to few MegaJoules of energy storage packaged within few cubic feet. In addition to the energy storage, Pulsed

*Paper presented at the RTO AVT Symposium on "Functional and Mechanical Integration of Weapons and Land and Air Vehicles", held in Williamsburg, VA, USA, 7-9 June 2004, and published in RTO-MP-AVT-108.*

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power loads require pulse forming networks (PFN) which impose another integration burden with a space claim of approximately 50ft<sup>3</sup>. Since, electric power is used for continuous loads such as mobility and also for pulsed loads such as electric weapons, it would make sense to have one common power and energy management system onboard the vehicle to distribute electric power to various users according to a defined precedence strategy. Thus, a Combat Hybrid Power System (CHPS) was introduced in 1995 to evaluate such a power management and distribution system.

### 2.0 BACKGROUND

The Combat Hybrid Power System (CHPS) program was initiated by DARPA and continued by the U.S. Army RDECOM -TARDEC. The major goal of the CHPS program was to design, develop and test a 15 ton notional hybrid electric combat vehicle, incorporating all the power demand onboard a vehicle system and assess the feasibility of simultaneous power distribution to propulsion and ETC gun i.e continuous and pulsed power. To achieve this goal a System Integration Laboratory (SIL) was built and commissioned in Santa Clara, California.

In the course of designing the components for the 15 ton notional combat vehicle, some critical and enabling technologies were identified. They included, high temperature power electronics, High energy density and high power density batteries, namely Li-Ion batteries, and high torque density traction motors. All of these technologies required innovations to advance the State Of The Art. Furthermore, the components had to be integrated within a series architecture that would represent an actual vehicle, i.e to the extent possible all the components and auxiliary systems had to be integrated within the space that would be available in a 15 ton combat vehicle.

Two technical challenges appeared soon after the auxiliary systems were introduced into the SIL for integration in a combat vehicle environment: The amount of power needed for all the loads and the size and weight of the components. A first estimation revealed that using State Of The Art technologies would require at least twice the space available within a combat vehicle as shown in table 1.

## Problem Definition

Hybrid Electric FCS component weights and Volumes

Some Development Substantial Development Normalized	Current Metrics (CHPS)	P&E SIL (03)		Lancer		FY(08) Goals		Future Metrics
		Volume (ft <sup>3</sup> )	Weight (lbs)	Volume (ft <sup>3</sup> )	Weight (lbs)	Volume (ft <sup>3</sup> )	Weight (lbs)	
Engine	0.53 kW/kg 0.42 kW/l	25.4	1250	30.8	1462	20	1136	1.08 kW/kg 1 kW/l
Generator	1.04 kW/kg 3.19 kW/l	2.87	550	3.4	632.5	2	400	1.88 kW/kg 6 kW/l
Rectifier (Generator)	19.4 kW/kg 35 kW/l	0.35	40	--	--	0.24	30	30 kW/kg 70 kW/l
Power Distribution	--	36.4	1175.5	8.62	466	5	270	--
2 Traction Motor Inverters	19.4 kW/kg 35 kW/l	0.7	80	27	1079	0.42	60	30 kW/kg 70 kW/l
DCDC Converters (30028V & 30800V)	2.63 kW/kg 1.6 kW/l	3.2 6.3	121 240			.85 2.4	69 200	6 kW/kg 8 kW/l
Batteries (10n 15 kWh Pack)	63 Whr/kg 65 Whr/l	10	600	21.2	1210	4	400	75 Whr/kg 130 Whr/l
Local Controllers	--	15	800	6	36	6	200	--
Thermal Management	90°C	25	721	22.1	731	18	400	200°C (SiQ)
Fuel (80 Gal)	--	10.7	555	10.7	555	10.7	555	--
Subtotal	--	<b>136</b>	<b>6130</b>	<b>129.8</b>	<b>6093</b>	<b>70</b>	<b>3700</b>	--
Traction Motors (2 Medium)	1.35 kW/kg 4 kW/l	3.8	700	9.5	1867	3	412	2.5 kW/kg 5.5 kW/l
PFN	153 kJ/rh	26	1000	Not Applicable		10.6	662	1000 kJ/rh
Total	--	<b>166</b>	<b>7830</b>	<b>139.3</b>	<b>7960</b>	<b>85</b>	<b>4800</b>	--

Table 1. Volumes and Weights for a combat hybrid power system

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### 3.0 METRICS

Most of the metrics have to be significantly increased to meet the established goals for volumes and weights. The most aggressive goals are set for the power electronics; the motor and generator inverters and rectifier and the DC-DC converters, and also for the thermal management. Another aggressive metric is set for the Pulse Forming Network (PFN) which must be reduced by more than half of its current size in the SIL in order to install it in the vehicle. Improvement in both the power converters and the PFN hinges on the development and maturation of Wide Band Gap (WBG) materials such as SiC. This material provides the capability to build converters that operate at high temperature, high frequency (50-100 kHz) and higher efficiency as has been demonstrated in the lab. For the PFN another critical technology needs further development, the capacitors. Currently high energy discharge capacitors used in the PFN have an energy density of 1.5-2 J/cc. Capacitor development in the U.S and Europe are targeting energy densities of 2.5 j/cc and higher. The high energy capacitors combined with SiC based solid state switches will result in a significant reduction of PFN weight and volume.

In this paper, Power and Energy will be discussed in two parts, the first deals with continuous power, and the second part deals with pulsed power.

### 4.0 CONTINUOUS POWER

In a combat vehicle, there are three main users of continuous power:

- Mobility
- Thermal management
- Silent watch

In addition, there are some hotel loads which are much smaller than the first three. Power is supplied to most of the mobility and thermal loads from the prime mover, the engine, whereas the silent watch is solely supplied from the energy storage, a battery bank, which is also recharged from the engine driven generator. For optimum performance, the power is split between engine and battery for either best fuel efficiency or burst power according to the specified vehicle duty cycle.

### 4.1 MOBILITY

Military vehicles must have the capacity to operate anywhere in the world, under extreme environmental conditions, from the frigid temperatures of the arctic to the intense heat of the deserts, and from hard rocky and paved roads to hilly and soft soil. They must withstand the vibrations, shocks and violent twisting experienced during cross-country travel over rough terrain, and they must be able to operate for long periods of time with very little or no maintenance.

The above description was extracted from a handbook published by the Army Materiel Command (AMC) in 1965. All of the conditions mentioned above are still valid today. However, there are additional requirements, which are changing the whole philosophy of vehicle design. Future vehicles must be lighter, faster, and more deployable but at the same time more lethal and more survivable. These constraints impose a departure from the traditional methods of making combat vehicles. Therefore, new enabling technologies have to be developed and implemented to meet the technical challenges of future vehicles.

For a 20-ton vehicle, the power required to meet the acceleration, top speed and gradeability requirement at 10 kph is about 400-500 kW. In a hybrid electric vehicle, the engine provides most of that power. The engine is normally programmed to operate within the band of optimum efficiency on its fuel map. Boost power for transient operation is supplemented by the stored energy from the battery pack. Thus for propulsion a relatively small energy storage system would be sufficient.

#### **4.1.1 Mobility levels**

There are three levels of mobility: Strategic, operational and tactical. Strategic mobility is the ability of the vehicle to move or be moved into the operational theatre. This implies that lighter and smaller vehicles have greater strategic mobility. Operational mobility is the ability of the vehicles to move by their own power at various speeds. Tactical mobility or battlefield mobility is the ability of the vehicle to move over various terrains and obstacles such as ditches, trenches and streams.

The operational and tactical mobility requirements are extreme but necessary because the vehicle must be able to operate in various military environments. The most critical mobility requirements are:

Vehicle top speed

Vehicle top cross country speed

Gradeability (60% max)

Steering

Acceleration

Braking

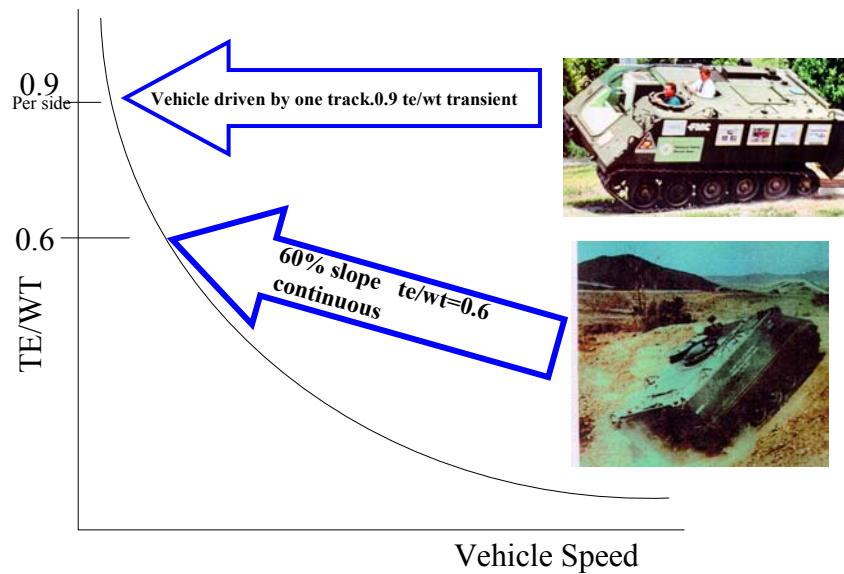
#### **4.1.2 Tractive forces**

Some of the mobility requirements (steering, gradeability) are specified in terms of tractive effort to weight ratio (te/wt). Tractive effort being the tractive force needed to cause vehicle movement. For further clarification, the torque at the wheel or sprocket is the product of the tractive effort and the sprocket or tire radius.

The te/wt for 60% grade and for pivot steer is approximately the same and is equal to 0.6, and a tracked vehicle traveling at 15 mph while turning on a 50 foot radius subjects its tracks to stresses comparable to climbing a 40% grade. The cooling point is 0.7 te/wt ratio. That means the vehicle cooling system must be designed so that the drivetrain components can be continuously subjected to loads equivalent to 0.7 te/wt without exceeding their thermal limits. The maximum transient te/wt requirement for the total vehicle is 1.2, which is needed under certain severe operating conditions such as pulling out of deep and frozen mud. The most critical te/wt ratio is required for regenerative steering and it is 0.9 per side, with 1.0 te/wt differential between the two sides. The rationale for the last requirement was specified for certain rare operating conditions where the vehicle's weight would be supported by one track only. Such conditions arise when one track is in a ditch or totally stuck in frozen mud or ice. Another situation is when one track is in a ditch to the extent that substantial earth movement is required. Under both of these situations the te/wt was calculated and

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found to be about 0.9 which must be achieved by the track that carries the weight of the vehicle. Fig 1. illustrates the different levels of  $te/wt$  ratio for the various conditions described above.



**Fig 1. tractive effort requirements**

It should be noted that the  $te/wt$  values for the cooling point and the gradeability requirements are continuous. Whereas the maximum vehicle  $te/wt$  of 1.2 and the regenerative steering of 0.9 per side are transient values ranging from 10 to 60 seconds.

### 4.1.3 Power requirements

Requirements such as acceleration, top vehicle speed, steering at large radii and cross-country speed depend on the available horsepower from the prime mover and the energy storage device (batteries) getting to the sprockets or wheels when needed for the various vehicle mobility conditions. For all vehicles the power is transmitted from the prime mover to the wheels or sprockets according to a specific architecture, series or parallel depending on the application and duty cycle of the vehicle. The relationship between power, torque and vehicle speed is shown in Fig2.

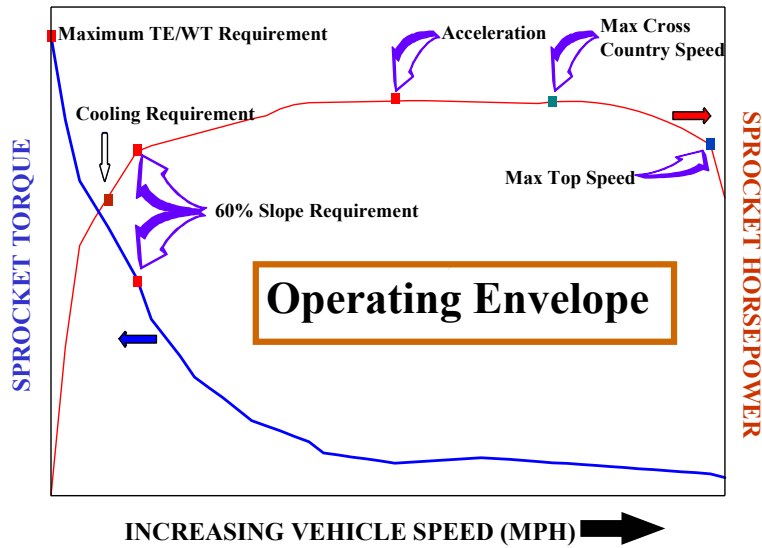


Fig 2 Power demand at various speeds

#### 4.2 Thermal Management

In the current fleet, in addition to the power demand to operate the vehicle, 10 to 15% of the generated power from the prime mover is needed for the cooling system. The cooling system must be designed such that the vehicle can operate continuously at 0.7 te/wt without exceeding the thermal limits of any of its components. Fig 3 shows the cooling envelope of a combat vehicle.

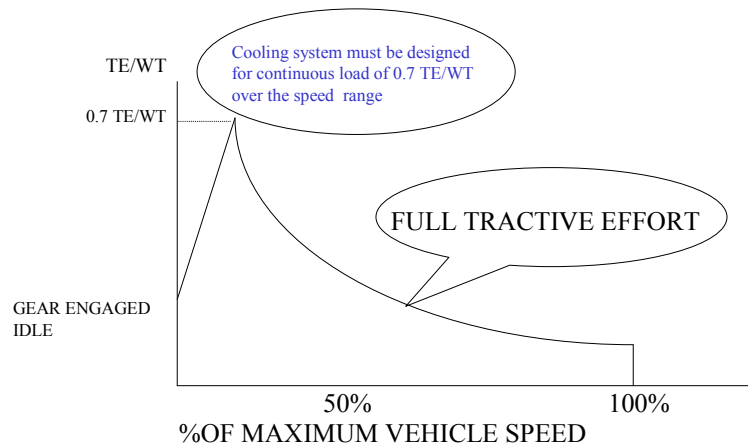
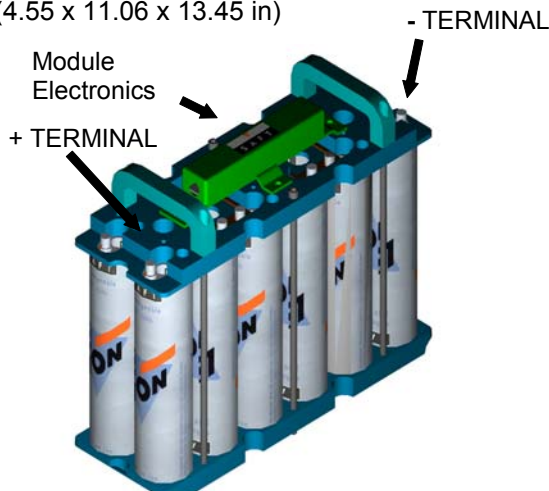


Fig 3 Cooling Envelope

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For a hydraulic drive using hydrokinetic or hydromechanical transmission as in most U.S military vehicles today, all of the mobility requirements described above are manageable. For a hybrid electric system the situation is more complex and more challenging. Although, the power generation can be met with reasonably sized components for a 20 ton vehicle, the cooling system size remains one of the biggest technical challenges to overcome. The cooling system of a hybrid electric vehicle with the currently available technologies can conceivably be four to six times the size of its mechanical counterpart. Consequently, high operating

6 series 2 parallel cell arrangement (6S2 P)  
 22 volts nom @ 60 Ah  
 Weight ~15 kg (33lbs)  
 116 x 342 x 281 mm  
 (4.55 x 11.06 x 13.45 in)



12 modules in series  
 264 Volts Nominal @ 60Ah  
 ~270 kg (595lbs)  
 356 X 775 X 890 mm  
 (14 x 30.5 x 35.3 in.)  
 Air tight closed loop with  
 liquid to air heat exchanger  
 Box: Steel --16 Ga. (0.09in.)

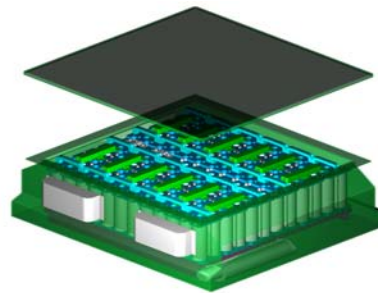


Figure 4 Lithium Ion Module and Pack Developed for CHPS

temperature components must be developed to reduce the current hybrid electric cooling requirements. The high temperature components needed to overcome the thermal management challenges include the power electronics, the DC brushless traction motors and the rechargeable storage batteries, although, the most critical among these three are the power electronic devices.

### 4.3 Silent Watch

The power demand for silent watch is difficult to establish because of the requirements that are not very well defined. However, one can approximate some amount of silent watch capability of hybrid electric based on the possible capacity onboard the vehicle. Using advanced high energy density batteries such as Li-Ion, it is conceivable to have 25-30 kW-hr of energy onboard the vehicle. This amount of energy storage can support silent watch missions for duration of 2 hrs if the power requirements do not exceed 10 kW. It should be noted that the amount of energy supply must exceed the amount of energy demand by 50% to account for the system efficiency, degradation at temperature extremes, and cycle life. Currently, a typical 30 kW-hr Li-Ion battery pack would have a space claim of 0.5 M<sup>3</sup> (17 ft<sup>3</sup>) Fig 4.



## 5.0 PULSE POWER

High voltage pulse power is required to power both the Electro-Thermal-Chemical (ETC)/Electro-Thermal-Ignition (ETI), the Electro Magnetic gun and the Electro-Magnetic Armor (EMA) envisioned for future hybrid-electric vehicles. ETI decreases the ignition variability associated with the launching of conventional munitions by roughly a factor of ten which, in conjunction with the systems ballistic computer, greatly enhances hit probability of the round. EMA uses stored electric energy to disrupt a shaped-charge jet and reduce its depth of penetration. ETI/ETC and EMA functions are shown in the figures below.

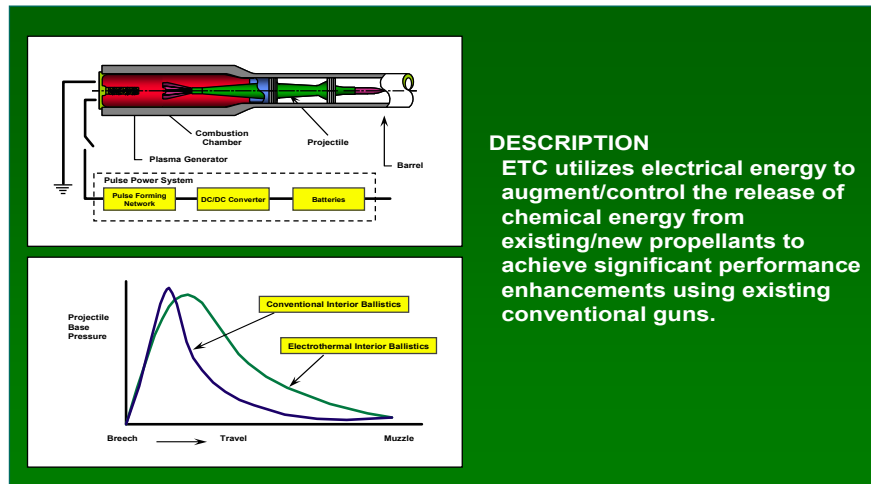


Fig5. ETC power flow

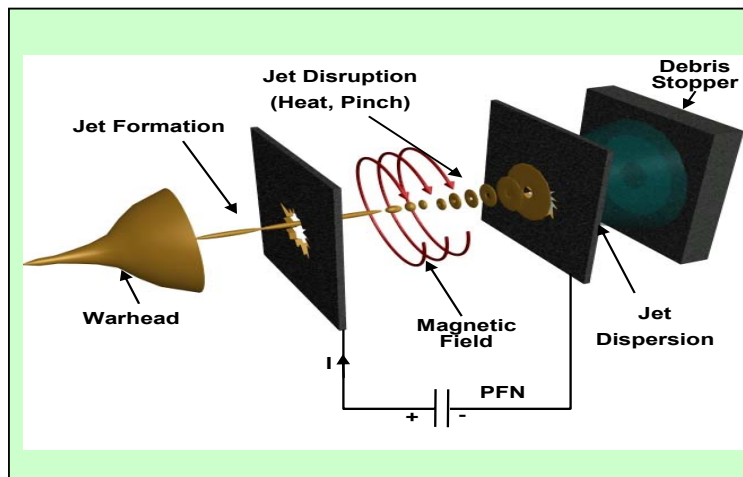


Fig 6 EMA Function

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### 5.1 Intermediate Energy Storage

Intermediate energy storage for these pulse power loads is achieved through the use of high energy-density thin film capacitors, currently utilizing Biaxial-Oriented Poly-Propylene (BOPP) as the dielectric film. The total amount of energy storage required varies based on such factors as simply achieving ETI (i.e. precision ignition) or full-blown temperature compensation (ETC), the type of propellant used, the specific armor design, the threats to be countered and the desired safety factor. This results in an intermediate energy storage range anywhere from tens to hundreds of kilojoules

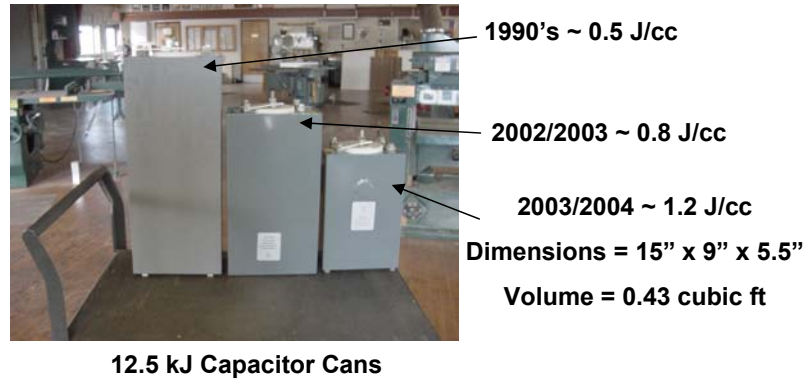
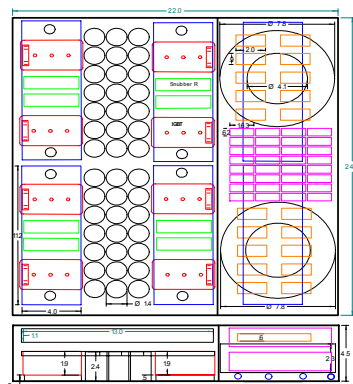


fig 7 capacitor bank

### 5.2 High Voltage Pulse Chargers

The basic building block for these high voltage pulse power systems is an extremely high power density (~4.5 kW/l) 150 kW pulse charger, shown in the figure below. Depending on factors such as the total amount of intermediate energy storage required, the number of rounds per minute the system is required to fire and the required rate of recharge for the EMA, additional chargers can be added, in 150 kW increments, increasing the power consumption to 300 kW, 450 kW, etc. For a hypothetical 600 kJ energy storage with a one second recharge rate, four chargers would be needed to achieve the required 600 kW



### Pulse Chargers

2004 150 kW Charger ~ 4.5 kW/l

Dimensions = 22" x 24" x 4.5"

Volume = 1.375 cubic ft

fig8 Pulse charger

### 5.3 Additional Pulse Power Loads

In addition to the previously mentioned high voltage pulse power applications, several lower voltage (~ 150V – 600V) lethality/survivability applications exist including lifting/slewing the Active Protection System (APS) launcher/radar and the Multi-Function Countermeasure (MFCM) Electronic Warfare (EW) jam-head. The AP launcher holds four AP rounds and the entire system weighs over 400 pounds and must be capable of extremely fast slewing over the full 360 degree hemisphere. The AP/EW system is shown below.

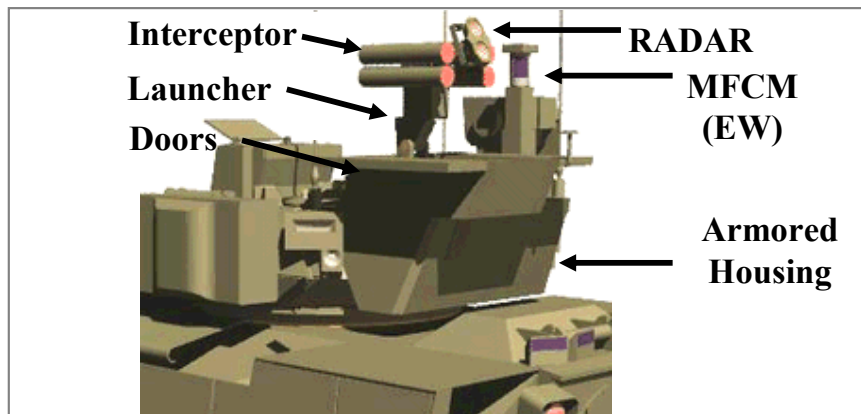


Fig 9 Active Protection System Concept

### 5.4 Directed Energy Weapons (DEW)

The most likely DEW to be integrated into a vehicle platform in the future is the Solid State Heat Capacity Laser (SSHCL). This system is envisioned to be integrated onto a hybrid-electric ground combat vehicle in order to provide forward air defense against UAVs, helicopters and other low-flying craft as well as area wide active protection against incoming threats including mortars and missiles. The future system will generate a 100kW laser output at ~10% electrical efficiency, meaning the hybrid electric vehicle will need to provide 1 MW for short durations (several seconds). The SSHCL concept is illustrated in the figure 10 below.



Fig 10 SSHCL



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### 6.0 SUMMARY

Hybrid Electric platform is the most suitable types of vehicle to incorporate the future vehicle power demand for both continuous and pulsed loads. Although, the power management and distribution to both types of loads is feasible within the hybrid architecture, the integration burden is extremely challenging in a 20 ton vehicle and depends to a great extent on the pulsed load specifications. The amount of power and energy envisioned for a hybrid system range from 400-600 kW from the engine and about 30 -50 kW-hr from the battery pack. The power from the battery ranges from few kilowatts to few hundreds of kilowatts depending on the mission duration dictated by the Users requirements. Currently, it is difficult to envision a hybrid electric combat vehicle without the development and maturation of the emerging technologies in power semiconductors and energy storage. However, in the last ten years these technologies have progressed by more than one order of magnitude and it is anticipated that their application becomes viable in 2008.