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**RECHARGEABLE LITHIUM-ION
BASED BATTERIES AND THERMAL
MANAGEMENT FOR AIRBORNE
HIGH ENERGY ELECTRIC LASERS
(PREPRINT)**



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Rechargeable Lithium-Ion Based Batteries and Thermal Management for Airborne High Energy Electric Lasers

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ABSTRACT

Advances in the past decade of the energy and power densities of lithium-ion based batteries for hybrid electric vehicles and various consumer applications have been substantial. Rechargeable high rate lithium-ion batteries are now exceeding 6 kW/kg for short discharge times (<15 seconds). Rechargeable lithium-ion polymer batteries, for applications such as remote-control aircraft, are achieving simultaneously high energy density and high power density (>160 Whr/kg at >1.0 kW/kg). Some preliminary test data on a rechargeable lithium-ion polymer battery is presented. The use of high rate rechargeable lithium-ion batteries as a function of onboard power, electric laser power level, laser duty cycle, and total mission time is presented. A number of thermal management system configurations were examined to determine system level weight impacts. Lightweight configurations would need a regenerative thermal energy storage subsystem.

INTRODUCTION

Electric lasers for airborne applications require lightweight power sources and present unique thermal management challenges. Personnel from the Plans and Analysis Branch, Power Division, Propulsion Directorate, Air Force Research Laboratory (AFRL/PRPA) are investigating ways to power and cool this type of weapon system.

One potential lightweight power source is that of lithium-ion batteries. Lithium-ion batteries are currently being developed for various commercial and military applications. Very high power density lithium-ion batteries have exceeded 12 kW/kg for millisecond pulses and 6 kW/kg for 15 second pulses [1]. However, these types of very high power density batteries have a relatively low energy density of about 60 Whr/kg. New

lithium-ion polymer batteries with both high power density (>1 kW/kg) and high energy density (>160 Whr/kg) have seen a great usage in the remotely-controlled (RC) airplane industry. Verification of the performance of a typical lithium-ion polymer battery is given below.

Safety is a potential concern for these types of high rate lithium-ion batteries. Safety devices would need to be present to prevent short-circuiting of the batteries. Battery cell voltages will also need to be monitored/controlled to prevent cell voltages being either too low or too high. Finally, battery cell temperatures will need to be monitored to prevent battery operation at too high of temperatures.

The thermal management challenge lies in the fact that typical laser systems based on solid state devices are low in overall efficiency, on the order of about 15%. Therefore, for a typical power output of 100 kW, the waste heat from such devices tends to be about 460 kW. With very tight control requirements, typical temperature gradients of $\pm 2^\circ\text{C}$ allowed across the laser system components, heat acquisition and disposal pose significant thermal management problems. The situation is further exacerbated by the relatively low operating temperatures of these devices. The reason for the latter problem is that for an airborne system one of the readily available sinks for the waste heat is the ambient air, via a ram air heat exchanger (RAHX). Since the thermal driving potential across the HX is determined by the difference in the hot and cold fluid temperatures entering the HX, for a given cold fluid temperature, higher hot fluid temperature would increase the thermal potential and consequently improve the HX effectiveness. In this case, the HX hot fluid is the laser system heat acquisition medium (e.g., water) and its temperature at the HX entrance is determined by the laser system operating temperature. The lower the laser system operating temperature, the lower the hot fluid temperature at the

HX entry is. This results in a lower driving potential and lower HX effectiveness.

Additional problems arise when the altitude at which the laser operates changes. At higher altitudes the ambient temperature tends to be very low, resulting in improved HX performance. On the other hand, at lower altitudes, due to higher ambient temperatures, there is deterioration in the HX performance. This deterioration in performance can necessitate the use of supplementary devices like thermal energy storage (TES) to cope with the same thermal load. We take a look at these various TMS options and assess their impact on the weight and power requirements.

REQUIREMENTS

The output power requirements for the electric laser system modeled were parametrically varied between 50-150 kW with nominal laser power output of 100 kW. Two different scenarios were envisioned. In the first scenario, we assumed that there would be no extra power available onboard the airborne platform. This required that all the power needed for the laser system was provided by an additional power source. In the second scenario, we assumed the airborne platform could provide up to 180 kW. These two different scenarios are now labeled Mission 1 and Mission 2, respectively. Table 1 lists the requirements for the two missions.

Table 1. Requirements for Mission 1 and Mission 2.

Parameter	Mission 1	Mission 2
Laser System Efficiency	0.135	0.18
Laser System Maximum Operating Temperature	20 °C	20-30 °C
Laser System Allowable Temperature Gradient	2 °C	2-5 °C
Number of targets/cluster (n)	100	16
Lasing time/shot	5 sec	target-1: 20 sec target-(2-n): 6 sec
Time between shots	3 sec	6 sec
Time between clusters	60 min	20 min
Number of clusters	1	13
Altitude	10-26 kft	10-26 kft
Platform Power Available	0 kW	180 kW

Mission 1 was envisioned as a scenario where the air platform would operate for up to an hour, taking a maximum of 100 shots. It would then return to base to recharge/refuel the laser power system, with a maximum recharge/refuel time of 60 minutes. To look at the worst case in terms of thermal management, we assumed that the platform would take all 100 shots (5 sec-on, 3 sec-off) with no breaks in between. Mission 2 was envisioned as a scenario where the air platform would be able to take groupings of up to 16 shots with a 20 minute break between shot groups or clusters. During this 20 minute down time the laser power system could recharge using the available power on board the platform.

POWER AND THERMAL MANAGEMENT

The proposed power and thermal management designs for Mission 1 and 2 are outlined below. Data used for the battery power designs are based either upon in-house experiments or a proprietary Simulink model. The in-house experiments were conducted in AFRL/PRPS and consisted of measurements taken to characterize several high rate lithium-ion polymer battery packs. The proprietary Simulink model was provided by SAFT America, Inc. to characterize the performance of their high-rate lithium ion cell, VL8V.

POWER

Mission 1

The electrical power required to operate the laser system for Mission 1 was assumed to be provided entirely from an additional power source added to the air platform. This electrical power source could be a battery, turbo-alternator, or a hybrid battery/turbo-alternator combination. For simplicity and minimal disturbance of the airborne platform, a battery only power system was proposed.

Several high rate lithium-ion polymer battery packs were purchased to determine their discharge characteristics. Each battery pack consisted of twenty 2 Ahr cells connected in a 5 series, 4 parallel string configuration. This resulted in a battery with about an 8 Ahr capacity with a voltage range of 15-21 volts. A picture of one of the battery packs in a temperature chamber is shown in Figure 1. This battery pack is about 13" long, 1.88" wide, and 1.13" deep. It weighed in at 801.1 grams.

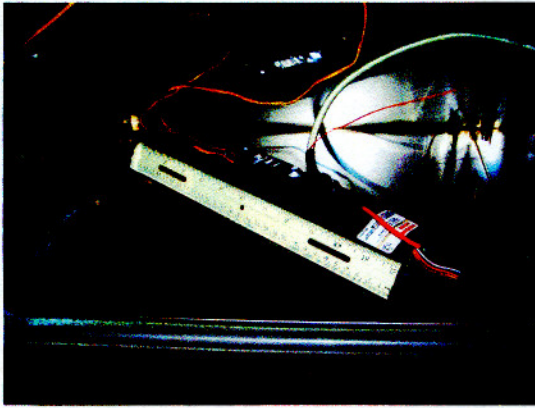


Figure 1. An 5S4P, 18.5V, 8 Ahr Lithium-Ion Polymer Battery Pack in a Temperature Chamber

Using the experimental results in Figure 2, performance results are tabulated in Table 2.

Using the Mission 1 requirements from Table 1 with a laser power output of 100 kW, a battery output power of 741 kW is required to operate the laser system. This results in a battery system weighing 641.4 kg with a volume of 360 liters, using the data for the 7C discharge rate in Table 2. For the same mission, an APU with a specific power of about 1.0 kW/kg and an efficiency of 25% (electric out/heating value of fuel in), would weigh, with fuel used, 775 kg.

Table 2. Performance Data for Lithium-Ion Polymer Battery Pack

Discharge Rate	Energy Discharged (Whr)	Energy Density (Whr/liter)	Specific Energy (Whr/kg)	Specific Power (W/kg)
7C	128.5	285.9	160.4	1203.1
5C	135.6	301.7	169.2	882.9
3C	139.4	310.2	174.0	543.7
1C	144.2	321.0	180.0	334.3

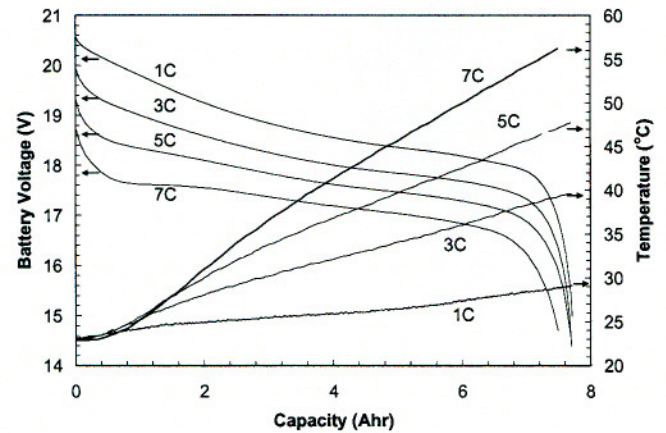


Figure 2. Temperature and Voltage Discharge Behavior of a Lithium-Ion Polymer Battery Pack

Mission 2

The electrical power required to operate the laser system for Mission 2 was assumed to be provided by a combination of onboard power and an additional power source. For simplicity, we assumed that the additional power source would handle the electric laser load and the onboard power would power any accessory loads and recharge the battery system between clusters. Due to the short recharge time, an experimental high rate lithium-ion cell from SAFT America, the VL8V, was proposed to power the electric laser load. Technical data on the VL8V cell is given in Table 3. A proprietary Simulink model was used to simulate the performance of a string of VL8V cells.

For Mission 2, a battery system output of 556 kW was required to power an electric laser system with a 100 kW power output. We chose an approach using only half the battery capacity, for safety and lifecycle considerations, which resulted in 1100 VL8V cells being required. Results from the Simulink model for this case with a recharge time of 20 minutes are shown in Figure 3. The weight and volume of the battery system would be about 646 kg and 283 liters, respectively. In addition, Figure 4 shows results if the battery was sized to use almost all of its capacity (575 cells, 338 kg, 148 liters) with a recharge time of 20 minutes. A conventional APU (1 kW/kg and 25% efficient) sized for Mission 2 would weigh, with fuel used, 631 kg. The battery sized for half its capacity would weigh 646 kg and would only be slightly heavier than the APU; however, the battery sized for its full capacity would weigh only 338 kg and would result in a significant weight savings for the power system.

Table 3. Parameters for SAFT VL8V Very High Rate Lithium-Ion Developmental Cell

Parameter	VL8V
Diameter (mm)	41
Case Length (mm)	156
Mass (kg)	0.47
Capacity (Ahr)	8.6
C-rate Specific Energy (Whr/kg)	65
C-rate Energy Density (Whr/liter)	155
Specific Power for a 18 sec. pulse at 50% SOC (kW/kg)	4.0
Continuous 60C rate (kW/kg)	2.5

THERMAL MANAGEMENT

The batteries for Mission 1 were assumed to not require active cooling during discharge. We assumed that they would be cooled, between missions, by the existing air vehicle platform environmental management system. Figure 2 illustrates that this assumption is valid for the lithium-ion polymer system if the initial temperature of the battery pack before discharge is 25 °C or less. Higher initial battery temperatures would require the design of an active battery cooling system; similar to the one used for Mission 2. For Mission 2, the VL8V Simulink simulation assumes active air cooling and the air temperature and flow rate were set to 20.5 °C and 5.0 cubic feet per minute, respectively. Due to the magnitude of the heat loads, the laser system was the primary source of heat for our thermal management calculations.

We assumed the "laser system" consisted of the pump laser diodes, laser gain media and any required power conditioning devices. For this system, we assumed an overall system efficiency value, a maximum operating temperature and a maximum temperature variation across the device components. These values for the two missions can be found in Table 1. The Mission 1 parameters contain more conservative estimates, representing what could possibly be achieved currently. The Mission 2 parameters represent more aggressive assumptions based on what might be possible in the near-term (2-5 years). Figure 5 illustrates the heat loads for a 100 kW laser system for both the Mission 1 and 2 systems.

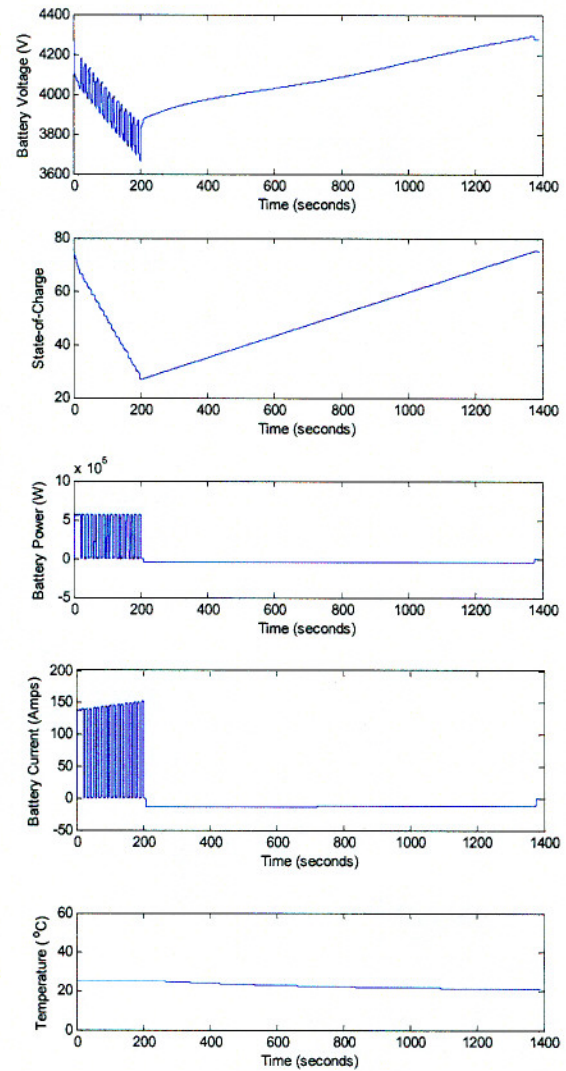


Figure 3. Simulink Results for 1100 Series Connected VL8V Cells for Mission 2 with a Recharge Time of 20 Minutes

To cool these systems, we considered a single-phase water loop to acquire the heat from the laser system device (diodes, gain media, power conditioner), which was then rejected into either the ambient air via a ram air heat exchanger (RAHX) or stored in a phase-change material (PCM). We assumed a PCM unit consisting of 80% carbon foam impregnated with the phase-change material. An illustration of the flow loop is presented in Figure 6. We considered two modes of operation:

- thermal energy storage (TES) only,
- ram air heat rejection with TES as required.

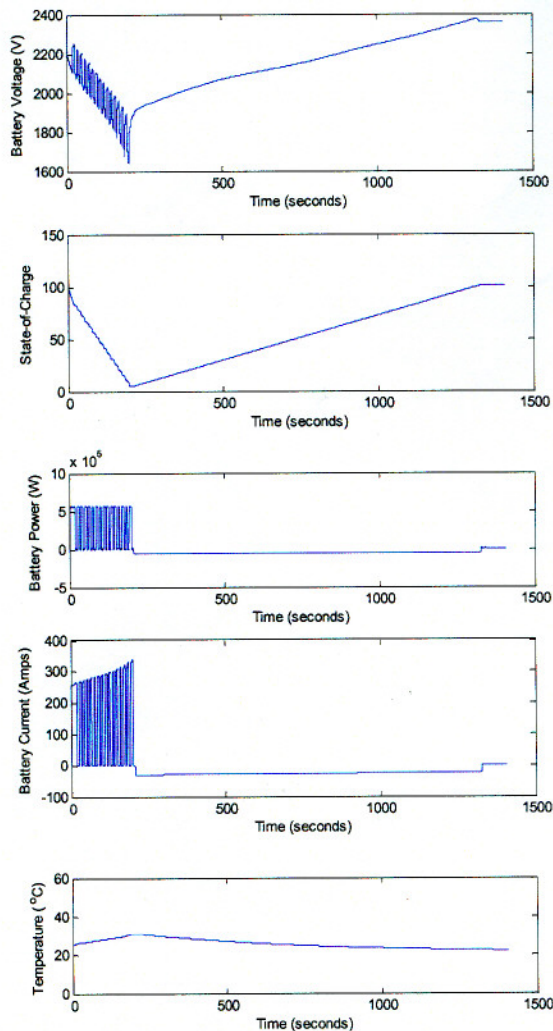


Figure 4. Simulink Results for 575 Series Connected VL8V Cells for Mission 2 with a Recharge Time of 20 Minutes

For the TES only option, a PCM was used to store the thermal energy for the entire mission and the RAHX was not included in the system. For this case, it was assumed that the PCM would be regenerated (i.e. re-solidified) or replaced after each mission. For the ram air heat rejection/TES combination, heat was rejected to the ambient air via a RAHX and PCM was only utilized if the ambient air conditions did not provide an adequate temperature gradient to perform the required cooling. For this case, heat was only rejected during laser operation. As in the TES only case, the PCM was sized to store the excess heat for the entire mission and regenerated or replaced after the mission was completed.

For our ambient environment, we assumed a platform airspeed of 100 m/sec and altitudes of 10,000 ft and 26,000 ft. For the 26,000 ft condition we assumed a Mid-Latitude North Summer Day as defined in the HELEOS laser simulation [1]. For the 10,000 ft condition, we assumed a Mil-Std Hot Day. The 26,000 ft condition was selected as a representative operating environment with an ambient air temperature of -27 °C while the 10,000 ft

condition was selected as a worst-case operating environment for the thermal management system with an ambient air temperature of 16 °C.

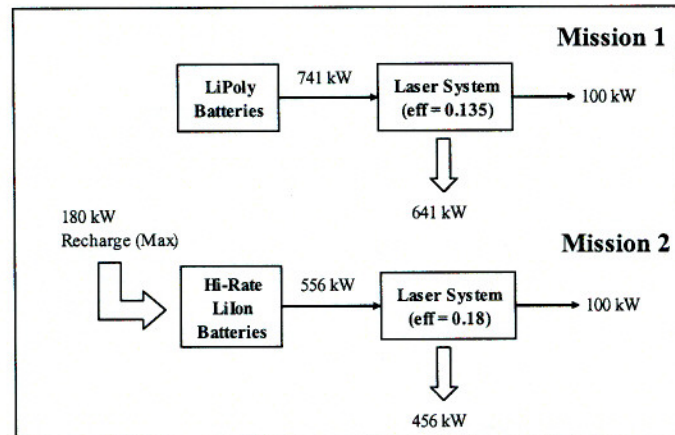


Figure 5. Laser System Heat Loads for Mission 1 and Mission 2.

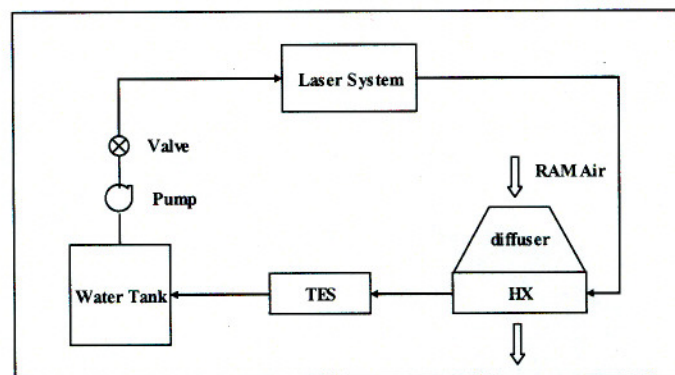


Figure 6. Thermal Management System Water Flow Loop.

Mission 1

The results of our calculations for the laser thermal management system for Mission 1 are in Table 4 below. For this case we only looked at a 100 kW of laser power out at the two altitude conditions. The RAHX-TES combination presented the best option at 26,000 ft, but it did not operate at the 10,000 ft, Std Hot Day conditions. This was due to the fact that once the ambient air passed through the diffuser of the RAHX system, it was not cold enough to cool the water back to the required temperature to maintain the 20 °C operating temperature of the laser system. In addition, the RAHX-TES option required the addition of a 0.31 m² area scoop, thus adding drag to the air platform. The TES only option was much larger than the RAHX-TES combination by over a factor of three, but was independent of the ambient air conditions and could therefore operate at all altitudes and conditions, from a thermal management perspective.

Table 4. Weight of the Thermal Management System Required for Mission 1 with a 100 kW Laser System.

Altitude (ft)	TMS System Weight (kg)	
	10,000	26,000
RAHX-TES	***	1,116
TES only	3,772	3,772

The results of our calculations for Mission 2 are in Table 5 for an altitude of 26,000 ft and in Table 6 for an altitude of 10,000 ft. For this case we looked at 50, 100, and 150 kW of laser power out for the two altitude conditions. Again the TES only option was independent of ambient conditions, but was also slightly heavier than the RAHX-TES combination, to achieve the required 13 clusters. For the 26,000 ft conditions, the RAHX-TES combination was even lighter than a TES only system sized for a single cluster. A breakdown of the system weight into the contributions of the various components is in Figure 7 and Figure 8 for 26,000 ft and 10,000 ft, respectively. The thermal management system weight consists of contributions from the RAHX, diffuser, PCM-TES, plumbing (pipes, pumps, etc.) and coolant (water). From these figures, the RAHX-TES combination does not require any TES to achieve the required cooling at 26,000 ft, but at an altitude of 10,000 ft the addition of PCM based TES is indeed required.

Table 5. Thermal Management System Weight for Mission 2 at an Altitude of 26,000 ft.

Laser Power Output (kW)	TMS System Weight (kg)		
	50	100	150
RAHX (TES as required)	520	640	919
TES only (1 cluster)	688	1,068	1,544
TES only (13 clusters)	4,624	8,940	13,351

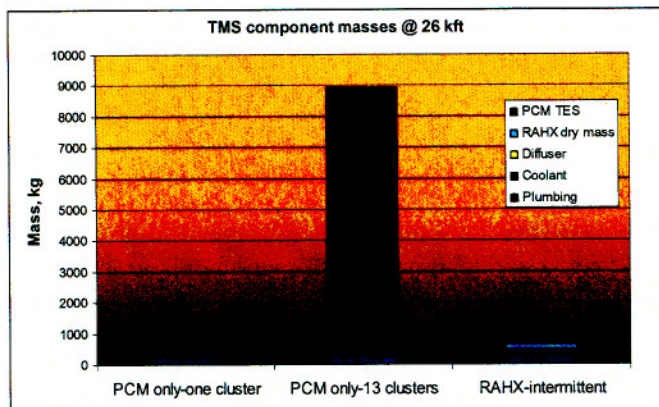


Figure 7. Breakdown of Thermal Management System Component Weights for Mission 2 at an Altitude of 26,000 ft and 100 kW Laser Power Output.

Figure 9 shows the impact of altitude and laser power output on the size of the ram air inlet required for cooling. This illustrates that for higher power and lower altitudes the size of the required ram air scoop, approaching 0.85 m² for the most extreme case, can start to make a

significant impact on the air platform. Table 7 shows the power required to meet the pumping requirements of the thermal management system, which can approach 20 kW, due to the large flow rates required to maintain the tight temperature gradient requirements of the laser system.

Table 6. Thermal Management System Weight for Mission 2 at an Altitude of 10,000 ft.

Laser Power Output (kW)	TMS System Weight (kg)		
	50	100	150
RAHX (TES as required)	4,198	8,173	12,593
TES only (1 cluster)	688	1,068	1,544
TES only (13 clusters)	4,624	8,940	13,351

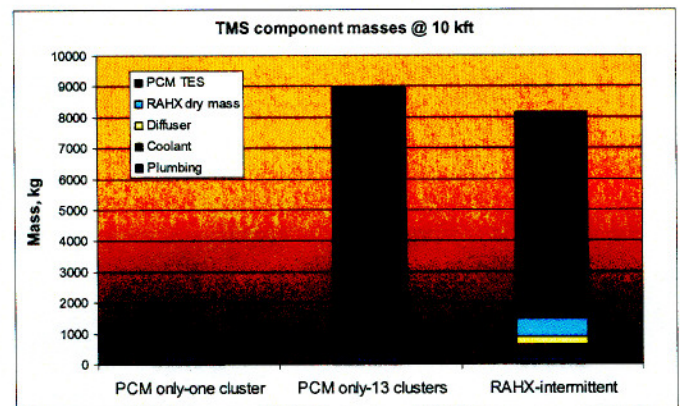


Figure 8. Breakdown of Thermal Management System Component Weights for Mission 2 at an Altitude of 10,000 ft and 100 kW Laser Power Output.

DISCUSSION OF RESULTS

POWER

One point to note about the laser power system for Mission 1 is that there would be additional power requirements for the thermal management system. As illustrated in Table 7, the flow loop requires 18.7 kW of pumping power to meet the flow rate and pressure drop requirements. This means that additional 26 kg of batteries would be required to complete the mission for a total battery weight of about 668 kg. This is still lighter than a conventional APU which would weigh about 775 kg.

Table 7. Maximum Pumping Power Requirements for 100kW Laser Power Output.

	Mission-1	Mission-2
System Efficiency	0.135	0.180
System ΔT (°C)	2	2-5
Required Water Flow (gpm)	1,214	619
Required Power (kW)	18.7	14.9

For Mission 2, the 14.9 kW of pumping power required falls well below the 180 kW of power available. In addition, since the heat is only rejected during laser

system operation, the 14.9 kW does not take away from the power available to recharge the batteries between clusters. Note that the battery weight is equal to or less than that of a conventional APU. The batteries can also be placed next to the laser diodes reducing wire weight. The batteries also don't induce any platform vibrations that may be harmful to the laser output.

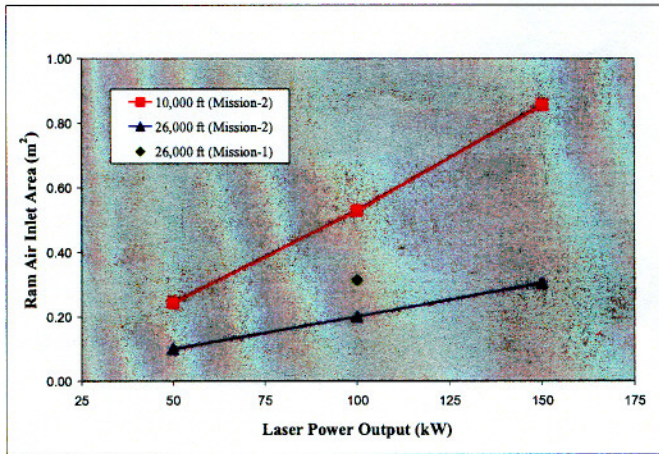


Figure 9. Required Ram Air Scoop Inlet Area.

THERMAL MANAGEMENT

One future option to explore for the laser thermal management system is the effect of utilizing a regenerative TES system. While a RAHX alone can effectively cope with the entire heat load of the laser system at 26,000 ft, at 10,000 ft there is a need to supplement the RAHX with PCM-based TES. As illustrated in Table 6 and Figure 8, the amount of PCM-TES necessary drives the system weight almost as high as using PCM-TES alone. An alternative to this would be to store the heat in the PCM during laser operation (i.e. size the PCM-TES to a single cluster) and then determine a method to regenerate the PCM between clusters. Depending on the relative conditions of the coolant and the ambient environment, the regeneration process could be handled by either a RAHX or a refrigeration cycle, as illustrated in Figure 10.

If it is a RAHX, as in the RAHX-TES combination above, the difference would be that in this case the RAHX is only used to pre-cool the water for PCM regeneration. This allows the heat load from the laser system to be gradually rejected over the battery recharge time. Looking at 100 kW laser power output for Mission 2 with a 20 minute recharge time, this would decrease the required heat load on the RAHX from 456 kW to 42 kW which, assuming a linear relationship between ram air inlet area and heat load, would result in a 90% reduction in the required scoop area.

If a refrigeration cycle or chiller is used to regenerate the PCM, as in Huddle-Lindauer et. al. [3], then we would have to determine the means for disposal of heat from the refrigeration cycle itself. This could be accomplished

using a RAHX or even the platform fuel system as a heat sink.

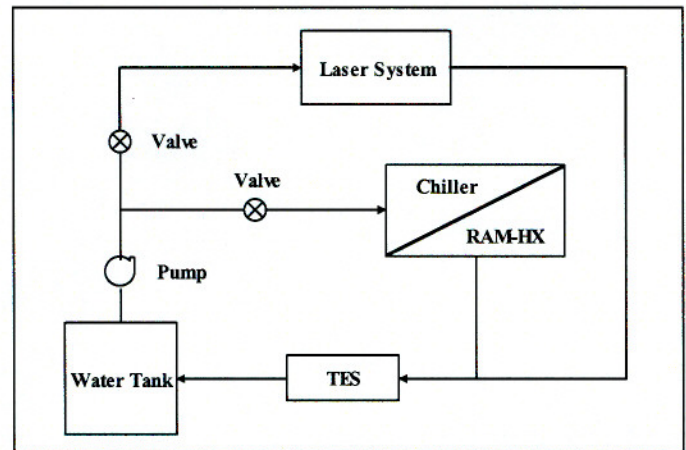


Figure 10. Flow Loop for a Regenerative TES System.

SUMMARY/CONCLUSIONS

Two different airborne missions for the use of a nominal 100 kW high energy electric laser were considered. The requirements for these missions were labeled Mission 1 and Mission 2, respectively. Mission 1 represents what could possibly be achieved today and Mission 2 represents more aggressive assumptions consistent with what could be done in the near term (2-5 years).

The battery power system weight for Missions 1 and 2 are projected to be equal to or less than that would be provided by using conventional APU's.

Looking at the two thermal management system options considered: TES only and RAHX/TES combination, it appears that a combination of the two, utilizing a regenerative TES system is the best option. This cuts down on the weight of the PCM-TES required, since only enough is needed to cool one shot cluster, and it also cuts down on the ram scoop inlet area, since the cooling load is averaged over a longer time period. In addition, if options utilizing a chiller unit are explored, it will enable the operation of the laser system at a greater range of altitudes and conditions.

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