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Preliminary Investigation on Battery Sizing Investigation for Thrust Vector Control on Ares I and Ares V Launch Vehicles

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Abstract

An investigation into the merits of battery powered Electro Hydrostatic Actuation (EHA) for Thrust Vector Control (TVC) of the Ares I and Ares V launch vehicles is described. A top level trade study was conducted to ascertain the technical merits of lithium-ion (Li-ion) and thermal battery performance to determine the preferred choice of an energy storage system chemistry that provides high power discharge capability for a relatively short duration.

Introduction

Historically, missiles and launch vehicles have employed hydrazine (N_2H_4) to feed into an auxiliary power unit which provides turbine power to operate hydraulic pumps for the TVC servo actuators. The actuators mechanically position the solid rocket nozzle to steer the vehicle to the correct trajectory. While this approach has been used successfully with a high reliability, NASA is interested in pursuing a less toxic, electric power approach that offers lower cost and improved operability.

Figure 1 depicts the overall architecture associated with the EHA system and the interfaces with a launch vehicle. The Flight Control Computer (FCC) communicates via the 1553 data bus to the Booster Control Unit (BCU) to command the Motor Control Unit (MCU). The MCU provides the necessary position and torque values to the electric motor to drive the hydraulic pump and ultimately drive the actuator which directs the thrust from the launch vehicle to obtain the proper yaw and pitch trajectory. The electrical energy necessary to power the EHA is derived from the high voltage battery system. The selection of the appropriate 270 V battery Line Replaceable Unit (LRU) is the focus of this paper. Ground Support Equipment (GSE) interfaces to the battery to provide state-of-health monitoring, proper temperature control, and power to recharge the batteries.

The current TVC architecture was based upon the following assumptions:

- 4 battery channels in parallel
- 4 Motor Control Units
- 2 TVC actuators each with a dual redundant internal design
- The 4 batteries are each tied to a single motor control unit. Each motor control unit provides input power to one channel of each actuator.

Battery requirements:

- The maximum power output of the actuators is expected to be 57 horsepower (hp). This corresponds to a 92 hp maximum output of the electric motors. Using a 70 percent efficiency of all components back to the battery, this is equates to a 100 kW output requirement at the batteries. Two batteries summed together must supply this power.
- Each battery should be designed for 270 +80/–30 VDC nominal operating range.
- Total energy requirement is 5110 hp-sec (1058 Wh) at the electric motor for two batteries based on mission duty cycle.
- 5110 hp-sec energy with a 70 percent power management and distribution efficiency yields 7300 hp-sec (1512 Whr).
- Two fault tolerant battery systems imply two batteries must supply the total energy demand.
- Each battery is therefore required to deliver 3650 hp-sec or 756 Whr.

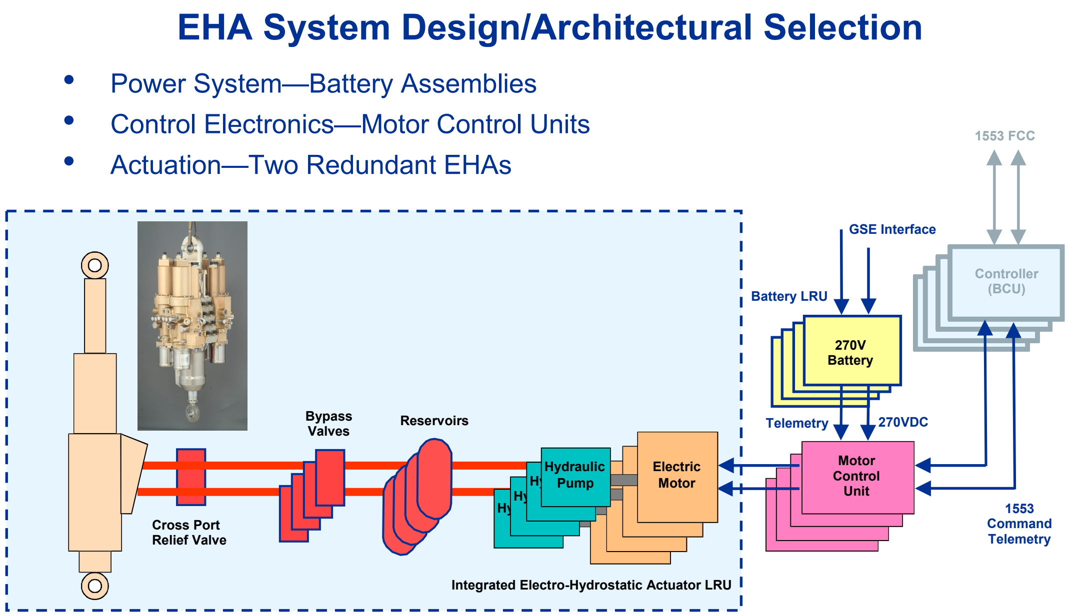

Figure 1.—Electro-hydrostatic actuator block diagram.

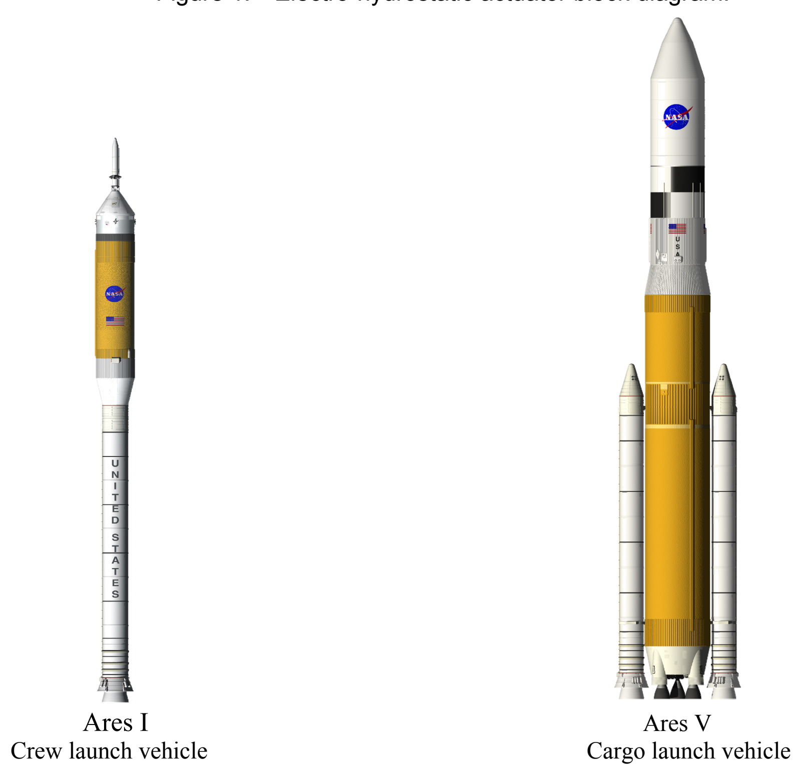

Figure 2.—Constellation launch vehicles.

A key driver in the selection of both battery and TVC hardware dealt with the Technology Readiness Level (TRL) and the ability to support development motor static firing tests in August 2010. Due to the tight schedule, existing heritage hardware was to be used to avoid extensive development time and to reduce overall risk to the program. A TRL of six “system/subsystem model or prototype demonstration in a relevant environment” was the minimum TRL to evaluate various concepts. EHA designs based upon the Space Shuttle Solid Rocket Booster (SRB) TVC were evaluated for the integration into the Ares I Crew Launch Vehicle and the Ares V Cargo Launch Vehicle first stage as depicted in Figure 2.

The trade study assessed the overall sizing of the TVC actuators and battery subsystems to meet the performance requirements of the vehicle. The selection of battery chemistry to power the EHA was based upon near-term cell level and battery level packaging concepts that would require minimal development resources. Factors of merit that were evaluated as part of the trade included mass of the packaged battery, system level impacts to the vehicle, and complexity of integration.

Mission Profile

Since the two Constellation launch vehicles are planned to replace the existing Space Shuttle system, a commonality assessment was evaluated to reduce the overall development cost of a TVC system. For the purpose of this evaluation it was assumed that the EHA system would be developed for the higher power worst case design. Figure 3 depicts the estimated duty cycle for the TVC system which bounds both launch vehicles.

Based upon previous NASA studies, electrically powered TVC system performance is predicated upon the selection of operating voltage. Systems with voltages of 28 VDC, 56 VDC, 118 VAC, and 270 VDC were evaluated with various architectures to evaluate overall electrical power system mass and battery performance. The major driver to decrease overall electrical power system mass was the selection of the highest bus voltage to assist in reducing electrical conductor mass to carry electrical current to meet the mission power demand (Ref. 1). Here the higher bus voltage equates to a minimum electrical power system mass. Figure 4 provides a summary of power system mass versus operating voltage at key voltages from 28 to 270 VDC. Specifically, a higher bus voltage reduced power management and distribution component mass, actuator mass and actuator mounting structures mass.

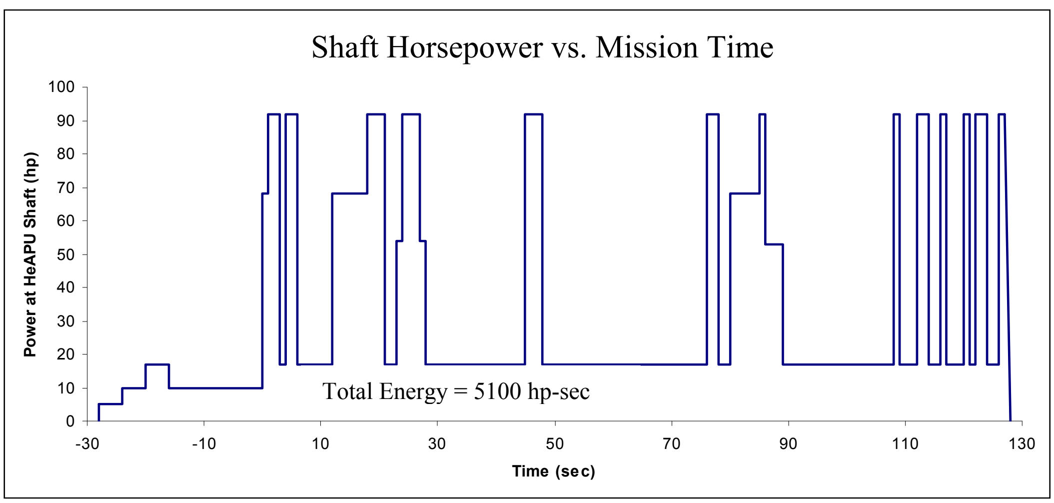

Figure 3.—Estimated TVC mission cycle bounds both Ares I and Ares V 1st stage.

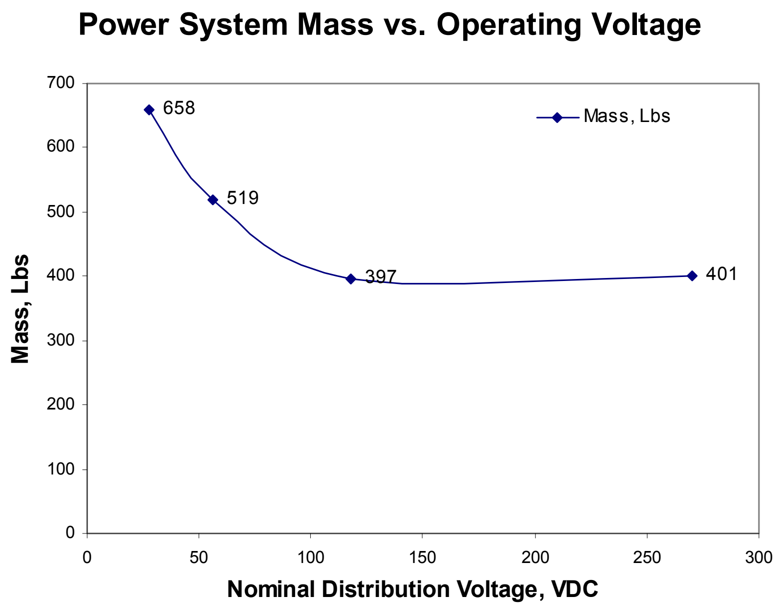

Figure 4.—TVC power system mass versus operating voltage.

Battery Chemistry Comparison

Lithium-ion and thermal battery systems were considered as potential energy storage candidates for this application. Table 1 compares the overall battery attributes between lithium-ion and thermal battery systems.

Thermal Batteries

There are three major aerospace thermal battery vendors: Eagle-Picher, ENSER, and Saft. Thermal battery technology is quite mature. ENSER fabricated and demonstrated a very large thermal battery for NASA's Solid Rocket Booster Thrust Vector Control System (Ref. 2). The logistics associated with a launch scrub is still a problem. Thermal batteries are inert and harmless until activated. Thermal batteries can be activated only once, whether they are used or not. After they cool down, they cannot be reutilized again.

Thermal batteries are primary, single use, reserve type devices often used for military applications. They are entirely inert until activated. Activation occurs when the electrolyte which is solid at room temperature, is heated to the molten state. They have a historically proven storage life of over 20 years and contain no liquids to spill or leak. When activated they can deliver full power in less than a second. Thermal batteries typically produce 1.85 V/cell, 65 Whr/kg, 150 Whr/L, and 2.5 kW/kg. Thermal batteries can operate over a temperature range of –55 to 75 °C. Thermal batteries can operate at any altitude, in any attitude, under conditions of extreme shock, acceleration, vibration or spin. Expended thermal batteries contain no lead, mercury, or cadmium and can be disposed of without lasting environmental impact. Thermal batteries have a low cost of ownership and require no maintenance. Thermal batteries have a 50+ year history of safety with no field injuries ever reported (Ref. 3). On the negative side, thermal batteries do get hot once activated with a skin temperature between about 50 to 135 °C, and once started, the reaction cannot be stopped.

TABLE 1.—LITHIUM-ION VERSUS THERMAL BATTERY ATTRIBUTES FOR 1st STAGE TVC

	Lithium ion	Thermal
Operational considerations	Secondary battery can be recharged multiple times	Primary battery can only be used once. Thermal battery is inert prior to activation and can only be activated once. Once the thermal battery is activated, operation cannot be interrupted.
Safety		
Pre-flight	Can be designed incorporating dead-facing switching or "keys" for safe handling of the fully charged 270 V battery	Inactive, no voltage on fully charged battery prior to activation of the battery.
Recovery	Continue to operate hydraulic pump off battery after separation. This will discharge the battery prior to recovery.	When battery temperature falls below operating temperature, after salt water immersion, battery is inactive/safe
Corona mitigation	A combination of coatings or immersion in high dielectric fluids has been successfully demonstrated.	Immersion in high dielectric fluids within a sealed battery box. High operating battery temperature may limit selection of dielectric material
High rate discharge	Capable, High rate cells have been developed for F-35 aircraft	Capable
270 V development	Space qualified design available Vendors include ABSL, Saft	Under development Venders include Enser, and Eagle-Picher
Pad operation		
Extended stand time	Battery recharging may be necessary Battery self-discharge rate will need to be assessed.	Possible prior to activation of the battery
Pre-flight check of battery/Electrical system	Feasible	Not-feasible prior to battery activation
Readiness for flight after abort	Quick turn-around after an abort situation. Lithium battery may require recharge prior to reinitiation of countdown	Thermal battery must be replaced after activation. Longer turn-around time before reinitiation of countdown.
Exercise of TVC Pre-flight	Feasible. Battery can be designed with additional capacity or recharged prior to flight	Feasible. However, flight battery must be replaced prior to flight or external ground batteries/equipment used.
Reliability	Proven—Commercial, Military, Space applications	Proven—Low voltage missile systems
Mass (lbs) (Estimated)	114	126

Lithium-ion Batteries

Li-ion batteries are much lighter than thermal batteries and in recent years have demonstrated excellent high power capability. Li-ion batteries can produce high power for short "pulses". Li-ion batteries are secondary batteries, can be recharged and used over and over. Lithium-ion batteries typically produce 3.6 V/cell, 90 Whr/kg, 250 Whr/L, and 700 W/kg. The organic electrolyte in the lithium-ion battery provides a –20 to 40 °C operating temperature. The lithium-ion battery cells are hermetically sealed and can operate in any orientation. While lithium-ion batteries have a higher initial cost, they have lower operational costs due to the ability to recharge and reuse the battery after multiple scrubs.

Based upon the benefits and drawback comparisons between the thermal and lithium-ion battery chemistries, it was determined that the thermal battery option would be dropped from the trade space and the focus would be solely on lithium-ion batteries. This was mainly based on the single use only associated with the thermal battery along with launch abort logistics associated with the costs for replacing the thermal battery and impacts on the schedule to remove and install a new set of thermal batteries.

Battery Sizing Approach

The battery sizing for this study was based on the voltage, current and power from the mission power profile from Figure 3. By using the total integrated energy from the mission profile, the duration of the mission, and factors such as electrical distribution efficiency and the desired depth-of-discharge for the battery to maintain the necessary design margin, the required watt-hours can be calculated. Next, the total ampere-hour capacity of the battery was determined by dividing the watt-hours by the average system voltage. The computed value for the total ampere-hour capacity of the battery provides a basis for the individual cell capacity required and allows a selection of possible cell candidates. Ampere-hour capacity of the battery can be achieved by paralleling strings. The number of cells required in series is determined by the required 270 V system voltage. In the case of thrust vector control missions, the high power application drives the selection of the lithium-ion cell that can meet both the peak and continuous discharge current. The mass estimate for the packaged battery was based on a mass packing factor (MPF) to scale-up from the lithium-ion cell level mass to the battery level mass. The MPF includes peripheral items of wiring, connectors and other related structural hardware associated with the battery design. Conservative packing factors of 1.8 for cylindrical cells were used based upon flight heritage battery designs.

Lithium-ion Battery Sizing

In order to minimize development risk and utilize flight heritage lithium-ion battery technology, the Saft high power lithium-ion battery cell developed for the Joint Strike Fighter F-35 was selected due to its high TRL 8 development, its high power discharge capability, and human-rated qualification for aircraft. Strict safety and abuse testing criteria are imposed on the batteries to ensure adequate performance margins are maintained under worst case conditions including two fault tolerant designs at the battery level. Saft's model VL4V lithium-ion cell was selected to size the Ares I/V TVC common design point. Although 270 V was specified as the system voltage, a higher operating bus voltage was advantageous to reduce peak discharge currents. 84 lithium-ion cells in a single series configuration were baselined to meet the energy and power demands for the TVC system.

- 84 cells in series @ 4.1 V/cell = 344 V fully charged
- 84 cells in series @ 3.0 V/cell = 252 V under peak load
- 50 kW peak/battery @ 252 V end-of-mission equates to 198 A for the worst case discharge rate
- The F-35 JSF lithium-ion cell VL4V nameplate is rated at 4.4 A-h

- 198 A/4.4 A-h = 45C discharge rate which is within the performance capability of the cell.
- Based upon 270 V average discharge voltage for mission estimated at 3.2 V/cell therefore 756 Whr/270 V = 2.8 A-h
- At the constant discharge 45C rate, the Saft VL4V cell provides 85 percent of its room temperature capacity which is equivalent to a 75 percent depth-of-discharge and provides little power margin for the mission.

Conclusions

Based upon the mission profile for the battery supported Thrust Vector Control system for Ares I/V, the lithium-ion battery selection is recommended. This was due to the rechargeable feature of lithium-ion chemistry which is advantageous for launch pad delays and scrubs. In addition, the lithium-ion cell design is at a higher Technology Readiness Level than the thermal battery/cell design which provides greater risk reduction. Finally, the lithium-ion battery system provides a slightly lower mass for the energy storage system. The actual mission profile for the TVC may increase in both duration and peak power demand which could skew the selection of specific lithium-ion cell and battery designs. The conservative electrical power management and distribution efficiencies of 70 percent from the output of the battery to the input of the electric motor are truly worst case. Improvements in motor design, electrical cable harness size, and the motor controller itself would greatly improve the inherent design margin of the battery by eliminating power losses. Recent developments at Saft have increased the performance of the VL4V cell design by increasing ampere-hour capacity within the existing cell dimensions to upwards of 6 A-h. It should be noted that the induced environments of the launch vehicle such as shock, vibration, and especially the thermal interface have not been factored into the analysis since they are ill-defined at this time. Additional refinement of the energy storage design can be made to quantify performance margins and will be performed once the mission profile, natural and induced environments, and available lithium-ion cell designs mature.

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