Defense Systems Information Analysis Center

DSIAC TECHNICAL INQUIRY (TI) RESPONSE REPORT

High-Rate Discharge Battery and Electric Motor for Space Use

Report Number:

DSIAC-BCO-2021-124

Completed October 2018

DSIAC is a Department of Defense Information Analysis Center

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
05-10-2018

2. REPORT TYPE
Technical Research Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
High-Rate Discharge Battery and Electric Motor for Space Use

5a. CONTRACT NUMBER
FA8075-14-D-0001

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Nicholas Keim and Scott Armistead

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Defense Systems Information Analysis Center (DSIAC)
SURVICE Engineering Company
4695 Millennium Drive
Belcamp, MD 21017-1505

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Defense Technical Information Center (DTIC)
8725 John J. Kingman Rd.
Ft. Belvoir, VA 22060-6218

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES
Energy and Power Technologies: Energy storage, Power generation / energy conversion, Space: Satellite Operations; Advanced Materials, Energetics

14. ABSTRACT
The Defense Systems Information Analysis Center (DSIAC) received a technical inquiry requesting information on available electric motor and high-rate discharge battery technologies for space applications. The inquirer provided a set of requirements for the technologies. DSIAC contacted Johns Hopkins University (JHU) to request subject matter expert (SME) support to respond to the inquiry. A JHU SME researched advanced battery-/capacitor-based energy storage and generation as well as electric motor technologies to provide information and compare various commercially available products that could potentially meet the inquirer's requirements.

15. SUBJECT TERMS
electric motor technology, battery technology, energy storage

16. SECURITY CLASSIFICATION OF: U			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Ted Welsh, DSIAC Director
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	UU	15	**19b. TELEPHONE NUMBER *(include area code)***
U	U	U			443-360-4600

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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A chief service of the DoD IACs is free technical inquiry (TI) research, limited to 4 research hours per inquiry. This TI response report summarizes the research findings of one such inquiry jointly conducted by DSIAC.

ABSTRACT

The Defense Systems Information Analysis Center (DSIAC) received a technical inquiry requesting information on available electric motor and high-rate discharge battery technologies for space applications. The inquirer provided a set of requirements for the technologies. DSIAC contacted Johns Hopkins University (JHU) to request subject matter expert (SME) support to respond to the inquiry. A JHU SME researched advanced battery-/capacitor-based energy storage and generation as well as electric motor technologies to provide information and compare various commercially available products that could potentially meet the inquirer's requirements.

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1.0 TI Request

1.1 INQUIRY

What electric motor and high-rate discharge battery technologies are available for a given set of requirements for a space application?

1.2 DESCRIPTION

The inquirer was particularly interested in an electric motor that could be used to drive an electric pump that needed ~67 kW of power for a set of lander engines.

2.0 TI Response

The Defense Systems Information Analysis Center (DSIAC) contacted Johns Hopkins University (JHU) Energetics Research Group (ERG) to request assistance with the inquiry response. JHU subject matter expert (SME) Nicholas Keim researched advanced battery-, capacitor-based energy storage and generation as well as electric motor technologies to provide information and compare various commercially available products that could potentially meet the inquirer's requirements.

2.1 SYSTEM DESCRIPTION

The inquirer requested information on technology similar to that used by Rocket Labs Co. with their Rutherford "electro-cycle" engine, which powers their Electron lift vehicle. The key drivers for space application of these technologies are power densities and energy densities that can provide the smallest size, weight, and power (SWaP) package that meets the requirements. Discussions with the requester indicated the following system requirements:*

- Purpose: power lander engines.
- Duration of Need: 65-minute descent.
- Total Energy: 3,854 Whrs.
- Power (peak/continuous?): 67 kW.
- Mass (battery package): 450 kg or less.
- Mass (inverter): not provided.
- Mass (motor): not provided.

* It appears that either the total energy or power provided by the inquirer is incorrect or that the power number is for peak power and the continuous power requirement is significantly less. It is unknown if power is peak or continuous, and the power duration does not match specified total energy. If the power and duration numbers are correct, the total energy would be in the range of 72,000 Whrs.

Some of the industry enterprises within the aerospace electric aircraft and automotive industry electric vehicle (EV) sectors are involved in energy generation/storage and electric motor research and development (R&D). This R&D may support the inquirer's space efforts.

Based on the provided requirements, a comparison chart of examples of advanced commercial off-the-shelf (COTS) battery packs (Table 1), inverters (Table 2), and motors (Table 3) providing capabilities near or exceeding the requirements was developed. Much of inverter and electric motor information was from a briefing on electric aircraft advanced powerplant technologies [1].

An example of a battery package, inverter, and pump combination that would appear to meet the inquirer's overall requirements is the combination of the Tesla Model 3 battery pack, the Siemens NextGen Si insulated-gate bipolar transistor (IGBT) inverter, and the Siemens SP70D motor, which has a total mass of 515.8 kg.

Table 1: State-of-the-Art COTS Battery Technology

Original Equipment Manufacturer (OEM)	Item Name/ Model	Energy† (Whrs)	Voltage (V)	I_{max} (A)	Mass (kg)	Energy Density (Wh/kg)	Notes
Chevrolet	Bolt Battery Pack [2−6]	60,000	350	428.6	435	137.9	I_{max} based on Bolt power output of 150 kW.
Tesla	Model 3 Battery Pack [2, 3]	80,500	350	971.4	480	167.7	I_{max} based on combined Model 3 power of 340 kW.

† This is the stated capacity; the usable capacity will be less. For instance, the usable capacity of the Model 3 battery is 78,270 Whrs [2], and the Bolt battery is between 57,000 and 59,000 Whrs [4].

Table 2: State-of-the-Art Inverter Technology

OEM	Item Name/Model	$P_{out\ max}$ (kVA)	I_{cont} (A)	I_{max} (A)	Mass (kg)	Notes
Siemens	NextGen Si IGBT [1]	130	250	500	9.8	500 A for 10-min duration.

Table 3: State-of-the-Art Motor Technology

OEM	Item Name/Model	P_{cont} (kW)	P_{peak} (kW)	U_{DC} (V)	N (rpm)	Mass (kg)	Power Density (kW/kg)	Notes
Chevrolet	Bolt Electric Motor [5]	—	150	—	8810	76	1.97	Speed is max.
Siemens	SP260D [1, 7]	260	—	—	2500	50	5.20	Power is assumed to be peak; $N_{cont} = N_{max}$.
Siemens	SP260D-A [1]	260	—	—	2500	44	5.91	Power is assumed to be peak.
Siemens	SP70D [1]	70	90	350–450	2600	26	2.69	90 kW can be provided for 2 min; stackable.
EMRAX	EMRAX 228 [8]	55	100	Various	5500	12.3	4.47	—

As shown in Tables 1–3, the inquirer's 67-kW power requirement for the motor is well within the experience base for the EV industry. The Tesla Model 3 and Chevrolet Bolt battery packages fit within or are close to fitting within the provided battery mass budget and exceed the power and energy requirements. However, the battery pack energy densities can be misleading as the mass used in the calculation is for the commercial battery package (i.e., battery case, base plate, etc.) needed to sufficiently cool, secure, and protect the battery in automotive applications. It may be possible to develop a significantly lighter package for a given space application. For example, the Tesla Model 3 case baseplate weighs 61 kg. If only the battery modules and associated cooling plates, etc., are considered, the module energy densities are 222 Whr/kg for the Tesla Model 3 and 195 Whr/kg for the Chevrolet Bolt EV [10].

In terms of state-of-the art motors, the Chevrolet Bolt's power capability (i.e., 150 kW) provides double the requirement. However, the important metric is specific power, which is not quite 2 kW/kg. More advanced electric motors are coming to market for the electric light aircraft industry, largely spearheaded by Siemens. Siemens produces a motor weighing only 26 kg that is capable of 70 kW continuous power output (specific power is 2.7 kW/kg). In addition, Slovenia is supposedly producing a 55-kW continuous, 100-kW peak power motor weighing only 12.3 kg (unsubstantiated). If this information is true, this motor would provide a specific power of 4.5 kW/kg, which is one of the highest identified in Table 3 for this size/power level. Siemens has achieved better specific power for larger motors.

The battery and motor are not all that would be required for an operational system; an inverter is needed to convert the direct-current battery pack to the appropriate voltage, frequency, and phase of the motor. Siemens has demonstrated a very light inverter marketed for the electric light aircraft industry.

Based on the information provided in Tables 1−3, battery and motor technology may already be available to support a solution for the inquirer's application.

2.2 ENERGY-STORAGE AND GAS-GENERATOR TECHNOLOGIES

In Table 4 and Figure 1, energy-storage and gas-generator technologies are compared. For a true comparison to a gas generator energy-storage device, the propellant mass used by the gas generator, the tankage, and required pressurants, if any, must be accounted for. These data were readily available for the 1960s/1970s-era S-IVB stage with the J-2 engine and the Titan IIIA second stage with the LR91 engine. When battery technology is compared to chemical storage of energy released via combustion, battery technology is nearly equal to gas generator technology in terms of energy density, but not power density. The opposite is true for supercapacitor technology, as it compares reasonably well to gas generator technology for power density but not for energy density.

Table 4: Energy-Storage and Gas-Generator Technology Comparison

Technology	Cell Energy Density (Wh/kg)	Pack/System Energy Density (Wh/kg)	Cell Voltage (V)	Cell Power Density (W/kg)	Pack/System Power Density (W/kg)
Li-ion [9, 10]	250	175	3.6	475	332.5
Li-S [11−13]	325	227.5	2.1	325	227.5
Metal Air [14]	470	329	1.4	100	70
Super Capacitor	5	3.5	3.0	700	490

Table 4: Energy Storage and Gas Generator Technology Comparison (continued)

Technology	Cell Energy Density (Wh/kg)	Pack/System Energy Density (Wh/kg)	Cell Voltage (V)	Cell Power Density (W/kg)	Pack/System Power Density (W/kg)
Pseudo Capacitor	10	7	3.6	900	630
Solid Oxide Fuel Cell	—	Fuel quantity dependent.	—	—	1000
S-IVB J-2 Gas Generator	—	633	—	—	4800
Titan IIIA 2nd Stage Gas Generator	—	61	—	—	1200

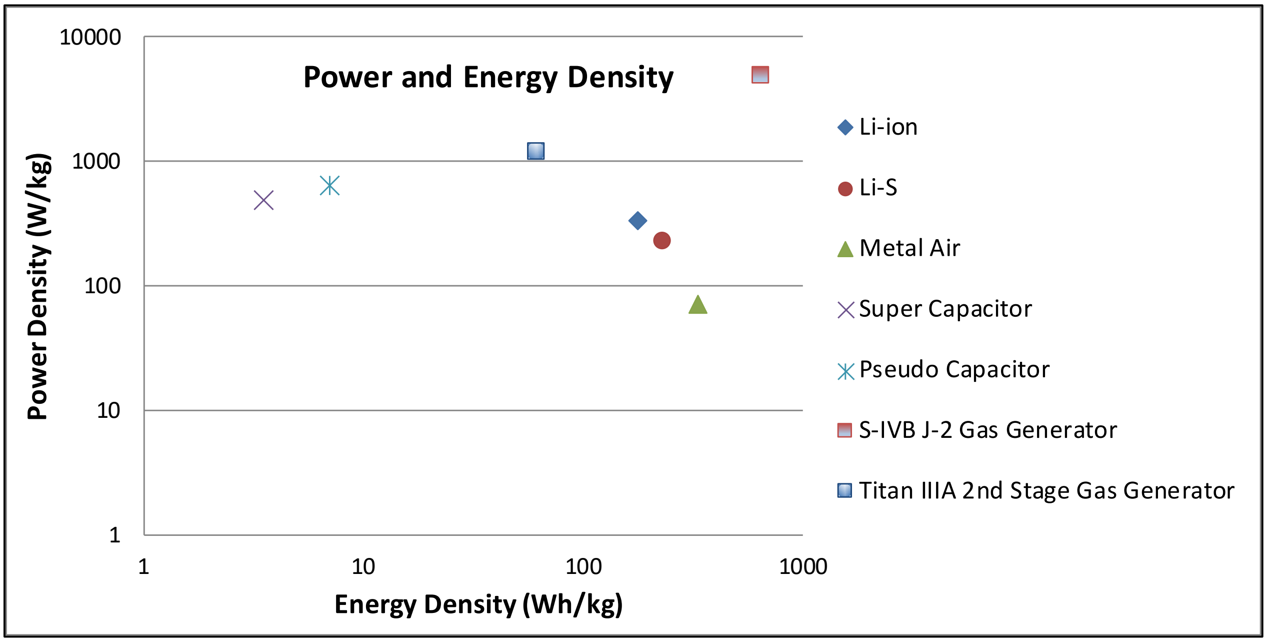

Figure 1: Comparison of Advanced Energy Storage and Generation Technologies.

The JHU ERG staff investigated performing a comparison of turbomachinery to electric motors. However, initial indicators are that the comparison is not favorable; electric motors are about an order of magnitude away from the needed power density to suit a generic liquid rocket engine application of reasonable size. However, there are technologies being developed that may improve this lack of power density, such as the use of high-temperature superconductors (which can take advantage of cryogenic temperatures of oxidizer and/or fuel). A full investigation of this technology is beyond the scope of a technical inquiry.

Storing energy for rocket turbomachinery is quite difficult. The Rutherford engine is 5,000 lbf, and that may be the current limit for state-of-the-art technology. State-of-the-art technology has reached a point where it can potentially meet the energy-density (Wh/kg) requirements or power-density (W/kg) requirements, but not both, unless it is for a small system. Rocket Lab Co. and TGV Rockets Inc. are working on promising electrically driven pumping systems and pushing these current boundaries.

2.2.1 Rocket Lab Co.

Rocket Lab is currently working on the Electron launch vehicle, which uses an in-house designed Rutherford oxygen/kerosene pump-fed engine that has high-performance electric propellant pumps [15].

At a SmallSat conference held in August 2018, Rocket Lab displayed the majority of the Electron rocket's additively manufactured second-stage engine and their second-stage propellant tanks inside their carbon composite case. With respect to the engine, Rocket Lab claims they can throttle a wider range than other engines by adjusting the electric power provided to the motors to adjust the flow rates and thrust. They also claim their electric motors are more efficient than turbo-pumps or gas generators and safer, in part, due to not having energetic materials. However, their motors do have the negative trade-off of added mass from the batteries; Rocket Labs did not indicate how large of a trade-off the added mass is. Rocket Labs did not bring the electric motor power packs, pumps, or batteries, and would not provide detailed answers to questions about the engines due to proprietary concerns.

Rocket Labs uses additive manufacturing to create a single-piece combustion chamber with a bell nozzle. To the maximum extent possible, the engine is composed of additively manufactured components with the goal of minimizing mass, cost, complexity, and manufacturing time. Nine of the engines together are used in the first stage (like SpaceX), and a single engine with an additively manufactured nozzle expansion is used for the second stage. When asked about the propellants, Rocket Lab personnel would only say it was liquid oxygen with a kerosene fuel. As they did not bring the relevant hardware or answer questions in detail, questions on SWaP characteristics of the electric motors, pumps, batteries, and the engine remained unanswered. Similarly, Rocket Labs doesn't appear to have presented anything at recent Joint Army Navy National Aeronautics and Space Administration (NASA) and Air Force Propulsion Subcommittee meetings. A brief search in the American Institute of Aeronautics and Astronautics' Aerospace Research Central repository did not reveal anything published on their electric motors.

2.2.2 TGV Rockets Inc.

TGV Rockets Inc. has developed its ElectroCycle™ electric-pump-fed engine and associated fuel feed system, which uses ultra-modern batteries to drive electric fuel pumps to feed fuel to their ElectroCycle engines [16]. The Defense Advanced Research Projects Agency is working with TGV on development of their ElectroCycle engines.

The ElectroCycle engines are modular and scalable, so the battery pack, inverter, and pump system may be available in a package suitable to meet the inquirer's SWaP requirements. TGV Rockets spoke of an engine with 25,000 lbf of thrust at a 2018 Commercial and Government Responsive Access to Space Technology Exchange (CRASTE) conference, and their Small Business Innovation Research award from NASA reiterates this goal. At CRASTE, TGV Rockets seemed to be relying on battery technology to catch up to their electric motor technology to make an engine system of that size possible. They did not provide any detail on their motor technology but did say that they have demonstrated upwards of 5 kW/kg. A cursory look at the specifications of electric motors catalogued in Wikipedia indicates that this metric is within the range of lighter-weight, high-end known motor technology [17]. However, based on the initial research, TGV may be overstating the power density possible with current battery and capacitor technology.

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BIOGRAPHIES

NICHOLAS KEIM is a DSIAC subject matter expert. He currently serves as the Deputy Director for the Johns Hopkins University (JHU) Energetics Research Group (ERG), formerly known as the Chemical Propulsion Information Analysis Center (CPIAC), and as the Principal Investigator for the Advanced Engine & Rocket (AERo) Fuels Laboratory. He has nearly 14 years of research experience in propulsion systems and rocket propellants to include heat transfer capabilities of rocket and hypersonic fuels using a high heat flux experiment and comparing results to modeling and simulation analysis to determine and improve the fuel thermal stability limits. Mr. Keim holds a B.S. in Mechanical Engineering from JHU and an M.Sc. in Mechanical Engineering with emphasis on turbomachinery and nuclear reactor technology from the Imperial College London.

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