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Cold Regions Research
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Cold Regions Energy RDTE

Cold Regions Vehicle Start

Cold Performance of Ultracapacitor-Based Batteries for Stryker Vehicles

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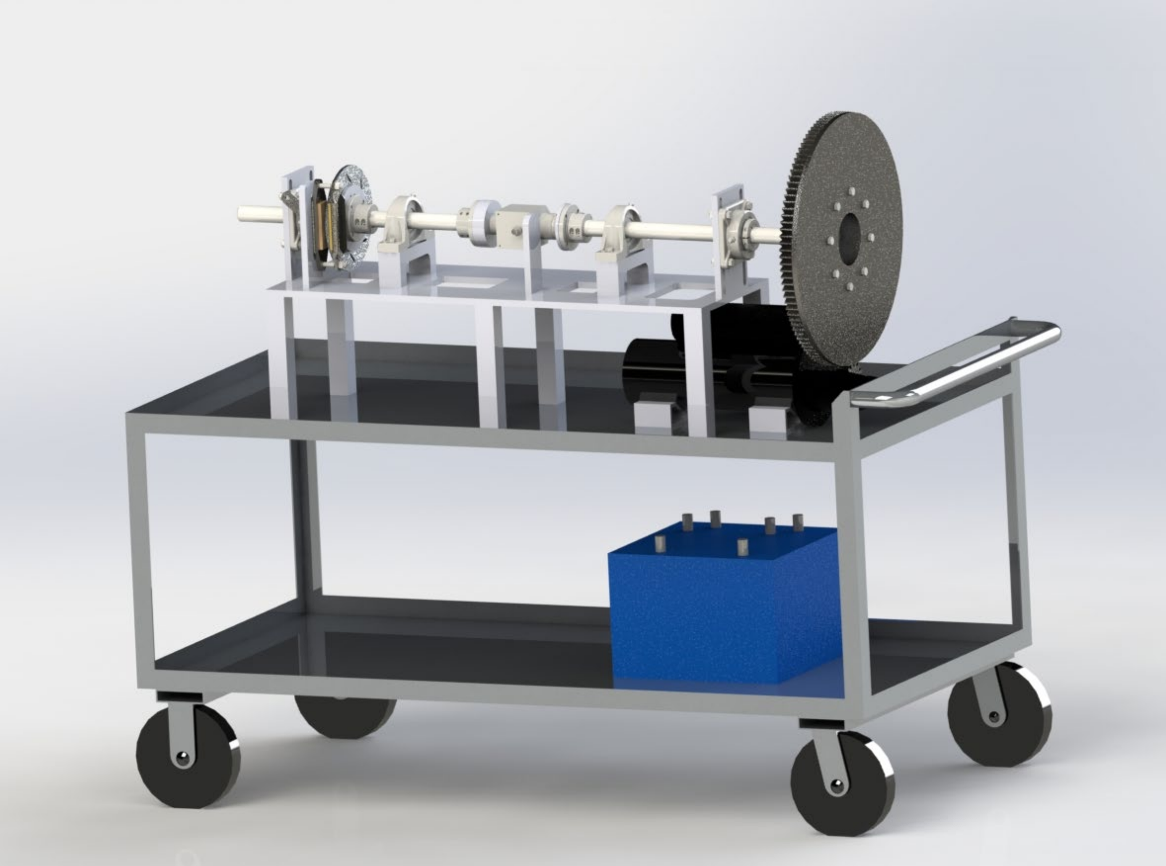
September 2022



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Abstract

Reliable vehicle start is necessary to support mission success, especially for response time. At Department of Defense installations in cold regions, vehicles using rechargeable battery and starter technologies have significant issues starting in the cold. Ultracapacitor engine start modules (ESMs) are an alternate technology to rechargeable lead-acid or lithium-ion batteries. The project develops a performance baseline for the ESM used in the M1126 Stryker Combat Vehicle under cold conditions. To test the performance of the ESMs in a cold room, a mechanical load system was constructed to replicate the load of starting a Stryker engine and instrumented with sensors to monitor parameters such as voltage, torque, and temperature. The ESMs were tested with the load system at temperatures from 24°C to −40°C. The results of the tests showed that there was some degradation of the ultracapacitor's performance at the colder temperatures, which was expected, but no permanent damage. This work provides a test protocol and capability to evaluate next-generation vehicle battery systems for cold regions applications. Additionally, the ESM cold performance data establish a baseline to compare next-generation vehicle battery storage systems and to support cold regions missions and identify potential performance requirements for future vehicle battery system acquisition.

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Preface

This study was conducted for the U.S. Army Corps of Engineers under PE 0603734A, “Energy and Technology Research in Cold and Arctic Regions.” The technical monitor was Mr. Jared Oren (CEERD-RRE).

The work was performed by the Engineering Resources Branch (RRE) of the Research and Engineering Division (CF), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Melisa Nallar was Acting Chief, CEERD-RRE; Dr. Caitlin A. Callaghan was Chief, CEERD-RR; and Dr. Robert E. Davis, CEERD-RZT, was the Technical Director for Cold Regions Science and Engineering. The Acting Deputy Director of ERDC-CRREL was Mr. Bryan E. Baker, and the Director was Dr. Joseph L. Corriveau.

COL Christian Patterson was Commander of ERDC, and Dr. David W. Pittman was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
inch-pounds (force)	0.1129848	newton·meters

1 Introduction

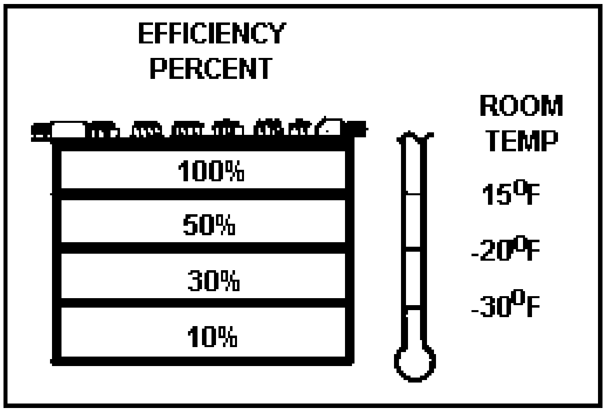
A vehicle's startup ability is of high priority to achieve the objectives of an operation. The battery system is a key aspect to successful startup, but its chemistry is generally challenged by cold regions, regardless of application. Ultracapacitors are an alternative technology to rechargeable lead-acid or lithium-ion batteries as another way to store and supply energy for both vehicle startup and auxiliary load supply, such as sensors, crew equipment, or weapon systems (Military Specification [MIL]-FM-9-207 1998).

1.1 Background

Cold climates introduce adversity to a vehicle's typical operation such that the system becomes less efficient as the temperature decreases. A vehicle's capability to start and operate is reduced significantly in cold regions. The main limitation in the system is the batteries since their performance is heavily affected by temperature (MIL-FM-9-207 1998). Without proper thermal management or alternative equipment and maintenance, a vehicle will fail to start, leaving it out of commission until further repairs or a new, warm battery can be installed.

When the storage capacity of a battery becomes depleted, the startup of a vehicle becomes more difficult due to an increase in the engine's power demand. As shown in Figure 1, as the temperature continues to decrease, the battery efficiency decreases as well (MIL-FM-9-207 1998).

Figure 1. Battery efficiency verse temperature (MIL-FM-9-207 1998).



The efficiencies shown in Figure 1 are a generalization and do not correspond to a specific battery technology.

Batteries rely on the kinetics of a chemical reaction between the anode and the cathode; these reaction kinetics become reduced when exposed to colder temperatures (Bates 2012). Battery preheaters can be installed to raise the battery temperature up to the operating range. Insulated battery boxes may also be installed to help maintain battery temperature for adequate operation (MIL-FM-9-207 1998). However, both these methods must be plugged in to an installation's power to function, which is not always available for more remote operations.

In addition to battery chemistry, other vehicle system components can be challenged when the batteries fail to perform for vehicle start applications in the cold. For example, the vehicle's starter could overheat during the startup attempt since the engine continues to crank without turning over when there is insufficient battery storage to support vehicle start. Vehicle manuals may specify a time limit or starter temperature to prevent the starter from overheating or becoming damaged. The manual may also specify a time limit in between each start attempt to ensure the starter has sufficient time to cool down (MIL-FM-9-207 1998).

1.2 Problem statement

Reliable and resilient vehicle start is necessary for response timing and mission success, especially in emergencies. Department of Defense (DoD) installations in cold regions have significant issues cold-starting vehicles with current battery and starter technologies. The M1126 Stryker is one of the systems challenged by cold weather operations. In particular, cold start of the Stryker's diesel engine using current battery technology poses unique challenges. To mitigate these challenges on DoD installations in cold regions, such as in Alaska (e.g., Fort Greely, Fort Richardson, and Fort Wainwright), military personnel are required to remove the batteries from the Stryker vehicle to be warmed in climate-controlled storage, or the vehicles are left running to maintain battery temperature.

In addition to warm storage for batteries, some Stryker battery systems utilize an ultracapacitor engine start module (ESM) to improve cold start capabilities. The ultracapacitor ESM currently provides support to the battery system for vehicle start but has limited additional benefit to the vehicle's energy storage needs, such as supporting auxiliary loads.

Therefore, next-generation battery technologies should be identified that perform as well or better than the ultracapacitor-based system. To accomplish this, it is important to understand the performance profile of the ultracapacitor-based battery system.

1.3 Objective

This project will provide a baseline of the performance of the currently used ultracapacitor ESM components under cold conditions reaching −40°C. The captured baseline can be used for future testing to compare performance of next-generation vehicle battery storage technologies in the cold and to identify any system design improvements that could be made to the current ultracapacitor ESM.

1.4 Approach

This effort aims to characterize the ultracapacitor ESM technology with the expectation that the information gained can be used to inform decision-makers how to mitigate the challenges experienced by vehicle batteries in the cold. Using the mechanical load system that was developed for these series of tests, the CRREL team collected measurements on the several parameters of the ultracapacitor ESMs during operations at varying temperatures.

Using this information, the performance of these ESMs was characterized to better understand how they were impacted by changes in temperature. Sections 3 and 4 provide more detailed information about the test setup, equipment, and data collected. These sections also identify challenges with both the technology as well as the system and identify areas for improvement for future consideration.

1.5 Impact to the Army

The U.S. military has unique operational challenges in the world’s cold regions. The military has a large investment in the cold regions of the world, with 21,407 active duty military personnel stationed in Alaska alone, of which the Army makes up 51% (State of Alaska 2020). Extreme conditions and demanding technical requirements inspire unique research opportunities for cold regions operations. Additional research on cold-regions-capable batteries for vehicles can provide highly valuable results.

The M1126 Stryker operates through a vehicle control unit (VCU) that is powered by the vehicle engine and a 14.4-volt (V) lithium-ion rechargeable battery. Inside the VCU is a Multiple Integrated Laser Engagement System (MILES) XXI, which is responsible for simulating the effect of direct enemy fire. The system helps inform personnel in real-time about any dangers to save soldiers' lives and equipment during enemy engagement (MIL-TM-9-6920-916-10 2005). If MILES is inoperable because of cold start failure, the safety of a military operation is threatened.

Improvement of vehicle cold start capabilities for Army installations has the potential to increase vehicle resilience by providing more consistent and reliable engine start in cold regions, which is especially important during emergencies. For example, utilizing improved engine start technology, personnel would no longer need to remove the battery system from the vehicle for warm storage, saving both time and effort as well as preventing the risk of potential low temperature exposure of personnel. Leaving the vehicles idling to maintain battery temperature increases unnecessary fuel consumption, which is a concern where fuel supplies may be limited due to supply chain challenges (e.g., within a remote location, hostile environment, or other dangerous situations) and which leads to environmental concerns and greater emissions. Additionally idle engine noise could disclose military positions.

Reliable vehicle start enhances an installation's ability to respond in a timely manner and successfully complete mission objectives. By determining the top performing battery technology for cold temperatures, an installation can implement said technology and be prepared to respond, no matter the conditions. The results from this project provide valuable insight for both DoD and non-DoD applications that experience vehicle start challenges in the world's cold regions.

2 Ultracapacitor Technology Overview

2.1 How ultracapacitors function

Ultracapacitors have garnered great interest in the research community recently. This is because they have many improved properties when compared to rechargeable batteries. One such property is extremely high power density, which allows the ultracapacitor to release high amounts of energy much more quickly than a lead-acid battery. Also, low temperatures have a minimal effect on an ultracapacitor's capacity, and ultracapacitors exhibit minimal degradation over thousands or even millions of charge/discharge cycles when compared to rechargeable batteries (Abbas 2020).

Capacitors consist of two conducting plates separated by an insulator. They differ from resistors because they store electrical energy when a voltage is applied across them, whereas resisters convert a portion of the energy to heat. Capacitors store energy by placing a positive charge on one plate and a negative charge on the other. This forms an electric field between the plates. The more charge stored on the plates, the larger the electric field is between them; hence, more energy can be stored. The amount of charge stored in a capacitor is proportional to the voltage applied (Alexander 2013). Equation 1 shows that charge is equal to the voltage applied across the capacitor times the capacitors capacitance.

$$Q = V \times C \tag{1}$$

where:

Q = charge
V = voltage
C = capacitance

A capacitor's storage is limited by its physical ability to store energy—this is a function of both breakdown voltage (insulating material) and the capacitance. Capacitance, measured in farads, is governed by Equation 2 (Alexander 2013):

$$C = \frac{\varepsilon A}{d} \tag{2}$$

where:

ε = permittivity
A = surface area
D = distance

Equation 2 shows that, for the same material, in order to increase the capacitance and, thus, increase the charge storage of a capacitor, you need to either increase the size of the plates, decrease the distance between them, or both. For simplicity, in this explanation it has been assumed the material between the two plates maintains physical properties such that (Alexander 2013)

$$V_{breakdown} > V_{across\ capacitor} \tag{3}$$

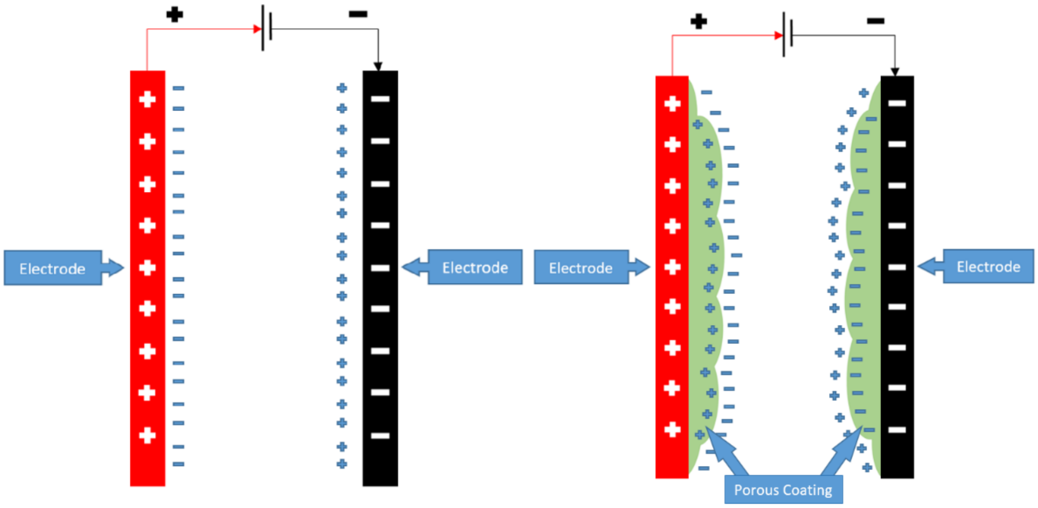
where:

$V_{breakdown}$ = voltage at breakdown
$V_{across\ capacitor}$ = voltage across the capacitor

Normal capacitors operate in the pico-farad (10^{-12}) to micro-farad (10^{-6}) range. While many standard commercial supercapacitors operate in the farad range, ultracapacitors are able to achieve a higher level of capacitance by both increasing the effective surface area and decreasing the distance between the plates. Capacitors come in many different shapes and materials depending on their application. However, two of the more popular constructions aimed at higher levels of capacitance are ceramic and electrolytic capacitors. Both of these constructions mostly follow a schematic that can be described as two plates, on opposite ends, with a dielectric between them. Many commercial ultracapacitors are cylindrical. This configuration is achieved by rolling up two current collectors with electrode material on either side. This type of configuration is often known as a “jelly roll.” Once the ultracapacitor has been rolled up, it is filled with an electrolyte (Berrueta 2019).

Similar to a normal capacitor, ultracapacitors have two plates that are separated. However, in an ultracapacitor there are two main differences. First, the plates are coated with a conductive porous material. This material is often an activated charcoal or carbon. The porous coating maximizes the usable surface area, thus increasing the value of A from Equation 2 (Berrueta 2019). This coating can be seen in Figure 2 below.

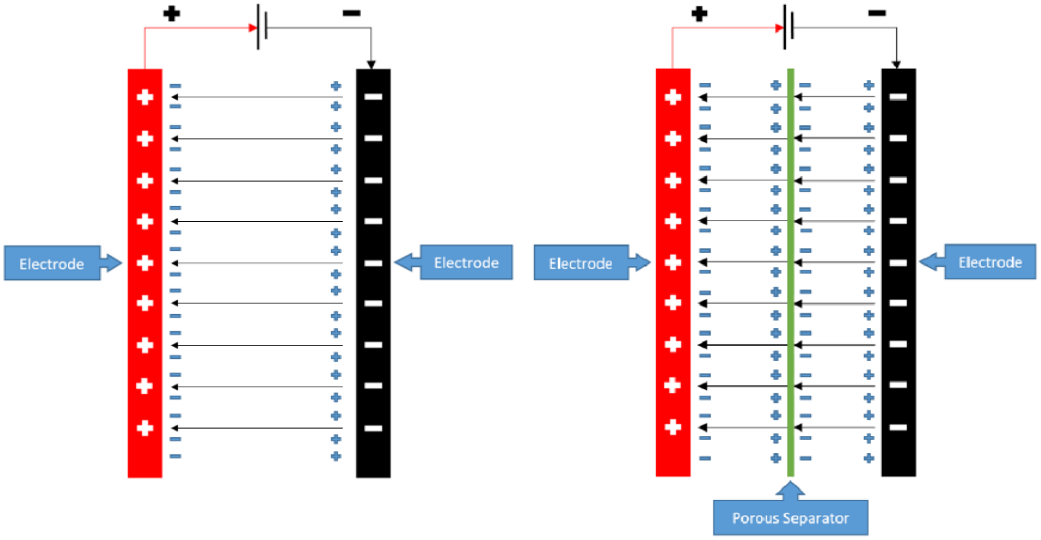
Figure 2. (Left) Metal capacitor plates without a porous coating. (Right) Metal capacitor plates with a conductive porous coating.



The left image in Figure 2 shows a schematic of the positive and negative plates of a capacitor, where the red is the positive and the black is the negative. The right image shows another capacitor but with a porous coating on the positive and negative plates. Again, the red is the positive plate and the black is the negative plate, and the green shape on the plates is the porous coating. The pluses and minuses show that there is more charge built up due to the coating.

An ion-conductive membrane—not a dielectric material—separates the plates. This allows ions to pass through while also preventing a short circuit within the capacitor. When the plates are excited, opposite charges form on both sides of the membrane. This creates a double layer at the electrode interfaces. The membrane is typically one or two molecules thick. Dissimilarly, a dielectric insulator has a thickness that ranges between from several microns up to a millimeter. The double layer membrane decreases the distance between the plates (Berrueta 2019). The difference can be seen in Figure 3. It’s of note that Figure 3 does not show a porous coating, but both the plates and the membrane would be coated with a porous material to increase surface area.

Figure 3. (Left) Standard capacitor with a dialectic material between the two oppositely charged plates. Arrows show the direction of the electric field. (Right) Ultracapacitor with conductive membrane (porous separator) between the two oppositely charged plates.



This double-layer capacitor phenomenon can oftentimes be more intuitively understood and accurately modeled through transmission line theory. This theory is useful for representing the overall behavior without having to focus in on the microscope pore scale. It is modeled by two transmission lines with an infinite chain of capacitors and resistors to mimic the resistance and capacitance inside the electrodes. The two lines are connected through a resistor, which is used to mimic the resistance of the electrolyte (Berrueta 2019).

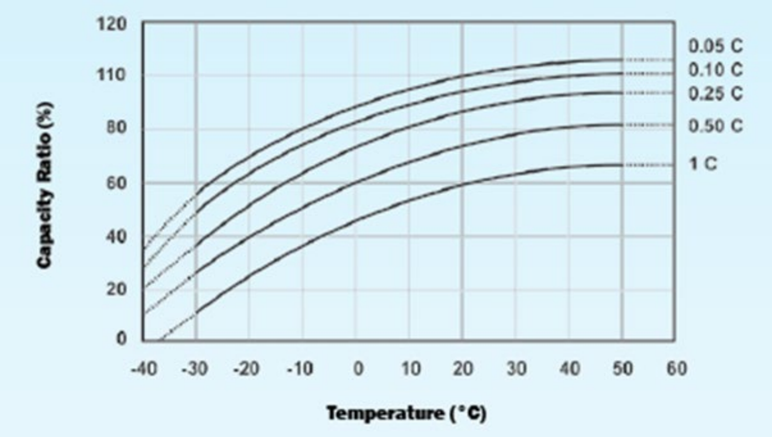
The porous coating and double layer created at the electrode interfaces may seem like a small change, but once the ultracapacitor has been rolled up, its effective surface area can be thousands of square meters.

2.2 Temperature effects on ultracapacitors

Temperature extremes pose many challenges for batteries. Lead-acid batteries rely on a chemical process where electrodes are separated by a liquid electrolyte that allows the electrons to pass between them (Battery University 2017). The optimum operating temperature for this process is 25°C (Hutchinson 2004). Higher temperature extremes will excite the electrons, increasing the conductivity. This increases the capacity of the battery, which in turn significantly decreases the overall life of the battery. Low temperature extremes have the opposite effect, where electrons are excited less than expected. This decrease in conductivity increases the internal resistance of the battery. The increase in resistance limits the amount of energy that can be extracted, decreasing the overall capacity of the battery (Jaguemont 2014).

Decreased battery capacity presents serious challenges. One of these challenges is the non-linear relationship between low temperatures and battery capacity. This relationship can be seen at five different rates of discharge in Figure 4 (Hutchinson 2004).

Figure 4. Effects of temperature on battery capacity (Hutchinson 2004).



In Figure 4, for a common discharge rate of 0.10°C, battery capacity drops to nearly 80% at 0°C, 60% at −20°C, and 30% at −40°C. On the other hand, an ultracapacitor stores energy electrostatically. Similar to a battery, it is an electrochemical device, but there is no chemical reaction involved. This means that, as the temperature drops, the ultracapacitor's internal resistance is barely changed when compared to a lead-acid battery. Testing has shown that resistance within an ultracapacitor is nearly constant from 0°C to −15°C and slightly increases at −40°C (Liu 2009).

The central difference between a capacitor and a battery is that a capacitor stores energy physically as a surface charge and a battery stores energy chemically using a liquid electrolyte. It's this difference that causes a battery to experience a cyclic degradation phenomena—called electroplating—that will limit its life. The chemical reaction used in a battery is not as easily reversible as the physically stored charge in a capacitor. A chemical charge storage device, such as a battery, leads to a volume change over time that is not seen in a physically stored device, such as a capacitor. This constant volume change limits the number of charge/discharge cycles possible. Generally, this number is limited to several hundred cycles. Under ideal conditions, physically storing charge with no chemical changes can be repeated constantly with no limit. In practice, Miller (2008) observed that ultracapacitors can complete hundreds of thousands to several million charge/discharge cycles.

Between the high power density, the lack of adverse interaction in cold weather, and seemingly unlimited lifespan, ultracapacitors have become a serious contender in energy storage innovation. However, batteries are still superior when it comes to energy density, which allows them to store large amounts of energy over long periods of time. Much of today's research focuses on the complete replacement of a battery with an ultracapacitor in a vehicle. But that technology still requires further investigation before commercialization is possible (Abbas 2020). This report will focus on a hybrid battery system where an ultracapacitor is used for the initial vehicle startup and then electrical system needs are passed to a lead-acid battery.

One characteristic of a vehicle motor is that the high initial power needed to start the motor is significantly higher than the steady state current. Starting, or cold cranking, the motor is when the battery is under the most strain and capacity is of most importance. This is the design basis behind a vehicle hybrid battery system. Wiring an ultracapacitor and lead-acid battery in parallel significantly lowers or completely removes the capacity needed from the battery for cold cranking (Liu 2009). An ultracapacitor can provide the high power needed for cold cranking in low temperature extremes, while a lead-acid battery can provide the energy density needed to run the electrical system once the vehicle is started.

A modified version of the Maxwell 24 V heavy duty ESM is used in some M1126 Strykers in an effort to improve the cold start capabilities of the vehicle from the existing batteries. The commercial off-the-shelf Maxwell 24 V heavy-duty ESM can be seen in Figure 5.

Figure 5. Maxwell 24 V ESM.

In conjunction with the four batteries of the Stryker battery box, the ESM is connected directly to the starter motor. This protects the other batteries from exposure to the load and stress of starting the motor, lengthening the life of the batteries as well as providing more starting power to crank the Stryker engine.

3 Methodology

The primary focus of testing was to replicate the crank power required for the start of the Stryker Combat Vehicle. While the Stryker Combat Vehicle is being used as the example vehicle, it is intended that all technologies evaluated will be applicable across multiple platforms. By investigating cold capable energy storage technologies, this work has the potential to inform both military and civilian energy storage applications. If this technology proves to have a high performance in the cold, it could potentially be utilized for commercial vehicles or even large-scale grid energy storage. While normal crank starting tests are based on supplied amperage, the objective of the CRREL tests is to replicate actual crank starting conditions. The ultracapacitor-integrated engine start module was tested at the following temperatures: 24°C, 15°C, 0°C, -10°C, −20°C, −30°C, and −40°C. These temperatures were chosen based on the temperature rating of the ultracapacitor module and the capabilities of the facilities at CRREL.

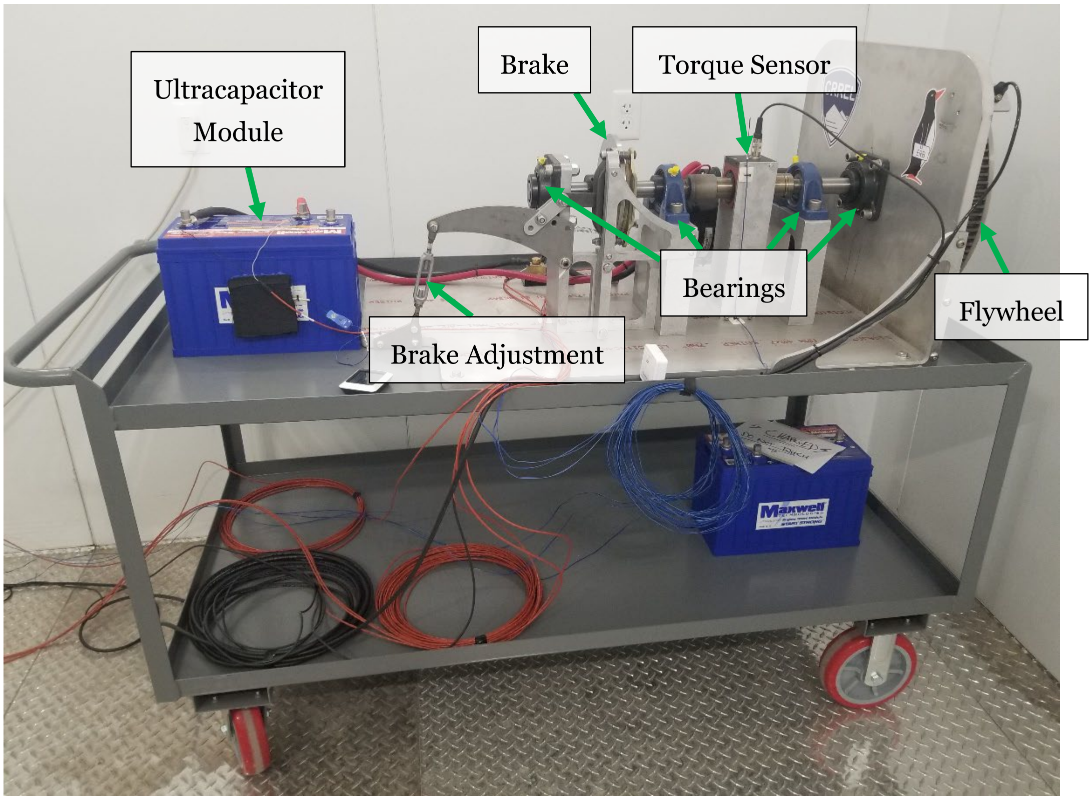
3.1 Test objectives

The goal of this work is to measure the variation of electrical power output as the temperature changes, creating a power curve for the ultracapacitor modules across this temperature range. Load testing across the range of temperature is also very important. By measuring the voltage and the current during use, it is possible to determine the efficiency of the ultracapacitor ESM. A test procedure will be developed to evaluate alternative battery technologies for Stryker applications, which will then be used to create a profile of the ultracapacitor ESM performance.

3.2 Test setup

Tests were conducted using an electrical circuit configuration with a simulated load equivalent to a Stryker crank (i.e., a Stryker starter motor and flywheel are part of the assembly). The test stand was instrumented with various sensors to monitor parameters such as voltage, torque, and temperature. The experimental test stand—including the simulated mechanical load of the flywheel with starter motor (Figure 6), the power storage devices, and any power switching controls—was installed in the cold room, simulating operational environment temperatures.

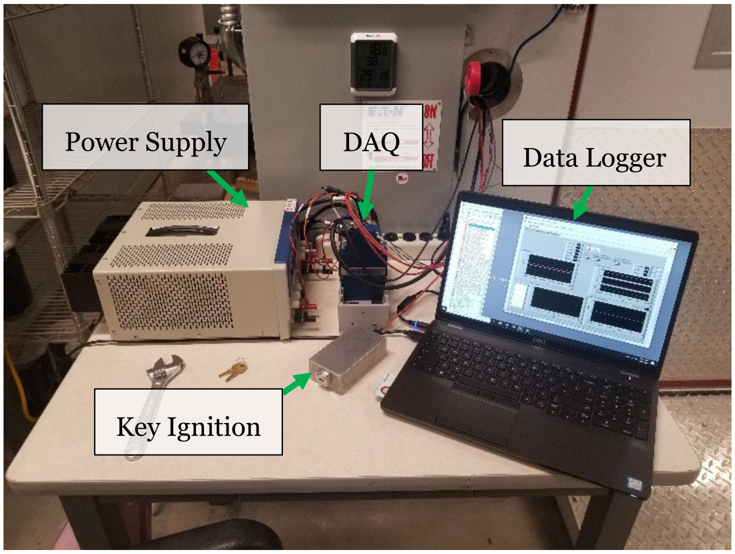
Figure 6. Mechanical load system installed in cold room.



The mechanical load system was constructed to simulate turning over a Stryker. The load system components include a CAT C9 starter motor and flywheel, two pillow block and two flange bearings, a rotating shaft, and an adjustable mechanical brake. The full assembly was mounted to a machined aluminum frame bolted to a metal cart. The brake had a turnbuckle that allowed the system to be set to the required torque to emulate the Stryker; the needed torque value was calculated to be approximately 300–600 N·m based on the specifications of the starter motor and the flywheel components.

The data acquisition system (DAQ) assembly and other data collection equipment (e.g., power supply, computer, hard drive) were installed outside the cold room as shown in Figure 7. A key ignition switch was also wired outside the cold room to allow the operator to engage the system and run the tests from outside.

Figure 7. External data acquisition system.



The power supply used 5V and 12V to power the sensors on the system, and the DAQ was connected to a project computer that used LabVIEW to collect the necessary data.

Once the test stand was assembled, it was tested at room temperature (approximately 24°C) to verify that the system operated correctly. For the system to function correctly, the starter motor must reliably turnover the flywheel with the correct torque rating, thus simulating the load of starting of a Stryker engine. Once the system was determined to function properly at moderate temperatures, cold performance testing was undertaken to observe any performance changes. The system was instrumented to enable the verification of the design constraints and power data acquired with temperature and time.

The cold room used for this testing was capable of operating at temperatures from 0°C down to −40°C. To reach a temperature above 0°C but below ambient air temperature (24°C), a small portable air conditioning unit was installed in the cold room, which allowed tests to be conducted at 15°C. Then the refrigeration system was started, and the tests were run at 0°C, −10°C, −20°C, −30°C, and −40°C. The temperatures inside the cold room were adjusted via a control screen on the outside of the chamber. Due to the temperature offset of the system, the selected temperatures for testing were spaced every 10 degrees. This was the smallest separation between tests that was possible based on the constraints of the refrigeration system.

3.3 Test procedure

The battery system performance was monitored during cold start at each temperature. For each temperature, the tests were repeated to confirm the system performance measurements. The tests were conducted in accordance with MIL-PRF-32565B. This military standard documents the requirements for performance of rechargeable lithium-ion 6T military batteries. The procedure created for this work was developed based on the requirements found in this document. However, there were some requirements the facilities at CRREL were not able to achieve, such as the desired temperature range. In the MIL-PRF-32565B specification, the required operating temperature range is −46°C to 71°C (MIL-PRF-32565B 2019), but the cold room used for this work could only operate within the temperature range of −40°C to 0°C.

The first step of testing is the initial charge of the ultracapacitor modules. To go from fully discharged to fully charged, it took approximately 23 minutes. The ESM was not charged while in the cold room due to availability of an appropriate power supply, and was instead charged at ambient room temperature (approximately 24°C). Once charged, the ESM was installed in the mechanical load system in the cold room via the positive and negative cables wired from the starter motor. The ESM was then left to cold soak to allow the module to reach the ambient temperature of the room. After verifying that the temperature sensor readings matched the ambient air temperature reading, testing was initiated.

The ultracapacitor ESM was tested through simulated cranking at one temperature three times per charge, or until failure. For each of the three tests at each temperature, the mechanical load system was run for approximately 3 seconds via a key switched wired to the starter motor. Three-second tests were chosen as the ultracapacitors did not retain enough voltage to run more than three, 3-second tests on one charge. This setup simulates a realistic cold start environment; if the engine doesn’t turn over, the ultracapacitor cannot be recharged.

Upon completion of the three tests at one temperature, the ESM was disconnected from the mechanical load system to be charged. After the ESM was charged it was then reinstalled back into the system, the ambient temperature of the room was decreased to the next increment, the device was cold soaked, and the device was tested again once the whole system reached the new ambient temperature.

The testing used two different ultracapacitor modules. This was done to shorten the time between the tests at each temperature to accommodate the entire test schedule. Both the modules were bought together and were new upon the start of testing.

This entire process was repeated, so that there would be two rounds of data collection, or a total of six tests per temperature (three tests per round of testing). This was done to evaluate if there was any permanent degradation of the performance of the ultracapacitor ESM when exposed to cold temperatures.

This established protocol for testing is intended to inform future work on evaluating the ability of a battery to cold start an engine in very low temperatures. The results from the tests are discussed in the following section of this report.

3.4 Data collection and analysis

There were several required measurements for data collection that needed to be obtained from testing. It was important to measure the torque on the load system to ensure the force of running the simulated engine was analogous to operating a real Stryker. This measurement was collected using a Futek rotary torque sensor mounted in-line with the rotating shaft of the load system. In addition to the torque, the speed of the flywheel needed to be accurate to that of a Stryker engine. A tachometer was mounted to the system, and was used to measure the revolutions per minute of the flywheel during testing. It was also important to monitor variations in voltage for both the ultracapacitor module and the starter motor. Two separate measurements were taken at the terminals of the ultracapacitor and the terminals of the starter motor. An additional measurement for current was taken in-line between the ultracapacitor module and the starter motor using a current shunt. Finally, three separate measurements of temperature were taken using thermocouples: one to measure the temperature of the ultracapacitor module, one to measure the temperature of the starter motor, and one to measure the ambient air temperature of the cold room. These were collected individually to monitor the variations in temperature of all the components to ensure that prior to testing, all of the components of the test stand were at the correct temperature after cold soaking in the cold room.

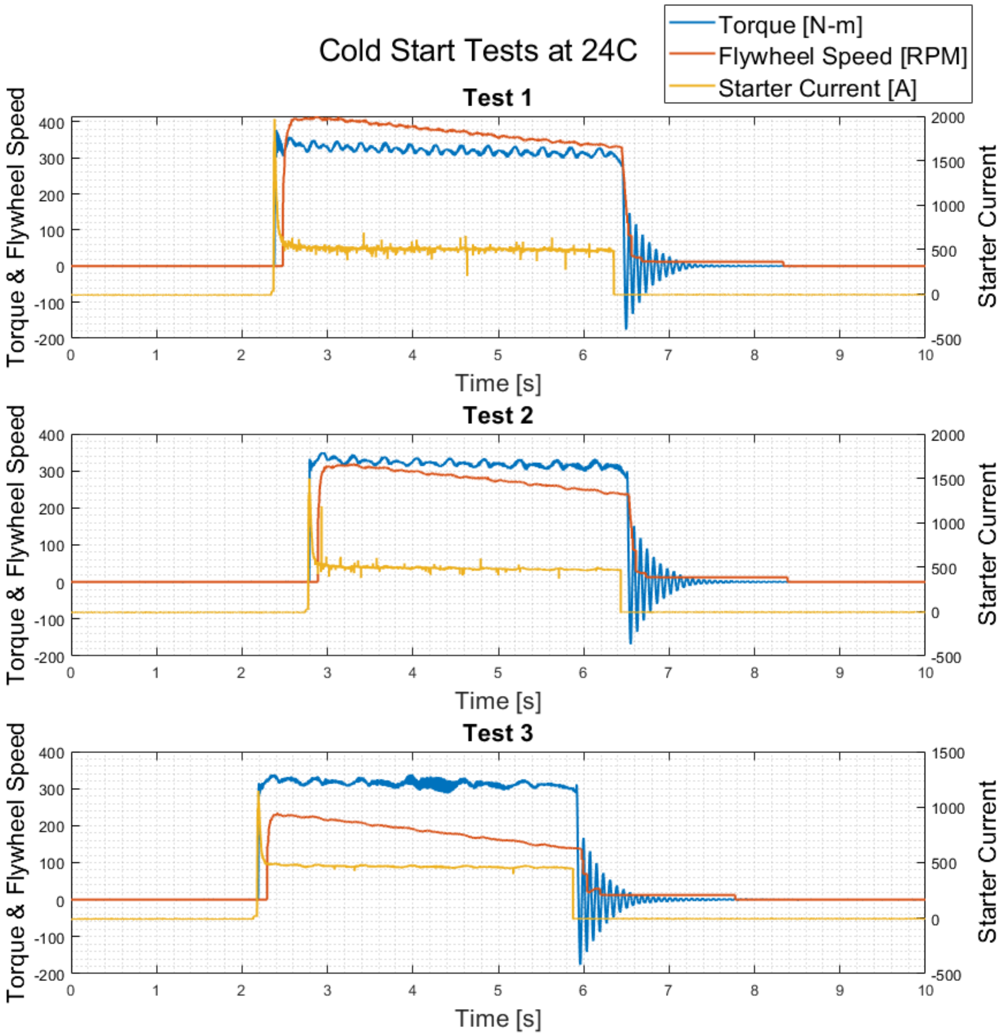
4 Results

Upon completion of the two rounds of three tests at each temperature (totaling six tests per temperature), the data were analyzed. The following sections discuss the resulting measurements for the torque of the system, speed of the flywheel, voltage at the ultracapacitor, voltage at the starter motor, and current at the starter motor for the first round of the three tests at 24°C, 0°C, −20°C, and −40°C as well as the measurements for the second round of the three tests at 0°C and −40°C.

4.1 Data at 24 °C

At a moderate temperature (approximately 24°C), the ultracapacitors were able to successfully start the mechanical load system for the three, 3-second tests without failure. The results from the three tests at 24°C are shown in Figure 8.

Figure 8. Measurements of torque, flywheel speed, and starter current from all three tests at 24°C.



The torque of the system in Figure 8 (shown in blue) is relatively consistent between the three tests, maintaining an average of about 325 N·m during the test, which was the torque value the brake was set to. However, the speed of the flywheel decreases as the second and third tests are run. The revolutions per minute (RPM) peak at around 400 RPM for the first test, but only reach around 225 RPM by the third test (shown in red). This is due to a decrease in the voltage of the ultracapacitor after each test; each test drops the voltage of the ultracapacitor by approximately 5V as shown in Figure 9.

Figure 9. Voltages of ultracapacitor for all three tests at 24°C.

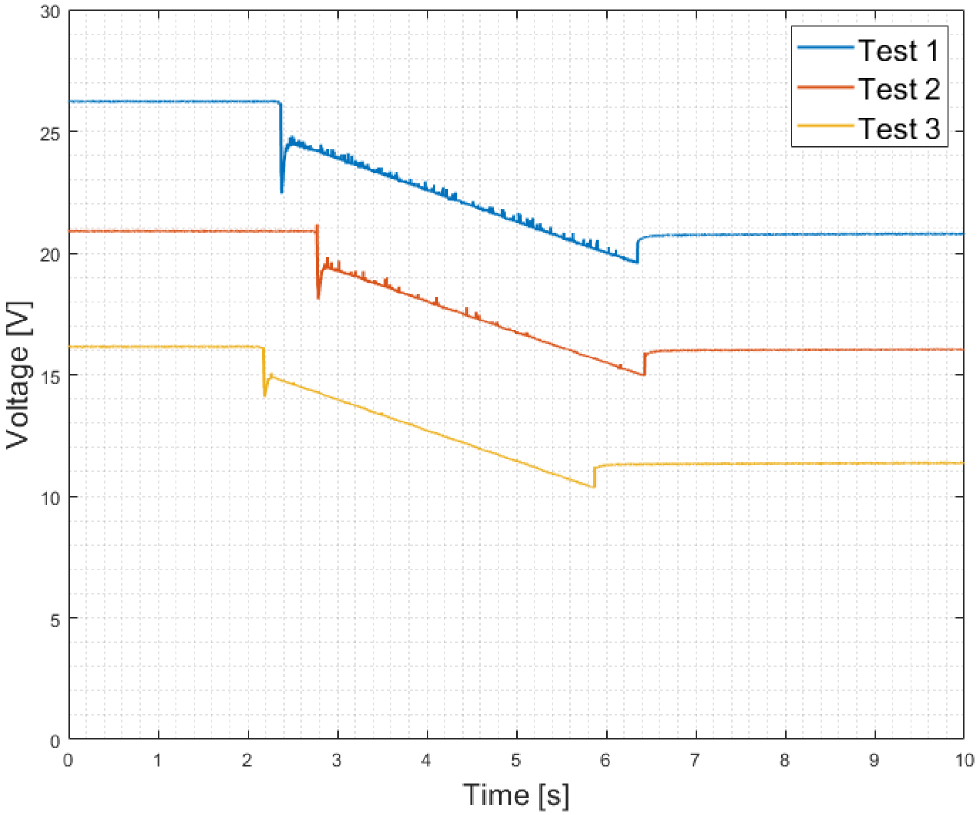


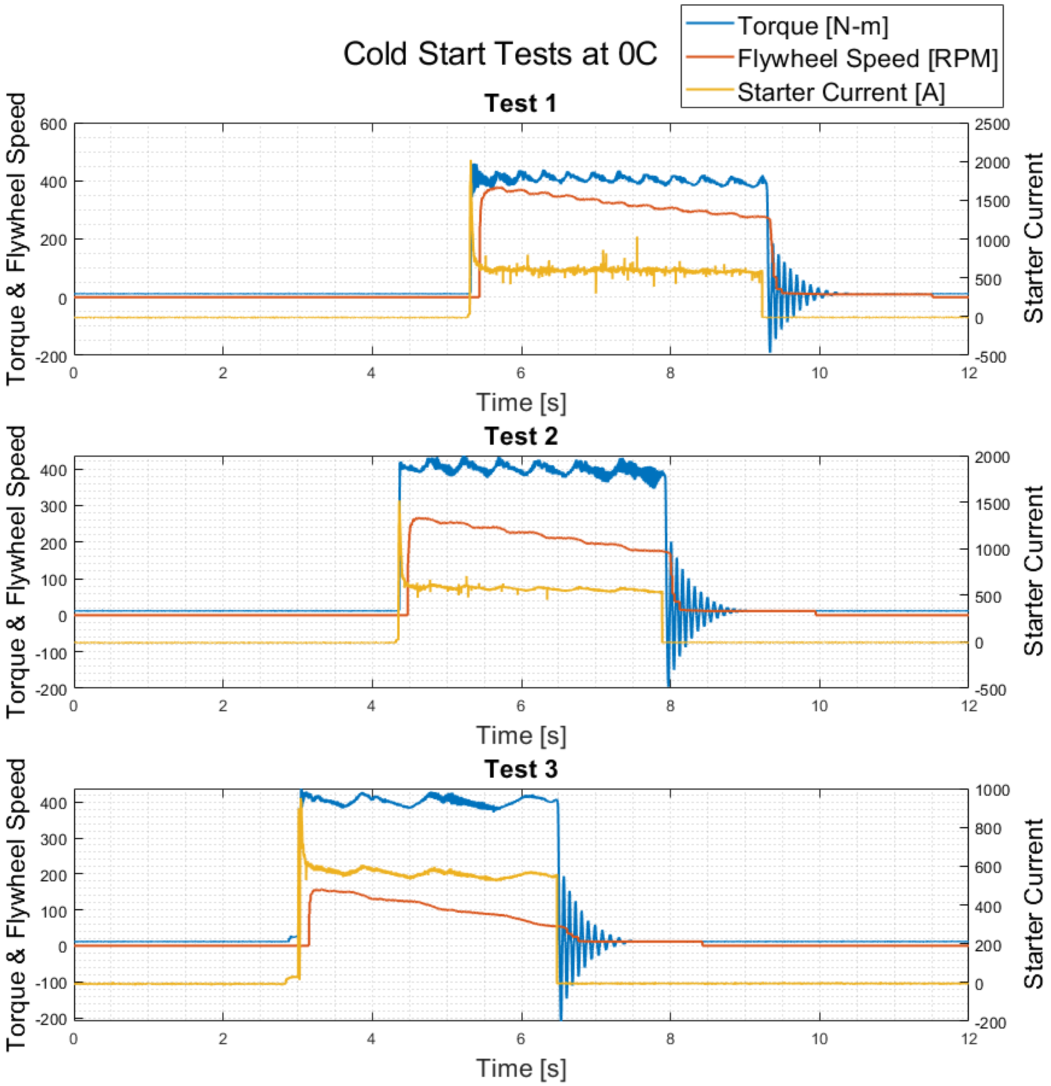
Figure 9 shows that the voltage of the ultracapacitor decreases linearly over the course of each 3-second test by about 1.25V/s. With an initial capacity of 26.2V and a final capacity of 11.4V, the total voltage of the ultracapacitor drops by 14.8V after running the all three tests at 24°C.

These tests at 24°C act as a baseline to compare how the cold impacts performance of the ultracapacitor. Changing parameters indicate that the ESM is affected by cold environments to some extent.

4.2 Data at 0°C

In comparison to the tests at 24°C, the tests run at 0°C begin to show the effects of temperature on the performance of the system. While the three 3-second tests were still able to be achieved, several differences between the tests at 0°C and the tests at 24°C are noticeable. The three tests at 0°C are shown in Figure 10.

Figure 10. Measurements of torque, flywheel speed, and starter current from all three tests at 0°C.



In Figure 10, the differences between the tests conducted at 0°C can be seen when compared to the 24°C tests. First, the torque at 0°C averages at about 400 N·m, compared to the 325 N·m average of the 24°C tests. This can be attributed to the effects of the cold on the mechanical load system itself. Similar to a real engine, the components of the load system, such as the bearings, brake, and starter motor, are all affected by temperature to some extent. Whether it is the grease in the bearing or the oil in the starter beginning to freeze up, or the brake being more rigid and applying more torque, the load system simulates real-world issues seen in large diesel engines in the cold. Another difference is the speed of the flywheel in the 0°C tests. The flywheel only reaches a peak of about 375 RPM on the first 0°C test compared to 400 RPM at the first 24°C test, and 150 RPM on the third 0°C test, which is a difference of almost 100 RPM from the third test at 24°C of 200 RPM.

This difference between the 0°C tests and the 24°C tests is clearly seen when comparing the voltages of the three 0°C tests to each other, as shown in Figure 11.

Figure 11. Voltages of ultracapacitor for all three tests at 0°C.

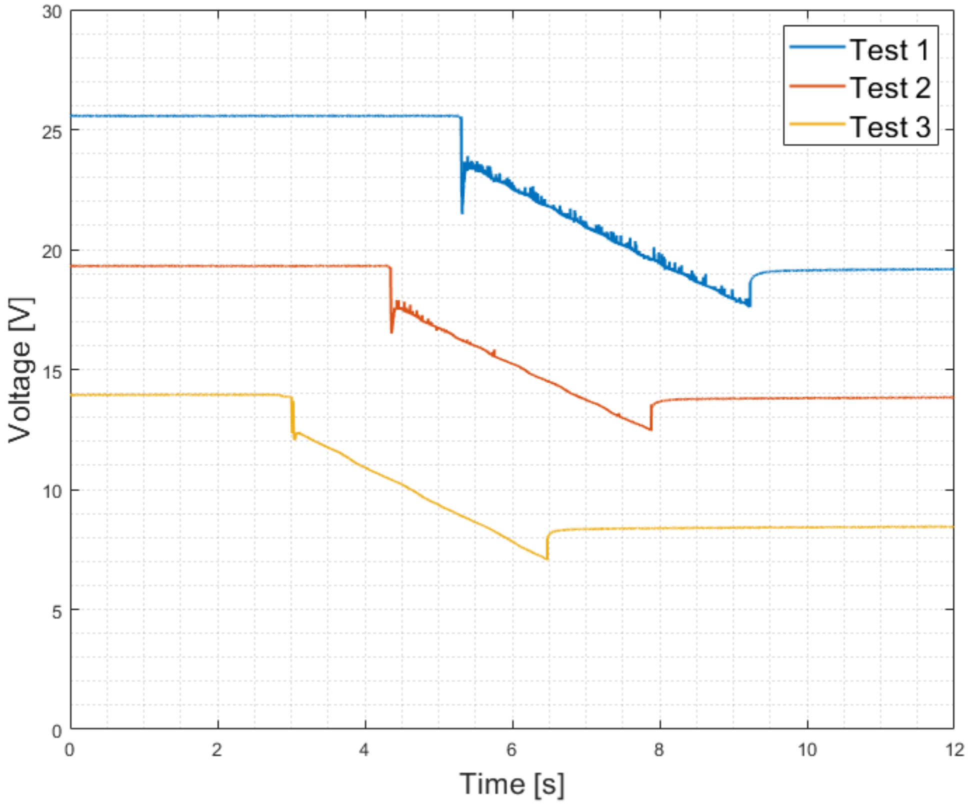
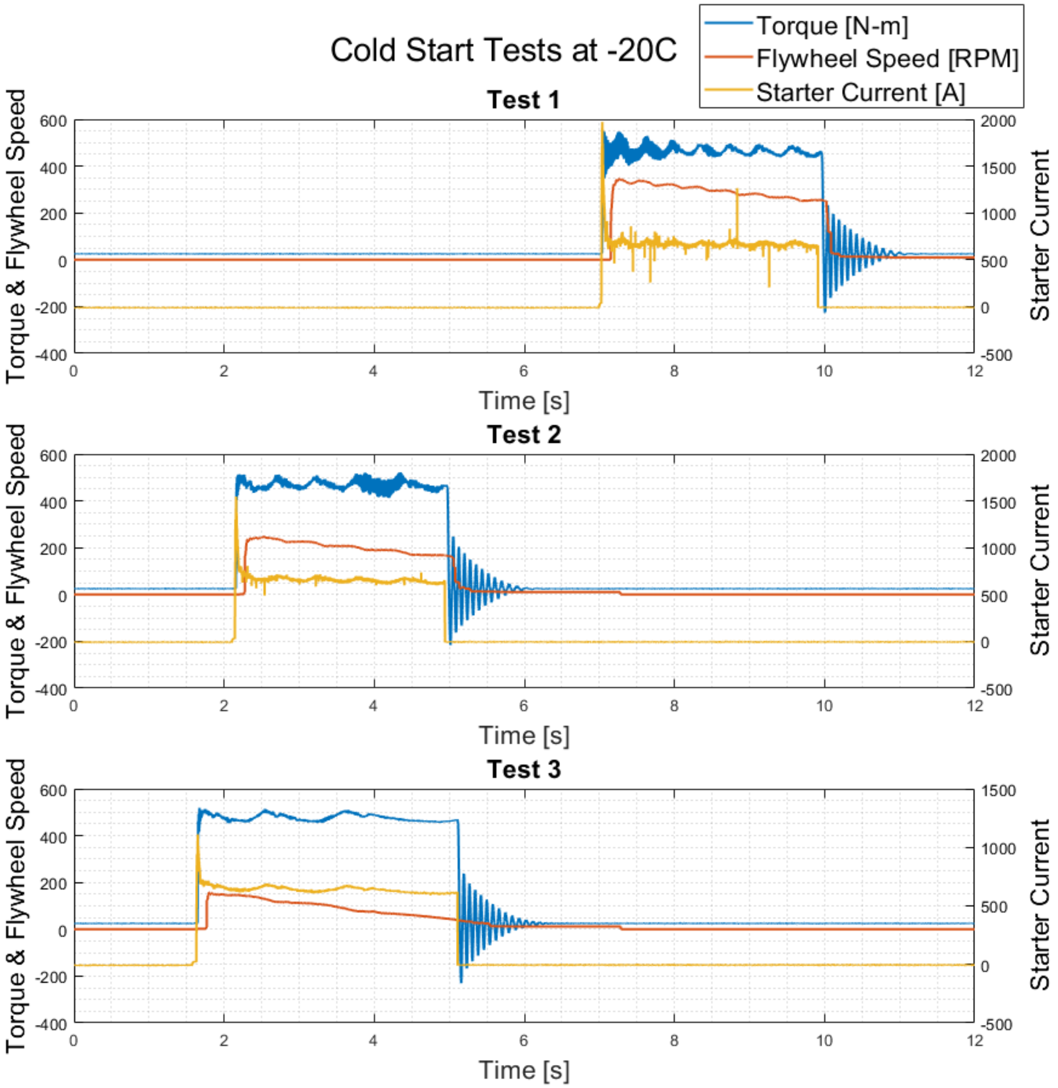


Figure 11 shows that the differences between the voltages of the 3 tests at 0°C (6V) are greater than the differences between the three voltages at 24°C (5V). The voltage of the ultracapacitor decreases linearly over the course of each 3-second test, by about 1.50V/s. With an initial capacity of 25.6V and a final capacity of 8.4V, the total voltage of the ultracapacitor drops by 17.2V after running the three tests at 0°C, which is a difference of 2.4V more voltage used than the 24°C tests. This shows that it takes more energy to run all three tests at a 0°C than at 24°C.

4.3 Data at −20°C

Again, as the temperature is decreased, the effects of the cold are visible in the measurements collected during testing. The same trends in the data in the 0°C tests can be seen in the −20°C tests; these are illustrated in Figure 12.

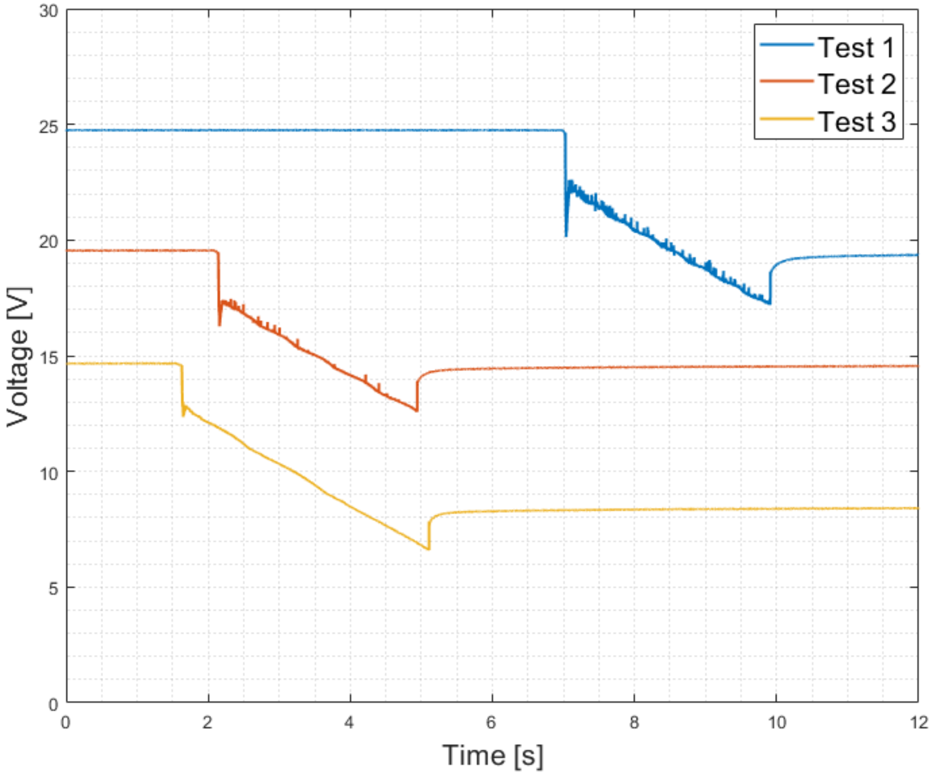
Figure 12. Measurements of torque, flywheel speed, and starter current from all three tests at −20°C.



While the tests at −20°C are similar to the 0°C tests, the most notable difference is the torque. Again, as the load system is impacted by the cold, the components yield a higher torque value. For tests at −20°C, the torque averaged 475 N·m, compared to 400 N·m at 0°C and 375 N·m at 24°C. Another difference between the temperature tests is the speed of the flywheel. At the end of the third 24°C test, the speed was 125 RPM; for the third 0°C test the speed was 50 RPM, and at the end of the third −20°C test, the flywheel was barely moving (<25 RPM).

The differences in the voltages of the −20°C tests and the 0°C tests are relatively small. Figure 13 shows a similar trend for the three −20°C tests.

Figure 13. Voltages of ultracapacitor for all three tests at −20°C.

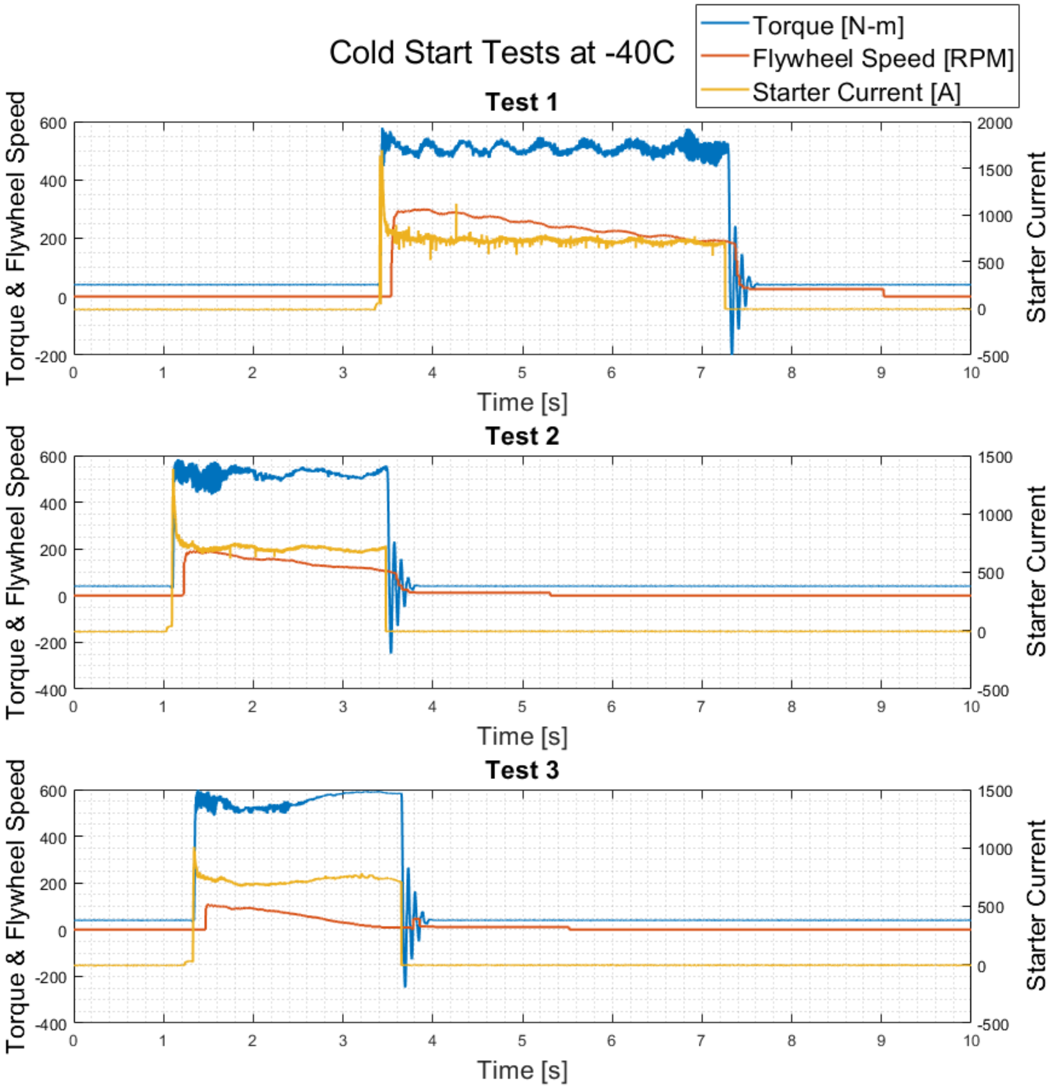


In Figure 13, the voltage differences between the three tests at −20°C are similar to the voltage differences at 0°C, which is approximately 6V. The voltage of the ultracapacitor decreases linearly over the course of each 3-second test, by about 2V/s. With an initial capacity of 24.7V and a final capacity of 8.39V, the total voltage of the ultracapacitor drops by 16.3V after running the three tests at 0°C, which is similar to the 0°C tests and with approximately 1.5V more voltage used than the 24°C tests.

4.4 Data at −40°C

Similar to the 0°C and −20°C tests, the −40°C tests continue to show the effects of temperature on the performance of the system. However, while the three tests were able to be completed at −20°C, during the third and final test at −40°C the system failed to complete the entire 3-second test. After approximately 3 seconds the ultracapacitor did not retain enough voltage and failed to continue running the system. This can be seen below in Figure 14.

Figure 14. Measurements of torque, flywheel speed, and starter current from all three tests at −40 °C.

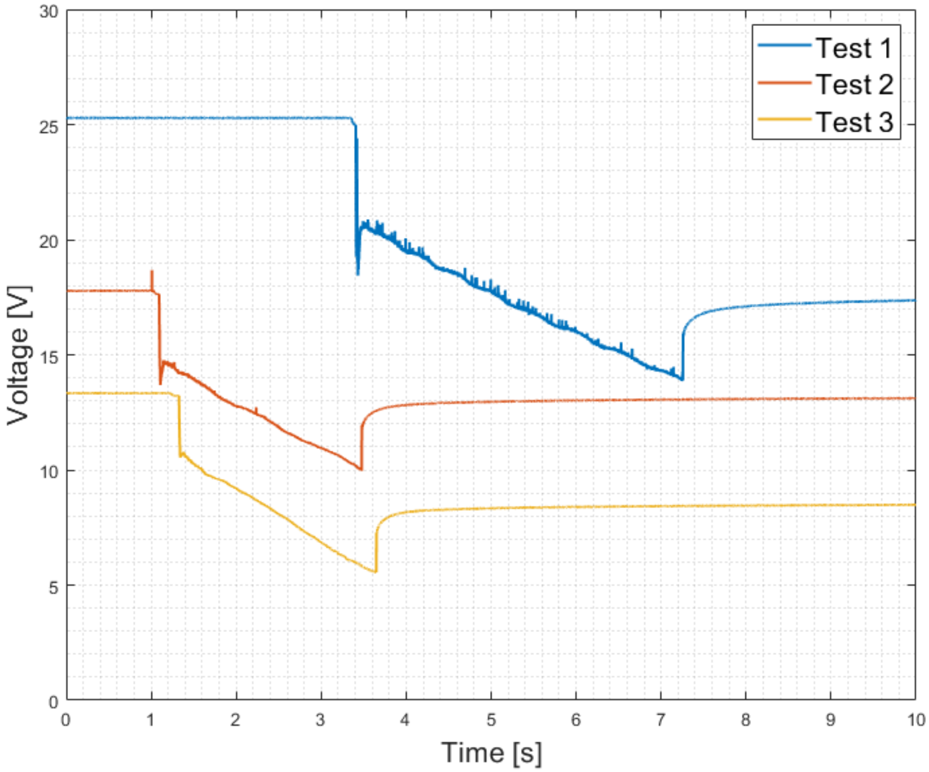


While Figure 14 shows the results from the tests at −40°C are similar to the results from the −20°C tests, the torque is different. Since the load system continues to be impacted by the cold, the components yield an even higher torque value. For tests at −40°C, the torque averaged 525 N·m, compared to 475 N·m at −20°C, 400 N·m at 0°C, and 375 N·m at 24°C. Again, there is a difference between the speeds of the flywheel for the −40°C tests compared to the other temperatures. At the end of the third 24°C test, the speed was 125 RPM; for the third 0°C test the speed was 50 RPM, for the third −20°C test the flywheel was less than 25 RPM, and for the third test at −40°C the flywheel stopped spinning after approximately 3 seconds. Additionally, while the speed of the flywheel between each test at −40°C decreases like it does in the other temperature tests, the speed at

−40°C does not reach the same magnitude as at the other temperature tests. The first test at −40°C reaches a peak of 300 RPM, compared to 325 RPM at −20°C, 375 RPM at 0°C, and 400 RPM at 24°C for the first tests.

The differences in the voltages of the −40°C tests and the −20°C and 0°C tests are relatively small. Figure 15 shows a similar trend for the voltages of the three −40°C tests.

Figure 15. Voltages of ultracapacitor for all three tests at −40°C.



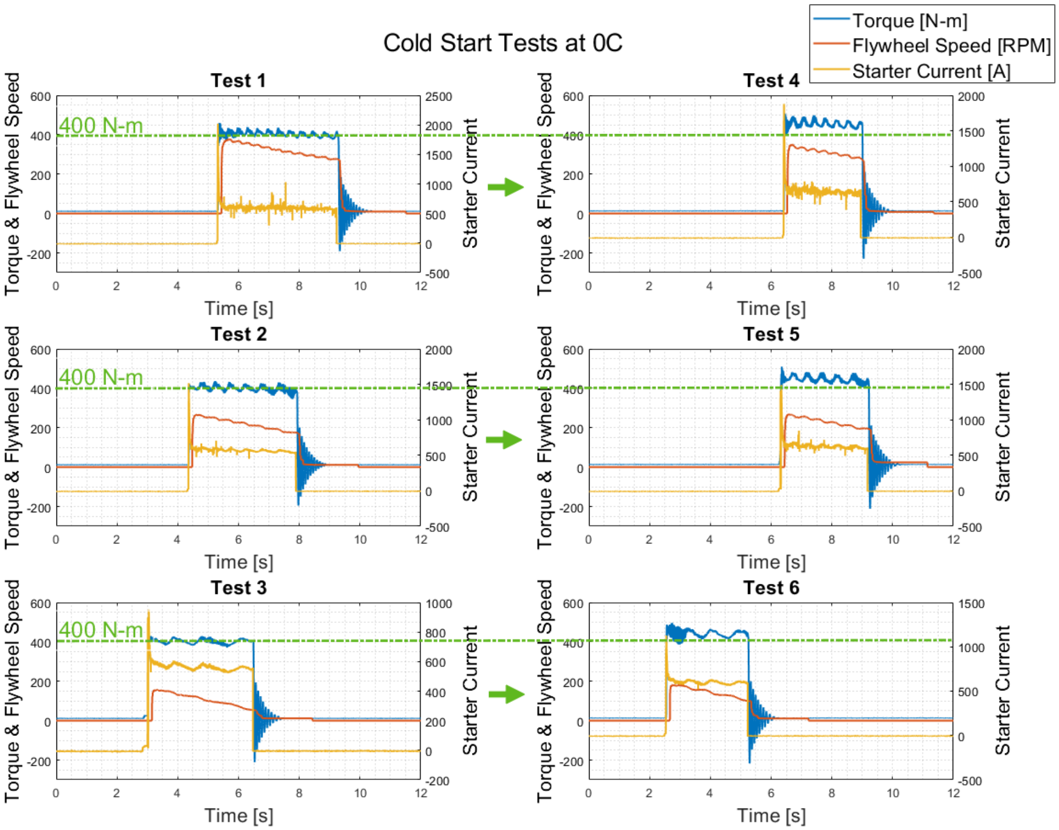
In Figure 15, there is, however, a larger disparity between the voltages of the first and second tests at −40°C. Figure 15 shows that there is a 7.5 V difference between the first two tests and only a 4.5 V difference between the second and third tests. Again, the voltage of the ultracapacitor decreases linearly over the course of each test, by about 1.5 V/s. With an initial capacity of 25.3 V and a final capacity of 8.47 V, the total voltage of the ultracapacitor drops by 16.8 V after running the three tests at −40°C, which is similar to the −20°C and 0°C tests and approximately 2 V more voltage used than the 24°C tests. This is significant because it shows that it is taking more energy for the ultracapacitor to run the load system at very cold temperatures. This means that as the temperature decreases, it becomes more difficult to turn over the load system, which is similar to what a real engine would experience. The large engine components are resisting motion as they get colder, thus requiring more energy to engage the system. So, while the total voltage used by the ultracapacitor is similar for the −40°C, −20°C, and 0°C, the tests at −40°C show that it requires more voltage to run the first test, so that by the time it gets to the third test, the ultracapacitor does not retain enough voltage to complete the third full, 3-second test.

4.5 Deterioration Investigation

In order to determine if there was any permanent deterioration of the performance of the ultracapacitor due to exposure to cold temperatures, an additional three sets of tests were done at each temperature. The purpose of the second round of tests at each temperature was to investigate if the cold temperatures had any permanent effect on the ability of the ultracapacitor ESM to run the simulated load system. If any degradation was noticed between the first and second round of testing, then it is possible the ESM was permanently impacted by the cold.

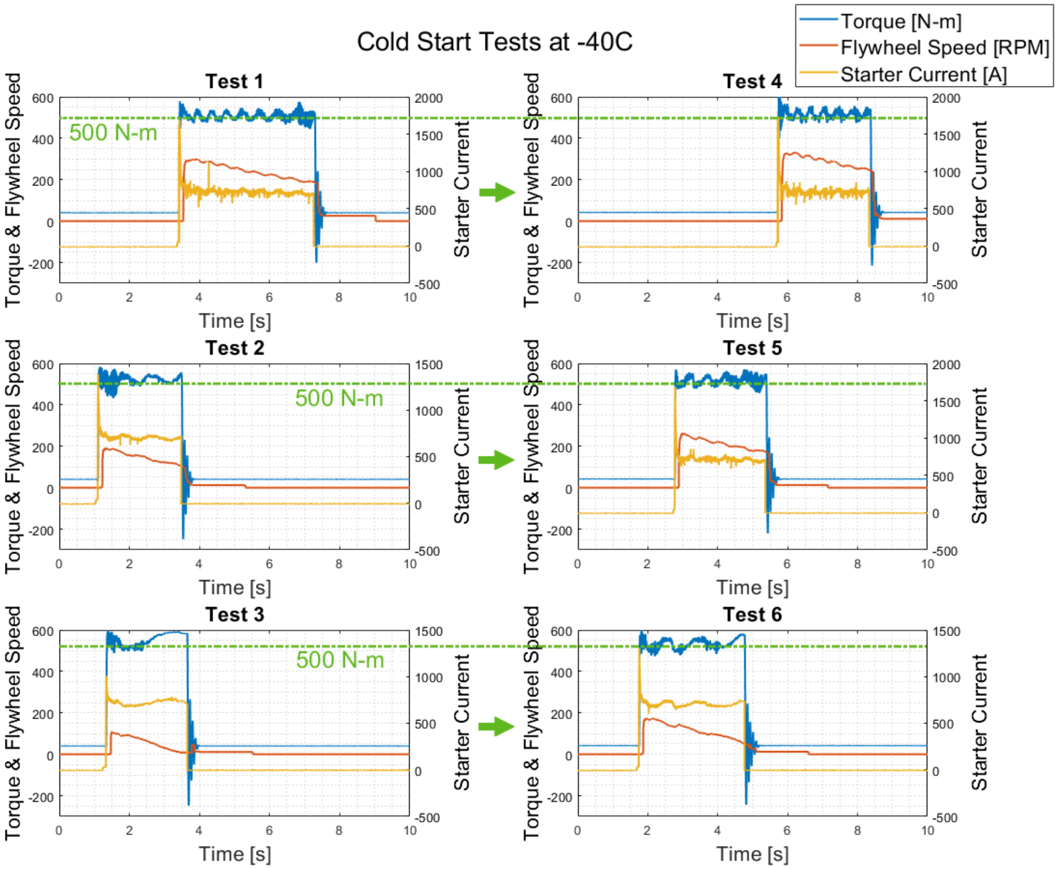
The same patterns in the data as before were noticed in the second round of testing. Looking at the second set of tests at 0°C, Figure 16 shows the same trends between the first three tests and the three repeated tests at 0°C.

Figure 16. Measurements of torque, flywheel speed, and starter current from all tests at 0 °C.



The measurements for both current and flywheel speed appear to be relatively consistent between the original and the repeated tests at 0°C. The flywheel speed for both of the first tests (tests 1 and 4) peak at approximately 450 RPM, 250 RPM for both the second tests (tests 2 and 5), and 150 RPM for both the third tests (tests 3 and 6). While the current and flywheel speed in all tests at 0°C show the same trends, the torque values are slightly different. The torque values in the 0°C repeated tests are on average 50 N·m higher than the first set of 0°C tests, indicated by the green dashed line, which is at 400 N·m. However, this trend appears to be true only for the warmer temperature range (24°C–0°C). The tests at −30°C and −40°C have similar torque values between the original and repeated tests. Figure 17 shows the repeated and original tests for all tests at −40°C.

Figure 17. Measurements of torque, flywheel speed, and starter current from all tests at −40°C.



The torque values in the −40°C repeated tests are, on average, approximately the same as the original −40°C tests indicated by the green dashed line at 500 N·m. Again, the current and flywheel speed measurements for the original and repeated tests are approximately the same, similar to the results at 0°C tests. The flywheel speed for both of the first tests (tests 1 and 4) peak at approximately 300 RPM, 200 RPM for both the second tests (tests 2 and 5) and 100 RPM for both the third tests (tests 3 and 6).

4.6 Discussion

Upon completion of the testing, it was determined that the performance of the ultracapacitor was not significantly affected by temperature. However, there was some small impact in the voltage used to run the three tests at each temperature. While the three tests were able to be completed at −20°C, during the third and final test at −40°C the system failed to complete the entire 3-second test. After approximately 2 seconds the ultracapacitor did not retain enough voltage and failed to continue running the system. However, this result is likely due to the increased torque of the load system due to the cold temperatures and not due to the degradation of the ultracapacitor's performance.

There also was a slight difference between the torque measurements for the repeated warmer temperatures and the original tests. The cause for the slight difference is unclear. It does not appear to be related to the performance of the ultracapacitor, as the measurements of all parameters at all temperatures are similar with the exception of the torque for those tests. It is possible that the tension of the brake on the mechanical load system was affected by the cold temperatures and was not readjusted prior to the repeated tests. Since it is a mechanical brake and not a hydraulic brake, it may not have been applying consistent pressure after the lower temperature range of the first set of testing. Perhaps the brake pads were stuck at a higher torque setting after the first set of testing due to mechanical parts freezing in place and the system was not properly recalibrated before the second set of testing. Due to the minimal difference between the original and repeated values, it was assumed that the issue was not the ultracapacitor. In order to verify that the performance of the ultracapacitor was not significantly affected by temperature, the degradation of the brake would need to be further investigated.

5 Conclusions

Cold starting large military vehicles in cold environments is an ongoing challenge. The majority of the problem can be resolved with innovated battery technology solutions used to start the diesel engine. This work focused on understanding vehicle cold start challenges of Stryker Combat Vehicles by investigating the performance of a 24 V Maxwell ultracapacitor engine start module when exposed to cold conditions. Using a simulated mechanical load system, the ultracapacitor was evaluated across a series of temperatures ranging from 24°C to −40°C.

The results obtained from these tests show that, while the ultracapacitor ESM was able to operate across the set temperature range, there were noticeable effects on the system due to the cold temperatures. The ESM proved capable of turning over a simulated engine all the way down to −40°C, but the usable capacity of the module was limited as the temperature decreased. It was also discovered that the simulated load system was impacted by the cold as well, similar to what a real engine system would experience. Finally, it was learned that modifications to the brake of the load system may be needed for any future investigations.

Based on the information gained from this work, the next steps in investigating cold-capable start technology would be to characterize next-generation lithium-ion battery technology. The batteries would have the same operational temperature range but increase the overall storage capacity of the vehicle. The goal of the next phase of this work would be to evaluate the batteries using the load simulation for the same temperature range to identify any improvements in performance from the baseline data of the ultracapacitor ESM.

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Acronyms and Abbreviations

CRREL	Cold Regions Research and Engineering Laboratory
DAQ	data acquisition system
DoD	U.S. Department of Defense
ERDC	Engineer Research and Development Center
ESM	engine start module
MIL	Military Specification
MILES	Multiple Integrated Laster Engagement System
RDTE	Research, Development, Test, and Evaluation
RPM	revolutions per minute
VCU	vehicle control unit

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14. ABSTRACT

Reliable vehicle start is necessary to support mission success, especially for response time. At Department of Defense installations in cold regions, vehicles using rechargeable battery and starter technologies have significant issues starting in the cold. Ultracapacitor engine start modules (ESMs) are an alternate technology to rechargeable lead-acid or lithium-ion batteries. The project develops a performance baseline for the ESM used in the M1126 Stryker Combat Vehicle under cold conditions. To test the performance of the ESMs in a cold room, a mechanical load system was constructed to replicate the load of starting a Stryker engine and instrumented with sensors to monitor parameters such as voltage, torque, and temperature. The ESMs were tested with the load system at temperatures from 24°C to −40°C. The results of the tests showed that there was some degradation of the ultracapacitor's performance at the colder temperatures, which was expected, but no permanent damage. This work provides a test protocol and capability to evaluate next-generation vehicle battery systems for cold regions applications. Additionally, the ESM cold performance data establish a baseline to compare next-generation vehicle battery storage systems and to support cold regions missions and identify potential performance requirements for future vehicle battery system acquisition.

15. SUBJECT TERMS

Cold Regions--Vehicles, Military; Stryker armored vehicle; Cold start (internal combustion engines); Supercapacitors; Vehicles, Military--Batteries--Evaluation

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