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Selection of the Cell and Cooling Method for the Next Generation Combat Vehicle Common Battery

Philip Stone, PhD[1]**; Santiago Lentijo, PhD**[1]**; Tony Thampan, PhD**[2]**; David Wilson**[1]

[1] UEC Electronics, Charleston, SC
[2] U.S. Army Combat Capabilities Development Command, Ground Vehicle Systems Center, Detroit, MI

ABSTRACT

In support of the Army's Next Generation Combat Vehicle the Ground Vehicle Systems Center (GVSC) and UEC Electronics have been evaluating current technologies to develop and demonstrate the feasibility of a High Voltage Common Module (HVCM). In this paper the authors describe the process used to select the optimal cells, as well as a comparison of the different cooling options for the battery module.

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1. Introduction

The global electricity demand is expected to keep increasing in the following years and the transportation sector is not an exception [1]. The need for additional electrical power on combat vehicles is not a new concept. Starting with standard automotive loads and communications systems to now full electric drivetrains, active protection systems, directed energy weapons, tactical networking, surveillance, and other technologies that increase the platform capabilities [2,3].

Electric military vehicles are part of President Biden's climate agenda, supported by Deputy Defense Secretary Kathleen Hicks. The Deputy Defense Secretary emphasized the military utility of electric vehicles - they are quiet, have a low heat signature, incredible torque, and because they tend to be low maintenance with fewer moving parts, they have the potential to reduce logistics requirements [4]. Additionally, the necessity of more electrical power is part of the "Army's Modernization Strategy" [5], where increased electrical power is a key enabling factor with a specific focus on the Next Generation Combat Vehicle (NGCV).

The main objectives for the NGCV relevant to the generation and use of electrical power are [6]:

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1. Increase fuel efficiency and thus operational range.
2. Allow operations in electric-only silent watch and silent mobility modes.
3. Provide battery backup, so crews can operate vehicle systems without the engine.
4. Reduce reliance on consumable fuels, simplifying the supply chain.
5. Improve component and system reliability, lowering impact on maintenance.
6. Enable situational power generation for off-vehicle applications, to power up tactical operations centers.

In support of the NGCV [2], GVSC is leading a Platform Electrification and Mobility (PEM) program [7], summarized in Figure 1. This program develops, integrates, and tests essential electrification (hybrid electric) technologies. As part of PEM, UEC with the support of GVSC has been evaluating current technologies to develop and demonstrate the feasibility of a High Voltage Common Module (HVCM).

This HVCM project is focused on developing a modular high voltage battery system based on lithium-ion (Li-ion) battery technology.

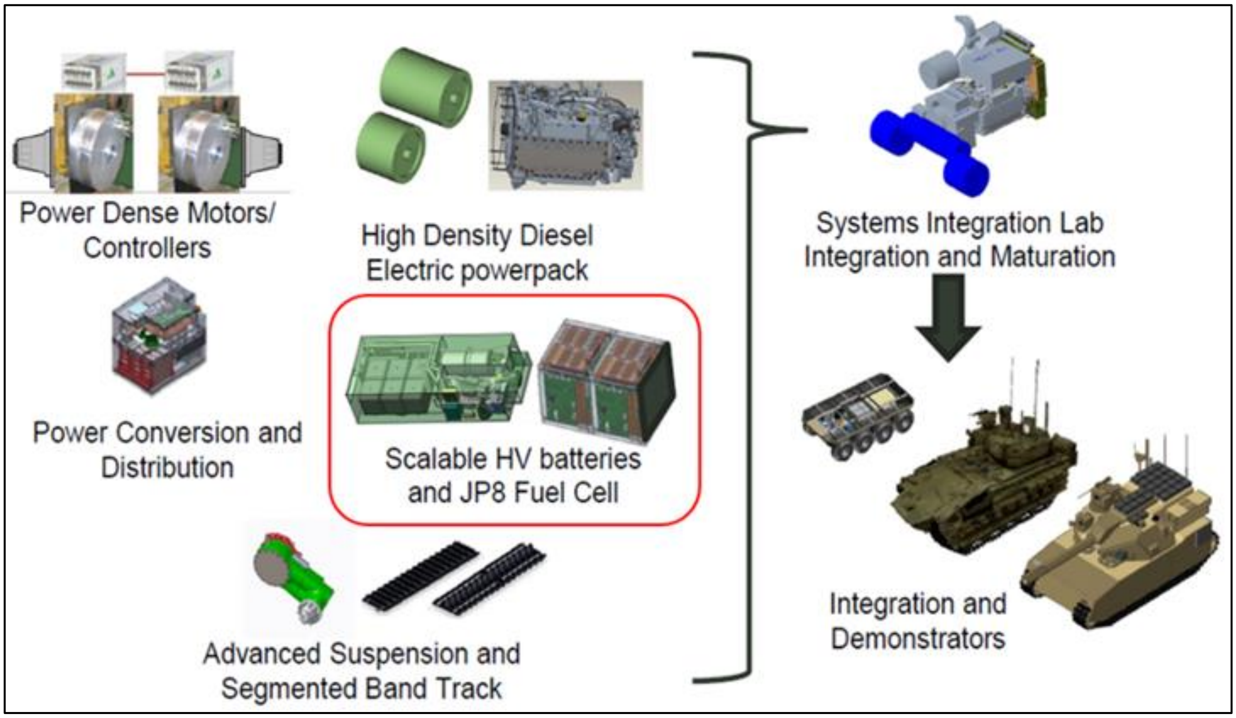

Figure 1. Platform Electrification and Mobility (PEM) program.

2. High Voltage Common Module

The High Voltage Common Module (HVCM) will function as a common building block module for high voltage battery packs in combat and tactical vehicle platforms. The HVCM is being designed with the following advantages:

- **Modularity**: Higher voltage, power, and energy per modular building block to balance scalability for different platforms with a lesser number of parts
- **Liquid-cooling**: Thermally capable of high, repeated pulse power demands with substantial base load
- **Safety**: Designed to mitigate the risks of utilizing high energy batteries, specifically effects of cell-level thermal

runaway and prevent propagation to the rest of the module and pack

- **High-Density**: State of the art cell and cooling technology to maximize power and energy density
- **Scalable**: Series and parallel connectable for a wide variety of applications and vehicle families
- **Standardized**:
  - Size and interface will be common over wide range of voltage and power
  - Similar form factor as the military 6T to enable some backwards compatibility
- **Extreme conditions**:
  - Operating temperatures: -46°C to 71°C
  - Meet military standards for EMI, fire, altitude, salt fog, sand, and dust
  - Nuclear event detection and limp-home capabilities

The HVCM (shown in Figure 2(a)) is a 50 VDC Li-ion rechargeable battery equipped with a smart cell supervisory circuit (CSC). The CSC senses voltage, current, and temperature, balances cells, and communicates with the supervisory Battery Management System (BMS). The module is liquid-cooled and can be connected in series and / or parallel to support high-voltage and high-power applications. The general HVCM specifications are shown in Table 1.

Table 1. HVCM General Specification.

General Specification	
Voltage	50 V nominal
Capacity	3.4 kWh
Continuous Current	134 A
Peak Discharge Current	715 A for 10 sec
Weight	30 kg
Dimensions (L x W x H)	290 x 290 x 230mm

An HVCM-based pack (shown in Figure 2(b)) contains an arrangement of series and/or parallel HVCM's, a supervisory BMS, power and communications connectors interfacing to the end use application, a cooling manifold, and mechanical shock absorbers.

(a) (b)

Figure 2. HVCM (a) single module - (b) 450 VDC pack

3. Cell Selection

An evaluation of the current Hybrid Electric Vehicle (HEV) and Electric Vehicle (EV) market revealed latest cell development trends and the most promising options for consideration.

3.1. Down Selection to 3 Candidates

As part of the process to select a cell, the search was narrowed to cells in a common cylindrical form factor. Cylindrical cells were typically lower in cost, allowing a larger budget for the prevention of thermal runaway propagation and active cooling. Because cylindrical cells come in common sizes from multiple vendors, there are supply chain advantages and lower risk that the design may be outdated by the time future production builds are a reality.

The search was then narrowed to the cylindrical cells that were produced by manufacturers with availability and quantity to match project timelines and future growth. The developers included Samsung, Panasonic, Molicel, LG, K2, PLB, Goldencell, and Kokam. From these manufacturers the following cell sizes were considered: 18650, 21700, and 26650 cells. Most of the cell chemistries in consideration were lithium nickel cobalt aluminum oxide (NCA) or lithium nickel manganese cobalt oxide (NMC) due to their high energy density or lithium iron phosphate (LiFePO4) for its combination of high energy density and relatively high safety.

A matrix of the potential candidates was compiled to simplify the comparison process. During the evaluation twenty-four potential cells were identified that would meet the energy, volume, and weight targets for combat vehicle applications. The matrix was developed from the manufacturer's data sheet specifications. From the cell characteristics, the following may be estimated: the number of series cells that would be required for the HVCM voltage, the minimum number of parallel cells to provide the required HVCM capacity and peak power, the minimum HVCM weight, and the minimum HVCM volume.

A weighting scale based on requirements was developed for comparing the characteristics. It was determined that the specific power density of the battery would have a weight of 3; the specific energy density would have a weight of 4; and the volumetric energy density would have a weight of 5. The cells were assigned a ranking value of 1-24 for each of the three characteristics with 24 being the best when compared to the other candidates. The ranking value was multiplied by the weighting factor and added to the results of the other two characteristics to come up with a total rating in which the highest value is best.

Using this weighting method, cells based on the LiFePO4 chemistry were eliminated. The top ten cell candidates as well their properties are shown in Table 2.

Evaluating the results from a slightly different perspective, a cell pack typical of what might be used for the HVCM was designed for each cell size. The configuration was developed to meet the minimum capacity requirements and provide an approximately equal volume for the various cell sizes. The 18650 cells were configured in a 14x29 configuration and the 21700 in a 14x20 configuration. These packs were compared by capacity and peak capacity with capacity having a weight of 4 and peak capacity a weight of 2. The results are shown below in Table 3.

From the list in Table 3, the top 3 that were readily available were selected for further evaluation and are highlighted in the table: Samsung INR21700-50E2, Molicel INR21700-M50A, and Molicel INR21700-P42A. A comparison of the critical elements from the datasheets of these 21700 cells is provided in Table 4.

3.2. Final Candidate Selection

A primary requirement for the HVCM is to be capable of providing 25 kW pulses of power at a relatively high frequency. Doing so requires active cooling and a cell that performs well under such loads. To determine the optimal cell for the HVCM application, a hybrid peak power capability test was performed on each cell based on the peak power capability test from SAE Standard J1798 Recommended Practice for Performance Rating of Electric Vehicle Battery Modules.

The peak power test data provides an indication of the cell capabilities under pulse load conditions and provides some insight into the battery scaling factor that must be applied to achieve the HVCM performance goals. The measured peak power under discharge and charge conditions for the three cell candidates is shown in Figure 3 and Figure 4, respectively. The data shows that although the Molicel P42A has a lower capacity than the other two candidates, it performs better under this scenario which is critical for the HVCM application.

The preferred cell for the HVCM application is the Molicel P42A. This decision is based on the wider operating temperature range, the cell weight, and the peak power performance which drives the number of parallel cells needed for an HVCM.

Further, the Samsung 50E2 and Molicel M50A cells do not function at 0.5C discharge at -40°C. This could become a serious problem in applications where the battery is required for pre-heating the cells at cold temperatures. While the total cell weight contribution to an HVCM for the Molicel M50A was below the 30 kg threshold, it did not leave sufficient margin for the thermal management system and structural components. Lastly, the packaging concept for the cells becomes complex when more than 18 parallel cells are required. A 14x17 cell pack fits comfortably within the physical HVCM footprint. A larger cell configuration might prove difficult to package.

4. Thermal Management Approach

4.1. Fundamental Requirements

In the development of a thermal management solution, an analysis of alternatives of available options is necessary. The analysis includes examination of prior research, thermal modeling, and laboratory testing of the most promising solutions. Before this can be undertaken it is necessary to choose a cell package, estimate the amount of heat that would need to be removed from the module, consider the operating temperature constraints, and estimate the available weight and volume margin for the thermal management system.

The HVCM needs to be limited in size to 230mm (H) by 290mm by 290mm. As the volume of the heat exchanger grows, the number of cells must be decreased to maintain the battery profile, which in turn reduces the battery capacity and increases the necessary current per cell. The maximum weight of the HVCM is 30 kg. Likewise, as the weight of the heat exchanger grows, the number of cells must be adjusted to meet the weight requirements.

4.2. Thermal Management Options

An examination of recent literature indicated five possible approaches to thermal management: air cooling, indirect liquid cooling (axial or radial tube cooling), direct liquid cooling (immersion cooling), and phase change material (PCM). Each of these are evaluated for this application.

4.2.1 Air Cooling

The HVCM is primarily used in mobile applications, so it is necessary to remove excess heat with forced air or a liquid heat exchanger through the vehicle cooling system. The battery system is packaged in a sealed enclosure which is itself packaged inside a second sealed battery compartment. The only replaceable coolant is ethylene glycol water mixture with a maximum steady state temperature of 50°C. Air cooling could only potentially be performed as a combined air/liquid cooling system by forcing air over the surface of the cells, then cooling the air with a liquid-cooled heatsink or a sealed refrigeration system. This approach, although feasible, is expected to have poor cooling power and uneven thermal distribution.

4.2.2 Indirect Liquid Cooling

Indirect liquid cooling encompasses a variety of solutions for removing heat from the cells. Axial cooling can be performed by locating a cold plate to the top or bottom surface of the cells. Radial cooling can be performed by either applying coolant-filled tubes to the sides of the cell or by inserting a thermally conductive material on the side of the cells that is attached to a cold plate above or below the cell array.

For a cylindrical cell, experimental measurements in literature indicate that radial thermal conductivity in the cell is about two orders of magnitude lower than axial thermal conductivity due to the construction of the cell [8]. Based on this, axial cooling was examined first.

In experiments in which cold plates were attached to cells in each orientation it was found that axial cooling did not perform as well as radial cooling. The factors that reduced the performance of the axial cooling were:

1. The limited surface area of the endcaps for connecting to the cold plate.
2. The necessity for electrical connections and electrical insulation between the cell contacts and the cold plate.
3. Reduced thermal conductivity between the positive endcap and the battery core.

In lab testing a single cell was mounted with cold plates secured to each end of the cell as shown in Figure 5. In a second test, a single cell was secured radially to a pair of cold plates as shown in Figure 6.

A series of charge and discharge cycles were made in each configuration. The graphs below show the results of these tests with a 2C (8 A) discharge in Figure 7 and a 3C (12 A) discharge in Figure 8. In each test, the cell temperature corresponds to a thermocouple attached to the center of the cell. For a 2C discharge the rise in cell case temperature over 900 seconds was 7.3°C for axial cooling but only 3.1°C for radial cooling. Similarly, for a 3C discharge the rise in cell case temperature over 600 seconds was 11°C for axial cooling but only 6°C for radial cooling.

In each case the radial cooling method performed significantly better than axial cooling.

4.2.3 Direct Liquid Cooling

Direct liquid cooling is a relatively new technique for battery thermal management and involves the submersion of the entire battery assembly in dielectric fluid. The process removes heat efficiently from the cells and maintains a relatively even temperature across the battery array but has several drawbacks that make it more difficult to use than other cooling techniques. It requires that the battery be contained in a sealed enclosure to prevent leakage. The system requires a liquid-to-liquid heat exchanger to remove the heat from the dielectric fluid. Direct liquid cooling was not considered further for this phase of the program due to the packaging complexity and fluid cost. Other more traditional techniques had already been developed to a stage that the added risk associated with developing this technique were considered too high. It would be appropriate for further research in the future.

4.2.4 Phase Change Materials

Phase change materials absorb energy from the environment when the temperature exceeds a material threshold by changing from a solid to a liquid phase. A separate heat exchange mechanism is necessary to remove the thermal energy from the material and return it to a solid state. PCM is suitable for transient heating but does not add significant benefits for continuous heat removal. It is not yet being considered for this application although transient testing of the other thermal management approaches may indicate that it would add benefit to the performance of the system.

4.3. Battery Safety

A factor in the selection of a thermal management solution for the HVCM is operational safety. This leads to an evaluation of whether one or more of the solutions would increase the safety risk or reduce it when compared to other approaches.

Air cooling reduces the safety risk because of the increased spacing between the cells. Axial indirect liquid cooling requires the development of a thermal connection to the positive and/or negative endcaps of the cells. The positive endcap requires adequate space for venting, so an obstruction in this area increases the risk of a thermal runaway spreading to adjacent cells. This makes the technique difficult to implement. Radial indirect liquid cooling allows cells to be packaged closely together with a thermal conductor separating the cells. The high-density packaging increases the possibility of thermal runaway heating adjacent cells if an insulating media is not incorporated.

Direct cooling with dielectric fluids reduces the safety risk of the system with the improved heat removal performance of the material. Phase change materials, while not suitable for use in this application as a stand-alone thermal management media, do increase the battery safety by absorbing energy without increasing the temperature of the environment and by filling voids between cells. This limits the spread of flames and gasses that can occur in a cell failure.

4.4. Thermal Management Selection

The analysis led the team to choose a radial cooling solution for the HVCM. The solution requires only 2mm of space between cells and allows heat to be directly transferred from the cell case to the ethylene glycol coolant efficiently. Formed aluminum cooling tubes are attached to the sides of each cell with a thermally conductive epoxy. The solution allows the thermal interface to directly contact approximately 30% of the cell surface. A thermal model of the solution indicates an even thermal distribution across the cell pack as shown in Figure 9.

From this point additional model simulations were performed to estimate the thermal performance of the approach under various load conditions. Safety testing was also conducted to assess the risk associated with a single cell thermal runaway in this pack configuration.

5. Conclusion

In support of the Army’s Next Generation Combat Vehicle UEC Electronics is designing an HVCM to function as a common building block module for high voltage battery packs in combat and tactical vehicle platforms.

This paper describes the process of evaluating current technologies to identify an optimal cell to use as the fundamental building block of the module and the appropriate approach to cooling a collection of those cells.

Analysis, trade-off studies, simulations, and experimentation led to the selection of the cylindrical Molicel INR21700-P42A as the choice of cell and indirect, radial liquid cooling as the cooling approach.

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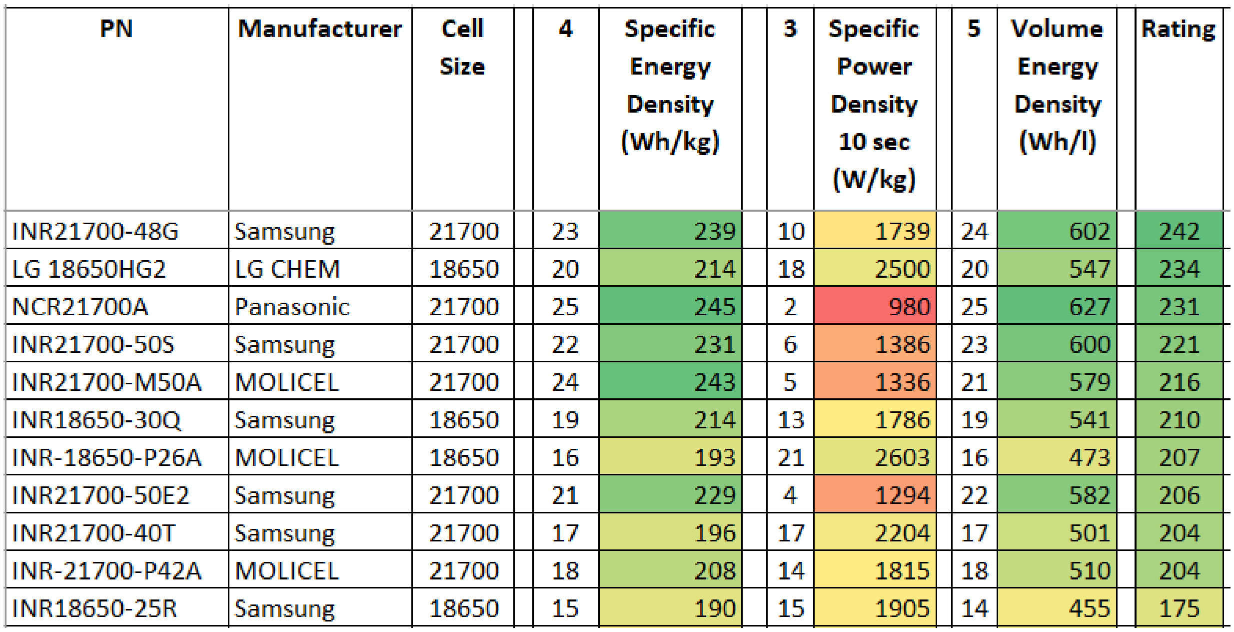
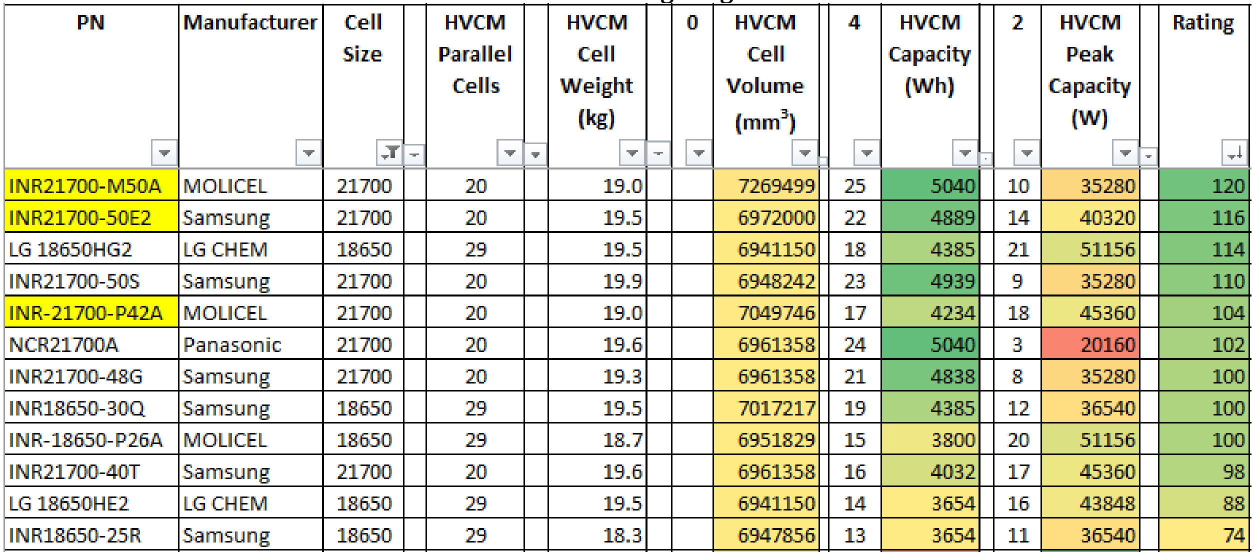
Table 2. Commercial battery cell selection showing factors and weights.



PN	Manufacturer	Cell Size		4	Specific Energy Density (Wh/kg)		3	Specific Power Density 10 sec (W/kg)		5	Volume Energy Density (Wh/l)		Rating
INR21700-48G	Samsung	21700		23	239		10	1739		24	602		242
LG 18650HG2	LG CHEM	18650		20	214		18	2500		20	547		234
NCR21700A	Panasonic	21700		25	245		2	980		25	627		231
INR21700-50S	Samsung	21700		22	231		6	1386		23	600		221
INR21700-M50A	MOLICEL	21700		24	243		5	1336		21	579		216
INR18650-30Q	Samsung	18650		19	214		13	1786		19	541		210
INR-18650-P26A	MOLICEL	18650		16	193		21	2603		16	473		207
INR21700-50E2	Samsung	21700		21	229		4	1294		22	582		206
INR21700-40T	Samsung	21700		17	196		17	2204		17	501		204
INR-21700-P42A	MOLICEL	21700		18	208		14	1815		18	510		204
INR18650-25R	Samsung	18650		15	190		15	1905		14	455		175

Table 3. HVCM weighting matrix.



PN	Manufacturer	Cell Size		HVCM Parallel Cells		HVCM Cell Weight (kg)		0	HVCM Cell Volume (mm^3)	4	HVCM Capacity (Wh)	2	HVCM Peak Capacity (W)	Rating
INR21700-M50A	MOLICEL	21700		20		19.0			7269499	25	5040	10	35280	120
INR21700-50E2	Samsung	21700		20		19.5			6972000	22	4889	14	40320	116
LG 18650HG2	LG CHEM	18650		29		19.5			6941150	18	4385	21	51156	114
INR21700-50S	Samsung	21700		20		19.9			6948242	23	4939	9	35280	110
INR-21700-P42A	MOLICEL	21700		20		19.0			7049746	17	4234	18	45360	104
NCR21700A	Panasonic	21700		20		19.6			6961358	24	5040	3	20160	102
INR21700-48G	Samsung	21700		20		19.3			6961358	21	4838	8	35280	100
INR18650-30Q	Samsung	18650		29		19.5			7017217	19	4385	12	36540	100
INR-18650-P26A	MOLICEL	18650		29		18.7			6951829	15	3800	20	51156	100
INR21700-40T	Samsung	21700		20		19.6			6961358	16	4032	17	45360	98
LG 18650HE2	LG CHEM	18650		29		19.5			6941150	14	3654	16	43848	88
INR18650-25R	Samsung	18650		29		18.3			6947856	13	3654	11	36540	74

Table 4. Comparison of the final 3 candidates.

	Molicel INR-P42A	Molicel INR-M50A	Samsung INR-50E2
Chemistry	NCA		
Weight [g]	67	68	69.5
Nominal Voltage [V]	3.6		
Capacity [Ah]	4	4.8	4.9
Max Const. Current [A]	30	20	9.8
Max Current 10s Pulse [A]	45	20	14
DC-IR [mΩ]	16	25	31
Max Const. Power [W]	94	62	33
Cycles to 70% cap.	500	500	500
Certification	UL1642, UN38.3, IEC62133		
Specific Energy [Wh/kg]	215	254	261
Energy Density [Wh/l]	563	666	723
Operating Temperature (°C)	-40 to 60	-30 to 60	-20 to 60

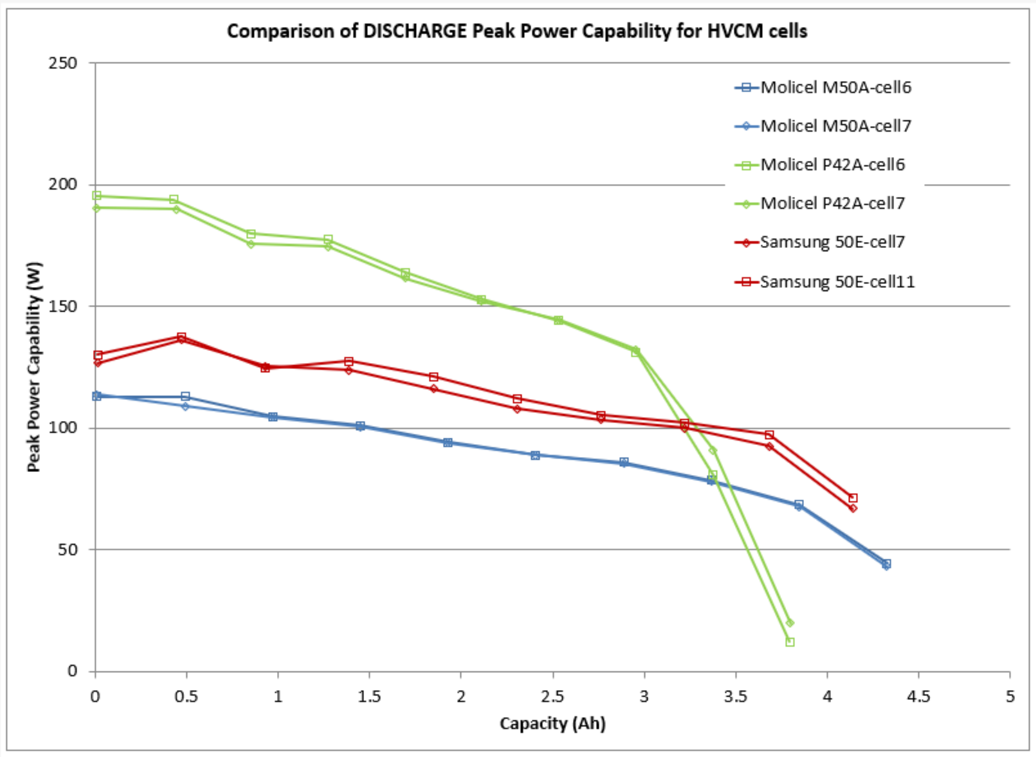


Figure 3. Comparison of discharge peak power capability for HVCM cells.

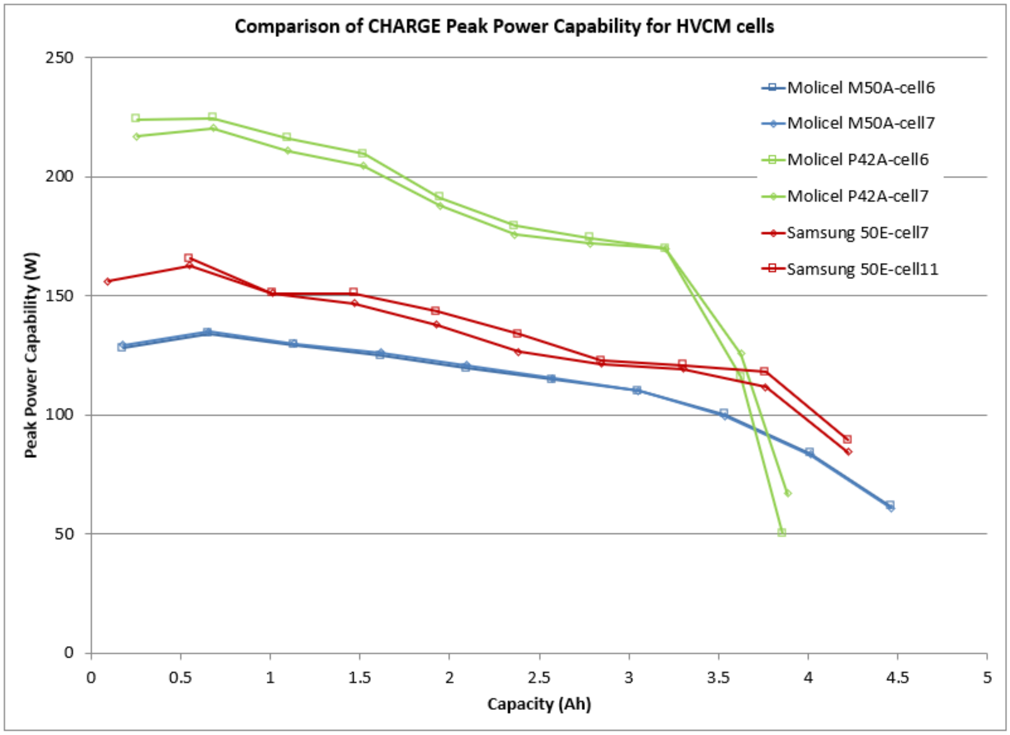


Figure 4. Comparison of charge peak power capability for HVCM cells.

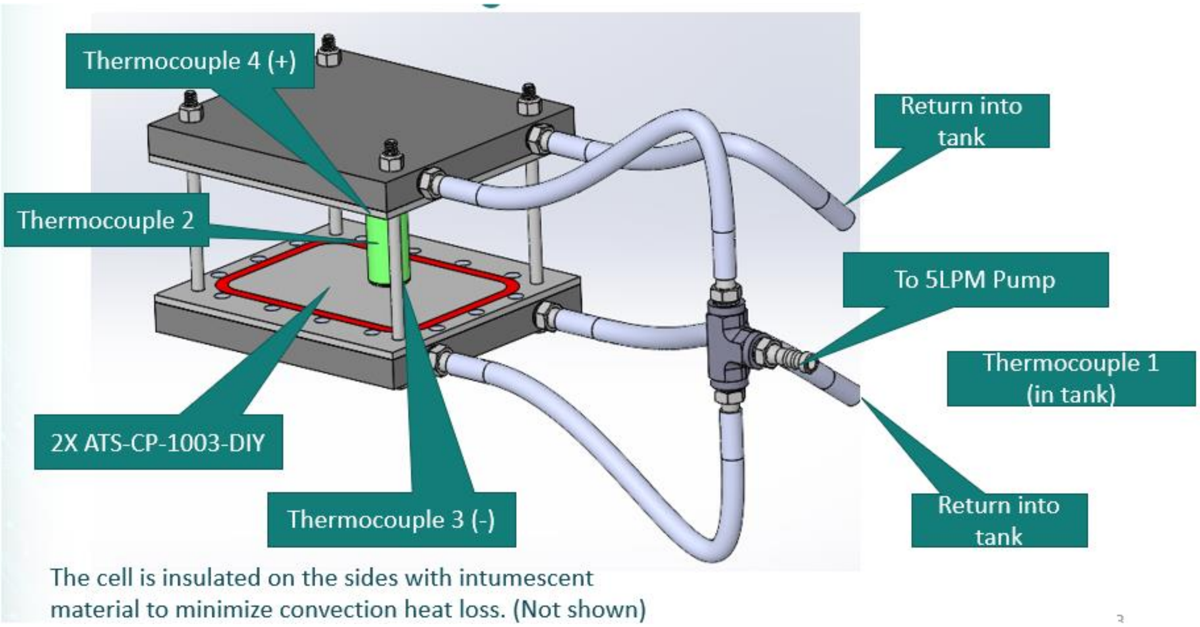


Figure 5. Axial cooling experimental set up.

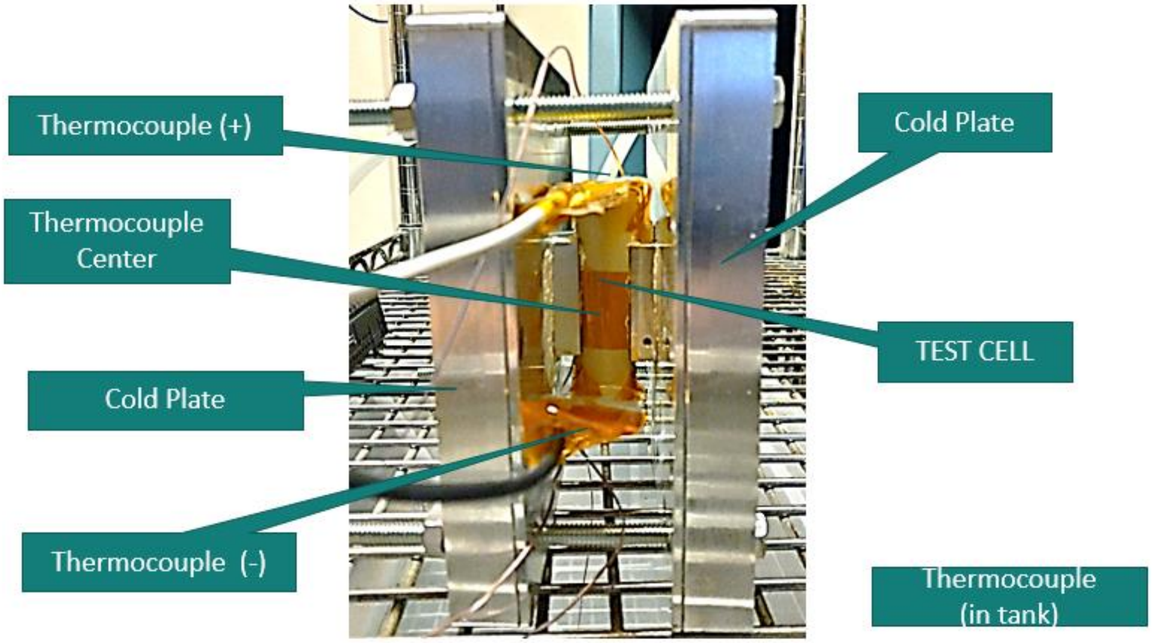


Figure 6. Radial cooling experimental set up.

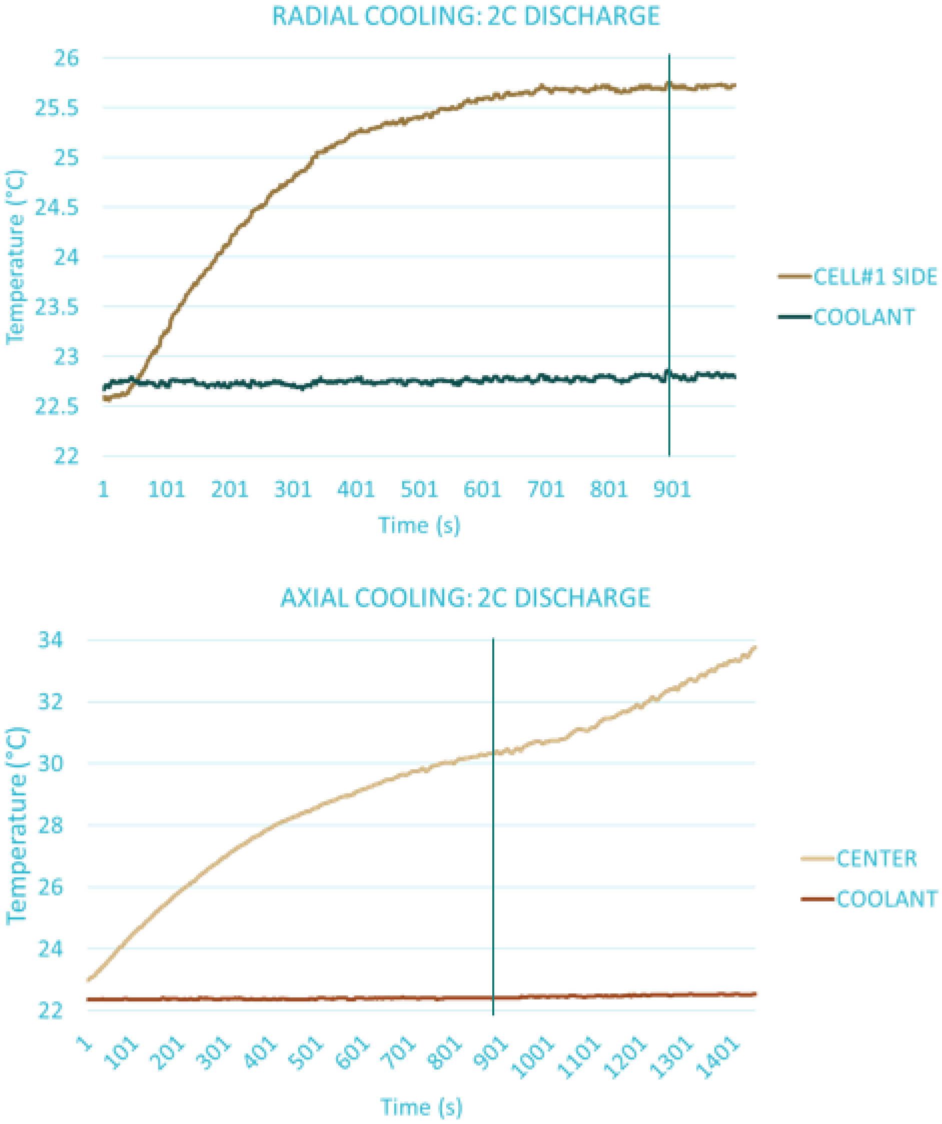


Figure 7. Comparison of radial and axial cooling approaches for a single cell under 2C discharge.

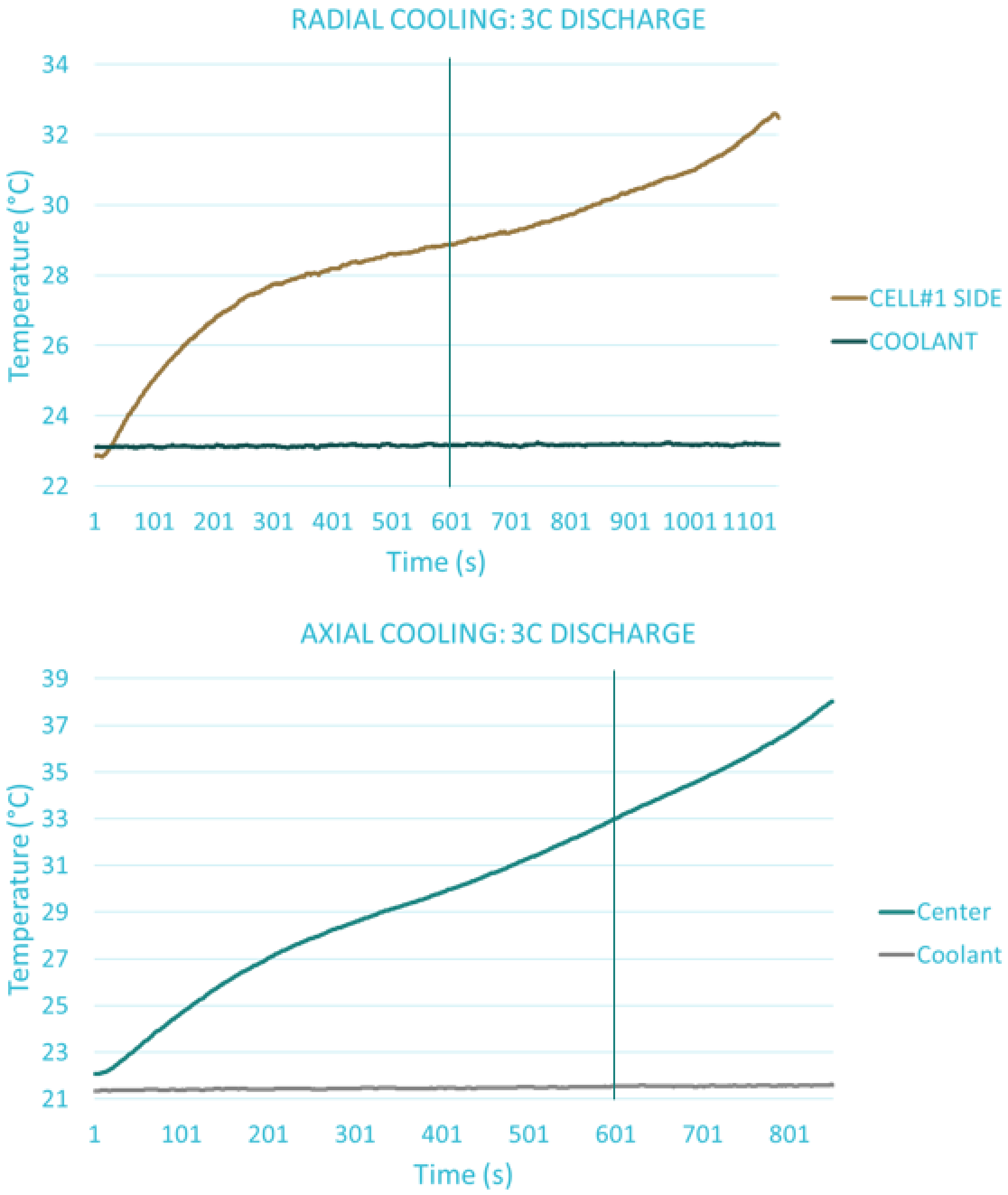


Figure 8. Comparison of radial and axial cooling approaches for a single cell under 3C discharge.

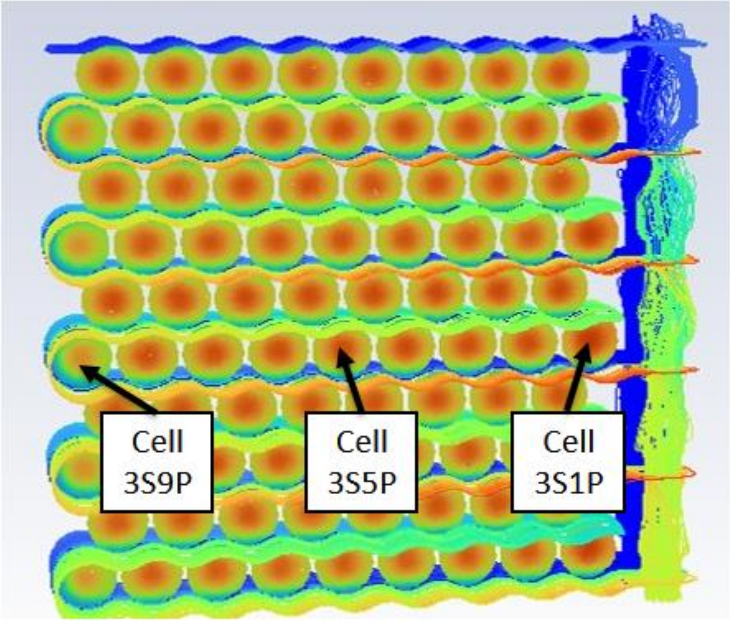


Figure 9. Thermal response of axial thermal management system.