# Thermal Management of Li-Ion Batteries with Single-phase Liquid Immersion Cooling

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***Abstract – Development of effective thermal management strategies for batteries in mobile and static energy storage systems is essential in enabling the advances in flexibility and longevity required to win widespread public acceptance of battery-based electrical storage. Both stationary battery arrays and electric vehicle ("EV") batteries are pressed to enable charging and discharging at faster C rates, increased Amp-hour capacity, and longer service life at reduced operating costs. All of these goals require more efficient and safer thermal management solutions to be achieved economically. Traditional air cooling and indirect liquid (cold plate) cooling methods have limitations in both effectiveness and weight.***

***Engineered Fluids has recently completed a series of experiments demonstrating the extreme efficiency of Single-phase Liquid Immersion Cooling (SLIC) technology in the thermal management of Li-ion batteries. This paper reviews the results of these experiments and discusses some of the issues and solutions for battery thermal management, and outlines the proper design of battery thermal management systems. We will discuss such topics as active cooling versus passive cooling, liquid cooling versus air cooling, cooling and heating versus cooling only systems, and relative needs of thermal management for VRLA, NiMH, and Li-Ion batteries.***

*Index Terms* - #immersioncooling, #thermalmanagement, #batterycooling #SLIC #AmpCool #EngineeredFluids

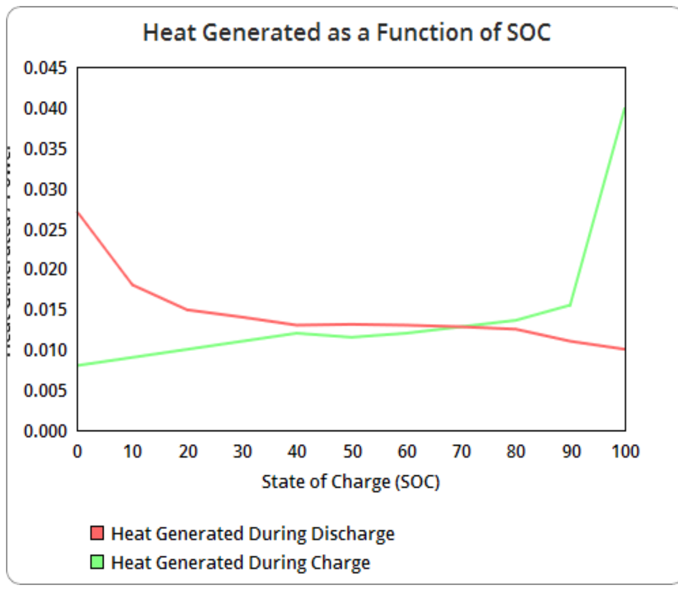
## INTRODUCTION

### *I. Heat Generation in Batteries*

Significant quantities of heat are created inside batteries during charge and discharge cycles. This heat is generated by exothermic chemical reactions, primarily, as well as losses from activation energy, ionic migration resistance, and chemical transport. [4] [5] [6] The majority of heat is generated at charge and discharge extremes; there is normally little heat generated at a State of Charge (SOC) between 20 and 80%, [1,2] as shown in Figure 1.

Heat generated during charge/discharge cycles increases as a battery ages due to the degradation of ion migration pathways. Increases of 35% to 70% are not uncommon, according to battery manufacturers. [3] Heat generation also increases at lower temperatures throughout the battery's life.

*Figure 1. Heat generated through a cycle at 1 C-rate showing heat generated as a function of State of Charge.*




### *II. Heat Transfer in Battery Modules*

Today, most stationary battery array systems use air as the medium to cool batteries. In automotive battery systems, a mixture of air-cooling and indirect "cold plate" cooling is used.

The steady state heat transfer equation that describes battery module cooling is:

$$Q_{BAT} = U' \ A(T_{BAT} - T_{Avg2,3})$$

Where ***U'*** [units: W/°C] is a combined heat transfer coefficient that uses both conductive heat transfer from the inside of the cells to the surface of the cells and the cell tabs as well as convective heat transfer from the cell surface and tabs to the air. The cooling surface is most often the external casing of the battery module and/or the metallic tabs. [4]

This equation can be simplified to one that uses only the heat transfer fluid's characteristics:

$$Q_{BAT} = (F \;\; r \;\; C_p(T_3 - T_2)$$

Where:
F= flowrate (cm^3/second)
Cp = heat transfer coefficient of the battery material
T3= high temperature recorded
T2= low temperature recorded

In order to adequately cool the battery module, two conditions must be met. First, the sum of all heat removed must be greater than all heat generated, or in equation form:

$$U' > \frac{Q_{BAT}}{T_{BAT} - T_{AMB}}$$

(Dictating that the sum of heat transfer coefficients must be greater than the heat generated by the battery divided by the delta-T allowable between battery temperature and ambient air temperature)

Second, the mass of heat transfer fluid past the battery modules must be sufficient to absorb the heat that they generate [5]:

$$F > \frac{Q_{BAT}}{r \cdot C_P \cdot \Delta T}$$

*III. Battery Thermal Management Requirements*

Thermal management affects the life of the battery in several ways:

1. By maintaining the battery cell's temperature in their optimal zone for operation.
2. By minimizing temperature variance and cycling. Beyond maintenance of the temperature inside a band that is optimum for the cells' performance, thermal cycling, or excursion has been identified as a key failure mechanism of electronic assemblies in general, and battery chemistry, in particular. Minimization of thermal cycling is key to obtaining maximum efficiency and service life from batteries. [6]
3. By minimizing thermal stratification within individual cells. During charge/discharge cycles, ion migration inside the cell results in non-uniform heating, which lowers the cell's charge/discharge rate, and ultimately, its service life.
4. By maintaining homogeneous temperature distribution from cell to cell. Temperature variation from cell to cell in a battery pack leads to different charge/discharge cycling behavior for each cell.
5. This, in turn, makes the pack electrically unbalanced, which reduces the overall pack performance [6]. The design of a battery module dictates its temperature distribution. Heat cell in a module may not be spatially uniform due to several factors: aspect ratio, number of cells and geometry of the cells and module, thermal conductivity of the module case, placement of the positive and negative terminals, the size of the tabs on the cells, and the size and position of the cell's electrical interconnects within the module. Non-uniform heat generation could lead to non-uniform temperature distribution in the module.

*IV. Air Cooling vs Liquid Cooling*

Traditionally, batteries have been cooled with forced air. Air cooling uses the principle of convection to move heat from the cell or battery pack into the surrounding air mass. Ambient or cooled air is directed across the surface of the battery pack, which may feature cooling fins or another means of increasing the surface area of the pack, where the air picks up heat generated internally. Although traditionally considered as an inexpensive means of cooling, thermal management with air requires that a significant amount of air is directed over the surface of the battery, typically this is accomplished with fans. Air has a very low heat capacity (Cp = 1.006 kJ/kg K at standard temperature), so a large volume of air must be used, particularly when delta in temperature between the battery casing and the ambient air temperature is low. Another challenge of air cooling is that a battery's heat transfer surface must be exposed to air, so its physical location is restricted to those locations where air flow is available or can be channeled.

This approach is being challenged due to new application demands placed on the batteries, as well as changing battery chemistries. The application demands that require more efficient thermal management include:

- faster charge/discharge cycles (higher amperages)
- longer service life (more charge/discharge cycles)
- higher battery voltages
- The need to maintain more stabilized, constant voltage output during discharge and over the service life of the battery.

One alternative to traditional air cooling is indirect liquid cooling, in which a water/glycol solution flows through the battery case, cooling the battery cells or module through conduction through the module case. Aqueous glycol solutions are electrically conductive, which means that they cannot be in direct contact with the battery, which limits their use to indirect cooling methods, such as water jackets around battery modules or cold plates placed within the battery module. Water/glycol solutions have very high heat capacity, and are efficient at removal of heat from the module. However, this efficiency is mitigated because the heat must be conducted through walls of the jacket/container or fins. In addition, because many battery modules are composed of pouch or cylindrical cells it is important that a heat sink which touches all the surface area of the battery cells be used to ensure proper conduction of the heat to the cold plate or jacket. This typically results in the use of a high precision manufactured aluminum framework to ensure there is no air gap between the battery cells' surfaces and the framework. Any such air gaps significantly reduce the overall efficiency of the heat transfer due to the low heat capacity of air.

The rate of heat transfer through the battery itself, through the walls of the battery module, and then through the electrically insulating water jacket, or heat sink framework and cold plate, is a function of temperature gradient and the thermal conductivity coefficients of the different materials involved in each of these layers.

Direct immersion cooling systems using single-phase dielectric liquids are another means of cooling battery cells and modules. In direct liquid immersion cooling, often called Single-phase Liquid Immersion Cooling, (SLIC), the battery cells are fully immersed in a dielectric cooling liquid. The dielectric coolant can be circulated with a pump to reject heat to the environment through the use of a heat exchanger, or, if the heat load is low enough, can be passively cooled by convective flow through the walls of the container, where heat is released to the atmosphere.

The rate of heat transfer between the walls of the battery module and the heat transfer media depends on several factors, including the thermal conductivity, viscosity, density, and velocity of the medium. For the same volumetric flow rate, heat-transfer with dielectric coolants is much more efficient than with air because of the thinner boundary layer and higher thermal conductivity of the liquid (approximately 1.3 -1.4 kJ/kg K). This high heat capacity allows a much lower flowrate with a dielectric coolant than with air.

Liquid coolants have higher thermal conductivity and heat density than air, and therefore perform very effectively. Of these options, direct immersion in liquid single-phase dielectric coolants (SLIC) will theoretically deliver the best performance for maintaining battery cells and packs in the correct temperature range and with a minimum of temperature variation and at the lowest cost and complexity for the system. The reduced complexity comes from the elimination of the need for any intermediate heat sink framework or complex manufacturing of a precision framework to hold the cells.

A key safety advantage that SLIC coolants have over water glycol and other conductive coolants is that some liquid cooling systems have safety issues related to leaking and disposal, as glycol can be dangerous for the environment if handled improperly. Also, the shorting of batteries due to an internal leak of conductive water glycol can cause the module to go into thermal overload, thereby destroying the battery.

*V. Liquid Immersion Testing*

Objectives of testing battery thermal management with Single-phase Liquid Immersion Cooling (SLIC) technology are:

- Determine compatibility of battery module and dielectric solution
- Evaluate heat transfer properties of the solution and impact to battery module
- Compare heat transfer characteristics with air cooling
- Hypothesize impact on safety, capital expenditures, operating and maintenance costs, and system level improvements
- Finalize system level design for immersion cooling

*VI. Experimental Procedure*

The efficiency of SLIC technology for thermal management of batteries was proven in a set of experiments performed at Engineered Fluids' Application Development Laboratory. In these experiments a prismatic 68AH cell (Samsung Model 286S) was subjected to a series of four charge – discharge cycles over a period of 15 hours, while being cooled with forced air and subsequently using the same cycle pattern while immersed in AmpCool™ AC-100 Dielectric Coolant cooled to ambient air temperature through the use of a radiator and fan.[1]

The test cycle parameters of the first experiment (Phase 1) are shown in Figure 2

Figure 2: Phase 1 Charge/ Discharge Test Parameters

| ACTIVITY | DURATION (MIN) | ENDING SOC |
|---|---|---|
| REST - INITIAL | 1 | 30% |
| CHARGE - CYCLE 1 | 110 | 100% |
| REST | 20 | 99% |
| DISCHARGE - CYCLE 1 | 60 | 0% |
| REST | 60 | 1% |
| CHARGE - CYCLE 2 | 110 | 100% |
| REST | 20 | 99% |
| DISCHARGE - CYCLE 2 | 60 | 0% |
| REST | 60 | 1% |
| CHARGE – CYCLE 3 | 110 | 100% |
| REST | 20 | 99% |
| DISCHARGE – CYCLE 3 | 60 | 0% |
| REST | 60 | 1% |
| CHARGE - CYCLE 4 | 110 | 100% |
| REST | 20 | 99% |
| DISCHARGE - CYCLE 4 | 60 | 0% |
| REST | 60 | 1% |

*Note: The charging cycle time of 110m / .55C to achieve 100% State of Charge (SOC) was necessitated by the limitation of the charging equipment's maximum output of 40 Amps.*

The test utilized "constant current charging and discharging." Phase 1: The first phase of the experiment utilized a charge cycle of 110 minutes using 40A is .55/C and a discharge cycle using a 68A load which is 1/C per the battery's design. Because the cell is designed for use using air cooling, we followed the manufacturer's recommendations for rest and stabilization between cycles. The cell was allowed to rest for 20 minutes between charge and discharge to allow the cell's voltage to stabilize. The cell was also allowed to rest after each full discharge for 60 minutes to allow the battery temperature to stabilize, again per manufacturer's recommendations.

During the second phase of the experiment, the time period for all rest periods was set at 20 minutes and the discharge cycle was accelerated to 30 minutes reducing in half the original 60 minutes, resulting in a 2/C discharge cycle. The purpose of this test was to determine the ability of Single-phase Liquid Immersion Cooling to manage more rapid and higher temperature variation and higher thermal stress on the battery cell. The parameters of Phase 2 of the experiment are shown in Figure 3:

Figure 3: Phase 2 Charge/ Discharge Test Parameters

| Activity | Duration (min) | Ending SOC |
|---|---|---|
| Rest - Initial | 1 | 30% |
| Charge - Cycle 1 | 110 | 100% |
| Rest | 20 | 99% |
| Discharge - Cycle 1 | 30 | 0% |
| Rest | 20 | 1% |
| Charge - Cycle 2 | 110 | 100% |
| Rest | 20 | 99% |
| Discharge - Cycle 2 | 30 | 0% |
| Rest | 20 | 1% |
| Charge – Cycle 3 | 110 | 100% |
| Rest | 20 | 99% |
| Discharge – Cycle 3 | 30 | 0% |
| Rest | 20 | 1% |
| Charge - Cycle 4 | 110 | 100% |
| Rest | 20 | 99% |
| Discharge - Cycle 4 | 30 | 0% |
| Rest | 20 | 1% |

During each full testing cycle, the temperature of the cell was monitored on each of the battery cell's tabs (positive and negative as well as on each cell face using type-K thermal probes and the temperatures were recorded in 10secd intervals. Parameters for these tests were:

Ambient Air Temperature: 21C +/- 3C

Air Cooling Test (Control)
Air Input Temp: 23.0 +/- 5.0C
Air Volumetric Flowrate: 28.4 liters per minute

Liquid Immersion Cooling Test:
Liquid Coolant Input Temp: 23.0 +/- 0.5C
Liquid Coolant Flowrate: 0.5 liters per minute
The temperature and volume of air flow specified for cooling was per the manufacturer's recommendations. The volume of the liquid coolant flow was determined as the lowest speed setting of the circulation pump used in the test setup.

Battery cell charge and discharge cycles were done with the use of a Cadex 8000 Battery Test module having all four 10A outputs interconnected and slaved to channel one for a total charging power of 40A and a B&K Precision 8518 DC Battery Load with a maximum load of 100A at 12VDC. Figure 2 shows the electrical connections from the Test Battery, the Battery Test Module and the Battery Load.

The fluid cooling unit used was a Koolance ERM-3K3UA Liquid Cooling System, Rev1.1 which has been retrofitted to be material compatible with the AmpCool AC-100 coolant. The retrofit required the replacement of all rubber seals and O-rings with FMK and the replacement of all vinyl hoses with Tygon tubing throughout the system. The cooling unit at maximum fan and pump speed at 20C has a maximum cooling capacity of 2kW. During the liquid testing the fan and pump speed were both set to their minimum speeds.

The coolant used in this study is AmpCool™ AC-100, a synthetic dielectric (electrically non-conductive) coolant made by Engineered Fluids, specifically for thermal management of electric motors and batteries. AmpCool™ AC-100 Coolant is clear, has no smell, is biodegradable, nontoxic and has been granted Food Grade Status in the US. (1). AmpCool™ AC-100 Coolant does not boil, remaining in the liquid phase at all application temperatures from -66 C to 280C. It has a low viscosity, which enhances its heat transfer efficiency.

*Figure 3: Electrical Connections for Battery Test*

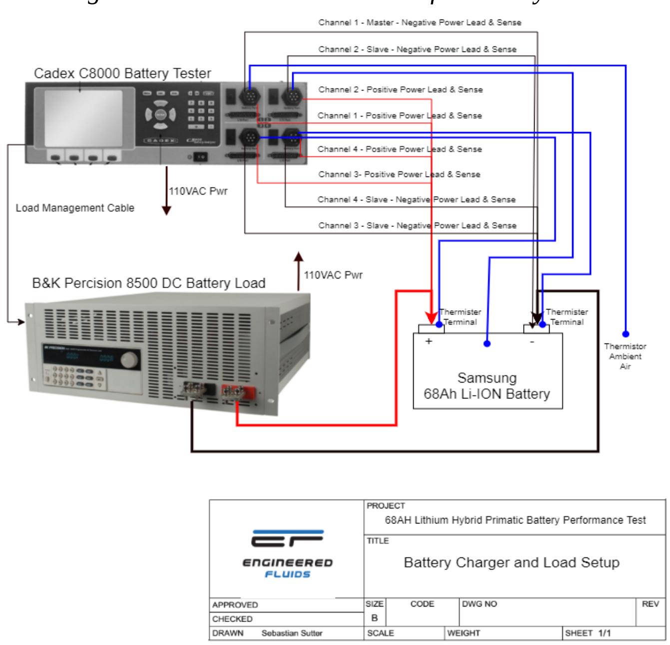


*Figure 4:*
*Battery Cooling Test Setup:*

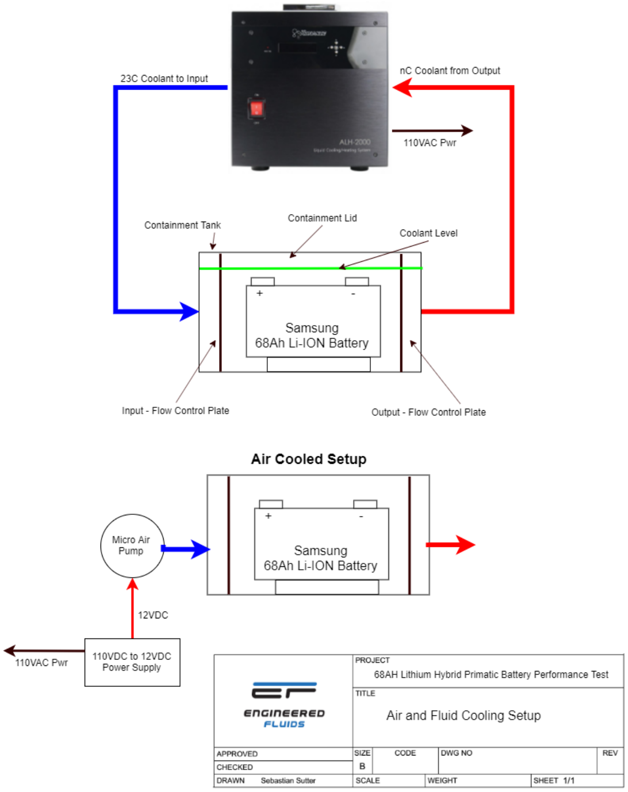



*Figure 5:*
*Characteristics of AmpCool AC-100 Coolant:*

| | |
|---|---|
| Product ID | AC-100 |
| Applications | Stationary and vehicular battery cooling |
| ISO 4460 Particle Count (Avg.) | 10/10/2012 |
| Appearance | Clear |
| Refractive Index nD20 | 1.462 |
| Dielectric Constant | 2.3 |
| Dielectric Strength, kV | >60kV |
| Resistivity (ohm-cm) | >1x1014 |
| Pour Point (ºC) | -55 |
| Flash Point (ºC) | 180 |
| Density, g/cc @ 16 ºC | 0.8113 |
| Coefficient of Thermal Expansion, vol./ ºC | 0.00068 |
| Viscosity (cSt) @ 40 ºC | 9.58 |
| Viscosity (cSt) @ 100 ºC | 2.68 |
| Thermal Conductivity (W/m*K) @ 40 ºC | 0.1373 |
| Specific Heat (kJ/kg*C) @ 40C | 2.2032 |
| Biodegradability (28 Days) | >96% |
| Global Warming Potential | 0 |

Figure 6 shows the placement of thermocouples on the Samsung Test Cell.

*Figure 6: Placement of Thermocouples*

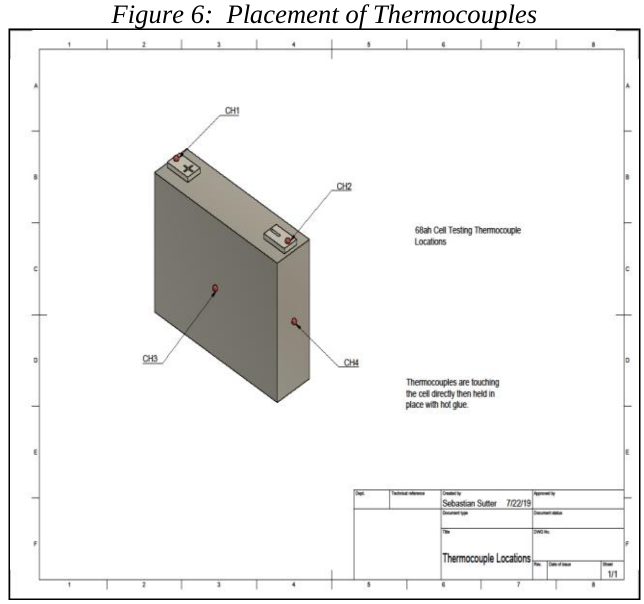



Figure 7 is a photo of the steel test tank used for both battery and air testing. The steel plates on each narrow end are removable baffles used during liquid testing to provide even non-laminar flow over all the surfaces of the battery. These baffles were removed during air testing. A foam cover was inserted over the top of the test tank during both air and liquid testing to isolate the battery test environment. During liquid test the battery cell was completely immersed in AmpCool™ AC-100 coolant such that 25mm of coolant were present on all sides of the battery. The net volume of the liquid coolant present in the tank during testing was2.786 Liters.

*Figure 7: Steel Test Tank with Battery Cell*

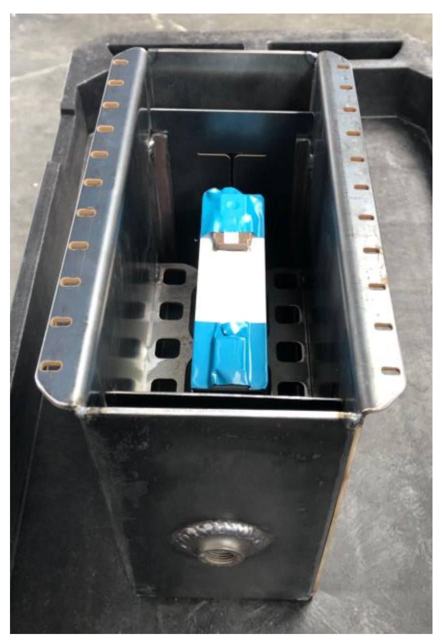


Figure 8 is a photo of the liquid immersion test rig with the battery fully immersed in AmpCool AC-100 prior to the cover being set in place.

*Figure 8: Liquid Immersion Test setup with Battery in AmpCool™ AC-100*

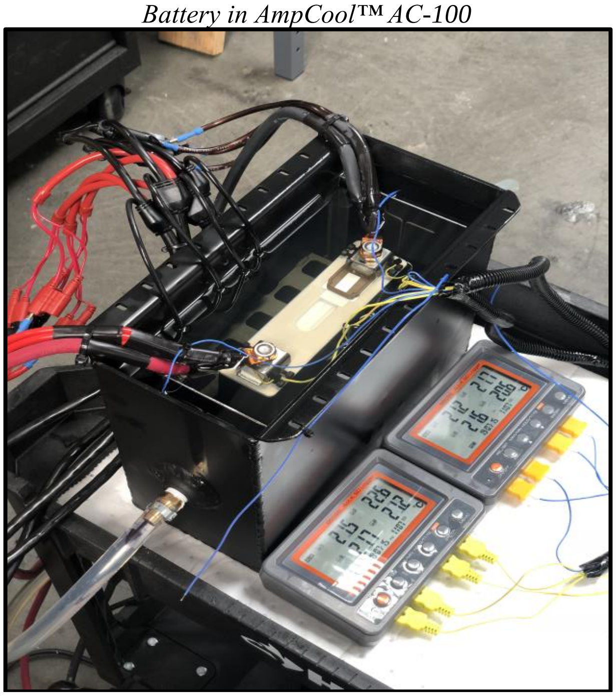


Figure 9 provides the dimensions of the internal volume of the steel test tank that was used to contain the battery cell during testing. The tank was constructed of cold rolled steel as a measure of safety during the testing should the cell go into thermal overload. Even with the added stress of very aggressive discharges while being liquid cooled the battery cell never reached its 120C overload temperature.

*Figure 9: Dimensions of Battery Cell and Fluid Volume in Test Tank*

| Battery and Coolant Volumes | 68AH Battery Cell | Test Tank Fluid Depth |
|---|---|---|
| Length, mm | 174 | 224 |
| Width, mm | 46 | 96 |
| Height, mm | 126 | 176 |
| | | |
| Total Volume, $mm^3$ | 999,988 | 3,784,705 |
| Total Volume, liters | 0.999 | 3.785 |
| | | |
| Net Volume Coolant | 2.786 Liters | |

***Figure 10: Characteristics of Samsung Model 286S Battery Cell***

| Battery Cell | Parameters | Specification |
|---|---|---|
|  | Shape | Prismatic |
| | Battery chemistry | NCM/LMO blend |
| | Dimension (L x W x H), mm | 173.9× 45.6 × 125.6 |
| | Weight, kg | 1.91 |
| | Nominal capacity, Ah | 68 |
| | Nominal voltage, V | 3.65 |
| | Nominal energy, Wh | 248.2 |
| | Operational voltage, V | 3.1 ~ 4.1 |
| | Charging method | CC-CV |

**Figures 11, 12, and 13**
**Transient Temperature Rise in a 68AH Battery Cell During Charge and Discharge by Cooling Method**

Comparison of Cell Temperatures with Air Cooling
vs. Single-phase Liquid Immersion Cooling (SLIC) with AmpCool™ Dielectric Coolant

Chart Legend:
Blue line: Temperature at Positive Tab
Red Line: Temperature at Negative Tab
Yellow line: Temperature at Short side wall
Green Line: Temperature at Long side wall

Figure 11: Air Cooled Battery Test – Phase 1 Charge / Discharge Cycle

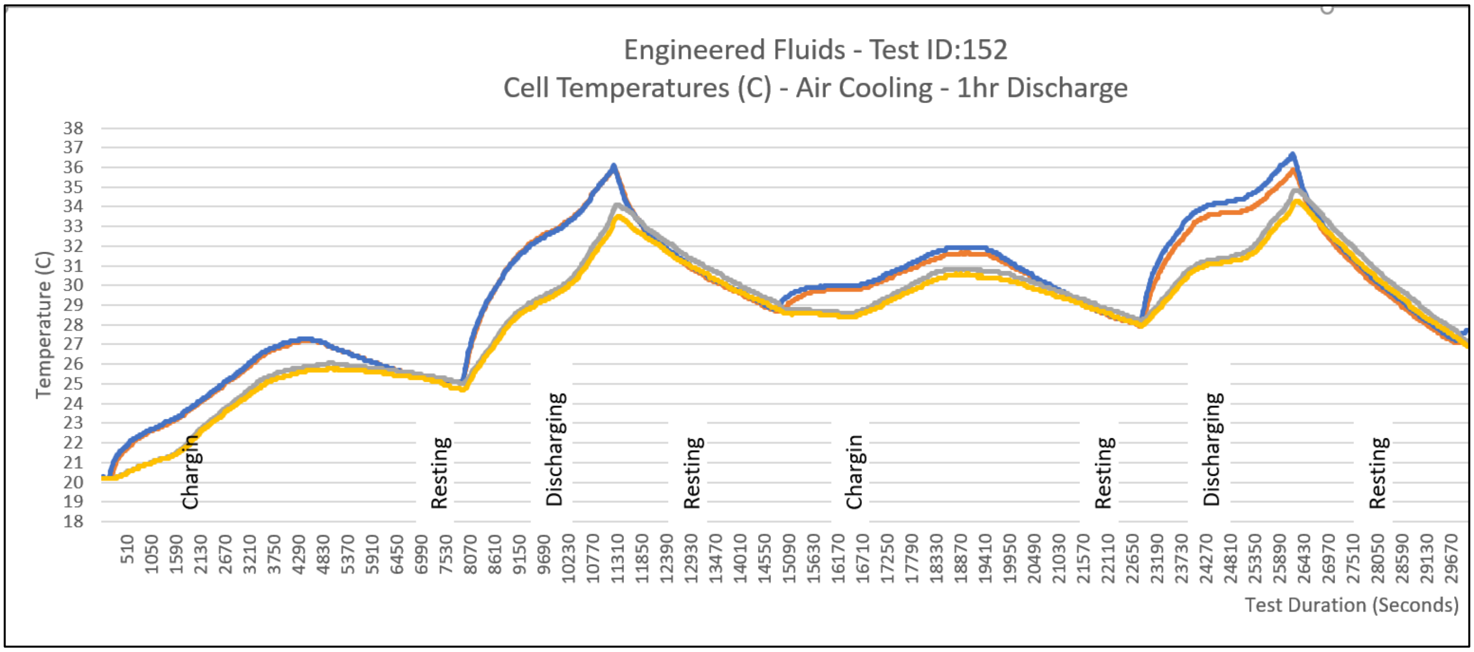



Figure 12: Liquid Cooed Battery Test – Phase 1 Charge / Discharge Cycle

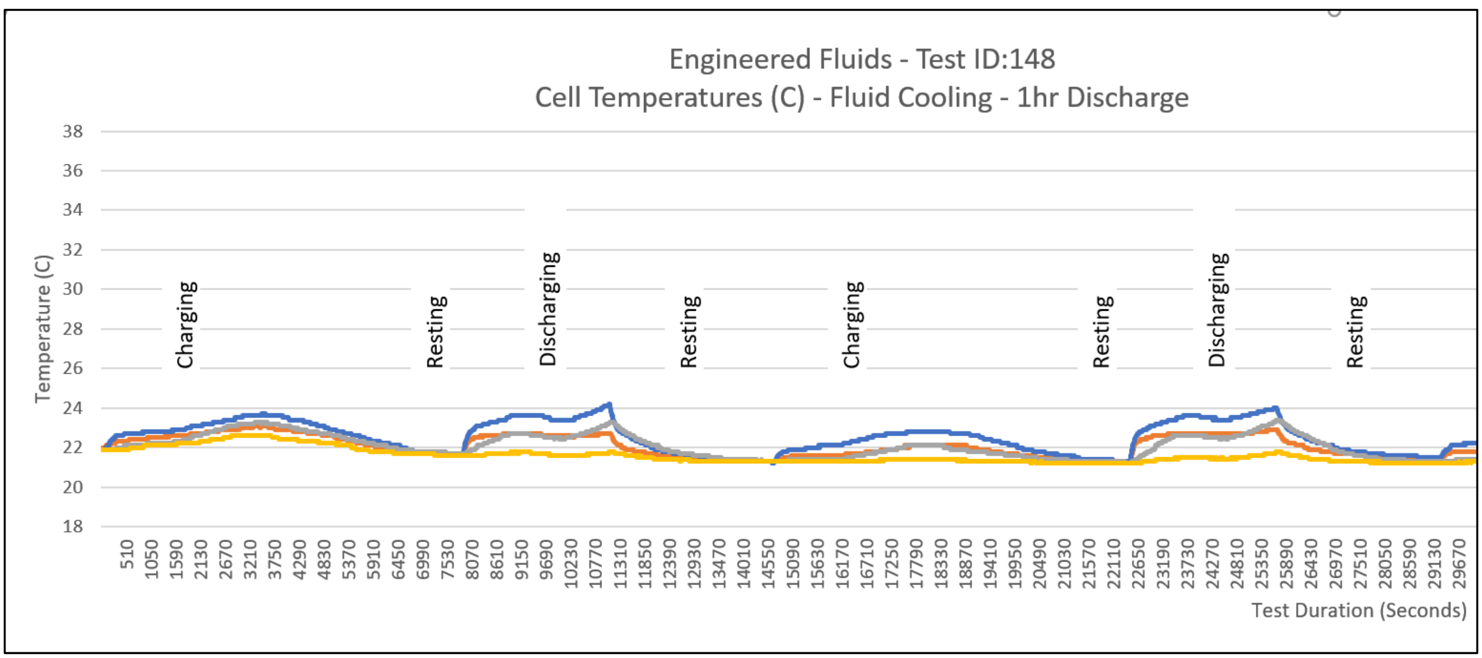


Figure 13: Liquid Cooled Battery Test – Phase 2 Charge / Discharge Cycle

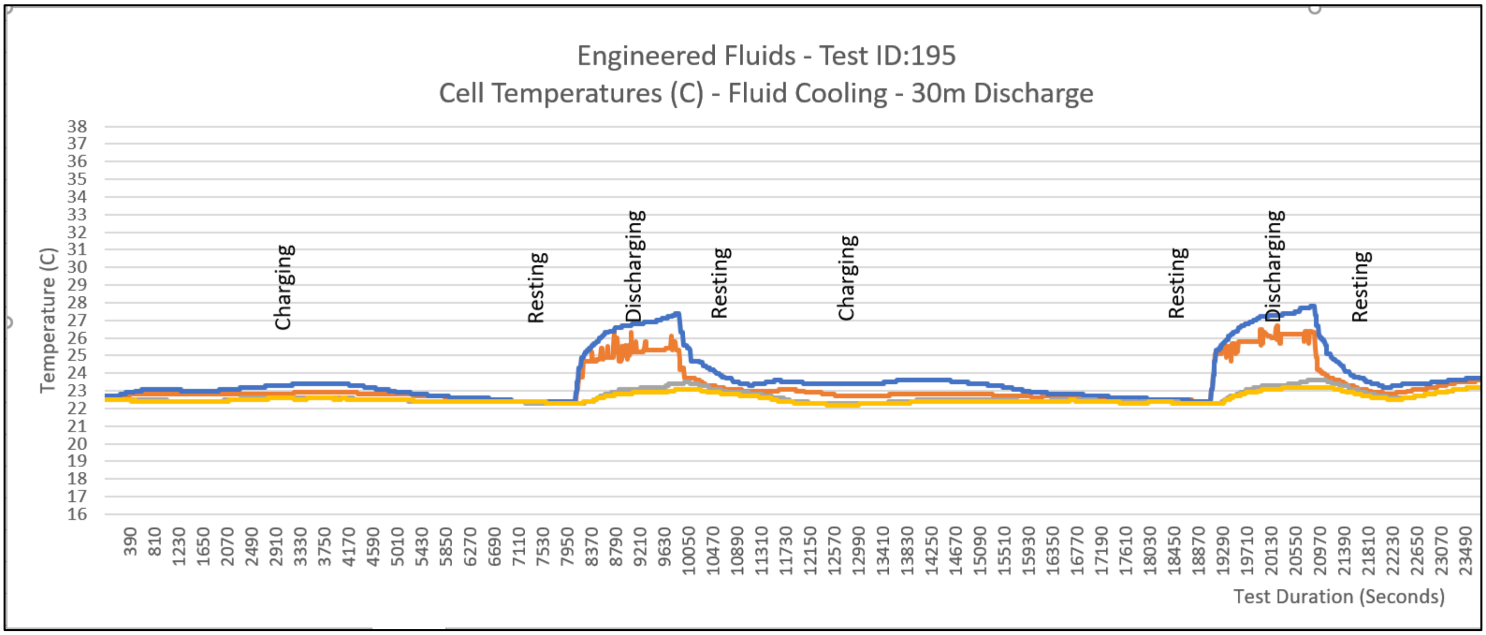



Figure 14: Summary of Maximum and Minimum Temperature by Location and Cooling Method

| | | *Test ID 152 - Air Cooled - 1hr Discharge* | | | | *TEST 148 - Liquid Cooled - 1hr Discharge* | | | | *Test ID 152 - Liquid Cooled - 30m Discharge* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Cycle** | **Status** | **Terminal + Max °C** | **Terminal- Max °C** | **Long Wall Max °C** | **Short Wall Max °C** | **Terminal + Max °C** | **Terminal- Max °C** | **Long Wall Max °C** | **Short Wall Max °C** | **Terminal + Max °C** | **Terminal- Max °C** | **Long Wall Max °C** | **Short Wall Max °C** |
| 0 | STARTUP | 20.2 | 20.3 | 20.2 | 20.2 | 22.0 | 21.9 | 21.9 | 21.9 | 22.6 | 22.7 | 22.5 | 22.5 |
| 1.1 | RESTING | 20.2 | 20.3 | 20.2 | 20.2 | 22.0 | 21.9 | 21.9 | 21.9 | 22.6 | 22.7 | 22.5 | 22.5 |
| 1.2 | CHARGE | 27.2 | 27.3 | 26.1 | 25.8 | 23.1 | 23.7 | 23.3 | 22.6 | 22.9 | 23.4 | 22.6 | 22.6 |
| 1.3 | RESTING | 25.6 | 25.6 | 25.6 | 25.4 | 21.8 | 22.0 | 21.9 | 21.7 | 22.5 | 22.5 | 22.4 | 22.4 |
| 1.4 | DISCHARGE | 35.6 | 35.7 | 33.2 | 32.6 | 22.7 | 24.1 | 23.1 | 21.8 | 26.3 | 27.3 | 23.4 | 23.0 |
| 2.1 | RESTING | 36.0 | 36.1 | 34.1 | 33.5 | 22.7 | 24.2 | 23.3 | 21.8 | 25.8 | 27.4 | 23.5 | 23.1 |
| 2.2 | CHARGE | 31.7 | 31.9 | 30.8 | 30.6 | 22.1 | 22.8 | 22.1 | 21.4 | 23.1 | 23.6 | 22.9 | 22.7 |
| 2.3 | RESTING | 29.1 | 29.2 | 29.3 | 29.1 | 21.4 | 21.6 | 21.3 | 21.2 | 22.6 | 22.6 | 22.4 | 22.4 |
| 2,4 | DISCHARGE | 35.6 | 36.3 | 34.2 | 33.6 | 22.9 | 23.9 | 23.2 | 21.7 | 26.7 | 27.7 | 23.6 | 23.2 |
| 3.1 | RESTING | 35.9 | 36.7 | 34.8 | 34.3 | 22.9 | 24.0 | 23.4 | 21.8 | 26.4 | 27.8 | 23.6 | 23.2 |
| 3.2 | CHARGE | 28.5 | 29.1 | 27.9 | 27.6 | 22.1 | 22.7 | 22.3 | 21.6 | 24.1 | 24.7 | 23.7 | 23.7 |
| 3.3 | RESTING | 25.7 | 25.8 | 26.0 | 25.7 | 21.6 | 21.6 | 21.6 | 21.3 | 22.4 | 22.4 | 22.3 | 22.3 |
| 3.4 | DISCHARGE | 32.3 | 33.3 | 31.1 | 30.6 | 22.9 | 23.8 | 23.2 | 21.9 | 26.3 | 27.2 | 23.2 | 23.1 |
| 4.1 | RESTING | 32.7 | 33.7 | 31.8 | 31.3 | 22.9 | 23.9 | 23.4 | 21.9 | 26.8 | 27.3 | 23.4 | 23.2 |
| 4.2 | CHARGE | 27.1 | 27.6 | 26.6 | 26.2 | 22.1 | 22.7 | 22.3 | 21.7 | 23.1 | 23.6 | 22.7 | 22.6 |
| 4.3 | RESTING | 24.3 | 24.4 | 24.6 | 24.3 | 21.6 | 21.6 | 21.6 | 21.4 | 22.4 | 22.4 | 22.4 | 22.4 |
| 4.4 | DISCHARGE | 31.1 | 32.1 | 29.8 | 29.3 | 22.9 | 23.8 | 23.2 | 21.8 | 25.9 | 27.1 | 23.1 | 23.0 |
| 5 | RESTING | 31.1 | 32.1 | 29.9 | 29.4 | 22.9 | 23.8 | 23.2 | 21.8 | 25.8 | 27.2 | 23.2 | 23.0 |
| 6 | FINISHED | 31.4 | 32.4 | 30.5 | 29.9 | 22.9 | 23.9 | 23.4 | 21.9 | 25.8 | 27.2 | 23.2 | 23.0 |

Figure 15: Comparison of Cooling Performance – Battery Cell Positive Terminal / Max Temp C

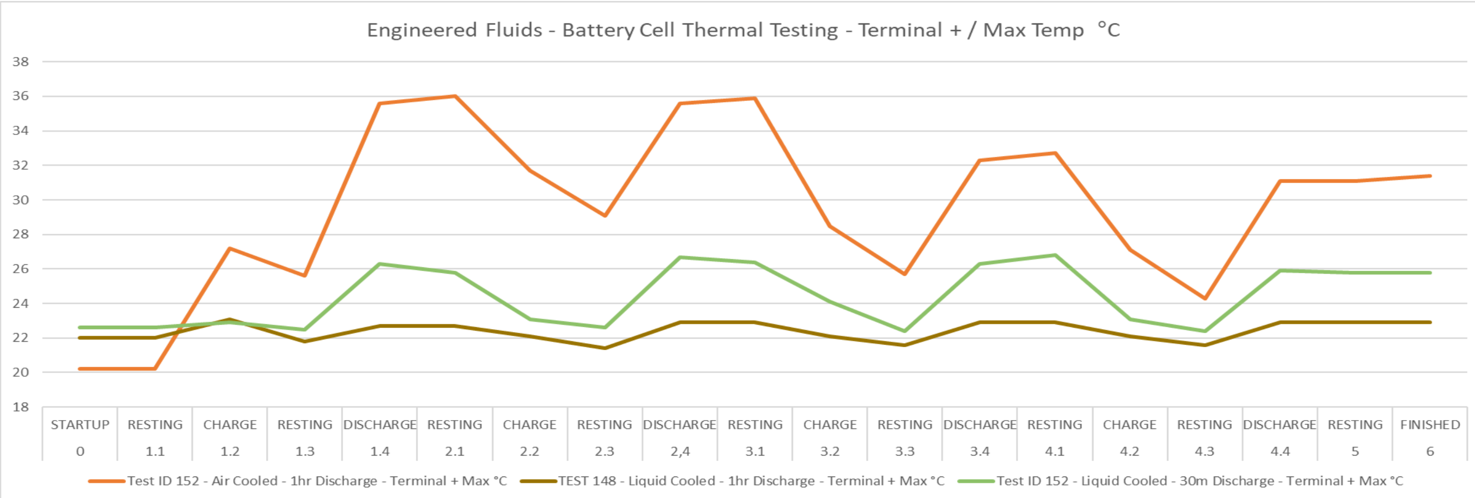



Figure 16: Comparison of Cooling Performance – Battery Cell Negative Terminal / Max Temp C

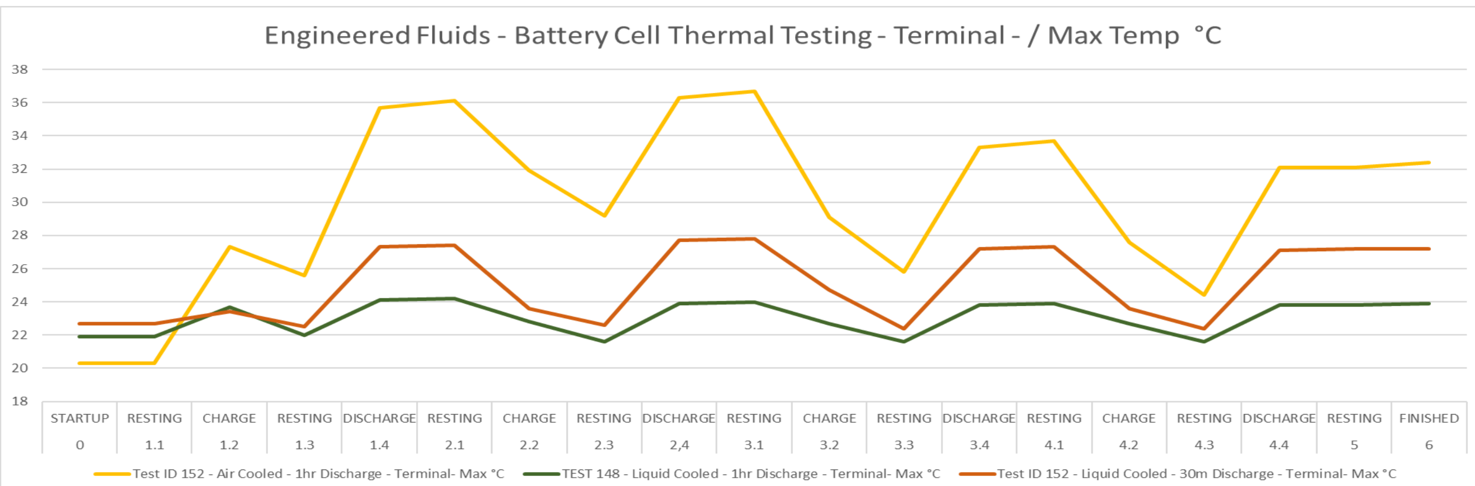



Figure 17: Comparison of Cooling Performance – Battery Cell Long Wall / Max Temp C

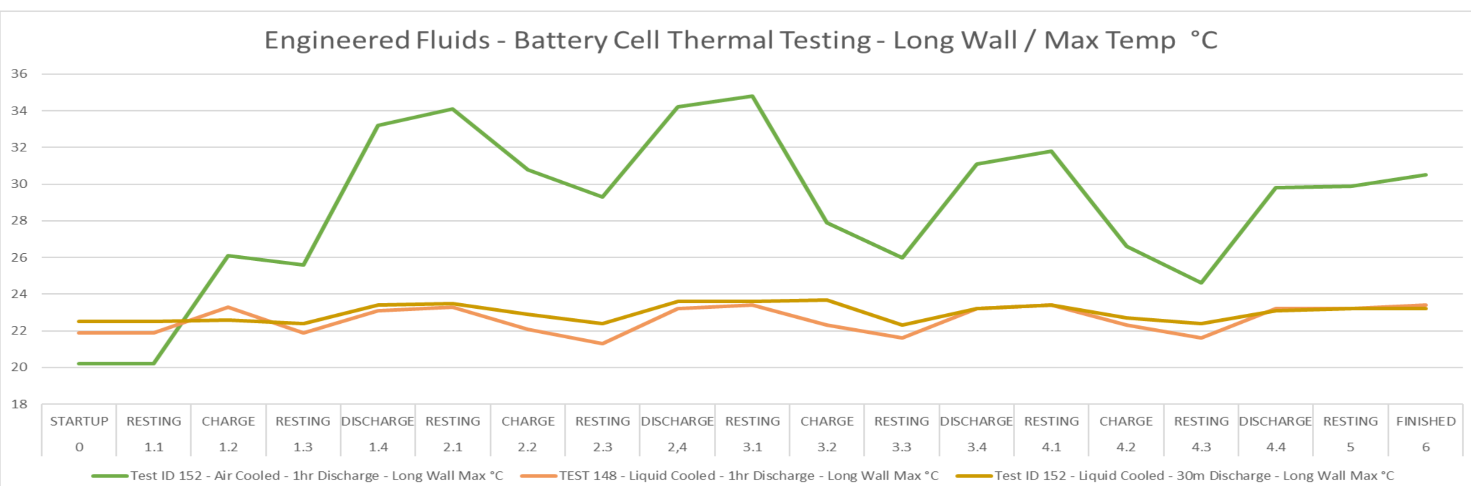
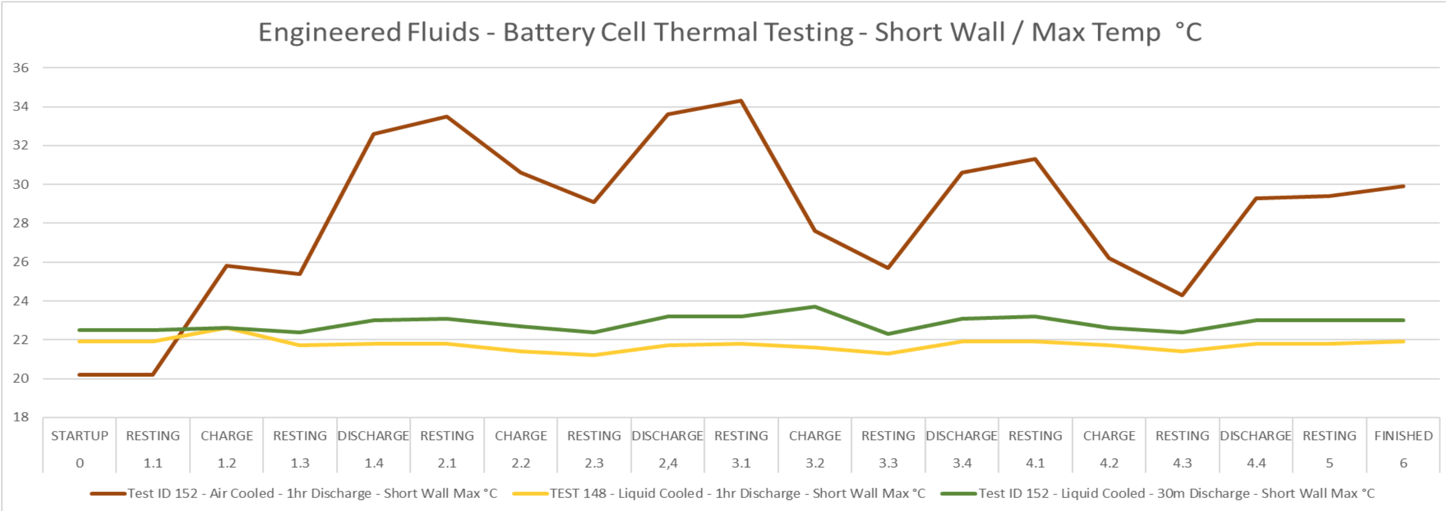


Figure 18: Comparison of Cooling Performance – Battery Cell Short Wall / Max Temp C




*VII. Results and Discussion*

Analysis of the test data shows that immersion cooling had the following effects, when compared with air cooling:

<u>Optimum Temperature Maintenance</u>: In Phase 1 of the experiment (0.55/C charge, 1/C discharge), the average battery temperature was five degrees C lower when the cell was immersed in AmpCool™ AC-100. Using the Arrhenius Rate Equation of chemical reaction kinetics, this 5 C difference in average cell temperature translates to an approximate extension of battery life by a factor of 1.4.

<u>Elimination of temperature swings:</u> When air cooled, battery temperatures varied more than 16 degrees from cycle to cycle. In the liquid immersion-cooled test, this temperature variation was only 1.8 degrees C.

Immersed in AmpCool™ Coolant, the battery was held within its manufacturers' recommended optimum operating temperature range of 23+/- 3C at all times during the 4 cycle test. The battery cell cooled with forced air experienced temperature swings from 20 to 37 C., with five times the standard variation around the average, and well above the manufacturer's recommended operating temperature range.

Figure 11 shows the cooling performance in greater detail, as it tracks surface temperatures measured along the long side of the cell through one charge/discharge cycle.

<u>Elimination of Cell Temperature Stratification</u>: Immersion cooling maintained homogeneous temperatures inside the test cell, air-cooling allowed temperature stratification inside the cell, lessening the cell's efficiency and service life. This can be seen in the graphs above as the temperatures of the battery cell's side wall deviated from the tab, or terminal temperature. With the immersion cooled cells, this difference was not seen.

Phase 2 of this experiment tested the AmpCool™ Coolant's ability to manage higher thermal stress by discharging the battery cell at twice the design rate. In this part, discharge was done at 2/C, taking the battery cell from 100% SOC to 30% in only 30 minutes, with only 10 minutes between cycles.

The accelerated discharge rate places higher thermal stress on the battery cell, raising its internal temperature. Maintenance of the cell's temperature within the desired range recommended by the manufacturer is vital to maximizing the battery's useful life. Figure 13 shows how liquid immersion cooling maintained the battery cell's temperature even with the additional thermal load brought about by rapid discharge and reduced rest times.

*VII Conclusions:* Advances in battery technology are facilitating their use in a wide range of stationary and mobile applications. Thermal management of these battery arrays will be one of the limiting factors in their adoption and application. Maintenance of battery temperatures within a narrow range maximizes the battery capacity, maximizes the rate of charging and discharging the battery, and extends the battery's useful life. [7,8]

Several means of controlling the temperature of batteries during charge and discharge cycles have been evaluated. Traditional air cooling cannot economically maintain the temperature within the desired range during charging and discharge cycles. Adding surface area and/or cooling fins to the battery case helps dissipate heat more rapidly, but adds too much bulk and weight to be considered for most applications.

Liquid cooling is the most effective and economical solution for keeping battery temperatures within the desired band. Liquid cooling can be done indirectly, using cold plates or pipes through which a water-based solution is pumped. This is more effective than air-cooling, but is inflexible and expensive (cold plates must be made specifically to fit every different cell shape and component to be cooled) and does not approach the efficiency of intimate contact between the battery and the heat transfer fluid.

The most efficient cooling method for batteries is direct immersion in a single-phase, nonconductive cooling fluid. Until recently, dielectric fluids were not available with the right combination of material compatibility profile, environmental impact and fire safety. Developed in 2017, AmpCool™ Dielectric Coolants are a safe and reliable way to optimize and extend the value of today's battery systems.

The experiment described in this paper used Samsung Model 286S battery cells that were subjected to multiple rapid charge-discharge cycles while being cooled with forced air and by immersion in a dielectric coolant, AmpCool™ AC-100.

The test cells that were immersed in AmpCool™ AC-100 Dielectric Coolant maintained an average cell temperature of 22.5 degrees C. with very low deviation from the mean. In contrast, when the cells were cooled with forced air, the average cell temperature was 28.7 degrees, with much greater temperature variation during charge/discharge.

The second phase of this experiment showed that immersion cooling can maintain a cell's temperature within a desired band even under high thermal stress brought about by accelerated discharge. This finding has powerful implications in terms of asset management mobile and stationary battery systems.

The experiment demonstrates that required relaxation times between discharge-charge cycles can be significantly reduced and battery lifetime will be extended. As battery efficiencies are raised, so are returns on battery asset investments.

As electric vehicles and stationary battery arrays become more widely used, there will be a high demand for longer battery life and higher power output. To achieve this, the battery thermal management systems will need to be able to transfer heat away from the battery pack as they are charged and discharged at higher rates. The heat generated as the battery is used can pose safety threats to passengers and bystanders. Due to the high stress and temperatures generated by the batteries, having the right cooling system is fundamental to maximizing battery efficiency, service life and profitability. This experiment has shown that thermal management through Single-phase Liquid Immersion Cooling (SLIC) technology can safely and efficiently maintain target temperatures in battery cells and modules.

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