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Modeling and Simulation of High Power Battery Cells – Ensuring Safe, Reliable Power for the Warfighter in Various Applications

David Carmen
Michael Marcel PhD
Les Alexander
Government Solutions Group
A123 Systems Inc.
Livonia, MI

ABSTRACT

Building battery packs for various, significantly different applications, is often complex and risky. Detailed cell and pack modeling and simulation tools, along with existing and predicted power and energy profiles significantly reduce the risk of designing and integrating a new pack for new applications on the battlefield. This paper will discuss a number of modeling and simulation techniques, using case studies as examples, that ensure a battery pack, when integrated to the application, will meet the predicted performance goals and specifications. Actual data will also be shown to validate these techniques that significantly reduce development time and risk when providing power to the Warfighter.

INTRODUCTION

The systems operating on today's battlefield are becoming significantly more complex and power hungry. These include high power radios and force trackers, high energy weapons, IED defeat systems as well as unmanned ground and air systems. These systems typically not only require a significant amount of energy to ensure long operating times, but also require the battery to provide short duration, high power. Often, their usage profiles are complex, but predictable. Because these systems are becoming more prevalent on the battlefield, increased modeling and simulation capabilities must be leveraged to ensure a safe, reliable product will be delivered to the Warfighter with a quick development time.

A123 Systems has developed several high power battery configurations built around its Nanophosphate™ cell chemistry. Cells using this chemistry show excellent power density and improved abuse tolerance. A123 has multiple variants of this technology in various cell formats to include cylindrical and prismatic. These devices are the building blocks of bigger systems and due to multitude of applications in which they operate, a significant amount of performance data exists and allows for prediction of performance in future systems.

Prior to and during a battery pack build, there are a number of ways modeling and simulation can be utilized to reduce the design risks to reduce reworks and redesigns which are often costly and time consuming. The techniques that will be discussed in this paper that are commonly used are solid modeling, drive cycle modeling and Thermal modeling. These are key performance drivers for typical battery packs and integrating these techniques will result in a better end product.

WHY MODELING AND SIMULATION

Increased computer processing power and more sophisticated modeling and simulation tools have allowed engineers to predict the behavior and performance of systems well before they are built. This provides a number of significant advantages to the engineering design process because it reduces the risk of integrating large, complex systems. Without modeling and simulation, a piece of a complex system, when integrated, may not perform as anticipated which will require rework to the piece, as well as rework to portions of the system. If this is done with multiple sub-systems, this can make the engineering process extremely costly and time consuming.

Often, when building a system, there is a significant amount of time placed on the preliminary design. This would include a requirements analysis and preliminary analysis to determine that the system meets the requirements. As the system progresses to Detailed or Critical design, a number of the subsystems details are finalized and the subsystems are built. Often, this build process takes some time, which allows, as time permits, a significant amount of modeling and simulation to be performed that can be integrated into the design, should potential problems areas be identified.

Modeling and simulation techniques can be used throughout the design process. During preliminary design, Modeling and Simulation can be used at a very high level to validate some of the analysis that is being done to the system. Examples of this may include the sizing of a DC/DC converter, used in conjunction with a battery, to tightly regulate a voltage. A top-level simulation can be performed to validate such things as proposed switching frequencies, inductor values (which often drive the physical size of these types of designs), and PWM duty cycles.

During detailed design, the modeling and simulation techniques can be taken a step further to include actual parts (often you can enter the device parameters or obtain a model from the manufacturer), the control loop (with parameters such as PID values, etc.) and other details. This model will allow you to validate any hand calculations/analysis that predicts how tightly a voltage is regulated and how it performs under load.

After detailed design and during the build of the DC/DC converter, the M&S techniques can be used to validate the hand calculated tuning parameters of the system. A detailed thermal model can also be integrated to predict any potential hot spots in the design that may not have been considered during the top level analysis. Further, "destructive" performance can be performed, using the simulation to predict safety prior to the system being built. Using M&S techniques to predict performance during a failure allows for reduced risk to life and hardware when tested on the real system. This may include a short circuit test, over-current or ground fault. Performing these tests in simulation during the pack build will not only give confidence and predicted performance when the system is actually tested, but may reduce the amount of hardware that could potentially be damaged during the test, which often results in costly reworks and time to repair systems instead of testing them.

MODELING AND SIMULATION TECHNIQUES USED FOR HIGH ENERGY/HIGH POWER PACKS

Top Level Analysis

Modeling and simulation techniques are extremely powerful, but to be used effectively, need to be performed hand in hand with a detailed analysis. Performing M&S without a method to validate the results (at various levels) is often only minimally effective. For instance, if a battery pack is being designed, M&S of a cell or Module would be an effective tool for predicting performance of a pack. The first step of the process would be to model the cell or module properties, then validate this model by actually testing the cell or the module and comparing it to the simulated data. A close correlation between the simulated data and simulated data would be extremely effective in modeling and simulating the pack.

There are a number of ways of modeling and simulating battery packs to effectively predict their performance. The techniques that are often common to battery packs include mechanical drafting/solid modeling (to predict how the pack will mechanically integrate to the system), Cycle Simulation testing (to predict performance of the system under a "realistic" use cycle) and Prediction of thermal heating (to identify "hot spots" or potential thermal issues for the battery and associated electronics). These M&S techniques will be discussed in further detail below.

Mechanical Drafting/Solid Modeling

In most applications, the user has a fixed space or area in which to include the battery system. Often, the user has a drawing or "space claim" for the system which is often not just a square or rectangular box. Sometimes this is for "replacement" batteries, often this is for a "new design" where there is a space allocation (sometimes given with dimensions, sometimes given with volume). Usually, the first (and most important) question is "How much power and/or energy can you fit in this given space". In these applications, a Wh/kg or Wh/L number (which is known for various products) can predict from a very high level what can accommodate the space.

Often Mechanical Drafting/Solid Modeling would be included in the preliminary design of a battery pack, or as a method of determining the feasibility of a solution "fitting" in a certain application. A123 has a detailed library of its common and non-common cell structures, modules and core electronics devices (Battery Monitoring Hardware, Contactors, Current sensors, interlocks, connectors). Often, an engineer can pull from this library quickly and "concept" a pack based on the electrical analysis of numbers of cells, modules, etc.

After analyzing the electrical requirements, the amount and type of hardware can be identified and packaging concepts can be made. This needs to include connectors (and clearance for mates), cooling interface (including clearance for connecting to it), access to interlocks, Cells/modules, integration clearance (how much "wiggle room" is available for integrating the pack), mounting features and Electronics. Given a good solid model of the application (for instance the space claim in the vehicle), a detailed solid model of the pack can be built (that includes all of the hardware) and determined if there are any potential integration issues when combining the solid model of the pack with the solid model of the system. This often facilitates coordination between the integration teams before and during the process so that these issues are not identified when trying to integrate the fabricated pack. Making modifications to a pack after it is made is significantly more time consuming and costly than the solid modeling/integration.

This M&S technique is extremely useful and is common practice in industry. A few things that are often overlooked during this process include wiring and wire routing (to include bend radius, etc.), backshells/connector details and mounting features. Depending on the level of complexity of the solution, these factors may or may not be significant.

Battery Performance using cycle information

Most applications that require batteries understand how and under what conditions that battery is going to be used. For instance, in a vehicle start battery application, the battery may serve a couple of purposes. If it is merely used for SLI (Starting, lighting and ignition), the ability to provide short bursts of power (for starting) may be the main purpose of the battery. In this application, depth of discharge (DOD) cycles may not be as important as the ability to store energy for long periods and provide significant power when needed. IF the battery is used for a significant amount of silent watch, then the requirements of the battery significantly change. Not only does it need to provide the power and energy, now the ability to provide lots of cycles is important. Often this usage can be generalized (using worst case conditions) by creating a “usage cycle” that includes starting events and cycling events. Simulation tools such as VPSET can allow the user to build vehicle models and subject the model to real world applications using data that has been already validated by TARDEC.

Once a “usage cycle” is determined, it is often agreed upon by the manufacturer and user. This usage cycle can be run in simulation (using validated cell and module data) to predict cycle life and performance. Performance parameters may include Voltage limits, current limits, how well the pack performs over time, cell temperatures, pack temperatures and amount of cooling required. This usage cycle can be run in short simulations (to predict performance during starting) or run repeatedly (to determine pack capacity, predicted run times and life).

The simulated data can identify potential weaknesses of the pack prior to build and as a way to reduce risk in the way of performance and safety. In most applications, the usage cycles that were simulated can be incorporated into a battery cycler (such as an ABC-150) that can subject the pack to the same cycle as was simulated to validate this pack and future packs with similar characteristics.

Prediction of Thermal heating

Thermal management is a significant parameter for battery packs from a performance and safety standpoint. At higher temperatures, the battery cycle life typically degrades, and at low temperatures, the performance typically suffers. From a safety standpoint, over-charging, over-discharging or fault conditions (short circuit, etc.) are typically more catastrophic at higher ambient temperatures.

Most packs include some form of thermal management system. This could include conduction cooling, convection cooling or active cooling methods such as forced air or circulating coolant in a cold plate. These devices not only regulate the temperature of the cooling interface, but are an extremely important asset to ensure the proper ambient temperature is maintained.

There are a number of simulation packages that can be used to model thermal performance. The software not only can identify “hot spots” in the pack, but can also predict the ambient temperatures and the effectiveness of the cooling. Because battery performance and safety is very significant, it is essential predict the temperatures in which the cells are going to operate. Like the other simulation techniques, it is often very costly and time consuming to try to integrate more or less cooling ability after the pack is built. By thoroughly performing M&S of the thermal system during PDR, CDR and pack build, it significantly reduces the risk upon integration.

CASE STUDIES FOR MODELING AND SIMULATION OF HIGH ENERGY/HIGH POWER BATTERY PACKS

UAV Application

Figure 1 shows a concept of an Unmanned Aerial vehicle pack drawn using PRO-E [1] CAD Package. This application had a specific space claim (and weight) that were critical to the UAV application. During the initial stages of the design process, it was important to determine whether enough power and energy can be stored given the stringent volume and weight requirements of the application.

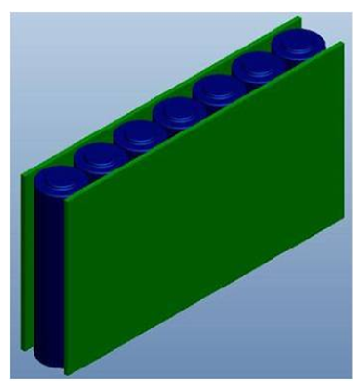


Figure 1. A123 Potential Unmanned Aerial Vehicle Pack.

This example shows that a “crude” solid model can be extremely beneficial when trying to determine whether or not a solution can meet identified needs of the system. This model only includes cells and two “squares” that represent

Circuit Card Assemblies (CCAs). It does not include wiring, packaging, etc. It does, however, provide the system integrator with a "tangible" representation of the battery solution that has the potential of meeting the needs of the vehicle. By incorporating this model with a solid model representation of the allocated area in which it will be located, both the battery integrator and system integrator will understand the obstacles (if any) when integrating an actual piece of hardware on the vehicle.

Hybrid Military Vehicle Pack

Figure 2 depicts a hybrid electrical vehicle pack that will be integrated into the XM1124 Hybrid Electric HMMWV [4]. Because this was an upgrade to an existing solution, this pack required a significant amount of time for system coordination to include software communications interface, hardware interface and electrical interface that already existed on the vehicle. M&S allowed this solution to be quickly and accurately integrated while the pack was being built.

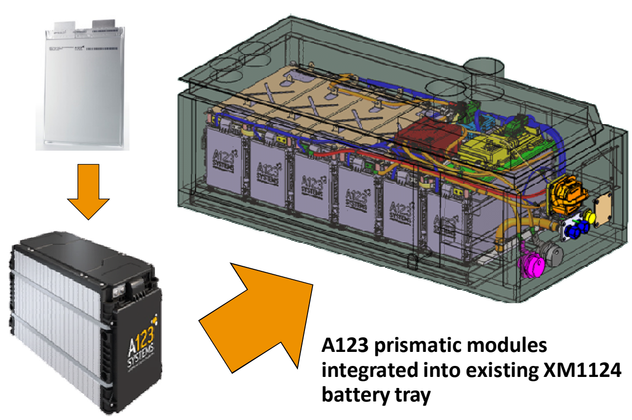
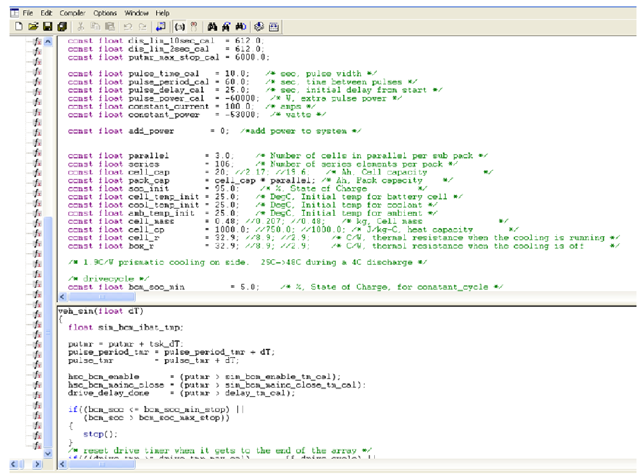


Figure 2. XM1124 Hybrid Electric HMMWV Pack.

First, a solid model of the pack (developed in Catia [2]) was built to include as many of the electrical and mechanical interfaces. This would include the coolant fittings, electrical contactors, vehicle mounting features and safety interlocks. This model was delivered to the customer so they could evaluate any potential integration issues that may be realized after pack delivery. It also allowed the customer to evaluate the interface to ensure it meets the requirements of the vehicle. Software simulation techniques (using CANalyzer) were used to ensure communication protocols were adequate upon pack delivery.

To evaluate the performance of the pack in simulation, the customer had a previous data document that showed the power profile of the actual vehicle navigating the Hartford Loop at Aberdeen proving Grounds. This is a "real world" profile that can be implemented in simulation to predict the performance of the pack before and during the pack build. Using this data, the system was modeled and simulated using a CANalyzer simulation tool. The simulation (to include thermal simulation data) was written in CAPL script. It utilizes existing data from previous, similar pack builds and allows the system to be accurately simulated using existing "drive cycles" and usage data. This tool is typically used for analyzing automotive hybrid applications and similar solutions, with similar hardware have been validated using this tool. Figure 3 shows a screen shot of the simulation script used for this application.



```
const float dis_lim_10sec_cal  = 612.0;
const float dis_lim_2sec_cal   = 612.0;
const float putmr_max_stop_cal = 6000.0;

const float pulse_time_cal    = 10.0;   /* sec, pulse width */
const float pulse_period_cal  = 60.0;   /* sec, time between pulses */
const float pulse_delay_cal   = 25.0;   /* sec, initial delay from start */
const float pulse_power_cal   = -60000;  /* W, extra pulse power */
const float constant_current  = 100.0;  /* amps */
const float constant_power    = -53000;  /* watts */

const float add_power        = 0;  /*add power to system */


const float parallel        = 3.0;    /* Number of cells in parallel per sub pack */
const float series          = 106;    /* Number of series elements per pack */
const float cell_cap        = 20; //2.17; //19.6;   /* Ah, Cell capacity          */
const float pack_cap        = cell_cap * parallel; /* Ah, Pack capacity    */
const float soc_init        = 95.0;    /* %, State of Charge              */
const float cell_temp_init  = 25.0;   /* DegC, Initial temp for battery cell */
const float cool_temp_init  = 25.0;   /* DegC, Initial temp for coolant */
const float amb_temp_init   = 25.0;   /* DegC, Initial temp for ambient */
const float cell_mass       = 0.48; //0.207; //0.48;   /* kg, Cell mass              */
const float cell_cp         = 1000.0; //750.0; //1000.0; /* J/kg-C, heat capacity       */
const float cell_r          = 32.9; //8.9; //2.9;    /* C/W, thermal resistance when the cooling is running */
const float box_r           = 32.9; //8.9; //2.9;    /* C/W, thermal resistance when the cooling is off     */

/* 1.9C/W prismatic cooling on side.  25C->48C during a 4C discharge */

/* drivecycle */
const float bcm_soc_min          = 5.0;    /* %, State of Charge, for conatant_cycle */

veh_sim(float dT)
{
  float sim_bcm_ibat_tmp;

  putmr = putmr + tsk_dT;
  pulse_period_tmr = pulse_period_tmr + dT;
  pulse_tmr        = pulse_tmr + dT;

  hsc_bcm_enable      = (putmr > sim_bcm_enable_tm_cal);
  hsc_bcm_mainc_close = (putmr > sim_bcm_mainc_close_tm_cal);
  drive_delay_done    = (putmr > delay_tm_cal);

  if((bcm_soc <= bcm_soc_min_stop) ||
     (bcm_soc > bcm_soc_max_stop))
  {
     stop();
  }
  /* reset drive timer when it gets to the end of the array */
```

Figure 3. CANalyzer CAPL script used for simulating the performance of the XM1124 HMMWV pack.

The simulation was first performed over 1 cycle of the loop to determine the performance of the pack (voltages, currents, temperatures, etc.). Upon completion, the loop was run repeatedly to determine long term performance and self heating. The simulation showed at ambient temperatures, the pack would perform well electrically and thermally with the existing thermal management system. It significantly reduced the performance risk and experimentation time for when the pack is to be integrated into the vehicle.

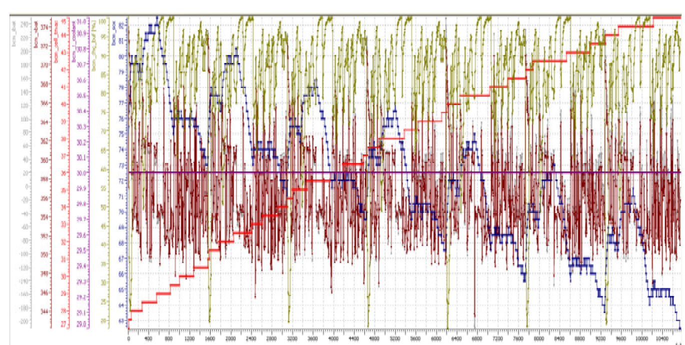


Figure 4. Hartford Loop Simulation of XM1124 Pack.

High Power Pack

Top Level Analysis/Requirements

The next case study involved a high power pack. For high power battery packs, the thermal management system is crucial to ensure the pack is operated within its safe operating area. This analysis started with the determination of which cell to use given the user's requirements. The cell selected for this pack was A123 Systems' AHR18700 Ultra cell. The cell, with an 18 mm diameter, and 70 mm length, is capable of providing up to 200 amps of current. The cell boasts an extremely high specific power, and is capable of operation at 100°C. Figure 4 shows the power capability of this cell.

Upon selection of the cell, a solid model was built to ensure it met the volume and weight requirements from the customer. The solid model is shown in Figure 5. The pack is capable of storage at -60° F (-51° C) to +160°F (+71° C) and operation at -37˚C to 60˚C (-35˚F to 140˚F). The detailed pack requirements are shown in Table 1.

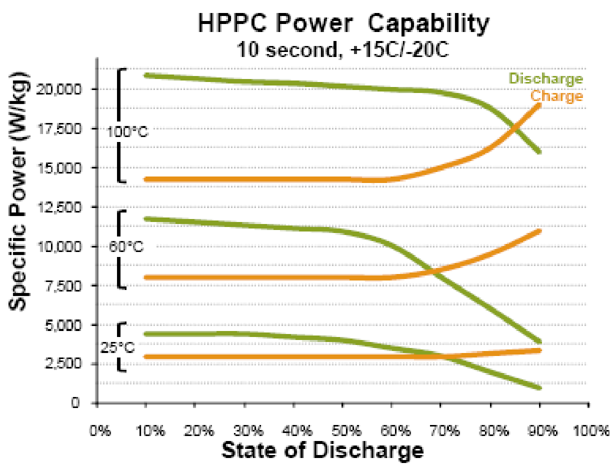


Figure 4. Specific Capacity Capability of the 18700 Cell

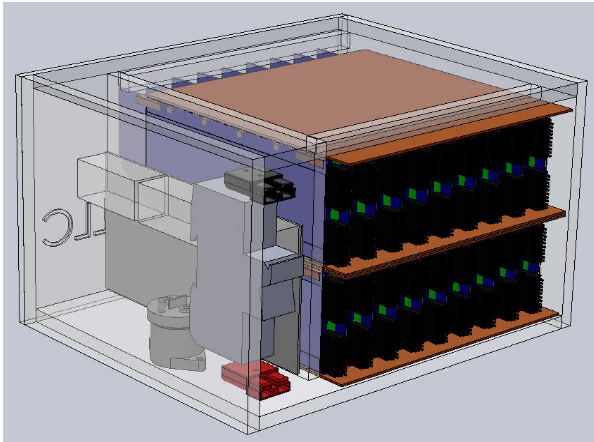


Figure 5. A123 High Power Pack for Directed Energy Applications.

Table 1. High Power pack requirements.

Nominal Voltage	**600 V**
Nominal Capacity	**0.7 Ah**
Module Dimensions (W x L x H)	**12 x 10 x 7.1**
Module Weight	**15 kg**
Operating Temperature	**0 to +60°C**
Storage Temperature	**-30 to +60°C**

Load Profile/Performance Modeling

The high power pack was designed to provide up to 40 kW of power with a nominal voltage of 600 Vdc. The pack will be subjected to an aggressive load profile that helped the team determine the pack parameters. The load profile is shown in Figure 6. In this case, a thorough analysis was performed on the pack to determine how well it would perform given the load profile. Mathematical M&S techniques were used to ensure the pack would perform well electrically and thermally upon realization of the pack. Often, the mathematically validated cell performance can be used with a simple spreadsheet or mathematical modeling package (such as MATLAB [3]) to predict performance of a pack that contains a number of these cells.

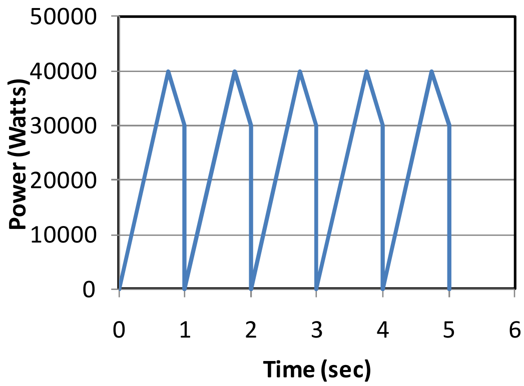


Figure 6. High Power Pack Pulse Load Requirements

Modeling/Test Data

The first step in the modeling of this pack was to test the cells to determine their capability to meet the load profile specified. This data was compared to the already existing mathematical performance models of a single cell that have been lab validated. Using the single cell data, a mathematical model can be developed for multiple cell configurations to predict performance prior to fabrication of the pack.

The load profile was appropriately scaled for testing on a single cell. Figure 7 shows the results of the testing, including the temperature rise of the cell measured in two locations, the positive lead and at mid cell. The cell level testing led to a refinement of the pack design, providing information to determine the required number of cells in the pack, and providing insight into the temperature rise that could be expected during the application of the pulse load.

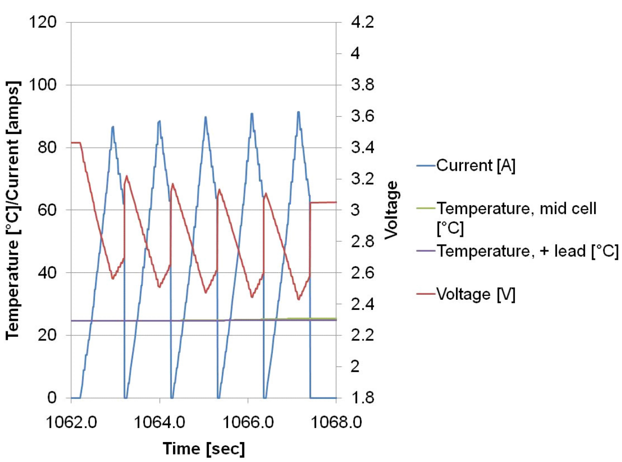


Figure 7. High Power Pack Predicted Performance.

The simple analysis/M&S techniques used in this design helped the team predict how the system could be packaged (and if it would fit in the given space claim, and how well it would perform given the aggressive duty cycle that was provided by the customer. If M&S was not used, it would have introduced a significant amount of risk from a performance and safety standpoint upon integration to the larger system.

CONCLUSION

M&S techniques are gaining momentum in the industry as designers realize that these powerful tools significantly reduce build time and cost. For battery systems, key M&S techniques include up-front mathematical modeling of small systems to predict behavior of larger systems, solid modeling, and performance of batteries using M&S of a given duty cycle and detailed thermal modeling. These M&S techniques, when used hand in hand with strong analysis will serve as an interim design validation that can be performed prior to pack integration into a system.

In all three of the case studies that are included in this paper, M&S reduced the risk of the program and mitigated significant redesign that would have resulted without M&S. The UAV solid model helped the designers determine if existing cells could meet the power and energy requirements given an existing volume on the vehicle. The thermal modeling for the XM1124 pack predicted the thermal management strategy and reduced risk to the program by validating the strategy used. For the high power pack, validated mathematical modeling of a single cell ensured that the fabricated system would meet the peak power needs without the addition of additional cells. In all of these cases, if M&S techniques were not used, potential problems would not have been identified and extensive re-engineering or experimental testing would have been necessary.

ACKNOWLEDGEMENTS

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