Battery Cell-to-Pack Scaling Laws for Electric Aircraft

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Battery pack gravimetric energy density is one of the most important, yet often miss-estimated design parameters for sizing all-electric aircraft. Proper accounting for thermal, structural, and operational safety margins are frequently lost when extrapolating performance from the cell level to the aircraft level. This paper summarizes the relevant engineering and certification details needed to better account for the penalties associated when assembling battery packs. The relationship between the cell and pack energy density is not linear, as is often assumed. Furthermore, the relationship varies depending on pack requirements, cell chemistry, and architecture. Parametric, high-fidelity models are used to determine optimal battery pack sizes over a range of conditions to better quantify technology scaling effects.

I. Nomenclature

CS	=	crash safety
DC	=	rapid discharge capacity
ϵ	=	battery gravimetric energy density ($\frac{W*hr}{kg}$)
η	=	efficiency
EC	=	explosion containment
HT	=	high temperature
κ	=	thermal conductivity
I	=	current (A)
P	=	power (kW)
R_{elec}	=	range (km)
R	=	internal cell resistance (Ω)
RD	=	rapid decompression
SOC	=	state-of-charge
t	=	time (s)
T	=	temperature (K)
TR	=	thermal runaway (K)
TS	=	temperature shock (K)
v	=	test function
W	=	mass (kg)
x	=	position (mm)
Wh	=	watt hours ($W * 3600 * s$)

II. Introduction

Due to the long development cycles for aircraft, designers attempt to forecast future attainable battery densities based on road-maps published for various cell chemistry. The lack of publicly released electric aircraft battery pack-level solutions gives vehicle designers minimal empirical data points to extrapolate results to future technologies. The X-57 battery is a common reference, using 225 Wh/kg Li-ion cells to create a 149Wh/kg pack.

Two assumptions are typically made when predicting battery weight; firstly that for a given pack architecture, that weight of the pack will scale linearly with the energy required. This assumption is generally accurate within certain

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ranges, with small exceptions due to discrete changes in weights for the battery management system (BMS) or for venting, mounting, etc. At a high-level, if you need double the number of cells, the overhead also doubles; essentially the pack could be created from two instances of the original battery pack size. The second common assumption is that improved cell energy density linearly translates to improved pack energy density. This assumption can be much less accurate, and is visualized on the green dashed curve in Figure 1.

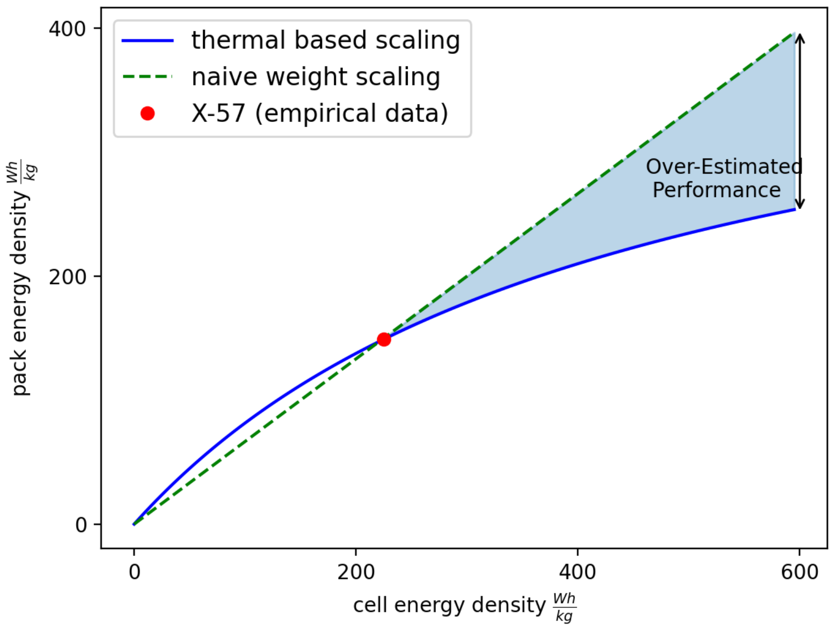


Fig. 1 Comparison of Scaling Assumptions

If a designer expects cell energy density to double in the next five years, they may fit a linear trend from origin through a known baseline (like X-57) and assume the achievable pack energy density is also doubled. If total battery pack capacity remains fixed, this means the number of cells required would be halved and the overhead would also need to be halved to achieve doubled energy density. However, a substantial amount of the overhead exists to prevent thermal runaway and the absolute energy of the cell has not changed. Cutting the overhead in half means the material would need to suddenly be twice as effective at diffusing thermal energy and containing thermal runaway. If packaging innovation and material property improvements advance as fast as cell chemistry improvements, then following the green trend-line is still possible. Otherwise pack density will likely trail in performance as cell technology improves, as shown by the blue curve in Figure 1.

Another common pitfall is to focus on managing nominal heat loads, and neglecting thermal runaway completely. These solutions are often advertised as being lightweight with high thermal performance, but fail to include any considerations for runaway scenarios. Understanding the extent of nominal heat loads is important, and covered in previous works [1], and can be important for setting realistic initial conditions for simulating runaway events.

The remainder of this paper details what factors would help contribute to more accurate battery pack-level weight scaling, with minimal discussion of the cell chemistry itself. The points outlined here have two main repercussions to consider. First that energy storage innovation requires technology improvements beyond the battery itself. Otherwise improvements in cells can quickly be lost at the pack level. Second, pack level innovation is driven by trades at the vehicle level. These designs are multidisciplinary in nature, and the optimal battery pack architecture and size is often driven by multiple considerations beyond the pack itself.

III. Battery Standards Relevant to Weight Scaling Estimates

Battery pack design for aviation must conform to multiple standards which specify design approach, performance, environmental tolerance, and safety expectations. These standards often also include testing methods, pass/fail criteria, and key metrics which battery manufacturers must report.

These requirements have varying impacts on overall pack weight, and so a review of the highest-impact items is necessary to sustain a full understanding of pack scaling performance. Table 1 lists the most directly relevant standards documents. Additional documents considered can be found in appendix A.

Table 1 Documents Governing Lithium Battery Design

Designator	Title
AC 20-184	Guidance on Testing and Installation of Rechargeable Lithium Battery and Battery Systems on Aircraft [2]
JSC 20793 D	Crewed Space Vehicle Battery Safety Requirements [3]
RTCA DO-160G	Environmental Conditions and Test Procedures for Airborne Equipment [4]
RTCA DO-311A	Minimum Operational Performance Standards for Rechargeable Lithium Batteries and Battery Systems[5]
RTCA DO-347	Certification Test Guidance for Small and Medium Sized Rechargeable Lithium Batteries and Battery Systems
TSO-C179a	Permanently Installed Rechargeable Lithium Cells, Batteries, and Battery Systems [6]
UN/DOT 38.3 T4	Manual of Tests and Criteria, Section 38.3 Lithium Metal and Lithium ion Batteries [7]

Many of these documents share similar requirements. Those focusing on the thermal design of the battery pack that are most likely to govern TMS weight are listed in Table 2. Table 3 indicates the shared requirements within the corpus. Military safety testing can be categorized into twelve different tests, with only seven being applicable to commercial applications. Of those tests, only four have a significant influence on the battery pack weight.

Table 2 Key Requirements that Impact Weight*

Designator	Requirement	General Weight of Solution
CS	Crash Safety	high
TR	Prevention of Thermal Runaway	high
HT	High Temperature Test	med
DC	Rapid Discharge Capacity	med
EC	Explosion Containment	high
TS	Temperature Shock	low
RD	Rapid Decompression	med

A. Descriptions of key requirements

1. Crash Safety ***(CS)***

The crash safety test is to ensure the battery system does not create hazardous conditions for passengers during a hard landing or crash landing. This will impact weight requirements by increasing the amount of material needed to structurally reinforce the walls and mounting points of the pack. Crash forces can be as large as a 20g acceleration over 11 ms.

2. Prevention of Thermal Runaway ***(TR)***

This requirement requires that the battery pack prevent self-sustaining, uncontrolled increases of temperature and pressure due to cell failure. In order to prevent cell failures from propagating due to thermal contact, the battery Thermal Management System (TMS) must be sized to handle large heat transients. The weight of this system will scale with the total energy released during an individual cell failure.

Table 3 Requirements Distribution in Regulations Documents

Document	CS	TR	HT	DC	EC	TS	RD
AC 20-184	x[2]	x[1]	x[1]	x[1]	x[1]	x[1]	x[2]
JSC 20793 D	*x*[3]	x	x	x	x		
RTCA DO-160G	x		x		x	x	x
RTCA DO-311A	x[2]	x	x	x	x	x	x[2]
RTCA DO-347							
TSO-C179a	x[2]	x[1]	x[1]	x[1]	x[1]	x[1]	x[2]
UN/DOT 38.3 T4	x		x	x		x	

[1] References DO-311A
[2] References DO-160G
[3] References Launch Accelerations

3. High Temperature Test ***(HT)***

This test includes measuring pack capacity and performance when operating at an ambient temperature as high as 50°C. This puts significant thermal demands on the TMS. In general, as the temperature gradient decreases, the rate of heat transfer decreases. To maintain a minimum heat transfer effectiveness the TMS must increase in size and weight.

4. Rapid Discharge Capacity ***(DC)***

This category of requirements specify the battery capacity at high discharge rates, up to 10C. (The rate required to discharge the full battery in 1/10th of an hour, 6 minutes) This intensive loading will likely produce significant thermal loads from the pack due to resistive heating. The thermal management system must be sized to safely dissipate this heat during operation. The amount of heat to be removed correlates with with the total energy capacity of the pack. *This is distinct from an "external short circuit" test in that current must flow uninterrupted from the battery.* In a short circuit test, current may be interrupted by a circuit breaker or similar interrupting or current-limiting device.

5. Explosion Containment ***(EC)***

The explosion containment test requires that, in the event of a single-cell Thermal Runaway (TR) event, all solid debris and flame is contained within the battery casing. Venting of gas and liquids is permitted in DO-311A. Weight considerations involve ensuring the structural integrity of the walls is sufficient to withstand the increased pressure due to the generation of gasses during a TR.

6. Temperature Shock ***(TS)***

This test verifies the effectiveness of the battery components when exposed to extreme temperature fluctuations, such as those encountered in flight. Temperature swings can range from 80°C to -55°C within a very short interval; weight considerations would include adequate sizing of the structure to withstand thermal stresses and maintain seals.

7. Rapid Decompression ***(RD)***

This test evaluates the ability of seals and vents to compensate for a step-wise rapid pressure change in the event of a battery undergoing rapid decompression from within the pressurized volume of the aircraft. This requirement imposes a weight penalty to ensure the battery casing will not rupture during the pressure change. Larger batteries with increased interior surface areas will require greater structural support.

IV. Pack Modeling Approach

A common aviation battery architecture encapsulates cells around a solid body of material. This interstitial solid core both contains runaway events and provides substantial mass to distribute the resulting high thermal load. The Maxwell X-57 vehicle and Embry Riddle HK36 vehicle both uses solid core pack, the former made from aluminum and the latter from a phase change composite. The Orion and LLB-2 battery modules are also constructed similarly, with the cells staggered diagonally rather than arranged in a square grid. Both configurations are examined here.

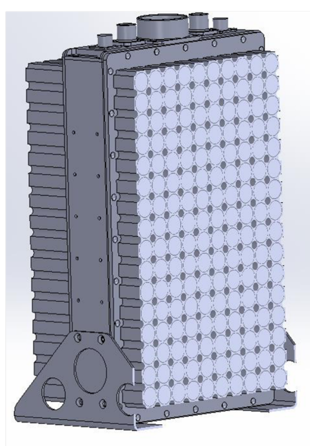
To fully understand how pack structure scales with energy density, high-fidelity thermal and structural simulations are used to determine the mass optimal pack geometry for various energy densities. A parametric geometry is used to perform shape optimization, with shape parameters defined in Figure 2c for the grid layout variant and 5 for the staggered honeycomb layout. Additional thermal constraints on boundaries and domains are illustrated in Figure 3. Simply adjusting two of these parameters can lead to drastically different designs as show in Figure 4.

Table 4 Battery Pack Design Parameters

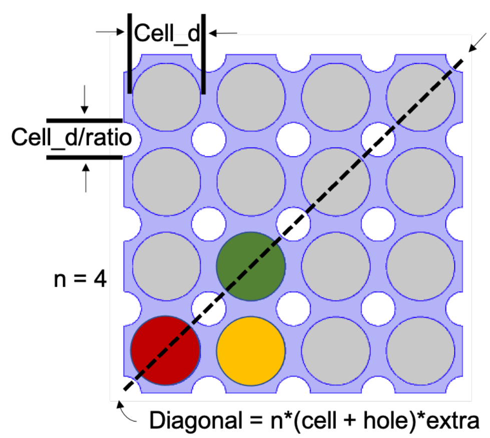
Parameter	Description	Value/Range/Units
$cell_d$	cell diameter	18 (mm)
extra	extra spacing along the diagonal	1-3 (unitless)
ratio	ratio of cell diameter to hole diameter	1-3 (unitless)
n_{cells}	Number of cells in each grid direction	any positive integer (unitless)
contact	Thermal Contact Resistance	$(1-5) * 10^{-3}$ $(\frac{K*m^2}{W})$
energy	energy absorbed into the case during runaway	10-30 (kJ)
k_{body}	thermal conductivity of the solid core	201 $(\frac{W}{m*K})$
k_{cell}	thermal conductivity of the battery cell	96 $(\frac{W}{m*K})$

By giving an optimizer control of the geometry, a mass optimal shape can be determined for any given cell size, material property, or thermal condition or limit imposed. The computational flow and data passing is visually charted using the eXtended Design Structure Matrix (XDSM) notation in Figure 6.

(a) X-57 battery module



(b) cross-section

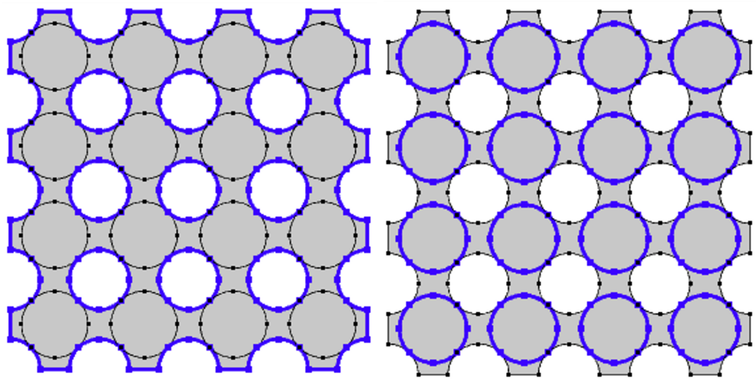


(c) parametric geometry dimension annotations, red = trigger cell, yellow/green = sensor positions

Fig. 2 Solid Core Battery Pack Architecture

The optimal shape is highly dependent on the imposed constraints. Simply imposing a maximum neighboring cell temperature will result in a design with vary large spacing between cells, with long and narrow thermal paths between them. This type of design would effectively isolate cells, but drastically hurts the volumetric energy density of the pack. It would also harm the effective thermal capacity of the pack since uneven heat loads would have difficulty spreading through the entire core mass.

Adding insulation between the cell body and the pack core would similarly achieve lower neighboring cell temperature, but reduce the packs ability to absorb heat. Therefore cells can't be sized exclusively for thermal runaway, but also must meet constraints for nominal thermal and structural performance. This creates conflicting interest in sizing cells. On one hand, the designer wants to encourage heat spread from the cell to the body, reducing thermal isolation of the cells.



(a) Insulation **(b) Thermal Contact Resistance**

Fig. 3 Solid Core Boundary Conditions

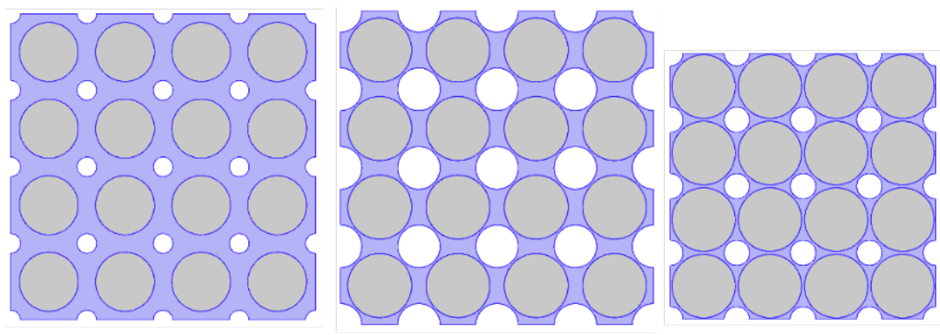


Fig. 4 Examples of variations using only two geometry variables (hole ratio and spacing), without changing cell size

On the other hand, the cells must be isolated as much as possible during thermal runaway. These competing interests make the design process ideal for multidisciplinary design optimization and analysis (MDAO) tool-sets.

Picking a constraint to meet nominal thermal performance can be challenging, because the definition of normal operation varies greatly between applications. Thermal runaway constraints are easier to quantify since they are often better defined and related directly to material properties.

To quantify the spread of the core heat in simple terms, the percent difference in max temperature between a vertically adjacent cell and diagonally adjacent cell are compared. The cells of interest are marked yellow and green in Figure 2c. By limiting the temperature gradient between neighboring cells during runaway, the optimizer is forced to rely more heavily on thermal capacity to reduce peak temperature, rather than thermal isolation.

High fidelity modeling is performed with two separate tools to ensure computational agreement. The COMSOL multi-physics software as well as the open-source FENICS platform [8]. The problem is set up identically in each environment, solving the underlying transient heat equation PDE.

$$\int_{\Omega} \frac{u^{k+1} - u^k}{k} v \, dx = - \int_{\Omega} \kappa \nabla \mathrm{um} \cdot \nabla v \, dx.$$

where $u = u(x,t)$ is the thermal capacity at location $x \in \Omega$ and time $t \in [0,T]$, with a test function v. The $\theta-$method for the time discretization is used with $u \approx \mathrm{um} := \theta \, u^{k+1} + (1-\theta) \, u^k$ with $\theta \in [0,1]$. κ is the thermal conductivity.

V. Thermal Modeling Assumptions

The amount of energy released by a cell during thermal runaway has been extensively researched for cylindrical format cells, although has been found to be highly stochastic. [9] Generally speaking, as the energy density or capacity

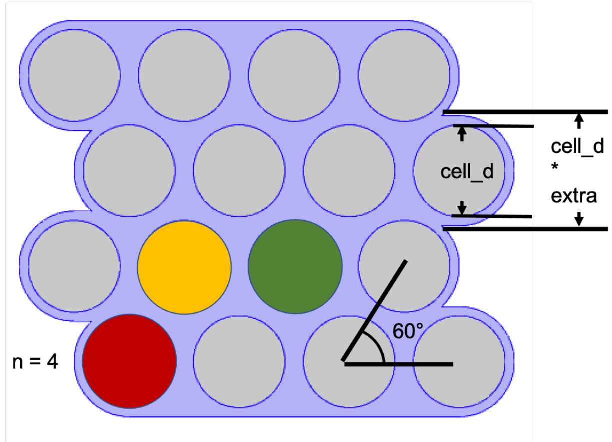


Fig. 5 Staggered "honeycomb" cell arrangement geometry parameters

of the cell increases, the runaway energy released from the cell also increases. Data taken from fractional calorimetry experiments shows that 20kJ released per Amp-hour of capacity is a good first estimate for high energy cells. However, there is much more variation in the percentage of that energy that is transmitted to the surrounding pack material versus ejected as hot gas. Anywhere between 20 and 70 percent of the energy is ejected as gas, with higher ejection rates being defined as having proportionally less energy thermally disbursed within the pack. Techniques for reliably reducing the transmitted heat to the cell case would certainly benefit system performance, making it an ideal candidate for future study.

Solutions are also sensitive to the thermal properties of the cell, which can be challenging to measure across many chemistry types and manufacturers. For this analysis, cell properties are characterized as separate bulk anisotropic properties based on materials, which differ in the radial and axial direction. [10] The bulk thermal capacity is conservatively assumed to be 0.8 $\frac{J}{gK}$ [11] and the axial thermal conductivity is assumed to be 28 $\frac{W}{mk}$. [12] The radial thermal conductivity through the layers of the jellyroll varies widely in literature between 3 and 0.4 $\frac{W}{mk}$. [13] The temperature threshold where self-heating and propagation begins is chosen to be 135 °C. Thermal resistance between the jellyroll, case, liner, and core is lumped into a single value. 0.05mm of Kapton 1.9 $\frac{C}{W}$, 0.75 $\frac{C}{W}$ metal to metal resistance. [14]

VI. Structural Modeling Assumptions

A highly conservative 20g acceleration load is simultaneously applied both downward and laterally, with a constraint on maximum Von-Mises stress within the core structure. For many aeronautic applications, such as X-57, loads do not exceed 5g in any direction. Since these geometries ignore fastener design, the model overlooks potential stress points coming from mounting locations. Although mounting designs are beyond the scope of this paper, the same analysis workflow could be applied with more detailed designs. Cells are assumed to be rigidly fixed within the core, however different material properties are assigned to the core and cells. Artificially high stresses can be a symptom of finite element mesh resolution around sharp corners, so results around the boundaries are ignored when required.

VII. Cell Performance Metrics

VIII. Results, Conclusions, Future Work

[This portion of the paper will be completed for the final paper submission]

The first study will show how battery pack energy density scales against changes in cell energy density.

The second study will show how battery pack energy density scales against changes in core material properties.

The third study will demonstrate sensitivity to external cooling, and cell insulation.

Future work will examine new pack architectures using materials with advanced heat conduction and specific heat properties.

Acknowledgments

The authors would like to thank the NASA Transformational Technologies and Toolsets (TTT) for sponsoring this work, and the X-57 team for providing the initial inspiration for this work.

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Appendices

A. Documents Considered

These documents were reviewed and found to lack requirements specific to lithium battery development. They are included here as they indirectly impact the aircraft development cycle and aircraft integration.

Table 5 Other Aircraft Standards Documents

Designator	Title
14 CFR Part 23/25/33/35	Code of Federal Regulations Normal Category/Transport Category/Aircraft Engines/ Propellers
AC 20-107B	Composite Aircraft Structure
AIAA G-077	Guide for the Verification and Validation of Computational Fluid Dynamics Simulations
AIAA S-136	Battery Safety Standard for Space Applications
ANSI/AIAA S-144	Large, Prismatic Li-ion Space Cell
GLM-QE-8715.1	Battery Safety and Design Manual for Payloads
IEEE 1625-2008	IEEE Standard for Rechargeable Batteries for Multi-Cell Mobile Computing Devices
IEEE 1725-2011	IEEE Standard for Rechargeable Batteries for Cellular Telephones
ISO TC-197	Basic Considerations for the Safety of Hydrogen Systems
MIL-HDBK-17-1F	Volume 1. Polymer Matrix Composites Guidelines for Characterization of Structural Materials
MIL-PRF-32052	Performance Specification for Batteries, Rechargeable, Sealed
MIL-STD-1541A	[CANCELLED] Electromagnetic Compatibility Requirements for Space Systems (Alternatives listed in $MIL - STD - 1541A\_Notice - 1$)
MIL-STD-464C	Electromagnetic Environmental Effects, Requirements for Systems
MIL-STD-461F	Requirements for The Control of Electromagnetic Interference Characteristics of Subsystems and Equipment
MIL-STD-704F	Aircraft Electric Power Characteristics
MIL-STD-810	Environmental Engineering Considerations and Laboratory Tests
NASA-RP-1353	Primary Battery Design and Safety Guidelines Handbook
NASA-SSP-41172U	Qualification and Acceptance Environmental Test Requirements
NASA-STD-0005	NASA Configuration Management (cm) Standard
NASA-STD-5001B	Structural Design and Test Factors of Safety for Spaceflight Hardware
NASA-STD-7009	Standard for Models and Simulations
NASA-TM-2005-213995	Preliminary Results of NASA Li-ion Cell Verification Testing for Aerospace Applications
NASA-TM-2008-215154	Progress of Ongoing NASA Li-ion Cell Verification Testing for Aerospace Applications
NAVSEA S9310-AQ-SAF-010	Technical Manual for Batteries, Navy Lithium Safety Program Responsibilities and Procedures
RTCA DO-178C	Software Considerations in Airborne Systems and Equipment Certification
RTCA DO-254	Design Assurance Guidance for Airborne Electronic Hardware
SAE ARP 4754	Aerospace Recommended Practice
SAE ARP 4761	Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment
SAE AS50881E	Wiring Aerospace Vehicle
SMC-S-008	Electromagnetic Compatibility Requirements for Space Equipment and Systems
SMC-S-017	Li-ion Battery for Spacecraft Applications
TOR-2007-8583-1	Li-ion Battery Standards for Spacecraft Applications
TOR-2007-8583-2	Acquisition Standard for Li-ion Based Launch Vehicle Batteries
TOR-2008-8583-8215	Space and Missile Center Compliance Specifications and Standards

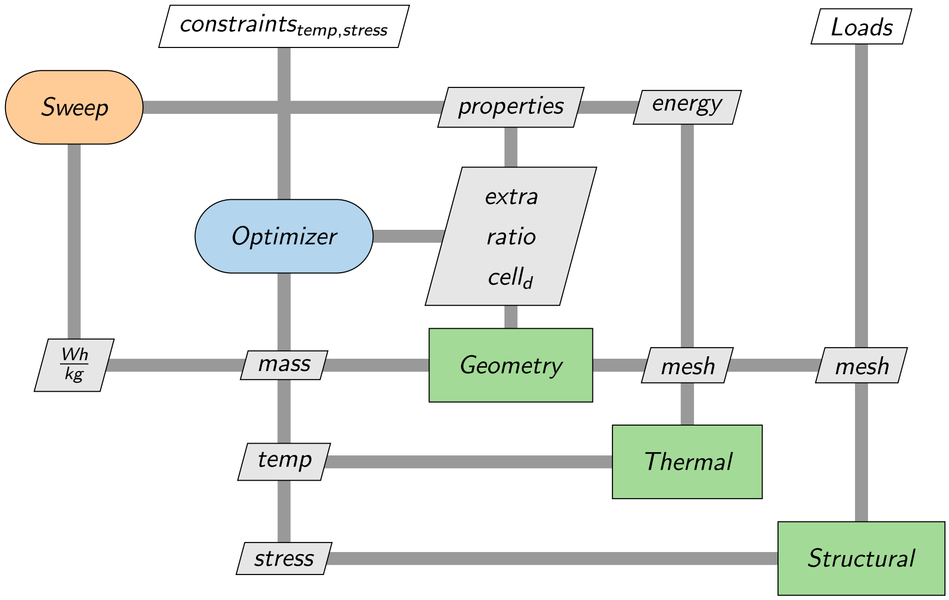


Fig. 6 Design structure (XDSM) for determining the optimal pack design for a sweep of inputs.

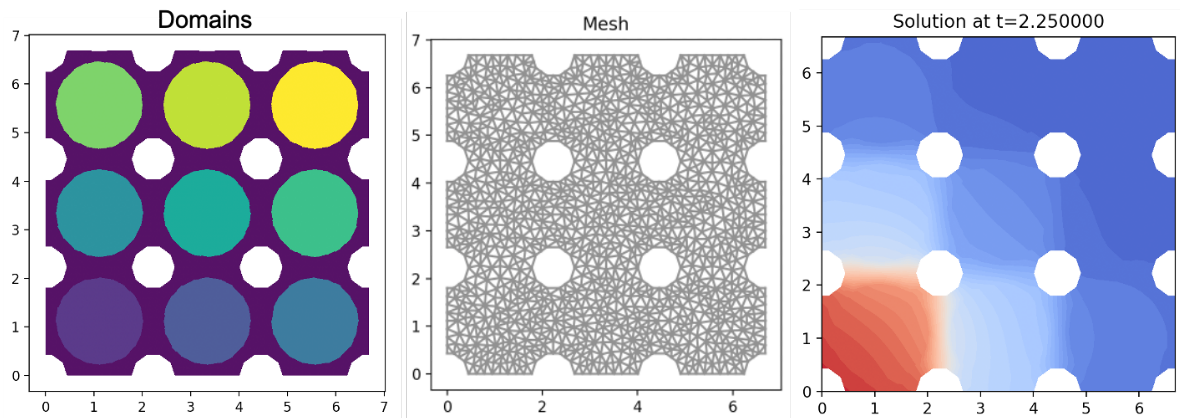
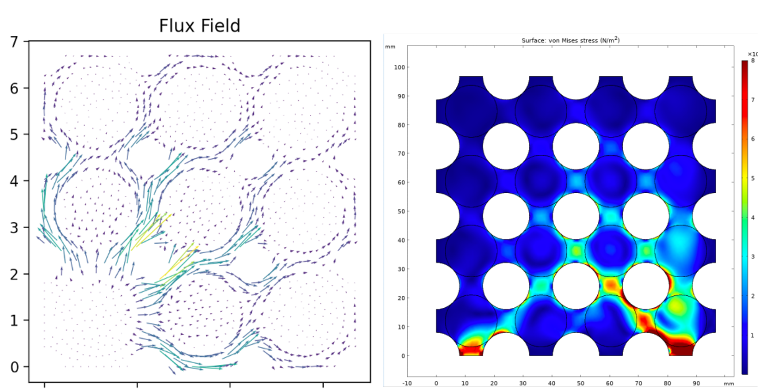


Fig. 7 Automatic resizing, to mesh generation, to FEM simulation



(a) Thermal Flux

(b) Von Mises Stress

Fig. 8 Thermal and Structural Analyses at for Multiple Configurations