Application of Emerging Structural Energy Storage Technology to Small Satellite Systems

Philip Lyman, John Olson, Timothy Feaver
Boundless Corporation
5445 Conestoga Ct., 1-B, Boulder, CO 80301 (303) 415-9029
plyman@boundlesscorp.com, jolson@boundlesscorp.com, tfeaver@boundlesscorp.com

ABSTRACT: Boundless Corporation and Composite Optics Inc. (ATK/COI), with funding from NASA and the Missile Defense Agency, are developing unique multifunctional structure technology that incorporates energy storage devices as load bearing elements in structural panel assemblies. The technology offers opportunities to save mass and volume that are especially attractive for small satellites.

This paper introduces Boundless' approach to structural energy storage and describes the development status of both structural lithium-ion batteries and structural ultracapacitors. Both devices employ carbon composites that combine energy storage and structural functionality at the level of the electrode.

NASA's proposed Magnetospheric Constellation (MAGCON) mission served as a straw-man small satellite application to guide structural energy storage development. Working prototype panel assemblies have been delivered to NASA and are undergoing evaluation.

The emphasis of this paper is on system-level implications of adopting structural energy storage. It discloses various means to realize maximum mass and volume benefit from structural energy storage while minimizing the impact on other satellite subsystems. Effects of adopting structural energy storage on integration and test flow are also addressed.

1. INTRODUCTION OF STRUCTURAL ENERGY STORAGE

Structural Energy Storage Concept: Structural energy storage reconfigures the materials of a battery to serve as structural load paths within a system, thereby saving weight and volume. Inert battery materials such as packaging, bulk current collectors and secondary structure are especially well suited to serve dual functions since they do not participate in chemical reactions and have solid physical characteristics. Electrochemically active materials and electrolytes are less well suited to serve dual functions since they participate in chemical reactions and ion transport and are, by their nature, mechanically weak.

Spacecraft structure and batteries rank high on most spacecraft mass breakdowns. Combining the functionality of these elements presents an opportunity to reduce spacecraft mass, or increase performance for a given mass. The new approach effectively reduces the mass of the system to the extent that the battery successfully replaces inert spacecraft structure. Significant volume savings can also be achieved by embedding the battery within a volume occupied by pre-existing inert structural elements.

Illustrative Embodiment: A structural sandwich panel incorporating structural energy storage is shown in **Figure 1**. This panel is 15 cm x 15 cm x 2 cm and is targeted for application to a NASA conceptual small-satellite mission called Magnetospheric Constellation (MAGCON).

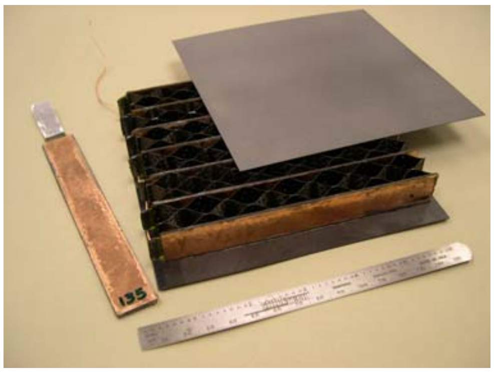

Figure 1. Prototype Structural Battery Panel

The MAGCON mission envisions up to 100 small spacecraft in highly elliptic orbits with perigee and apogee spanning the magnetosphere. Such dispersed fleet of satellites could capture simultaneous science data on the interaction of the solar wind with the magnetosphere over huge distances. This would improve our understanding of the dynamic structure of the magnetosphere in a way that cannot be done with a single, larger satellite[1].

The panel shown in Figure 1 uses electro-chemically active ribs interspersed with inert structure. The ribs, one of which is shown adjacent to the panel, are liquid lithium-ion battery cells. The panel has a nominal capacity of 1.25 Ah at a nominal discharge voltage of 3.7 volts. The panels serve as the side panels of an octagonal spacecraft that spins about its symmetry axis.

Figure 2 presents a schematic cross-section of the ribbon-like reinforcing rib, called a "bicell" because it is comprised of a two-sided cathode sandwiched between two anodes. The anodes are fabricated from high-modulus carbon fabric. Part of the fabric is saturated with resin yielding a high-strength structure. Free fibers are exposed to the electrolyte so that they intercalate lithium ions during charge and release ions during discharge.

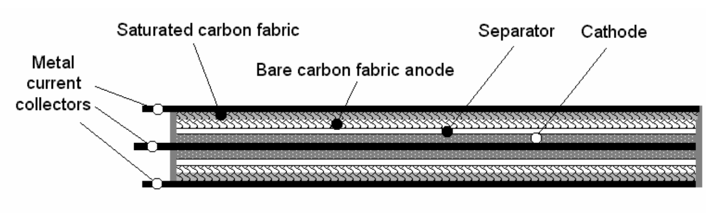

Figure 2. Battery anode provides strength and stiffness that is integral to the electrochemically active assembly.

Quantifying Benefits From Structural Energy Storage: The basic measures of merit for battery cells or assemblies are:

- Specific Energy: energy stored per unit mass
- Specific Power: power delivered per unit mass
- Energy Density: energy stored per unit volume
- Power Density: power delivered per unit volume

Structural energy storage devices can be evaluated on both the panel and cell levels. At the panel level, energy and power density are effectively infinite if the battery is embedded in a pre-existing structural sandwich panel without increasing the volume of the panel. This volume efficiency is particularly attractive for small satellites. Several other developers have pursued means to embed energy storage within structures[2-4]. However, these efforts amount to attaching energy storage to existing structure. By contrast, Boundless is showing an improved mass benefit is realized if the battery elements themselves can carry loads, thereby reducing the mass of the original structure and effectively increasing specific energy and power.

To compare the specific energy performance of a structural battery panel to that of a traditional stand-alone multicell battery pack, we introduced the definition of Effective Specific Energy shown in Equation 1.

$$ESE_{panel} = [E_{panel}] / [M_{panel} - M_{equivalent}] \qquad \textbf{(1)}$$

Where:

E_{panel} is the capacity in Wh of a structural battery assembly
M_{panel} is the mass of the structural battery assembly
$M_{equivalent}$ is the mass of an inert structural assembly with equivalent structural

The cell-level performance of a structural battery can be compared to that of an inert structural material such as aluminum. This allows us to assess dual-function performance at a lower level of assembly.

$$ESE_{bicell} = [E_{bicell}/M_{bicell}] * [(S_{aluminum}/D_{aluminum}) / \{(S_{aluminum}/D_{aluminum})-(S_{bicell}/D_{bicell})\}] \qquad \textbf{(2)}$$

Where:

E_{bicell} is the capacity in Wh of a structural bicell
M_{bicell} is the mass of the bicell
$S_{aluminum}$ is the strength or stiffness of a reference structural material (aluminum)
$D_{aluminum}$ is the density of a reference structural material (aluminum)
S_{bicell} is the strength or stiffness of the bicell
D_{bicell} is the density of the bicell

In Equation 2, the second square-bracketed quantity is essentially a non-dimensional comparison of the bicell structural performance to that of a reference structural material (aluminum).

Effective specific power, energy density and power density all have similar equations that tie back to the mass and volume performance of reference assemblies or materials.

Bicell rail-shear properties are one of the most important structural characteristics of interest. This is because the bicell's planned application is as a structural element within a sandwich panel core. Sandwich panel designs tend to be driven by bending stiffness, and panel bending translates into plate shear in the bulk core. Core plate shear, in turn, translates into rail shear in the individual discrete elements of the core.

High-Power and Ultracapacitor Variations of Structural Energy Storage: The benefits of structural energy storage are amplified in high-power applications. All battery cells and assemblies designed for high power have a disproportionate amount of inert material in current collectors. This material may be used to additional advantage by structural batteries. First, more bulk current collector is used to provide low-resistance paths. Second, inert material is used for thermal management to conduct heat out of the assembly and maintain a safe operating temperature. Since a structural energy storage device employs the extra inert material for structural support, the mass discount is potentially greater for high-power applications.

Figure 3 illustrates a further advantage of structural energy storage for high-power applications. This figures shows the relative temperature of a compact spiral-wound lithium-ion cell next to that of a cell of the same design, but unwound and laid flat. The configuration with the greater surface area more effectively transfers heat out of the cell. The structural energy storage approach distributes thin, ribbon-like cells throughout a sandwich panel, thereby greatly enhancing such heat transfer. Thermal control in high-power applications is especially important for lithium-ion batteries because of the onset of exothermic decomposition reactions above 100ºC.

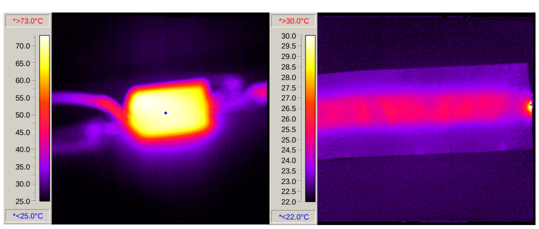

Figure 3. Battery configurations that expose high surface area allow operation at lower temperatures than compact spiral-wound or prismatic designs.

Ultracapacitor technology offers another variation on structural energy storage. Ultracapacitors rely on the formation of energy storing ionic double layers on high-surface-area electrodes. They are distinct from batteries in that the surface materials do not undergo electrochemical reactions. They are similar to batteries in design and a substantial amount of material is used for bulk current collection and packaging. **Figure 4** presents a dual-function structural ultracapacitor electrode. The electrode uses activated carbon fabric that achieves 40-60 Farad per gram.

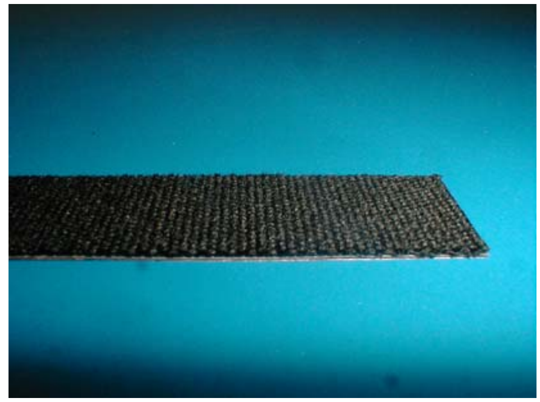

Figure 4. Dual-function carbon composite ultracapacitor electrode

2. MISSION DRIVERS – WHEN TO APPLY STRUCTURAL ENERGY STORAGE

A design process that is responsive to mission objectives and requirements results in effective development of complex space systems. Multifunctionality and structural energy storage are likely to be more costly than the use of traditional, stand-alone components. Therefore its use should be targeted at systems with a specific need. Requirements analysis; derivation of lower-level requirements from high-level mission and system requirements can be used to indicate such a need. Drivers for selection of structural energy storage are discussed in the following paragraphs. A top-level view of the requirements flow-down is presented in **Figure 5** on the next page.

Energy, Power and Battery Sizing: The energy storage and power profile of a small satellite are established by:

- Payload (instrument) load power, duty cycle and operating modes
- Orbit and attitude effects on eclipse duration and solar array view factor vs. time
- Spacecraft bus loads, modes and duty cycles such as transmitter duty cycle
- Constraints on battery rates and depth of discharge to achieve the required mission reliability and life

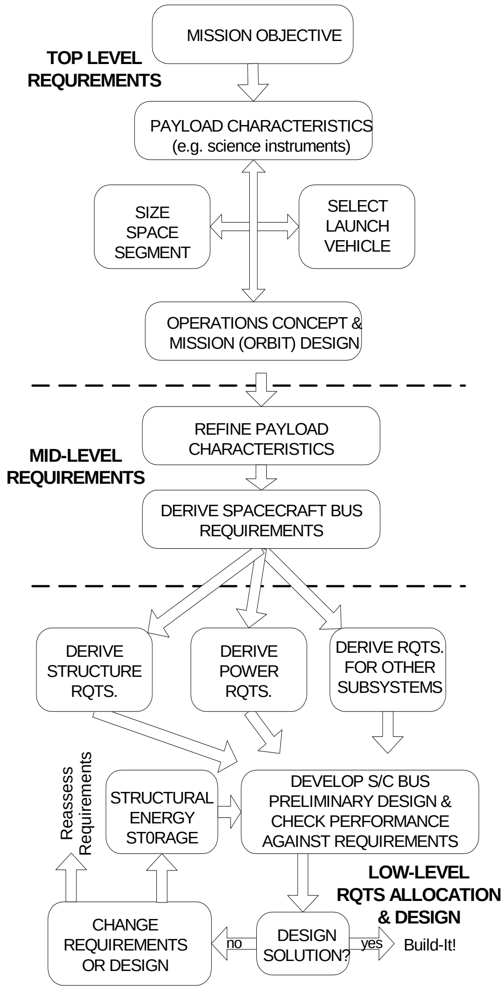

Figure 5. Flow-down of requirements drives need for structural energy storage technology for some missions.

All of these parameters trace back to the high level mission requirements, mission design and top-level system design. Payload technical requirements and operating profiles affect power consumption and data rates. The data rate drives computing power and radio transmission power and frequency. Ultimately, these factors set the requirements for battery capacity with its attendant physical size and mass.

Launch Vehicle and Structural Loads: The selected launch vehicle and fairing configuration define limits on mass and volume of the space segment. Launcher selection also establishes the launch environment including quasi-static, random and acoustically-induced accelerations and forces. Knowledge of these environments, when coupled with the space segment mass properties, allows engineers to derive the structural loads that must be sustained by the system. Launch vehicle selection also establishes the lower bound on the structural resonant frequencies of the coupled system (launcher plus spacecraft). Limits on allowable frequency ensure launch vehicle controllability and ensure that the spacecraft does not contact the launch fairing during flight. Finally, acceptable design margins dictate some degree of structural over-design. These margins are coupled to the fidelity of verification and to the desire to avoid over-test of flight articles. A lower margin is acceptable if more testing is used to validate analytical performance predictions. However, a test article is not flown if it is over-stressed by testing.

System Reliability: Most small-satellite missions are intended to be low-cost missions, and therefore do not incorporate extensive redundancy. Employing block redundancy, or N for M partial redundancy schemes has a corresponding impact on battery size and mass.

Mission Drivers Summary and Case in Point: For some missions, the requirements for energy storage and launch vehicle compatibility, combined with the myriad of functional and performance requirements for the rest for the space segment, create a situation for which a traditional approach does not yield a design solution. Such a situation arose early in the 1990s when a team, including one of the authors, was working on the conceptual design of the IRIDIUM low-Earth orbiting communications spacecraft. Original planning called for the constellation's individual replacement satellites to launch on the low-cost Pegasus launcher with its mass and volume constraints. The spacecraft were predicted to draw high power over ground population centers with the spacecraft in eclipse. High reliability and long life were needed to limit the total life cycle cost and ensure user communication access. An adequate battery size drove the structure strength and mass in a cat-chases-tail scenario. This was at least one factor that led to the eventual deployment of a larger satellite requiring multiple launches on medium-class launch vehicles, at significantly higher total system cost. Multifunctional design and structural energy storage, had they existed, may have allowed a solution within the originally intended mission constraints.

3. DESIGN IMPLICATIONS OF USING STRUCTURAL ENERGY STORAGE

Once mission requirements establish a need for structural energy storage, complicating factors beyond those of the structural and power subsystems remain that also affect spacecraft design and development. Thermal control and integration & test are two specific areas requiring extra coordination.

Design and analysis tools for structural, power and thermal subsystems come together at the system-level to verify performance versus requirements. In the new approach these tools must be used concurrently at a lower-level of assembly to ensure a design solution that satisfies requirements across the multifunctional structural energy storage assembly.

The following subsections expand upon the design implications and describe high-level design solutions and design methodologies to ensure a cohesive spacecraft design.

Thermal Control Implications: Batteries usually have the narrowest allowable temperature range of any spacecraft component. While most active electronics can operate over a range from –10°C to +60°C, lithium-ion batteries perform best between 10°C and +40°C. Traditionally, the thermal control subsystem employs battery isolation and independent control features, both passive and active, to maintain battery temperature separate from the rest of the spacecraft system.

Use of structural batteries could result in complications involving control of temperature gradients between battery cells. Unequal temperatures can affect proper current sharing. A warm battery cell may accept more charge, than does a cooler neighbor, resulting in string capacity imbalance. This cell divergence is a serious concern for power system designers. Controlling thermal gradients across cells distributed in a large structural panel assembly could be more challenging than doing so within a compact stand-alone battery assembly.

As with traditional batteries, thermal control of a structural battery can be complicated if it is installed adjacent to major heat sources or sinks. For example, if the structural battery were used to support a high-power transmitter, keeping it from being heated beyond its acceptable high-temperature limit could prove challenging. Thermal coupling between batteries and other components would increase if the other components were mounted directly onto a structural battery panel.

One positive aspect of thermal control for a structural battery lies in its ability to efficiently remove internally generated heat. A percentage of power delivered by any battery pack shows up as heat within the battery. This is due to internal resistance and reaction kinetics. Traditional compact cells and battery assemblies do not provide especially good heat conduction. However, the distributed nature of the cells in a structural battery facilitates heat removal.

Thermal Control Solutions: A number of measures can be taken to facilitate thermal control. Spacecraft with stand-alone batteries routinely employ some of these measures, but their importance increases with structural energy storage to ensure a cohesive design.

Low conductivity structural connections: Use of low-conductivity material such as titanium at mechanical interfaces decreases thermal coupling with the rest of the structure.

Hig- conductivity face-sheets: Use of high - conductivity face sheets helps maintain uniform temperature across the panel, avoiding battery cell temperature gradients.

Support low-dissipation items: Avoid placement of high-power items such as transmitters onto the structural battery and favor mounting low-power items such as on/off switching electronics.

Independent thermal zone: Provide a dedicated thermal zone with heater control, external radiators, louvers and internal blankets, as necessary, to isolate this portion of the structure and provide tighter thermal control than for the rest of the system.

Integration and Test Implications: For most spacecraft, the structure is assembled first. Then, components are integrated one by one to create the fully functional system. Often a test battery is integrated as a workhorse to support integration and test activities. The flight battery is substituted late in the flow so as to preserve maximum on-orbit battery life. If the battery and structure are one, then either the battery is integrated early or the structure is integrated late as compared to the traditional flow.

Integration and Test Solutions: It is possible that the core structure has sufficient integrity that temporary removal of structural battery elements does not result in deformation. This would allow late integration of a structural battery without much difficulty. If the structure depends on the presence of the battery panel, there are means to mitigate the impact on structural energy storage has on I&T.

No cold storage: Older nickel batteries benefit from cold storage. This is one of the drivers for waiting until late in the integration flow to install the battery. Lithium-ion batteries operate at warmer temperatures and are compatible with room-temperature storage.

External test battery at arming plug: Spacecraft include a plug that is externally accessible to allow battery connection and system "arming" just prior to launch. This plug allows an easy means to connect a test battery in place of the flight battery. This would allow a flight structural battery to remain in storage even after installation. The work-horse battery then supports early integration and test activity.

Strong-back MGSE: The spacecraft mechanical ground support equipment can be designed to serve as structural support, allowing installation and removal of the battery panel.

Support assembly that is normally late: The structural energy storage could also be integrated into a modular assembly, having significant structure, that typically is integrated late in the flow. Two items often fit this description: the solar array and the propulsion subsystem.

Implications for Design and Analysis Tools: An integrated structural battery assembly will require design and analysis across three disciplines: structure, power and thermal. Spacecraft developers tend to think of the analytical tasks occurring in tandem at system-level. At first glance it appears onerous to mix these analytical jobs at lower levels of assembly, but this is not necessarily so.

Design and Analysis Similarities to the Present State of the Art: In fact, all spacecraft components and subassemblies require some level of simultaneous analytical work across multiple engineering disciplines.

Similarities to Stand-Alone Battery: A stand-alone battery assembly must be sized for capacity, thermal control (usually heat conduction to base-plate) and structural integrity. The differences lie in the scale of the analytical work and the simplicity of the requirements and interfaces. But all three analytical considerations apply: power, thermal and structural.

Similarities to Solar Array: A solar array subsystem presents a better example of analogous development. The solar array involves complex mechanical interfaces with structural loads that are directly driven by the launch vehicle environment. Deployed solar array modes and frequencies must be compatible with attitude control. Power generation drives the surface area, resulting in strong coupling between the power and structure analyses. Lastly, the thermal performance of the array strongly couples with the voltage and current performance of the photovoltaic elements. Solar array development practices provide the best guide with respect to "concurrent design" of a structural energy storage assembly.

4. DESIGN EXAMPLES

This section presents illustrative examples of how multifunctional energy storage could be incorporated into a small spacecraft system. The first example is explored in detail, showing how mission requirements, requirements flow-down and design and analytical processes may be used to arrive at a design solution. Subsequent examples are presented as cursory design concepts and are intended to trigger application-specific thinking and new ideas.

Multifunctional Spacecraft Sidewall Having Structural Energy Storage, Power Switching, Charge Control and Battery Thermal Control Functions: Often traditional spacecraft designs incorporate a stand-alone battery that mounts to a dedicated spacecraft sidewall with a large outward-facing radiator. This design solution was employed, for example, on NASA GSFC's WIRE spacecraft and carried forward to their TRIANA spacecraft [5,6]. It is also used on larger systems such as NASA's ICESat spacecraft. This approach offers advantages for a traditional spacecraft:

- Facilitates thermal control by providing a dedicated battery radiator
- Facilitates thermal control by mounting battery separately from other active components
- Facilitates late change-out of test battery (whole panel may be removed for battery replacement)

The importance of these advantages are amplified for a structural battery assembly. So, a first example is proposed that adopts this basic approach – replacing the stand-alone battery and dedicated side-wall with a structural battery sandwich panel. Power switching and charge control may be included as part of the assembly to enhance multifunctionality.

Straw-man requirements derivation: A hypothetical set of requirements and flow-down is presented in **Figure 6**. We envision a nadir-pointed science mission that requires a small satellite at 600 km altitude in a sun-synchronous orbit with a 9:00 ascending node. Key derived requirements for the structural battery panel include physical, structural, battery capacity and thermal interfaces. These are presented at the bottom of Figure 6. The figure omits many spacecraft requirements that are not germane to the structural battery (e.g., data rates and on-board data storage capacity).

Mission, Top-Level Requirements
-Nadir-looking science instrument
-Sun-synchronous orbit with 9AM ascending node
-600 km altitude
-Pegasus launch
-One year design life

Space Segment & Bus Requirements
-Rectangular prism S/C bus occupying 40% of fairing volume
-Deployed, fixed solar arrays
-200 watt orbit-average power
-300 watt peak load for 10 minutes
-28 volt nominal power
-32 minute longest eclipse (28 to 32 minute range)
-6000 eclipses over design life
-Fixed yaw orientation with one face on the anti-orbit normal always away from the sun

Structural Battery Assembly Requirements
-71 cm wide x 50 cm tall (LV axis) x <4 cm total thickness
-<15 kg
-Strength & stiffness equivalent to 1" thick honeycomb having 3.8 lb/cu ft Al core and 30 mil Al face sheets
-8 lithium ion cells in series for 28 volt nominal discharge
-12.7 Ahr capacity (200 watt load for 32 minute eclipse & depth of discharge limited to 30%)

Figure 6. Derivation of Key Requirements for Structural-Battery Side-Wall

Goal for enhanced performance: The derived requirements at the bottom of Figure 6 should impose mass and volume constraints that are tougher than could be achieved with a traditional approach. There is limited value in specifying requirements for a structural battery implementation that can be met by the older approach of using stand-alone components.

Design Process: **Figure 7** presents the processes used to derive a structural energy storage design.

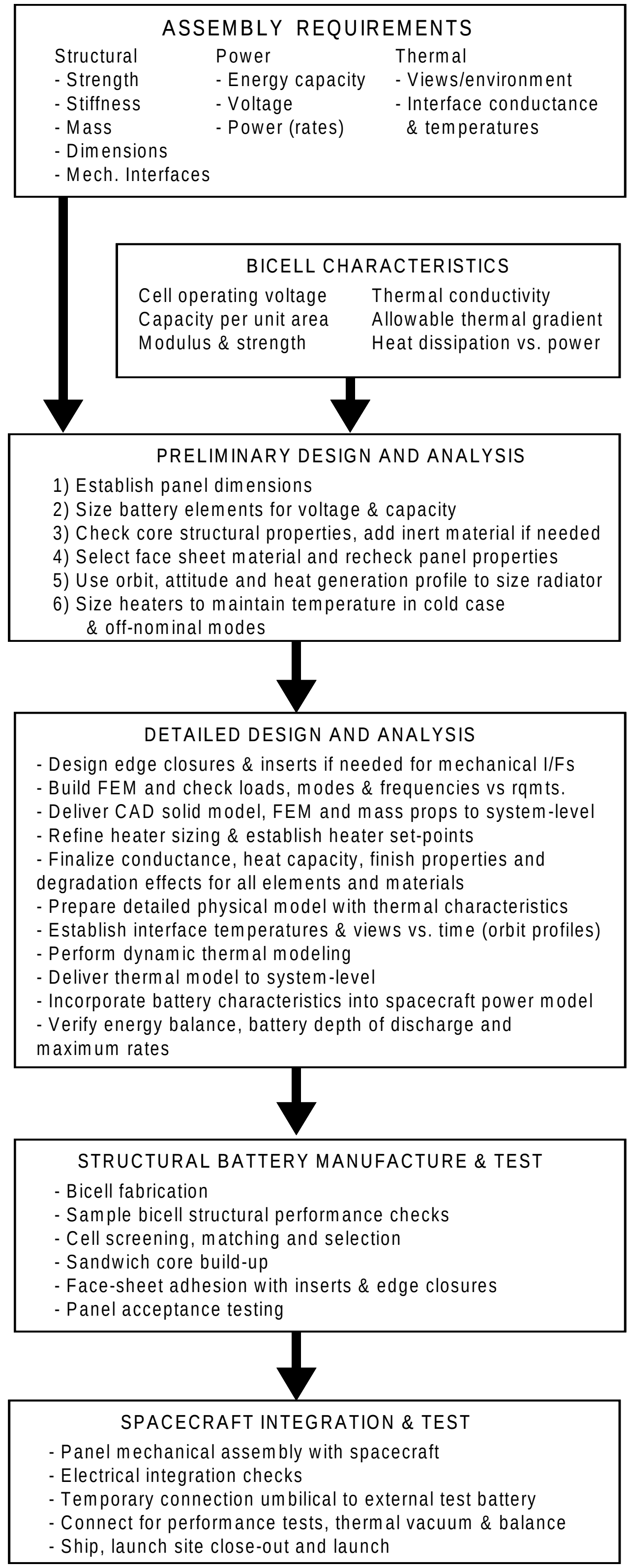

Figure 7. Flow Shows Structural Battery as Part of a Spacecraft Development Process

Preliminary Design Concept: A suitable preliminary design is shown in **Figure 8** on the following page. Corrugated battery bicells are formed into two types of Core Blocks as shown in **Figures 8a and 8b**. The block dimensions are 24.75 cm by 17.5 cm with a thickness of 1 cm. The corrugations run the length of the rectangle in the Type I Core Block and widthwise in the Type II.

The electrochemically active core material has a total surface area of ~875 cm^2 in both Type I and Type II blocks, and the capacity of each block is 6.25 Ah.

Figure 8c shows an exploded view of the panel assembly. Two layers of core, each holding 8 Core Blocks nest within divider frames. The divider frames incorporate parallel and series electrical interconnects. Face sheets are bonded to the top and bottom surfaces with a third face sheet serving as a divider between the two layers. The face sheets include a thin layer of Kapton film for electrical insulation. This same film material and design technique is used beneath solar cells on photovoltaic assemblies.

We align the corrugations within adjacent core blocks in all three directions, perpendicular to one another. This design feature offers good bending resistance for the panel in all directions.

Electrically, the Core Blocks are connected in parallel pairs to give a total of 12.5 Ah per pair. Each of these pairs forms a single series-connected battery cell. The numbers 1 through 8 identify the series cells in Figure 10c.

The series connections run a serpentine course as viewed from the long edge of the panel. This design feature provides relatively small current loops, with adjacent loops opposing one another to minimize spurious magnetic fields – an important consideration for some spacecraft.

Structurally, the battery core material occupies just over 5% of the core volume in the design shown in Figure 8. By comparison, 3.8 pound per cubic foot (PCF) aluminum honeycomb core has 2.25% of the core volume occupied by aluminum. So, it is reasonable to estimate that the configuration shown will provide ample strength and stiffness to the panel assembly.

As described by the design process shown in Figure 7, additional design and analysis tasks would need to be completed to verify the performance and benefits of this preliminary design. And higher fidelity design and analysis tasks remain to be accomplished in the detailed design phase.

Alternative Designs Incorporating Structural Energy Storage: The previous section presented one preliminary design concept for incorporating structural energy storage into a small spacecraft**.** There are several other design embodiments of structural energy storage. **Figure 9** lists alternative spacecraft design approaches. Each alternative has advantages and disadvantages, most of which tie back to thermal control or integration and test implications described in Section 3. Advantages and challenges for each alternative approach are listed qualitatively in the Figure.

5. DEVELOPMENT STATUS

The structural energy storage technology described here is at a relatively low Technology Readiness Level (TRL) per the NASA definitions. It is considered to be at TRL 3. Electrochemically compatible materials have been identified, anode intercalation proven and prototyping has been completed for electrodes, bicells and small panel assemblies providing empirical proof-of-concept evidence.

To achieve higher readiness levels will require additional development. Further design optimization is needed to maximize the strength vs. capacity (or power) of the electrochemically active core material. Material and process controls need to be improved such that consistent performance is achieved from one assembly to the next. Design improvements for sealing and ease of electrical interconnections are also needed. Scale-up from lab-scale fabrication to larger production quantities will be required.

Of great importance is qualification testing. Environmental extremes must be applied to demonstrate that the materials, designs of low-level assemblies and full panel assemblies will survive launch environments and operate in the space environment over mission life-times.

We also look forward to a flight demonstration experiment, on a technology demonstrator mission as a pathfinder for more widespread application of this new technology.

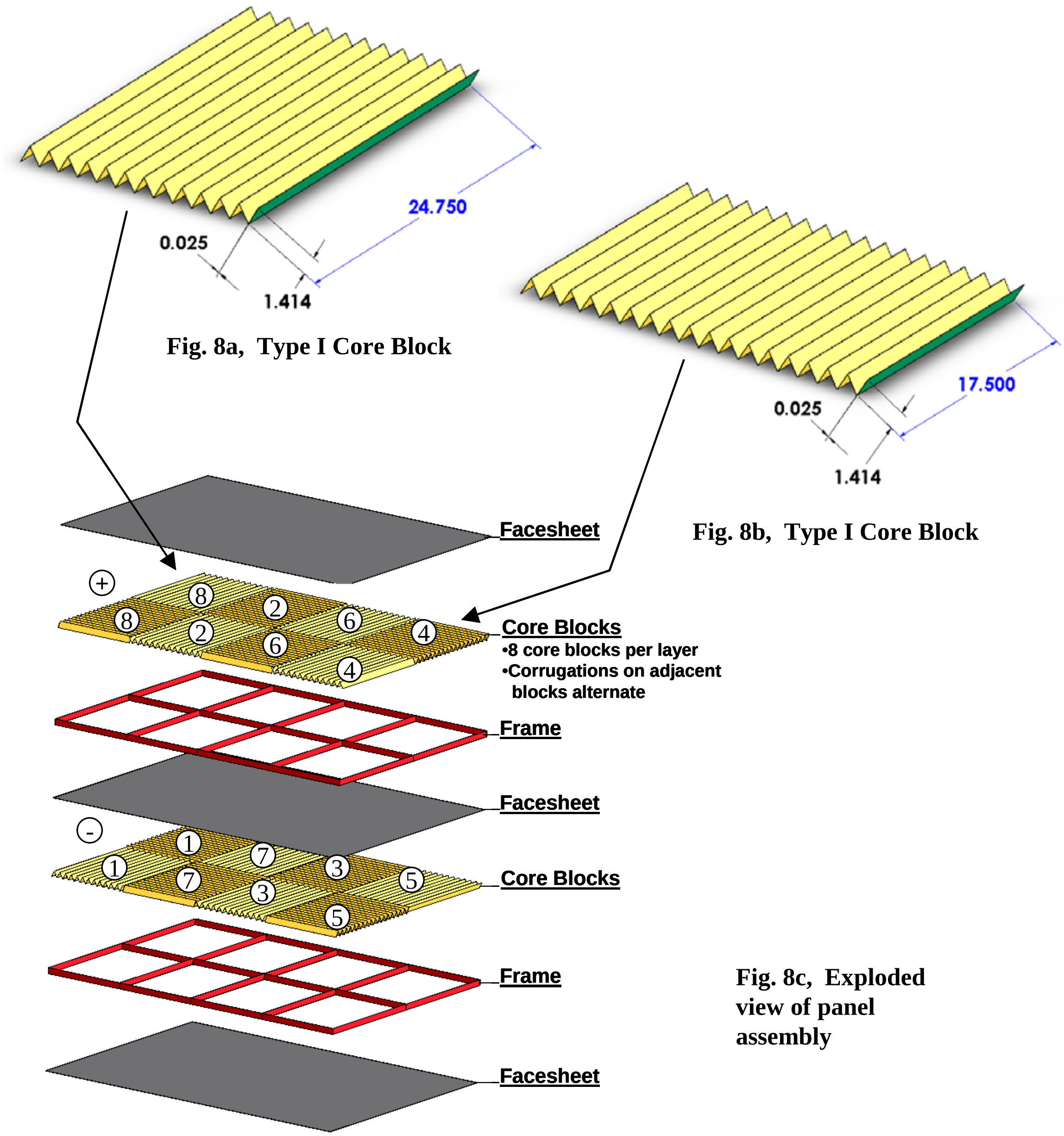

Fig. 8a, Type I Core Block

Fig. 8b, Type I Core Block

Fig. 8c, Exploded view of panel assembly

Figure 8, Corrugated, electrochemically active subassemblies are layered to form 50 cm x 70 cm x 2.3 cm sandwich panel

Design Description	Advantages	Challenges
Use structural battery as solar array substrate	Both solar array and battery are late integration. Allows power generation to be integrated as a subsystem Couples multifunctional design and analysis for energy storage with that of solar array, which is already multi-functional. Limits thermal interaction with most spacecraft components	Solar cell temperatures vary widely, whereas battery cells need tight temperature control Could adversely affect system deployed mass properties – affecting control system performance (stability and agility)
Use structural battery as solar array yoke, window frame or side-wall reflector for a trough concentrator array (i.e., in solar array, but not beneath the cells)	Same as above Thermal control facilitated as compared to above since battery elements are not closely tied to solar cells	Battery elements remain distributed and exposed to space environment, hampering thermal control Potential impact on mass properties and control system
Use structural battery as load path at major core structure interface such as the launch vehicle separation plane or plane of attachment for a payload module.	High strength and stiffness requirements make these elements of the core structure heavy, and therefore attractive targets for replacement. Less likely locations for other spacecraft components since the exterior of these interfaces are blocked for part or all of the mission.	Thermal paths may be constrained by payload or affected by exposed structure such as a separation clamp-band. Integral nature of these structural elements require special work-around if late battery integration is desired (e.g., strong-back)
Load path for fuel tanks	Hydrazine fuel has temperature limits that match battery needs Fuel load demands strength and stiffness that make support elements attractive targets for replacement Propulsion subsystem often treated as a module, facilitating thermal control and late integration	Safety organization could be wary of battery integral with propulsion despite completed spacecraft sharing this characteristic

Figure 9. Alternative Implementations of Structural Energy Storage

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- Department of Energy

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