# SYSTEM-LEVEL MASS SAVINGS FROM A MULTIFUNCTIONAL POWERSTRUCTURE

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## 1. OVERVIEW

The paper shall describe the nature and benefits of a multifunctional structure to the power storage system of a satellite. A brief overview of the principal of a multifunctional power structure shall be given, along with a description of the qualitative benefits of some proposed systems. These benefits shall then be studied with respect to various performance parameters, showing that spacecraft with high power requirements and heavy structures (the latter corresponding to smaller spacecraft) have the potential to gain the most benefit from multifunctional structures. It is found that, under the correct circumstances, a well-designed multifunctional structure can effect a similar mass saving (of the order of 2% of the spacecraft's launch mass) to a higher performance cell type.

## 2. INTRODUCTION

### 2.1. Multifunctional Structures

The principal of a multifunctional structure is to reduce the mass, and so the cost, of a spacecraft by combining a functional subsystem component with the structure, either by eliminating the mass of the component's associated structural support or by utilising the structural attributes of the subsystem itself. Various subsystems have been suggested for employment in such a structure, including thermal control [1], electronics (embedding of electronic components in composite materials [2]) and power (generally involving the insertion of chemical batteries into the structure).

Batteries are a particularly promising candidate for use in a multifunctional structure. Unlike many other components in a spacecraft, the battery is composed of a series of identical items (electrochemical cells), each of which is fairly robust and homogenous. Compared to an electronic component composed of printed circuit boards, for example, the task of dividing the battery into a series of similar and discrete elements to be distributed throughout the structure is fairly straightforward.

Whilst such "power structures" differ in design, certain common benefits of their multifunctional approach may be identified. Firstly, the use of the multifunctional structure effectively eliminates the mass of the battery enclosure, consisting of boxes, mounting systems, and any other inert, non-functional components of the complete battery pack. This element (collectively referred to as "parasitic mass") can make up as much as a quarter of the battery's total mass.

Secondly, multifunctional structures effectively remove all or part of the volume of the battery from the inside of the spacecraft bus, either distributing this volume within the structure (replacing structural elements and thus not adding volume) or distributing it over the surface of the spacecraft in a thin film, adding negligible volume. This reduction in volume may in itself have implications for the success of the mission - for example, by allowing the spacecraft to fit within a smaller launch envelope - though such advantages are difficult to quantify, as they depend greatly on the constraints and requirements applicable to the mission. However, the reduction in required volume allows a more compact structure to be produced, which will thus further reduce the mass.

### 2.2. Examples of Multifunctional Power Structures

Several multifunctional structures of this type have been suggested, each of which presents certain advantages and limitations. This section shall briefly describe these systems and how they allow mass to be saved on a spacecraft.

ITN Energy Systems have proposed 3 different multifunctional power structures based on lithium thin-film batteries (TFBs). The earliest of these was the Flexible Integrated Power Pack (FIPP), which constituted a complete power system - solar cells, power processing electronics and batteries - in a single thin film material [2]. FIPP comprises a 3-layer laminated film made up of thin PV cells, lithium polymer thin-film batteries (TFBs) and power management electronics on a polyamide substrate.

FIPP would, ideally, be attached to the existing external structure of the spacecraft. Thus, the main limitation of FIPP is the large amount of area that is required to mount it, as the thin-film solar cells have relatively poor conversion efficiency. However, if sufficient area was available for mounting, FIPP would eliminate the parasitic mass of the battery pack and virtually all of the volume of the battery. Since it does not perform a structural function, the existing structure would have to be slightly reinforced to allow for the mass added to it.

LiBaCore (Lithium Battery in a honeycomb Core) also uses TFBs but uses the large surface area available in honeycomb core materials to deposit the battery material, as shown in FIG 1 [4]. This results in a core material with integrated power storage.

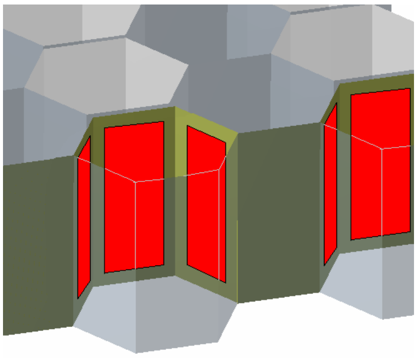

FIG 1. LiBaCore. Red (dark) areas indicate TFBs

LiBaCore entirely eliminates the parasitic mass of a conventional battery pack. However, due to the mass added to the panel in the form of the TFB cells, some structural reinforcement would be necessary, and thus some non-functional mass would be associated with the LiBaCore battery. The increase would probably be small due to the high energy storage capacity per unit mass (350 $Whkg^{-1}$ is claimed) of the TFBs, and so a notable overall mass saving compared to a conventional battery pack using TFBs may safely be assumed. The effective volume of the LiBaCore battery is zero, since the volume it does occupy could not normally be used.

The final multifunctional structure concept from ITN is the Powerfiber [5]. This also uses TFBs, but instead of depositing onto a flat surface, the substrate used is a fibre of carbon, glass, silicon carbide or a metal, as shown in FIG 2. If a carbon or glass fibre is used, then the fibre may then be used to produce a woven fabric, which may in turn be incorporated into a resin matrix to produce a composite material.

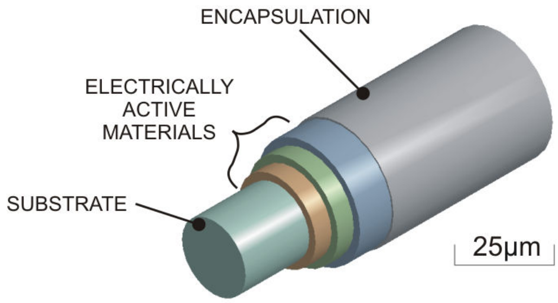


FIG 2. Powerfiber concept

The TFBs deposited onto a structural fibre could, in theory, contribute to the structural performance of the matrix of the composite material. Hence, the Powerfiber composite would eliminate the parasitic mass of the battery enclosure, and potentially replace part of the inert structure, thus reducing the battery mass and the structural mass. This also means that the battery would not occupy any volume in the spacecraft bus.

Boundless Corporation have produced PowerCore [6], a technology similar in some ways to ITN's LiBaCore, consisting of a battery system that also acts as a core for a sandwich material. Unlike LiBaCore, PowerCore uses nickel metal hydride chemistry. The honeycomb material is fabricated from nickel foam, which is then used as part of the electrochemical cell. This means that part of the battery is a direct load-bearing component of the structure, and so as well as removing the parasitic mass and volume of the battery, part of the structure may be removed. The nickel foam has similar mechanical properties to the aluminium that it replaces. The main drawback of PowerCore is that the nickel-based cells have poor electrical performance compared to modern lithium ion types.

In order to apply the principal of PowerCore to a battery type with state-of-the-art electrical performance, Boundless have produced structural bicells based on lithium-ion cells [7]. A lithium-ion cell uses carbon as an anode material rather than pure lithium in order to improve cycling characteristics, and so Boundless use carbon fabric as the anode of their cells. This fabric is then partially impregnated with epoxy resin to produce a structural composite which doubles as the cell's anode. Two such anodes are placed either side of a common cathode to produce a bicell. Flat bicells have been constructed and tested for general reinforcement and use as core components [8], whilst corrugated bicells have been fabricated in order to make honeycomb cores entirely from structural bicell materials.

As with PowerCore, a structural bicell core replaces part of the structure in addition to eliminating the parasitic mass of the battery enclosure and the volume of the battery.

Fabricating custom-built electrochemical cells is a lengthy and expensive process, and can add thousands of dollars to the cost of a battery [9]. As such, producing custom-built cells for multifunctional structures is not always cost-effective for small production runs. Work is underway at the University of Southampton to produce multifunctional panels that harness the structural properties of commercial off-the-shelf plastic lithium-ion (PLI) cells [10]. Prismatic PLI cells, which have previously been tested for use in spacecraft applications [11], are used as a core component in a sandwich panel, as indicated schematically in FIG 3.

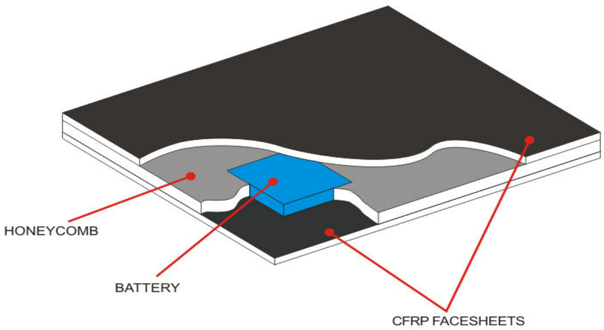


FIG 3. Multifunctional panel using commercial cells

Once again, this method replaces part of the structure with battery cells, thus eliminating the parasitic mass and the volume of the battery. The cells themselves, whilst not structurally optimised, are in a position to contribute to the structure and placing them in appropriate places should ensure that no additional structure is required, or even reduce the structural mass.

## 3. MASS SAVINGS

The following sections shall assess the mass savings that may be made by changing from a conventional battery pack to a multifunctional power structure. The mass saved in a spacecraft by eliminating parasitic mass and structural volume shall be calculated relative to launch mass.

### 3.1. Spacecraft Parameters

In order to calculate the range of mass savings achievable through the use of a multifunctional power structure, several important parameters have been identified that may be used to define the relevant attributes of a spacecraft and its power storage system. These attributes are summarised in this section.

**Parasitic mass fraction**: This is the amount of inert mass added with the battery in addition to the cells that store the electrical energy. In the case of a typical battery pack, this is around 25% of the total mass of the battery. In the case of a multifunctional structure, this will be significantly less, and, if the cells are able to perform a structural function, part of the inert structure may be removed which would make the parameter negative. Hence, a lower limit of -5% is used.

$$(1) \quad \eta_{para} = \frac{M_{para}}{M_{batt}}$$

**Specific energy capacity**: The amount of energy stored by the battery per unit mass is necessarily an important factor to determine them mass of the battery. The energy stored within a cell is calculated by multiplying the nominal voltage and charge capacity. The range considered in this study is from 120 Whkg$^{-1}$ (a typical cylindrical lithium-ion cell, such as the Sony 18650 used in ABSL battery packs) to 320 Whkg$^{-1}$ (representative of an optimised TFB), though the limit of performance for commercially available cells is around 220-240 Whkg$^{-1}$.

$$(2) \quad SEC_{cell} = \frac{C_{nom} V_{nom}}{M_{cell}}$$

**Specific energy requirement**: The SER of a satellite is defined as the total energy storage requirement (i.e., the total energy capacity of the battery) at BOL divided by the launch mass of the satellite. This parameter varies from less than 0.5 Whkg$^{-1}$ (spacecraft with small eclipse power requirements, for example, some meteorological and optical Earth observation satellites) to 5 Whkg$^{-1}$ or higher (for spacecraft with very high power requirements which continue during eclipse, such as communication satellites).

$$(3) \quad SER_{sat} = \frac{E_{sat}}{M_{sat}}$$

**Structural mass density**: This parameter allows the volume reduction achieved by removing the battery from the spacecraft bus to be translated into a saving in structural mass. It is defined as the mass of the satellite structure divided by the volume of the bus (in stowed configuration if appropriate). For some satellites, this parameter is effectively zero, as the volume may be fixed (for example, if external surface area is required for solar cell mounting). For large spacecraft (with masses over 1 tonne) the parameter is fairly small, taking a value of around 25 kgm$^{-3}$. For smaller spacecraft, it increases sharply, to as much as 500 kgm$^{-3}$ for nanosat-class (sub-10 kg) satellites. Values of up to 300 kgm$^{-3}$ shall be considered in this study, roughly corresponding to a spacecraft with a mass around 50 kg.

(4) $$\delta_{vol} = \frac{M_{stru}}{V_{bus}}$$

The volume of the cells is established using the density of the cells and their mass as calculated from the other parameters. The density is assumed to following a simple linear relationship with $SEC_{cell}$ up to a value of 240 $Whkg^{-1}$ (based on data for commercial cells) and as a constant beyond this value (the limited information available on TFBs indicates this). Since the battery itself takes up considerably more volume than the volume of the cells (due to irregularly shaped boxes, clearance, the volume of the enclosure and so on), this volume is increased by a factor of two to approximate the volume that may be removed from the spacecraft.

### 3.2. Results

In this section, potential mass savings for various values of the parameters given previously shall be presented. These mass savings are calculated as a function of the spacecraft launch mass.

#### 3.2.1. Variation of Specific Energy Requirement

The size of the mass saving varies linearly with $SER_{sat}$, as can be seen in FIG 4, which shows the mass savings that may be made for a baseline spacecraft battery with an $SEC_{cell}$ of 120 $Whkg^{-1}$ and $\eta_{para}$ of 0.25. It is a natural conclusion that more mass may be saved by reducing the mass of the battery when the battery itself is larger. The upper grey area in FIG 4 represents the absolute maximum value of the mass saving that may be made by modifying the secondary power system, increasing the $SEC_{cell}$ from 120 to 320 $Whkg^{-1}$ and eliminating the parasitic mass (i.e., modifying $\eta_{para}$ from 0.25 to -0.05) and volume of the battery pack; the heavy line indicates the saving that may be made by increasing $SEC_{cell}$ but using a conventional battery pack; the lower grey area indicates the saving made by using a multifunctional structure and keeping $SEC_{cell}$ fixed. The area is used to show the variation of $\delta_{vol}$ from 0 to 300 $kgm^{-3}$.

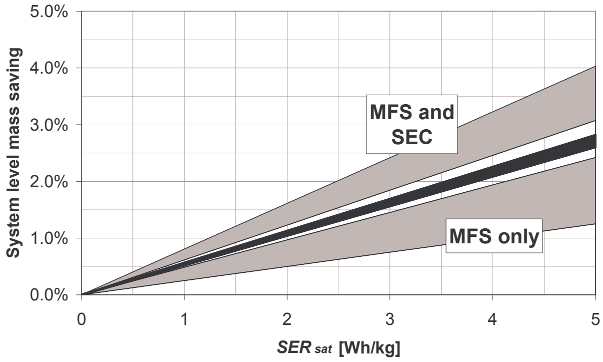


FIG 4. Maximum achievable mass savings vs. SER

Since the variation in mass saving with $SER_{sat}$ is linear, from here onwards it shall be fixed at a value of 2 $Whkg^{-1}$. Mass savings for other values of $SER_{sat}$ can be derived by multiplying the 2 $Whkg^{-1}$ results by an appropriate factor.

The following sections shall break down the total mass savings shown in FIG 4 into their constituent parts, describing briefly how they are calculated and allowing the relative importance of each to be shown.

#### 3.2.2. Changes in Cell Chemistry

The next parameter considered is $SEC_{cell}$. How much mass may be saved by changing the cell type ($\Delta M_{SEC}$) is derived by calculating the mass of the battery as a function of the spacecraft mass for various values of $SEC_{cell}$, using the parameters $SEC_{cell}$ and $SER_{sat}$ listed in section 3.1. Although changing the battery type would also result in a change in volume (which would increase the mass saving), it can be seen from FIG 4 that the effect of this volume change on $\Delta M_{SEC}$ is fairly small, and so it is not included from here onwards.

Changing the cell type is the conventional means to save battery mass where the energy requirement is fixed, and so makes an effective baseline to which the multifunctional structure mass savings may be compared. FIG 5 shows $\Delta M_{SEC}$ for various values of the parameter before and after the change is made.

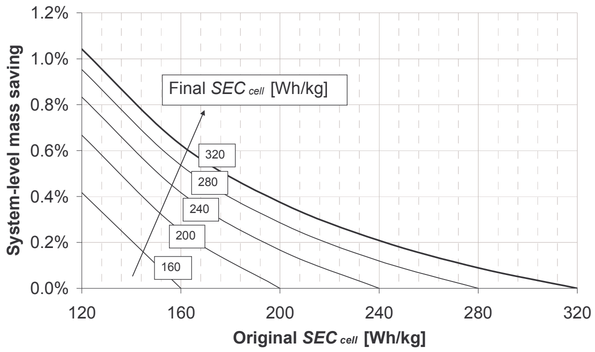


FIG 5. Available mass saving from chemistry change

### 3.2.3. Parasitic Mass Removal

In some cases, the effect of volume elimination may not be significant. If $\delta_{vol}$ takes a small value or the spacecraft volume cannot be reduced, the only mass saving achieved by using a multifunctional structure is that due to eliminating the parasitic mass of the battery enclosure. The change in mass is calculated using the $SER_{sat}$, $SEC_{cell}$ and $\eta_{para}$ parameters.

FIG 6 shows the savings that may be made by this method ($\Delta M_{para}$) plotted against $SEC_{cell}$. The savings are based on a baseline battery with an $\eta_{para}$ of 0.25; the series of lines show the mass saving according to how much parasitic mass is eliminated. In addition, the chart indicates how much mass may be saved by increasing $SEC_{cell}$: The lower and upper grey lines show the mass saved by using an $SEC_{cell}$ of 240 and 320 $Whkg^{-1}$ respectively.

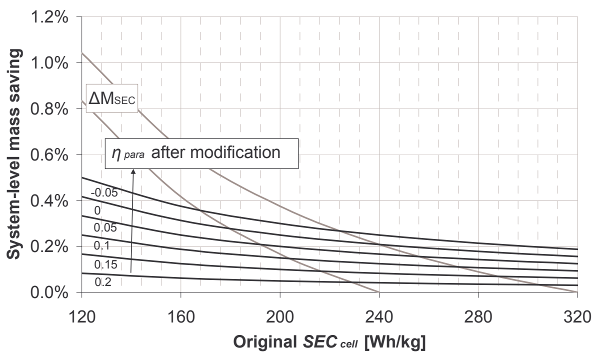


FIG 6. Comparison of $\Delta M_{SEC}$ with $\Delta M_{para}$ for various values of $\eta_{para}$

### 3.2.4. Volume Reduction

When $\delta_{vol}$ has a high value, the mass reduction arising from the structural volume reduction ($\Delta M_{vol}$) must be considered. $\Delta M_{vol}$ is directly proportional to $\delta_{vol}$, and varies slightly with the $SEC_{cell}$ parameter since this determines the density (and hence the volume) of the battery. The value of $\Delta M_{vol}$ is plotted against $SEC_{cell}$, for values of $\delta_{vol}$ from 50 to 300 $kgm^{-3}$, in FIG 7. This is compared with $\Delta M_{SEC}$ (increasing $SEC_{cell}$ to 320 $Whkg^{-1}$) and $\Delta M_{para}$ (baseline $\eta_{para}$ of 0.25, final $\eta_{para}$ of -0.05).

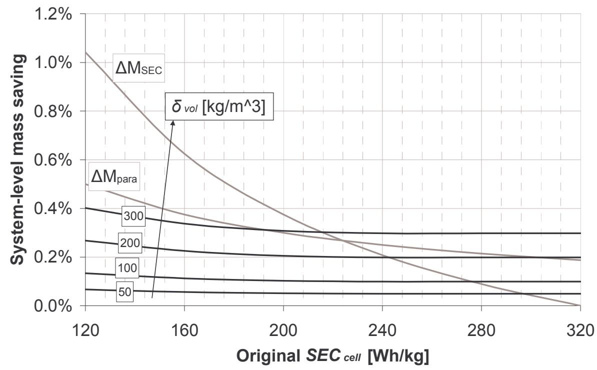


FIG 7. Mass savings due to volume reduction vs. $SEC_{cell}$, for various values of $\delta_{vol}$

### 3.2.5. Combined Savings

An ideal multifunctional structure would combine the savings from volume and parasitic mass reduction. FIG 8 shows the maximum total mass saving arising from parasitic mass elimination and volume reduction, compared to the available mass saving from changing $SEC_{cell}$ to 240 or 320 $Whkg^{-1}$.

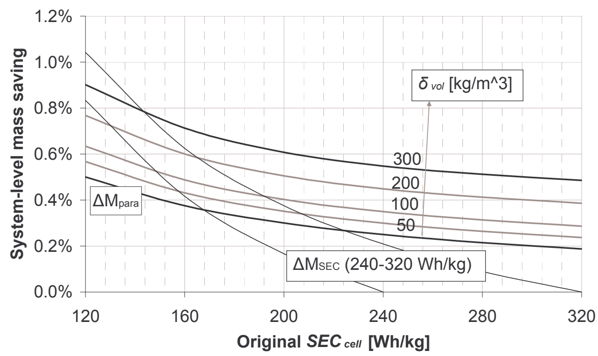


FIG 8. Combined savings from parasitic mass and volume reduction vs. SEC

## 4. SUMMARY AND DISCUSSION OF RESULTS

The first factor that identifies spacecraft that can benefit from a multifunctional structure is a high energy storage requirement. Spacecraft with a higher energy requirement will, naturally, have a heavier battery, and hence will benefit from reduction in battery mass by any means. It can be seen from FIG 4 that spacecraft with an $SER_{sat}$ below 1 Whkg$^{-1}$ benefit from a mass saving of less than 1%, which is unlikely to justify the cost of developing a multifunctional structure. If the $SER_{sat}$ parameter is above 4 Whkg$^{-1}$, however, then any saving from a well-designed multifunctional structure or chemistry change is significant.

The comparison between $\Delta M_{para}$ and $\Delta M_{SEC}$ (FIG 6) shows that, under certain circumstances, elimination of parasitic mass allows more mass to be saved than changing the cell chemistry does. If commercial cells are to be used, then the mass saving from parasitic mass removal exceeds that from changing cell chemistry if $SEC_{cell}$ is around 160 Whkg$^{-1}$ or higher. In this case, a multifunctional structure may become particularly attractive, since the cost of qualifying a new cell type might well be similar to that of utilising an existing cell type in a multifunctional structure. Even if the highest performance TFBs are available, more mass can be saved by eliminating parasitic mass above 220 Whkg$^{-1}$.

The structural mass saved due to volume reduction can be highly significant for spacecraft with high structural mass densities. For a $\delta_{vol}$ value of 300 kgm$^{-3}$ $\Delta M_{vol}$ is similar to $\Delta M_{para}$ throughout the range of values of $SEC_{cell}$ considered, though for the highest values of $SEC_{cell}$, $\Delta M_{vol}$ is significantly higher. Eliminating structural volume is thus, for some satellites, at least as beneficial as eliminating parasitic mass, and so a multifunctional structure need not be structurally optimised in order to make significant mass savings.

If both aspects of the multifunctional structure mass savings may be achieved, then more mass may be saved than by changing $SEC_{cell}$ for all but the lowest initial values of $SEC_{cell}$. This leads to the conclusion that using a fully optimised multifunctional structure can save as much mass as changing the cell type when attempting to save battery mass.

For satellites that already use a high performance cell type (i.e., where the initial $SEC_{cell}$ is at the higher end of the range studied), the only way to make an appreciable saving in battery mass (given a fixed storage requirement) is to utilise a multifunctional structure. Thus, multifunctional structures are attractive for spacecraft with very high performance requirements.

The benefits of these mass savings must, however, be offset against the cost of designing, qualifying and building a multifunctional structure, as discussed in [12]. Integrating the structure and battery of the spacecraft would increase the complexity of the design and, hence, the cost of the spacecraft itself. It is possible that this cost could exceed the reduction in launch cost effected by reducing mass.

## 5. CONCLUSIONS

Various multifunctional power structures have been shown to achieve similar mass reductions in a spacecraft battery and structure. The magnitude of these mass reductions has been calculated for hypothetical spacecraft with various attributes.

Even if the constraints of the spacecraft mission or multifunctional structure type allow only partial advantage of the potential benefits to be taken, it has been shown that the mass saved through using a multifunctional power structure can still exceed the savings made by using a different battery type.

Whilst implementing a multifunctional structure would incur additional design and manufacturing costs, the reduction in launch costs has the potential to make such a structure economically beneficial for certain spacecraft missions.

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