Battery Verification Study

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Purpose

1. Verify current battery selection will meet requirements for successful mission
2. Clarify and extend battery documentation

Summary

This document analyzes the effects that low temperature operation, discharge rate, and cycle life have on the battery capacity. It also discusses what is being or must be done to mitigate the possibility of over discharging, over charging, and cold charging the battery. The 'Mission Critical Concerns' section, immediately below, describes each of these issues. The document also contains a brief discussion regarding determination of the state of charge of the battery.

Mission Critical Concerns

- Over discharge / Self discharge: Over discharge of a li-po cell happens when the terminal voltage drops below roughly 2 V. When this happens the internal structure of the battery begins to break down. This causes the self discharge rate to increase and may result in permanent capacity loss. Many li-po cells (ours included) come with internal protection circuitry that will cut the discharge when the cell voltage drops to ~2.5 V. Over time however the cell will continue to discharge at a small rate. Given enough time the voltage may drop too low. We need to avoid this condition.
- Over charge: Over charge of a li-po cell happens when the terminal voltage rises above 4.2 V (for most li-po cells). This situation causes metallic lithium to build up on the anode and results in irreversible capacity loss. In the worst case it can cause a short to the cathode. Internal protection circuitry generally also protects against this, but may allow the voltage to rise just above 4.2 V to insure use of the full battery capacity.
- Cold discharge: Lithium polymer cells have a reduced chemical reaction rate at cold temperatures. This causes the internal resistance to increase and the usable capacity of the battery (while cold) to decrease.
- Cold charge: Many li-po batteries can discharge at temperatures below 0° C although the efficiency may be lower. Generally, however, charging below 0° C should be avoided. At these temperatures a charge causes metallic lithium plating on the anode. The plating rate increases with charge rate. It is considered wise to limit the charge rate to 1C when near (5° C) freezing (don't think we'll ever achieve that charge rate).
- Cycle life: Over many charge-discharge cycles, batteries begin to lose their ability to deliver charge. The internal resistance of the cell increases with time. This causes the voltage to drop prematurely, and the battery is not able to deliver its charge.
- Peukert's Effect: Every battery has a rated capacity. This capacity is based on the discharge time at a given discharge rate. Peukert's effect says that the discharge time and thus the effective capacity will vary based on the discharge rate. Discharging a battery at its rated discharge current will yield its nominal capacity. Discharging the same battery above its rated discharge current will yield a shorter discharge time and a reduced effective capacity. Also, discharging at below its rated discharge current will yield a larger effective capacity.

  This effect is caused by two (main) things. Joule heating within the battery increases with discharge current. This effect causes some of the battery capacity to be lost to heat. This capacity will not be regained without charging. The chemical reactions within the battery happen at a certain rate. This rate determines the battery's ability to provide power to its terminals. If the current draw on the battery is such that the battery "can't keep up", so to speak, then the battery voltage will drop prematurely. This will cause the battery to appear more discharged than it really is. Ceasing the current draw and allowing the battery to rest will give the battery time to replenish the charge available at the terminals. This effect only causes an apparent loss of capacity. However our spacecraft will not be resting the battery until it is insolated. There is plenty of time to fully charge before the next eclipse, so we might as well consider it to be an actual capacity loss.

Requirements

Capacity

Requirement 3.EPS.FR.2 states "the EPS shall have battery capacity for continuous operation when in eclipse for 50% of orbit". Here the orbit altitude determines the period. This determines the approximated eclipse time which then influences the minimum battery capacity.

```
In[1]:= << Units` (*load units package*)
        << PhysicalConstants` (*load physical constants package*)
```

```
In[3]:= M = EarthMass;
        G = GravitationalConstant;
        r♁ = EarthRadius;
```

Orbit period based on r, the orbit altitude above sea level in kilometers:

In[6]:=

$$\texttt{p[r\_] := Convert}\left[2\,\pi\sqrt{\frac{(\texttt{r♁}+\texttt{r})^3}{\texttt{M G}}},\ \texttt{Minute}\right];$$

```
In[7]:= eclipsetime = 0.5 p[600 Kilo Meter]

Out[7]= 48.3355 Minute
```

According to the power budget 200-018_E, the average power drained from the battery during an eclipse with an 8 minute communications pass is 3120.98 mW. Assuming this is taken assuming the battery always operating at its nominal voltage (average voltage over a full discharge), the charge removed from the battery is as follows:

```
In[8]:= PdrainEcComm = 6223.7 Milli Watt;
        PdrainEcSci = 2505.6 Milli Watt;
```

$$\texttt{PdrainEc} = \frac{\texttt{8 Minute}}{\texttt{eclipsetime}}\,\texttt{PdrainEcComm} + \frac{\texttt{eclipsetime - 8 Minute}}{\texttt{eclipsetime}}\,\texttt{PdrainEcSci}$$

```
Out[10]= 3120.98 Milli Watt
```

```
In[11]:= Voperate = 3.7 Volt 2;
```

In[12]:=

$$\texttt{Creq = Convert}\left[\frac{\texttt{PdrainEc eclipsetime}}{\texttt{Voperate}},\ \texttt{Amp Hour}\right]$$

```
Out[12]= 0.339762 Amp Hour
```

Thus the battery capacity must be greater than 0.34 Ah.

Cold Discharge

A Li-polymer battery has a reduced capacity when discharging at a low temperatures. Our batteries will likely be operating near 0° C. At this temperature the usable battery capacity must still be greater than Creq.

Cycle Life

The battery must be able to satisfy the requirements listed above for the 4 month mission lifetime. The total number of cycles experienced will be $4\,\text{months}\cdot 30\,\frac{\text{day}}{\text{month}}\cdot 15\,\frac{\text{cycles}}{\text{day}} = 1800\,\text{cycles}$. Thus after cycling 1800 times, the battery must have a usable capacity near 0° C greater than Creq.

Technical Specifications

Properties :	Required :	IP – Battery IP752880	Sparkfun 063 048	Sparkfun 063 450
Pack Configuration :	–	1 P2S	1 P2S	1 P2S
Peak Voltage :	8.4 V	8.4 V	8.4 V	8.4 V
Nominal Capacity :	0.429 Ah	2.2 Ah	1.720 Ah	2 Ah
Weight :	–	44 g	30 g	40 g
Size / Battery (mm) :	–	85 x30x17	6 x30x48	6 x34x50
Rated Discharge Current :	–	2.2 A	.172 A	.2 A
Max Discharge Current :	1.13 A	–	1.72 A	2 A
Max Charge Current :	–	–	.86 A	1 A

The table provides the available technical specifications for the IP-Battery IP752880 and a series of Sparkfun batteries. The IP battery is sold in the listed configuration where the Sparkfun batteries are sold in a 1P1S configuration. We require 2S to achieve 8.4 volts and thus the specifications given are for a pack created from 2 Sparkfun batteries. These are listed against the current requirements for the battery. Some requirements and battery specifications are not available and are listed with a '-'. Additional specifications are given in the Sparkfun datasheets and at www.ip-battery.com.

Analysis

Peukert Effect

Peukert's constant determines how much a batteries capacity changes based on its discharge current. We only have data about this effect for the Sparkfun batteries. Therefore I assume that the IP752880 behaves similarly and has the same Peukert constant. The value of Peukert's constant for the Sparkfun batteries is computed below.

```
In[13]:= t = 51. / 60 Hour;
         H = 300 / 60 Hour;
         c = 2 Amp Hour;
         i = 2 Amp;
```

$$n = \frac{\text{Log}[t / H]}{\text{Log}\left[\frac{c}{i\,H}\right]}$$

```
Out[17]= 1.10098
```

Now the usable capacity of each battery pack is computed when discharging at the max, eclipsed current rate.

```
In[18]:= Cnom = {2.200, .860 × 2, 1. × 2, 2. × 2} Amp Hour;
         (*nominal battery capacity. order same as table above*)
         H = {1 Hour, H, H, H};
```

In[20]:=

$$\mathbf{i = Convert\left[\frac{PdrainEc}{Voperate}, Amp\right];}$$

$$\mathbf{Cuse = Cnom \left(\frac{Cnom}{i\, H}\right)^{n-1}}$$

```
Out[21]= {2.59933 Amp Hour, 1.68497 Amp Hour, 1.98933 Amp Hour, 4.26712 Amp Hour}
```

Cold Discharge

We only have data regarding cold discharging for the Sparkfun batteries. As a result this analysis assumes that the IP752880 behaves similarly in cold conditions.

According to the Sparkfun datasheet the standard 0.2C discharge time is ≥300 minutes as expected. Under cold test* conditions the 0.2C discharge time is ≥210 minutes. The usable capacity when cold is thus 70%.

In[22]:=

$$\mathbf{Cuse = \frac{210.}{300.}\, Cuse}$$

```
Out[22]= {1.81953 Amp Hour, 1.17948 Amp Hour, 1.39253 Amp Hour, 2.98699 Amp Hour}
```

This shows that, at 70% capacity, each battery has greater capacity than Creq

*Due to a typo in the Sparkfun datasheets we do not know the exact temperature at which the cold tests were conducted.

Cycle Life

The Sparkfun battery's datasheet gives a cycle life of ≥300. This represents the number of 100% DoD (depth of discharge) cycles the battery can undergo before its full usable capacity drops to 70% of its initial full usable capacity. This specification is not available for the IP battery, and is thus assumed equal. Cycle life varies greatly with the DoD of the battery. Cycle life in Li-ion/polymer batteries varies reciprocally with DoD, where 1 cycle at 100% DoD is roughly equivalent to $\frac{1}{x}$ cycles at x DoD ($0 \le x \le 1$).

DoD based on max current draw during eclipse:

In[23]:=

$$\mathbf{DoD = 1 - \frac{(Cuse - Creq)}{Cuse}\ \ (*nominal\ depth\ of\ discharge\ per\ eclipse*)}$$

```
Out[23]= {0.186731, 0.288061, 0.243988, 0.113747}
```

```
In[24]:= cyclelife = 300 / DoD (* # cycles where usable capacity > 70% *)
```

```
Out[24]= {1606.59, 1041.45, 1229.57, 2637.42}
```

Battery capacity decreases roughly linearly with the number of cycles. Therefore the number of cycles available for each battery where the usable capacity remains above Creq is:

In[25]:=

$$\mathbf{cycles = \frac{-cyclelife}{0.3}\left(\frac{Creq}{Cuse} - 1\right)}$$

```
Out[25]= {4355.31, 2471.49, 3098.56, 7791.42}
```

Therefore all of the battery packs meets the cycle life requirement. The batteries may last for nearly the number of months shown below.

```
In[26]:= cycles / 15 / 30

Out[26]= {9.67847, 5.49219, 6.88569, 17.3143}
```

Additional Issues

Over Discharge / Self Discharge

Our battery must be usable at the time of launch. This means that it must be able to survive the storage period after delivery. At most this period will last for 12 months. During this time the battery will be discharging at some small rate. According to the Sparkfun battery datasheets the self discharge rate is roughly 20% per month. If we assume the discharge rate is constant with respect to battery capacity then we will arrive at a 0% SOC (state of charge) after 5 months. This assumption is not true but represents a worst case scenario. As stated above, the batteries contain internal circuitry to cut discharge at 0% SOC (state of charge). This happens for the Sparkfun at 2.75 V. After this point we don't know the rate at which the battery will continue to discharge. If it's low enough, the battery cells may still be above 2 V at launch. If not it will drop below 2 V per cell and the battery will begin to deteriorate. In order to verify that this won't happen we need to more accurately characterize the self discharge rate of the battery. It would be helpful to answer these questions:

1. How does the self-discharge rate change between 80% and 0% SOC?
2. How does the self-discharge rate change after the internal protection circuit has cut discharge?

Over Charge

Overcharge protection has been implemented by setting the "8.4 V" buck converter output voltage just below 8.4 V. This provides an extra level of protection beyond the internal protection circuitry.

Cold Charge

The possibility of a cold charge (< 0° C) will likely be mitigated with battery heaters. This issue is currently being researched.

Determining State of Charge

Lithium polymer cells have a reasonably flat discharge voltage curve. This means that over the course of the discharge, the voltage does not change significantly (8.4-5.5 V). It also does not change linearly. There is generally a quick voltage drop near the beginning of the discharge, a wide flat region in the middle of the discharge, and another quick drop in voltage right before reaching 0% SOC. This voltage profile varies based on the instantaneous and recent discharge rates, the temperature, and the age of the battery. Based on this, additional information and possibly battery characterization should be considered when attempting to determine the SOC of the battery. This must be possible while in orbit, so it is likely that we will need to develop some model for SOC that is based only on voltage, current draw, temperature, and the time on orbit. This model should probably be the result of battery characterization testing but could also be theoretical.

It is important to determine the SOC with some degree of accuracy because C&DH will be making spacecraft mode decisions based on SOC. There may be potential for erroneously becoming stuck in a safety state based on an incorrect SOC determination.

In general this issue needs to be considered further before any conclusions are drawn.

Conclusion

Based on Analysis:

The analysis above shows that all of the batteries will be sufficient for our needs. At this point in time we have decided not to use the IP Battery for lack of reliable documentation. We have selected the 2 Ah Sparkfun pack for now.

Future Work/Analysis

Work currently needs to be done in 3 areas:

1. Characterizing the self discharge rates of the battery
2. Working with the thermal team to refine the thermal model relating to the battery and consider/implement battery heaters as needed
3. Deciding the level of accuracy at which we must know the battery SOC and researching what it will take to determine it.

Appendix

C-rate

C-rate is a battery discharge rate. It is the reciprocal of the discharge time. In the simplest form C–rate = $\frac{1}{t} = \frac{\text{Discharge Current}}{\text{Capacity}}$.

Sources

1. www.wikepedia.org
2. www.batteryuniversity.com
3. www.mpoweruk.com
4. www.smartgauge.co.uk