The Oil Drum
DISCUSSIONS ABOUT ENERGY AND OUR FUTURE

Who Killed the Electric Gas Tank?

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A few months from now, or perhaps 5-10 years from now, we will know whether or not EEStor can make good on its promise to sell a electrical storage device capable of propelling a reasonably-sized automobile down a freeway for a couple hundred miles before needing a recharge. There are some indications that they are making progress and that this could happen, but there are many reasons to remain skeptical. In this post, I will wade into these waters -- and then get out quickly. Will EEStor revolutionize motor transportation and more? Will it even work?

The human quest for energy is an interesting topic. Mostly by burning things, we have transformed our relationship with the planet and each other. It has been said that we are addicted to oil, but it is more the case that we are addicted to what harnessed energy can do. As it is learned that some utilization of energy is not sustainable for environmental reasons, or for lack of supply, the natural response is to search for other ways of doing the same activity but with another energy supply. And conventional economics promises us that something will come along.

In modern times, one of our sacred rights (or rites?) is the ability to drive a 1-2 ton vehicle up to a fuel station, fill it up without spending a fortune or more than a few minutes of time, and then drive around at 70 miles per hour without worrying about needing more fuel for awhile. A car with a battery and an electric motor, for whatever reason, didn't bring us to this present state of mind. But take away the gasoline (or diesel), and the dream lives on -- even better, because maybe we can skip the trip to the gas station and refuel the car at home. Zenn Motor Company makes and sells electric cars, and they are clearly appealing to those with this dream:

> Imagine a car that was whisper quiet at highway speeds, could go for hundreds of miles and left no trail of emissions behind. This car would never need to visit a gas station, and would top off its 'tank' within a few minutes.
>
> The car is electric…and it's powered by a revolutionary energy storage system: EEStor's EESU (Electrical Energy Storage Unit). To put this into perspective, imagine a car that enabled guilt-free driving, eliminated dependency on foreign oil and that completely changed transportation as we know it.

Zenn electric car: automotive absolution

Ah yes, "guilt-free driving". I won't get into that right now.

What is the EEStor EESU?

The aforementioned EESU is essentially a capacitor which is designed to be charged up and then slowly drained to power an electric vehicle, similar to a battery or fuel cell. In the simple model below, an external voltage is applied across two conducting plates separated by a small distance, usually with a dielectric or insulator in the gap. Charge flows until the voltage across the plates equals the applied voltage.

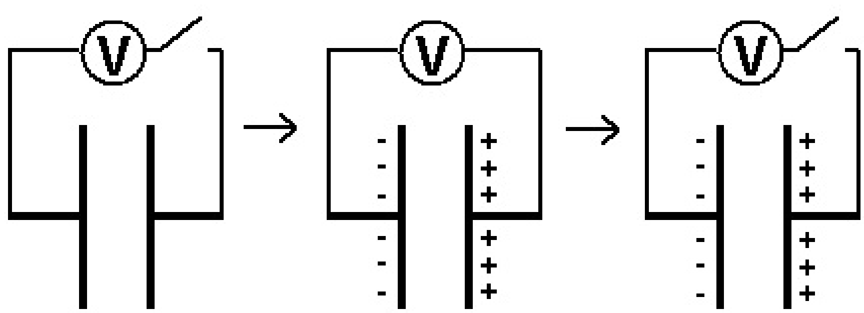


Figure 1. Charging a capacitor

The charge that is dislocated per volt applied is termed the capacitance. With the external voltage is removed, the charge remains. Place an external load across the plates, and current will flow through the load (providing power), with the voltage available decaying with time.

$$C = \frac{Q}{V}$$

where Q is the charge measured in coulombs and

C is the capacitance, measured in farads

V is the voltage between the plates

$$\textit{Energy stored (J)} = \frac{1}{2}CV^2$$

The energy stored by the capacitor is thus a function of the specifics of the capacitor and the voltage to which is is charged. Typical capacitors found in electronics store very little charge (or energy) compared to what is needed to power devices (not to mention cars) in continuous operation. There would seem to be two options a) find new capacitor technology with a higher capacitance, or b) ramp up the voltage. At first glance, it would seem logical to take the latter route, as the energy stored increases with the square of the voltage. As we will see, it hasn't work out that way in practice up to the present. Most research and development has focused on new materials.

Before continuing, it might be helpful to highlight a few terms used to characterize capacitance:

Capacitance Terms

- **dielectric**: another term for an insulator, which emphasizes the fact that it polarizes in response to an external electric field (as when placed between the plates of a capacitor connected to a voltage source)
- **permittivity**: a measure of how much a dielectric can be polarized (i.e. how it responds to an electric field)
- **dielectric constant**: the permittivity of a material divided by that of free space (therefore, dimensionless)

The capacitance is determined by the geometry of the two plates, the distance between them, and the electrical properties (permittivity) of the gap material. For large plates relative to the separation distance, the following approximation can be used:

$$C = \epsilon_r \epsilon_0 \frac{A}{d} \text{ (in SI units)}$$

where

C is the capacitance in farads, F

A is the area of overlap of the two plates measured in square metres.

ε_r is the relative static permittivity

ε_0 is the permittivity of free space where $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m

d is the separation between the plates, measured in metres.

To make capacitors with large values of C, the most common approach is to (dramatically) increase the area. One way to do this is to employ porous materials with intrinsically large surface areas. The term ultracapacitor is usually used to characterize such devices which are designed to store a lot of charge. One common type of ultracapacitor, electrochemical double layer capacitors, utilize high surface area materials and also the charge-storage properties of the interfacial region between the surface and an electrolyte in solution. An internet search will reveal a wealth of information about recent developments in ultracapacitors.

Why the Fuss About EEStor?

What has raised much cash and many eyebrows are the stated specifications for the EESU:

- 52.22 kW-h of energy storage, or 188 MJ
- Weight of 281.56 lbs, or 127.71 kg
- 31,351 capacitors stacked and connected up in parallel, each with dielectric layers of 9.732 micron thickness
- Each capacitor layer consists of alumina-coated composition-modified barium titanate ($BaTiO_3$) powder sandwiched between two thin poly(ethelene terepthalate) layers and aluminum electrodes. The $BaTiO_3$ has relative permittivity (dielectric constant) of 21,072 and the overall dielectric permittivity (including PET layers and alumina coating) is 18,543.
- Total capacitance of 30.693 Farads, and total volume of 2.628 cubic feet.
- Temperature stable to 85°C and voltage stable to 5000 V, with 0.1% discharge over 30 days
- One million recharge cycles from 0-3500 volts and back again
- Can be charged in 3-6 minutes
- Manufactured by screen printing and sintering

The above information was obtained from the patent which was granted to EEStor, Inc. in December, 2008 (EEStor has applied for more). The key material, alumina-coated composition-modified barium titanate powder, is made in a process described in a patent application by the same inventors. The modified powder is then mixed with about 6% PET and binder and suspended in nitrocellulose resin and solvent for use as a screen printing ink. The surrounding PET and aluminum layers are also formed via screen printing. Put the layers down in succession, baking in between until golden brown. Let cool and then serve.

One thing that catches one's attention is the excessive number of significant digits in the figures. What is apparently the case is that the configuration of the overall EESU is designed to match the energy storage density used by the battery in the Tesla. Measured capacitance values for a proof-of-concept unit (100 layers) were then used to determine the overall requirements for the full unit. The values for energy storage, volume, and weight translate to energy densities of 1.47 MJ/kg and 2.52 MJ/liter, a 2-3 fold improvement over lithium batteries, but still wanting when compared to gasoline (~45 MJ/kg and 33 MJ/liter). (Note that, because an internal combustion engine is much less efficient than an electric motor, the comparable values will be perhaps 20% of these figures.)

As of now, there is a lot of scattered information including this patent and previous filings as well as some apparent verification of some aspects of the manufacturing and materials by supposedly independent experts. There is also some investors and some negotiated agreements with partners, most prominently Zenn cars (see the news item bar on the home page), and Lockheed Martin. A lot of initial reaction is detailed in an issue of MIT Technology Review from January

2007. Reactions by everyone else run the gamut from giddy true belief to skepticism to accusations of fraud. For some interesting reading, check out the following discussions:

- The EEStory.com, with occasionally heated discussions and some poetry
- EEStor Ultracapacitors: Battery Revolution begins with Electric Cars? (with comparisons of the EEStor inventors to the Wright brothers)
- Wikipedia entry for EEStor and a talk page with lots of angst
- A timeline detailing the play-by-play.

Sort of a game of "choose your F word" (fact, feasible, fantasy, fallacy, fiction, fraud, ...). But unlike other controversies that get batted about endlessly, this one would seem to have a clear endpoint: either EEStor can make it or they can't. Of course, a negative result might take awhile, as exemplified by the example of cold fusion research twenty years from the initial media splash. In that case, the dream that abundant energy can be obtained quite easily has kept research alive, despite the absence of either clear evidence or a plausible physical explanation. In contrast, some ideas that "should" work take awhile to become reality because of engineering difficulties. Conventional fusion-based electricity generation and high-temperature superconductors probably fall into this category. Which is the case with the EEStor capacitor?

The Road Less Taken

The principle material used in the EESU, barium titanate, has been of interest for along time. If you have access to the bound set of the Feynman's Lecture Series (1963), you will find it discussed in depth in Volume 2, Chapter 11. Barium titanate is a common material for both capacitors and actuators (a related application where an applied voltage deforms a material, allowing precise movement of objects). This article provides a good background on the utility of barium titanate as a dielectric in capacitors in general and in multilayer capacitors in particular. EEStor's improvement over what is currently available is an increase in the voltage to which the capacitor (or a stacked set of capacitors) can be charged to. Thus, though the target capacitance of 30 farads listed above is not particularly high in the world of ultracapacitors, by assuming a large voltage, the energy that can be stored goes up considerably (with the square of the voltage). What is the downside, and why doesn't everybody just design for a higher voltage? First, high voltages (3500 volts) in many situations would not be practical. Second, the capacitor has to withstand the voltage applied (i.e. not break down). But there is one more problem: the simple formula for energy stored in a capacitor assumes that the permittivity of the dielectric is constant. In practical application, there exists the phenomenon of dielectric saturation.

Getting Saturated

A material with a high permittivity means that it distorts in response to an external electric field. This can be just a displacement of the electrons with respect to the nuclei, or it can include relative displacements of the nuclei. In the case of electrochemical double layer capacitors, it also includes relative positions of ions and solvent near the surfaces. Perovskite oxides (which includes barium titanates) have high permittivities because they can, in effect, store a lot of energy by distorting when an electric field is applied. But there are limits to the amount of distortion possible; with increases in voltage above a certain point, permittivity begins to decrease, with large changes in voltage moving less and less charge. Companies have spent a lot of money trying to develop capacitors which do not have this limit, but without success. (See http://bariumtitanate.blogspot.com/2009/04/intelligibility-of-eestors-re...)

Skeptics have politely mentioned this "feature" of dielectrics in discussions for awhile now, but EEStor and Zenn have recently put out PR which says that independent permittivity tests on

EEStor's barium titanate powders have shown that they support their claims. Their patent clearly suggests that dielectric saturation is not observed for their samples. Much of the recent debate is thus about whether this is really plausible, based on a review about is known about $BaTiO_3$ from prior research or first-principles calculations. One unabashed enthusiast (I'll call him "true believer", or TB) has reported that (according to Zenn and/or EEstor) their materials are in a particular phase (paraelectric) which does not exhibit dielectric saturation at these voltages. However, there is a paper published which indicates that dielectric saturation does indeed occur in the paraelectric (cubic) phase. Meanwhile, TB from above has contacted the independent tester and found that the voltage used in the test was 1 volt, but that measurements were made at multiple temperatures and there was no observed temperature dependence to the permittivity. And according to a source of TB, temperature dielectric saturation always accompanies the voltage kind. Maybe they perhaps have some phase that hasn't been seen before. Even more interesting is TB's blog post with interview snippets with other researchers in the field. This snippet is from a discussion with Dr. Eric Cross of Penn State:

> B: So your view is EEStor is possibly on to something but the information they have released is not a good body of evidence from which to draw any conclusions.
>
> EC: I would go along with that yes. I think they have something interesting and they may not know that they have a tiger by the tail.
>
> B: Meaning that the complexity may lie ahead for what they are working on?
>
> EC: I think that's true. One needs to understand in detail what one is doing. This is an area of extreme interest at the moment. I can't say more about it.
>
> B: It's of extreme interest just because of the applications, right? Not because there's some sort of breakthrough? I do not understand.
>
> EC: I think these people are scientists and I think they have made an interesting discovery but their explanations of what they have discovered are not reasonable...which is not to say that what they have discovered is not itself reasonable. That I won't say any more about it.

A Peaceful Queasy Feeling

As I have looked into what is known about the EEStor technology, and read as much as I could stand, I have gone back and forth as to whether I believe they have indeed created a dielectric material which has the necessary properties to make the EESU function as promised. It's hard for me not to root for these guys, as there is something noble about someone striving for 20 years to bring one's ideas to fruition. The problem is that, while creative ideas and persistent attention to detail in engineering can solve almost any problem, you are sometimes stuck with what nature hands you. That they came up with a secret recipe which has eluded so many others sure seems very unlikely -- but not impossible. Will it work? Ask me tomorrow.

At this point, the only people who really know what their technology is and whether they have something that can really be brought to market soon is EEStor (and they probably don't either). Everybody else (including Zenn, until they get one in hand) is relying on partial information. But if EEStor succeeds, it will be an amazing scientific and engineering achievement by a couple of people with limited resources.

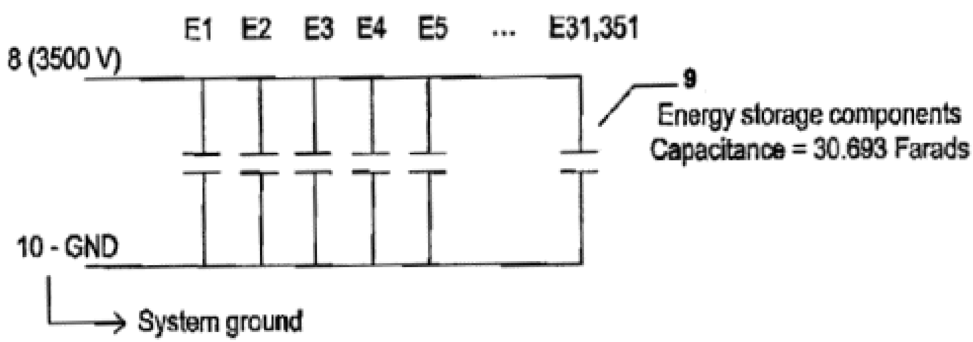
Seem Warm To You?

But what if it works? Before it can be used in automobiles, many other questions remain -- although many of these apply to electric cars in general. Where will the electricity for this really come from in the next few years? Charging infrastructure? Safety? Assorted colors?

Some of these I will reserve for another article. But I will consider here the issue of safety, which is given scant mention in the EEStor patent.

> None of the EESU materials used to fabricate the EESU, which are aluminum, aluminum oxide, copper, composition-modified barium titanate powder, silver-filled epoxy, and poly(ethylene terephthalate) plastic will explode when being recharged or impacted.

The inherent danger is not necessarily the risk of explosion, but simply the sudden release of 52 kilowatt-hours of energy if the capacitor self-discharges. As shown in this illustration from the patent,



the individual energy storage units (capacitors) are connected in parallel such that, at full charge, a potential of 3.5 kV sits across each of the 31,351 units of 10 microns thickness. Although the dielectric breakdown voltage is sufficiently high such that leakage current is low, there is a finite probability that a stress fracture from impact due to an accident or a manufacturing defect propogated as the EESU ages results in electrical breakdown in one of the units. If this occurs, all of the energy stored in the EESU (52 kilowatt-hours) could potentially be released in a very short period. It is somewhat disingenuous to stress the large amount of energy which can be stored in the device and the rapidity of charging and discharging without acknowledging the downside of these.

In a rapid electrical breakdown of the device, the stored energy would essentially result in the instantaneous generation of a vast amount of heat. For example, the EESU is made primarily of barium titanate, which has a heat capacity of 434 J/kg-K. The 52 kW-hr released will heat the 280 lb unit to about 3400°C. Of course, it would probably start heating up everything around it before it got that hot. One ton of steel (with about the same value for heat capacity) would heat up to 460°C. Best to get out fast.

There are possibly ways to deal with this risk, but preferably not the Ford Pinto strategy. In any case, an extensive testing phase is warranted to assess both damage and age-related risk for a catastrophic self-discharge event. Crash-test dummies are cheaper than lawyers.

Disclaimer: I own no stock whatsoever