A STRAIN ENERGY STORAGE SYSTEM FOR AUTOMOBILE APPLICATIONS

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This paper describes an energy storage system based on the superior characteristics of a hypothetical glass 50 times stronger than conventional materials. The burgeoning use of batteries represents an increased use of toxic metals harmful to human health and the environment. This paper describes the novel design in detail and compares it to conventional energy storage technologies. The analysis will show that such a system will have the potential to revolutionize the electric vehicle industry and allow them to compete with their less efficient internal combustion engine counterparts by solving the range issue.

TABLE OF SYMBOLS

Below are symbols used throughout this paper. Units are given in the square brackets.

A = frontal area [m^2]
C_d = coefficient of friction []
E = Young's Modulus [Pa]
ε = strain []
ε_{yp} = yield strain point []
ε_u = ultimate strain []
ε_f = failure strain []
I = Moment of Inertia
KE = kinetic energy [J]
σ = stress [Pa]
σ_{uts} = ultimate tensile stress [Pa]
σ_{ys} = yield stress [Pa]
ρ = density [kg/m^3]
U_e = potential energy [J]
v = velocity [m/sec]
ω = angular velocity [radians/sec]

STRESS STRAIN DIAGRAM ANALYSIS

The stress strain plot captures many of the important material properties of a material. Stress can be described as the amount of per unit area the material is subjected to whereas strain is the normalized change in length when a material is subjected to a load. In equation form:

$$\sigma = \frac{Force}{Area}$$

$$\varepsilon = \frac{length_{final} - length_{initial}}{length_{initial}}$$

Materials generally exhibit a linear stress-strain relationship until a certain stress is reached, denoted as the yield stress. Prior to the yield stress, this relationship can be described by Hooke's Law:

$$\varepsilon E = \sigma$$

As more stress is applied, the relationship between the stress and strain is no longer linear due to atomic dislocations; this is called the plastic region.

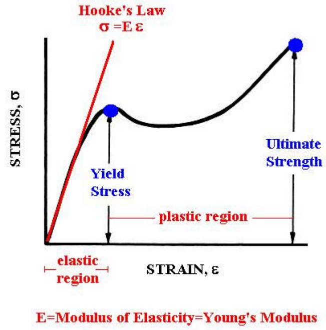

Figure 1 A typical stress strain curve for a ductile material.

The area under the curve is denoted as the toughness of the material and signifies the amount of energy per volume a material can absorb prior to failure[1].

$$U = \frac{1}{2}E\varepsilon^2 = \frac{1}{2}\frac{\sigma^2}{E}$$

Ductile materials such as steel are used in structures because their large ductile region provides the material an inherent ability to absorb more energy, allowing the structure to fail "gracefully." However, for applications where reusability is a main design objective, the ductile region cannot be used in energy storage calculations. Only the area prior to the yield stress may be used.

The hypothetical "super" glass will have an ultimate tensile stress 50 times stronger than conventional glass, providing it with a failure stress of 3.5 GPa. This translates to a failure strain of 0.048 (Appendix 1). Using the above equation, the amount of energy a cubic meter of this super glass can absorb is 85 MJ/m^3 (Appendix 2). Superglass can hold more than 12.5 times the amount of energy than a comparable volume of steel.

DEVICE DESIGN

In the proposed system, energy is stored by straining a mass of superglass. As it contracts, its linear deformation is translated into rotational movement via a gearbox, which in turn drives a generator. The generator transforms the rotational movement into electrical energy for use. In order to “charge” the battery, electrical energy is inputted into the generator, which now acts as a motor. The gearbox strains the superglass, storing energy for future use. This is contained within a hermetically sealed housing to alleviate static fatigue concerns.

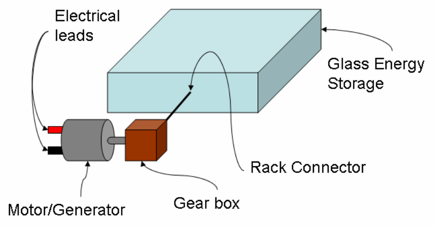

Figure 2 Exploded schematic of strain energy system

The gearbox is used to change the translational motion of the glass due to strain recovery to a rotational motion that can drive the generator. This is done via a rack and pinion gear. Additional gearing may be used to transform the high force, small motion into a low force, large motion which can be translated into electrical energy via the generator.

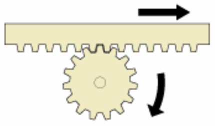

Figure 3 Rack and pinion gearing

Because the material is operating in the elastic region of the stress-strain curve, the energy lost for each cycle due to heating, dislocations, etc. is insignificant. Unlike most materials, the key concern with glass under cyclical loading is static fatigue, which occurs when a subcritical static load is imparted on glass for an extended length of time[2]. It is worsened by exposure to a humid environment[3]. If placed in a hermetically sealed, moistureless environment, the superglass mass should be able to operate at sub-fracture stresses indefinitely. Its high energy density, near lossless energy recovery and near infinite lifecycle makes this material ideal for an energy storage system.

Generators are widely used throughout industry and can achieve efficiencies near 95%. A voltage applied to a generator will turn it into a motor with just as high efficiency. The synergistic effect of a motor/generator enables a single component to act as a highly efficient liaison for electricity during charging and discharging.

Using superglass as an energy storage system represents a novel use of its unique properties. The rack and pinion gearing transforms the linear deformation into a rotational movement that drives a generator, ultimately producing electricity and providing viable alternative to chemical energy storage devices.

CONCEPT HISTORY

Prior to the advent of widespread chemical battery use, windup springs were used to store the energy for pocketwatch operation. However, as energy storage demands outstripped the potential energy stored in steel springs, chemical batteries became the main portable energy source.

Trevor Baylis revived the concept of storing energy in mechanical deformation by using a torsion spring to power radios in developing countries[4]. The design has a low energy density because a torsion spring comprises mostly of empty space and is limited by the maximum strain conventional materials can achieve before plastic deformation (roughly 2%). As a result, it is used only in low power applications.

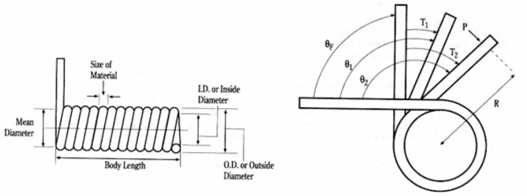

Figure 4 A Torsion spring

The proposed advance in glass technology enables strain energy storage devices to compete with their chemical counterparts. Unlike the space wasting torsion spring based design, which depends highly on the geometry of the spring, the strain energy storage system utilizes the inherent material properties exclusively.

BATTERY MARKET

Noncombustion based portable energy storage devices are almost exclusively the realm of chemical batteries. The global battery market is roughly \$50 billion US and is expected to grow 6% annually[5]. The lead acid battery market, primarily geared toward automobiles, currently represents a \$5 billion demand.

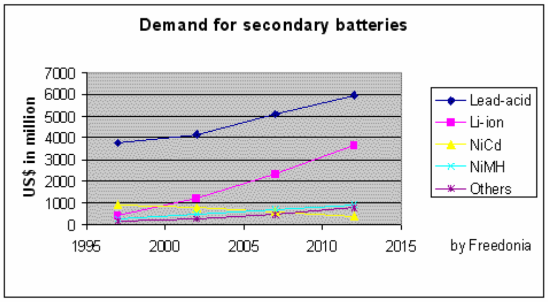

Figure 5 Global battery market

COMPARISON WITH CURRENT CHEMICAL BATTERIES

The proposed system addresses many of the deficiencies associated with contemporary chemical batteries. A key concern with chemical battery technology is their use of dangerous materials such as lead and mercury, both of which are linked to neurological and developmental disorders. These materials pose a significant environmental hazard, especially in developing nations where there is burgeoning battery use but insufficient disposal and recycling infrastructure[6]. The superglass based energy storage system is composed mostly of glass, whose raw material is readily available and is easily recyclable.

Current battery technology allows for reuse on the order of 1000 cycles before battery degradation[7]. Even if all batteries in the world were reusable, the disposal problem would be diminished but not entirely eliminated as batteries reach the end of their useful life. As previously mentioned, the superglass energy storage device has near infinite theoretical lifespan.

Manufacturers do not recommend complete chemical battery discharge, reducing the amount of energy one can actually obtain from a chemical battery pack. "Deep discharge" of a battery significantly reduces its lifespan due to corrosion of internal components. In order to reduce static fatigue, the optimal charge discharge profile for the strain energy storage system is to draw as much energy as possible before charging.

Chemical batteries do not output a constant voltage. Because the stress-strain relationship is linear, the energy storage system will output a near constant voltage, as opposed to conventional batteries whose output decreases precipitously as it reaches the end of its life.

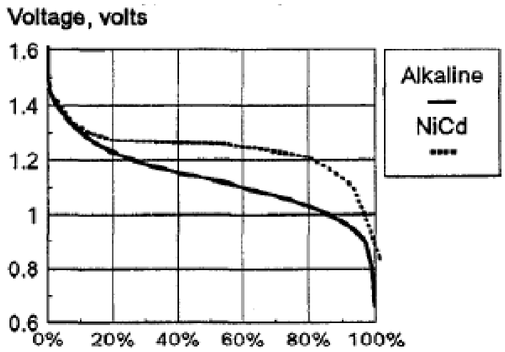

Figure 6 Typical discharge curves of chemical batteries[8]

In addition to solving the aforementioned concerns, the super glass energy storage system provides superior performance. The superglass energy storage system can theoretically achieve two orders of magnitude superior performance in comparison to conventional technologies.

Table 1 Energy density comparison[9]

Energy Storage Method	MJ/m^3
Superglass battery	85
Lithium Ion	0.9
Nickel Metal Hydride	0.36
Lead-Acid	0.14
Torsion Spring	0.0006

SAFETY CONCERNS

While Lithium ion batteries have enabled more capable mobile computing, their chemical makeup poses a significant safety concern, prompting numerous recalls. Although the strain energy storage device has a higher energy density, it manages to decrease the safety concerns associated with current technologies.

A chemical battery "short circuit" has the potential to cause harm by overheating the battery and causing a fire or possibly electrocuting its user. However, in a strain energy storage device, the discharge rate would be inherently limited by the gearing and the rate at which the generator spins.

One conceivable failure mode is the breaking of the mechanical link between the energy conversion and storage system. This simply would result in the glass contracting. Because the link is severed, the energy could not escape and cause harm.

THE AUTOMOBILE APPLICATION

Due to their ubiquitous nature, advances in automobile technology can have a profound impact on the environment. Transportation comprises 63% of the United States' 20 million barrel a day oil demand in 2004, releasing 1.9 billion tons of CO_2 annually[10]. The strain energy storage system can significantly reduce the carbon footprint of the United States by replacing the internal combustion engine in automobiles.

As mentioned previously, electrical motors have achieved 95% efficiency. In comparison, an internal combustion engine achieves at most 35% efficiency; a majority of its energy is lost as waste heat. Basing the transportation infrastructure not on gasoline but on electricity can increase the efficiency of the nation, mitigate the environmental impact and reduce the United States dependence on foreign oil.

At average highway speeds, drag resistance can represent 80% of the total force.

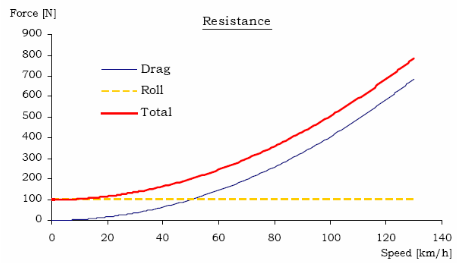

Figure 7 Resistance in an automobile[11]

Drag for an object can be obtained by the following expression:

$$D = \frac{1}{2}\rho v^2 A C_d$$

The significant space used by chemical battery pack influences the shape of the car, increasing frontal area, C_d and ultimately, drag. If the car's current lead acid battery were replaced with the strain energy storage system, the lost internal volume could be recaptured or reduced to make more efficient vehicles.

The Tesla Roadster represents the epitome of production technology in electric vehicles. Were it to use a strain energy based storage system, it could achieve a range of 9,300 miles for the same amount of space (Appendix 4). The main drawback to electric vehicles, their limited range, would be effectively solved and thus enable wider adoption.

CONCLUSION

Since the turn of the 20th century, the internal combustion engine has been the cornerstone of the world's transportation, with dire consequences to the environment and our health. Electric vehicles have the possibility to reduce the amount of toxins we put in our world, but will never be accepted if they offer reduced capability and higher costs. The strain energy storage system can be the catalyst that allows them to compete, and beat, conventional automobiles by offering superior range and safety at lower environmental cost.

APPENDIX 1

Typical glass has a yield/failure stress of 70 MPa. The specifications call for a glass 50 times stronger, resulting in a material with a yield stress of 3.5 GPa. Hooke's Law can be rearranged to predict the yield strain:

$$\varepsilon E = \sigma$$

$$\varepsilon = \frac{\sigma}{E} = \frac{3.5\times10^9}{72\times10^9} = 0.0486 \approx 5\%$$

APPENDIX 2

To calculate the "toughness" or energy absorbed before deformation, we begin with the nonlinear form of the potential energy equation:

$$U = \int \frac{EA_0\Delta L}{L_0} dL = \frac{EA_0\Delta L^2}{L_0}$$

For a unit volume,

$$\frac{U}{A_0L_0} = \frac{\frac{EA_0\Delta L^2}{L_0}}{A_0L_0} = \frac{E\Delta L^2}{2L_0^2} = \frac{1}{2}E\varepsilon^2$$

where $\varepsilon = \frac{\Delta L}{L_0}$

For superglass:

$$\frac{U}{A_0L_0} = \frac{1}{2}E\varepsilon^2$$

$$= \frac{1}{2}\frac{\sigma^2}{E}$$

$$= \frac{1}{2}\frac{\left(3.5\times10^9\right)^2}{72\times10^9}$$

$$= 85\times10^6 \frac{J}{m^3} = 85\frac{MJ}{m^3}$$

APPENDIX 3

We desire to calculate the theoretical energy density of a power storage device based on energy derived from mechanical deformation of the superglass. From our analysis of the stress strain diagram, we concluded that the power density, by volume is 85 MJ/m^3 . The density of glass is 2530 kg/ m^3. Therefore:

$$\left(85\times10^6\frac{J}{m^3}\right)\left(\frac{m^3}{2530kg}\right) = 33.6\frac{kJ}{kg}$$

APPENDIX 4

The Tesla Roadster's 450 kg battery pack can deliver 201 MJ and provide a range of 200 miles[12]. The battery packs' volume was calculated using the energy density and energy per volume estimates taken from online resources[13]. The volume allocated for the battery pack in the Tesla is

$$450kg\left(0.72\frac{MJ}{kg}\right)\left(\frac{L}{1.9MJ}\right) = 110\,Liters$$

Using the same volume but replacing the energy density with that of the strain energy storage device

$$110L\left(85\frac{MJ}{L}\right) = 9{,}400MJ$$

A simple proportionality will provide the range of the Tesla with a battery based on superglass.

$$\frac{201\,MJ}{200\,miles} = \frac{9400\,MJ}{x}$$

$$x \approx 9300\,miles$$