Subject: **Fly Wheel Preliminary Estimates**

Date: 15 March, 2016

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To: ICs Files

1. Fly Wheel Proposal

This investigation considers the option of replacing battery wall storage power unit with a fly wheel spinning reserve, as recently suggested by Evan Pryor. Batteries are considered problematic because they have been known to catch fire, have a limited life span, and can be expected to suffer from technological superseding. Flywheels on the other hand are well known technology and should have a very long service life - albeit at a higher initial capex.

2. Assumptions

2.1) Some current wall storage units have a nominal capacity of 3.6 kWh. To replace this unit with equivalent spinning reserve will require an undefined electro/mechanical input and output. We assume this includes 15% efficiency loss to the storage requirement increasing the capacity to 4.14 kWh. An alternative consideration is the Tesla wall unit quoted with 6.40 kWh of capacity and marketed as a substantial domestic standby capacity unit (together with a second unit in reserve).

2.2) The conversion from kWh to Joules is 1kWh = 3.6e+6 Joules and 4.3 kWh is equivalent to 15,480,000 J

2.3) A possible fly wheel design is a rotating wheel with most weight on the outer solid rim and includes a smooth inner hub attaching the rim to the axle. This is a similar design to a gyroscope wheel, and broadly described as a Torus for purposes of calculating the moment of inertia.

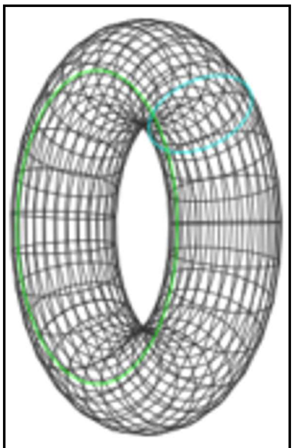
2.4) Weight in the outer hollow rim can be increased by filling it with heated mercury before sealing the feed hole. As the mercury cools it will induce a reduced internal pressure thereby assisting with the hoop strength of the Torus ring. The cited vapour pressure for mercury at 42 ºC is 1 Pa. To maintain rotational balance in this system, the mercury is fed through a hole in the centre of the support axle which is linked to the Torus void. The Hg vapour void remains in the axle and has no influence on the fly wheel rotational stability. This option is not further considered here, but is worthy of study using finite element technology.

2.5) An alternative design is a hollow cylinder (cylindrical shell) rotating around a central axis. This has the advantage of being able to increase the storage capacity by lengthening the shell without significantly changing the hoop stress.

2.6) Assume the maximum rotational speed for the fly wheel is limited to 10,000 rpm. Converting rpm to rad per second: 1rpm = Pi/30 Rad/s, so 10,000rmp = 1,047 Rad/s

2.7) A minimum safety factor of 3.0 times is considered appropriate and is relevant to the maximum yield stress derated to 60% of yield stress to account for the anticipated drop due to fatigue stress.

3. Calculation



Torus - Exhibit 1.

3.1) Rotational kinetic energy is given by
$KE=\frac{1}{2}(It+Id)\omega^2$ (Joules)

Where It is the Torus moment of inertia = $m/4(4a^2 + 3b^2)$ about a central axis, and "m" is the mass of the Torus, "a" is the radius of the tube and "b" is the cross sectional radius. Where ω is angular velocity in Rad/s.

There is also a flat disc connecting the Torus to the central axle hub. This disc element has a value of $Id = \frac{1}{2} \times m \times r^2$ where m is the mass of the disc and r is the radius.

For the thick walled cylindrical shell option the moment of inertia is given by $Ic = \frac{1}{2} \times m \times (a^2 + b^2)$ where a and b are the inner and outer radii respectively.

3.2) Disc structural safety is controlled by the "hoop strength" along the rim. This is calculated from:
$\sigma_t = \rho r^2 \omega^2$
where σ_t is the tensile strength on the rim of the cylinder in MPa for SI units.
ρ is the material density of the cylinder, r is the peripheral radius, and ω is the angular velocity.
The safety factor is the ratio of hoop strength to the derated tensile yield strength for the selected material. In this exercise we have chosen Steel AerMet 340 with yield strength of 2160 Mpa.

3.3) The results for the nominal 3.6 kWh unit with two different geometries show in Table 1.

			Option #1	Option #2
Inputs			Torus Wheel	Torus Wheel
	Required Capacity	kWh	3.60	3.60
	System Efficiency	%	85%	85%
	Installed Capacity	kWh	4.24	4.24
	Conversion kWh -> J	#	3.6E+006	3.6E+006
	Maximum rotational speed	rpm	6,400	5,400
	Torus tube radius "a"	m	0.250	0.330
	Torus ring radius "b"	m	0.100	0.080
	Torus mass density (steel)	kg/m3	7,850	7,850
	Disc thickness	m	0.01	0.01
	AerMet 340 Steel Yield Strength	MPa	2,160	2,160
	Fatigue Strength Derate	%	60%	60%
Outputs				
	Required Energy Storage	J	15,247,059	15,247,059
	Torus X-Sect Area	m2	0.196	0.342
	Torus Length	m	0.628	0.503
	Torus Volume	m3	0.123	0.172
	Disc Volume	m3	0.001	0.002
	Fly Wheel Mass	kg	974	1,365
	Torus Inertia It	kg.m2	68.18	155.24
	Torus Inertia Id	kg.m2	0.06	0.48
	Combined I	kg.m2	68.24	155.72
	Maximum rotational speed	Rad/s	670	565
	KE maximum	J	15,326,511	24,898,231
	Maximum Storage	kWh	4.26	6.92
	Torus Outside Diameter	m	0.70	0.82
	Torus Hoop Stress	MPa	432	422
	Safety Factor	#	3.00	3.07

Table 1.

4. Table 1. Interim Conclusions

4.1) Table 1 shows the basic unit can supply the required storage capacity of 4.24 kWh when spinning at 6,400 rpm and includes a safety factor of 3.0 times. This unit weighs 974 kg.

4.2) The alternative design unit spins at 5,400 rpm while maintaining a safety factor of 3.07. This unit weighs 1,365 kg and can store 6.925 kWh, some 63% more than the base unit.

5. Cylindrical Shell

A cylindrical shell design is commercially available from http://www.power-thru.com/ showing a cut through section of the unit, Exhibit 2:

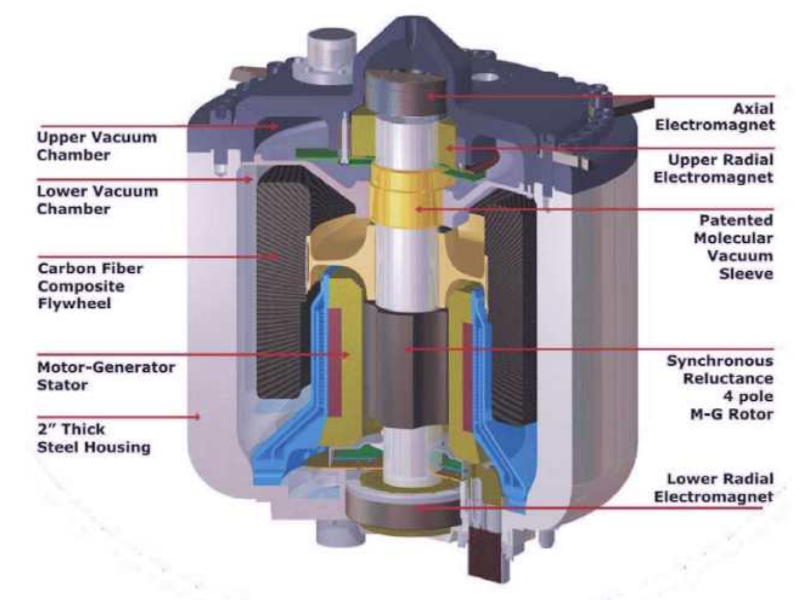


Exhibit 2.

Two simulations for the cylindrical shell show in Table 2:

			Option #3 Cylindrical Shell	Option #4 Cylindrical Shell Long
Inputs				
	Required Capacity	kWh	3.60	3.60
	System Efficiency	%	85%	85%
	Installed Capacity	kWh	4.24	4.24
	Conversion kWh -> J	#	3.6E+006	3.6E+006
	Maximum rotational speed	rpm	7,000	10,000
	Cylinder outside radius "a"	m	0.300	0.224
	Cylinder inside radius "b"	m	0.100	0.100
	Cylinder Length	m	0.600	1.350
	Cylinder mass density (steel)	kg/m3	7,850	7,850
	AerMet 340 Steel Yield Strength	MPa	2,160	2,160
	Fatigue Strength Derate	%	60%	60%
Outputs				
	Required Energy Storage	J	15,247,059	15,247,059
	Cylinder X-Sect Area	m2	0.251	0.126
	CylinderVolume	m3	0.151	0.170
	Fly Wheel Mass	kg	1,184	1,338
	Cylinder Inertia Ic	kg.m2	59.19	40.25
	Maximum rotational speed	Rad/s	733	1,047
	KE maximum	J	15,902,086	22,066,861
	Maximum Storage	kWh	4.42	6.13
	Cylinder Outside Diameter	m	0.30	0.22
	Cylinder Hoop Stress	MPa	380	432
	Safety Factor	#	3.41	3.00

Table 2.

6. Table 2. Interim Conclusions

6.1) A safety factor of 3+ is maintained, for our design requirement, with a heavier 1.184 kg shell rotating at 7,000 rpm

6.2) A cylindrical shell allows for an axial extension to increase the storage capacity, without drastically increasing the hoop stress.

6.3) Increasing the rotation speed to 10,000 rpm and the weight inline with option #2 at 1,334 kg, increases the storage capacity to 6.13 kWh, some 39% ahead of the base unit.

7. Bearing Loads

The gyroscope places extra stress on the bearings when the axis of rotation is not parallel to the earth's axis of rotation. In Brisbane this would require the axis to be pointing N/S and inclined towards the south by 63 degrees from the vertical, Exhibit 3. Bearing friction can be reduced to very low values by using magnetic bearings.

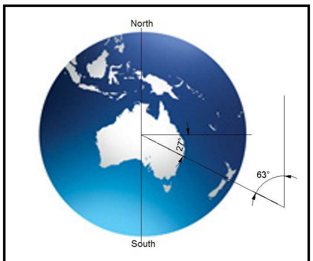


Exhibit 3.

8. Housing Considerations

A rarefied gas surrounding the fly wheel will reduce friction losses. The gyrobus unit, Exhibit 4 used low pressure hydrogen with the unit placed in a vacuum sealed steel casing.


Exhibit 4.

9. References.

John Robertson provided reference http://cdn.intechopen.com/pdfs/20363.pdf which shows a wide range of applications for fly wheels and "off the shelf" units suitable for home storage applications. Also a US Government Safety Assessment of the 'Power Beam' flywheel energy storage device. This is a much smaller system than proposed here and is for an automotive or pedal cycle application. The principles are the same.
http://info.ornl.gov/sites/publications/files/Pub21756.pdf
Another interesting application was post war in Switzerland where buses (gyrobus) were powered in a related technology.

9.1 Flywheel Kinetic Energy http://www.engineeringtoolbox.com/flywheel-energy-d_945.html

9.2 List of moments of inertia - Wikipedia, the free encyclopedia https://en.m.wikipedia.org/wiki/List_of_moments_of_inertia

9.3 Uniform circular motion (centrifugal force) Calculator - High accuracy calculation http://keisan.casio.com/exec/system/1271292951

9.4 Flywheel - Wikipedia, the free encyclopedia https://en.m.wikipedia.org/wiki/Flywheel

9.5 Rotor Design for High-Speed Flywheel

9.6 Centripetal and Centrifugal Force - Acceleration http://www.engineeringtoolbox.com/centripetal-acceleration-d_1285.html

9.6 Pressure Vessel, Thin Wall Hoop and Longitudinal Stresses - Engineers Edge http://www.engineersedge.com/material_science/hoop-stress.htm

9.7 Density, Specific Weight and Specific Gravity http://www.engineeringtoolbox.com/density-specific-weight-gravity-d_290.html

9.8 Calculating Vacuum Pressure within a Cylinder??? - Mechanical engineering other topics - Eng-Tips http://www.eng-tips.com/viewthread.cfm?qid=288689

RAB update of 10 April, 2016