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A 100 kWh ENERGY STORAGE COIL FOR SPACE APPLICATION[*]

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Abstract

The design of a 100 kWh superconductive storage unit for space application is the subject of this paper. High current densities in NbTi-copper composites, adiabatic stability and advanced construction techniques with Kevlar/epoxy tensile supports are used for a $\beta = 0.3$ solenoid cooled to 1.8 K at 10 T. The best weight efficiencies are 26.4 Wh/kg and 21.2 Wh/kg for current densities of 5 and 2.5×10^8 A/m^2 respectively.

Introduction

A 100 kWh energy storage solenoid for a space application should contain a minimal amount of conductor, structure, and dewar wall materials in order to compete with other means of energy storage (batteries or flywheels).

Solenoids are preferred over other magnets because solenoids require less conductor and structural mass.[1] The solenoid is rippled to minimize the strain in the magnet winding. Structure materials chosen are Kevlar/epoxy and boron/epoxy because of their excellent mechanical properties and light weight. The dewar inner shell is epoxy-fiberglass to eliminate eddy currents. The vacuum jacket is aluminum.

Using a reference design of aspect ratio = 0.3 and maximum field 10 tesla, the optimized design is 8 to 10 tesla for aspect ratios from 0.1 to 0.5.

Rippled Solenoids

Figure 1 is a sketch of a rippled pancake design. The magnet is rippled so that the circular structure required to react the radial force can be at a very high tensile strain of 1% without subjecting the conductor to strains larger than 0.2%. This concept results in a lighter structure compared to unrippled conventional coils limited to 0.2% strain. The radial structure is Kevlar/epoxy which has excellent tensile strength and fatigue properties under cycling loads.[2] The axial structure is boron/epoxy with a compressive stress up to 1.72×10^9 Pa depending on the fiber orientation.[2] Both the axial and the radial structures carry the circumferential tension resulting from the local radial forces on each ripple. The ripple radius is chosen so that the strain in the superconductor does not exceed 0.2% strain.

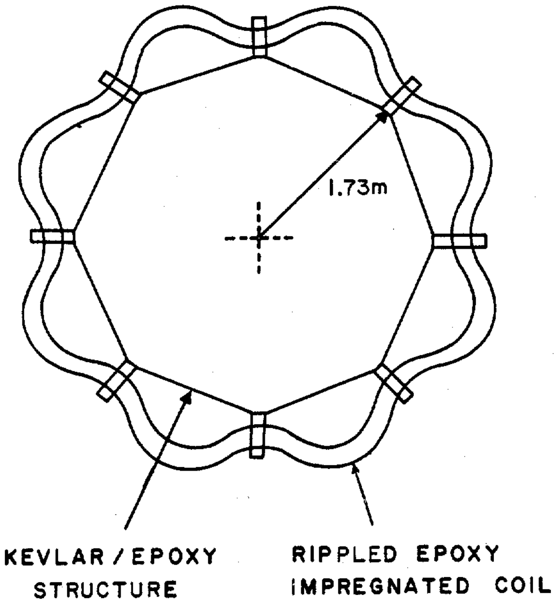

Fig. 1. A sketch of a rippled pancake magnet for space energy storage. Design reported on in this paper has 36 ripples.

The storage magnets considered here are similar to those developed for magnetically levitated trains.[3] They must be lightweight, strong, rigid and capable of high current operation. One such coil with a current density greater than 2×10^8 A/m^2 is subject to premature quenching due to friction between the coil and epoxy structure.[4] Subsequently premature quenching was removed by use of low friction Kapton and epoxy-fiberglass films. Space energy storage magnets should use this and other proven technology to provide the optimum combination of energy density and reliability.

The NbTi to copper ratio is 2:1. NbTi has a critical current density greater than 10^9 A/m^2 in a 10 tesla field in superfluid helium at 1.8 K.[5] The fabrication is a pancake winding on a cylindrical form (5 cm high x 2 cm radial thickness) molded into the rippled geometry prior to epoxy impregnation. Alternatively, the turns could be wound on a rippled form so that no molding strains would occur.

100 kWh Energy Storage System Specifications

Magnet Specifications

The coil is a 1.73 m radius, 10 tesla midplane field solenoid rippled in the radial direction. The specifications are listed in Table I.

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TABLE I. Magnet specifications.

Height	1.257 m
Winding Thickness	2.0 cm
Aspect Ratio	0.363
Current	500
No. of Turns	25,180
No. of Ripples	36
No. of Pancakes	20
No. of Layers	25
Maximum Voltage	480 v
Operating Temperature	1.8 K

The main features of the design are (see Fig. 2):

1. 36 ripples with major ripple radius of 24.1 cm and minor ripple radius of 4.04 cm, Fig. 3.
2. 20 pancakes each of which is 5.08 cm high, 20 layers, and 1259 turns.
3. Boron/epoxy spacers between pancakes are 1.27 cm thick with slots for helium circulation.
4. Plates between windings and inside walls of axial structure have grooves for helium circulation.
5. Boron/epoxy axial structure is pre-rippled and is 1.27 cm thick on each side of the winding.
6. At each ripple node there are pins inside and outside. Outer pins pick up radial ripple load from ripple axial structure and transmit load to the through plates. Inner pins stand away from the inner axial structure enough to allow positioning of the internal radial tension bands.
7. The conductor is graded from one layer to another according to the local field. The weight of the superconductor composite is approximately 818 kg.

Structure

The radial structure is Kevlar/epoxy in tension with a modulus of 7.48 x 10^{10} Pa. The design stress is 830 MPa based on creep data[2] which uses 70% of ultimate in 10^5 cycles and 85% factor of safety.

The axial structure is boron/epoxy in tension and compression. The compression results from the axial forces and the tension results from the radial pressure of the ripples on the axial structure. The tension in the axial structrue and winding tension is reduced for small ripple radius. The design stresses are 748 MPa in tension at 90° fiber orientation and 775 MPa in compression at 0° fiber orientation. The tensile modulus is 1.22 x 10^{11} Pa, see Table 5.9 of reference 2.

The plates separating the pancakes experience compression and bending due to the axial load and tension in the radial and circumferential directions. The material is boron/epoxy with the fibers oriented for optimum reaction to the tension and compression loads. The maximum design stresses are 5.17 x 10^8 Pa in bending due to axial load, 7.58 x 10^8 Pa in tension, and 7.86 x 10^8 Pa in compression. The 1.27 cm thickness of these plates is governed by the radial force at each node 2.08 x 10^5 kg.

Boron/epoxy composite is used for pins that go through the plate-spacers at each node. The 3 cm pin diameter is needed for bending loads between each plate-spacer. Our estimate of the structure requirements is 1684 kg. Details of the design are in ref. 6.

Dewar

The dewar is in the form of an elongated torus which closely conforms to the shape of the thin solenoid magnet. The inner shell will be made of epoxy-fiberglass with an electrically discontinuous stainless steel foil layer impervious to helium diffusion. The outer shell is aluminum. Minor eddy current losses are dissipated to the environment and not to the cryogenic system as would be the case for an inner aluminum wall.

The centerline diameter of the dewar is 346 cm and the overall height of the vacuum jacket is 152.4 cm. The radial thickness of the vacuum jacket as sketched in Fig. 4 is 34.3 cm excluding external attachments. Nominal spacing between the inner container and vacuum jacket is 7.5 cm which allows for 5 cm of multilayer insulation and three gas cooled shields with space to hang the Kevlar-epoxy support straps.

The shell design requirements are unusual in that one cylinder of each is under internal pressure and the other is exposed to external pressure. For this reason, the cylinders have different thicknesses and stiffening arrangements. Thus, the outer cylinder and end caps of the helium container are 0.23 cm epoxy fiberglass and the inner cylinder is 0.318 cm thick with additional stiffeners formed in the composite. A stainless steel 0.00508 cm foil is laminated approximately midway in the composite lay-up to prevent helium diffusion. Ends of the foil sheets overlap but are insulated by a layer of epoxy-fiberglass material to reduce mutual inductance.

The aluminum inner cylinder of the vacuum jacket is 0.114 cm thick and outer cylinder is 0.476 cm thick with rolled stiffeners spaced 15.2 cm apart. Outer end caps are 0.25 cm thick aluminum. Estimated weights of the two shells are summarized in Table II.

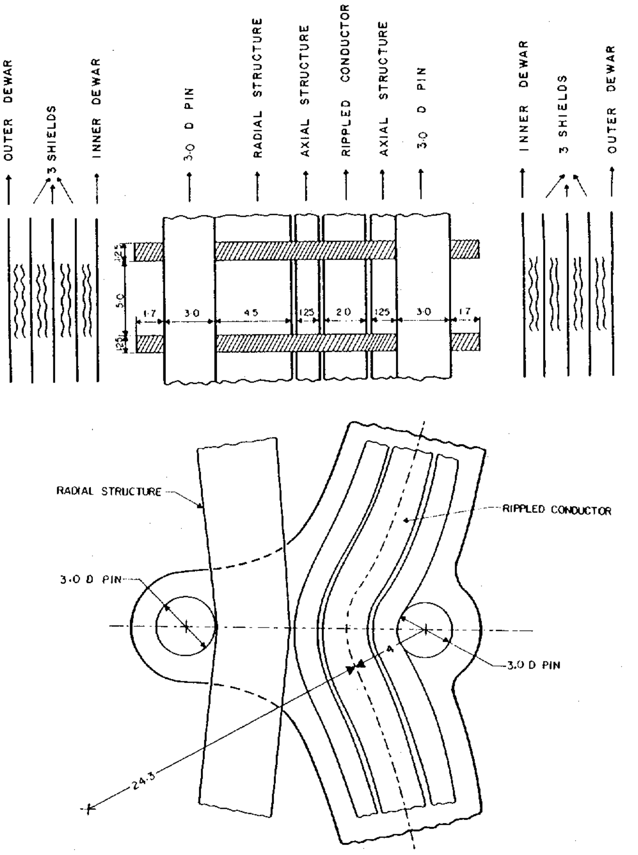


Fig. 2. Vertical and top cross-section of winding and structure. All dimensions are in centimeters

TABLE II: Dewar weights.

	Weight	
a) Inner Shell Weight		
stainless steel "Tee" rings	143.9 kg	316.5 lb
ends	12.6	27.7
outside shell	48.0	105.5
inside shell + stiffeners	68.4	150.5
b) Outer Vacuum Jacket Weight		
inner cylinder + stiffeners	65.0	142.9
outer cylinder	264.6	582.1
end caps + angles	114.3	251.3
weld metal and contingency	44.5	100.0
c) Total Inner and Outer Shell Weight	762.1 kg	1676.5 lb

Support System

The rippled magnet is axially supported to two support rings by internal fiberglass straps that wrap the magnets and are connected to the support rings as shown in Fig. 4. The unrippled inner dewar shell (epoxy-fiberglass) is two parts (upper and lower) connected to the magnet support rings. The outer aluminum dewar (vacuum jacket) is connected to the magnet rings, Fig. 4, by major support fiberglass straps which are connected on the other side to heavy aluminum angle hard points.

The transverse support of the magnet/inner dewar shell is a Kevlar-epoxy polygon attached to multiple points on the inner magnet support ring. The polygon leans on a transverse support stiffener through the inner vacuum jacket.

The support system concept design is based on a 6 g acceleration in one axial direction and 3 g laterally and in the opposite axial direction.

Cryogenics

Losses

The space energy coil is desgined for use on an earth orbiting space vehicle having a period of approximately 90 minutes. In each orbit the coil will be charged from a solar cell array and discharged during the time the vehicle is in the earth's shadow. Because of the transient duty cycle, the magnet has important losses in two categories: (1) electrical losses during the 90 minute charge/discharge cycle and (2) steady state thermal and lead losses. Electrical losses are reduced for a fiberglass-epoxy inner shell and by electrical breaks in the equatorial support rings.

Steady state losses due to support and insulation heat leak are about 0.6 watt and lead losses are about 1.5 watts for a total steady loss of 2.1 watts. Ac losses in the conductor are mostly hysteresis losses of about 1 watt. The total loss is 3.1 watts. If 277 liters of the total 1777 liter liquid helium volume are set aside for reserve, then the 1500 liter working volume provides a holding time of 343 hours at 4.37 liters per hour which is equivalent to 3.1 watts.

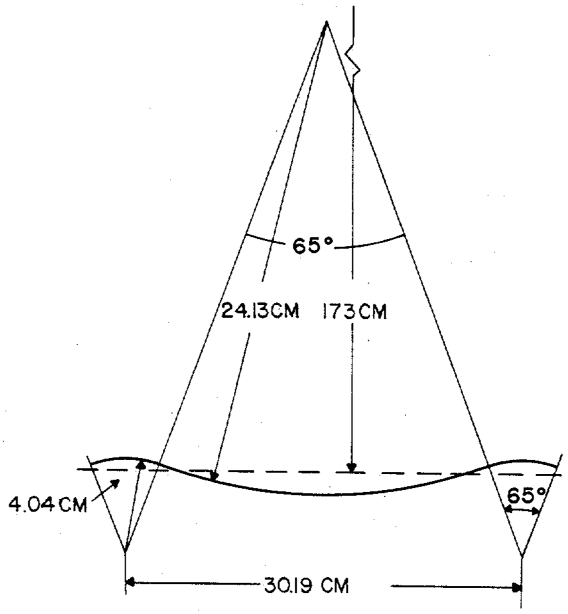


Fig. 3. Dimensions of the inner and outer ripples. The coil has 36 ripples with the support pins spaced 30.19 cm apart.

Figure 5 is a flow schematic sketch for the energy storage space coil. It is similar to the IRAS (Infrared Astronomical Satellite) flow system.[7] The main features are:

1. Communication lines to superfluid zero gravity reservoir (dewar) need internal cold valves to prevent liquid from creeping.
2. A porous (stainless steel) plug with an area = 32 cm^2 to accommodate normal heat leak of 3.1 watts.
3. An added feature of the space magnet is a wick surrounding the magnet to draw liquid to it instead of letting helium coat the dewar walls.

Optimization Study

The weights of the different components of the 100 kwh, 10 tesla, $\beta = 0.3$ coil are summarized in Table III. The energy stored per unit mass is 12 wh/lb.

TABLE III: Total weight of a 100 kwh unit.

Structure	1684 kg	3705 lb
Dewar + Insulation	883	1943
Conductor	818	1800
Epoxy	114	250
Support	68	150
Helium	205	450
Total	3773 kg	8300 lb

Using the reference design of Table III, the optimization study considers aspect ratio, field, and energy stored in reference to the total weight of a system. For an energy stored E', midplane field B_M', and an aspect ratio β', the radius R' is related to the radius of the reference unit R by

$$\frac{R'}{R} = \frac{G(\beta')}{G(\beta)} \left(\frac{E'}{E}\right)^{1/3} \left(\frac{B_M}{B_M'}\right)^{2/3} \qquad (1)$$

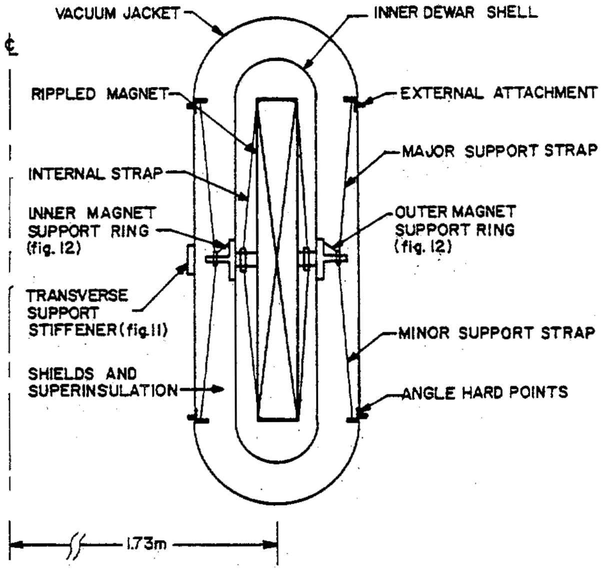
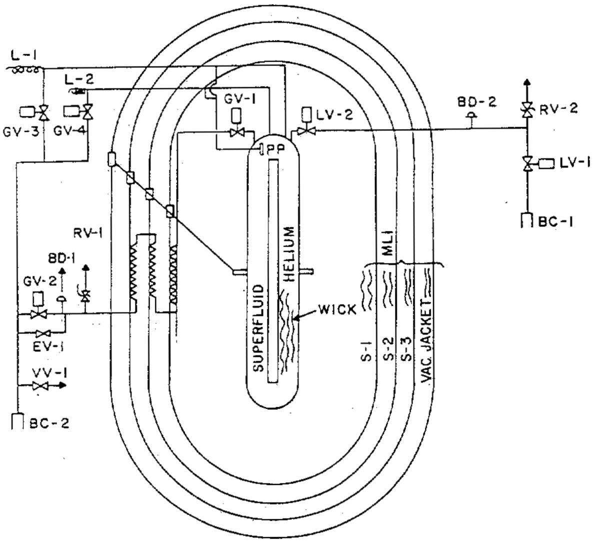


Fig. 4. Magnet dewar and support arrangement.



LV - Liquid Valve
GV - Gas Valve
EV - Explosive Act. Valve
VV - Vacuum Valve
RV - Relief Valve
MLI - Multilayer Insulation
BD - Burst Disc
BC - Bayonet Connector
PP - Porous Plug
S - Vapor Cooled Shield
L - Vapor Cooled Lead

Fig. 5. Fluid flow schematic and thermal arrangement.

The total mass of the conductor M_{cd}' is

$$\frac{M_{cd}'}{M_{cd}} = \frac{J_{sc}}{J_{sc}'} \frac{Q_{is}(\beta')}{Q_{is}(\beta)} \left(\frac{E'}{E}\right)^{2/3} \left(\frac{B_M}{B_M'}\right)^{1/3} . \quad (2)$$

where J_{sc} and J_{sc}' are the respective design current densities in the superconductor. Values for the G and Q factors are in references 1 and 6. The mass of tensile structure M_t' and the compressive structure M_c' are

$$\frac{M_t'}{M_t} = \frac{Q_t\ (\beta')}{Q_t\ (\beta)} \frac{E'}{E} \quad \text{and} \quad (3)$$

$$\frac{M_c'}{M_c} = \frac{Q_c\ (\beta')}{Q_c\ (\beta)} \frac{E'}{E} \quad . \quad (4)$$

The mass of superinsulation M_{SI}' and liquid helium M_{HE}' are

$$\frac{M_{He}'}{M_{He}} = \frac{M_{SI}'}{M_{SI}} = \frac{\beta' R'^2}{\beta R^2} \quad (5)$$

The scaling law for both walls of the inner shell, and the inner wall of the outer shell is

$$\frac{M_{DWI}'}{M_{DWI}} = \frac{\beta' R'^3}{\beta R^3} \quad . \quad (6)$$

For the outer wall of the outer shell, the scaling law is

$$\frac{M_{DW2}'}{M_{DW2}} = \frac{\beta'}{\beta} \left(\frac{R'}{R}\right)^{13/5} \quad . \quad (7)$$

For end caps and angles the scaling law is the same as for the radius. For rings and attachments the weight is proportional to the total weight of the system.

Figs. 6 and 7 are plots of stored energy per unit mass vs. aspect ratio β, field B, and energy stored E. The conclusion of this optimization study is that a field of 8 to 10 tesla and aspect ratios from 0.1 to 0.5 are optimum choices.

Conclusions

The weight per unit energy is plotted in Figs. 6 and 7 vs. B and β. The total weight efficiency is 12-18 watt hours per pound in the energy range 100 kWh to 10,000 kWh. The optimal solenoid designs are $8\ T < B < 10\ T$ and $0.1 < \beta < 0.5$. In Table IV are listed overall weight efficiencies which improve slowly with energy storage capacity. The expensive conductor benefits most by better utilization in larger storage units. Tensile structure, of course, is proportional to stored energy and shows no benefit for larger sizes. A major improvement would be to use already available structure and higher stress ratings.

An optimistic overall current density 5×10^8 A/m^2 was used in the design of the 100 kWh unit. The use of a lower value results in lower energy stored per unit mass. Table IV lists the efficiency in Wh/kg and Wh/lb vs. overall current density. The difference in the energy stored per unit weight between 5×10^8 A/m^2 and 2.5×10^8 A/m^2 is less significant for 10,000 kWh because the structure and dewar predominates. For the 100 kWh unit the above change in current density only accounts for a 20% change in weight efficiency.

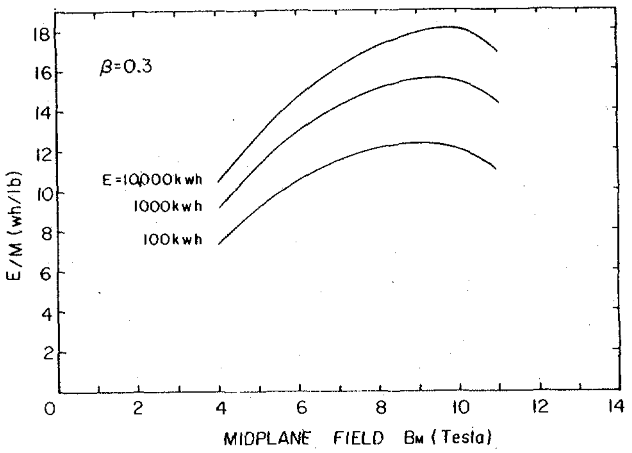


Fig. 6. Energy stored per unit mass vs. midplane field B_M and the energy stored E for β = 0.3 solenoid.

Table IV: Solenoid storage efficiencies (B = 10 T, β = 0.3).

Energy (kWh)	100	1,000	10,000
Radius (m)	1.73	3.73	8.03
Height (m)	1.26	2.71	5.83
Structure, Support Dewar, & Helium (kg)	2,840	24,848	230,637
Conductor & Epoxy Weight (kg)	932	4,325	20,473
Total Weight (kg)	3,772	29,173	251,110
Efficiency at 5 x 10^8 A/m^2			
(Wh/kg)	26.5	34.27	39.82
Efficiency at 2.5 x 10^8 A/m^2			
(Wh/kg)	21.26	29.9	37.0

Acknowledgement

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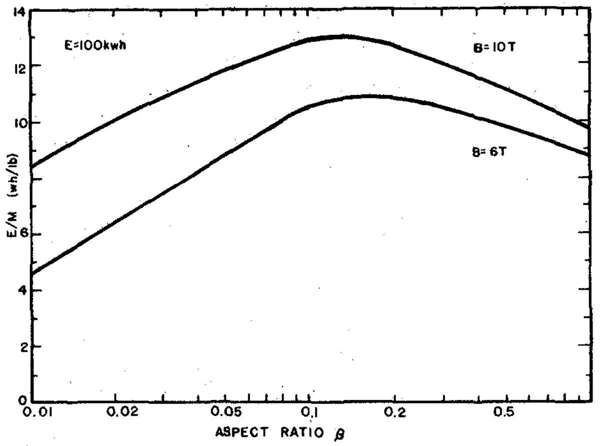

Fig. 7. Energy stored per unit mass vs. aspect ratio β for different values of B.

References

1. R. W Moses, Advances in Cryogenic Engineering, Vol. 21, p. 140.
2. "Commerical Opportunities for Advanced Composites", ASTM publication No. STP704.
3. T. Ohtsuka and Y. Kyotani, "Superconducting Maglev Tests", IEEE Transactions on Magnetics, Vol. MAG-15, No. 6, Nov. 1979.
4. T. Yamada et al., "Cause of Quenching in Epoxy Impregnated Superconducting Coils", IEEE Trans. on Magnetics, Vol. MAG-17, No. 5, Sept. 1981.
5. D. C. Larbalestier, "Superconducting Materials", IEEE Trans. on Magnetics, Vol. MAG-17, No. 5, Sept. 1981, p. 1668.
6. Y. M. Eyssa, R. W. Boom and G. E. McIntosh, "A 100 kWh Energy Storage Coil for Space Application", Report to NASA, Grant NAG3-170, University of Wisconsin, Madison, 1982.
7. A. R. Urbach et al., "Progress Report of the Infrared Astronomical Satellite Cryogenic System", paper P E-2 Cryogenic Engineering Conference, San Diego, 1981.