DESIGN AND OPTIMIZATION OF HYDROGEN COOLED PULSED STORAGE INDUCTORS FOR ELECTROMAGNETIC LAUNCHERS

Y. M. Eyssa, M. K. Abdelsalam, R. W. Boom, X. Huang, G. E. McIntosh⁺ and J. Waynert^{*}

The Applied Superconductivity Center
The University of Wisconsin-Madison
1500 Johnson Drive
Madison, WI 53706

⁺Cryogenic Technical Services
Boulder, CO 80301

^{*}Astronautics of America
Madison, WI 53716

Abstract

Cryoresistive magnetic energy storage systems that can deliver Meg-Amp Kilo-Volt levels of pulsed power for a short time (200-1000 s) have important potential applications in space-based strategic defense systems. Hydrogen cooled aluminum cryoresistive coils operating at frequencies > 1 Hz are efficient and light weight ($\Delta E/M = 20-50$ J/g). In this paper we report on: analysis of eddy current losses; the use of aluminum inductors at $15\text{ K} < T < 30\text{ K}$ in fields $B < 10\text{ T}$; inductor cooling; optimization of energy stored per unit mass; and conceptual designs of 300 MJ hydrogen cooled cryoresistive toroids and solenoids.

Introduction

Pulsed applications such as magnetic fusion, accelerators and electromagnetic launchers (railguns) require energy delivery into the load in very short huge bursts. For such applications, there is a need for an energy storage inductor that can be charged at low power from a primary energy source and discharged directly into the load over a short time (1-10 ms). The purpose of this paper is to relate the periodic pulse shape required for railguns to the I^2R losses. Hydrogen cooled high purity aluminum is proposed as the low loss conductor because of the available liquid hydrogen fuel.

Fig. 1. Electromagnetic launcher circuit with storage inductor.

The circuit shown in Fig. 1 illustrates the voltage or power amplification function of the series inductor connected to the railgun. The homopolar generator (HPG) which is the primary energy source, charges the inductor to a peak current, $I_{\max}$, as shown in Fig. 2 in τ_1 , at which time switch S_2 opens, forcing current into the railgun. The inductor then discharges into the railgun through a plasma armature behind the projectile in a short time, $\tau_2 \ll \tau_1$, and the current decreases to $I_{\min} = n I_{\max}$. The inductor

should be large enough so that the current does not drop appreciably during the discharge. The cycle is periodic for repetitive firing of projectiles, as seen in Fig. 2.

Fig. 2. Inductor electric current representing periodic charge and discharge.

The ohmic loss in a coil is divided into two parts: the dc loss, P_{dc} , related to the average current, I_{av} ; and the ac loss, P_{ac} . The total power loss, P_t , is exactly equal to the sum of P_{ac} and P_{dc} . P_{ac} is calculated by summing the power loss due to the fundamental and all Fourier harmonics of the field or current pattern. Detailed analysis of power loss calculation are included in reference (1). The analysis covers losses for cable conductors or multilayer coils where each cable wire or coil layer tries to shield itself from ac fields. Figure 3 shows how a dimensionless resistance α_t , the ratio of losses due to actual current distribution to the losses for uniform current distribution vs. $I_{\max}$ and $I_{\min}$ for either the cable wire diameter or the layer thickness. The curves shown cover a 4 cm thick aluminum conductor in a single layer coil that is either replaced by a transposed cable conductor of wire size d or multilayer conductors with reduced thickness d . As shown a non-cabled single layer coil has smaller resistance unless the cable size or the layer thickness in a multilayer coil is smaller than the skin depth.

The resistivity ρ that is used in the above calculations is the final resistivity at 20 K after strain and at magnetic field.² For small wires ($d \approx 0.1$ mm and less), the apparent resistivity increases due to a size effect.³ The curves in Figure 3 are not realistic for $d < 10^{-4}$ m, unless an additional resistivity is considered.

Fig. 3. Dimensionless total resistance versus cable wire size or layer thickness d for different $Q = (I_{\max} + I_{\min}) / (I_{\max} - I_{\min})$.

Inductor Configuration

Most energy storage coils are either short solenoids or D-shaped toroids.^{4,5} The solenoid has minimum conductor mass while the D-shaped toroid has zero stray field and constant tension to minimize structure requirements. Both concepts are considered in this study.

Conductor Materials

Pulsed energy storage conductors carry 1 to 2 MA currents with minimum electrical resistance. For best storage efficiency an inductor system in space should be cooled with available liquid hydrogen. The useful temperature range is $15 < T < 25$ K and the magnetic field is $B < 12$ T.

Aluminum is the preferred cryoconductor material at 20 K for high field applications for the following reasons: 1) lower resistivity ratios RRR, 2) magnetoresistivity is low, 3) pure metal is commercially available, and 4) ease of handling and fabrication. The disadvantages are: 1) mechanically weak in the annealed form and 2) difficult to join electrically to itself or other metals because of a tenacious surface oxide.

The effect of plastic strain, cyclic strain and magnetic field on resistivity of aluminum is considered in detail in reference 6 and is not included in this paper.

Inductor Cooling

Cryoresistive inductor designs are all based on low aluminum resistivity which can only be realized with relatively strain free 10,000 RRR material cooled at or below 20 K. Aluminum temperatures of 20 K require the saturated hydrogen coolant to be maintained at sub-atmospheric pressure. Thus, all of the calculations are based on 5 psia hydrogen with a saturation temperature of 17.11 K. This makes possible a conductor design temperature of 19 K after allowing 1.4 K for heat exchange temperature difference and about 0.5 K for contingency.

The conductor cooling should either be done with boiling hydrogen liquid or with entirely subcooled non-boiling hydrogen. Boiling liquid requires much lower flow work and does not need a large, heavy subcooling heat exchanger used in a single-phase system. However, two-phase cooling is restricted to fairly low maximum quality values in order to avoid premature transition to film boiling and the large temperature differences involved. We assume saturated liquid at the inlet, maximum quality of 10% or 25% at outlet, and a maximum forced flow heat transfer rate of 4 W/cm^2 . In some cases, the heat transfer surface area is increased by broaching or otherwise shaping the heat transfer surfaces with deep longitudinal saw-tooth grooves.

Factors influencing heat transfer include pressure, quality, flow rate, surface roughness, flow channel configuration, gravity field and other lesser contributors. Very high heat transfer is desired for the proposed inductors in order to reduce conductor mass. Significant limitations are built in, however, because low saturation pressures must be maintained to keep the conductor temperature as low as feasible and, at such high flow, low pressure conditions can cause transition from nucleate to film boiling at relative low quality values. The objective of this work is to design with a maximum Q/A value which presents minimal risk of burnout when combined with a maximum allowable quality. The value of $Q/A = 4 \text{ W/cm}^2$ and maximum quality of 25% meets this criterion as discussed below.

One design problem is that there is very little published data on hydrogen forced flow nucleate boiling. The principal reference is the work of Wright and Walters. In fact, Walters is the only nucleate boiling reference used in NBS Technical Note 317⁸ which is a general survey of cryogenic boiling data. With somewhat rough interpolations, the Walters data of reference 7 is as follows:

Table 1

Flow	$220,000 < Re < 330,000$
Quality	$0.023 < X < 0.043$
Pressure	1.6 atm

$\Delta T\text{-K}$	$Q/A\text{-W/cm}^2$
0.5	0.96
1.11	2.84
1.4	4.0
1.67	5.04
1.94	6.3
2.06	6.62

The last value is not the burnout point but is believed to be the highest stable Q/A obtainable. While this is lower than some pool boiling burnout values obtained at higher pressures, it is considerably higher than pool boiling based on a given ΔT . To illustrate this point, Table 2 listing Q/A vs. ΔT values were constructed utilizing pool boiling data from the Kutateladze correlation for hydrogen given in NBS Technical Note 317 and the Walters data (P.B.--pool boiling; F.F.--forced flow).

Table 2 clearly indicates that forced flow boiling heat transfer is higher for a given ΔT , about double at low Q/A , than for pool boiling. However,

forced flow boiling results in transition to film boiling at moderately low quality values which suggests that the peak Q/A rate may in fact be lower than pool boiling burnout at the same pressure.

Table 2. Q/A vs. ΔT

Q/A-W/cm ²	ΔT -K Kutateladze P.B.	ΔT -K Walters-FF	PB ΔT /FF ΔT
1	1.3	0.56	2.32
2	1.7	0.85	2
3	1.9	1.15	1.65
4	2.2	1.4	1.57
5	2.4	1.7	1.41
6	2.6	1.9	1.37

Pressure has a profound effect on boiling. A second set of Walters' data at 2.2 atm extends to Q/A = 13.24 W/cm² for ΔT = 2.78 K. For a given temperature difference, the pressure increase from 1.6 to 2.2 atm (along with doubling Reynolds' number) increased Walters' Q/A values by 30% to 75% with ΔT increases from 0.56 to about 2 K.

It is concluded that, for a design inlet pressure of only 5 psia and Reynolds' numbers comparable to those measured by Walters, the design value of 4 W/cm² is not excessively conservative when coupled with a maximum quality of 25%. Experimental data to explore the safe envelope of Q/A values for various quality,

ΔT , pressure and Reynolds' number combinations would be of great value.

Cooling System

Liquid hydrogen cooling requirements for cryoresistive magnets present uniquely difficult system demands. High flows, zero gravity and the need for multiple passes without wasting liquid form a combination different from other space cryogenic applications. Current planning exemplified by the SHOOT⁹ superfluid helium experiment involve screen acquisition devices with limited flow and delivery head capabilities. Both helium and hydrogen space tanker studies now being started (helium) or in bid evaluation (hydrogen) by NASA contemplate flow rates from several hundred to one or two thousand litres/hour. The typical net hydrogen flow requirement calculated above is for over 50 litres/second or some 180,000 litres/hour. For the relatively small, 10,000 to 20,000 litres, the total liquid hydrogen requirement, it seems unlikely that acquisition screen areas can be made large enough to provide the necessary flow.

In this study we are proposing a hybrid system consisting of a dewar with a positive expulsion bladder and a centrifugal vapor-liquid separator to re-cycle unboiled liquid. As shown in Fig. 4, the complete system consists of the refrigerated storage dewar, low NPSH circulation pump, vapor-liquid separator, initial helium pressurant gas supply and related controls. Design of the dewar anticipates ability to cool the cryoresistive coil by conduction during standby conditions so that a single closed cycle 17 K refrigerator can maintain the entire system without loss or circulation of liquid hydrogen.

In operation, helium gas initially compresses the expulsion bladder to start liquid flowing to the pump. Flow from the pump circulates through the

Fig. 4. LH₂ cooling system for a pulsed energy storage toroid.

cryoresistive coil to the vapor-liquid separator (VLS). The VLS provides artificial gravity to separate vapor and liquid with liquid returning to pump inlet and vapor exiting the system. A small portion of the vapor is used to pressurize the expulsion system when the initial helium gas supply is depleted. Although some contingency liquid will be provided, the hydrogen system should be able to run until the dewar is empty.

Design Concepts

Design concepts for both solenoidal and toroidal cryoresistive pulsed inductors cooled with liquid hydrogen are discussed below. The energy delivered is 80 MJ at I_{min}/I_{max} = 0.875. The specifications of the reference unit are listed in Table 3.

Table 3. Specifications for reference designs

Energy delivered, $4E$	(MJ)	80
Average current, I	(MA)	1.5
$\eta = I_{min}/I_{max}$		0.875
I_{max}	(MA)	1.6
I_{min}	(MA)	1.4
Energy stored at I_{av}	(MJ)	300
Energy stored at I_{max}	(MJ)	341.33
Energy stored at I_{min}	(MJ)	261.33

Solenoids

The 300 MJ solenoid shown in Fig. 5 has two layers and five turns. A two-layer coil is preferred over single layer or multilayer coils because it has more cooling surface to remove the high surface heat flux ($q = 4W/cm^2$).

The conductor shown requires a strong skin for

Fig. 6. Top view of the hydrogen cooled cryo-resistant toroid magnet.

Fig. 7. D-shaped toroid. Dimensions are in cm.

Magnetic pressure forces the D-shape pipes into constant tension with a maximum tensile force of 3.30 MN for each pipe. The cross-sectional area of the pipe, as shown in Fig. 8, is 81.46 cm^2 . Therefore the overall maximum tensile stress of the pipes is $\sigma = 405 \text{ MPa}$ (58.7 ksi).

The structural pipes are Gy-70 graphite epoxy composite. At 20° K its tensile strength is 759 MPa (110 ksi) and Young's modulus is 324 GPa. The cross-section of the central bucking cylinder is shown in Figs. 8 and 9. It consists of a 1 cm thick cylinder and thirty-three 1 cm thick outer rings with a spacing of 8 cm. The purpose of such arrangement is to increase the bending stiffness to prevent buckling. Boron/epoxy composite is chosen for the cylinder due to its high specific strength and specific stiffness in compression.

Fig. 8. Cross-section of the D-coil showing conductor, cooling surface, and hydrogen cooling channel. Dimensions are in cm.

Fig. 9. Cross-section of central bucking cylinder. Dimensions are in cm.

Weight Optimization

An optimization study has been undertaken to find the energy delivered per unit mass, $\Delta E/M$, for all input parameters such as ratio of maximum energy stored to energy delivered, inductor current, initial resistivity ratio of aluminum, operating temperature, pulse shape, surface cooling parameters, structure modulus, coil configuration (solenoid or toroid), coil aspect ratio and number of turns. The final effective resistivity is determined based on magnetoresistance, cycling strain, and eddy current losses. In addition, conductor dimensions, winding mass, hydrogen mass and the optimum value of $\Delta E/M$ are found.

All inductor component masses are used, including conductor, structure, piping, refrigerators, pumps, hydrogen, storage tanks, and insulation. Two cases are considered in this optimization: 1-Hydrogen is

Fig. 10. Delivered $\Delta E/M$ for solenoids. Fig. 11. Delivered $\Delta E/M$ for toroids.

not available from other sources for cooling, therefore its mass (including storage dewar) is included in the inductor total mass. The optimum conductor dimensions minimize the sum of all masses (including hydrogen). 2-Part or all of the hydrogen for cooling is available from fuel storage. Part or all of the hydrogen mass and storage tanks are not included in the total inductor mass.

The reference solenoid and toroid designs detailed earlier are used. $\Delta E/M$ as high as 50 J/g are possible, see Figs. 10 and 11 for solenoids and toroids. Tables 4 and 5 show the increase of E/M vs. the extra cooling available for case 2.

The first column in Tables 4 and 5 show the range of $\Delta E/M$ between two cases: 1 - the hydrogen is not available for cooling from other sources, hence its mass plus storage mass are fully included in total mass, M ; 2 - the hydrogen available from other sources is just equal to the optimum amount required in case 2, hence its mass is not taken in the total coil mass, M . If more hydrogen is available then the conductor mass can be reduced as shown in the tables.

Table 4. $\Delta E/M$ for $\Delta E = 200$ MJ solenoid vs. conductor mass, M_C . Other masses = 1510 kg.

M_C (kg)	2575	1946	1502	1088
$\Delta E/M$ (J/g)	30-49	57	66	77

Table 5. $\Delta E/M$ for $\Delta E = 200$ MJ toroid vs. conductor mass, M_C . Other masses = 1320 kg.

M_C (kg)	4670	3357	2620	2027
$\Delta E/M$ (J/g)	17-30	37	42	48

Conclusions

1. Eddy current losses due to pulsing are minimized by using single-layer coils. Higher losses of cabled conductors and multilayer coils are caused by self shielding of each conductor or layer, from the ac fields from the other conductors. I^2R losses for cable is low if the wire size is much smaller than the skin depth ($d \ll 2$ mm). However, small wire sizes may have higher resistivity due to size effect.
2. High purity aluminum inductors pulsed at 1 Hz for a few minutes have storage efficiencies greater than 95%. $\Delta E/M$ as high as 50 J/gm is possible if hydrogen is available.
3. High modulus-low density structural materials are required to limit conductor strain and resistivity degradation.

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