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Superconducting Materials Applied to Electric Propulsion Systems

Claudio Bruno* and Daniele Casali†
University of Rome "La Sapienza," 00184 Rome, Italy

Applications of superconducting materials in electric thrusters are reported in this investigation. The benefits of using superconducting coils instead of copper coils in a magnetoplasmadynamic thruster are conceptually analyzed and illustrated. The calculations performed show a potential increase in performance and a large reduction of coil weight. Scaling down of Hall thrusters is examined and it is found that applying superconducting coils to the thrusters affects the scaling positively because superconducting coils do not limit the volume scaling. Moreover, scaling without excessive engine performance penalty requires an increase of the magnetic field, a requirement fulfilled by the application of superconducting coils. Finally, issues are raised related to the structural stresses on superconducting coils and the cooling systems required to maintain the superconductivity property, and solutions are proposed.

Nomenclature

A_w = coil wire section, m^2
a_l = solenoid inner radius, m
B = magnetic induction, T
F = Lorentz force, N
g = gravitational acceleration, m/s^2
H = magnetic field, Oe
h = channel width, m
I = current, A
I_d = discharge current, A
I_{sp} = specific impulse, s
J = current density, A/mm^2
k = scaling factor
L = channel length, m
l_a = ions acceleration region length, m
l_w = coil wire length, m
$\dot{m}$ = mass flow rate, kg/s
P = pressure, N/m^2
P_w = electric power, W
S = cross-sectional area, m^2
T_c = transition temperature, K
T_e = electron temperature, K
t = thickness, m
U_a = voltage drop, V
U_d = discharge voltage, V
V_{coil} = coil volume, m^3
v_i = average ion velocity, m/s
λ_i = mean free path ionization, m
η_p = propellant utilization factor
σ = normal stress, N/m^2

Introduction

RECENT years have witnessed a rising interest in electric propulsion (EP), not only for applications to satellites but also for future interplanetary travel. Comparing EP performance to that of classical chemical thrusters, the latter have I_{sp} in the range 300–500 s and the former in the range 400–8000 s, implying a potential dramatic reduction in propellant consumption for a given mission. Propellant mass saved by using EP can go toward either heavier payloads, or to perform a given mission with smaller and less expensive launch vehicles. In Fig. 1 the ratio of propellant total weight to satellite total weight for a 2400-kg satellite, raised from 250 km to geostationary Earth orbit (GEO),[1] is shown.

A second advantage of EP systems over chemical thrusters is their thrust modulation, making them ideal for attitude control, station keeping, and orbit adjustment. On the other hand, EP systems need considerable electrical power to produce reasonable thrust at high I_{sp} and efficiency. This large power requirement implies a mass penalty [mostly due to solar panels and power conditioning units (PCU)]. The limits imposed by the electrical power system are mirrored in the maximum available thrust, which is of the order of millinewtons to newtons (depending on applications). To overcome such limits, and to make EP more appealing for future interplanetary missions, superconducting (SC) materials could be utilized.

The goal of this paper is to quantify in a preliminary way the beneficial effects of replacing copper wiring with SC wiring.[2] The main feature of SC materials is the property of having, under certain conditions, resistivity and magnetic permeability close to zero; thus, after startup, high-density currents can flow in the material indefinitely without the need to maintain voltage (and power). Such materials could lead to significant reduction of electric power and coil mass, while magnetic fields up to several teslas can be generated with lighter SC coils. Therefore, SC materials can enable high Lorentz thrust ($F = J \times B$) and I_{sp} in electric thrusters using high B, such as future magnetoplasmadynamics (MPD) and Faraday-type Hall thrusters (HT).

This is not the first paper suggesting the use of SC in EP. In fact, prior to Refs. 1 and 2, which comprised the starting point for the present work, SC wires have been proposed[3,4] and tested.[5] However, to the authors' knowledge, this is the first time that a quantitative assessment of mass savings and effect of size reduction (scaling) is presented.

Superconducting Materials

Superconductivity is a property of materials in which resistivity and magnetic permeability are close to or nearly zero. Superconductivity is explained by the BCS theory developed by Bardeen, Cooper, and Schrieffer (see Ref. 2): when a material is in its superconductive state, conducting electrons propagate without any resistance because they form a moving pair (Cooper pair); Cooper pairs form due to the interaction of electrons with the mechanical vibrations of the crystalline lattice; the atomic vibrations in the reticulated structure

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*Professor, Department of Mechanics and Aeronautics, Via Eudossiana 18. Associate Fellow AIAA.

†Aeronautical Engineer, Department of Mechanics and Aeronautics, Via Eudossiana 18.

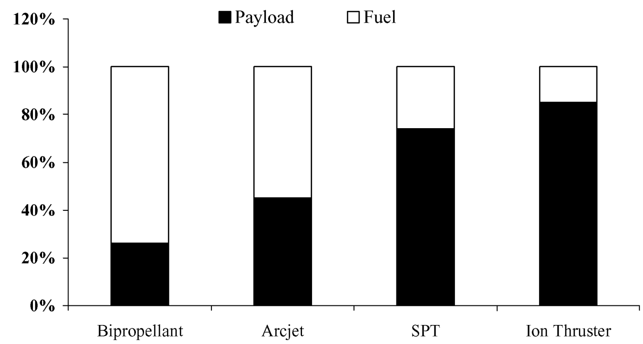

Fig. 1 Propulsion systems and corresponding satellite weight distribution.[1]

tend to diminish the repulsive force among electrons, a phenomenon equivalent to an attractive force between electron pairs. The intensity of this interaction depends strongly on temperature. The temperature at which a material switches from SC to a normal conductivity (NC) state is the "critical" or "transition" temperature T_c. A second important feature of SC materials is their ability to expel a magnetic flux (self-induced or applied); this feature is known as the Meissner effect.

Two important microscopic reference lengths have been determined for SC materials if a magnetic field B is applied: the distance between two electrons in a Cooper pair, called coherence length, and the characteristic B field decay length, called London penetration depth.

Based on these reference lengths, SC materials can be classified as type I SC or type II SC. Type I SC materials are characterized by a coherence length greater than the penetration depth; these become SC materials at very low transition temperatures (5–10 K) and low-intensity magnetic fields. If either of the two conditions is not met, the SC state disappears. Such materials are of much scientific interest but difficult to use in space applications.

More interesting, from a technological point of view, are type II SC materials. These are characterized by a penetration depth greater than the coherence length; therefore, they can remain superconductive at higher magnetic field intensity, that is, up to the so-called upper critical field. As a consequence, more intense currents may flow in such materials.

Among type II SC materials, a new family of superconductors has been recently discovered: these are copper oxide ceramics (e.g., YBCO, an yttrium, barium, and copper oxide ceramic[6]). They are characterized by higher transition temperatures (>120 K); hence, they are often called high-temperature superconducting (HTSC) materials, whereas ordinary type II SC materials with "low" transition temperature (20–25 K) are called low-temperature superconducting (LTSC) materials. This feature initially seemed to make oxide ceramics ideal for SC application, but it was discovered that when immersed in high magnetic fields (magnetic fields of technological interest can be as high as 40 T) the material resistivity may rise up to 100 times that of an NC material (e.g., Cu) unless the temperature is lowered to 20–30% of the transition value. The reason for this behavior is currently explained as follows: when high currents are applied to an SC material, the magnetic field forms flux tubes ("fluxoids") inside the material. In an LTSC material the fluxoids are arranged in a rigid triangular reticulated structure, whereas in an HTSC material their structure is disordered and aggregated (forming the so-called liquid of vortices). When a current flowing in the HTSC material interacts with that around the fluxoid, a force (Magnus force) is created and applied to the fluxoid, forcing it to move in a direction perpendicular to both the current and the fluxoid. In this way energy is dissipated by the difference of potential induced, which is equivalent to creating resistivity in the material. This phenomenon limits the maximum current that can flow in an HTSC material without destroying its SC state.

To fully exploit HTSC materials without having to keep their temperature too low, defects or impurities are purposely inserted in the material; these imperfections work as obstacles ("pinning forces") for the fluxoids, preventing their motion in the material, and, therefore, reducing resistivity.

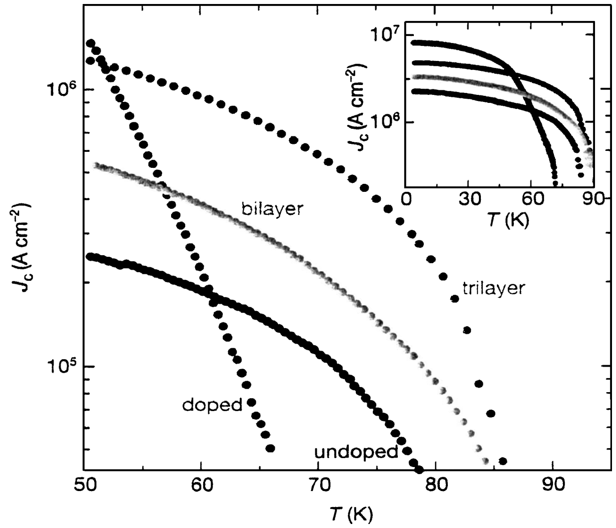

Fig. 2 Behavior of YBCO in terms of current densities vs temperature.[2]

Their appealing properties notwithstanding, HTSC materials exhibit a major problem that could hamper the manufacturing of wires and tapes in lengths practical for electric devices such as coils; in fact, the polycrystalline compounds, of which HTSC materials are made, usually consist of multiple grains whose boundaries impede the supercurrent flow. A solution to this problem is to dope the material; for example, in the case of YBCO, some yttrium ions (Y^{3+}) can be replaced by calcium ions (Ca^{2+}) almost identical in size. Studies in this field have shown that calcium doping leads to strongly enhanced current densities at low temperatures (<77 K). At 77 K, however, the critical current densities are not significantly increased[6]; this is due to the fact that if the grains, as well as the boundaries, receive the same amount of Ca^{2+}, the grains become overdoped; as a consequence the material critical temperature T_c becomes lower. A solution to this second problem consists of overdoping the grain boundaries (while keeping the grains optimally doped) by growing a calcium-doped YBCO film over an undoped one. Using this technique, it has been found that some of the Ca^{2+} appears to migrate into the grain boundaries, partially "healing them."[4] Figure 2 shows the behavior of the material in terms of current densities vs temperature for an undoped material, for a "generic" doped material, and for "targeted" doped materials to illustrate the current densities available for applications.

Benefits of Applying SC Materials to EP Systems

Early studies have shown how replacing a conventional magnet with an SC magnet in an MPD thruster could improve performance and efficiency. For instance, Fig. 3 shows the performance obtained with an SC magnet MPD thruster with hollow cathode and argon propellant.[3] At temperatures less than T_c, SC materials have resistivity (and permeability) close to zero, making SC materials ideal for EP thrusters: currents flowing in the material do not need voltage (and power) to be maintained; they keep circulating (almost) indefinitely. Magnetic fields can therefore be imposed without ohmic losses in the winding. High current density implies high B fields and high Lorentz thrust ($F = J \times B$); for a specific mission and thrust profile this expression suggests a reduction in power requirement and weight,[4] scaling roughly with B.

SC materials are, thus, good candidates for applied field MPD and HTs. In these propulsion systems the electric coils needed to generate a magnetic field could be made of SC instead of NC materials. The number of turns in a coil is inversely proportional to current density, and so SC materials could save coil volume, not just mass.

To see the benefits of employing SC instead of NC material (e.g., Cu), we considered a model coil for an MPD thruster, with the

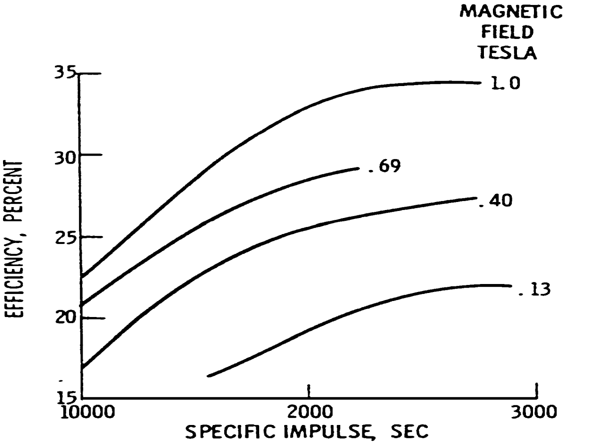

Fig. 3 Performance and efficiency of an MPD thruster with an SC magnet.[7]

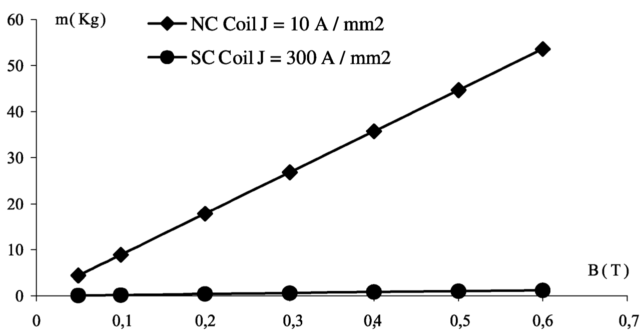

Fig. 4 Coil mass vs *B*.

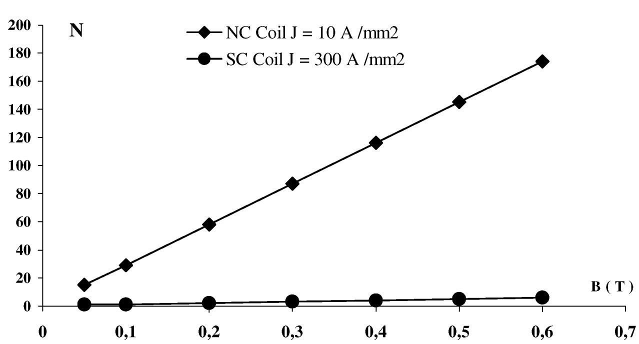

Fig. 5 Coil winding *N* vs *B*.

following features[7]: length $L = 0.1$ m, diameter $D = 0.14$ m, and wire diameter $d_w = 1$ mm.

Figures 4 and 5 show the results of calculations performed for copper and for a type II SC material (NbTi), varying the B field in the range 0.1–0.6 T, which is of interest to current (typical) EP satellite applications. For a given B field, SC coils have a clear advantage in terms of coil mass and number of turns (and therefore in terms of volume). It must be noticed that the results reported are for a current that is well below the upper limit of current densities, of the order 10^3 A/mm^2. Conversely, SC materials can be used to produce B fields up to 7 T with low weight and volume, as shown in Fig. 6.

The high B fields generated by SC coils may increase the Lorentz force ($F = J \times B$) for thrust. Figures 7 and 8 show estimates of thrust and I_{sp} obtained using B fields in the range 0–7 T. To perform the calculations, the following assumptions have been made[1,7,8]: arc current $I = 400$ A, anode to cathode distance $l = 0.02$ m, and propellant (Ar) flow rate $\dot{m} = 100$ mg/s.

The following conclusion can be drawn. With a current $I = 400$ A and a magnetic field $B = 7$ T, a Lorentz force $F = 56$ N and an I_{sp}

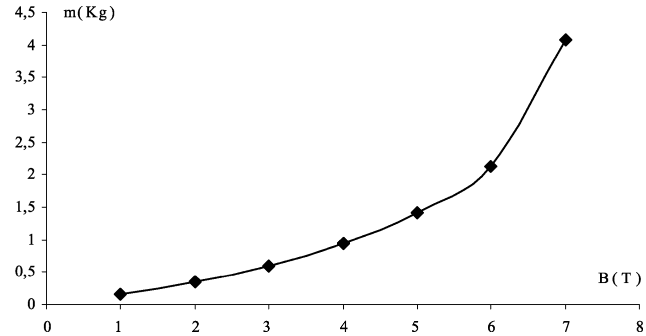

Fig. 6 SC coil weight as a function of *B*.

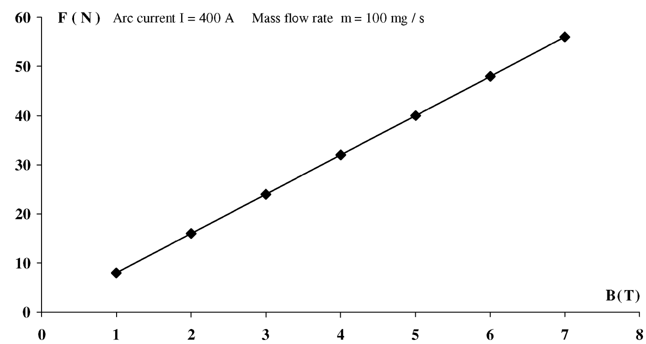

Fig. 7 Thrust generated by an SC coil as a function of *B*.

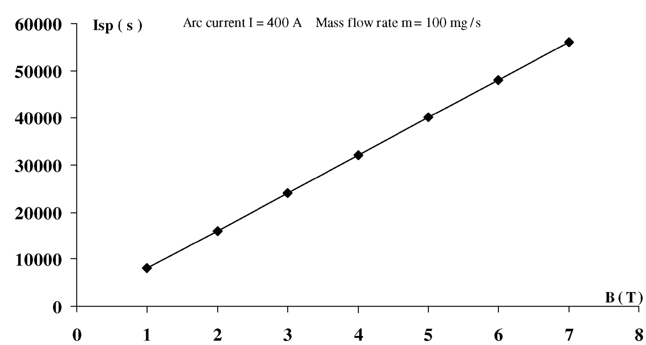

Fig. 8 I_{sp} as a function of *B* generated by an SC coil.

up to 56,000 s can be (ideally) achieved; in this case the SC coil would weigh about 4 kg. This performance is obtained with relatively low currents ($I = 400$ A) and with a corresponding reduction in cathode erosion. A Cu coil of the same weight would produce only $B = 0.05$ T and a Lorentz force $F = 0.4$ N. Balancing these conceptual advantages is, of course, needed for onboard cryocooling and specialized switching and PCUs.

Scaling of Hall Thrusters Using SC Coils

In fact, electric thrusters in the medium- to high-power range ($P_w > 500$ W) require a power supply mass that can maximize their advantages. The downscaling of power (<500 W) in HTs without excessive penalty in engine performance (e.g., in the range $I_{sp} \sim 1500$ s with reasonable thrust, and propulsive efficiency ~50%) is, therefore, a prime concern, especially for microsatellites.[9]

Electric power can be downscaled by reducing the discharge voltage U_d and/or the discharge current I_d ($P_w = U_d I_d$). Since the specific impulse (in seconds) is $I_{sp} = \eta_p v_i / g$, in which $v_i \propto U_a$ is the average ion velocity ($U_a - U_d$ is the voltage drop in the acceleration region), lowering the discharge voltage is not desirable, because it will also lower I_{sp}. On the other hand, $I_d \propto \dot{m}$; therefore, reducing I_d will lower $\dot{m}$. For a given thruster geometry, this will in turn negatively affect I_{sp} and efficiency. This can be seen by considering the mean free path for ionization, $\lambda_i = S/(\eta_p \dot{m})$, where S is the

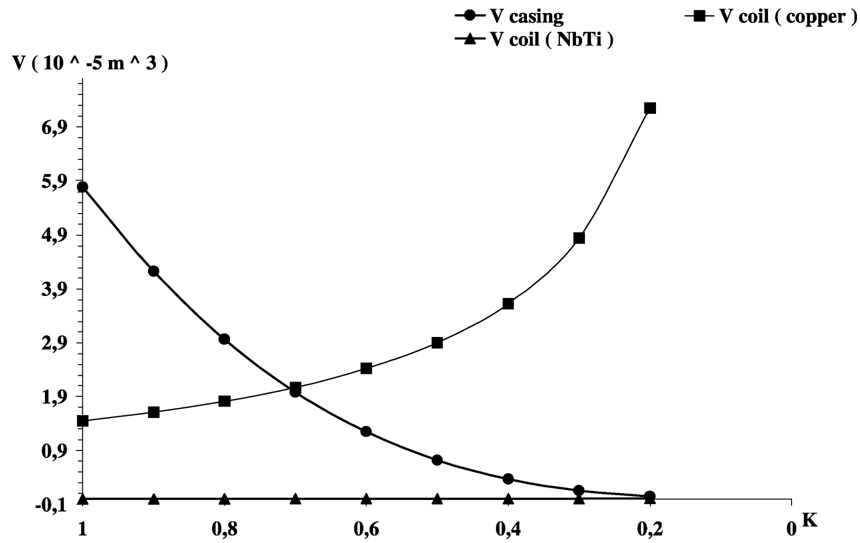

Fig. 9 Scaling relations for case and coil volume.

surface cross-sectional area of the channel and η_p is the propellant utilization factor: reducing I_d (and thus $\dot{m}$) will increase λ_i. To use propellant efficiently, λ_i must be shorter than L, where L is the channel length. Even assuming constant η_p, reducing the mass flow rate increases λ_i, thereby lowering the probability of atom ionization and resulting in poor propellant utilization. This has a negative effect on thruster performance (i.e., $I_{\rm sp}$ and efficiency).

To keep λ_i constant while reducing $\dot{m}$, thus avoiding penalties in thruster performance, in a thruster characterized by its scale S and scaled down by a factor $k(0 < k \leq 1)$, scaling is a must to prevent power losses. These losses depend mainly on ions hitting the wall (and recombining) in the accelerating region; the fraction of the ion flux leaving the channel without hitting the wall is a measure of efficiency. This fraction depends primarily on the angle under which the accelerated ions "see" the exit, scaling as h/l_a (where h and l_a are the channel width and the ions acceleration region length, respectively), and the dispersion in the direction of the accelerated ions, estimated to be proportional to $[kT_e/(eU_a)](l_a/h)$. As a result, the fraction of ions accelerated without hitting the wall scales as $[(eU_a)/kT_e](h/l_a)^2$. This expression shows that losses depend mainly on the ratio r between channel width and accelerating region length, $r = h/l_a$, and the electron temperature T_e:

$$T_e \propto m_e U_a^2 \Big/ (l_a B)^2$$

To prevent these losses, the following considerations apply. First, if the width h of the channel is reduced, the length of the accelerating region, l_a, must be reduced correspondingly. Second, to keep the electronic temperature constant while downscaling the geometry, B must scale as the inverse of l_a, which means that when the geometry (size) is downscaled, B must be raised. Increasing B is constrained by weight and size limitations if copper is the conducting material. This can be seen by considering the following equations valid when scaling down the coil case:

$$V_k = k^3 V_{\rm fs} \tag{1}$$

where V_k is the downscaled volume and $V_{\rm fs}$ is the original full-scale volume.

For the coil volume,

$$V_{\rm coil} = l_w A_w \tag{2}$$

where A_w is the coil wire section and $l_w = (\pi D_{\rm coil} L_{\rm coil}/\mu_0 I_{\rm coil})B$ is the coil wire length.

Because B must scale as the inverse of l_a, if we scale the thruster h as $h_k = kh_{\rm fs}$, the scaled B_k must be

$$B_k = B_{\rm fs}/k \tag{3}$$

Assuming $D_{\rm coil} = {\rm const}$, $L_{\rm coil} = {\rm const}$, and $I_{\rm coil} = {\rm const}$, finally,

$$(V_{\rm coil})_k = (V_{\rm coil})_{\rm fs}/k \tag{4}$$

Equation (4) is valid for both NC and SC materials; the only difference is the initial value for $(V_{\rm coil})_{\rm fs}$. In fact, Fig. 5 illustrates the number of turns (and, thus, the total wire length) needed to produce the corresponding B field and shows that, whatever B, the volume of the SC coil will be about two orders of magnitude smaller than that of the NC coil.

To show the limitations on scaling if copper winding is used to produce B, we consider an HT from the literature[10]; the coil volume $V_{\rm coil}$ and case volume $V_{\rm case}$ are, respectively, 1.45×10^{-5} and 5.78×10^{-5} m^3.

Results of applying Eq. (1) for the case volume and Eq. (4) for the case and coil volumes are shown in Fig. 9. This figure shows how using NC coils to generate B quickly sets limits on thruster scaling, whereas, at a first glance, SC materials do not.

To conclude, the use of SC (instead of NC materials such as copper) to generate high B fields can be exploited to conveniently scale thrusters. It is possible to obtain low-power thrusters (<500 W) without excessive penalties in their performance and, also, to save mass, due to the reduction of power supply and coil mass. Moreover, increasing B to downscale the thruster without penalties can produce larger Lorentz forces.

The questions to be examined next are related to the possible excessive stress on the SC coil and also to the means of maintaining the coil in its superconductive state.

Stresses on Magnetic Coils

In a solenoid subjected to a Lorentz force due to the interaction between the B field and the current itself, stresses tend to burst the coil radially and crush it axially.

For the radial ("hoop") stress the following expression applies[11]:

$$\sigma_t = (HIa_l/lt)c \tag{5}$$

where the dimensional constant $c = 10^{-6}/9.8$. The field is assumed to be produced by the current I per unit length l with the following relation between current and H:

$$I/l = H/(4\pi/10)\cos\theta \tag{6}$$

In this expression, θ is the angle between the axis z of the solenoid and the lines drawn from the origin to points on the endplane of the solenoid (Fig. 10).

For a solenoid whose length is much greater than its diameter, $\cos\theta \approx 1$; then Eq. (5) yields

$$\sigma_t = 4 \times 10^{-8} H^2 (a_l/t) \qquad (7)$$

In Eq. (7) the dependence of the stress on coil geometry (i.e., the ratio a_l/t) and on H^2 is worth noting. The stress σ_t on a model magnetic coil can be calculated considering again a model coil with length $L = 0.1$ m, diameter $D_t = 0.14$ m, and wire diameter $d_w = 1$ mm. For B in the range 1–7 T, the loop stress σ_t acting on the material is shown in Table 1.

Because of the brittle nature of SC materials, structural jackets are needed to take on the stress. The choice of jacket materials depends on weight as well as on its ultimate strength; even though steel could be a suitable candidate material due to its high ultimate strength, its density is too penalizing for satellite applications. Composite materials, such as C–C, could be a solution; Fig. 11 shows typical properties of carbon composite materials: at 0°C their ultimate strength is in the range 400–700 MPa.

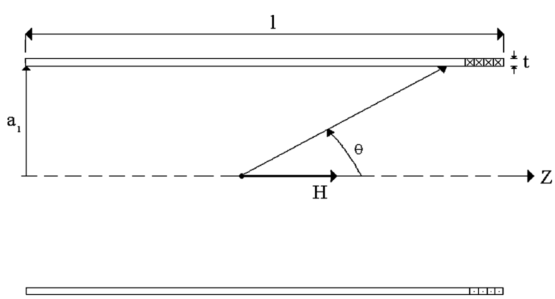

Fig. 10 Schematic view of the solenoid.

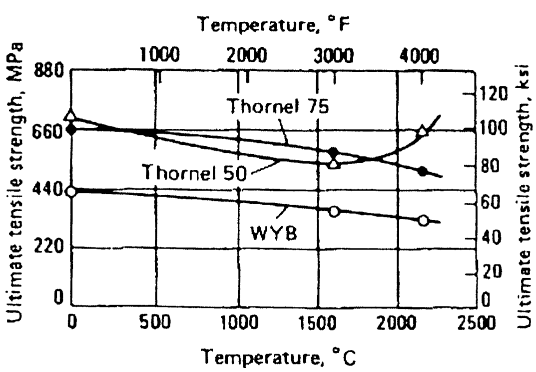

Fig. 11 Typical properties of composite materials.

To size a C–C structural jacket apply the Poisson formula to a first approximation:

$$\sigma = P \cdot D/2t_j \qquad (8)$$

where P is the pressure, D is the diameter, and t_j is the jacket thickness. For ease of calculation, a mean diameter $D = 0.14$ m has been assumed. The pressure acting on the jacket is given by

$$P = 2\sigma_t t/D_t \qquad (9)$$

Therefore,

$$t_j = (\sigma_t/\sigma)t \qquad (10)$$

To calculate t_j, the ultimate strength of the three composite materials reported in Fig. 11, at 0°C (273 K), have been assumed as follows: 440, 660, and 700 MPa for the C–C materials, respectively.

The stresses σ_t are reported in Table 1 for B in the range 1–7 T; the wire thickness t has been assumed 1 mm. Table 2 and Fig. 12 show the jacket thickness t_j for the three different materials, indicating that carbon composites could indeed be suitable jacket materials within the B range 1–7 T.

Table 1 Stress on magnetic coil

B, T	σ_t, MPa
1	28
2	112
3	252
4	448
5	700
6	1008
7	1372

Table 2 Jacket thickness (in millimeters)

		t_j		
B, T	σ_t, MPa	WYB	Thornel 75	Thornel 50
1	28	0.064	0.0424	0.04
2	112	0.255	0.17	0.16
3	252	0.573	0.382	0.36
4	448	1.02	0.679	0.614
5	700	1.591	1.06	1
6	1008	2.291	1.53	1.44
7	1372	3.118	2.079	1.96

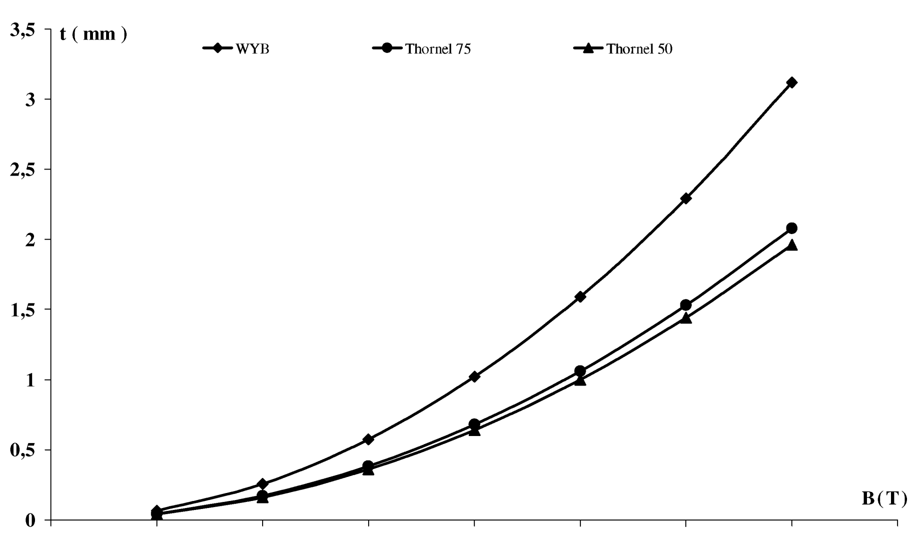

Fig. 12 Jacket thickness vs applied *B*.

Table 3 Total mass budget[1]

Component	Mass, kg	B, T	Thrust, N
Dewar	0.6	——	——
Liquid nitrogen	0.9	——	——
Cooling system	7–8	——	——
Superconducting + mechanical support	1–2	——	——
Superconducting solution (total mass)	∼11	5	10–20
Traditional copper solution	∼11	0.1	0.4–1

Cryostats for SC Coils

To work properly, SC coils must operate below their critical temperature. Therefore, it is important to realize a cooling system for space applications that must match the following conditions: high reliability; automatic operation; low power consumption; ability to work in a microgravity environment, and/or for certain applications, while accelerating; capability of ensuring proper temperature conditions during the whole mission; compactness and low weight. Cryogenics for SC coils can be borrowed directly from space cryogenics technology utilized in satellites to cool components such as infrared instrumentation.

Until recently, preferred satellite cryostatic techniques consisted of an evaporative "cold bath" for the systems to be cooled; although this system is simple, its limits are mainly due to the volume, weight, and operational time. As an example, the system employed on the Infrared Space Observatory[12] contained 2000 l of liquid helium to ensure an operational time of 2 years. This meant a volume 2 m^3 and a weight of about 2 tons, and this for a mission rather limited in time. New concepts in space cryogenics since then have been or are being developed to reduce volume and weight of cooling systems; these are based mainly on 'manufacturing' refrigeration onboard and belong to either of two classes, passive or active cooling systems.

Passive cooling systems radiate heat to space without using energy. This technique has the advantage of high operability, low volume and weight, and long life. On the other hand, there are limitations due to minimum temperature (about 70 K), satellite architecture, and orbital parameters.

Active cooling systems employ a thermodynamic refrigerating cycle. There are systems without external work (Joule–Thomson refrigerators) and systems in which external work is required (Stirling refrigerators). Crycoolers based on the latter systems can provide refrigeration with a reasonable power demand and for a lifetime up to 10 years. By using nitrogen (boiling temperature $T_b = 77$ K) as a refrigerating fluid for an HTSC material (critical temperature $T_c > 120$ K), commercial active coolers[3] can provide 1 W of cooling power by consuming 60–70 W of electrical power and keeping cryostat temperature at 70 K.

As a final consideration, the total mass budget for such a system[7] (e.g., dewar, coolant, cooling system, SC coil, and mechanical support) is only about 11 kg; with such cryostat, an SC-coil MPD thruster can produce ideally 10–20 N of thrust, depending on B and discharge current; a copper coil weighing the same would produce 1 N at best. These results are reported in Table 3.

Conclusions

SC material technology is positioning itself as a future technology enabling the construction of high-power electric thrusters for future deep-space unmanned and manned missions. Rapid commercial development of HTSC materials is the weathervane of such applications, where gains in coil mass and volume can be preliminarily quantified in one to two orders of magnitude at the expense of moderate complexity. It is also probably safe to say that without SC technology nuclear space power and propulsion appear unfeasible.

Acknowledgments

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A. C. Tribble
Associate Editor