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# Electromagnetic Propulsion for Cargo Submarines

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**An application of electromagnetic propulsion to large submarine tankers may lead to increased propulsion efficiency. The general theory of external field d.c. electromagnetic propulsion is discussed and propulsion efficiencies are deduced for 2-, 4-, or 6-pole configurations. Application for submarine tanker hulls of $L/d$ = 8.75 and prismatic coefficient 0.68 is then discussed for cases of 4 or 6 poles and submerged displacements of 25,000, 50,000, and 100,000 metric tons. For the 6-pole arrangement, at 29 knots, the thrust power is estimated to be 86% of the electric power supplied at 100,000 tons, 83% at 50,000 tons, and 79% at 25,000 tons. Values over 90% are reached at 20 knots. Arrangement of equipment inside the hull is discussed. Attention must be given to supporting the coils of the superconducting magnets; separating forces are very large and the restraints must not give excessive heat leakage. Other problems are those of the magnetic field inside the hull and the attraction of foreign iron bodies.**

## Nomenclature

**j**, $j$ = current density
**B**, $B$ = magnetic induction
**E**, $E$ = electric field intensity
**H**, $H$ = magnetic field intensity
**M**, $M$ = induced magnetization
**f**, $f$ = force per unit volume on magnetized body
**u**, $u$ = flow velocity, or ship speed
$u_j$ = jet speed
$x$, $y$ = rectangular coordinates
$k$ = number of anodes or cathodes
$V$ = electric potential
$V_e$ = half-voltage between electrodes
$I$ = half-current from one anode
$J$ = current in magnet coil, ampere turns
$B_o$ = value of $B$ at $r = b$, $\theta = 0$
$B_{cr}$ = critical $B$ for superconducting material
$b$ = hull radius of submarine amidships
$L$ = hull length
$L_C$ = length of cylindrical centerbody
$L_{EF}$ = length of figure of revolution section of forward end
$L_{EA}$ = length of figure of revolution section at aft end
$L_E$ = $L_{EA} + L_{EF}$
$A_m$ = cross section of conductors in winding, total
$r_m$ = radius of annular conductor
$t$ = thickness of annular conductor
$W_m$ = mass of composite material in magnet coils
$F_m$ = force per unit length on magnet conductor
$B'$ = hypothetical $B$ value, uniform field
$B_i'$ = hypothetical $B$ value inside shielded region
$N$ = demagnetizing factor of magnetized body
$d^*$ = lifting distance for iron body on sea bottom
$r_1$, $r_2$ = inner and outer radii of interior tunnel
$n_g$ = g moles of gas evolved per sec
$v_g$ = liters of gas evolved per sec
$U$ = energy in magnetic field
$n$ = ratio $uB/E$
$C_D$ = hull drag coefficient based on $S$ for appended hull
$S$ = surface area of bare hull
$D$ = drag of fully appended hull
$P_T$ = thrust power
$P_E$ = electric power to electrodes
$a$ = length of active field region
$V_c$ = cargo storage volume
$h$ = value of $|dw/d\zeta|$
$v_g^*$ = defined in text
$r$, $\theta$ = polar coordinates
$\alpha$ = defined in Eq. (24)
$\eta$ = propulsive efficiency, $P_T/P_E$
$\eta_j$ = jet efficiency
$\eta_D$ = MHD duct (pump) efficiency
$\mu$ = magnetic permeability
$\mu_o$ = permeability of free space, $4\pi \times 10^{-7}$
$\mu_r$ = relative permeability
$\varphi$, $\psi$ = conjugate harmonic functions
$w$ = $w(\zeta) = \varphi + i\psi$
$\zeta$ = $x + iy$
$\xi$ = interaction parameter, $2a\sigma B_o^2/\rho\mu$
$\xi'$ = interaction parameter, $2a\sigma B_{cr}^2/\rho u$
$\theta_e$ = value of $\theta$ where electrode meets hull
$\omega$ = ratio of $\pi/(2k - \theta_e)$ to $\delta$
$\delta$ = half-angle subtended by magnetic winding
$\varphi_e$ = value of $\varphi$ on electrode surface
$\sigma$ = electrical conductivity of seawater
$\rho$ = density of seawater
$\delta^*$, $\varphi_e^*$ = optimum values for maximum $\eta$
$\Delta$ = submerged displacement in metric tons
$\Delta_S$ = normal displacement of submarine at surface

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## 1. Introduction

THE submarine tanker offers certain advantages over a surface ship.[1,2] The principal gain comes from reduced resistance at high speeds, due to the absence of wave drag. A comparison is shown in Fig. 1 for vessels of 20,000 dead weight tons.† The point of breakaway of the drag curves depends on the Froude number $u^2/g\Delta^{1/3}$, so that for larger tankers this point shifts to higher speeds. Generally, however, at speeds above 20–22 knots the submarine would have an advantage, and at a speed of around 30 knots this advantage is quite appreciable. (Fig. 1 is based on data from Ref. 2.)

The ratio of dead weight tonnage to displacement will be less for the submarine than for the surface ship because the main ballast tanks are about 10% of submerged displacement. This means that the submarine hull displacement tends to be larger, for given dead weight tonnage, than for the surface ship. Drag comparisons, therefore, should be on the basis of the same dead weight tonnage, as shown in Fig. 1. In spite of the displacement penalty, the submarine drag is still lower at high speeds.

To realize the full advantage of the reduced resistance at high speed, the submarine must cruise at a depth of about 4-hull diameters or more[3] to eliminate surface disturbances and wave formation. A further advantage of the submarine tanker is that economical cruising speed may be maintained even in very rough seas. By contrast, the surface ship must reduce its speed, its wave resistance increases, and there are the usual dangers and ship damage that may attend bad weather at sea. The hull design, for these reasons, may also be lighter for the submarine than for the surface tanker for moderate depths of submersion.

These apparent advantages of the submarine tanker are offset by several disadvantages. Chief of these is the requirement of larger draft. A hull of circular section is desirable to minimize resistance, but since the diameter may be 80 ft for a large submarine tanker, the draft at the normal surface condition may approach 65 ft. This is considerably more than is allowed in many channels and estuaries, and passage in Panama or Suez canals would be restricted. To reduce draft, an elliptical or rectangular hull could be used,[2] but then there appears to be a considerable increase in resistance. Even with circular hulls, resistance goes up because of bottom effects in shallow water. The submarine tanker is most feasible with a nuclear powerplant, although further developments may indicate some possibilities for fuel cell systems, or a semiclosed-cycle gas turbine using oil and liquid oxygen. Snorkeling is not feasible because of required operating depth. In any case, initial capital cost of the vessel may be considerably higher than that of a surface tanker of the same dead weight.

In the present paper the possible application of electromagnetic propulsion to the submarine tanker is discussed.

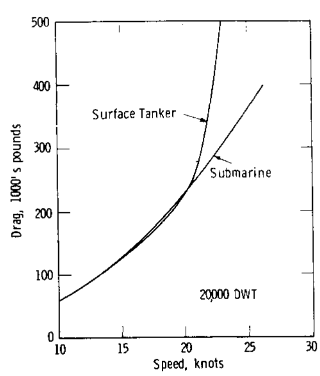



**Fig. 1 Resistance of surface and submarine tankers of same dead weight.**

† Dead weight tonnage refers here to cargo (pay load) plus useful load.

Electromagnetic submarine propulsion has been considered by several investigators.[4–9] It held little promise until it became evident that large electromagnets could be made from superconducting metals. With them it might be possible for large submarines to realize a significant increase in propulsive efficiency. However, many difficult problems arise in construction and in applying the electromagnetic propulsion system. This paper is descriptive and highlights the problem areas, emphasizing difficulties and advantages of the electromagnetic system of propulsion. No attempt is made to evaluate economic factors.

## 2. Electromagnetic Propulsion Methods

Electromagnetic propulsion of a submarine can be effected either with internal or external flows, and either by a direct current or an induction system. These several methods are shown schematically in Figs. 2a–2d. Internal flow systems use an electromagnetic pump, either in simple crossed-field[7,8] arrangement (Fig. 2a) or as a linear induction motor[9] (Fig. 2b). The external field method may also use either direct currents and crossed fields[6] (Fig. 2c) or a varying magnetic field with induced currents[9] (Fig. 2d).

In the induction method, a magnetic field intensity proportional to $\sin 2\pi(x - ct)/\lambda$ is provided by energizing a number of magnet coils successively. Circulating currents are induced in the conducting seawater which interact with the magnetic field to provide forces directed rearward on the water. No electrodes are necessary. The magnetic wave speed $c$ must be larger than the water flow speed. This induction motor method is not amenable to use of superconducting magnets, and requires large energy storage in the electrical circuits.

The internal duct direct current system, although simple in concept, leads to a waterjet of high velocity. This is undesirable, as is shown by the expression for jet efficiency

$$\eta_j = \frac{2}{1 + (u_j/u)} \tag{1}$$

where $u_j$ is jet velocity and $u$ is boat speed. This jet efficiency must be multiplied with the electromagnetic pump (duct) efficiency $\eta_D$ to obtain the propulsive efficiency

$$\eta = \eta_j \cdot \eta_D \tag{2}$$

Since $u_j/u$ must be about 1.4–1.5 for a duct of reasonably small size, $\eta_j$ becomes about 0.8; the product in Eq. (2) then becomes less than 0.7 in most cases, and this propulsion system is not efficient.

The external field system, by virtue of applying small body (Lorentz) forces to a very large expanse of surrounding water, can achieve an $\eta_j$ essentially unity, and the propulsive efficiency $\eta$ can be quite high. However, the magnetic field that spreads out from the hull into the surrounding sea, could, under certain circumstances, be troublesome.

Advantages and disadvantages of the several schemes of Fig. 2 are indicated in Table 1. The advantage of no electrodes for the schemes shown in Figs. 2b and 2d is not great, as preliminary experimental studies have shown that polariz-

**Table 1 Advantages and disadvantages of different methods of electromagnetic propulsion**

| Method | Advantages | Disadvantages |
|---|---|---|
| Internal, d.c., Fig. 2a | Compact; slight external field | Low $\eta$; larger powerplant |
| Internal, a.c., Fig. 2b | Compact; no electrodes | Low $\eta$; nonsuperconducting magnet |
| External, d.c., Fig. 2c | Good $\eta$; low flow disturbance | Spreading magnetic fields |
| External, a.c., Fig. 2d | No electrodes | Low $\eta$; nonsuperconducting magnet; spreading magnetic fields |

a) Internal flow, d.c.

b) Internal flow, induction

c) External flow, d.c.

d) Internal flow, induction

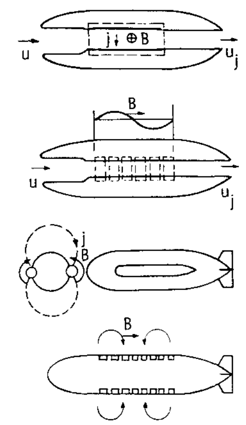



**Fig. 2 Methods for electromagnetic propulsion.**

ation losses at electrodes are negligible. On the basis of the foregoing comparison, an external flow d.c. arrangement was selected for analysis.

## 3. Theory of the External-Field Direct-Current System

A multipole system may be used as indicated in Fig. 3. A 6-pole arrangement is preferred because it leads to an acceptably good efficiency while keeping the stray field inside the hull reasonably low. A simple 2-pole configuration could yield higher efficiency, but shielding against the internal field is a more serious problem.

At the outset, we shall summarize certain relations that apply for the case of $2k$ electrodes and exciting conductors. The assumption is made that the field configuration has an active length at least four times the hull diameter. The equations are given in two-dimensional form, neglecting end effects. The water flow along the sides of the hull in this active field region is assumed to have uniform velocity $u$. The latter assumption is justified on the basis of the use of the center section only for the propulsion system, and the relatively small momentum changes given the water in the "stream tubes" by the small applied Lorentz forces. There will be reduced velocity in the boundary layer, of course, and this will tend to lead to larger dissipative joule losses. It is possible that certain design measures can mitigate the latter losses. In any case, the theoretical limitations in the present treatment may be removed in later, more detailed analyses.

The electric and magnetic fields for a configuration as shown in Fig. 3, with $2k$ electrodes, are described in terms of two conjugate harmonic functions $\varphi$ and $\psi$, which are proportional to the electric and magnetic potentials,

$$\mathbf{E} = -(v_e/\varphi_e)\,\mathrm{grad}\varphi \qquad \mathbf{B} = -(B_e b/k)\,\mathrm{grad}\psi \tag{3}$$

Expressions for $\varphi$ and $\psi$ are as follows:

$$\left.\begin{aligned} \varphi &= \frac{1}{2}\ln\frac{r^{2k} - 2r^k b^k \sin k\theta + b^{2k}}{r^{2k} + 2r^k b^k \sin k\theta + b^{2k}} \\ \psi &= \tan^{-1}\frac{r^k \sin k\theta - b^k}{r^k \cos k\theta} - \tan^{-1}\frac{r^k \sin k\theta + b^k}{r^k \cos k\theta} \end{aligned}\right\} \tag{4}$$

The curvilinear coordinates $\varphi$ and $\psi$ are derived as the real and imaginary parts of a function of the complex variable, $\zeta = x + iy$;

$$w = \varphi + i\psi = \ln\frac{(\zeta/b)^k - i}{(\zeta/b)^k + i} \tag{5}$$

The magnitudes of the gradients of $\varphi$ and $\psi$ are equal and are denoted by $h$;

$$h = |dw/d\zeta| = |\mathrm{grad}\varphi| = |\mathrm{grad}\psi| \tag{6}$$

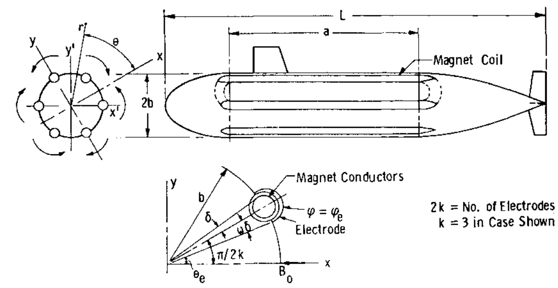



**Fig. 3 Electromagnetic submarine configuration, schematic.**

The magnitudes of **E** and **B** then become

$$E = -V_e h/\varphi_e \qquad B = B_0 bh/k \tag{7}$$

The parameter $\varphi_e$ is the value of $\varphi$ on the electrode surface, the latter being chosen to conform to a surface of const $\varphi$ in order to insure that **E** and **B** are perpendicular vectors. There is a relation of $\varphi_e$ to the angle $\theta_e$ where the electrode surface meets the hull (see Fig. 3);

$$\varphi_e = -\tanh^{-1}(\sin k\theta_e) \tag{8}$$

This may be deduced from the first of Eqs. (4) with $\varphi = \varphi_e$ and by using the relation $\tanh x = (e^{2x} - 1)/(e^{2x} + 1)$.

The active field region is assumed to be of length $a$ along the middle section of the hull. In this region the current density is expressed as

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B}) \tag{9}$$

Since the vectors **E**, **u**, and **B** are perpendicular and since $\mathbf{j} \times \mathbf{B}$ (the Lorentz force) is to be in the same direction as **u**, it follows that $\mathbf{u} \times \mathbf{B}$ is oppositely directed to **E**. Since the ratio of magnitude of $B$ and $E$ is a constant, we may introduce the constant parameter $n$,

$$n = uB/E = -u(B_0 b/kV_e)\varphi_e \tag{10}$$

$$\mathbf{u} \times \mathbf{B} = -n\mathbf{E} \tag{11}$$

The magnitnde of the current density is then expressed as

$$j = \sigma E(1 - n) \tag{12}$$

or

$$j = -V_e(h\sigma/\varphi_e)(1 - n) \tag{13}$$

Note that parameter $\varphi_e$ is negative. Parameter $n$ is positive and less than 1 and is the ratio of Lorentz force work to electrical work, per unit volume. The Lorentz body force per unit volume in the seawater is

$$jB = -V_e h^2 \sigma B_0 b(1 - n)/\varphi_e k \tag{14}$$

Integration of $jB$ in the external region, consisting of the $4k$ sectors, gives the total propulsive force. In this integration the transverse element of area can be expressed in terms of increments of the orthogonal curvilinear coordinates $\varphi$ and $\psi$ as simply $d\varphi d\psi/h^2$, since $d\varphi/h$ and $d\psi/h$ are elements of distance in directions normal to curves $\varphi$ = const and $\psi$ = const. The region of integration extends from $\varphi = \varphi_e$ on the electrode to $\varphi = 0$ on the $x$ axis, and from $\psi = -\pi/2$ at $r = b$ to $\psi = 0$ at $\theta = \pi/2k$;

$$F = 4ka\int_{\varphi_e}^{0}\int_{-\pi/2}^{0} jB\,\frac{d\varphi d\psi}{h^2} \tag{15}$$

Substitution from (14) gives directly

$$F = 2\pi V_e \sigma B_0 ab(1 - n) \tag{16}$$

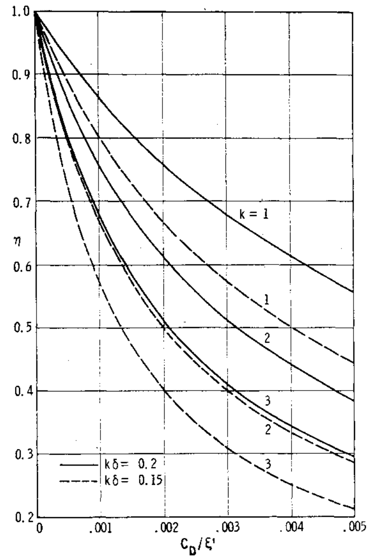



**Fig. 4 Propulsive efficiencies for $S/\pi b^2 = 27.6$, $\omega = 1.1$, and various $k$ ($2k$ = number of electrodes). Abscissa is ratio of drag coefficient to interaction parameter $\xi'$.**

The thrust power then becomes

$$P_T = Fu = 2\pi u V_e \sigma B_0 ab(1 - n) \tag{17}$$

The current $I$ from one electrode to its neighbor, on one side, is found by integrating current density $j$ along the $+x$ axis from $b$ to $\infty$, as follows:

$$I = a \int_b^{\infty} (j)_{y=0} dx = -\frac{\pi a}{2} \cdot \frac{\sigma V_e}{\varphi_e} (1 - n) \tag{18}$$

Here, the integrand is found by making use of the expression for $h$ at $\theta = 0$,

$$(h)_{\theta=0} = \left\{ \left( \frac{1}{r} \frac{\partial \varphi}{\partial \theta} \right)^2 + \left( \frac{\partial \varphi}{\partial r} \right)^2 \right\}^{1/2}_{\theta=0} = \left| -\frac{2er^{k-1}kb^k}{r^{2k} + b^{2k}} \right| \tag{19}$$

Having the current $I$, we may express the electric power $P_E$,

$$P_E = 4IV_e k = -(2\pi a \sigma V_e^2/\varphi_e) \cdot k(1 - n) \tag{20}$$

The propulsive efficiency is the ratio $P_T/P_E$, and one sees that

$$\eta = P_T/P_E = n \tag{21}$$

The propulsive efficiency in an operating submarine is determined by the condition that the voltage $V_e$ is sufficiently high to make the thrust equal to the hull drag. This means that

$$2\pi V_e \sigma B_0 ab(1 - n) = \tfrac{1}{2}\rho u^2 S C_D \tag{22}$$

where $C_D$ is a drag coefficient based on wetted surface $S$. Combination of Eqs. (10, 21, and 22) now gives

$$\eta = \frac{1}{1 - \alpha C_D k/2\xi\varphi_e} \tag{23}$$

where

$$\xi = 2a\sigma B_0^2/\rho u \qquad \alpha = S/\pi b^2 \tag{24}$$

Choice of an appropriate value for $\varphi_e$, which determines the relative size of the magnet winding and the electrode shell, depends on considerations of the limiting critical field $B_{cr}$ for the superconducting material. Figure 3 shows schematically, in section, the outline form of the magnet winding, which is circular in cross section, and the electrode. The field $B_{cr}$ exists at the point $r = b$, $\theta = \pi/2k - \delta$. Calculation of $B$ at $r = b$ leads to the relation

$$B_0 = B_{cr} \sin k\delta \tag{25}$$

The angle $\theta_e$ where the electrode intercepts the hull is slightly removed from the periphery of the magnet coil, as indicated in Fig. 3. We may relate $\delta$ and $\theta_e$ by means of a multiplier $\omega$,

$$\theta_e = \pi/2k - \omega\delta \tag{26}$$

In this way we obtain the following relation of $\varphi_e$ and $\delta$, in place of (8):

$$\varphi_e = -\tanh^{-1}(\cos\omega k\delta) \tag{27}$$

The efficiency $\eta$ may also be formulated in an expression alternatively to Eq. (23), as follows:

$$\eta = \left\{ 1 - \frac{\alpha k C_D}{2\xi' \varphi_e \sin^2 k\delta} \right\}^{-1} \qquad \xi' = \frac{2a\sigma B_{cr}^2}{\rho u} \tag{28}$$

The parameter $\omega$ determines the space available for thermal insulation (vacuum space and radiation shields) around the magnet conductors. The value $\omega = 1.1$ would be appropriate for large submarines.

For any value of $\omega$ there is an optimum $k\delta$ and a corresponding optimum $\varphi_e$ that makes $\eta$ maximum. The optimum values are $k\delta^* = 0.805$ and $\varphi_e^* = -0.747$ for $\omega = 1.1$. Actually, it is unlikely that in a practical design $\delta$ could be chosen as large as $\delta^*$, because this would imply excessively large coil and electrode dimensions, with corresponding excessive heat infiltration into the very cold magnet windings. Only for cases of very large $k$ (many electrodes) might $\delta$ approach the value $\delta^*$.

Design calculations may be made as follows: 1) Assume hull form, dimensions $L$, $b$, and $a$, and coefficient $C_D$, and determine $\alpha$. 2) Select an appropriate value for $B_{cr}$ and electrode number $2k$. 3) Calculate $\xi'$ for various speeds $u$. 4) Select $\omega$ and $\delta$ and determine $\varphi_e$. 5) Calculate $\eta$ for various speeds $u$. 6) Calculate drag for each speed from

$$D = \tfrac{1}{2}\rho u^2 S C_D \tag{29}$$

7) Calculate $P_T$ and $P_E$ from

$$P_T = Du \qquad P_E = P_T/\eta \tag{30}$$

8) Calculate voltage $2V_e$ between electrodes from

$$2V_E = -2ub\varphi_e B_{cr} \sin k\delta/k\eta \tag{31}$$

9) Calculate current $2I$ from one anode by

$$2I = P_E/2V_e k \tag{32}$$

If we compare designs with different $k$ values, several alternate assumptions could be made. One possibility is to hold $\delta$ constant while varying $k$. This procedure leads to higher efficiencies with larger $k$ values; however, by holding $\delta$ constant while increasing $k$, the amount of superconducting material is considerably increased, as are also refrigeration power requirements. Therefore, one may proceed on another assumption, namely, keep the product $k\delta$ constant while varying $k$. It then turns out that the amount of superconducting material remains constant, as well as the total electrode surface area. In this case, better efficiency is realized with small $k$ values. Curves are shown in Fig. 4 for $\eta$ vs $C_D/\xi'$ for three values of $k$, for $\omega = 1.1$, $\alpha = 27.6$, and $k\delta = 0.20$ and 0.15.

## 4. Application to Submarine Tankers

It will be assumed that the hull is of circular cross section and that four or six electrodes are used. Although an elliptical or rectangular cross section would lead to a smaller and more favorable draft, the increase in resistance of such hulls tends[2] to nullify any advantage of the submarine tanker.‡

‡ It is possible that an elliptical hull section of beam to depth ratio 2:1 could be applied without excessive increase in drag.

**Table 2 Hull dimensional parameters for submarine tankers**

| Δ, metric tons | 25,000 | 50,000 | 100,000 |
|---|---|---|---|
| $L$, m | 151.2 | 190.8 | 240 |
| $a$, m | 75.6 | 95.4 | 120 |
| $2b$, m | 17.28 | 21.80 | 27.46 |
| $b$, m | 8.64 | 10.90 | 13.73 |
| $L_{EF}$, m | 48.4 | 61.1 | 76.8 |
| $L_{EA}$, m | 72.6 | 91.6 | 115.2 |
| $L_C$, m | 30.2 | 38.1 | 48.0 |
| $S$, m$^2$ | 6,480 | 10,330 | 16,350 |
| $\Delta_S$ metric tons | 22,500 | 45,000 | 90,000 |

The optimum hull configuration, with consideration of appendage drag, is one with $L/2b$ approximately 7, with maximum diameter at about 40% of $L$. However, in order to avoid excessively large diameters for hulls of large displacement, a larger value will here be assumed. It is also advantageous to have an approximately cylindrical portion of the hull amidship to facilitate application of electromagnetic propulsion. The hull form adopted for the present study is similar to that treated by Russo et al.[2] for the 30,000 dead weight tonnage (DWT) version, designed for 30 knots. (See 4 of Ref. 2.) This hull has a cylindrical centerbody of 20% $L$, and a ratio $L/2b$ of 8.75. The combined length $L_E$ of the fore and aft figure of revolution portions is 80% $L$ and the surface area of these portions is 0.7374 $(2\pi b L_E)$. The total hull wetted surface is

$$S = 0.7899(2\pi bL) \tag{33}$$

The prismatic coefficient of the hull is 0.68. The profile of the hull is shown in Fig. 5.

Hull dimensional parameters for submarine tankers of three submerged displacements are given in Table 2. In this table $L_{EF}$ and $L_{EA}$ are the lengths of the figure of revolution forebody and afterbody, respectively, and $L_C$ is the length of the cylindrical center body. The surface displacement $\Delta_s$ is that which corresponds to 10% reserve buoyancy. The sum of $L_{EF}$ and $L_{EA}$ is equal to $L_E$, which is 80% of $L$. The parallel centerbody length $L_C$ is 20% of L. The active field length $a$ is chosen somewhat larger than $L_C$, but the hull is actually very nearly cylindrical over the length $a$.

The drag coefficient $C_D$ for the complete hull with appendages may be estimated from towing tank results. The value adopted for the hull configuration of this study is $C_D$ = 0.00156. This is based on values deduced from data given by Russo et al.[2] and Todd,[3] but with the modification that a smaller roughness contribution is assumed, 0.0001 instead of 0.0004. Actually a slight reduction is introduced into $C_D$ to allow for the possibility of future refinements of hull forms. This should, of course, be taken into account, along with the lower roughness contribution, in making comparisons with conventional submarines. We assume that the electromagnetic submarine tanker has an exceptionally smooth

**Table 3 Assumptions for specific tankers**

| | Case A | Case B |
|---|---|---|
| $C_D$ | 0.00156 | 0.00156 |
| $k$ | 2 | 3 |
| $B_{cr}$, tesla | 7 | 7 |
| $\sigma$, mho/m | 4.5 | 4.5 |
| $\rho$, kg/m$^3$ | 1030 | 1030 |
| $\omega$ | 1.1 | 1.1 |
| $\alpha$ | 27.6 | 27.6 |
| $\delta$ | 0.10 | 0.08 |
| $k\delta$ | 0.20 | 0.24 |
| $B_o$, tesla | 1.39 | 1.664 |
| $\varphi_e$ | −2.203 | −2.019 |
| $\xi'$ | 0.428 $a/u$ | 0.428 $a/u$ |
| $\eta$ | $1/(1 + 1.157\ u/a)$ | $1/(1 + 1.322\ u/a)$ |

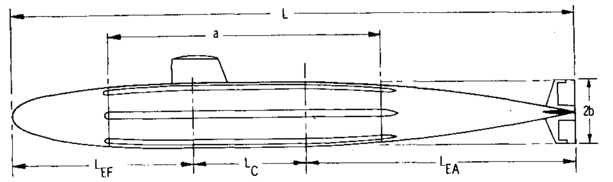



**Fig. 5 Assumed hull form. Bare hull—volume = $0.68\pi bL^2$; surface = 0.7899 $(2\pi bL)$.**

hull, free from plate overlaps and other sources of parasitic drag. A 15% allowance has been used for appendages, as in Ref. 2. In Eq. (28), the parameter $\alpha$ appears. Its value for the assumed hull configuration is 27.6.

For the specific tankers under consideration we make the assumptions listed in Table 3. Values of $\eta$ for both cases for the three vessels are plotted in Fig. 6. Values of $\eta$, $P_T$, $P_E$, $2V_E$, and $2I$ are given in Table 4 and for the tankers of three displacements, and for three speeds of 5, 10, and 15 m/sec (9.7, 19.4, and 29.1 knots).

The design speed of 15 m/sec is of prime importance since it determines the size of the powerplant. Note that for given Δ, $k$, and $\delta$ results are given for the same submarine operating at various speeds, rather than for different vessels designed to operate at different speeds. Though detailed calculations have not been made, the dead weight tonnage would be expected to be about 50% of the submerged displacement.

The general arrangement of the submarine tanker for configurations A or B is shown in Fig. 7. The magnet coils, of long rectangular form, lie along the sides of the hull, the electrodes forming slightly protruding bulges which run axially.

A tubular passage way, or tunnel, with steel walls, running through the center section, would connect fore and aft sections of the hull. This tunnel might be of radius about $0.3b$, and could have at least two decks. Refrigeration equipment for the cryogenic system could be located in the lower portion. The steel walls would constitute a pressure barrier against the sea pressure, and would also serve as magnetic shielding.

The main cargo space would lie in the center section of length $a$, between the tunnel of radius about $0.3b$ and the inner face of the double wall of the hull, of radius about $0.9b$. Thus, the cargo storage volume is approximately $V_C = 0.72 \pi ab^2$. If $a$ is $L/2$ and if we have prismatic coefficient 0.68, $V_C$ is about 53% of the hull displaced volume. The liquid cargo would exist at a pressure equal to that of the sea, at the hull bottom.

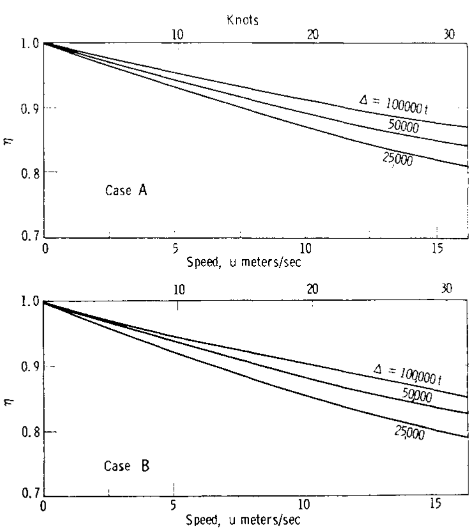



**Fig. 6 Efficiencies for case A and case B submarines.**

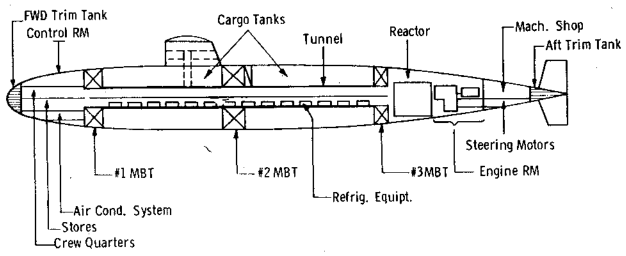



**Fig. 7 Disposition of tanks and equipment in hull.**

## 5. Problems of the Electromagnetic Submarine Tanker

### Superconducting Magnet

Great progress in the technology of large superconducting magnets has been made in recent years.[10] However, in the construction of magnet coils as large as those anticipated in an electromagnetically propelled submarine tanker, there will be further difficult engineering problems.

The exciting current $J$ in any one of the several coils can be calculated from

$$J\mu_0 = -\oint \mathbf{B}\cdot d\mathbf{s} \tag{34}$$

where the integration extends around the winding. Evaluation is most simply made if the path of integration follows a curve of constant $\varphi$, upon which the magnitude of $B$ is $B_0bh/k$. The path length increment is $d\psi/h$ and the calculation leads to

$$J = 2\pi b B_{cr} \sin k\delta / k\mu_0 \tag{35}$$

One sees that for small $\delta$, the effect of neighboring windings disappears and the current $J$ is related to the field at radius $b\delta$ by the usual relation.

To use the superconducting material more effectively, the winding preferably should be in the form of a hollow annulus, in cross section, as shown in Fig. 8. The outer radius of the annular bundle is designated $r_m$, and its thickness is $t$. The conductors would be of composite construction; with optimized design it is anticipated that the composite would consist of about 10% void for liquid helium circulation, 81% shunt conductor material and 9% superconducting material with a combined density of around 3000 kg/m$^3$. Current density in the composite may be as high as 10,000 amp/cm$^2$. We thus have the relations,

$$A_m = 10^{-8}J \qquad r_m = b\delta \qquad t = A_m/2\pi r_m \tag{36}$$

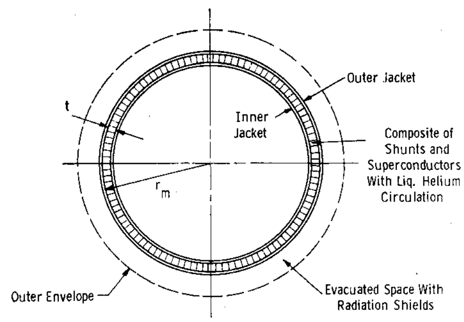



**Fig. 8 Annular magnet conductor.**

Total mass of the composite material in the $k$ magnet coils is given by

$$W_m = 3000kA_m(2a + 2\pi b \sin\pi/2k) \tag{37}$$

Values are given in Table 5 of $J$, $r_m$, $A_m$, $t$, and $W_m$ for the cases A and B. The thickness $t$ remains constant for all cases, a result that may be anticipated from relations (35) and (36).

The mass of composite magnet material varies as the square of the scale factor, while $\Delta$ varies as the cube. Hence, the larger the submarine, the more favorable is the situation as regards the relative weight of the magnet.

The most serious problem in the magnet design is the coil support. The annular bundle comprising the winding, held together by the inner and outer metallic jackets, must be held in a centrally located position within the outer housing. The intervening space must be designed for the minimum possible heat transfer, yet the forces to be transmitted across this space are very large.

The force per unit length on the magnet winding due to interaction of current $J$ and the magnetic field is radially outward, and may be shown to be

$$F_m = J^2\mu_0/4\pi b = 10^{-7}J^2/b \tag{38}$$

Values are given in Table 5 for the several cases. $F_m$ is extraordinarily large, but case B, with six poles, has some advantage over case A with four poles.

The methods illustrated in Figs. 9a and 9b might be considered to provide force transmission from the winding to the main hull structure. One involves tie rods and the other spacers of high compressive strength and low thermal conductance. In both cases, the heat flow inwards must be carefully considered. With tie rods, heat leakage can be

**Table 4 Results for submarine tankers**

$\omega = 1.1$, $k = 2$, $\delta = 0.1$, $\alpha = 27.2$, $C_D = 0.000156$, $B_{cr} = 7.6$

| $\Delta$, metric tons | 25,000 | | | 50,000 | | | 100,000 | | |
|---|---|---|---|---|---|---|---|---|---|
| $L$, m | | 151.2 | | | 190.8 | | | 240 | |
| $a$, m | | 75.6 | | | 95.4 | | | 120 | |
| $2b$, m | | 17.28 | | | 21.80 | | | 27.46 | |
| $u$, m/sec | 5 | 10 | 15 | 5 | 10 | 15 | 5 | 10 | 15 |
| $\eta$ | 0.928 | 0.868 | 0.813 | 0.943 | 0.892 | 0.846 | 0.955 | 0.913 | 0.875 |
| $D \times 10^{-3}$, N | 130.1 | 520.1 | 1,172 | 207.3 | 829 | 1,868 | 328.5 | 1,313 | 2,960 |
| $P_T$, kw | 650 | 5,201 | 17,600 | 1,036 | 8,290 | 28,020 | 1,642 | 13,130 | 44,400 |
| $P_E$, kw | 700 | 5,990 | 21,650 | 1,098 | 9,290 | 33,100 | 1,720 | 14,380 | 50,700 |
| $2V_E$, v | 143 | 305 | 490 | 178 | 375 | 593 | 221 | 462 | 723 |
| $2I$, amp | 2,445 | 9,810 | 22,100 | 3,080 | 12,360 | 27,900 | 3,890 | 15,360 | 35,050 |

$\omega = 1.1$, $k = 3$, $\delta = 0.08$, $\alpha = 27.6$, $C_D = 0.00156$, $B_{cr} = 7$ tesla

| $\Delta$, metric tons | 25,000 | | | 50,000 | | | 100,000 | | |
|---|---|---|---|---|---|---|---|---|---|
| $u$, m/sec | 5 | 10 | 15 | 5 | 10 | 15 | 5 | 10 | 15 |
| $\eta$ | 0.920 | 0.852 | 0.793 | 0.936 | 0.878 | 0.828 | 0.948 | 0.901 | 0.859 |
| $P_E$, kw | 707 | 6,110 | 22,200 | 1,107 | 9,440 | 33,860 | 1,733 | 14,570 | 51,750 |
| $2V_E$, v | 105 | 227 | 366 | 130 | 278 | 442 | 162 | 341 | 537 |
| $2I$, amp | 2,244 | 8,975 | 20,220 | 2,830 | 11,330 | 25,520 | 3,566 | 14,250 | 32,100 |

**Table 5 Magnet winding size, current, and forces**

| | Case A, $k$ = 2 | | | Case B, $k$ = 3 | | |
|---|---|---|---|---|---|---|
| $\Delta$, metric tons | 25,000 | 50,000 | 100,000 | 25,000 | 50,000 | 100,000 |
| $b$, m | 8.64 | 10.9 | 13.73 | 8.64 | 10.9 | 13.73 |
| $r_m$, m | 0.864 | 1.09 | 1.373 | 0.691 | 0.872 | 1.098 |
| $J \times 10^{-7}$, amp | 3.00 | 3.79 | 4.77 | 2.40 | 3.02 | 3.81 |
| $A_m$, m² | 0.300 | 0.379 | 0.477 | 0.240 | 0.302 | 0.381 |
| $t$, m | 0.0552 | 0.0552 | 0.0552 | 0.0552 | 0.0552 | 0.0552 |
| $W_m$, metric tons | 341 | 544 | 862 | 385 | 611 | 972 |
| $F_m \times 10^{-7}$, N/m | 1.041 | 1.318 | 1.657 | 0.664 | 0.838 | 1.055 |
| $F_m$, lb/in. | 59,550 | 75,000 | 94,700 | 37,960 | 47,900 | 60,300 |

kept within acceptable limits, but the structure is complex. With spacers, the structure is greatly simplified, but it is not known whether materials and a design configuration can be found to keep heat leakage within bounds.

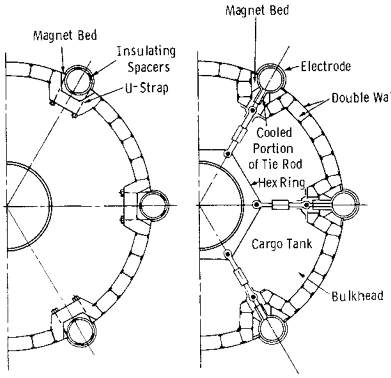
Calculation of required tie rod dimensions for 50,000-ton vessels for rods running radially inward 72 in. apart, of high-strength material of 300,000 psi working stress, leads to 4.8-in.-diam rods for case A and 3.8-in.-diam rods for case B. The total number of tie rods for all coils is 260 for case A and 366 for case B including restraints on the end turns. Tie rod heat leakage will be about 10% lower in case B than case A. The major advantage of the low conductivity spacer method of support is that the casing structure of the magnet can be fastened to the hull structure by simple tie-bands.

A rough estimate may be made of the refrigeration power requirement for the magnet. With well-designed thermal shielding and evacuated space in the region between the outer jacket of the winding and the tubular casing, the heat infiltration due to radiation across this space will be about 0.14 w/m². For the 50,000-metric ton submarine of case A the casing area is about 3600 sq. m, and for case B about 4040 sq. m. Corresponding heat leaks are 503 and 566 w. Refrigeration power required would be, for this portion of the heat leakage, approximately 503 kw in case A and 566 kw in case B. The other major part of the heat infiltration is due to conductance along the tie rods. The tie rod heat leakage with vapor cooling and rods 3 m long, would be such as to require an additional refrigeration power of 475 kw for case A and 425 kw for case B. Thus, for $\Delta$ = 50,000 tons, the tie rod method of coil support could lead to combined radiation and conduction refrigeration power requirements of about 1000 kw for either case A or B.

With the use of insulating spacers, the final solution would depend on the ratio of compressive strength to thermal conductivity for the spacers. Here also, two-stage or vapor cooling would help reduce refrigeration power requirements. The feasibility of the spacer method of construction from the standpoint of refrigeration requirements has not yet been ascertained. A design goal might be set at keeping refrigeration power less than 5% of the power $P_E$ at the top speed of 29.1 knots. The great simplification of structure and assembly could justify acceptance of higher refrigeration power in the spacer support method than in the tie rod method.

**Table 6 External magnetic field; *B* values, teslas**

| | Case A, $k$ = 2 | | Case B, $k$ = 3 | |
|---|---|---|---|---|
| $r/b$ | $\theta = 0$ | $\theta = \pi/4$ | $\theta = 0$ | $\theta = \pi/6$ |
| 1 | 1.390 | ... | 1.664 | ... |
| 2 | 0.328 | 0.371 | 0.205 | 0.211 |
| 3 | 0.1017 | 0.1041 | 0.0410 | 0.0411 |
| 4 | 0.0432 | 0.0435 | 0.0130 | 0.0130 |
| 5 | 0.0222 | 0.0223 | 0.0053 | 0.0053 |
| 6 | 0.0129 | 0.0129 | 0.0026 | 0.0026 |
| 7 | 0.0081 | 0.0081 | 0.0014 | 0.0014 |
| 8 | 0.0054 | 0.0054 | 0.0008 | 0.0008 |
| 9 | 0.0038 | 0.0038 | 0.0005 | 0.0005 |
| 10 | 0.0028 | 0.0028 | 0.0003 | 0.0003 |




**a) Tie rods b) Spacers and U straps**

**Fig. 9 Techniques of magnet coil support.**

**Stray Magnetic Fields**

For naval submarines the spreading magnetic field outside the hull might be objectionable and, in that case, a large $k$ value would be selected. For the tanker, the spreading external field is chiefly of concern in its attractive forces on iron objects, either boats on the surface or debris on the bottom.

The strength of the external magnetic field, in teslas, along lines passing through windings ($\theta = \pi/2k$) or centered between windings ($\theta = 0$) is given in Table 6. Expressions for the magnetic induction along these two axes of symmetry are

$$\begin{aligned} \theta &= \pi/2k & B &= 2B_0 r^{k-1} b^{k+1}/(r^{2k} - b^{2k}) \\ \theta &= 0 & B &= 2B_0 r^{k-1} b^{k+1}/(r^{2k} + b^{2k}) \end{aligned} \tag{39}$$

The attracting power of the exterior field for an iron object depends on the induced magnetization **M** and on the vector field **B**. The force per unit volume is

$$\mathbf{f} = (\mathbf{M} \cdot \text{grad})\mathbf{B} \tag{40}$$

The magnetization **M** induced in a body having "demagnetizing factor" $N$ in a region of magnetic field intensity $H$ is

$$\mathbf{M} = (1/N) \cdot [(\mu - 1)/(\mu + 1)]\mathbf{H} \tag{41}$$

For a spherical body the factor $N$ is $4\pi/3$. In order to lift an iron object from the sea bottom, $f$ would need to be 6680 dynes/cm³, considering the buoyancy as well as the weight. The lifting distances $d^*$ between hull bottom and sea bottom, listed in Table 7, are found by evaluation of the right-hand member of Eq. (40) on the vertical axis. It would be preferable to maintain a bottom clearance somewhat larger than $d^*$ to guard against metal pickup. Elongated objects, oriented toward the hull, will have an $N$ value somewhat smaller than the value for the sphere.

The field inside the hull could prove hazardous to personnel unless shielding is used. The value of $B$ on a radial line passing through the center of a magnet winding ($\theta = \pi/2k$) is

$$B = 2B_o r^{k-1} b^{k+1}/(b^{2k} - r^{2k}) \tag{42}$$

Numerical values for cases A and B are given in Table 8.

With the cylindrical steel tunnel in the center section the $B$ value inside the tunnel will be greatly reduced. We note in Table 8 that for case A the flux density at $0.3b$ is 0.841 tesla, or 8410 gauss. To indicate the possible degree of

**Table 7 Lifting distances for steel ball on bottom**

| | Case A | | | Case B | | |
|---|---|---|---|---|---|---|
| $\Delta$, metric tons | 25,000 | 50,000 | 100,000 | 25,000 | 50,000 | 100,000 |
| $2b$, m | 17.28 | 21.80 | 27.46 | 17.28 | 21.80 | 27.46 |
| $d^*$, m | 7.36 | 8.40 | 9.57 | 6.56 | 7.90 | 9.22 |

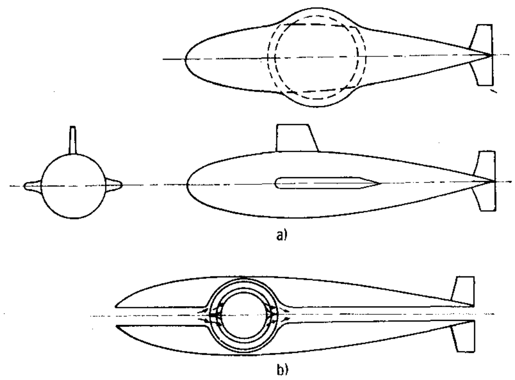



**Fig. 10 Self-restraining magnet systems.**

shielding provided by a steel cylindrical shell, imagine that we had a uniform field $B'$ and in it placed a cylindrical shell of inner radius $r_1$ and outer radius $r_2$. If $\mu_r$ is the relative permeability, the residual field $B_i'$ inside the cylinder is

$$B_i' = \frac{4B'}{\mu_r(1 - r_1^2/r_2^2)} \tag{43}$$

This indicates a shielding ratio $B_i'/B'$ of about 0.1 for an iron cylindrical shell with $r_1/r_2 = 0.95$. However, in the present case, Eq. (43) is hardly applicable on account of saturation. Reference to Table 8 indicates that the shielding problem will definitely be more difficult for case A, with $k = 2$, than for case B, with $k = 3$. A cylindrical wall of thickness 0.01b at $r_2 = 0.3b$ will probably suffice in case B.

### Gas Evolution

Gas evolved at the electrodes will amount to 1 g equivalent for each 96,500 coul of electricity. At the anodes, 0.25 g moles of $O_2$ are released and at the cathodes 0.50 g moles of $H_2$. If current $2kI$ flows out of the anodes and into the cathodes, the number of g moles released per sec is

$$n_g = 0.75 \times 2kI/96{,}500 = 1.555 \times 10^{-5}Ik$$

The total volume of gas evolved per sec at STP is

$$v_g = 22.4 \times 1.555 \times 10^{-5}Ik = 3.485 \times 10^{-4}Ik \text{ l/sec}$$

The volume of gas (at STP) left behind the submarine per linear meter of ocean (i.e., in a "slice" of water 1 m thick, extending out in all directions, and perpendicular to the direction of motion) may be designated $v_g^*$; it is $v_g/u$. Values of $I$, $v_g$, and $v_g^*$ for $u = 15$ m/sec are given in Table 9. At a cruising depth of 90 m, the volumes $v_g$ and $v_g^*$ would be multiplied by 0.1, since the pressure is then 10 atm.

Preliminary experiments have shown that the insulating effect of the gas bubbles is quite negligible. Gas evolution would not appear to be a serious problem.

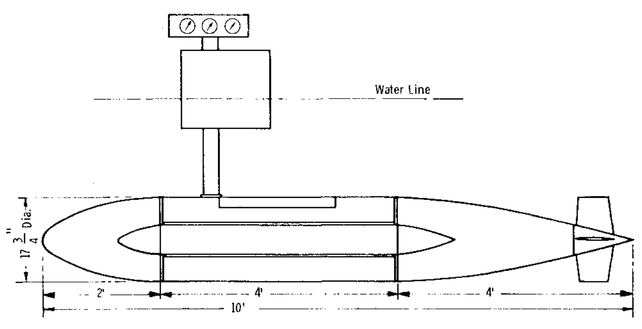



**Fig. 11 Electromagnetic submarine model.**

**Table 8 Values of $B$ in teslas on line at $\theta = \pi/2k$**

| $r/b$ | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 |
|---|---|---|---|---|---|---|
| $B$, case A | 0 | 0.278 | 0.558 | 0.841 | 1.140 | 1.482 |
| $B$, case B | 0 | 0.033 | 0.133 | 0.299 | 0.534 | 0.845 |

## 6. Designs with Self-Restraining Coils

It is conceivable that the electromagnetically propelled tanker could be designed with a self-supporting coil. In this case, the simplest configuration would be a magnet coil in the form of a circular ring. The cryogenic chamber would be of torroidal form.

We might here consider either an external field or an internal duct arrangement. The external configuration is pictured in Fig. 10a. The coil would extend laterally outwardly, leading to a vessel with quite a large beam. The draft might thereby be slightly reduced, which would be an advantage. There would be some lowering of propulsive efficiency because of the relatively smaller active field region, but this would be offset by a reduction of refrigeration power requirements because of the much simpler problem of coil support since only the weight of the coil would have to be carried.

The winding itself would restrain the electromagnetic forces. The tension in the coil and enclosing jackets can be estimated from

$$T = (1/2\pi)\cdot(\partial U/\partial a_c) \tag{44}$$

where $a_c$ is the coil radius and $U$ is the energy stored in the field.

The internal arrangement with the self-restraining coil is pictured in Fig. 10b. An electromagnetic pump is used with circumferential flow in an annular torroidal passage. This arrangement is relatively compact, would require smaller refrigeration power than other schemes, and would not give rise to excessive internal or external fields. However, because it delivers a waterjet, it is handicapped by having a jet efficiency $n_j$, which is perhaps as low as 80%, and which must be applied as a multiplier on the duct efficiency in accord with Eq. (2).

## 7. Model Experiments

In 1966, at the University of California in Santa Barbara,§ a model 10 ft long, of 900-lb displacement was constructed. This model had as its objectives 1) demonstration of an operating external field electromagnetic submarine, and 2) provision of an interesting design project for mechanical engineering students.

The model, designated EMS-1, was of bipolar field arrangement, as illustrated in Fig. 11. The center section consisted of a basic structure of $17\frac{3}{4}$-in.-o.d. steel tube of about $\frac{1}{4}$-in. wall (after machining) with recessed troughs on the side formed from half-sections of 5-in. pipe. This assembly formed a spool, on which was wound the magnet coil. The coil consisted of two windings, about 1275 ft each, of no. 4 aluminum wire, plus an additional 1200 ft of no. 12 copper wire.

**Table 9 Gas evolution at 29.1 knots**

| | Case A, $k = 2$ | | | Case B, $k = 3$ | | |
|---|---|---|---|---|---|---|
| $\Delta$ metric tons | 25,000 | 50,000 | 100,000 | 25,000 | 50,000 | 100,000 |
| $I$ amp | 11,050 | 13,950 | 17,525 | 10,110 | 12,760 | 16,050 |
| $v_g$ l/sec | 7.70 | 9.72 | 12.22 | 10.56 | 13.35 | 16.78 |
| $v_g^*$ l/m | 0.514 | 0.648 | 0.815 | 0.704 | 0.890 | 1.118 |

§ The author was serving as Professor of Mechanical Engineering during the period.

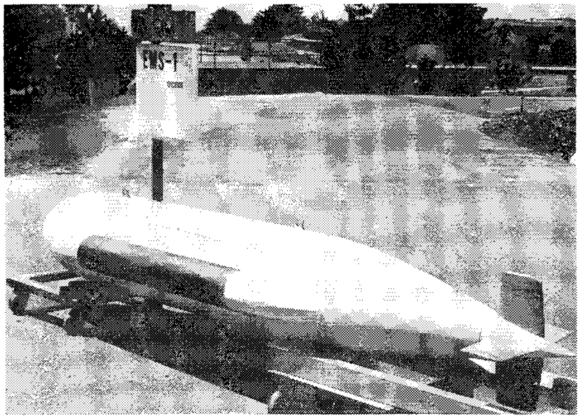



**Fig. 12 Experimental electromagnetic submarine model.**

Nose and tail sections were made of molded fiberglass reinforced plastic. A mast and "sail" provided a mounting point above the water line for meters and a starting switch, and a means for automatic depth control, since the sail afforded ±8-lb buoyancy variation depending on submersion depth. The length of the active field region was approximately 1 m, and the hull radius $b$ was 0.225 m. The $B_o$ design value was 0.015 tesla. The parameter $\varphi_e$ was $-1.914$ and, of course, $k = 1$. With an assumed drag coefficient of 0.09 based on hull cross section the design speed was 0.4 m/sec.

Power for magnet and electrode circuits was provided by five series-connected 6-v lead-acid batteries of 217 amp hr each. At the high current drawn by these two circuits, discharge time was about 20 min, and ampere hours available fell to 72.

Tests were made of this model[11] and the design operating speed was closely approached. Separate tests indicated negligible polarization effects at the electrodes.

## 8. Concluding Remarks

The submarine tanker offers some advantages and some disadvantages; the principal disadvantage is the large draft in the normal surface condition. With electromagnetic propulsion it appears possible to realize an added gain in propulsive efficiency that should further enhance the competitive position of the submarine tanker. However, this will be possible only if 1) certain difficult problems of magnet design and support can be solved, 2) the refrigeration power can be kept less than about 5% of the full load power, and 3) economic considerations do not rule out the electromagnetic tanker on the basis of higher capital costs.

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