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APPLICATION OF ADVANCED MATERIALS TO ROTATING MACHINES

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In discussing the application of advanced materials to rotating machinery, we will cover the following topics: the torque-speed characteristics of ac and dc machines, motor and transformer losses, the factors affecting core loss in motors, advanced magnetic materials and conductors, and design trade-offs for samarium-cobalt motors.

Figure 1 shows the torque-speed characteristics for various types of motors. The series motor has a high starting torque for very low speeds. The shunt motor and the permanent-magnet motor can be used as control devices for many of the components within the all-electric airplane. Many of the characteristics of the shunt and permanent-magnet motors can be duplicated with a wound-rotor motor by varying the rotor resistance.

Figure 2 compares the losses within a 5-hp, three-phase motor and a 15-kVA transformer. The basic difference is that the motor has friction and windage losses in addition to core (iron) loss and I^2R loss. However, as the load on the transformer increases, the copper loss (the I^2R loss) predominates. Similarly in the motor the I^2R loss is the major loss at higher loads.

Figure 3 shows weight and efficiency as functions of frequency for a 50-kVA transformer. It illustrates the advantage of using higher frequencies. Of course, from 60 Hz to 400 Hz there is a dramatic change. At slightly higher frequencies, around 1000 Hz, there is another significant drop in weight. However, at too high a frequency, the weight gain is not that significant. The peak efficiency for this particular design is at 5 kHz. This contradicts the old adage of copper loss and iron loss being the same. For this particular design the copper and iron losses are the same at 10 kHz, which is not the optimum efficiency point. The figure shows that significant trade-offs can be made in designing both transformers and motors for advanced all-electric airplanes.

Figure 4 shows some of the factors affecting core loss. For a simple two-segment commutator (on the left), if we look at one phase, it is essentially a pulsating square wave; if we combine a number of elements (lower left), we get a high-frequency voltage ripple. This would translate into a loss within the material. The diagrams on the right show that under the pole faces, without any rotor current, the magnetic field is constant. However, when current is applied in either a generating or a motoring mode, the distribution of flux density tends to increase in one pole face and to decrease in the other pole face as the machine goes through a cycle. This would limit the flux density at which the motor or generator could be operated.

Figure 5 shows this even more significantly. The current flowing in the rotor actually decreases the flux density in the left side of the pole pieces (shown by path 2). Through path 1 the flux density is essentially constant. Through path 3 the current actually enhances the flux density within the machine. Therefore flux density changes linearly across the pole face as current is applied. At higher flux densities magnetic saturation is approached, as shown by the flattened tip of the flux waveform. This would result in additional core loss.

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Figure 6 compares three materials with the properties required in rotating machinery. A fairly high flux density is required to get the windings of the machine smaller and reduce the accompanying I^2R loss. Armco M-4 steel is presently being used in most rotating machinery. The new Metglas 2605 significantly reduces core loss to about one-fourth that of M-4. However, this may not be a fair comparison because the M-4 is much thicker than the Metglas - 4 mil as compared to 1 mil. Another material, Supermendur, also has high flux density characteristics, but its losses are greater than those of M-4 even though it is thinner. Thus from a loss standpoint, M-4 is better than Supermendur at this point. However, Metglas may be a formidable contender as a new material for rotating machinery.

Metglas has been applied to some transformer designs with a significant reduction in iron loss (fig. 7). Also because of the reduction in iron loss and the higher flux density characteristics, the copper loss could be reduced. Since this is a phenomenon that increases with the square of the current, the reduction in copper loss is fairly significant.

Lewis is investigating a new material called intercalated graphite. Table I shows that intercalated graphite can achieve the same levels of resistivity as copper and aluminum at one-third of the weight. It also has a much higher strength than copper, so that it could be integrally wound as part of the structure of either the rotor or stator of the machine. This should significantly reduce the weight and increase the strength of the motor.

Samarium-cobalt motor studies have been performed for electric vehicle research. Figure 8 shows the percentage of total weight for the different components for a current and two advanced samarium-cobalt motor designs. The current motor weighs 1.7 lb/hp. Using the Metglas, a lighter material with less loss than the iron presently used for motor designs, significantly reduces the percentage of total weight of iron while keeping the same amount of copper used in the current design. The specific weight decreases to 0.74 lb/hp. Incorporating intercalated graphite fibers changes the weight distribution again. Here intercalated graphite would also be used in the frames. The weight of the machine is again significantly reduced, to 0.57 lb/hp. These machines operate at 8000 to 9000 rpm. Raising the operating speed to 20 000 to 26 000 rpm would decrease specific weight further, to around 0.31 lb/hp. It appears that quite a bit of design work could be done in this area to support an all-electric airplane motor.

In summary, the major motor losses are core (iron) loss and I^2R (copper) loss. With Metglas, core loss can be reduced by a factor of 4, and Metglas is lighter than conventional electrical steels. Intercalated graphite conductors may have resistivity equal to that of copper at one-third of the weight. Also high-speed samarium-cobalt motors have high efficiency and low specific weight. Therefore significant latitude is available in designing rotating machinery for an all-electric airplane.

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TABLE I. - CHARACTERISTICS OF INTERCALATED GRAPHITE AS COMPARED WITH COPPER, ALUMINUM, AND GRAPHITE

Material	Density, g/cm^3	Resistivity, Ω-cm	(Figure of merit)$^{-1}$, m	Cost, ¢/cm^3
Copper	8.9	1.8×10^{-6}	16	19.6
Aluminum	2.7	2.8	7.6	
Graphite	1.7	40	68	
Intercalated graphite	2.7	[a]1.8 [b]2.8 [c]6	4.9 7.6 16	10.5

Material	Density, g/cm^3	Strength, psi	Ratio of strength to weight	Thermal expansion, °C^{-1}
Copper	8.9	32×10^{-3}	3 600 psi	16×10^{-6}
Aluminum	2.7	16×10^{-3}	6 000 psi	14
Steel	7.9	600 000	76 000	7
Intercalated graphite	2.7	$(300 \text{ to } 1000) \times 10^{3}$	$(180 \text{ to } 600) \times 10^{-3}$	~1

[a]Possible.
[b]Needed to compete with aluminum.
[c]Needed to compete with copper.

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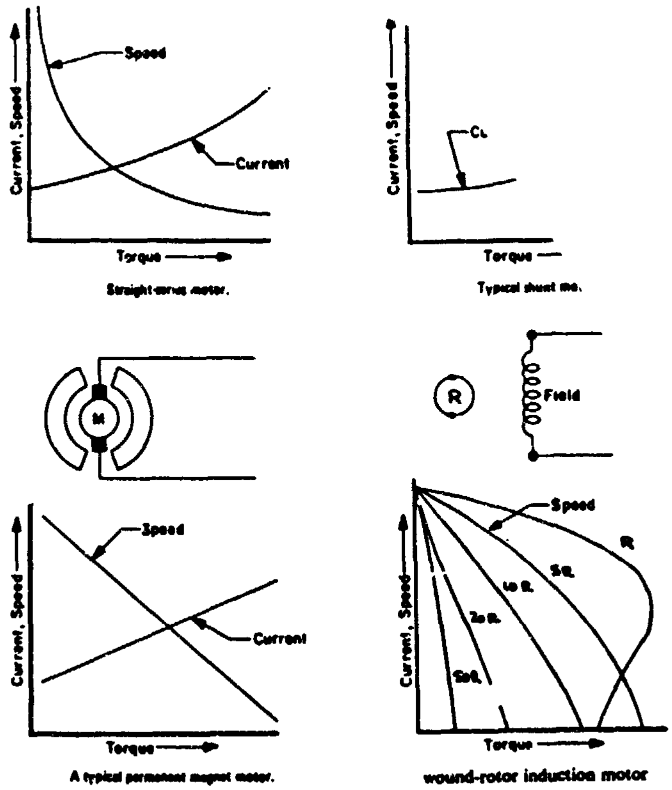

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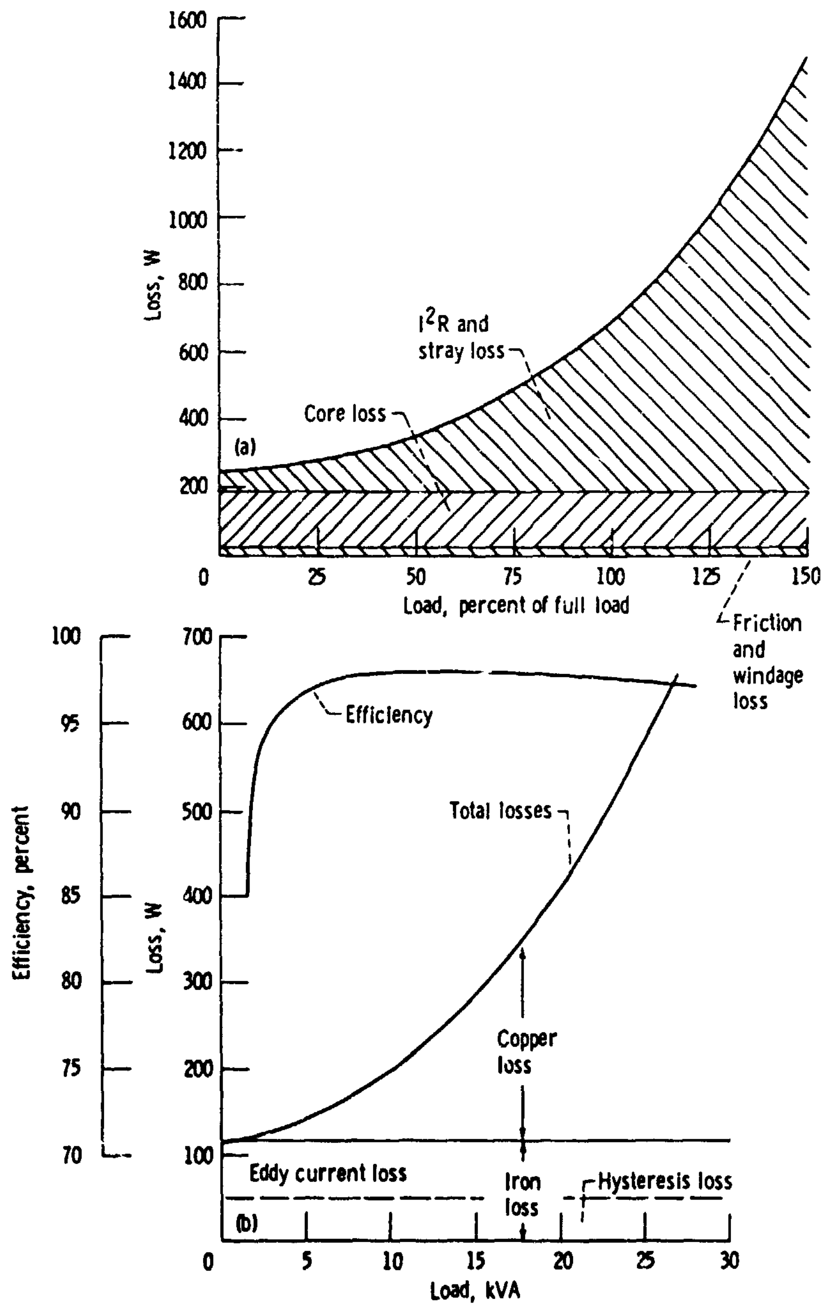

(a) 5-hp, three-phase motor.
(b) 15-kVA transformer.

Figure 2. - Comparison of loss characteristics for 5-hp motor and 15-kVA transformer.

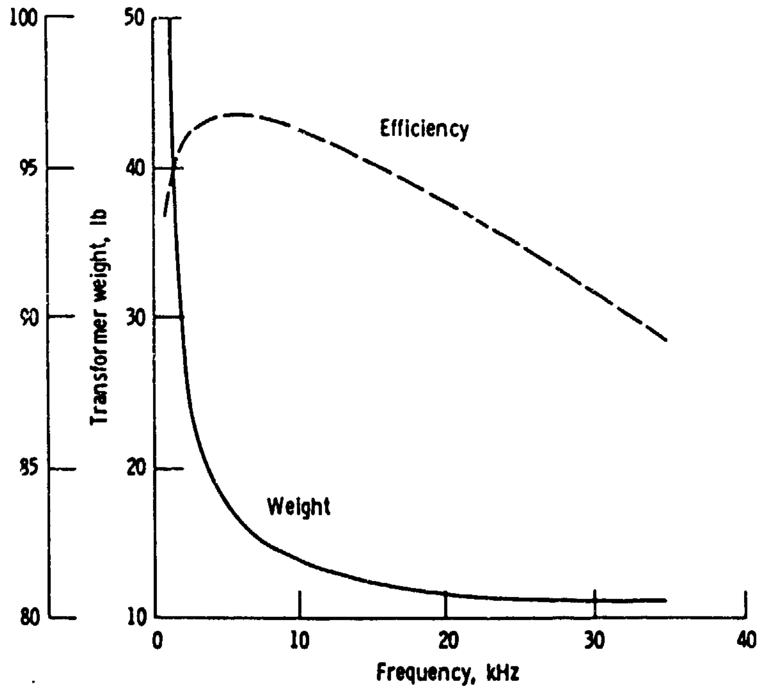

Figure 3. - 50-kVA transformer design for constant flux density. Primary voltage, 440 V; secondary voltage, 1 kV.

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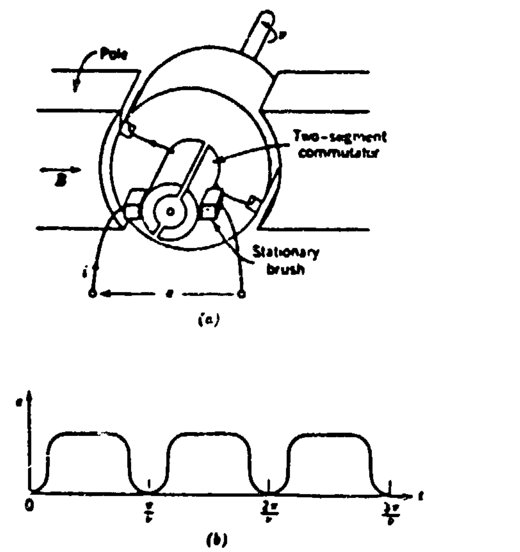
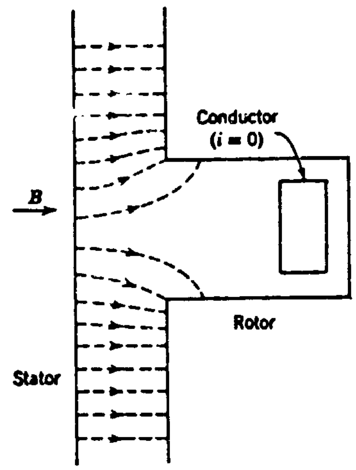
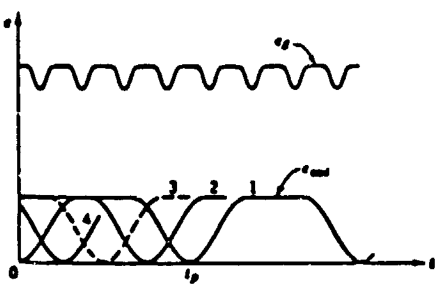


An elementary commutator machine and its generated voltage *e*.





Summation of coil voltages to produce the generated voltage e_g.

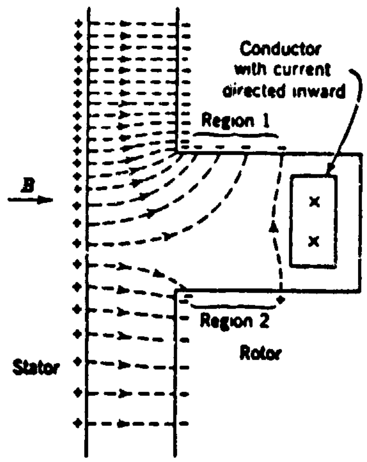


Figure 4. - Core loss factors.

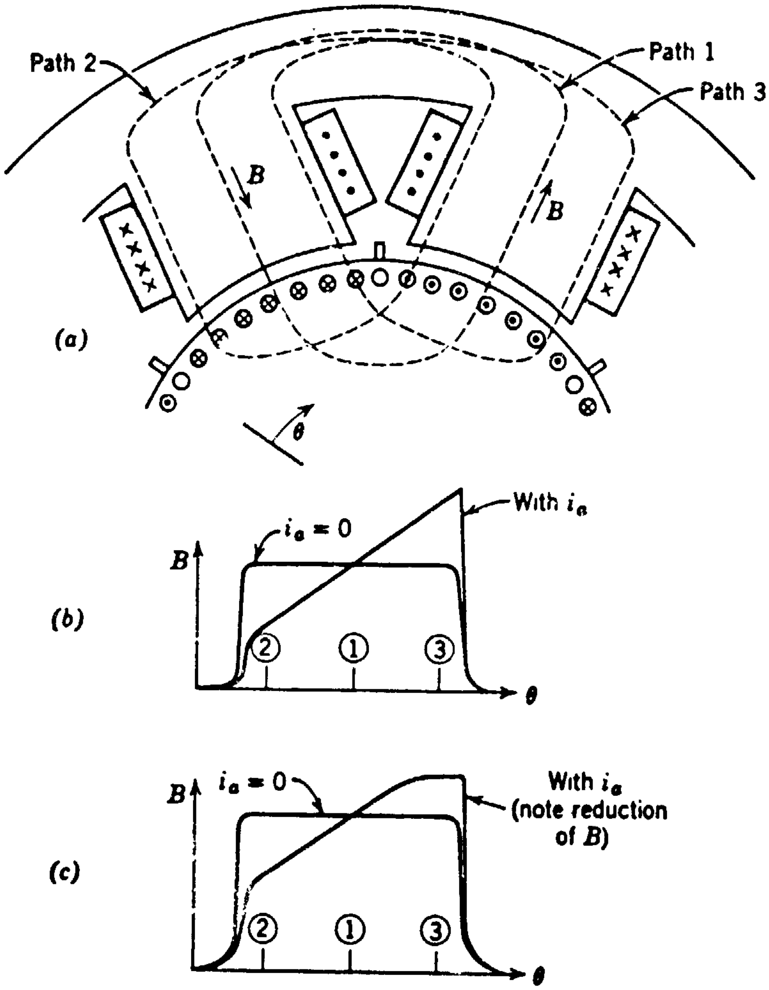


Figure 5. - Effect of armature magnetomotive force.

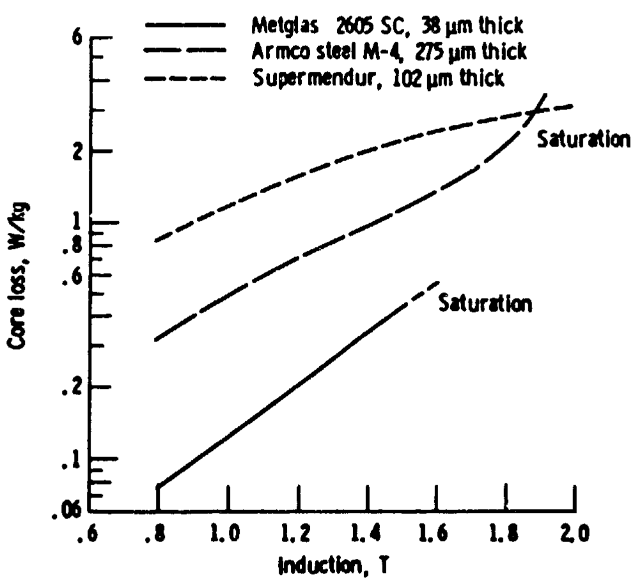


Figure 6. - Core loss as a function of induction for various materials. Frequency, 60 Hz.

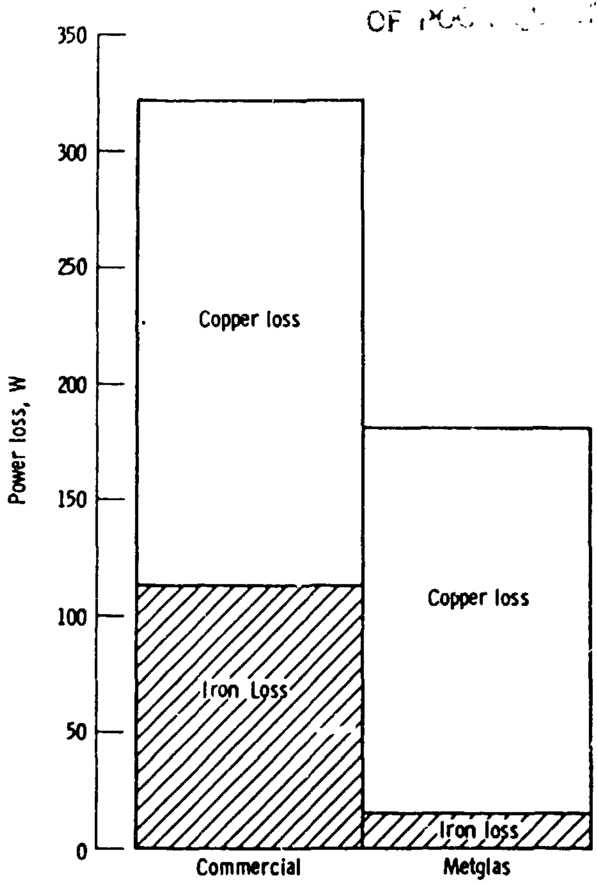


Figure 7. - Improvement on 15-kVA transformer using Metglas.

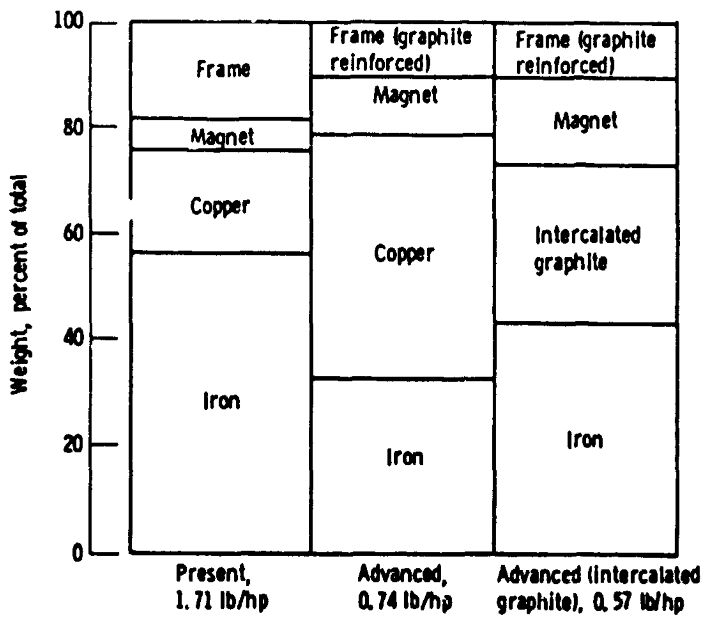


Figure 8. - Weight of samarium-cobalt motors. Efficiency, 93 percent; horsepower, 15 hp.