SOFT MAGNETIC METALLIC MATERIALS

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Introduction

Good magnetically soft metallic materials are characterized by low hysteresis losses, low eddy current losses, high magnetic permeability, high saturation values, and either a minimum or a decided change in permeability with temperature.

Air Force applications of these materials are dictated by the attainment of these properties in concert with minimum weight, size, and cost. Air Force requirements for soft magnetic metallic materials encompass their usage in transformers, for power and audio frequencies; controls, such as motors and relays; magnetic amplifiers; and thin films with very fast switching times for computers. Many of these applications will require the ability to withstand hyper-environments, due to hypervelocity vehicles and space flights. Normal operations in the future may infer sustained high temperatures or nuclear radiation or both. The principle radiation hazard will consist of fast neutrons. The thermal environment is much harder to predict. High temperatures are well-known to be deleterious to soft magnetic materials and the effects of nuclear radiation have not yet been thoroughly studied. For devices which must operate during re-entry the temperatures encountered exceed even 1000°C at some points in the vehicle.

In spite of these adverse conditions, however, magnetic materials will still play an important part in the space flight age. The properties of soft magnetic materials today, as outlined above, have developed only through investigations of the basic mechanism requirements. There is now and will continue to be a need for additional basic research of this kind as well as an extensive search for new materials to meet the increasingly difficult requirements being encountered as a result of the extreme temperature and radiation environments imposed by aerospace operations.

Factors Affecting Magnetic Properties

Magnetic properties, or more specifically, ferromagnetic properties, are highly dependent upon chemical composition and crystal structure. The phenomena of ferromagnetism results when a paramagnetic material possesses a spontaneous magnetic moment. (Although individual atoms of paramagnetic materials exhibit magnetic moments because of their unpaired electron spins, they are so randomly oriented that no net moment can be observed in volumes as small as a few lattice constants of the material.) Ferromagnetism is a crystal property and results from the parallel alignment of the individual magnetic moments because of favorable interactions between paramagnetic atoms and their neighbors within the crystal lattice. As shown in figure 1 these individual magnetic moments tend toward parallel alignment with increasing strength as the separation between nuclei becomes optimum. This desirable condition reaches its maximum with the transition metals, iron, cobalt, and nickel. Crystals of these rare earth elements are ferromagnetic only near absolute zero. Where the nuclei are too close together the forces align moments anti-parallel and the substances have no net moment; however, the non-magnetic elements, chromium and manganese, can be made ferromagnetic by increasing their interatomic distances in the lattice structure by alloying (i.e., there are many alloys of manganese which are ferromagnetic). When the disorientation effects of thermal vibrations overcomes the orientation effect of these alignment forces, the substance becomes non-ferromagnetic. Table 1 gives the Curie temperatures of the various ferromagnetic elements.

Magnetic properties are also very sensitive to impurities which tend to occupy interstitial spaces in the lattice and impede the easy formation of magnetic domains, thereby increasing the coercive force and hysteresis losses. But, on occasion "impurities" are deliberately added to improve other properties, such as the addition of vanadium to improve the workability of "Permendur." Usually "impurities" are added to suppress the eddy current losses by raising the resistivity of the bulk material. Iron normally has up to 4 percent silicon added to it or is alloyed with aluminum to achieve this result. Iron very often is alloyed with other metals to attain desirable effects such as higher permeability with nickel or higher saturation with cobalt.

Large grain size, or rather the exclusion of grain boundries, is important for better magnetic properties. Since almost all ferromagnetic materials are anisotropic, grain orientation is fundamental in controlling magnetic properties. The preferential crystal directions for easy magnetization are well-known for iron and nickel and are utilized to attain higher efficiency in transformers of all types.

Heat treatment can also influence the magnetic properties of materials. In fabrication, annealing is employed to remove stresses induced which would otherwise raise the coercive force and hysteresis losses. Yet, some iron-nickel alloys which have been drastically cold rolled are under-annealed to produce a partially strained alloy with almost constant permeability.

The usual method of fabricating magnetic cores is to cast the metal and then subsequently hot or cold roll it or machine and anneal it. In some instances, the material is ground to a powder, compacted to the shape desired, and sintered. This procedure usually saves much of the production cost, but a disadvantage is a considerable loss in the magnetic properties as a natural result of the application of high temperatures. Temperature compensation may be achieved with powdered cores, however, by using two materials with opposite temperature coefficients in the desired range.

Specific Metal Core Materials

The silicon steels have gained universal acceptance in most low frequency transformer applications. The best magnetic properties are achieved by cold reduction and heat treatment techniques which produce good grain orientation; silicon steels can be heat treated so that they will not age significantly. The silicon content of the best materials is from 3 percent to 3.5 percent.

The reaction of aluminum to electrical resistivity and other magnetic properties is similar to that of silicon when alloyed with iron. Until recently, however, difficulty of fabrication has suppressed the use of aluminum-iron alloys.

The nickel-iron alloy system produces ferromagnetic material at nearly all ratios of composition. The maximum saturation values are obtained at about 50/50. The highest permeabilities are found at about 78 percent Ni (i.e., Permalloy). Other elements are often added to these alloys to accentuate desired characteristics for particular applications. Figure 2 shows the dc magnetization curves for several common magnetic core materials.

The iron-cobalt alloys attain the highest saturation values of all common core materials, to wit 24,200 gauss. The inherent brittleness and low resistivity of iron alloys with greater than 30 percent cobalt, however, limits their application. But, a 2-percent vanadium addition makes the 50/50 iron-cobalt alloy workable and still maintains its very high saturation value. These alloys are of special interest to the Air Force because of their possibilities for higher temperature applications if the air oxidation problems can be solved.

Thin films of soft magnetic materials have gained increased emphasis, and much of the basic knowledge of magnetism in recent years has resulted from these studies. Thin films of nickel-iron have been produced which have nearly square hysteresis loops and magnetization cycling times of less than 0.2 seconds (3). They are particularly applicable for use in high speed computer devices; and, for thin film memory devices, cycling times in the nanosecond range can be expected if proper control of the magnetic parameters can be achieved.

Effects of Hyperenvironments

Some preliminary experimental work has been done to determine the effects of neutron irradiation and high temperature on soft magnetic materials (4). The results indicate that the softest magnetic materials are the most drastically degraded under these conditions. Neutron irradiation introduces imperfections in the crystal lattice which increases the coercive force. This explains the fact that the softest materials, having lowest coercivity because of minimum imperfections, are most radically changed by irradiation. Figure 3 shows the magnetic saturation as a function of long time exposure to an integrated neutron flux.

The "structure-insensitive" properties are generally unaffected by neutron irradiation. Core materials with coercive forces greater than 0.5 oersted are essentially undamaged by this irradiation, however these materials have initial and maximum permeabilities lower than the softer materials thereby making them less useful for may applications. Figures 4, 5, and 6 show the effect of irradiation on the coercive force and the initial and maximum permeabilities of several common core materials. Other investigators have found that the irradiation of nickel-iron alloys in the presence of a magnetic field produces a square hysteresis loop and increases residual induction but also increases the coercive force (5). Metal powders are affected less by irradiation than metal sheets and tapes because of stress relief effects, and the greatest changes are increases in the high frequency losses.

High temperature environments are also a serious problem area. Oxidation has a very deleterious effect on iron-cobalt alloys (6). However, if neutral atmospheres are employed these same materials are stable to as high as 600°C. A great many materials are limited to lower temperature applications because their Curie points are too low. Silicon-steels, for example, with Curie temperature above 700°C, have already decreased up to 20 percent in saturation induction at 500°C, and nickel-iron alloys are already at their Curie point at about 450°C.

Thermal cycling can produce irreversible changes in the magnetic properties of many core materials. Figure 7 shows the effect of such cycling on Supermendur, and figure 8 illustrates the relative insensitivity of 50/50 nickel-iron to thermal cycling. Grain-oriented materials show pronounced effects of high temperature degradation just as one should expect.

Conclusions

Although the progress of soft magnetic metallic materials has been rapid, as in many other materials, change in concept of recent years has caused change in direction of research for the future.

Immediate applications require the ability to withstand hyper-environments and require, specifically, investigations on the following subjects:

(1) Development of magnetic materials with higher Curie points. Thermal gradient can be achieved only by displacement or by some bulk thermal insulating material, either of which may not be tolerable.

(2) Research into the basic relationships between magnetic properties and atomic structures. This is necessary to develop materials for more reliable performance and greater environmental stability. Thin film investigations have done much to explain anisotropy and domain formation and should constitute a large part of this research.

(3) Development of corrosion resistant materials. This may be accomplished by more fully understanding the effects of corrosion on materials having magnetic properties.

(4) Reduced nuclear radiation effects on magnetic materials. Attention should be directed to the possible use of heavy elements (i.e., rare earth or low cross-section materials). A means to manipulate the crystal structures of the rare earth elements may result in materials with ferromagnetic properties more interesting than any materials now in existence.

(5) Finally, a re-evaluation of conventional materials is in order to determine what present materials can meet the foregoing requirements and in what areas new materials with enhanced properties must be sought.

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Table 1

FERROMAGNETIC ELEMENTS & THEIR CURIE TEMPERATURES

ELEMENT	CURIE POINT
Iron	770°C
Cobalt	1127°C
Nickel	358°C
Gadolinium	16°C
Dysprosium	178°C

MAGNETIC BEHAVIOR AS A FUNCTION OF ATOMIC & CRYSTAL STRUCTURE

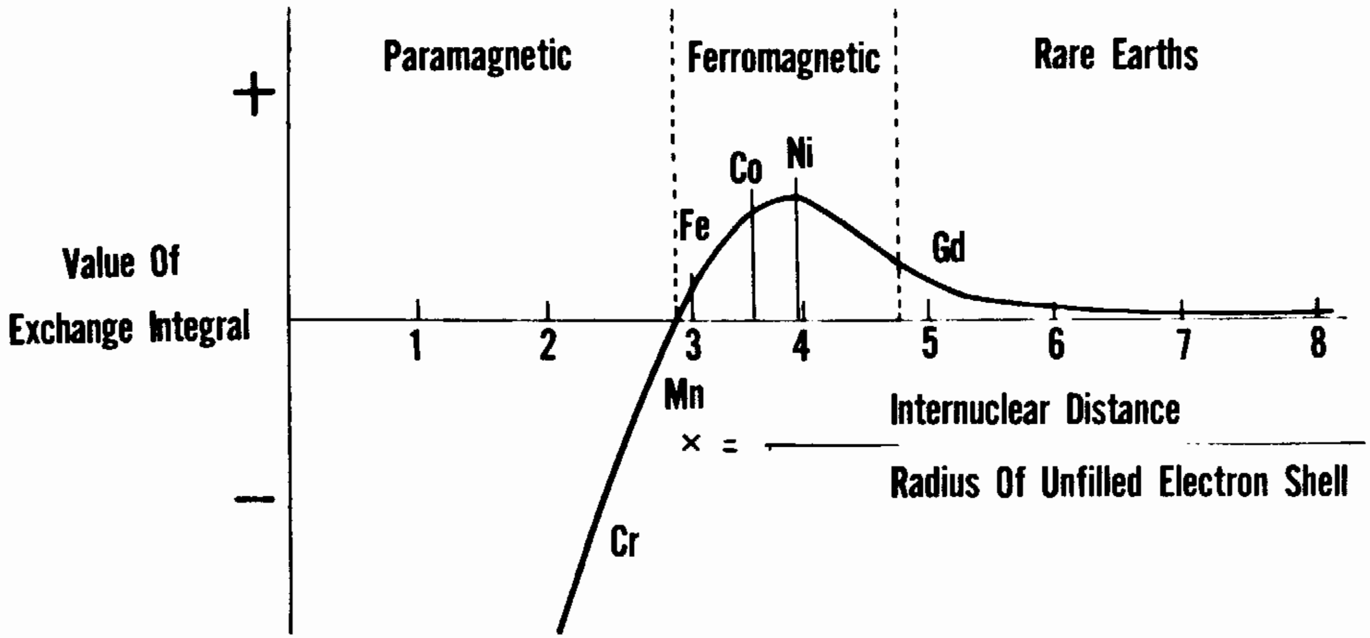

Figure 1.

D.C. MAGNETIZATION CURVES OF VARIOUS MATERIALS

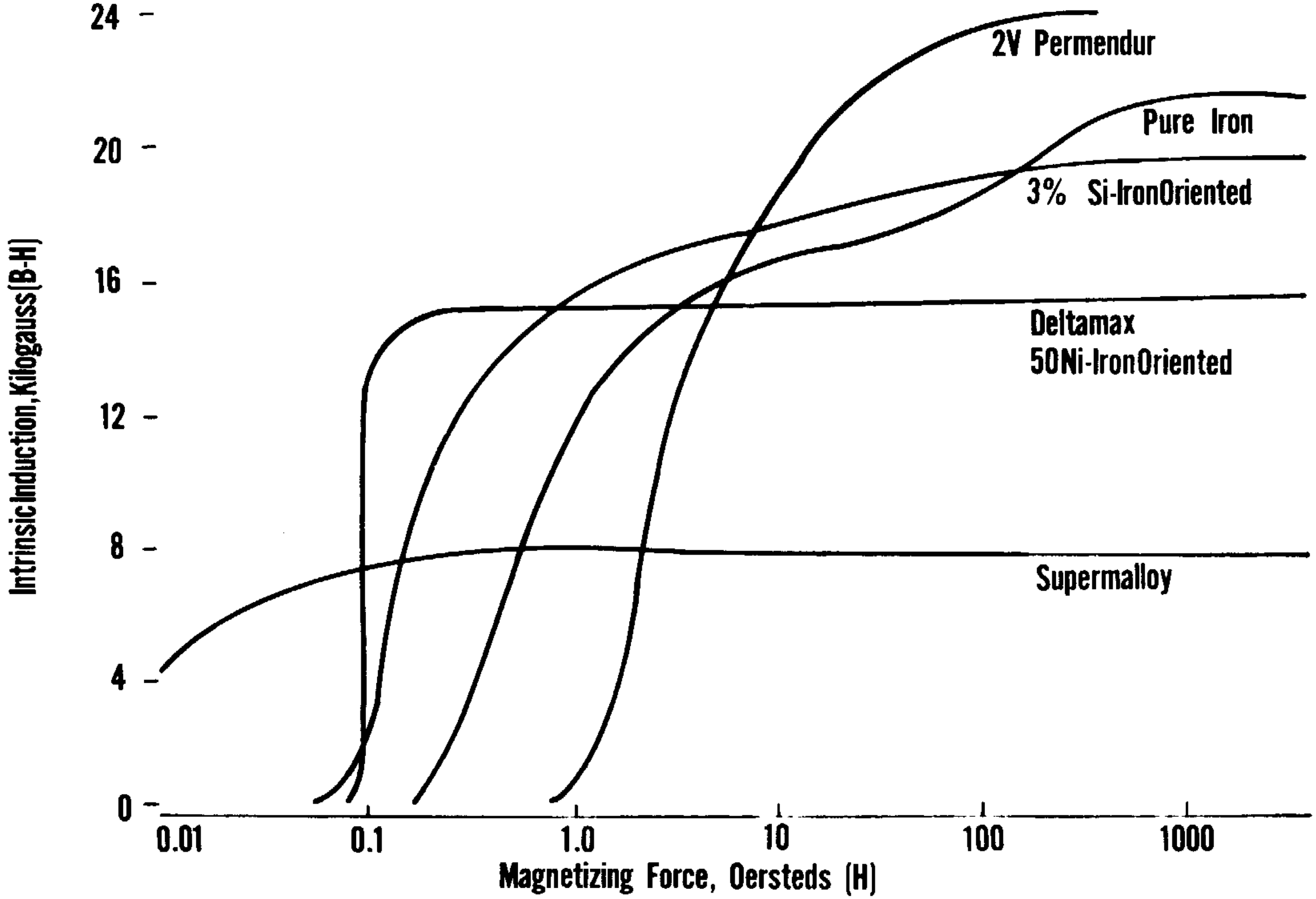

Figure 2.

EFFECT OF RADIATION ON MAGNETIC SATURATION

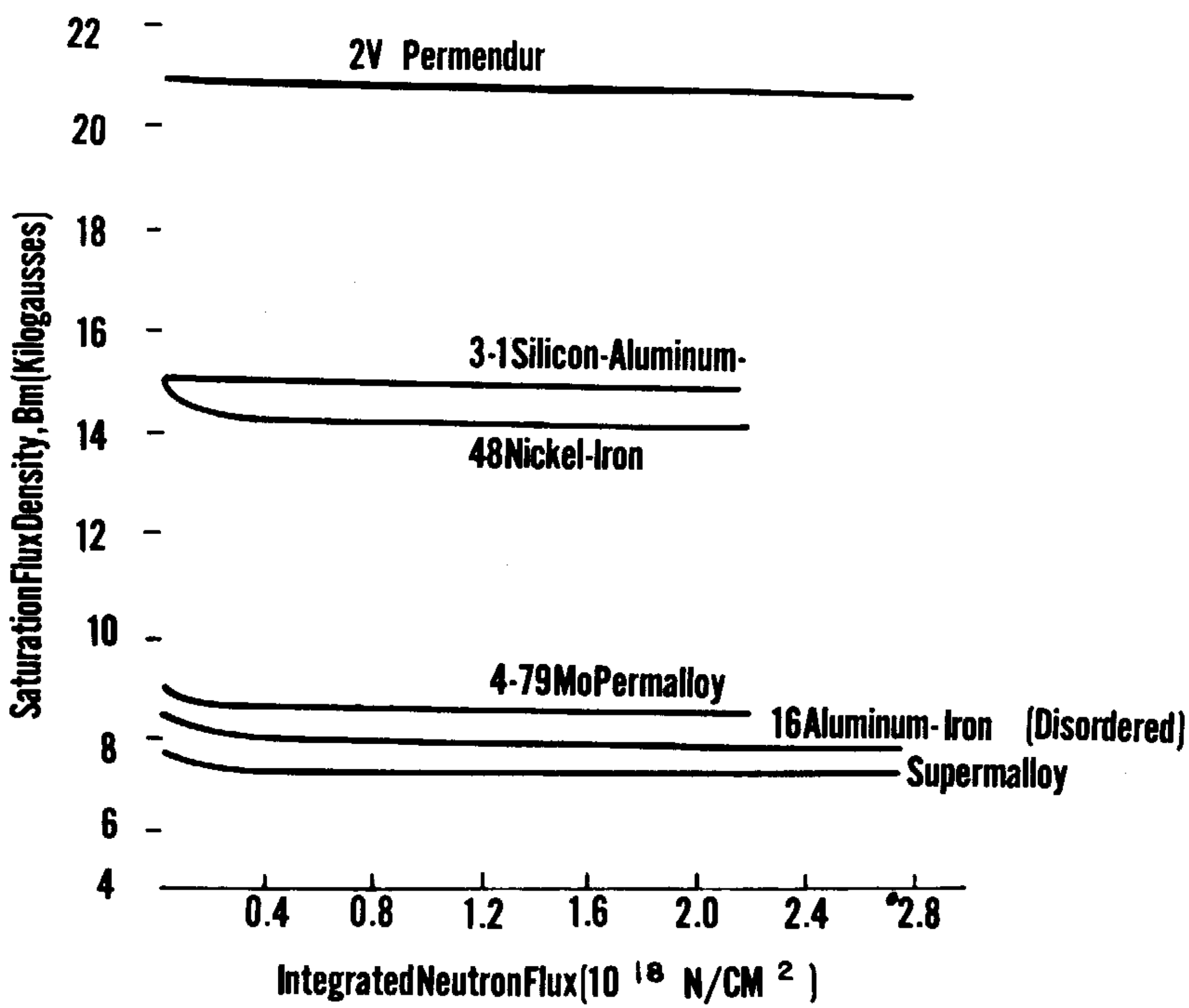

Figure 3.

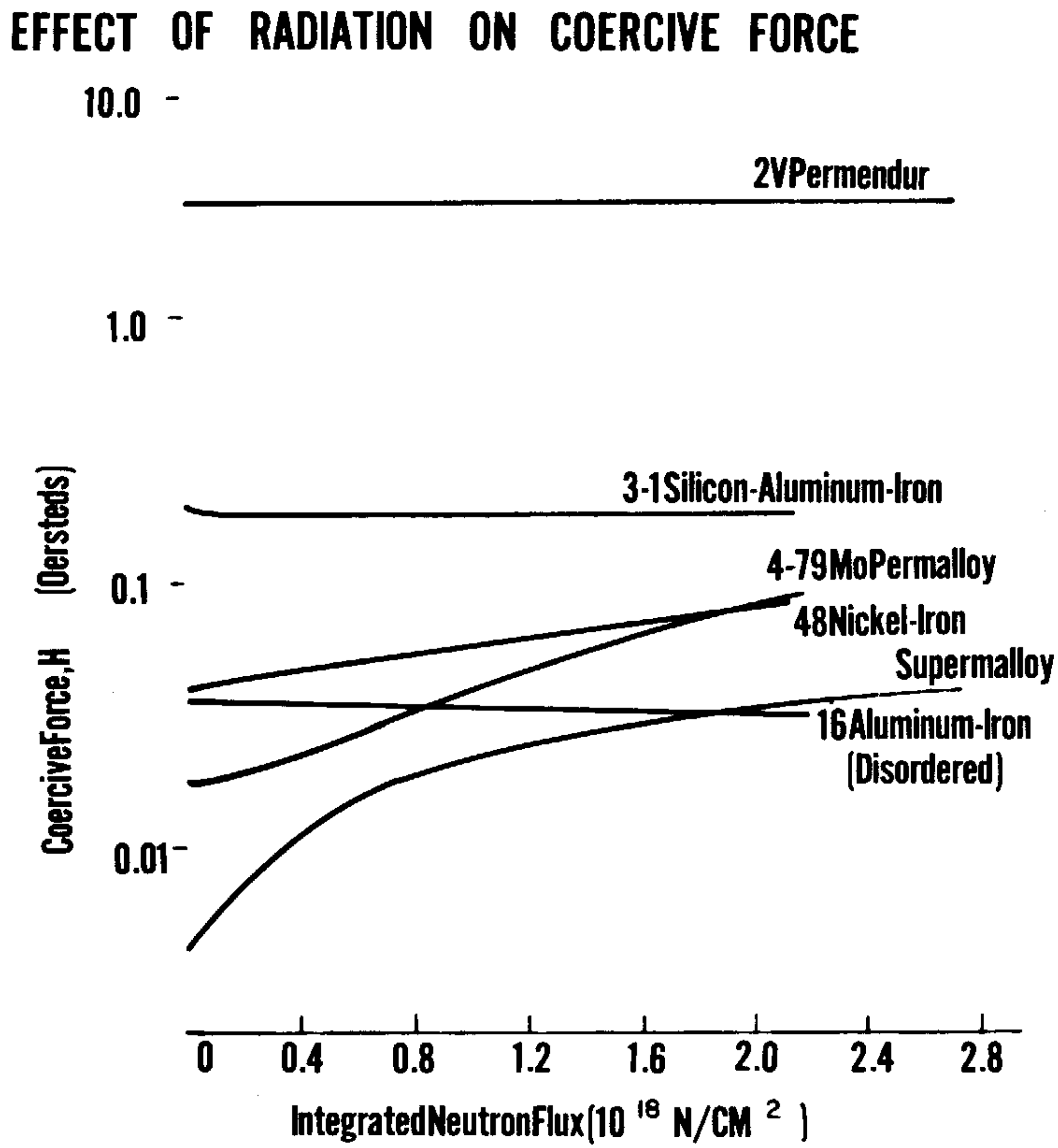
EFFECT OF RADIATION ON COERCIVE FORCE
10.0
1.0
0.1
0.01
CoerciveForce,H (Oersteds)
2VPermendur
3-1Silicon-Aluminum-Iron
4-79MoPermalloy
48Nickel-Iron
Supermalloy
16Aluminum-Iron
(Disordered)
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
IntegratedNeutronFlux(10 18 N/CM 2)

Figure 4.

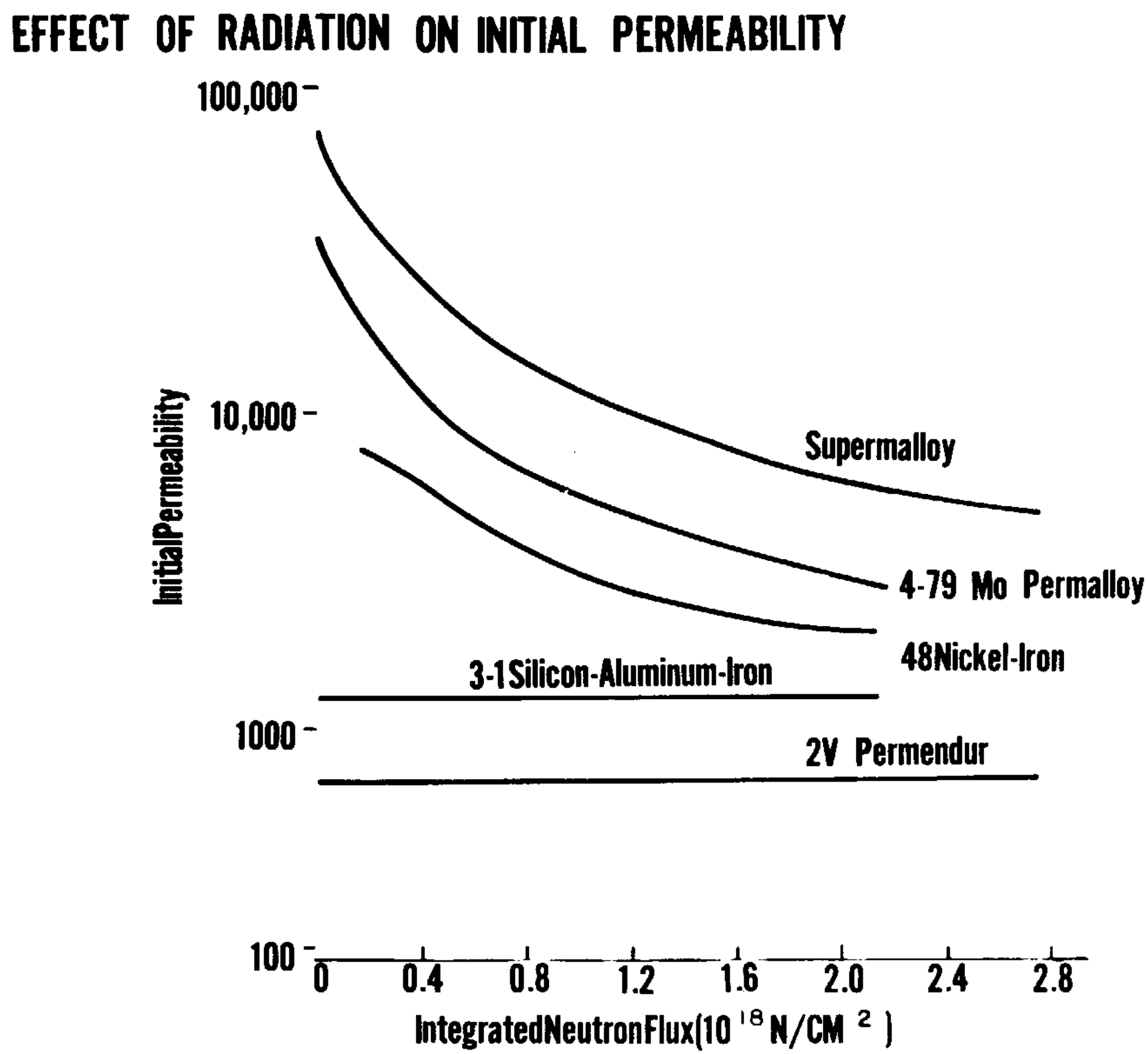
EFFECT OF RADIATION ON INITIAL PERMEABILITY
100,000
10,000
1000
100
InitialPermeability
Supermalloy
4-79 Mo Permalloy
48Nickel-Iron
3-1Silicon-Aluminum-Iron
2V Permendur
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
IntegratedNeutronFlux(10 18 N/CM 2)

Figure 5.

EFFECT OF RADIATION ON MAXIMUM PERMEABILITY

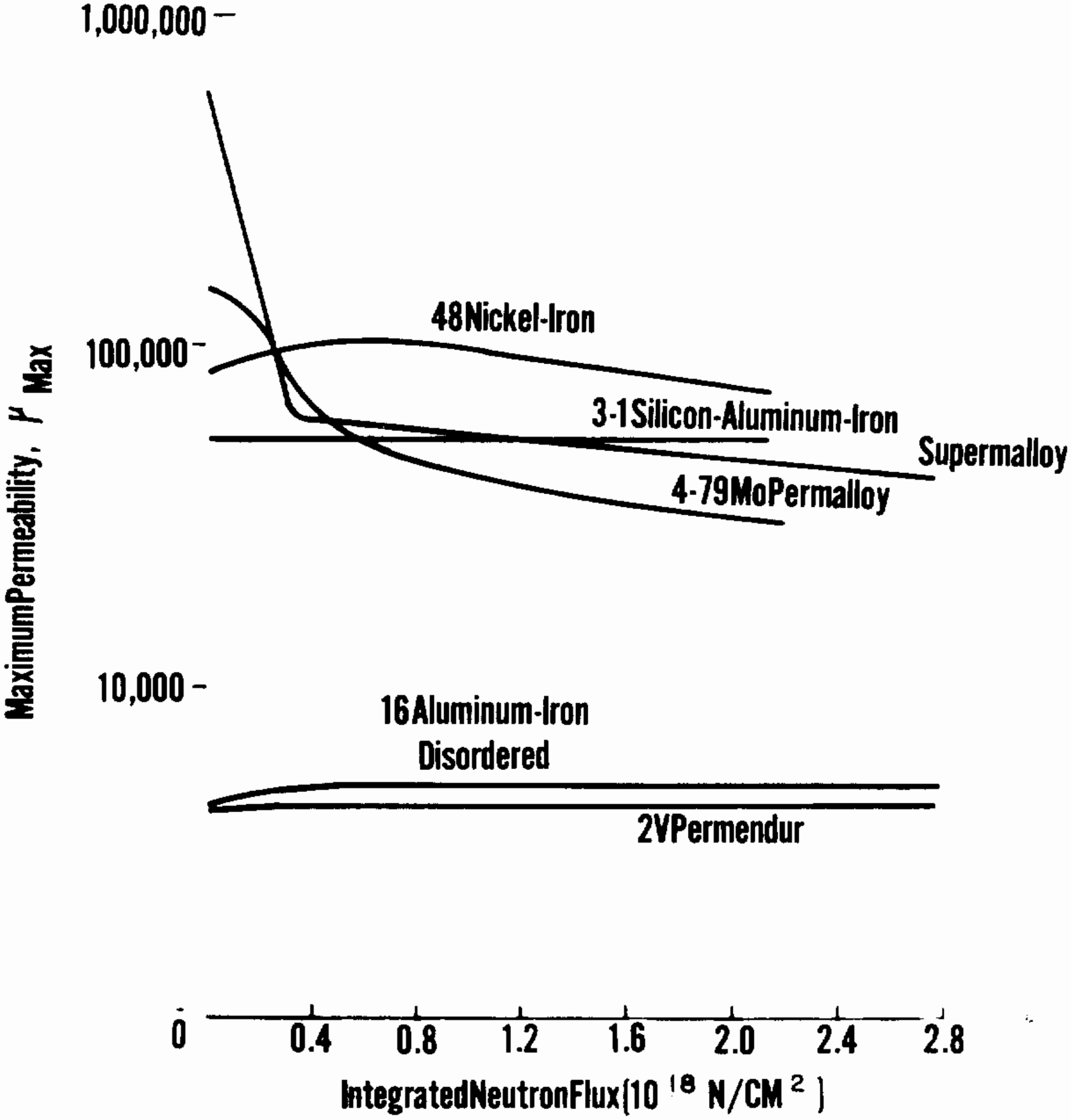

Figure 6.

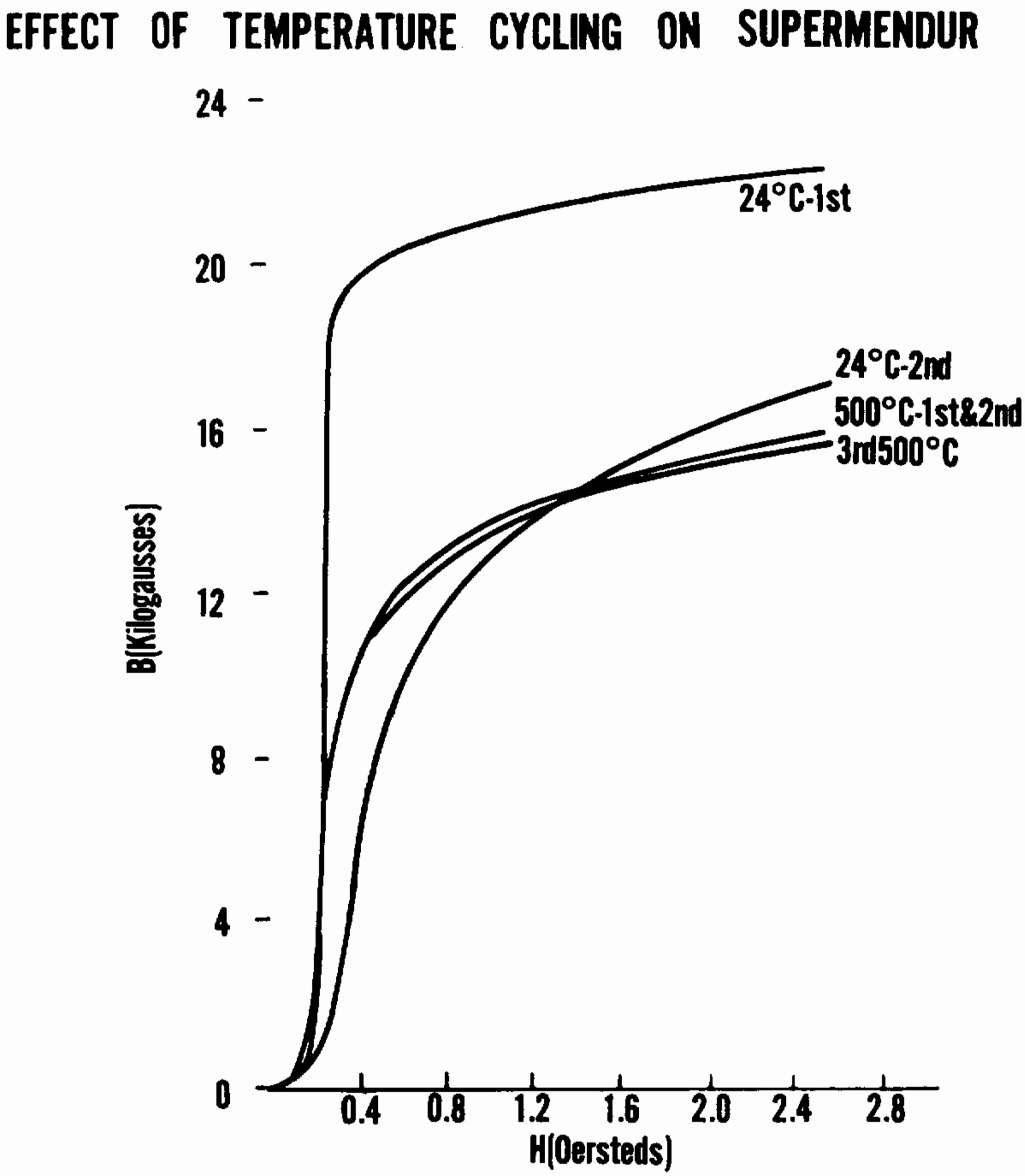
EFFECT OF TEMPERATURE CYCLING ON SUPERMENDUR
24
20
16
12
8
4
0
B(Kilogausses)
0.4
0.8
1.2
1.6
2.0
2.4
2.8
H(Oersteds)
24°C-1st
24°C-2nd
500°C-1st&2nd
3rd500°C

Figure 7.

EFFECT OF TEMPERATURE CYCLING ON 50 NICKEL-IRON

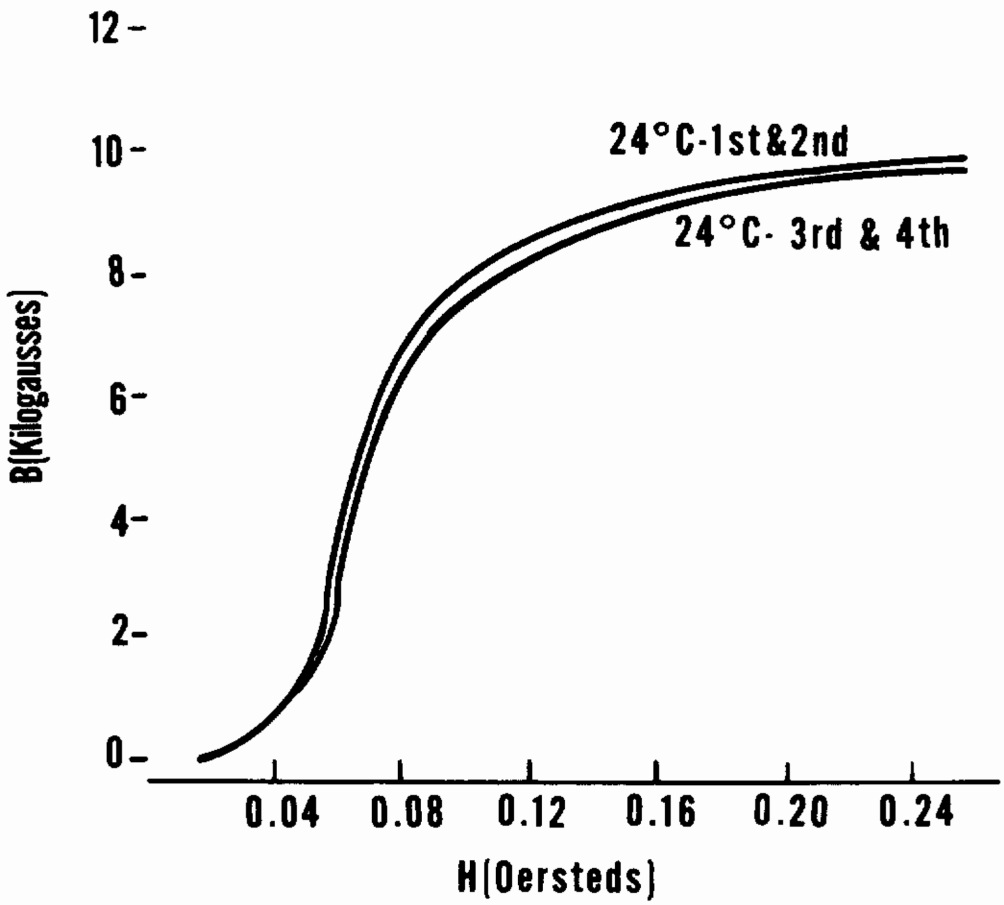

Figure 8.