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ABSTRACT

MATERIALS IN ELECTROMAGNETS AND THEIR PROPERTIES*

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Properties of low carbon and silicon steels at room, elevated, and cryogenic temperatures such as magnetic and mechanical characteristics are discussed. The effect of impurities on coercive force, remanence field and saturation values, as well as the influence of material inhomogeneities on field distribution in the useful aperture of magnets and on mechanical properties, are given.

Nonferromagnetic materials used in magnetizing coils as Copper and its alloys, Aluminum of various grades and purities; their physical properties such as resistivity, specific heat, magneto-resistance as a function of temperature and strain, are discussed.

Also dealt with are various types and techniques of insulation based on structural material and thermoset composites, their properties, such as hygroscopicity mechanical strength, and fatigue. External influences, such as effect of water vapor and radiation are discussed. A short section is devoted to various aspects of manufacturing and insulation techniques, as well as current and proposed means of destructive and nondestructive testing procedures and programs.

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Introduction

A review of all material problems used or considered in electromagnets will provide some general knowledge in quantitative form. To give some qualitative information about specific properties of materials to be used, one has to consider the type of magnet application, the mode of operation and environmental conditions. Material quality and knowledge of its properties are significant, if the magnet is an important component in the overall structure of an accelerator and has to operate without trouble over the lifetime of the machine, or if it is a component in an experiment which may last for a long period and thus lifetime properties are of prime concern.

Material specifications are different for low field, large volume magnets, i.e., in conjunction with high energy physics application (iron core or iron bound magnets), high field continuous duty magnets, high field pulsed magnets and cryogenic magnets. In each case specific requirements on active materials are different, although common features may pertain to all types.

In the design of large ac and dc magnets the correct choice of steel is important. If several magnets of the same type are used in an accelerator or in beam transport areas, it is required that all magnets should be identical with respect to field characteristics within (10^{-3} - 10^{-4}) for all field values during the acceleration period. Nonuniformity in the magnetic characteristics will be troublesome. If steel is used in combination with ac magnets, it will be required that the coercive force and the ac losses should be small and that it should not age such as to affect the magnetic characteristics.

The requirements on conductor material are equally stringent. Low resistivity combined with high mechanical strength will be prime candidate materials. Availability of hollow conductors in great length, (to eliminate brazed joints) uniformity of cross sections in strips, and flatness of discs are desirable. The conductor should not stress or thermal fatigue under continuous or pulsed operation.

The conductor insulation has been the most delicate part of the magnet. As the weakest link, the magnet's lifetime may depend on it. The requirement such as non-hygroscopic behavior, uniform insulation without voids, resistance to thermal shocks, continuous shear, pressure and tensile, environmental conditions, where nuclear irradiation effects are of prime concern, are desired features.

By scanning through specific characteristics of all the components, one faces a wealth of information in scattered form. Much quantitative information and general outlines may be found. For specific purposes, however, mainly in the limited area of magnets, information about material behavior is scarce. More thorough investigation of the above areas, i.e., steels, conductor and insulation materials is desirable. Facing the fact that larger and more complex accelerators are being built, higher fields in larger volumes with specific characteristics are attempted requirements. Proper material performance in lieu of increased mechanical and thermal stresses, combined with more severe environmental influences, are even more stringent. This paper attempts to collect available data pertinent in magnet design, give as much as possible quantitative data, and point out what additional information is needed to understand the complex properties of materials commonly used in this area.

Choice of Steel

The proper choice of steel is different for ac and dc magnets and must be dealt with separately. It is common knowledge that the magnetic properties of steels are a function of their chemical composition, melting practice, hardening process and heat treatment. The magnetically soft alloys must combine as many as possible of the following characteristics at moderate cost:

1. Low hysteresis losses.
2. Low eddy current losses.
3. High permeability at low field strength.

4. High saturation value.
5. No aging effects.
6. Uniform magnetic characteristics over each slab. Insignificant change in characteristics over an entire procurement phase consisting of the same type of magnets.
7. Ease in machinability for maintaining tolerances.

Some of these requirements are conflicting due to the nature of the steel and thus optimum solutions must be found.

Factors that influence the properties of soft magnetic materials are as follows:

Alloying elements
Impurities (solid solution, precipitates)
Grain Size
Mechanical stress, elastic and plastic strains
Order - Disorder
Preferred orientation
Magnetic annealing and heat treatment
Temperature
Nuclear radiation.

Alloying Elements

Pure iron is a good ferromagnetic material; however, in "high purity" form it is very difficult to cast into a porosity-free ingot because the trace amounts of carbon and oxygen combine to form CO bubbles. It is expensive, has a low electrical resistance and thus unusable for ac magnets. Due to softness, it is difficult to machine to adequate tolerances. The main objective of alloying elements such as Silicon or Aluminum, is to increase electrical resistivity, improve aging properties and machinability.

Si and Al form substitutional solid solutions and do not distort the lattice which adversely affect the magnetic properties. They eliminate allotropic transformations in iron so that these alloys can be annealed at a high temperature without undergoing phase change.

Si and Al are excellent deoxidizers and oxide inclusions are formed when they are added to undeoxidized iron. Inclusions are, however, harmful to magnetic properties. Oxides formed with Al are more harmful than those formed with Si.

Alloying with Si or Al lowers the saturation field and embrittles the steel and thus an upper limit of $\sim 3.2\%$ is chosen for Si steel sheets. For ac magnet cores optimum values are reached at (1 - 2)% Si alloyed in steel. Magnetic aging is reduced, but is still present using 1.5% Si steel.[1] However, coercive force is reduced to about 0.7 A cm^{-1} and the low field relative permeability increased to about 750. Of the commercial grades of steel, it can be observed generally, that sheets with high permeability values at low flux densities have lower values of coercive force, but lower permeabilities at high flux densities. BNL's measurements[2] for 3% Si steels indicate a permeability value of 1000 at 10^{-2} T, coercive force of 0.4 A cm^{-1}.

Electric grade steels (1.5% Si) have a permeability of 750 at 10^{-2} T and H_c of 0.72 A cm^{-1}. Low carbon steels ($\sim 0.1\%$ Si) exhibit values of $\mu_r \cong 250 - 500$ and $H_c \cong 1.2 - 1.6$ A cm^{-1}. For some applications, mainly cryogenic magnets, soft magnetic steels have been alloyed with up to 9% Nickel, resulting in excellent mechanical properties down to 4.2°K with only a small reduction in the saturation.[3]

A comparison of mechanical properties of low carbon steels (0.1% C) and 9% Ni-Fe is given in Fig. 1a at cryogenic temperatures. Low carbon steel exhibits lower yield and tensile strength than 9% Nickel steel and it becomes more brittle and crush sensitive. The more important impact test yields results shown in Fig. 1b, where the impact strength of low carbon steel drops continuously to a value of 300 cm-kg, at 78°K, and

230 cm-kg, at 4.2°K, whereas the impact strength of 9% Nickel steel shows a gradual decrease from 300°K values to 500 cm-kg at 4.2°K.

Coercive force of low carbon steels is generally increased from room temperature to 78°K, approximately twofold, and low flux density permeability is reduced. However, saturation flux density of 0.1% C steel is increased at cryogenic temperature (2.2 T) at 4.2°K. Saturation value of 9 Ni-steel is 2.085 T at 293°K and 2.1 T at 4.2°K.

In dc magnets alloying elements are not used. As aging effects are not of prime concern, low amounts of Si and Al; e.g., 0.1% Si and approximately 0.01% Al can be tolerated. However, if the amount of Si content in the slab varies in the range of 0.05 - 0.2% the B-H curve in the medium flux density range of (1 - 1.5) T is affected seriously and may create problems if several equal magnets are connected in series and operate simultaneously.

Impurities

Ferromagnetic properties depend on the perfection of the crystal lattice. Impurities in solid solution as coherent or incoherent precipitates influence the magnetic properties. Most nonmetallics such as Carbon, Nitrogen and Boron form interstitial impurities and strain the lattice. They are more harmful than the substitutional impurities such as Sulfur and Phosphorous, or alloying elements such as Manganese, Chromium and Copper.

Hydrogen is an interstitial impurity but no effects on magnetic properties have been measured systematically. Carbon and Nitrogen are the most harmful interstitial elements, but fortunately, commercial steels with a Nitrogen content of about 0.003% may be obtained quite readily and thus no serious problems are encountered. Carbon is a harmful element that is difficult to keep out of iron.

Measurements by Gerold[4] give a first-order indication about tolerable impurities. His measurements indicate that additions of impurities up to 1% in an otherwise pure ingot reduces proportionately the iron flux density. B-H curves and ΔB-H curves obtained for various 1% impurities (Fig. 2) can be proportionately adjusted to any desired impurity content less than 1%; e.g., a steel used for the SLAC beam transport magnets has an impurity content given in Table I.

TABLE I

Impurity Composition of Steels Used in SLAC Beam Transport Magnets

Element	Percentage in Iron	Total Allowable Content (%)
C	0.06	0.08
Si	0.1	0.1
Mn	0.3	
S	0.03	Al + Mo + S + P max 0.1
Ni	0.06	
Cr	0.05	
Mo	0.01	Mn + Ni + Cr + Cu max 0.5
Cu	0.04	
P	0.01	
Al	0.01	
N	0.005	0.003
B	traces	traces
O	0.002	0.002

The fields at various flux intensities can be calculated as follows; e.g., at $H = 10^4$ $A.m^{-1}$ the field of ultra-pure iron is $B_{Fe} = 1.9$ T. Corresponding values of field reduction are as follows:

1% C	$\Delta B = 0.3$ T	0.08% C	$\Delta B = 0.024$ T
1% Si	$\Delta B = 0.032$ T	0.1% Si	$\Delta B = 0.0032$ T
1% Mn	$\Delta B = 0.075$ T	0.3% Mn	$\Delta B = 0.0225$ T
1% Cr	$\Delta B = 0.033$ T	0.05% Cr	$\Delta B = 0.00165$ T
1% Mo	$\Delta B = 0.075$ T	0.01% Mo	$\Delta B = 0.00075$ T
1% Cu	$\Delta B = 0.016$ T	0.04% Cu	$\Delta B = 0.00064$ T
1% Al	$\Delta B = 0.068$ T	0.01% Al	$\Delta B = 0.00068$ T
1% N	$\Delta B \cong 0.7$ T	0.005% N	$\Delta B = 0.0035$ T
		Total	$\Delta B = 0.0569$ T

The expected actual flux density in the iron is thus:

$$B = B_{Fe} - \Delta B = 1.843 \text{ T}$$

No values for other impurities are available to date, but their influence is probably small.

Gerold's measurements yield good results for $H \geq 2.5 \times 10^3$ $A.m^{-1}$ but gives low B values at low flux densities.

In iron-silicon alloys, the carbon content should be kept below 0.005% in order to obtain low hysteresis loss and high maximum permeability at low fields with little aging. The solubility of Carbon in α - iron in 3% Si-alloy is reduced to 0.005% at 700°C.

The coercive force depends both on the total volume fraction of inclusion and the state of dispersion. The effect of inclusions on the coercive force is based on the presence of internal poles at the interface between inclusions and the crystal matrix. In passing an inclusion, the domain wall causes redistribution of these magnetic poles which results in a lowering of the magnetostatic energy and hence a tendency of the wall to adhere to the inclusions. Qualitatively, it is found that Nitrogen and Carbon have a pronounced effect on the coercive force as seen from Fig. 3.

As mentioned, basic open hearth, low carbon steel contains between 0.007% and 0.008% Nitrogen. Commercially there is no economical way to reduce these amounts by more than 0.002%. Technically, it can be reduced to zero, but special techniques involving the use of high purity Oxygen (with no Nitrogen) in the open hearth and long-time heat treatment at high temperatures in vacuum are required. Cost becomes an important factor.

Residual steel-making alloying elements, such as Chromium, Vanadium and even Molybdenum combine with Nitrogen to form stable chemical compounds at even very high temperatures. Tied up in this form, the Nitrogen is not as deleterious to magnetic properties.

These comments pertain mainly to large core-iron applications. Thin gauge steel material can readily be decarburized and denitrited by "open coil" annealing in vacuum or hydrogen. Commercially, Nitrogen can be reduced to 0.001% in this manner.

The nonmetallic interstitials such as Oxygen, Carbon and Nitrogen are troublesome because they have limited solid solubility in iron and cause dispersion hardening. In sheet materials (hot slabs), they can be removed in reasonable time, because they diffuse through the metal and combine with hydrogen at high temperatures, below the melting point of iron. Carbon is removed readily in moist hydrogen. Phosphorous is not affected by hydrogen, but neither does it affect the magnetic properties of otherwise pure iron, if present in quantities less than 0.01%.

Impurities can be removed by heat treatment. The nonmetallic impurities must diffuse through the iron to the surface of the specimen and then leave the surface either by evaporation, or reduction by the presence of a flow of hydrogen, or other suitable reducing gases. The residual impurity must be less than the solid solubility at room temperatures.

The amount of gases such as Oxygen and Nitrogen that are dissolved in iron decreases as the temperature is lowered after casting. The free gases form bubbles which may be scattered over the slab, are most objectionable. Inclusions or gas bubbles have adverse effects; they act as "stress raisers" in fatigue service and cause premature failure, and reduce the average flux density in steel.

Forgings:

Based on these deficiencies, dc magnets are preferred to consist of forgings, or rolled slabs, which after a final annealing have a number of advantages:

1. Most of the gas pockets and blow holes found in castings are closed up and sealed. The metal at the surface of these voids is in an active condition, because of the generally reducing atmosphere (CO and some hydrogen) in the ingot. The combination of the preheat temperature and the forging pressure causes the void surfaces to weld together.
2. Homogenization and redistribution of various inclusions. Hard intermetallic components are broken up and sometimes redissolved by the forging process. Forging also minimizes segregation patterns found in castings and ingots.

Forging may refine grain size; however, some control over grain size is maintained by guarding the temperature at the final forging operation and subsequent annealing practice. Final forging at low temperatures, to introduce some lattice strain, followed by a relatively high temperature annealing process promotes large grain size.

Magnet Aging:

One of the most important aspects is the magnetic aging of steels. Despite this importance, comparatively little work has been done to determine the causes or rates of such changes which demonstrates itself in the form of increasing coercive force and lower permeability. Those steels are of interest in magnet designs which have a low coercive force in the order of 0.5 - 0.8 A cm^{-1} or better. The energy to reverse H_c is little. In ac magnets the energy of reversal is converted into core losses and heat. Core losses are broken up into hysteresis, eddy current and "anomalous" loss.

The coercive force may be the most structure-sensitive property of ferrous materials. It is related to the core loss given by area within the hysteresis loop. The magnetic aging of low carbon steels can be minimized by reducing the carbon content, or by slow cooling to room temperature. In order to reduce aging in SLAC ac and dc magnets, the heating and successive cooling of slabs in an inert atmosphere was performed according to Fig. 4.

Commercially, the most important soft magnetic materials sheets are low carbon steels containing up to 4% Silicon. Measurements indicate that the increase of H_c in these alloys is less than plain low carbon steels with low Silicon content.

In conclusion, we may summarize the result of many tests regarding aging:

1. Increase of H_c and decrease of permeability with time (in the temperature range where these materials are used) are due to precipitation of interstitial solutions such as Carbon and Nitrogen. The extent of such aging is roughly a linear function of the supersaturation of Carbon and Nitrogen at the aging temperature.

2. The precipitate particles are highly anisotropic in shape, being plate-like or dendritic, depending on the particle compound structure. For a given temperature, the coercive force frequently reaches a maximum at a particular average precipitate size. The maximum dimensions of the particles at this "critical" size are much greater than the thickness of the domain walls.
3. At equivalent concentrations in solid solution, Nitrogen can produce a greater coercive force than can Carbon.
4. Magnetic aging can be minimized by reducing the total Carbon and Nitrogen content of the alloy or by thermal treatment which will precipitate carbides and nitrides as large ineffective particles and which will also reduce the concentration of Carbon and Nitrogen in solid solution to a minimum.

Segregation:

When either iron or steel is molten, the various impurities are dissolved in it. Some of them, especially Carbon, Phosphorous, and Sulfur make the metal more fusible; i.e., they lower the melting point. However, the impurities have significantly less solubility in the solid metal and therefore tend to separate on solidification. We can conceive of the freezing process of each layer, beginning at the outside working towards the inside. As the metal freezes, each layer rejects some of its impurities, to be dissolved by the liquid in the interior. When the next layer freezes, that will, too, reject a part of its impurities into the contiguous molten layer. Thus, the concentration will proceed so that the portion of the metal richest in impurities, especially Carbon, Phosphorous and Sulfur, will be that which freezes last. In ingots, the portion to freeze last is just below the bottom of the pipe or shrinkage cavity that forms. The location of the richest segregation may vary, however, in steel. The most impure parts are generally near the top of the thickest section of metal, since exothermic, or "hot-topping," materials are usually added to the poured ingot to promote directional freezing from the bottom. The riser is calculated to be the last portion to freeze and the richest segregate should be located in it. Then the position of the shrinkage cavity is seen to be of great importance, because it also indicates the probable location of most impure metals.

As a general rule approximately 25% of the top part of the ingot and 5% of the bottom part are cut out. As segregation cannot be prevented it is hoped that the removed parts are the location of the richest segregates.

Generalizations on impurities:

1. Pearlite (lamellar intermixture of Fe_3C and pure Fe) is magnetically more detrimental than Fe_3C particles (Cementite).
2. A grain boundary network of Fe_3C is more detrimental than the same volume of carbide in agglomerate form.
3. Carbon held in solution is less harmful than carbon precipitated as carbides in grain boundaries or within the grain.
4. Magnetic aging is related to the amount of carbon in solution which is a function of the quench temperature.
5. Rapid cooling leads to lattice strain and should be avoided.
6. The influence of Nitrogen is two to three times more than that of Carbon. The coercive force can be reduced by $\sim$15% by reducing the Nitrogen content from 0.005% to 0.002%.

7. Acid steels[a] are generally superior magnetically than basic steels[b]. Basic open hearth steels normally have a higher Oxygen content than acid open hearth steels. Basic steels are associated with defects of oxygenated steels, like blow holes and inclusions. The inclusions are SiO_2, MnO, silicates of FeO, MnO, etc. Blow holes are prevented by adding Al, Si, Mn to the molten metal.

Grain Size

Optimum magnetic properties are obtained with single crystals. The lattice disregistry between crystals in a polycrystalline material is a source of energy loss and thus undesirable. Hence, larger grains favor lower energy losses and greater permeability. As illustrated in Fig. 5, grain size has a substantial effect on the coercive force. Grain size varies with Carbon and Silicon content. Even in large grain size the effect of impurities should not be discarded. It was found; e.g., that the magnetic properties of large grained 0.06% Carbon steel were inferior to a small grained 0.01% Carbon steel.

Large grains may be obtained in pure metals by cold work and successive annealing. However, if this cold work is associated with grain orientation, substantial improvements with respect to magnetic properties in the direction of grain orientation is obtained.[5] Unfortunately, these magnet properties such as low core losses, low hysteresis force and high permeability at low and medium flux density regions cannot be utilized fully in magnets, as will be discussed below.

Plastic Strain

Thorough investigation of elastic and plastic strain with subsequent work hardening yields many difficulties. Even in single alloy steels no unambiguous quantitative treatment has been proposed yet. Hence, only qualitative results with general conclusions are given. The effect of strain or cold work is based on stored energy in the grain. Cold work increases the overall dislocation density and the formation of dislocation tangles. The decrease of external mechanical stress does not completely restore the initial conditions due to the resistance of alloys to recover spontaneously.

Elastic and plastic strains have a profound influence on magnetic properties. With materials having a positive magneto-striction, (e.g., iron) a tensile strain improves relative permeability in the medium B-H range up to a certain stress limit illustrated in Fig. 6 and then harms it. In materials with negative magneto-striction, the permeability is reduced as a function of tensile stress.

Plastic strains are harmful to all soft magnetic materials, decreasing the permeability, increasing coercive force and increasing core losses.

In ac magnets where low-carbon, silicon-steel sheets (0.35 - 0.5 mm thick) are used, even compression of the core stack will insure that the laminations are subject to uniform compression only and not to a combined compression and tensile stress. Pure compressive stress on cold reduced and hot rolled sheets increase coercive force and core losses

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[a] Acid steel: Steel melted in a furnace with an acid bottom and lining and under a slag containing an excess of an acid substance such as Silica. The inner bottom and lining of a melting furnace consist of materials like sand, silicon rock or silica brick that gives an acid reaction at the operating temperature.

[b] Basic Steel: Steel melted in a furnace with a basic bottom and lining and under a slag containing an excess of basic substances, such as magnesia or lime. The inner bottom and lining of the melting furnace consist of material like crusted, burnt dolomite, magnesite bricks or basic slag that give a basic reaction at the operating temperature.

only slightly. Uneven compression has a much more pronounced effect on losses, as can be seen in Fig. 7. Increasing the compressive stress from 1 kg cm^{-2} to 11.5 kg cm^{-2} in a stack of grain-oriented sheets yielded an increase in core losses of 8% at a flux density of 1.5 T. The coercive force in grain-oriented sheets is increased by ~12% if the compressive stress is increased from 1 kg cm^{-2} to 10 kg cm^{-2}. The increase of coercive force in hot rolled sheets in the same pressure range was about 3%.

In practice, individually insulated sheets are stacked in fixtures, and an average pressure of ~5 kg cm^{-2} is applied to the core. The magnet core can then be held together by means of bolts or adhesives applied to the surfaces of each sheet, and/or finally welded at the outer surfaces. The latter solution gives better pressure uniformity, although the welding process may deform the sheets, if local heating is not avoided. If stacks must be bolted for additional strength, in the vicinity of each bolt the pressure on the grain is much higher (four to six times) than the average value. Grain distortion and plastic strain is a natural result. Bolt holes also lead to a local increase in flux density and thus to an increase of coercive force. All modern magnet designs avoid the use of bolts and utilize high temperature adhesives. For additional safety, the core stacks can be either welded to steel support structures located at the external surfaces, or fixtures may be used.

Cyclic Strains

AC magnets are subject to cyclical strains, although compressive stresses due to pulsation of the magnetic field will seldom reach values of 1 kg cm^{-2}. However, over the lifetime of the magnet, one may expect 10^7 - 10^{11} stress cycles. It is known that even at this low (< 1 kg cm^{-2}) compression, the low carbon Silicon sheets show aging effects. The percent of elongation is increased, tensile strength decreased following cold work. Coercive forces increase with the subsequent effect of higher core losses and lower permeabilities at low fields. Cyclic straining tends to cause the material to revert to what is apparently a more stable condition, which is intermediate between annealed conditions and the cold worked state. Even annealed sheets show cyclic strain softening characteristics, but their softening behavior is less than in cold reduced sheets. In both cases, there exists an asymptotic stress range, which can be regarded as a material characteristic. The cyclic characteristic lies below the static stress-strain curve.

In the design of ac and pulsed magnets, one should consider the fatigue or endurance limit and should use, depending on the cycling, core flux densities which do not lead to an appreciable increase in H_c and thus increase in core losses, which are more sensitive indicators of aging than mechanical aging.

The effect of "order - disorder" is not germain in pure iron and thus not dealt with in this paper.

Preferred Orientation

Anisotropy of magnetic properties exists in polycrystalline materials as a consequence of the magnetic anisotropy of the grains. A high degree of anisotropy or orientation can be developed by a proper combination of cold working (cold rolling) and annealing operation.

Oriented Silicon and Nickel steel alloys are common and used in transformers. Coercive force and core losses are lowest in the rolling direction (grain orientation) and much higher (three to four times) perpendicular to the rolling direction.[6] Permeability at lower B values are approximately 15% lower in the direction perpendicular to the grain orientation. In ac magnets the use of grain-oriented steels lead to a complete redesign of magnet cores. "C" and "H" type magnets must be built as interleaved structure, rather than from single punchings. However, if very low coercive force, and subsequently low core losses are of prime requirements, the sheet rolling orientation must coincide with the magnetic flux direction and proper designs can be adapted.

Annealing and Heat Treatment

Annealing the steel at temperatures above the Curie-point and cooling down at a rate of ~50° C/hour or less to room temperature in an atmosphere such as pure H_2, or a mixture of $(4 - 5)\%$ H_2 and $(96 - 95)\%$ N_2, eliminates crystal tension and removes most crystal dislocations caused by mechanical operations such as cutting, machining and punching.

Punched sheets require careful annealing, to reduce H_c and core losses to their initial value. 1.5% Silicon steel with a carbon content of 0.01% resulted in an H_c value of ~ 0.7 A cm^{-1} and increase of permeability of $\sim 14\%$.

Temperature

Generally ac magnet cores are designed in such a way that even the hot-spot temperature lies much below the Curie temperature. In general the temperature may primarily effect the adhesive strength of thermosets between laminations. However, as pointed out, the temperatures combined with cycling lead to early fatigue and thus coercive forces may increase to values intolerable for the magnet performance. Even if the hot-spot temperature is kept below 80° C, Silicon steels may still age over the lifetime of the magnet.

Samples of low carbon steels subjected to higher temperatures ($\sim 100^\circ$ C) expected in magnet cores for a period of several days showed acceleration of the aging process. Small changes were measured in coercive force, where the values increased approximately twofold. Addition of Silicon to about 1.5% to low carbon steels decelerate aging markedly. When the above tests were repeated at 100° C at a cycling frequency of 60 cps, the steels exhibited aging effects. After fourteen days the coercive force had increased 8%.

In high frequency pulsed magnets, maximum flux density in the core was chosen less than 1.2 T. Steel material specified was 3% Silicon steel with a Carbon content of 0.002%.

Radiation

A survey of literature[7] shows that only mechanical properties of alloyed low carbon steels have been evaluated. Measurements by Porter show an increase in yield strength at radiation levels of at least 5×10^{10} rads. As shown in Fig. 8, the rate of change in yield strength between 5×10^{10} rads and 10^{12} rads is quite sharp. The increase is less pronounced beyond the dose rate of 2×10^{10} rads.

The ultimate tensile strength increases at the same rate as the yield strength. It may be noted that large grain size steels are more affected by irradiation than fine grains. The large grain size steels become brittle when irradiated at 1.5×10^{19} n cm^{-2} (fast) neutrons.

These experiments indicate a drastic change for the worse in magnetic properties of irradiated steels. Unfortunately, very limited data are available pertaining to changes in fatigue properties, creep properties, effect of heat treatment, coercive force, core losses due to irradiation.

Choice of Conductor

Copper

The most common conductor material used for air, water, and cryogenic liquid-cooled magnets is copper and its alloys. In medium field regions ($\leq$ 2T) where electromagnetic forces are not excessive, soft annealed copper, preferably OFHC or copper with low phosphorous content, is utilized.

Copper commercially available exhibits low resistivity combined with good mechanical properties (see Table IV). Coils built with hollow copper conductors may have average optimum current densities of (500 - 2000) A cm^{-2}. The winding cross section does influence the overall size of the magnet and its cost. Compact coils with higher average current densities need better insulations, more extensive cooling and result in more complicated winding configurations. High current densities lead also to a high operational cost due to high power dissipation. Generally low voltage, high current coils are preferred which have a number of advantages, such as safety of operation, where the interturn voltage can be kept low to avoid voltage breakdown in case of faulty insulation. High current, low voltage coils are better optimized. Current regulation (better than 10^{-4}) is simpler.

In high current dc magnets (10^4 A), the conductor cross section may become very large which has two adverse effects:

1. Due to limitations in manufacturing facilities, the conductor length would be short (15 - 30 m). Many brazed joints may be required for each hydraulic passage. Joints are costly and time consuming. If they are not prepared properly, they leak and damage the insulation during operation and lead to flash-overs or voltage breakdowns between turns or pancakes.
2. Parallel current and hydraulic passages must be used to avoid many joints and improve cooling conditions. Connections could be made outside the coil's active area. This solution yields lower overall current densities and is costly.

Two remedies are feasible and are currently being studied:

1. Continuous copper casting; however, this process is still in a preliminary stage; surface contamination and microporosity has not yet been controlled.
2. Use of Aluminum conductor which eliminates brazing, but requires either higher power costs, or larger coil cross sections and thus the magnet becomes inefficient and control of fringing fields may be a problem.

Depending on the type of magnet, several conductor configurations are widely used:

1. Coils with hollow conductors: the coolant, generally low conductivity water which has low viscosity, high specific heat, and considerable specific mass, is pressurized through the conductor hole with speeds of (2 - 5) m sec^{-1}, resulting in Reynold's number of $\gg 2.4 \times 10^3$. Higher water speeds through the hydraulic passage have been tried with medium conductivity water leading to copper erosion due to cavitation.

   For a constant pressure drop across the hydraulic passage (maximum pressure given by the laboratory's main water supplies and pumping system) and a safe upper temperature limit (ΔT being constant), the maximum permissible current density in a conductor is proportional to:

$$j = C \, \frac{1}{\ell_h} \left[\frac{d_h^5}{\rho \cdot A_{cu}} \right]^{1/2} \tag{1}$$

   and the current intensity proportional to:

$$I = C \, \frac{1}{\ell_h} \left[\frac{d_h^5 \cdot A_{cu}}{\rho} \right]^{1/2} \tag{2}$$

   The significance of the hydraulic diameter d_h and the material resistivity ρ is obvious.

   Without difficulty a heat transfer coefficient of h = (2 - 4) W $cm^{-2}\,{}^{o}C^{-1}$ is achievable. If the water temperature increase is approximately 40^{o} C (conservative value) the heat dissipation value of (80 - 160) Wcm^{-2} would give an upper limit in designing coils with hollow conductors. The power dissipation per unit volume yields maximum value of current intensity through the conductor:

$$P = \frac{8}{6\pi^2} \frac{\rho I^2}{d_h^3} \leqq 160 \text{ W cm}^{-2} \qquad (3)$$

2. Edge-cooled coils: conductors wound in layers or pancakes are spaced such that at least one conductor surface is in direct contact with the coolant. Adjacent turns are insulated by means of a thin insulation strip or sheet. The length of each hydraulic passage can be short and thus a heat flux of ~500 W cm^{-2} can be reached. The copper surface in contact with the coolant has to be hard chrome-plated to eliminate corrosive action of the liquid.
3. Axial or radial cooled discs: high power density coils are composed of Bitter discs with axial or radial cooling channels. The copper discs are punched or machined to provide flow of water [8] and a heat flux density of ~1000 W cm^{-2} has been achieved.

In the first case, dimensional tolerances of the hydraulic diameter passage of 10^{-2} cm, cross sectional tolerances of better than 10^{-3} cm and absolute surface roughness of $\epsilon \leqq 5 \cdot 10^{-3}$ cm for the hydraulic passage are required.

In the second case, uniformity in cross sectional area, proper shaping of edges, uniform grain structure over the total length of the strips are necessary. Although soft or hard copper are frequently used, the magnets are more of the high field type, and high strength copper alloys are preferred.

In the third category, (ac and pulsed magnets), two conflicting requirements have to be satisfied. Low resistivity materials combined with high mechanical strength at elevated temperatures. A good compromise are copper alloys, such as Cr-Cu and Zr-Cu. At very high fields Be-Cu is used. Stress and cooling limitations for different copper alloys are illustrated in Fig. 9. Copper resistivity as a function of impurities, is shown in Fig. 10. Most harmful impurities in Copper are Phosphorous, Iron and Cobalt.

Mechanical properties, such as stress-strain curves for soft, half-hard and hard copper, and Zirconium Copper are given in Fig. 11. The stress-strain measurements were performed by compressing a stack of eleven discs of 0.7 mm thick copper discs (2.54 cm diameter) between hardened polished pistons.[9] The tests with Zr-Copper used seven discs of 1.15 mm.

Effect of temperature on mechanical properties of OFHC Copper is given in Fig. 12. The tensile strength as a function of temperature for Zr-Cu and Cr-Cu given in Fig. 13 is compared to tensile strength of hard OFHC Copper. Figure 14 gives resistivity values of OFHC, Cr-Cu and Zr-Cu as a function of temperature.

Aluminum

In cryogenic magnets, utilizing liquid hydrogen cooling, ultrapure Aluminum strips has been used successfully. Unfortunately, the Aluminum in high purity form is soft and not suitable for water-cooled magnets. It is expensive compared to wrought, electric-grade, commercially available Aluminum, which is used more often for experimental magnets utilizing water-cooled hollow conductors.

Commercially available pure Aluminum (99.6 + %) Al has a resistivity of 2.83×10^{-6} Ohm cm at 20°C. The typical impurity content for electric-grade, commercially available Aluminum is given in Table II.

Table II[10]

Chemical Composition of Wrought (99.6 + %) Al

Element	Al	Si	Fe	Cu	Mn	Mg	Zn	Ti	Be
% by weight	99.6 min	0.25	0.35	0.05	0.03	0.03	0.05	0.03	0.0008
		max							

Wrought (99.6 + %) Aluminum is available in a variety of forms and is used in low and medium field ranges, where stresses are not high. Table III illustrates its typical mechanical properties. Tensile strength of wrought (99.6 + %) Aluminum is illustrated in Fig. 15.

Table III[10]

Typical Mechanical Properties of Wrought (99.6 + %) Al

Temper	Tensile Strength (kg cm^{-2})	Yield Strength (kg cm^{-2})	Elongation %	Hardness Bhn	Shear Strength (kg cm^{-2})	Fatigue Limit* (kg cm^{-2})
O	714	185	43	17	500	214
H_{12}	857	785	16	23	570	285
H_{14}	1,000	928	12	26	640	357
H_{16}	1,142	1,070	8	30	714	464
H_{18}	1,357	1,285	6	35	785	464

*Based on 5×10^8 cycles.

Fatigue properties:

Although static mechanical properties provide a basis of comparison for the choice of conductor material, the determination of endurance limit is important in magnets where thermal fluctuation or pulsing fields are expected. The endurance curve in the vicinity of the endurance limit plotted on log-log coordinates has a slope γ. Based on ASTM measurements, Manson[11] has derived the relation:

$$\frac{\sigma}{\sigma_{end}} = \left(\frac{N}{N_{end}}\right)^{\gamma} \tag{3}$$

σ_{end} and N_{end} are values of endurance stress at the N_{end} cycle. It may be noted that γ is not constant and thus the extrapolation from ultimate tensile values to the endurance limit may yield wrong results. In case of pulsed magnets, where 10^8 - 10^{10} stress cycles may occur on coils, γ may be determined from two measurements in the vicinity of 10^8 - 10^9 cycles.

For wrought (99.6 + %) H_{12} - tempered Al, the following mean fatigue strengths are available at 20° C:

Cycles	10^5	10^6	10^7	10^8	5×10^8
Mean Fatigue (kg cm^{-2})	571	464	392	321	285

Ultimate tensile strength determined at 20°C (Table III) was 857 kg cm^{-2}. Calculating γ in the range $10^5 - 5 \times 10^8$ cycles gives a gamma value of -0.081. For ETP copper at 21°C the slope of the fatigue curve is not constant (Fig. 16). In the range of $10^5 - 10^7$ cycles $\gamma = -0.036$. Values of γ ranges in wrought (99.6+%) Al between -0.06 and -0.1 and for ETP copper between -0.03 and -0.08 at 20°C. Depending upon the data used, a wide range of gammas can be calculated. No attempt to report extrapolated values is made in this paper.

Physical properties:

Resistivity values are given in Table IV for several temperatures. The samples have not been subjected to transverse and longitudinal magnetic fields. The magneto-resistance curves of commercially available OFHC Copper and pure Aluminum conductors have been tested at 4.2°K and are illustrated in Fig. 17.

It may be pointed out that the effect of strain on the Aluminum conductor at cryogenic temperatures are severe, (Fig. 18), thus making it less useful than Copper for a number of applications in combination with high field superconductors of Type II.

Table IV

Tensile Strength and Resistivity of Copper, Copper Alloys and Al

Material	Ultimate Tensile Strength ($kg\ cm^{-2}$)			Resistivity $.10^{-6}$ ohm.cm		
	293°K	78°K	4.2°K	293°K	78°K	4.2°K
OFHC Copper Hard[a]	2070±35	3570		1.66	0.218	0.015
OFHC Copper Annealed[c]	2000	3360	3790	1.61	0.20	0.012
ETP Copper Hard	2285	3650		1.72	0.26	0.019
ETP Copper Annealed[c]	2050	3400	4100	1.69	0.24	0.015
Cr-Copper (0.7% Cr)[a, b]	4200+71	6290		2.1	0.618	
Zr-Copper (0.15% Zr)[a, b]	3860	5790		1.9	0.432	
Be-Copper (2% Be)[b]	8560	10200		6.5	3.65	
Be-Copper (0.55% Be)[b]	5720	7860	8720	3	1.29	
Al Pure (99.99%) (Commercial)	850			2.53	0.38	0.101
Al (99.6 + %) Wrought[d]	1355	2100	2550	2.8		

[a] Samples taken from 53.3 cm diameter, 3.81 thick discs.

[b] Samples annealed and then heat-treated.

[c] 2.5 cm Bar.

[d] Tempered H 18 (Table III).

The specific heat of OFHC Copper and (99.6 + %) Al as a function of temperature are given in Fig. 19 and the thermal conductivity in Fig. 20.

Irradiation:

A short note on irradiation properties of Copper and Aluminum conductors will conclude this section.

As with ferrous materials, the mechanical properties such as yield, tensile and shear strength are increased if irradiated at dose rates higher than 10^{18} n cm^{-2} (fast neutrons).

The yield strength of ETP Copper at 20^{o} C changed from 500 kg cm^{-2} (10^{18} n cm^{-2}) to 2210 kg cm^{-2} (10^{20} n cm^{-2}) and the ultimate tensile strength from 2285 kg cm^{-2} to 2785 kg cm^{-2}, indicating material embrittlement.

Irradiation in Copper and Aluminum resulting from fast neutron bombardment causes lattice imperfections. These imperfections cause residual disorder, especially if the irradiation temperature is low compared to the recovery temperature of the metals. This effect is manifested by an increasing resistivity in Copper, when irradiated.

Copper irradiated with 10^{19} n cm^{-2} showed an increase in resistivity of 20%, Aluminum about 33%.

Resistivity change is a sensitive indication for all changes in atomic structure. It can be pointed out that annealed Copper and Aluminum are less sensitive to radiation than hard materials. Irradiation effects at low temperatures are less permanent and they can be removed almost entirely by annealing.

The change in mechanical and physical properties has been associated with defect formation and subsequent defect mobility. The mobility of point defects, interstitials, and vacancies can be investigated by the change of properties, resulting from annealing at elevated temperatures. The mobility can lead to interaction of defects with each other and with other imperfections, migration of defects to surfaces and grain boundaries where they are absorbed.

Insulation

It has been stated that insulation in magnets is a necessary evil. It is not an active component of the magnet, but serves to protect the coils from electric breakdown and flashovers. In ac magnets, it insulates individual steel sheet laminates and in multi-stranded conductors, individual filaments, to control eddy current core and coil losses.

The insulation is also the most neurological part in the magnet. Unfortunately, the life expectancy of the magnet depends on the soundness of the insulation, its aging properties and its initial and final endurance limitations.

Several factors govern the choice and application of suitable insulations:

1. Availability and ease in manufacturing and applicability.
2. Initial and final endurance characteristics.
3. Mechanical, electrical and thermal characteristics.

We can distinguish between two major types of insulation, according to their functional application:

1. Insulation not in direct contact with coolants, such as conductor, layer and pancake insulation in hollow conductor-type coils.
2. Insulations in direct contact with coolants in coils with high thermal flux, such as in high field magnets (heat flux $\gg 4$ W $cm^{-2 o}C^{-1}$), and in pulsed magnets where short coolant passages and direct contact between the high thermally stressed conductor and the coolant is essential.

Several factors influence the performance of insulations:

1. Magnetic and thermal stresses (continuous or cyclic).
2. Cooling media.
3. Environmental influences (water vapor, corrosive and ionizing gases, irradiation effects).
4. Dielectric stresses.

Magnetic stresses in insulations are compressive, flexural and shear. Thermal stresses occur due to the inherent coil design. In dc magnets the temperature gradient along a hydraulic passage is constant during the magnet operation, but may change sporadically when the energizing current is turned on and off. In ac and pulse magnets the thermal stresses are cyclic, corresponding to the current frequency.

Cooling media for most magnets is low conductivity water. In a few cases special oils, kerosene, alcohol and cryogenic liquids are used. If the conductor's outer surface is in contact with the coolant (edge cooling) the interturn insulation is also in contact with the coolant and will absorb moisture, which reduces the insulation properties.[12]

Environmental influences such as the presence of water vapor at the cool parts of the coils (areas of water entrance) has a damaging effect on insulation due to the fact that water vapor penetrates the insulation structure more readily than water.

The effect of nuclear irradiation on insulation has been investigated extensively the last two years.[12,13,14] In addition to the radioactive isotopes (e.g., Tritium), chemical reactions and formation of H_2, O_2 and ionization of air with consequent formation of NO_2 and O_3, has a damaging effect on insulations. The difficult problem which must be met in the design of magnet coils is the pattern of beam loss through a system; e.g., through a number of transport magnets. Where the high power beam is deliberately absorbed by means of collimators or slits, intense activation will exist. The slit penetration, scattering or energy spectrum tails may produce activation in other locations of the system such as in magnet coils, not sufficiently shielded by the surrounding iron blocks.

Damaging problems are severe in special typesof accelerators, such as in "Meson Factories" as they produce localized sources of fast neutrons. Electron machines produce ionizing radiation fields; proton machines produce intense fast neutrons, but their shower density is less damaging due to their relatively large volume.[15]

Insulation Structure:

Modern coil insulation is comprised of an inorganic structural material, an organic impregnant, organic and inorganic additives. The inorganic structural material is an E-type glass cloth, or unidirectional S-glass structures, or tapes, heat cleaned and chemically treated in order to improve the adhesion of the thermosetting to the filament. The organic impregnant or binder is generally an epoxy system, either of the type Diglycidyl Ether of Bisphenal A or Epoxy Novolac. In mechanically high stressed insulations, where temperatures may exceed 300° C glass fiber impregnated Polyimids have yielded good results.

Catalysts are preferably either aromatic amine types or anhydrides. Additives used are reactive diluents such as wetting agents, which lower viscosity, improve fluidity during casting and impregnation, improve handling characteristics and most of all, improve wetting capability to accept inorganic fillers and improve the adhesion to the structural material.

Diluents for flexibilizing purposes decrease heat deflection temperature and hardness, and raise the coefficient of thermal expansion, thus creating additional tension due to relative shrinkage between the impregnant and the conductor and structural material. Due to these adverse effects they are not particularly recommended.

Fillers improve irradiation properties, reduce thermal expansion coefficients (making the impregnant more compatible to the conductor and reduce internal stresses), increase thermal conductivity, lengthen pot life and improve the heat distortion temperature. Their adverse effects are reduction of flexural and shear strength, and increase in water absorption of the composite insulation. The correct balance between the various components will result in an optimum insulation used for high energy magnet coils.

With respect to the above mentioned influences, the optimum insulation structure should comprise the following composition:

	Irradiation Environment			Nonirradiation Environment		
	Max.	Min.		Max.	Min.	
Inorganic Materials	30	50	p.b.w.	50	60	p.b.w.
Organic Materials	70	50	p.b.w.	50	40	p.b.w.

The best results had been achieved in vacuum impregnating dry glass fiber insulations with, or without mica fleece with either pure epoxies (no irradiation environment) or epoxy filled with granulous inorganic fillers (Alumina, Silica) with grain sizes of approximately 10 microns.

The epoxy systems most recommended and tested with and without fillers are the following:

		Parts by Weight
1. CERN:	Epoxy EPN 1138	100
	Catalyst HY 905 (anhydride)	105
	or HT 976 (aromatic amine)	40
	and DY 062	0.5
2. Rutherford:	Epoxy X 33/1020	100
	Catalyst MNA	110
	and BDMA	15
3. SLAC:	Epoxy Araldite F (6005)	100
	Catalyst NMA (anhydride)	80 - 100
	and DY 062	1.5
	Wetting Agent Z6040, (Epoxy-functional material)	1 - 2

The addition of inorganic fillers to epoxies in large scale for magnet insulation was utilized by SLAC[16] and since then all beam switchyard and accelerator magnets have been impregnated with Alumina-filled thermosettings, where the amount of filler varied between 120 p.b.w. of epoxy at the early stage to 200 p.b.w. at the last stage of procurement.

Other types of insulation used frequently are summarized: B-stage or semi-cured tapes, resin rich glass tapes, wrapped around dry and cleaned conductors, or pancakes, etc., are subjected to heat and mechanical pressure. Evacuating the coils prior to final compression will remove part of the trapped air. Heated, the resin starts to flow, filling voids. B-stage tapes with Alumina fillers are also available commercially.

Dry glass cloth, impregnated with Phenolic resin, epoxies or polyimids are used in high field coils composed of Bitter discs.[17] Stainless steel discs or strips coated with suitable high temperature thermosettings, where the stainless steel insulation discs act as coil reinforcement if subjected to compressive forces have been utilized.

Physical and Mechanical Properties:

The coil insulation, being subjected continuously or intermittently to magneto-mechanical forces is also subjected to dielectric stresses (high voltage coils) and thermal influence.

The heat affects the insulation in the following way:

1. Due to the existance of a thermal gradient, internal strains are created which lead to structure defect and insulation rupture.
2. Heat changes mechanical properties of all organic thermosetting. The Young's modulus of elasticity is charged about one order of magnitude from 10^5 kg cm^{-2} to 10^4 kg cm^{-2} if the temperature changes from 20^{o}C to 150^{o}C. The flexural, shear and tensile

strength are reduced considerably, if Martin's temperature is exceeded.

3. Aging affects are accelerated in presence of temperature leading to an early breakdown of insulation.

Aging of thermosetting impregnated insulation depends on the temperature to which it is exposed and themechanical stress during this exposure time. The insulation deterioration can be approximated by a first-order chemical reaction. The deterioration rate can be expressed as:

$$D_r = C_1 \cdot e^{-C_2/T} \tag{4}$$

The insulation lifetime and the insulation deterioration are related by:

$$t_L \cdot D_r = C_3 \cdot e^{C_2/T} \tag{5}$$

or

$$\ln (t_L \cdot D_r) = C_4 + C_2/T \tag{6}$$

The constant C_1, C_2 and C_4 can be obtained from experimental results and the gas constant at the temperature T ($^{\circ}$K). Insulation aging is plotted as a function of time in Fig. 21 for a number of epoxy systems and polyesters. At temperatures $T \geq 293^{\circ}$K, Montsinger's[18] conclusions for insulation immersed in oil are valid quantitatively for thermosets. In the temperature range $T \cong 120 - 273^{\circ}$K due to severe material embrittlement the insulation aging is increased markedly. Unfortunately, no conclusive data were available in the temperature range $T = 20^{\circ}$K down to $T = 4.3^{\circ}$K. Only few epoxy systems loaded with fillers (120 - 200 p.b.w.) used at cryogenic temperatures and subjected to magneto-mechanical stresses in the order of 0.7 kg cm^{-2} shear stress have failed after ~ 200 hours of continuous operation. Some data available on fatigue properties of insulation materials at 20°K are given in Fig. 22.

Loss in mechanical strength when the thermoset is continuously stressed, is due to internal stresses in the molecular structure of thermosettings and due to different expansion coefficients between glass fiber and thermoset or between insulation and metallic parts.

After reaching the lowest value in mechanical strength (endurance limit) observations had shown no further decrease in mechanical properties at constant temperatures. In temperature ranges of 150°C or higher modern thermosettings exhibit plastic deformations as well as pure elastic deformation. Explanation of the behavior of thermosets within the elastic-plastic limits is complicated. In addition to the above, a retardant elastic expansion (elastic flow) is observed (contrary to metals), which disappears when the load is reduced to the elastic endurance limit.

The retarded elastic expansion is relatively easy to measure in thermoset samples, but difficult if the thermoset is bonded to metals.

The elongation of thermosettings appear to consist of three components:

1. Immediate elastic deformation (ϵ_1) (Time independent).
2. Elongation due to viscose flow (ϵ_2), according to the relation:

$$\epsilon_2 = C_5 \cdot \sigma \cdot t_r \tag{7}$$

3. Elongation due to elastic flow (ϵ_3):

$$\epsilon_3 = \sum_{i=1}^{n} \epsilon_{3i} \left(1 - e^{-\gamma_i t_r}\right) \tag{8}$$

with the relaxation time:

$$t_r = C_6 \cdot e^{-C_7/T} \tag{9}$$

ϵ_2 and ϵ_3 are stress and temperature dependence.

To measure the three elongations, the stress on probes is reduced. The elastic elongation occurs simultaneously with the load reduction. Relaxation time for several thermosets may vary between minutes and days. In structures where thermosettings are used for adhesions or insulation purposes in combination with core sheets, or conductors, the relaxation time can be fractions of seconds.

Most organic insulations suffer in presence of water and water vapor.[12] Glass reinforced thermosets have an affinity towards water absorption. Presence of moisture leads to surface erosion until glass filaments are exposed. Due to the glass capillarity affect, moisture penetrates along individual fibers and generates a condensation ring around the fiber, which if the insulation is subjected to heat, evaporates and cracks the confining thermoset. When large areas of insulation surface are wetted, electric flashover over moist and contaminated surfaces are inevitable, which burns deep furrows through insulation structures.

Presence of voids, insulation deficiencies and cracks lead to corona effects in high voltage coils. Organic materials are generally not corona resistant and are carbonized. Mica and glass fibers are corona resistant and would give some protection against dielectric breakdown, but the water absorption is accelerated until the spongy insulation has no mechanical and dielectric strength.

Radiation:

Radiation effects on insulations have been dealt with extensively, but due to complexity of the problems, much more work is still required. Irradiation effects organic materials, where covalent bonds are broken by ionization and displacement of atoms in the lattice structure.

Primary observations indicate the following influences:

1. Permanent changes - in appearance--color effects, ($< 10^7$ rads).
2. Chemical changes - double bond formation, cross linking, oxidative degradation, polymerization and depolymerization, gas evolution, ($10^7 - 5 \times 10^9$ rads).
3. Mechanical changes - hardness, elongation, tensile and flexural strength, elastic modulus, flexibility, embrittleness, ($10^5 - 10^{12}$ rads).
4. Physical changes - conductivity, dielectric strength, heat distortion, water absorption, ($10^5 - 10^{12}$ rads).

Several reactions may occur simultaneously. The initial effect is a curing process which improves tensile, flexural and shear stress by cross linking. The end result is always a thermoset so highly cross linked, as to be fragile and crush sensitive. It becomes brittle and disintegrates into a black, powdery substance.

Irradiation makes the thermoset susceptible to oxidation and moisture absorption.

Recommended Thermosetting Structures:

Epoxies have been preferred by most magnet designers due to their excellent mechanical properties and ease in applicability. Two types of epoxies have been recommended:

1. Diglycidial Ether of Bisphenol A.
   Epoxies recommended in this class were: EPN 1138, X 33/1020, Araldite 6005 and DER 332 LC.
2. Epoxy Novolacs.
   Recommended type: Epicote 828 and Epicote 154.

Two types of hardeners are recommended:

1. Aromatic Amines.
   Recommended: HT 972, HT 976, HY 905.
2. Anhydrides.
   Recommended: NMA (906), DDm.

Recommended diluents are:

Epoxy functional material Z6040.

Recommended fillers:

Alumina, Silica, Micafleece.

Recommended glass cloth:

Medium or open weave E-glass cloth, heat cleaned and chemically treated (Volan A; Silan).
For superior mechanical properties of the dry glass cloth, a pre-impregnation with (90% Acetone, 10% Epoxy, no hardener) is recommended. Unidirectional S-glass tapes in prepreg form are commercially available and can be utilized.

Radiation Test Procedures:

Three types of irradiation tests have been reported:

1. Tests using linear, electron and proton accelerators.[12] Prepared samples can be directly bombarded with electrons or gammas. The ionization and thermal effects can be separated readily and the maximum temperature rise controlled in samples.
2. Tests using reactors: pool-type reactors using enriched uranium.[14] It is not clear how the sample temperature is controlled. However, if the bombarding is mainly performed by thermal neutrons, the thermal effect on the insulation may severely impair mechanical properties and may lead to erroneous conclusions.
3. Tests using fuel element facilities: particles may be mainly gammas.[13] Temperature effect seems to be less dangerous.

Conclusions

Test methods in ferrous materials to evaluate mechanical, physical and thermal properties are specified by ASTM. Data on fatigue properties in the range of 10^7 - 10^{10} cps are still not available and a lack of information is apparent. Also, little information is available on how to specify and test for voids, gas bubbles, cracks, their size and distribution, micro and macroporosity, in ferromagnetic castings and forgings.

Ultrasonics give a rough indication of the void location and X-ray pictures of large slabs are costly. Much data is needed to evaluate quantitatively magnetic characteristics as a function of interstitial impurities, fatigue and proper heat treatment.

In nonferrous current conducting metals, several areas lack systematic knowledge. Most of all investigation of continuous cast copper alloys, which may be used in water-cooled magnets, elimination of microporosity, surface contamination, and control of impurities, is required. Effect of alloying metals on electrical and mechanical properties in the temperature range of 4.2^{o}K to $1,000^{o}$K need investigation. Effect of segregation at cryogenic temperatures also needs further study.

Also, required, are data on long-term steady state and pulsed behavior of insulation materials. Some work has been done to investigate mechanical properties of thermosets under environmental influences, but quantitative data on fatigue properties, endurance limit and lifetime studies of composite structures are required. Much work is necessary to evaluate irradiation effects in the range of 10^{11} - 10^{13} rads, or higher, and perform studies on the effect of fillers, investigate combined influences of radiation, water absorption, contaminating gases and temperature.

It is well understood that the above work is of gigantic proportions and cannot be attacked by laboratories building and using electromagnets alone, but facing the facts that requirements on magnets and their insulation is steadily increasing and thus we may encounter situations where profound material knowledge in designing large future accelerator magnets, may be a necessity.

Acknowledgement

It is a pleasure to acknowledge the valuable information on ferrous and nonferrous materials provided by Mr. J. Fritzke of SLAC, and the many helpful discussions with him, during the preparation of this paper.

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LIST OF FIGURES

21. Thermal lifetime of thermosets as a function of temperature (AIEE No. 57).
22. Fatigue curves of thermosets at room and cryogenic temperatures.
    1. 20^{o}K
    2. 293^{o}K

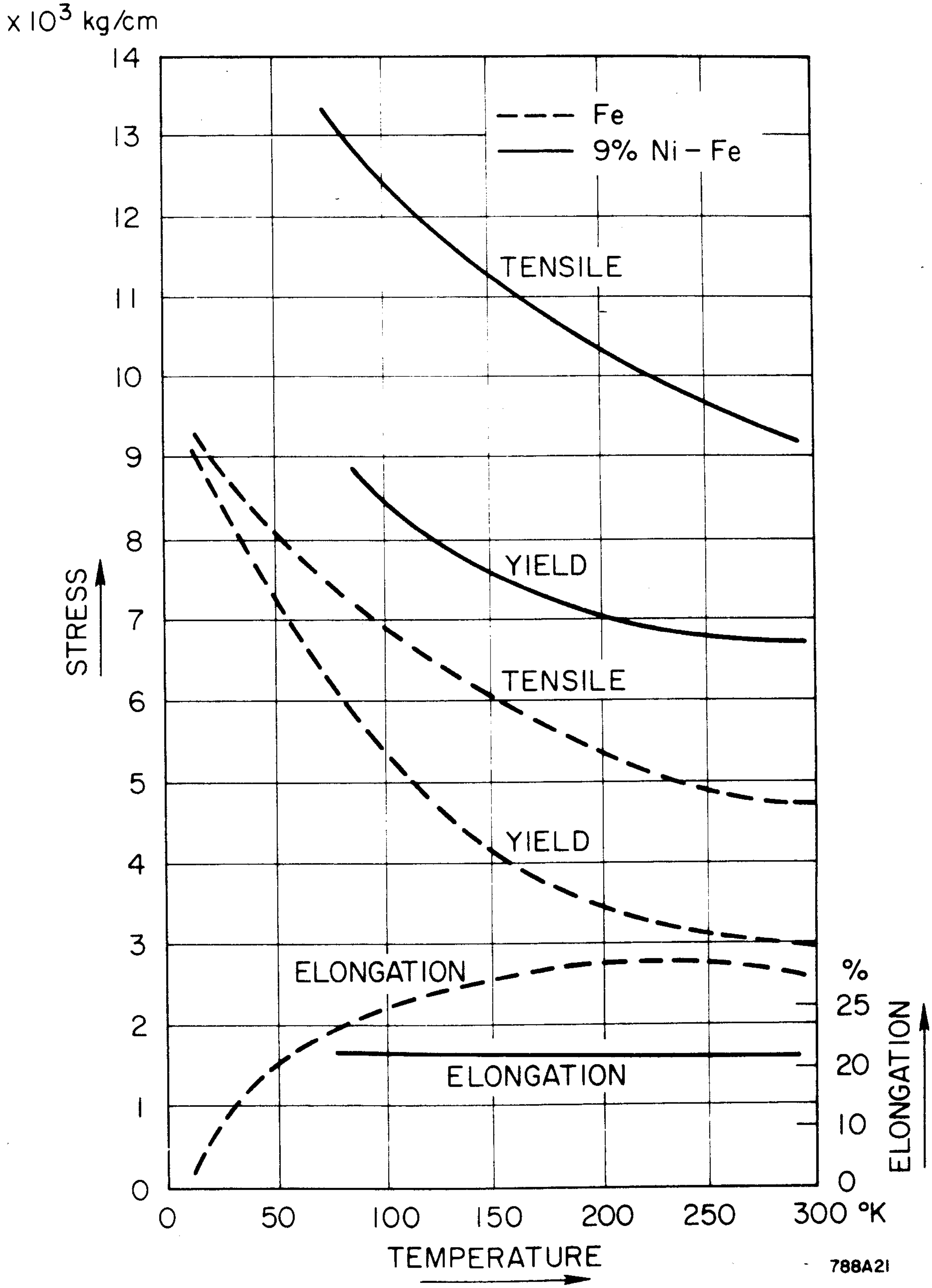

x 10³ kg/cm
Fe
9% Ni - Fe
TENSILE
YIELD
TENSILE
YIELD
ELONGATION
ELONGATION
STRESS
%
ELONGATION
TEMPERATURE
300 °K
788A21

FIG. 1a

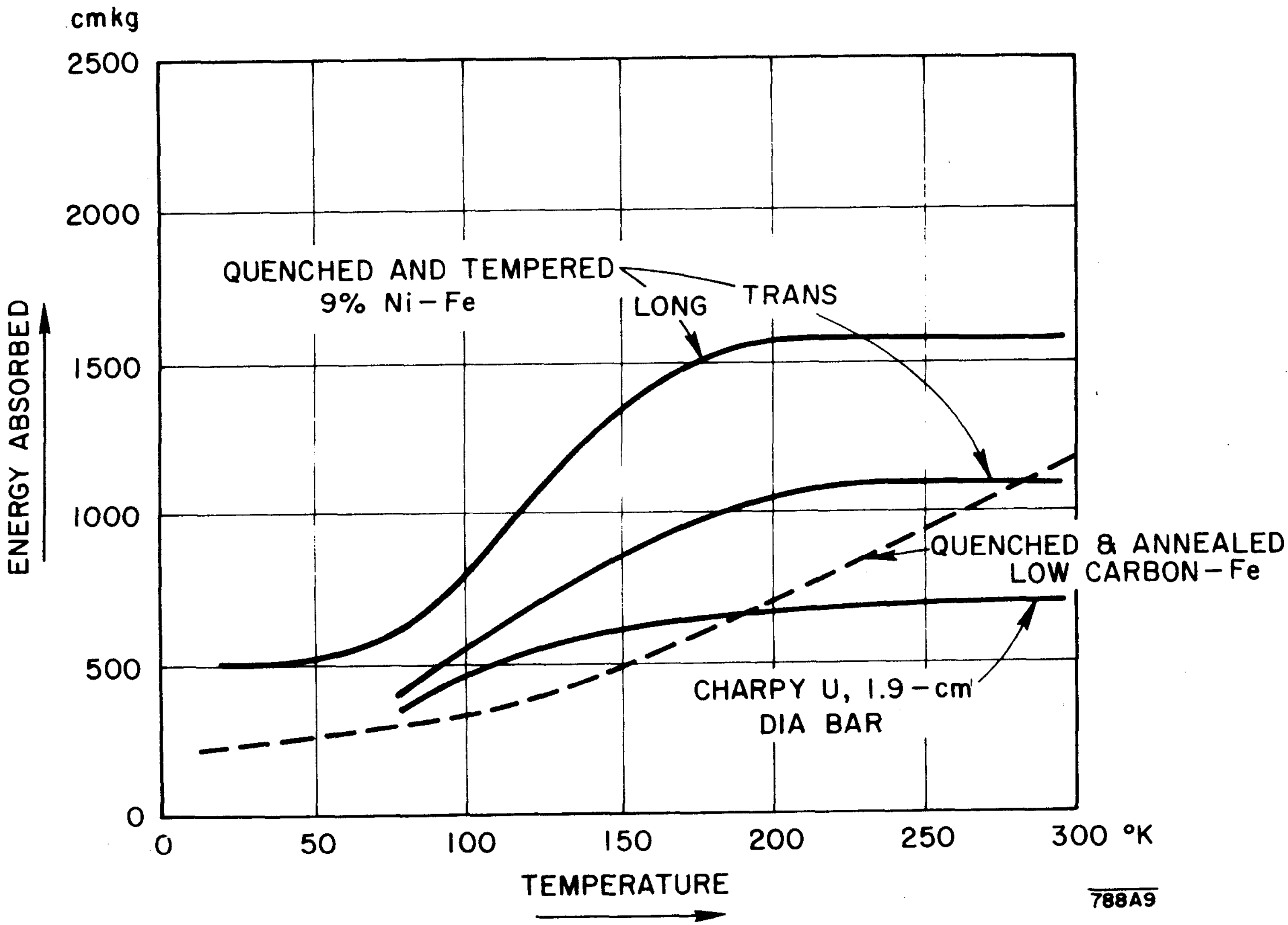
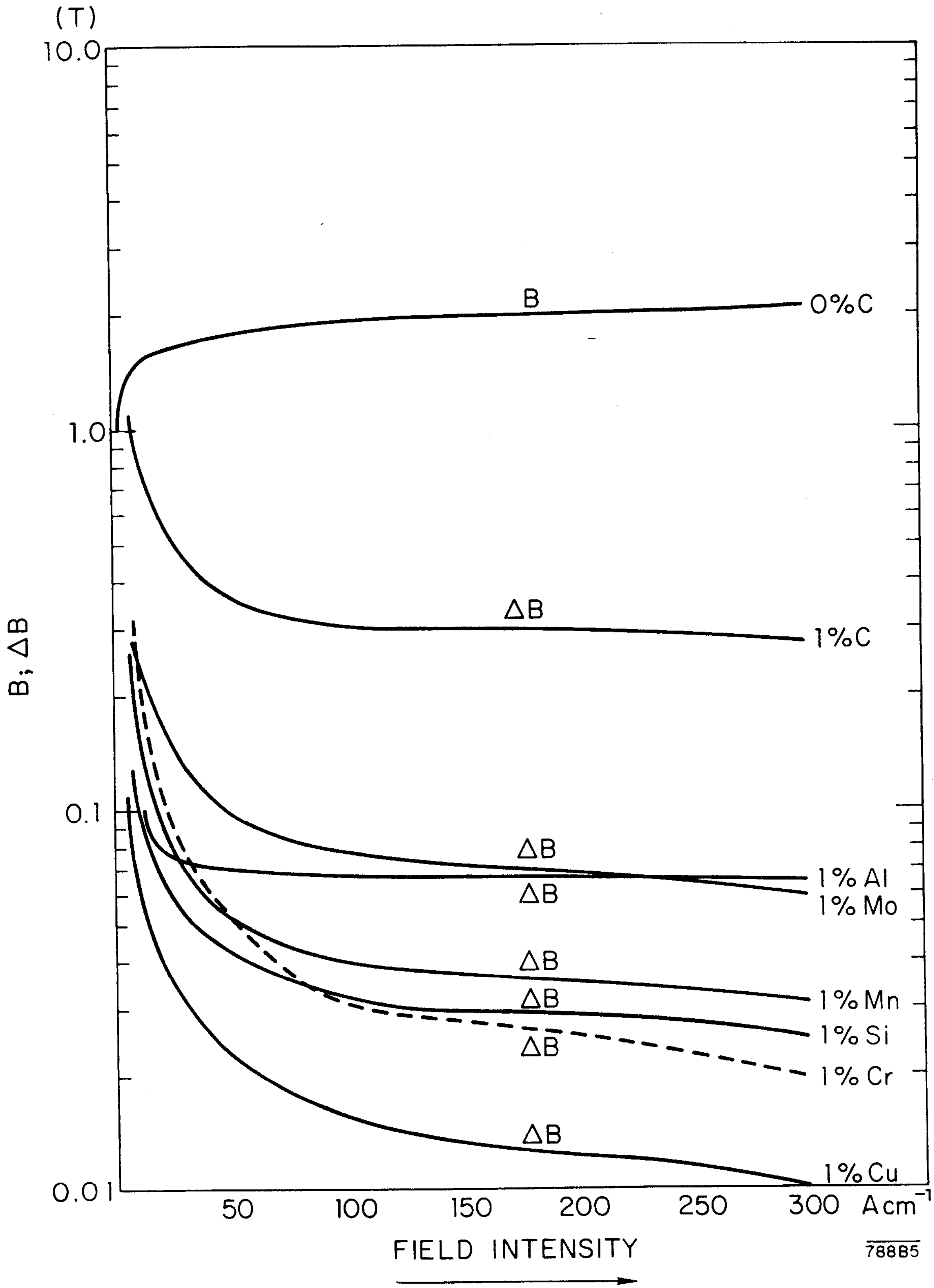
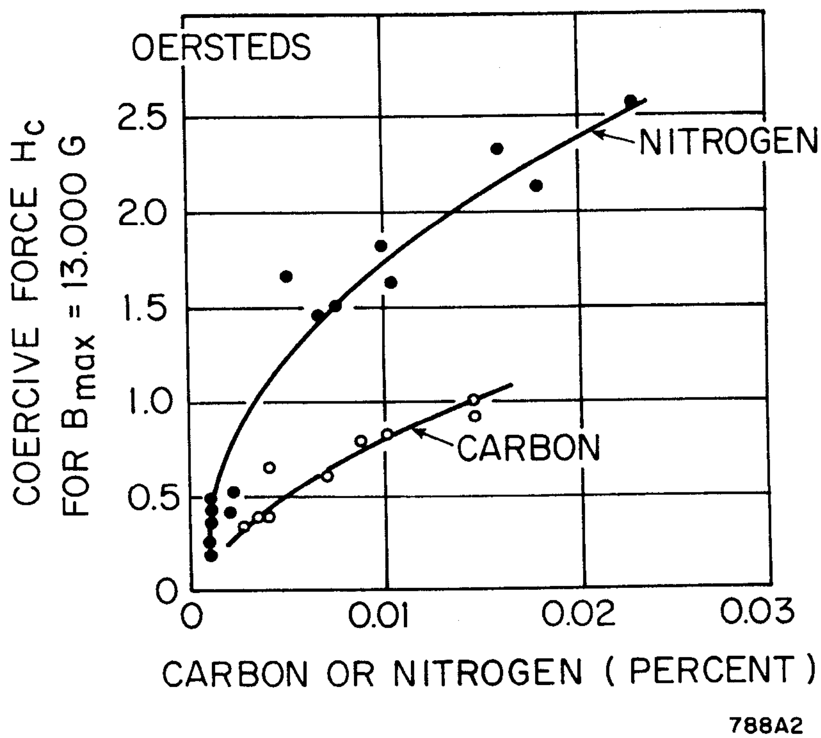

cmkg
2500
2000
1500
1000
500
0
ENERGY ABSORBED
QUENCHED AND TEMPERED
9% Ni-Fe
LONG
TRANS
QUENCHED & ANNEALED
LOW CARBON-Fe
CHARPY U, 1.9-cm
DIA BAR
0
50
100
150
200
250
300 °K
TEMPERATURE
788A9

FIG. 1b



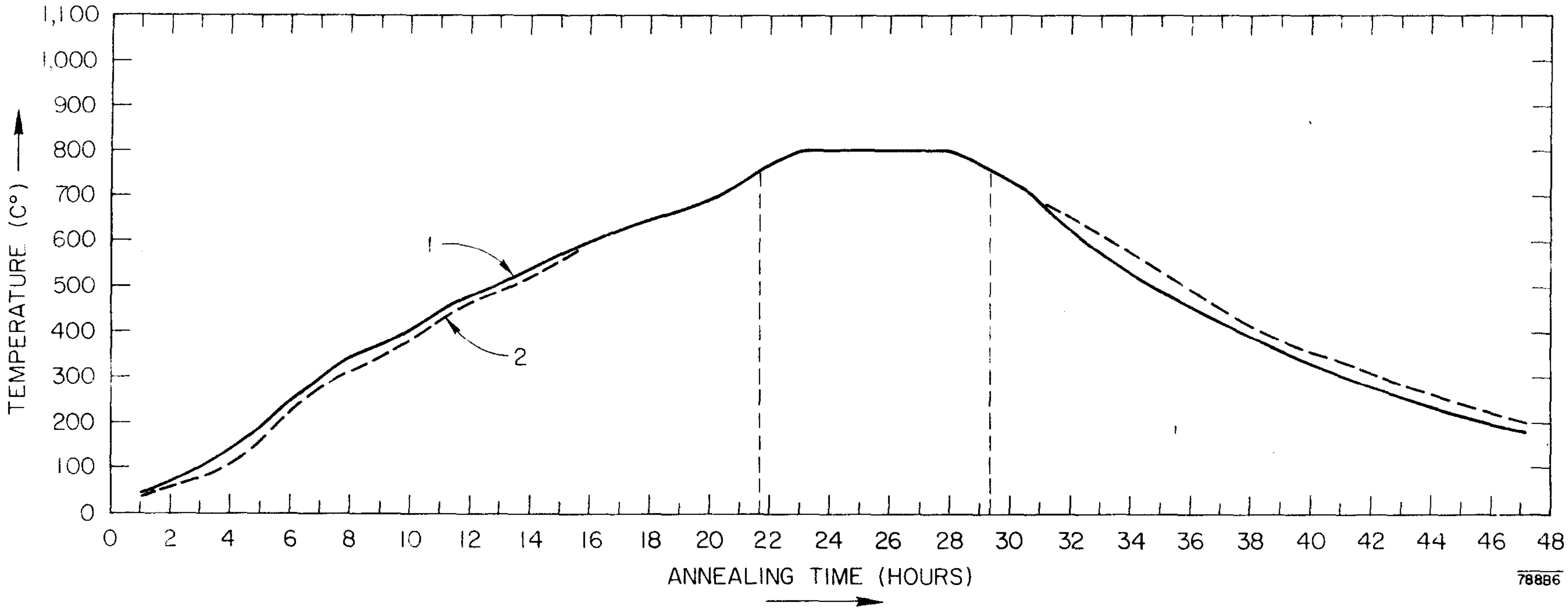
(T)
10.0
1.0
0.1
0.01
B; ΔB
B
0%C
ΔB
1%C
ΔB
1% Al
ΔB
1% Mo
ΔB
1% Mn
ΔB
1% Si
ΔB
1% Cr
ΔB
1% Cu
50
100
150
200
250
300
Acm⁻¹
FIELD INTENSITY
788B5

FIG. 2



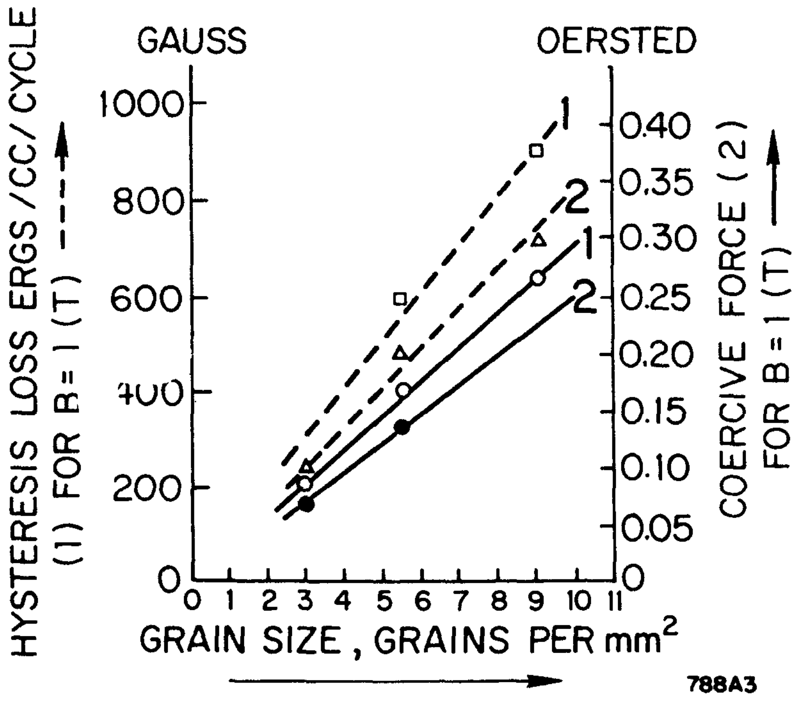
OERSTEDS
COERCIVE FORCE Hc
FOR B max = 13.000 G
2.5
2.0
1.5
1.0
0.5
0
0
0.01
0.02
0.03
NITROGEN
CARBON
CARBON OR NITROGEN (PERCENT)
788A2

FIG. 3



1,100
1,000
900
800
700
600
500
400
300
200
100
0
TEMPERATURE (C°)
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48
ANNEALING TIME (HOURS)
1
2
78886

FIG. 4



HYSTERESIS LOSS ERGS /CC/ CYCLE
(1) FOR B = 1 (T)
GAUSS
OERSTED
1000
800
600
400
200
0
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
1
2
1
2
0 1 2 3 4 5 6 7 8 9 10 11
GRAIN SIZE, GRAINS PER mm²
COERCIVE FORCE (2)
FOR B = 1 (T)
788A3

FIG. 5

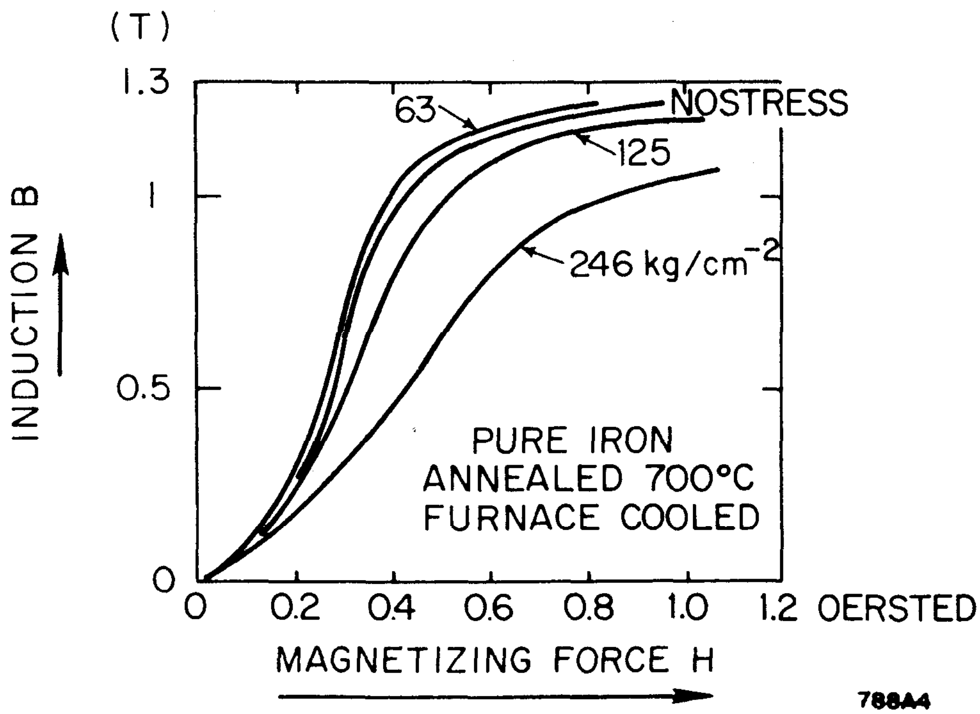
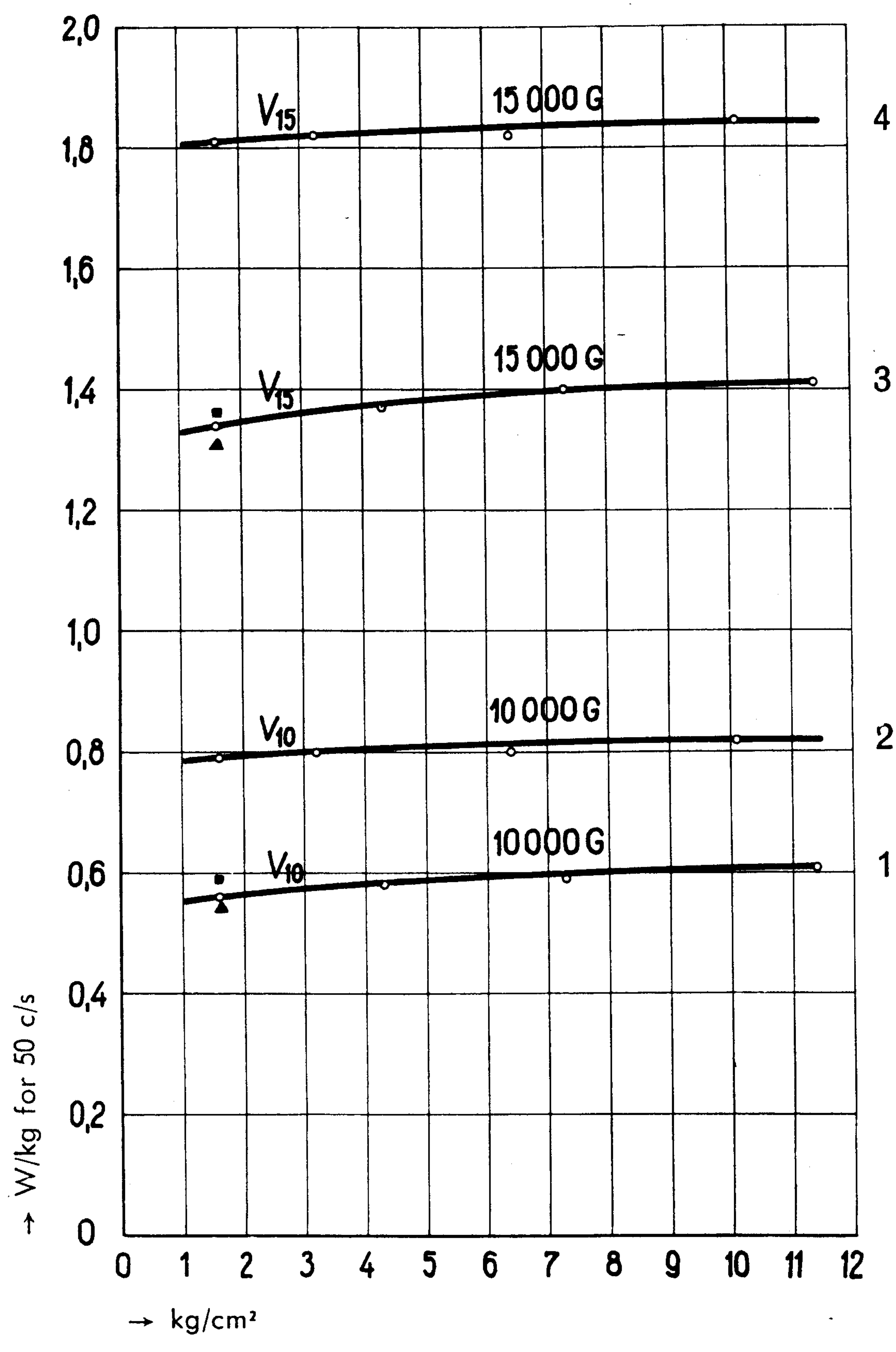
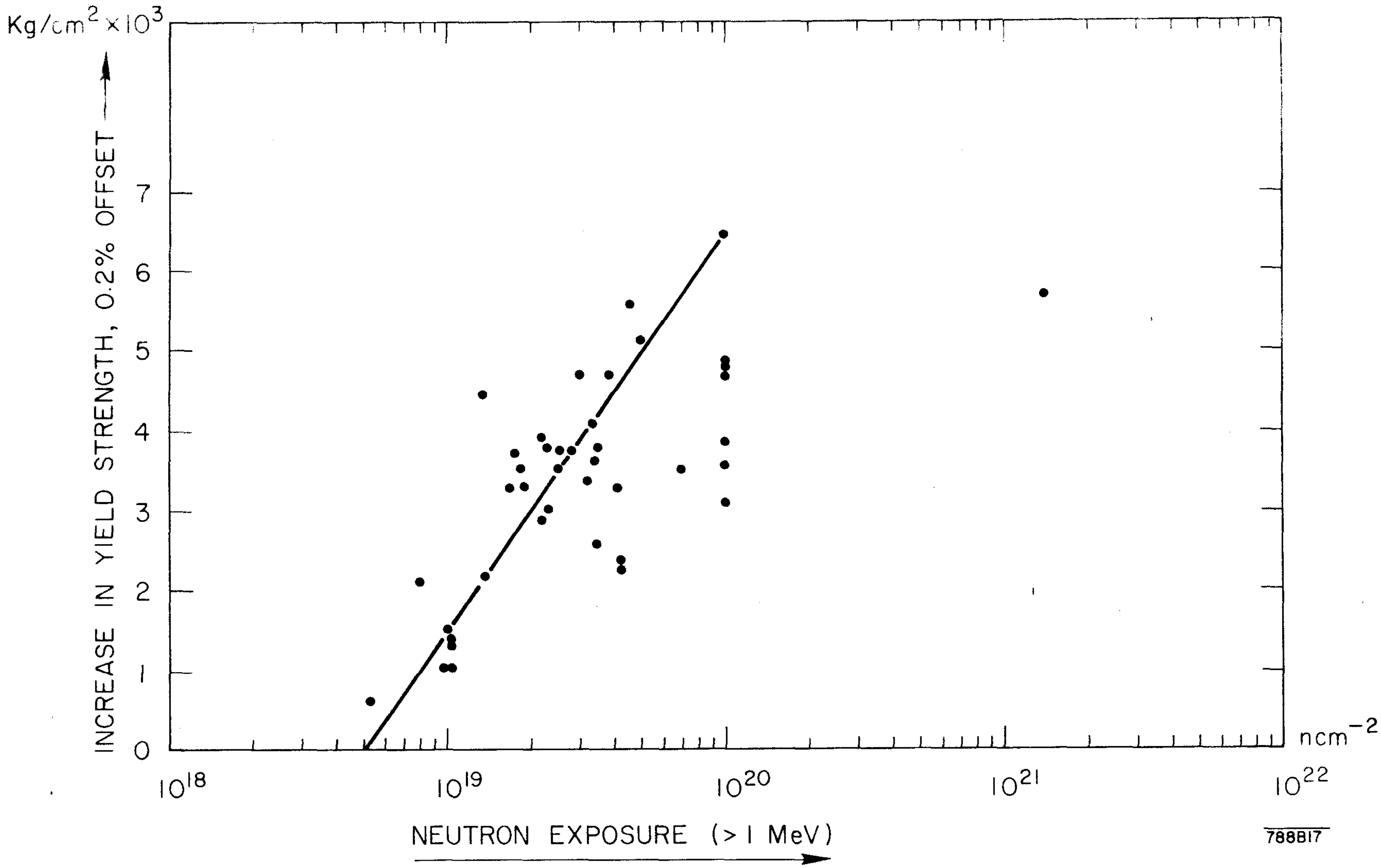

(T)
1.3
1
0.5
0
INDUCTION B
63
NOSTRESS
125
246 kg/cm^{-2}
PURE IRON
ANNEALED 700°C
FURNACE COOLED
0 0.2 0.4 0.6 0.8 1.0 1.2 OERSTED
MAGNETIZING FORCE H
788A4

FIG. 6



2,0
1,8
1,6
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0
0 1 2 3 4 5 6 7 8 9 10 11 12
→ W/kg for 50 c/s
→ kg/cm²
V15
15 000 G
4
V15
15 000 G
3
V10
10 000 G
2
V10
10 000 G
1

FIG. 7



Kg/cm^2 × 10^3
INCREASE IN YIELD STRENGTH, 0.2% OFFSET
0
1
2
3
4
5
6
7
10^{18}
10^{19}
10^{20}
10^{21}
10^{22}
ncm^{-2}
NEUTRON EXPOSURE (> 1 MeV)
788817

FIG. 8

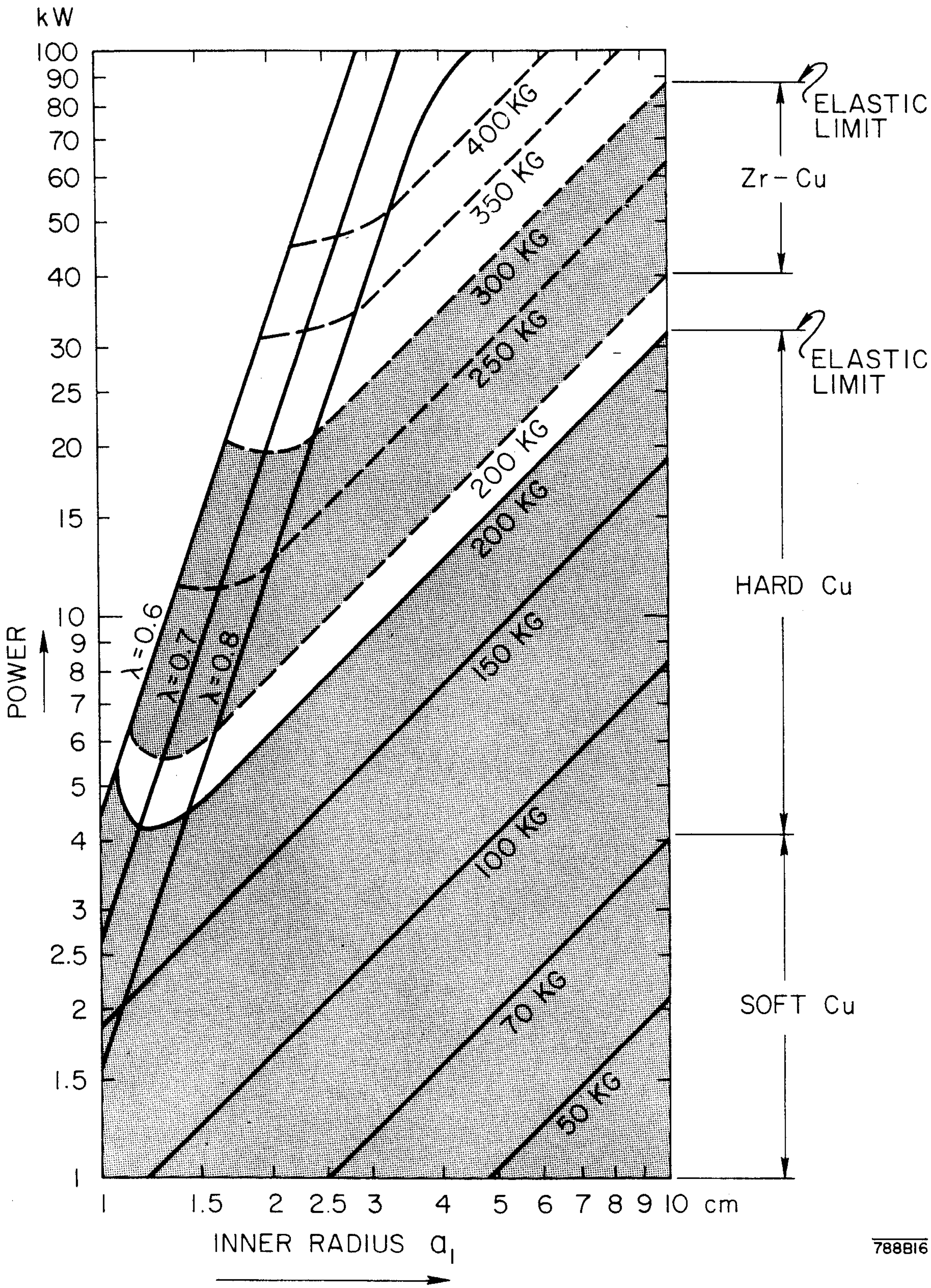
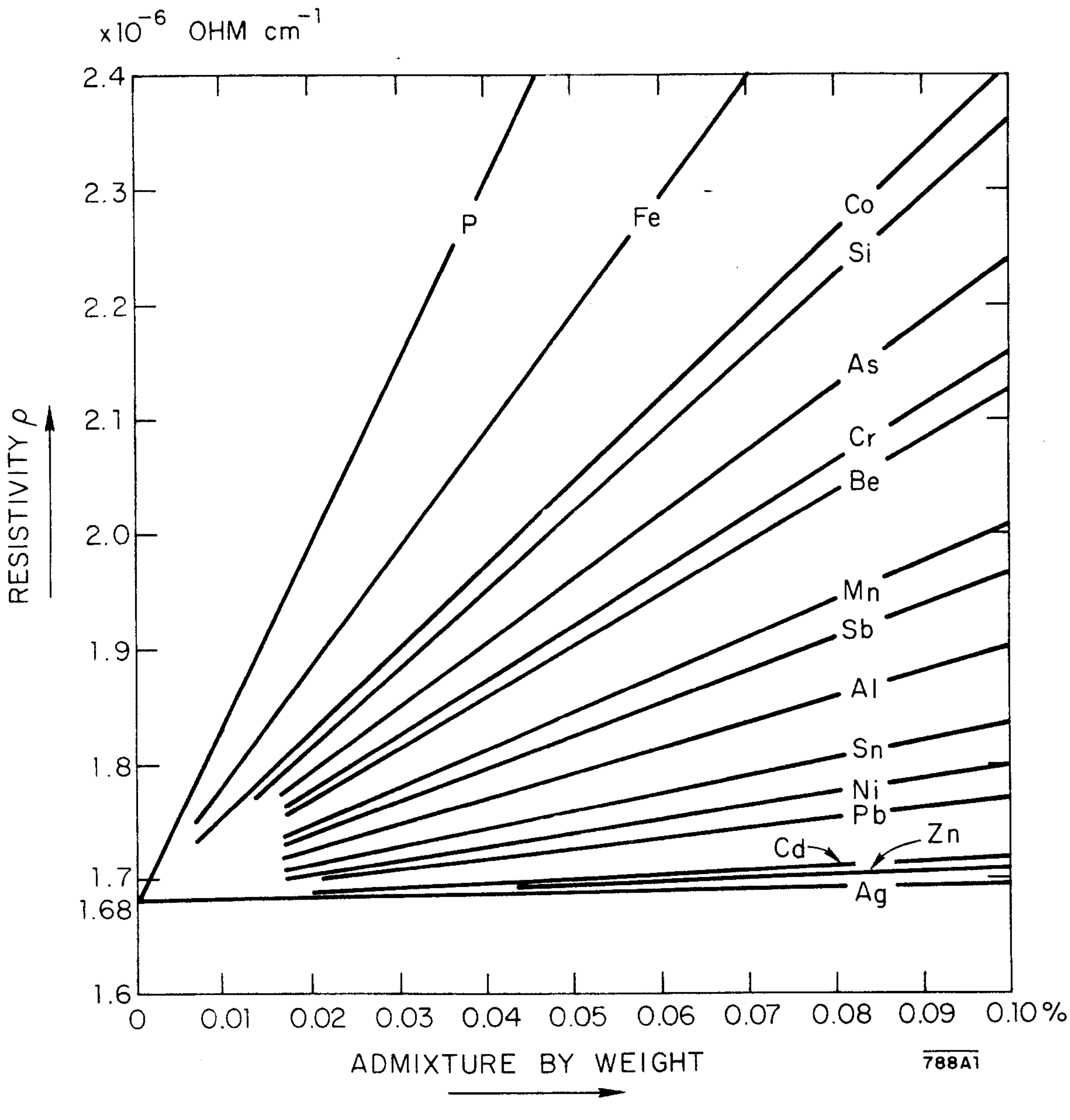

kW
100
90
80
70
60
50
40
30
25
20
15
10
9
8
7
6
5
4
3
2.5
2
1.5
1
POWER
400 KG
350 KG
300 KG
250 KG
200 KG
200 KG
150 KG
100 KG
70 KG
50 KG
λ=0.6
λ=0.7
λ=0.8
ELASTIC LIMIT
Zr – Cu
ELASTIC LIMIT
HARD Cu
SOFT Cu
1
1.5
2
2.5
3
4
5
6
7
8
9
10 cm
INNER RADIUS a_1
788B16

FIG. 9



x10^{-6} OHM cm^{-1}
RESISTIVITY ρ
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.68
1.6
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10%
ADMIXTURE BY WEIGHT
P
Fe
Co
Si
As
Cr
Be
Mn
Sb
Al
Sn
Ni
Pb
Cd
Zn
Ag
788A1

FIG. 10

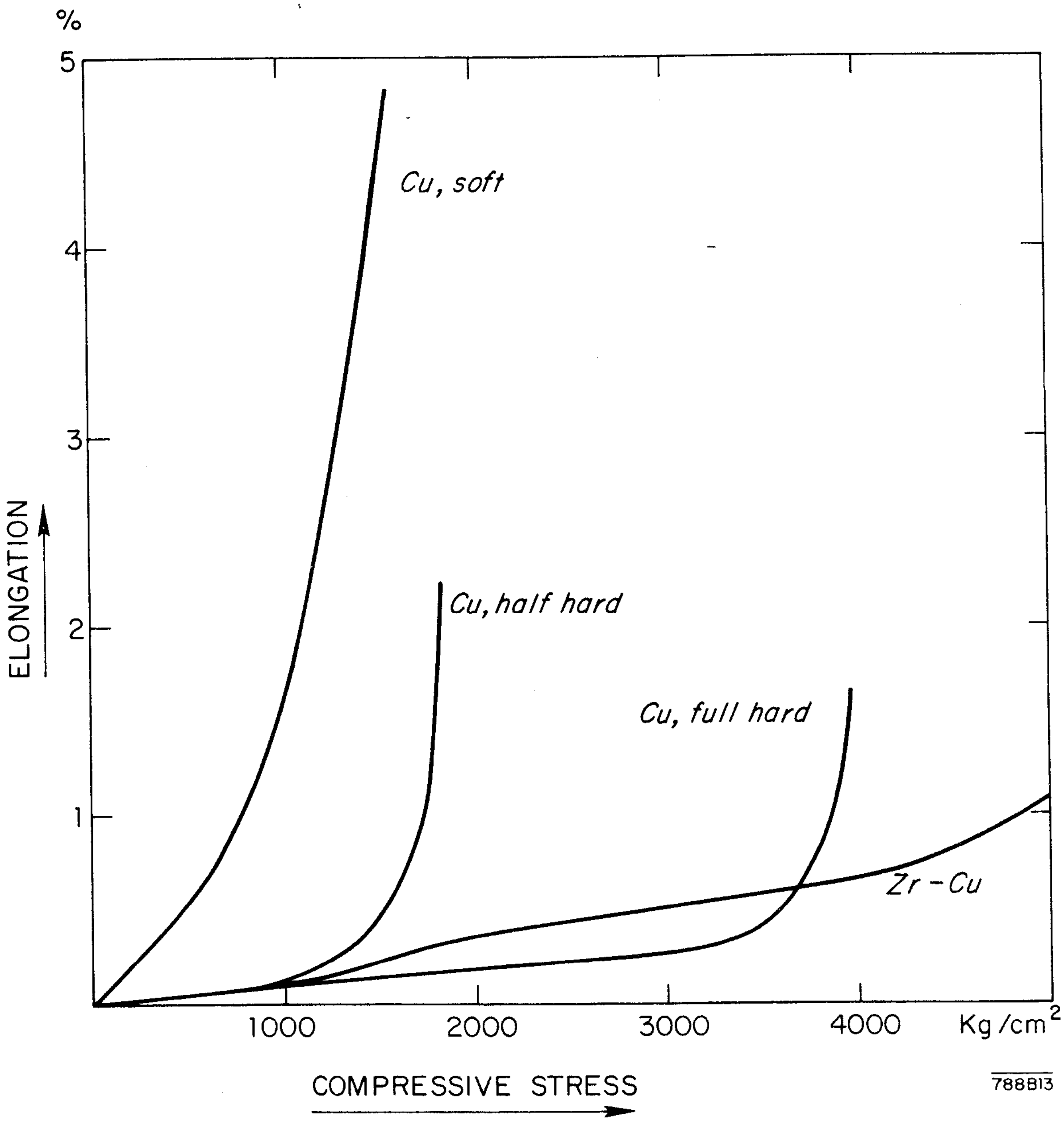

%
5
4
3
2
1
ELONGATION
Cu, soft
Cu, half hard
Cu, full hard
Zr - Cu
1000
2000
3000
4000
Kg /cm^2
COMPRESSIVE STRESS
788B13

FIG. 11

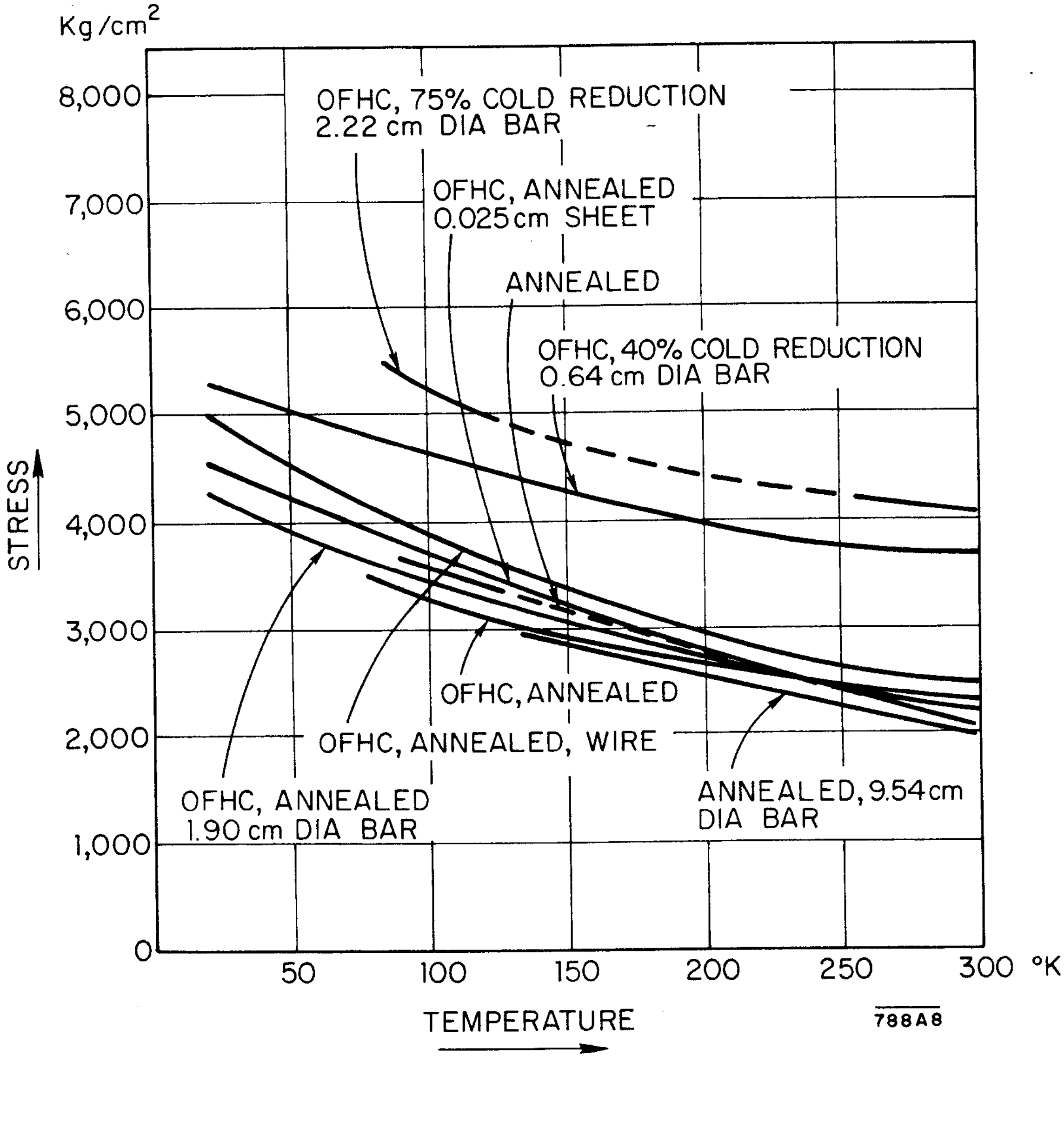
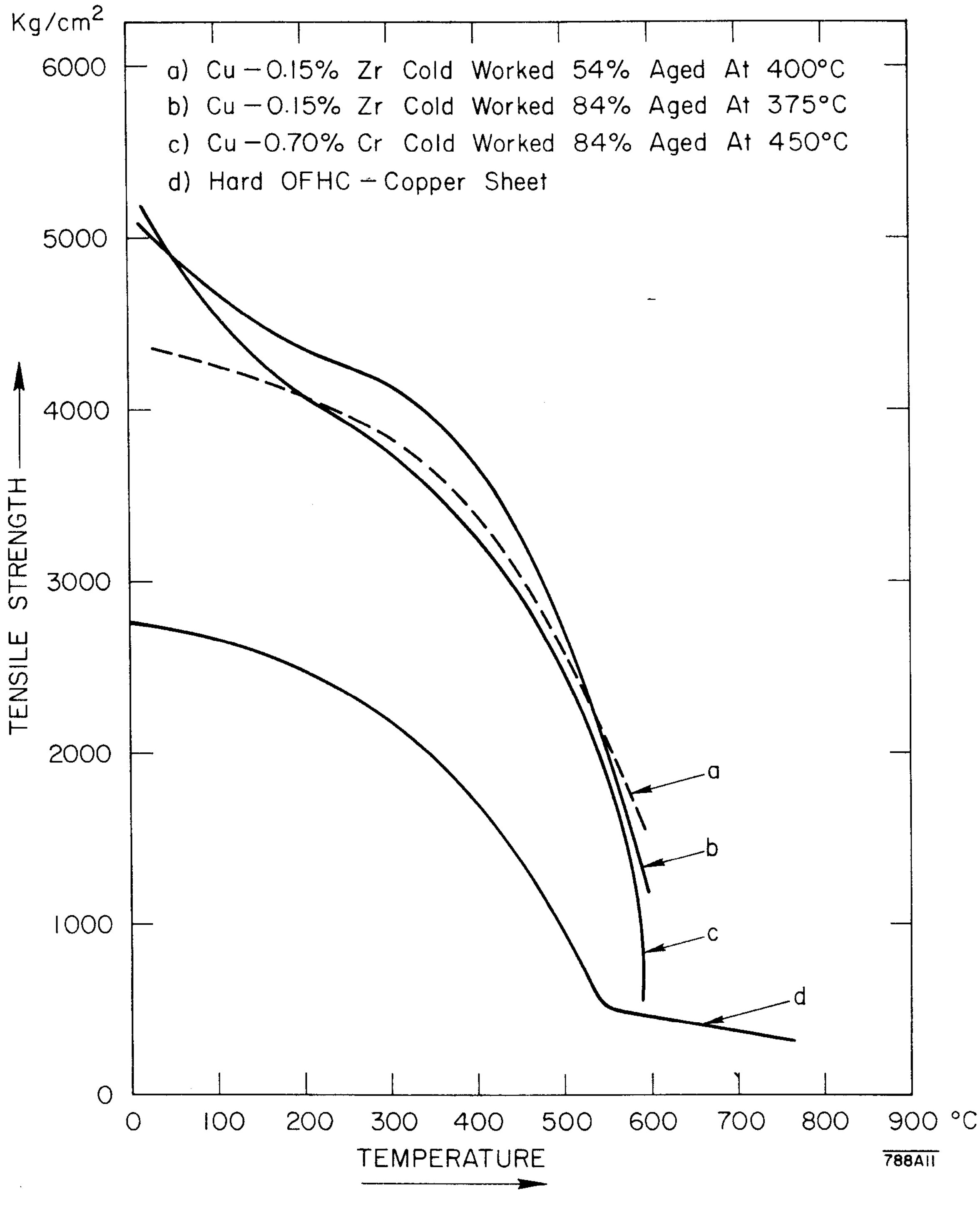
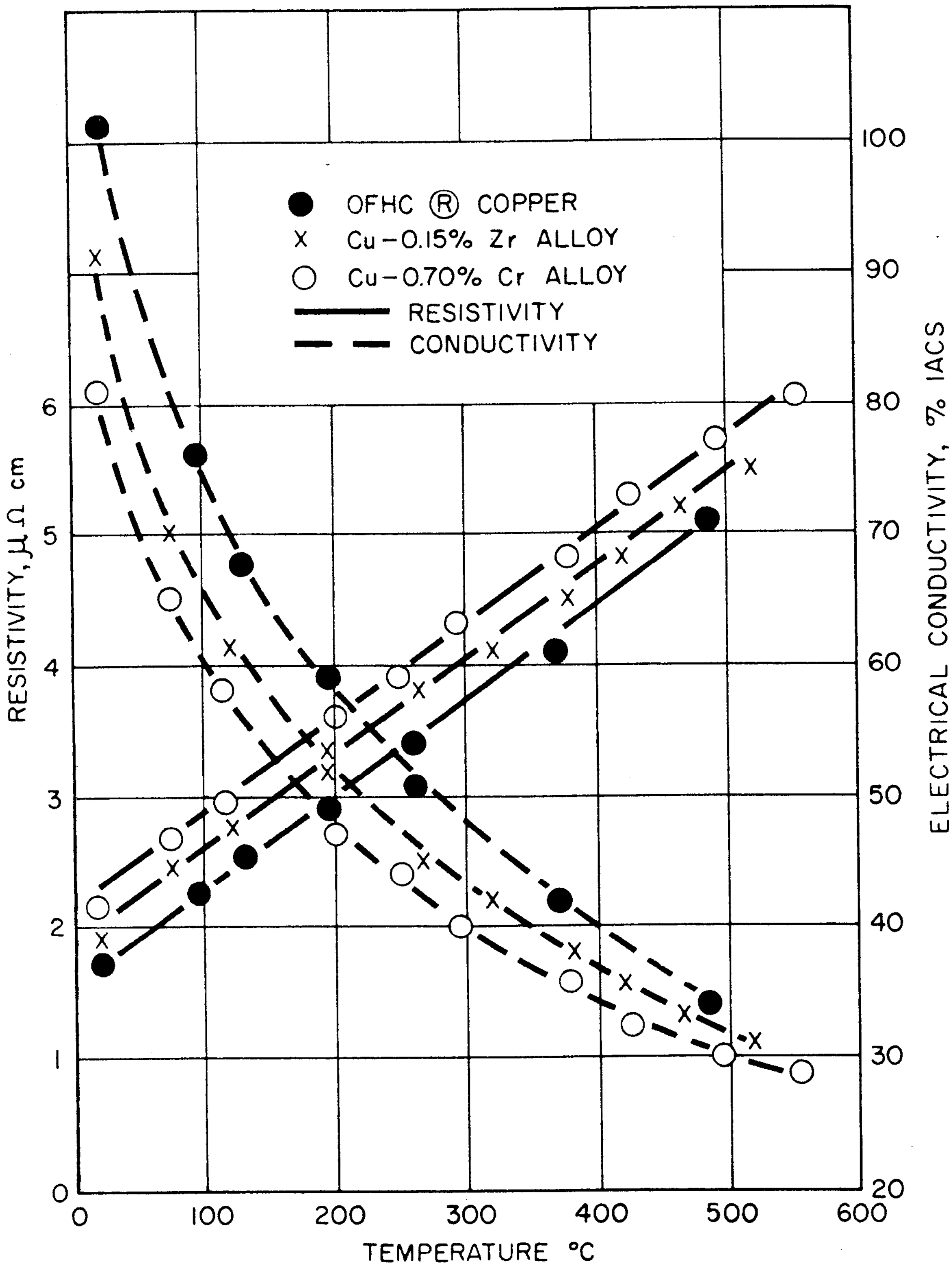

Kg/cm^2
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
STRESS
OFHC, 75% COLD REDUCTION
2.22 cm DIA BAR
OFHC, ANNEALED
0.025 cm SHEET
ANNEALED
OFHC, 40% COLD REDUCTION
0.64 cm DIA BAR
OFHC, ANNEALED
OFHC, ANNEALED, WIRE
OFHC, ANNEALED
1.90 cm DIA BAR
ANNEALED, 9.54 cm
DIA BAR
50
100
150
200
250
300 °K
TEMPERATURE
788A8

FIG. 12



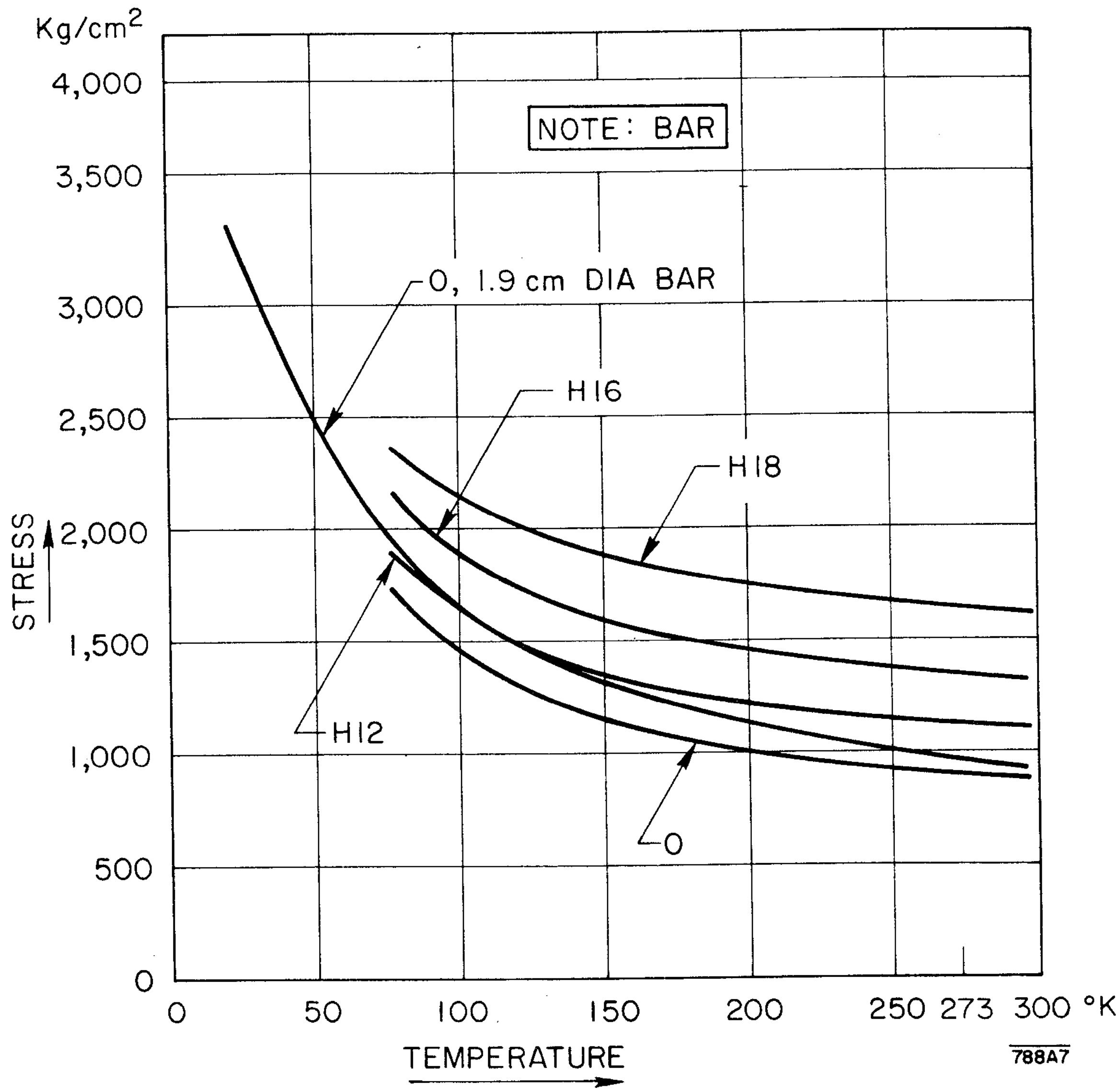
Kg/cm2
6000
5000
4000
3000
2000
1000
0
a) Cu – 0.15% Zr Cold Worked 54% Aged At 400°C
b) Cu – 0.15% Zr Cold Worked 84% Aged At 375°C
c) Cu – 0.70% Cr Cold Worked 84% Aged At 450°C
d) Hard OFHC – Copper Sheet
TENSILE STRENGTH
a
b
c
d
0
100
200
300
400
500
600
700
800
900 °C
TEMPERATURE
788A11

FIG. 13



OFHC ® COPPER
Cu-0.15% Zr ALLOY
Cu-0.70% Cr ALLOY
RESISTIVITY
CONDUCTIVITY
RESISTIVITY, μΩ cm
ELECTRICAL CONDUCTIVITY, % IACS
TEMPERATURE °C
0
1
2
3
4
5
6
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600

FIG. 14



Kg/cm2
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
NOTE: BAR
0, 1.9 cm DIA BAR
H16
H18
H12
0
STRESS
0
50
100
150
200
250 273 300 °K
TEMPERATURE
788A7

FIG. 15

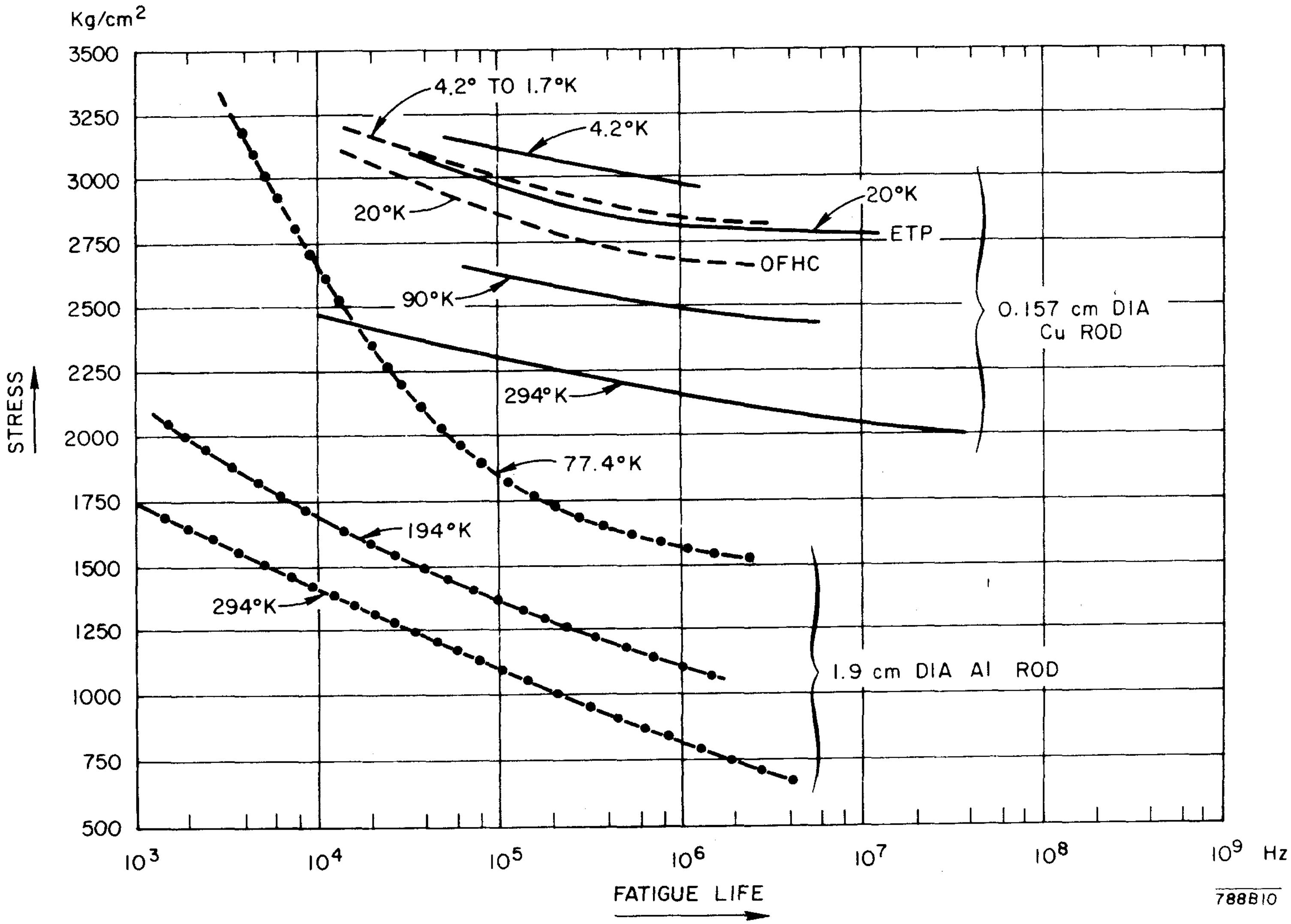
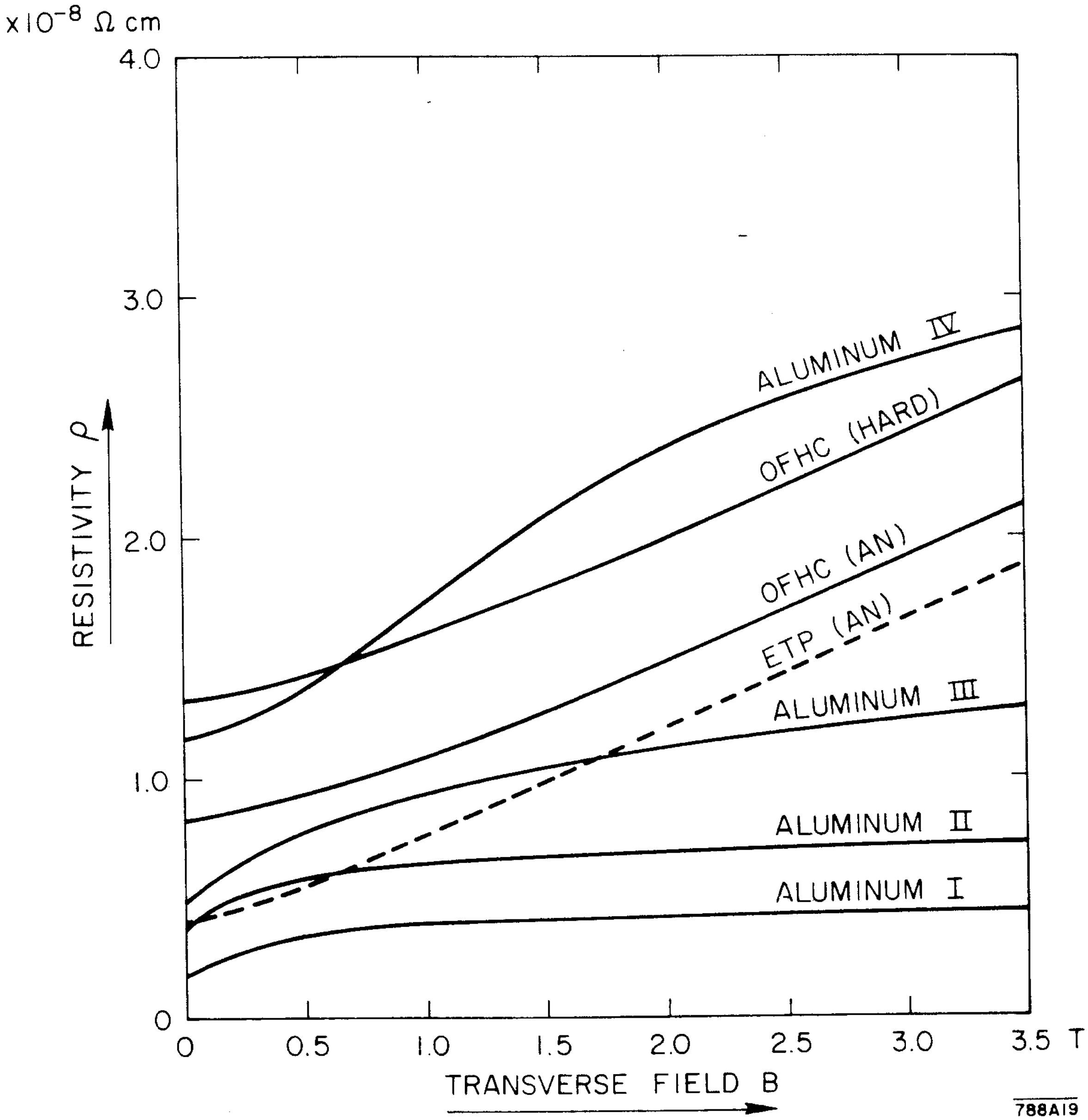
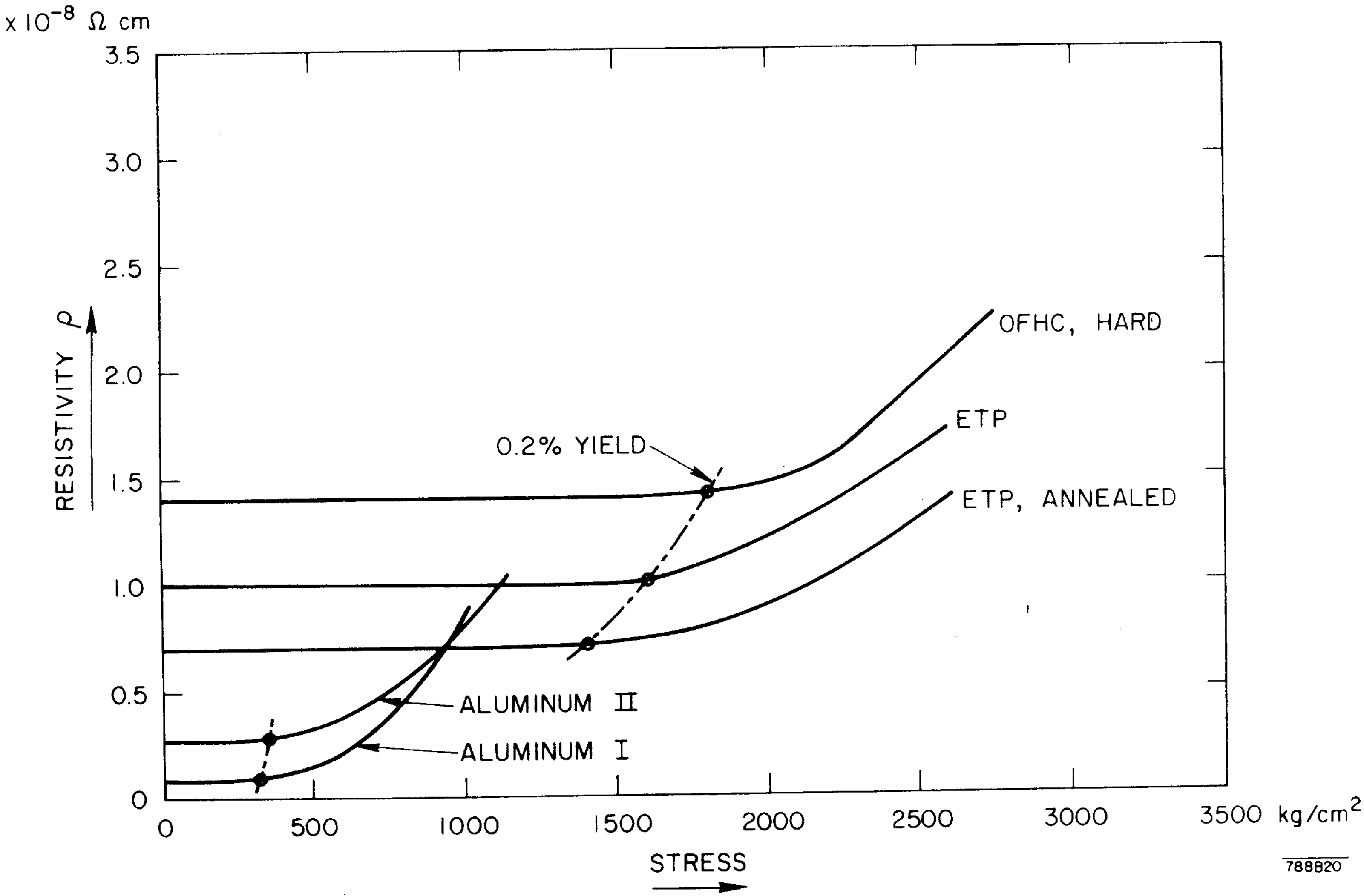

Kg/cm2
3500
3250
3000
2750
2500
2250
2000
1750
1500
1250
1000
750
500
STRESS
4.2° TO 1.7°K
4.2°K
20°K
20°K
ETP
OFHC
90°K
0.157 cm DIA
Cu ROD
294°K
77.4°K
194°K
294°K
1.9 cm DIA Al ROD
10^3
10^4
10^5
10^6
10^7
10^8
10^9 Hz
FATIGUE LIFE
788B10

FIG. 16



x10^-8 Ω cm
4.0
3.0
2.0
1.0
0
RESISTIVITY ρ
ALUMINUM IV
OFHC (HARD)
OFHC (AN)
ETP (AN)
ALUMINUM III
ALUMINUM II
ALUMINUM I
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5 T
TRANSVERSE FIELD B
788A19

FIG. 17



x 10^{-8} Ω cm
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
RESISTIVITY ρ
OFHC, HARD
ETP
ETP, ANNEALED
0.2% YIELD
ALUMINUM II
ALUMINUM I
0
500
1000
1500
2000
2500
3000
3500 kg/cm²
STRESS
788820

FIG. 18

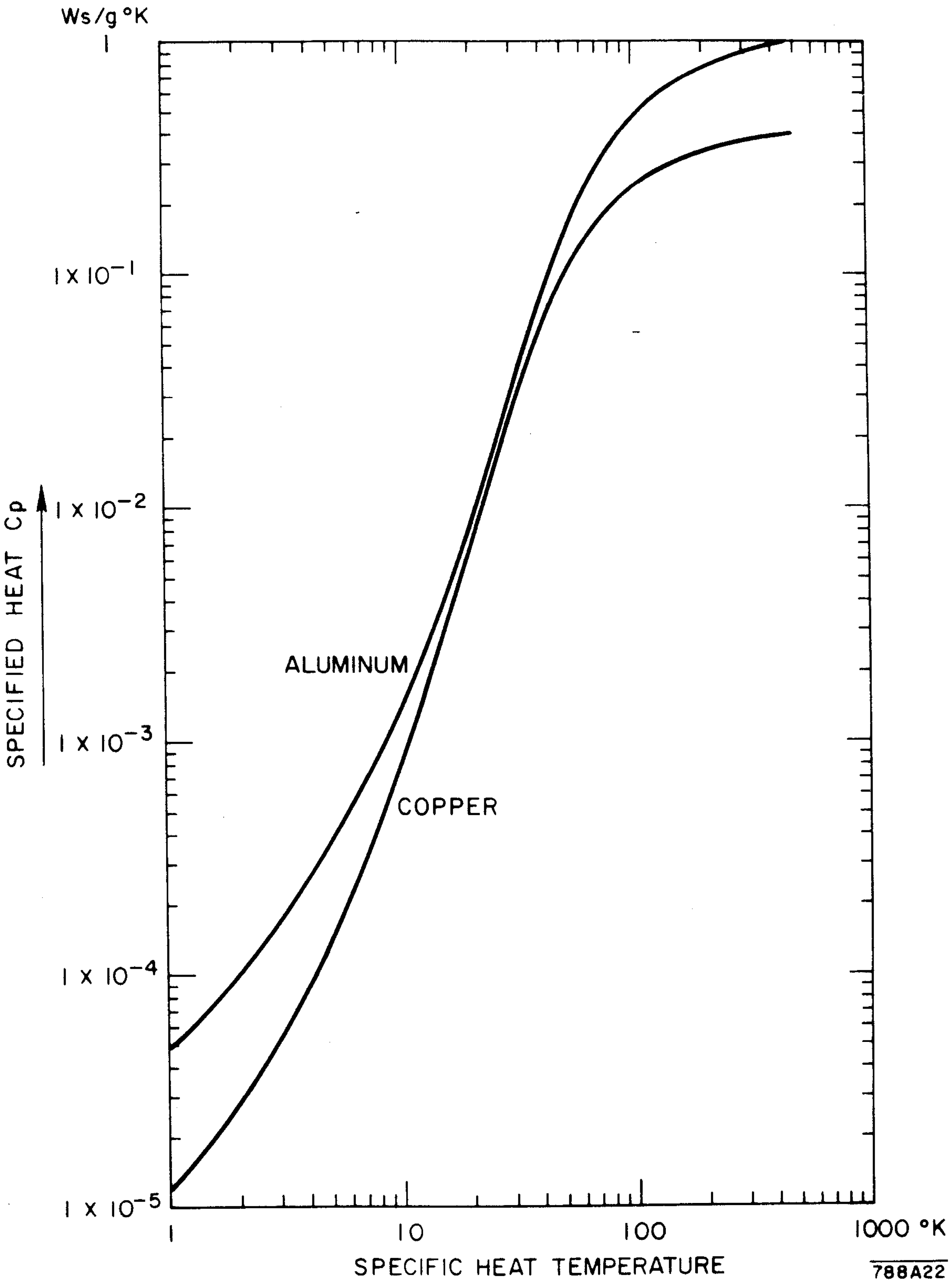

Ws/g °K
1
1 x 10⁻¹
1 x 10⁻²
1 x 10⁻³
1 x 10⁻⁴
1 x 10⁻⁵
SPECIFIED HEAT Cp
ALUMINUM
COPPER
1
10
100
1000 °K
SPECIFIC HEAT TEMPERATURE
788A22

FIG. 19

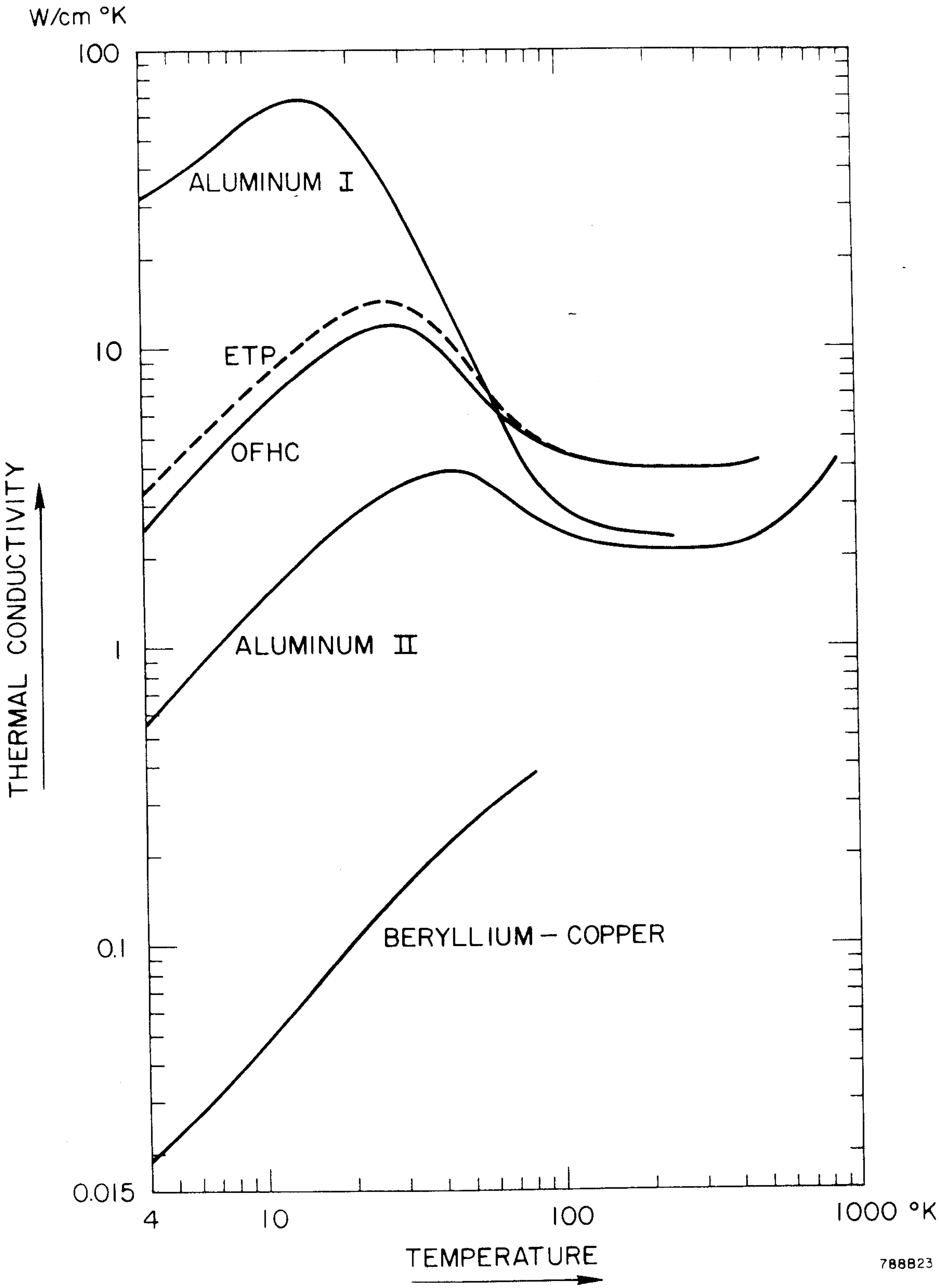
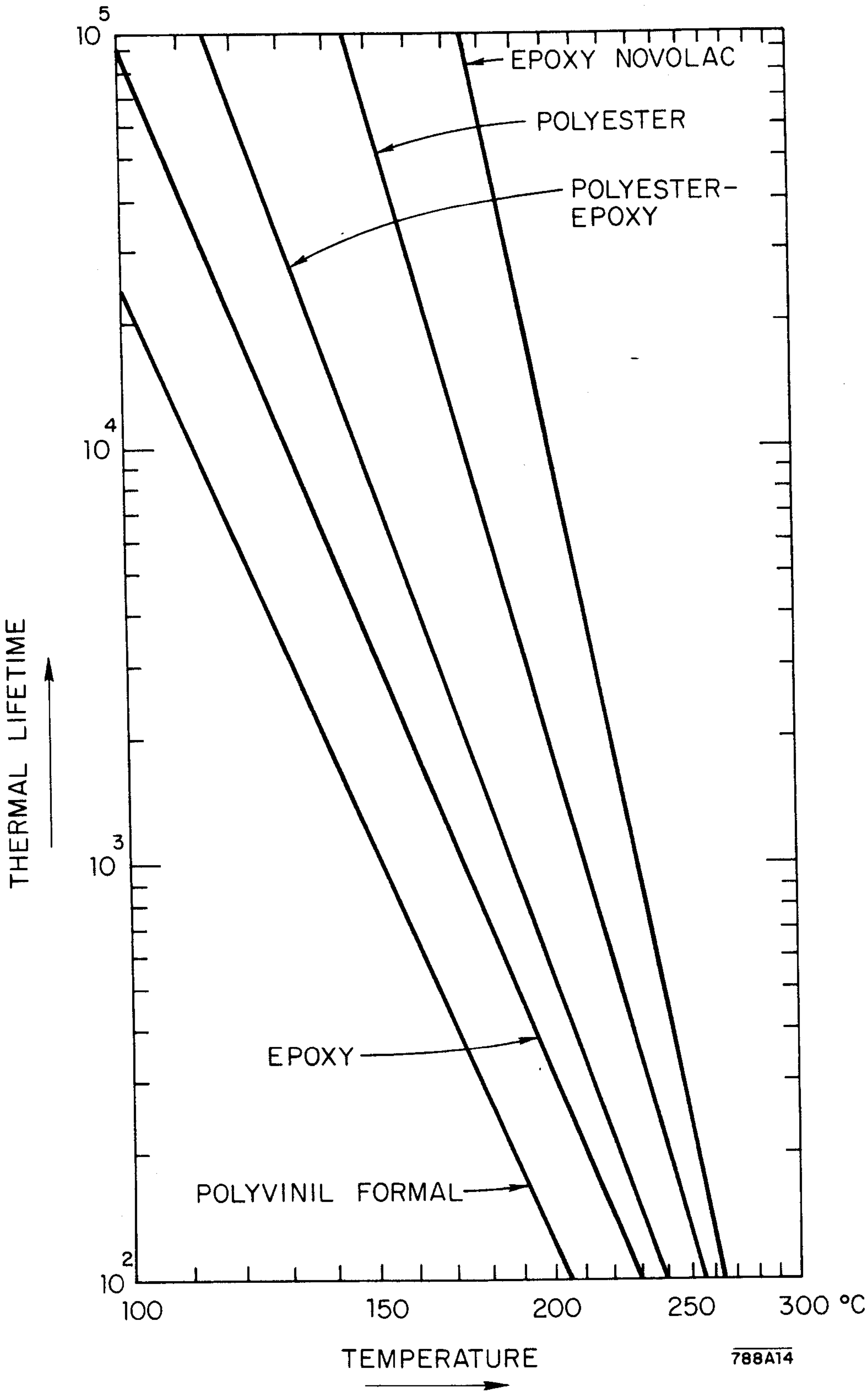

W/cm °K
100
10
1
0.1
0.015
THERMAL CONDUCTIVITY
ALUMINUM I
ETP
OFHC
ALUMINUM II
BERYLLIUM – COPPER
4
10
100
1000 °K
TEMPERATURE
788823

FIG. 20



EPOXY NOVOLAC
POLYESTER
POLYESTER-EPOXY
EPOXY
POLYVINIL FORMAL
THERMAL LIFETIME
TEMPERATURE
10^5
10^4
10^3
10^2
100
150
200
250
300 °C
788A14

FIG. 21

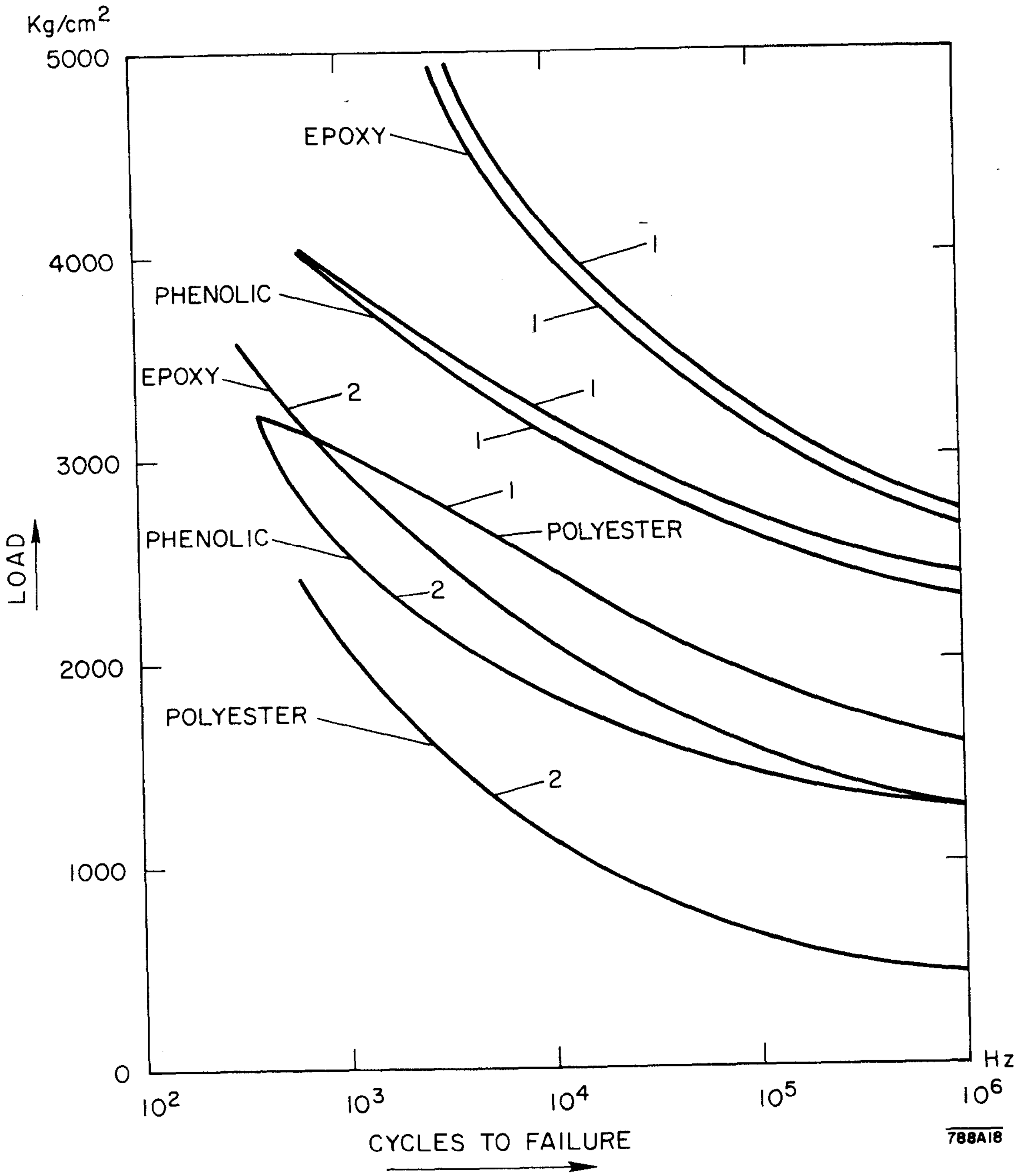

Kg/cm2
5000
4000
3000
2000
1000
0
LOAD
EPOXY
1
1
PHENOLIC
1
1
EPOXY
2
1
POLYESTER
PHENOLIC
2
POLYESTER
2
Hz
10^2
10^3
10^4
10^5
10^6
CYCLES TO FAILURE
788A18

FIG. 22