**Structural Materials for Large
Superconducting Magnets for Tokamaks**

C. J. Long

MASTER

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$4.50; Microfiche \$3.00

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Energy Research and Development Administration/United States Nuclear Regulatory Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Contract No. W-7405-eng-26

FUSION ENERGY DIVISION

STRUCTURAL MATERIALS FOR LARGE SUPERCONDUCTING
MAGNETS FOR TOKAMAKS

C. J. Long

Date Published: December 1976

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

NOTICE This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

CONTENTS

ABSTRACT	v
INTRODUCTION	1
CRITERIA FOR CHOICE	3
WORKING STRESSES	3
RADIATION RESISTANCE	11
ELECTROMAGNETIC INTERACTION	13
FEASIBILITY	15
CANDIDATE MATERIALS	19
AUSTENITIC STAINLESS STEEL	19
SUPERALLOYS	24
ORGANIC-MATRIX ADVANCED COMPOSITES	26
METAL-MATRIX ADVANCED COMPOSITES	30
OTHER STRUCTURAL ALLOYS AND MATERIALS SYSTEMS	33
COPPER AND COPPER ALLOYS	33
ALUMINUM AND ALUMINUM ALLOYS	33
FERRITIC STEELS	34
LOW-EXPANSION IRON-NICKEL ALLOYS	34
GLASS-REINFORCED COMPOSITES	35
SPECIAL-PURPOSE MATERIALS	37
POTTING MATERIALS	37
LOAD-CARRYING THERMAL INSULATION	37
FURTHER WORK	39
SUMMARY	41
ACKNOWLEDGMENTS	43
REFERENCES	45

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

ABSTRACT

The selection of structural materials for large superconducting magnets for tokamak-type fusion reactors is considered. The important criteria are working stress, radiation resistance, electromagnetic interaction, and general feasibility. The most advantageous materials appear to be face-centered-cubic alloys in the Fe-Ni-Cr system, but high-modulus composites may be necessary where severe pulsed magnetic fields are present. Special-purpose structural materials are considered briefly.

INTRODUCTION

The purpose of this paper is to discuss the problems confronting the designer when he selects structural materials for superconducting magnets for tokamak controlled thermonuclear reactors. Structural materials are those whose principal function in the magnet is transmission of mechanical loads. They are necessary because in the large magnets presently envisioned for the Experimental Power Reactor¹⁻³ and later devices, the body forces are larger than the conductor alone can withstand. Even if catastrophic structural failure should not occur, deflection could cause a large enough strain in the conductor to degrade its electrical properties.

The important criteria for material choice, which will be discussed first, are allowable working stress, radiation resistance, electromagnetic interaction, and general feasibility. The working stress will be determined by the elastic stiffness, the yield stress, and the notch toughness. Electromagnetic interaction is determined by such qualities as magnetic susceptibility and electrical resistivity. Feasibility is a general term which here includes such considerations as availability, ease of fabrication, engineering experience, and installed cost.

One can conceive of an ideal material, in which the values of all the parameters are very high or very low, as appropriate. The fact that such a material does not exist, of course, raises the question of whether one might be developed. This does not seem to be possible within the schedule now set forth for the end devices; the most innovation we can permit ourselves is refinement and adaptation of existing alloys and material systems. In some cases, in fact, time and effort are better spent characterizing existing materials or solving specific problems than attempting to develop better materials, at least in the near term. The existing materials which seem most likely to be usable for large superconducting magnets may be grouped as austenitic stainless steels, iron- and nickel-base superalloys, and polymer- and metal-matrix advanced composites. The alloy systems need characterization and research on specific points, while the advanced composites probably call for more fundamental work. These systems are discussed below and their advantages,

disadvantages, and unanswered questions are contrasted. A few systems which have been used or suggested for magnets but seem inappropriate to large, high performance magnets are also discussed, including aluminum alloys, ferritic steels, and glass reinforced composites.

CRITERIA FOR CHOICE

We may evaluate each structural material candidate in terms of four general sets of properties: the allowable working stress, the radiation resistance, the electromagnetic interaction, and the feasibility of the material. There is no single figure of merit which can be used to combine all the possible criteria for the choice, but we can indicate whether large or small values of each parameter are preferable and possibly suggest limit values beyond which the material is unacceptable. The relative importance of different material properties will vary sharply among different coil systems, and it may be that the optimum structural material for one service is entirely unsuited to another.

WORKING STRESSES

The allowable working stresses will be largely determined by the mechanical properties of the material and by the accuracy with which we can predict them. In general, each of several different properties will limit the allowable stress in a given situation; the working stress is then the lowest of these limits. We should properly speak of stress field rather than stress, as some triaxiality of stress will exist at each point in the magnet and must be considered in evaluating materials.

The fact that the electrical performance of superconductors is degraded by even small amounts of strain limits the allowable deflection of the coil when energized. The amount of elastic coil deflection is an inverse function of the stiffness, measured essentially by the Young's and shear moduli, of the structural material. It will be necessary to choose some finite conductor strain which does not degrade electrical properties excessively; in principle, zero deflection would call for an infinite amount of any real structural material. Assuming that strain

in the conductor and the structure are equal* and that stiffness provided by the conductor is negligible, we may write:

$$\sigma_{T,S} = E_{T,S} \epsilon_c, \quad (1)$$

where

$\sigma_{T,S}$ = tangential stress in the structure,

$E_{T,S}$ = Young's modulus of the structural material in the tangential direction of the coil,

and

ϵ_c = allowable longitudinal strain in the conductor.

$E_{T,S}$, the Young's modulus of the structural material in the tangential direction of the magnet, is a measurable material property which will be discussed shortly. The allowable conductor strain, ϵ_c , is very much a matter of judgment; current research in a number of laboratories should provide useful data. At present it appears that, considering fatigue induced degradation⁴ as well as single cycle behavior, the total working strain of NbTi-based conductors will be in the range 0.15-0.20% and that of Nb₃Sn-based conductors, which are less well characterized in this respect, will be 0.15% or possibly less. It is emphasized that these numbers are advanced here only for the sake of discussing structural materials. The upper bound stress in the structure placed by an elastic-strain limit will be directly proportional to the Young's modulus in the tangential direction. For this reason a high Young's modulus in at least one direction is required; for some structural materials elastic deflection actually determines the working stress. Because the loads are not tangential everywhere in the coil, the transverse Young's moduli are also important. In a structural metal all Young's moduli are nearly equal,

* It is not obvious that they must be equal. It would be easy to design a magnet in which the strain in the conductor exceeded that of the structure, but we would have no purpose in doing this unless the allowable working strain of the conductor exceeds that of the structure. This would occur only in the case of a low-yield-stress structural material and would imply a large amount of structure. It may be possible to design such a cable that the individual strands experience a lower strain than the cable as a whole. In the absence of other limitations, this might allow a higher strain in the structure and therefore a higher working stress than predicted by Eq. (1).

but in a composite they can be very different (an order of magnitude) and can be tailored to some extent to suit the designer. Therefore, one can trade off one modulus against another in composites and caution is appropriate in comparing moduli between metals and composites. In summary, one materials induced failure mode of the structure is excessive elastic deformation and ensuing conductor strain; to prevent this, we want the stiffness of the structural material to be as high as possible.

A second structural failure is permanent deformation caused by plastic yielding of the structural material. The relevant material property in this case is the yield stress, often called the yield strength. In a face-centered-cubic metal like those being considered for tokamak coil structures, the yield stress is not a sharp point on the stress-strain curve and is defined as the stress at some stated plastic strain, usually 0.2%. Therefore, some permanent deformation has already occurred at stresses below the yield. Yield stress is still useful for comparison of metals' resistance to plastic deformation. Fiber composites tend not to have a yield stress as the term is used here; rather than yielding, they generally behave brittly — that is, rupture with little prior plastic deformation. This is analogous to the yield stress in metals, except that metals (at least those under consideration here) yield at one stress and break at a higher — sometimes much higher — one, called the ultimate stress. This ability of metals to deform before breaking, called ductility, is useful to designers and will be discussed below. Yield behavior, like elastic deflection, is sensitive to all the stresses acting on the member, not just the maximum stress. The way in which the stresses in different directions interact will vary with the material, especially between composites and metals. In the absence of any other changes, a higher yield stress will be preferable. In a tokamak coil, it is a second limit on the allowable structural working stress. The working stress, multiplied by some appropriate safety factor, must not exceed the yield stress.

A third failure mode which places a limit on structural operating stress is failure by propagation of a crack. Cracks may propagate in the presence of a constant stress, a time-varying stress (fatigue), or a

shock load. The resistance of a material to such failure is called its fracture toughness. Of a number of ways of measuring and quantifying toughness, none is wholly satisfactory. The conventional measure of toughness is the energy absorbed in breaking when a notched sample of specified geometry is struck by a pendulum (such as the Charpy and Izod tests of ASTM D256 and E23). While impact-break tests are simple and comparatively inexpensive, they are extremely difficult to relate to design; much experience with a particular alloy is necessary before impact-break values can be related to service behavior. Therefore they tend to be unsuited to novel material systems. Also, the adiabatic temperature rise during the impact can be large enough, owing to the small values of specific heats at liquid helium temperatures, to raise questions of what was really tested and what the results would have been had the metal been continuously at 4.2 K. A number of more sophisticated and more thoroughly controlled crack propagation tests have been devised to avoid the disadvantages of the Charpy and Izod tests. Of these, the one most used for metals at LHe temperatures is the compact tension test described in ASTM E399, which measures the crack opening displacement of a pre-cracked notched specimen as load is applied perpendicular to the plane of the crack. The data thus obtained make it possible to predict the behavior of a preexisting small crack in a structure. E399, however, presumes that the plastic zone at the crack tip is insignificantly small. This is generally not the case⁵ in the tough alloys considered for cryogenic service, and various means reviewed elsewhere^{5,6} have been used to predict the behavior of cracks in such materials using substantially the same test. The K_{Ic} (J) parameter, a critical stress intensity for crack initiation derived from crack tip energy considerations, will be used here as it is fairly easy to relate to elastic fracture analysis and a comparatively large amount of data is expressed in K_{Ic} (J). Unfortunately, this work has been done at 4 K for homogeneous materials only and extension to composites will be difficult. Such concepts as "critical crack length" will probably have to undergo extensive revision. For now, impact tests may be used to rank composites, but few of these have been performed at 4 K, and temperature extrapolations are of limited reliability.⁷

It is evident that high toughness is a good thing. Unfortunately, we have only a limited amount of it available at 4 K. A number of metals with reasonable toughness at room temperature, such as the carbon steels, are very brittle at cryogenic temperatures. In metals, testing and analysis are beginning to be sophisticated enough to predict a reasonable working stress from design parameters, material properties, and knowledge of the largest pre-existing crack not detectable by nondestructive examination. Much thought and experimentation will be required before composites are even that far along. In the meantime, some sort of fracture toughness test will be necessary for any composite system used in working coils.

A crack which does not propagate to failure in a single load cycle may nevertheless do so in fatigue (repeated loading and unloading). An EPR pulsing every two minutes for five years will see about 1.3×10^6 charge-discharge cycles in the pulse coils, and as many small cycles in the TF coils superimposed on a few large charging cycles. The trends in fatigue testing are similar to those in other toughness measurement: toward more complex and better characterized tests. The E399 CT specimen mentioned above has also come into use for fatigue tests which relate crack growth per cycle, $\frac{da}{dN}$, to the change in the stress intensity during a cycle. Fatigue data at 4 K is as yet limited in metals and almost nonexistent in composites. These tests are expensive to run at any temperature because of the equipment occupied, and even more so at cryogenic temperatures because of the amount of cryogen consumed. While the newer fracture mechanics techniques reduce the time somewhat, conventional techniques are still valuable. In advanced composites, what little information exists⁷ gives cause for optimism, but many more measurements are necessary before such materials can be used confidently, especially for pulse coils (where their high electrical resistivity makes them especially valuable). Crack propagation, from either one or many cycles, is likely to place an upper limit on structural stresses which is of the same magnitude as the elastic deflection and plastic yield induced limits. Only a careful analysis of each situation can identify which of the three is controlling.

A number of material properties do not set absolute limits on working stress but do affect the relationship between it and elastic stiffness,

yield stress, and toughness. Included in this category would be such things as anisotropy, ductility, and conventionality.

Anisotropy is the variation of material properties with direction. In an annealed metal, it is negligible; the properties are substantially the same in any direction. In a composite, all the mechanical properties are highly directional and the designer has a challenge. He is probably used to working in isotropic materials and must be careful to examine his assumptions during the design process. At the same time, the properties in one direction of a composite can often be traded off against those in another, especially the other in-plane direction. The designer thus has an option of choosing material properties in accordance with the directionality of load. Anisotropy is thus neither inherently desirable nor undesirable, but it does provide one more design variable which must be considered.

Ductility, defined as "the ability of a material to deform plastically without fracturing,"⁸ is the quality that makes a material forgiving of local overstresses. It is typically measured as the elongation to fracture in a standard tensile test. A ductile material will locally deform but maintains its load bearing ability, whereas a nonductile material breaks or crushes. Nonductile materials therefore require more care on the designer's part in predicting transfer of load between the material and its surroundings. While not all ductile metals are tough, there is a good correlation within a given alloy system, and all the metals commonly used or considered for cryogenic structural service are reasonably ductile. Composites, by contrast, have very limited ductility. They fracture with little or no plastic deformation and local loads must be calculated very carefully.

"Conventionality," in this context, is used to describe the collective body of engineering experience in using a material at 4 K. Stainless steel 304, which has been used in a great many cryogenic structures, would be a conventional material in this sense; boron-reinforced aluminum, to choose one of many possibilities, would be unconventional. These are, of course, extreme cases. Obviously there may be no reasonably well known material suitable for some structural applications in tokamak coils. In this case

a comparatively new material must be used, and extra efforts at characterization must be made. Here we see the advantage of an older material: lot-to-lot variations are quantified, fabrication and joining methods are better developed, and smaller safety factors can generally be applied. A better-known but slightly inferior material could in fact be more highly stressed than a stronger material which requires larger safety margins because of its novelty. Past experience at temperatures above 4 K should certainly be considered, but with due regard for possible variations in behavior. More conventional materials also tend to be available with shorter lead times and in more product forms. Of course, a new material will not be introduced unless it has some demonstrable advantage over existing ones, so that the desire for well-known materials will almost always involve a trade-off against mechanical properties and a choice can be made only with reference to a particular situation.

To summarize, then, one criterion for choosing among structural materials for tokamak magnets is the working stress field each will allow. This working stress will be determined by 1) elastic stiffness, 2) yield stress, and 3) toughness, in both single- and multiple-cycle loading, as measured at 4 K. To arrive at an allowable stress, these must be modified appropriately according to the anisotropy, ductility, and conventionality of each material.

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

RADIATION RESISTANCE

A power producing tokamak is a nuclear reactor and its components will be exposed to energetic radiation. While only a small fraction of the radiation emitted by the plasma will pass the blanket and shield and be absorbed in the magnet, that fraction is large enough to demand consideration of both its heat deposition and its effect on material properties. The radiation flux will vary depending on which place in which magnet is considered, but for our purposes we need consider only the point of maximum flux in each magnet system. The toroidal field and poloidal field systems must be considered separately since their material requirements are different in some other respects (such as eddy currents, discussed later) and different compromises may be appropriate. The description of the radiation field can only be approximate because the flux at the first wall will depend on plasma parameters as yet unknown and because the relation between first-wall flux and that at the magnets is impossible to calculate exactly. In addition, cutouts in the shield for various access ports cause local "hot spots" that can be averaged into the overall heat load but cause greater materials degradation locally.

Added to uncertainty in the amount of radiation at any particular point is uncertainty about radiation effects on materials. While some stainless steels have been studied extensively, the experiments were conducted at temperatures (350-800°C) appropriate to fission reactors and CTR first walls rather than to superconducting magnets. The temperature is important because the enhanced transport at high temperatures promotes both annealing and void coalescence; these are negligible at 4 K.

In the toroidal field coils the maximum radiation exposure will occur at the inside of the coil structure near an access port. Neglecting the port, the flux for an 800 MW (th) reactor at the inside of the TF coils is estimated⁹ at $9.6 \times 10^9 \text{ n-cm}^{-2}\text{sec}^{-1}$ ($E > 0.1 \text{ MeV}$) and $2.5 \times 10^{10} \text{ n-cm}^{-2}\text{sec}^{-1}$ (all energies). Corresponding figures for the outside of the TF coils (the inside of the PF coils) are $1.9 \times 10^7 \text{ n-cm}^{-2}\text{sec}^{-1}$ and $5.0 \times 10^7 \text{ n-cm}^{-2}\text{sec}^{-1}$ respectively. These fluxes correspond to fluences, over 20 years, of

$6 \times 10^{18} \text{ n-cm}^{-2}$, $1.6 \times 10^{19} \text{ n-cm}^{-2}$, $1.2 \times 10^{16} \text{ n-cm}^{-2}$, and $3.2 \times 10^{16} \text{ n-cm}^{-2}$, respectively, if no allowance is made for duty cycle. It appears at present that if the radiation flux is low enough to hold damage to insulation, damage to conductor, and heat input within bounds, then damage to a metal structural material should not be a problem.

Superconducting poloidal field coils (which are presumed to be on the inside of the torus, shielded by the TF coils) may call for a different assessment because they are pulsed and eddy currents must be held down. The use of graphite- or boron-reinforced epoxies here, which is attractive in other respects, would require testing to verify the suitability of both fiber and matrix for radiation service. Other problems that occur will be dealt with below when specific materials are discussed. It appears that radiation will not present major problems in either coil system structure, but this question is not as well defined as some others and needs more thought and study.

ELECTROMAGNETIC INTERACTION

For our purposes, "electromagnetic interaction" comprises interactions between a structural material and the electrical and magnetic fields present in a magnet system. They may produce field disturbances (spatial or temporal), forces on the structure, reaction forces in the conductor, and energy loss and heat deposition due to various hysteretic effects. The magnitude of each effect will be a function of the amount and geometry of structural materials, their material properties, and the fields and their changes with respect to space and time. Design is simplified if each interaction is zero, but there may be circumstances in which a designer can make use of a specific interaction.

To consider the effect of material properties, it is useful to deal with constant and time-varying magnetic fields separately. We will deal here only with field effects related to structural materials and not, e.g., with pulse losses in the conductor.

According to their behavior in a magnetic field metals are classified as diamagnetic, paramagnetic, or ferromagnetic. The internal magnetization of a diamagnetic metal is proportional to the applied field but much smaller and of opposite sense. Such a material is repelled by a nonuniform field. Pure copper is diamagnetic but trace impurities can change its behavior. Paramagnetic metals display an internal magnetization which is proportional to but much less than the external field. Such metals are attracted toward higher field regions of nonuniform fields. Most common metals and alloys, except steels, are paramagnetic; the lower alloy austenitic stainless steels are paramagnetic so long as they entirely retain the face-centered-cubic crystal structure. Ferromagnetic metals' magnetization initially increases sharply with field but then saturates at a magnetization substantially above that of paramagnetic metals. Some of this magnetization remains when the external field is removed, so that time-varying external fields cause a hysteresis loop and energy deposition. Of the pure metals, iron, cobalt, nickel, and gadolinium are ferromagnetic. Ferromagnetic metals experience a second order phase transition and become paramagnetic above a temperature known as the Curie temperature (after Pierre Curie) which may be either

above or below room temperature. Some commercial nickel-base alloys are paramagnetic at room temperature but ferromagnetic at cryogenic temperatures. Other terminology is sometimes used to describe the magnetic behavior of materials. "Ferrimagnetism," "antiferromagnetism," and "superparamagnetism" refer to various sets of properties intermediate between paramagnetism and ferromagnetism. Ferromagnetism is so much stronger an interaction, especially at weak fields, than para- or diamagnetism that ferromagnetic alloys are sometimes described as simply "magnetic" and others as "nonmagnetic."

The designer's task would be simpler if the structural materials were all paramagnetic or truly nonmagnetic rather than ferromagnetic. At present it appears that this is possible, but at the cost of fairly severe compromises elsewhere in the design. The question of the constant-field magnetic interaction between the structural material and the rest of the magnet and the plasma deserves careful, quantitative analysis. The most obvious forms of this interaction are: 1) perturbation of the magnetic field to the detriment of plasma confinement; 2) perturbation of the field inside the coil, increasing the field at the conductor; 3) self-forces on the structure, with corresponding reaction forces on the conductor; and 4) energy deposition due to hysteresis. While it appears that a ferromagnetic structure may not greatly hurt plasma containment,¹⁰ the other effects seem not to have been investigated. The analysis might be done analytically, but is by no means trivial. The possibility of nonuniformly distributed ferromagnetic material (weld ferrite, for example) exacerbates the problem. For the present, paramagnetic alloys are preferred over ferromagnetic ones.

The problems presented by time-varying magnetic fields are somewhat different. Transient versions of the effects noted above do occur, but in addition to these the designer must account for eddy currents induced by the changing field. These are not a function of the magnetic nature of the structure but rather of its electrical conductivity. Since they occur at 4 K and must be removed by the magnet refrigeration system, they must be minimized. It has been estimated³ that stainless steel structure in the poloidal coils could contribute as much eddy current heating as the conductor losses, but the amount of heating in the structure is

extremely sensitive to the particular coil design and operating cycle. The much higher electrical resistivity of organic-matrix composites could be very useful here, as the eddy current losses scale directly as the electrical conductivity.

A structural material may experience electric as well as magnetic fields, especially in the poloidal coils. Toroidal coils have their largest voltages, very roughly 2 kV, only under abnormal conditions (such as quenches), whereas poloidal coils routinely experience voltages of about 35 kV. An insulation system capable of withstanding such potentials will be hard enough to develop that a nonconductive structure would be most welcome. The stainless steel conduit structure as used in the ORNL EPR Reference Design TF coils³ has the characteristic that all electrical insulation isolates the conductor from ground and thus resists the full coil potential, if the structure is electrically conductive.

FEASIBILITY

Feasibility is a general word used here to mean the readiness of a material for use in nonexperimental, cost effective, engineering design. It comprises such things as availability, ease of fabrication, engineering experience, and cost as installed. It is evident that these are inter-related and that each will affect the others, but it is useful to discuss them individually.

Availability as a concept is readily understood, but actually predicting the availability of a specific material in a specific form over a period of decades is extremely difficult. Materials become more or less available as a function of technological development, exhaustion of resources, economics, politics, and many other factors. Technological development may introduce or make obsolescent either specific materials or whole classes while the other factors tend to operate on classes rather than individual materials.

Development may introduce either new materials or new ways of handling an existing material so as to make it more useful. Older materials may disappear as better ones supersede them. All these effects

occur on time scales of years or decades. A particular application for materials can both stimulate solutions to its specific problems and adapt solutions developed for others' problems. The smaller the field (in terms of resources available for materials), the more it must rely on adaptation. Presently it appears that the CTR magnet program will not be able to develop any major new structural materials systems to suit its needs because of lack of both time and resources, unless it becomes evident that all existing materials are inadequate. It is the more necessary, therefore, to study the ways in which existing materials can be adapted. These might include, for example, the welding of the newer austenitic stainless steels for cryogenic service or the selection of cryogenic epoxies for use in epoxy-matrix composites. The adaptations will be largely the qualification for cryogenic service of materials and techniques developed for higher temperature. The word "qualification" is important: it means not merely selection of the optimum material for a purpose, but also sufficient study to identify and quantify all its limitations and accurately predict its behavior in a design. It does not appear likely that any of the materials now considered for CTR magnets will become technically obsolete. The areas in which useful new materials seem most likely to be developed are the manganese-containing austenitic stainless steels and the high-modulus (graphite- and boron-based) composites.

The exhaustion of raw materials is a question which has led to much discussion and much less agreement.¹¹ A particular area of concern is alloying elements for steels. The most important to us are chromium, manganese, and nickel, all of which occur at low average concentrations in the earth's crust. The presently workable sources are few in number and thus subject to political interruption. As leaner ores are worked, the cost (i.e. commitment of resources) increases and the raw materials cost can rise considerably for a steel containing 26-45% Cr, Mn, and Ni. Substitutes containing more readily obtainable elements (aluminum, carbon, and boron, for example) would ease worries about availability of structural materials, especially for commercial reactors.

Almost any raw material is available if sufficient resources are committed to its production.¹² When the cost of extraction exceeds the

incremental value of the end product, however, that material is no longer available for that end product. The availability of a raw material will depend, therefore, not only on the cost of extraction, but also on the value of the end product.

Because some materials occur in a limited number of areas, their supply may be interrupted or reduced because of decisions made in the realm of national and international politics. The most striking recent example is petroleum. For fusion reactors, the raw material through which politics interacts with materials most strongly is probably chromium. Other metals, such as nickel, manganese, and aluminum, are imported in comparable proportions (70% or more of annual U.S. consumption)¹³ but either come from politically more stable sources or have U.S. sources which seem readily usable in the long term. The particular concern about chromium is that the principal sources are the U.S.S.R. and the Republic of South Africa (and historically Southern Rhodesia); either international conflicts or internal U.S. political decisions could cut off these sources. In general, the composites should be less sensitive to politics, except that an increase in international tension would increase the demand for advanced composites for aerospace hardware.

While technology is available today for metallic structures, advanced fiber-reinforced composites still require development before use in tokamak magnets. Conversely, in the long term the composites appear to be less susceptible to resource exhaustion and political interruption. It is axiomatic that an unproved material should not be used in a large, expensive structure; nevertheless, if possible we should avoid building early magnets with a material which will not be used in later ones.

A second aspect of the feasibility of a material is its ease of fabrication — that is, the readiness with which it may be formed into a structure of suitable size and shape. The order in which we rank materials may depend a good deal on what that size and shape are. Furthermore, the design itself will be conditioned by the material the designer expects to use. In this situation, it is almost impossible to compare materials' ease of fabrication except very qualitatively, and

with reference to a particular design. We should, however, be careful not to commit ourselves implicitly to a particular material by way of design unless we are certain that material is adequate in every respect.

The value of engineering experience with a material in a given environment is obvious. We would like to use older, better known materials as long as they will serve. Conversely, the need for experience may actually call for the use of new materials; if later, larger projects require an advanced material, we should begin using it as soon as feasible in order to build up some design experience.

To the extent that any single figure of merit may be used to choose one material over others, that figure of merit is cost for the complete structure, in place. Cost will be a function, in particular, of cost per kilogram, amount required (set by such things as density and working stress), and fabrication cost. Obviously we are neglecting materials which are entirely unsuitable on technical grounds. Compromises elsewhere in the reactor which are forced by the choice of structural material should also be regarded as material costs.

To summarize, the choice among candidate structural materials for superconducting magnets will be made on the basis of mechanical properties, radiation resistance, electromagnetic interaction, and feasibility. With these in mind, we will discuss the materials which are considered.

CANDIDATE MATERIALS

Quite often, a group of materials with similar composition and structure offer similar advantages and disadvantages. We will therefore discuss the characteristics of each class and then relate these to particular materials. The four most promising classes are austenitic stainless steels, iron- and nickel-base superalloys, organic-matrix advanced composites, and metal-matrix advanced composites; after dealing with these we will review some of the material groups which presently seem less worth pursuing.

AUSTENITIC STAINLESS STEEL

The austenitic stainless steels are face-centered-cubic alloys of iron with chromium, nickel, and other elements. The alloy content (total of all elements except Fe) is seldom less than 25 wt% and may approach 50 wt%. They have been used for cryogenic structures for many years and are generally the first choice for structures below liquid nitrogen temperature (77 K).

The austenitic stainless steels have a number of advantages over the other materials proposed for superconducting magnet service. They are the least expensive of the leading candidate systems in terms of material cost per kilogram. Also, because they have been in use longer than the materials discussed below, more is known about production, design, and fabrication techniques. The stainless steels are ductile and reasonably tough at all temperatures, and have a high elastic modulus — 200 GPa or 30×10^6 psi. Like most of the materials a designer is accustomed to, they are substantially isotropic; that is, their mechanical properties are not functions of direction. No heat treatment other than a solution anneal is required to develop optimum mechanical properties; this considerably simplifies the welding of large structures. Stainless steels are not degraded by radiation of the doses which other coil considerations set as maxima.

At room temperature, annealed stainless steels are paramagnetic. When cold-worked or cooled to cryogenic temperatures, however, they

tend to transform martensitically to a ferromagnetic body-centered-cubic structure.¹⁴ The likelihood, critical temperature, and extent of such a transformation are very strong functions of chemical composition and therefore vary considerably¹⁵ among different heats of what is nominally the same alloy. This variability makes characterization difficult. There is not space here to discuss martensitic transformations and the interested reader is referred to Reed and Breedis.¹⁴ We note in passing that the transformation affects magnetic properties and causes a dimensional change but, contrary to expectations, appears not necessarily to reduce toughness.¹⁹

While martensitic transformations are the major problem with austenitic steels in cryogenic service, others may be adduced. Some of the structurally stable steels, such as AISI 310 and 310S, go through a ferrimagnetic transition at low temperatures¹⁶ which is also dependent on exact composition. These stable alloys tend also to be harder to weld into large, complicated structures. Austenite which is stable at low temperatures is also stable at elevated temperatures, making the ferrite which is beneficial to sound welds difficult to produce. Another problem, present in any iron-containing alloy, is an (n, γ) nuclear reaction experienced by iron which is responsible for most of the gamma flux in the coil. The austenitic stainless steels are electrically conductive [$\rho \sim 600 \text{ n}\Omega\text{-m}$ ($60 \mu\Omega\text{-cm}$) at 4 K] and thus are subject to eddy currents in a changing magnetic field. These currents appear to be minor in the toroidal-field coils but may disqualify any metallic material for use as structure in the poloidal coils.

We are dealing here with an entire class of alloys; some of them are certainly better than others for any particular application. The three which presently appear to be the best compromises for tokamak coil structures, especially toroidal-field coils, are 21-6-9, AISI 310S, and AISI 304/304L.

Alloy 21-6-9 was developed by Armco Steel Corporation; they now call their version "Nitronic 40." The nominal chemical composition is 21 wt% Cr, 6 wt% Ni, 9 wt% Mn, 0.3 wt% N, < 0.04 wt% C, balance Fe. The nitrogen acts as an interstitial strengthening agent, resulting in

exceptional strength in the annealed condition. [The measured tensile yield strength at 4 K is about 1200 MPa (175 ksi).]¹⁷ This strength comes at the sacrifice of some notch toughness as compared with steels 310S and 304.¹⁸⁻²⁰ Problems have also been reported²¹ in welding 21-6-9 with high-rate processes, such as electron beam welding, due to formation of nitrogen bubbles. It appears, however, that the welding problems can be solved with a reasonable amount of research. The Baseball II mirror containment magnet at Lawrence Livermore Laboratory used 21-6-9 as its main structural material; the welding problem was circumvented by the use of high nickel (Inconel 182) filler metal at a sacrifice in mechanical properties. Alloy 21-6-9 is covered by a number of standard specifications; the plate is grade XM-11 in American Society for Testing and Materials (ASTM) A412-75.²²

American Iron and Steel Institute (AISI) 310S is an older austenitic steel developed for service in high-temperature oxidizing environments; its nominal composition is 25 wt% Cr, 20 wt% Ni, 1 wt% Mn, 0.08 wt% C max., balance Fe. This steel makes up for a lower yield strength (about 750 MPa or 110 ksi at 4 K)²³ with austenite which is stable even under deformation at 4 K.^{16,24} There are indications,²⁵ however, that 310S goes through some sort of magnetic ordering on cooling to 4 K. The penalty imposed by the structural stability occurs during fabrication, because it is difficult to induce the formation of the 2-8% delta ferrite which improves the quality of restrained stainless welds. This difficulty, which is especially pronounced in autogenous processes (those without filler, such as electron beam welding), may call for special designs to avoid constrained welds in assemblies in which 310S is used. If this alloy is determined to be satisfactory in other respects, a welding development program would be a wise investment.

AISI 304 is one of the most widely used stainless steels for both cryogenic and general service. Its nominal composition is 19 wt% Cr, 9 wt% Ni, 1 wt% Mn, 0.08 wt% C max., balance Fe. A low-carbon version, 304L, has slightly more nickel and a maximum carbon content of 0.03 wt%. The purpose of the low carbon content is to prevent the formation of metal carbides along grain boundaries in weld heat-affected zones.

Because of the extent of their use, the weldability of both alloys has been extensively studied and documented. Fabrication techniques are probably better known for 304 and 304L than for any other possible coil structural material. Aside from comparatively poor yield strength — as low as 400 MPa (60 ksi) for 304L at 4 K²⁶ — use of these alloys is hindered by their susceptibility to low temperature martensite formation.^{14,16,23} The transformation occurs on cooldown without mechanical stress or deformation and is irreversible. The permeability of the alloy is, however, quite small²⁷ even at 4 K, and this matter should be considered quite carefully before the alloy is dropped from consideration.

It is sometimes proposed that, because large magnets and pressure vessels alike have considerable potential for damage in case of failure, magnets should conform, as far as possible, to the requirements of appropriate sections of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. One respect in which the code might be used is in the selection of structural material and the design stresses allowed. Of the steels discussed so far, 310S, 304, and 304L are accepted for use in "fusion welded unfired pressure vessels."²⁸⁻²⁹ The minimum yield stresses in both ASTM²⁸ and ASME²⁹ codes are 205, 205, and 170 MPa (30,000; 30,000; and 25,000 psi) respectively. In terms of structural materials, the most important difference between superconducting magnets and the pressure vessels contemplated in SA-240 is operating temperature. The Code is based on tests and experience not much below room temperature. At cryogenic temperatures, the yield strength of an austenitic steel is higher but no extra stress is allowed by the Code. Conversely, at 4 K the notch toughness of even austenitic stainless steels is sufficiently low to require attention, but the Code assumes that such materials will behave ductilely. No toughness requirements are imposed in either the ASTM²⁸ or ASME²⁹ specifications for the steel plate itself. Section III, "Nuclear Power Plant Components," of the ASME Code includes an appendix³⁰ on linear elastic fracture mechanics for ferritic steels. Such analysis has been shown¹⁹ to be inapplicable to austenitic steels. Elsewhere in the same section,³¹ austenitic stainless steels are specifically exempted from impact testing. Section VIII, "Unfired Pressure Vessels," requires Charpy tests on all materials

below 19 K (-425°F) but the value of such tests at 4 K is in considerable question. In general, it appears that Code adherence is neither necessary nor sufficient for a sound magnet, because the Code is largely inapplicable. It may be that some years (or decades) in the future, when much more experience has been accumulated, we can write a section entitled "Large High-field Magnets." In the meantime, the Code should be consulted as a distillation of good practice in a related field, but cannot be regarded as a substitute for engineering tests, measurements, and calculations.

Aside from 21-6-9, 310S, and 304/304L, discussed above, there are other austenitic steels which have been used from time to time for superconducting devices and therefore present themselves for consideration. It is sometimes difficult to determine why a particular alloy was used in some applications. One suspects that immediate availability ("We had some on the shelf.") was the most important factor in many instances. Among the conventional Cr-Ni stainless steels used for LHe service are AISI 316, 321, and 347, all of which are commonly used at ambient temperatures in aqueous environments. These appear to be among those in which some but not all heats are susceptible to martensitic transformation.^{16,24} Steels 316, 321, and 347 are modifications of 304 for improved performance in certain corrosive environments at or above room temperature. AISI 316 has a higher yield stress at 4 K than 304; it has been proposed in some magnet designs for this reason. It is, however, less well characterized than 304. The other alloys, 321 and 347, have been used at cryogenic temperatures but confer no evident advantage over 304.

There are also several nonstandard Cr-Mn-Ni steels which have attracted interest for cryogenics. Aside from 21-6-9, discussed above, there are several steels in Armco's "Nitronic" series which appear somewhat intriguing but need much further study before they can be used. A Westinghouse steel called Kromarc 58 (10 wt% Cr, 21 wt% Ni, 10 wt% Mn, 1.25 wt% Mo, 0.08 wt% C max., 0.17 wt% N) has been extensively studied³³ and would be very interesting were it available in commercial lots on a continuing basis.

SUPERALLOYS

As used here the term "superalloy" means an iron- or nickel-base, precipitation-hardening, face-centered-cubic alloy. The iron-base superalloys are sometimes referred to as precipitation-hardening stainless steels, but for cryogenic service they have more in common with the nickel-base superalloys than with single-phase stainless steels. All the superalloys were developed for service in very high temperature, gaseous environments — gas turbines, for example — and are therefore optimized for resistance to high temperature oxidation and creep (slow deformation at constant stress). Much of the interest in their cryogenic properties arises from their use in airborne generators designed for the U.S. Air Force, and ensuing research funded by the Defense Department Advanced Research Projects Agency (ARPA). As a class, the superalloys offer a number of points to recommend them. Along with an elastic modulus near 200 GPa (30×10^6 psi), comparable to the stainless steels, they offer high yield strengths: more than 860 MPa (125,000 psi) at 4 K after heat treatment. They do not tend to transform to another microstructure at low temperatures. Ductility and toughness are reasonable when compared with other alloys operating at 4 K.

Along with these advantages, there are several points which must be considered carefully before superalloys can be used in superconducting magnets for fusion reactors. The first is that they require heat treatment to develop optimum properties. Such alloys cause problems when welded because either the entire assembly must be heat treated (at temperatures up to 1000°C for superalloys) or inferior properties must be tolerated in the region around the weld. Heat treatment for these alloys is complex; aging treatments and original melting practice interact in ways which are difficult to characterize.³⁴ Superalloys, then, become less attractive as the size of the structure or its reliance on welds increases. Superalloys are less attractive in large structures for another reason: they are expensive. Aside from containing as much as 90% nickel and chromium, these alloys require special melting and forming practice. The cost tends to be less important in a relatively small airborne generator than in a large tokamak. The last problem which must be addressed is that of magnetism. All the superalloys studied thus far exhibit some degree of

ferromagnetism.^{15,35} While the magnetic interaction is not severe, it would be more desirable to have none at all.

Having reviewed the character of superalloys as a class, we will briefly discuss a few which have been considered for liquid helium service. Trade names are used where necessary for clarity and in no way imply endorsement by Oak Ridge National Laboratory or ERDA to the exclusion of others that may be suitable. "A-286" (ASTM A-453) is an iron-base superalloy often referred to as a precipitation hardening stainless steel. With a nominal composition of 15 wt% Cr, 26 wt% Ni, 2 wt% Ti, 1 wt% Mn, 1 wt% Mo, 0.3 wt% Al, 0.01 wt% B, and balance Fe, A-286 actually is less highly alloyed than some of the single phase austenitic steels such as 310S. A-286 is not available in all forms; one pertinent ASTM specification (A453-75)³⁶ is written with high-strength bolts in mind, but sheet, bar, and plate are also available.³⁷

Inconel X-750 is the nickel-base alloy used structurally for some early airborne-type superconducting generators. It was developed a number of years ago for gas-turbine and other high-temperature service.³⁸ X-750 contains large amounts of nickel-its nominal chemistry is 15 wt% Cr, 7 wt% Fe, 2.5 wt% Ti, balance Ni.

Inconel 706 and Inconel 718 are somewhat similar to Inconel X-750 in properties and in the service they were developed for. Both contain less nickel and more iron than X-750. Inconel 706 in particular appears to have remarkably good cryogenic mechanical properties, including ductility and toughness,^{15,39} and is very interesting in applications where the high cost of nickel-base alloys can be tolerated. Nickel-base alloys in general seem to be sensitive to processing history^{15,34,39,40} and further work relating thermomechanical processing to cryogenic mechanical properties is necessary before these alloys can be used on a large scale. These are by no means the only superalloys in the Fe-Ni-Cr system, but these are the only ones for which even a reasonable amount of cryogenic data is available, and there are no others on the horizon with markedly improved properties.

ORGANIC-MATRIX ADVANCED COMPOSITES

Advanced composites are made of high elastic modulus fibers (graphite, boron, or others) in a matrix which may be either organic (epoxy, polyamide) or metallic (aluminum). The term "advanced" distinguishes them from glass-fiber composites, which are much less stiff; the two types of composites are generally not interchangeable. Because for some magnet applications the nature of the matrix is important, we will discuss organic-matrix composites and metal-matrix composites separately. Properties of composites will only be commented on here; the interested reader is referred to Kasen's recent thorough reviews on cryogenic behavior of composites.^{7,41} Advanced composites are very much developmental materials, and one may reasonably hope for rapid progress in alleviating their problems. At present, however, their use is justified only where some specific combination of properties unavailable elsewhere is required.

Organic-matrix composites still do have a few distinct points in their favor. Tensile strengths and elastic moduli in the fiber direction are comparable to, and in some cases better than, stainless steels. The composites may often be joined adhesively, using a resin similar to the matrix material. They possess low densities, which are convenient in magnets if less important than in air frames. The quality that really makes organic-matrix composites interesting to magnet designers, however, is their minimal interaction with both constant and changing electromagnetic fields. Because both fiber and matrix are electrical insulators, eddy currents due to changing magnetic fields are negligible. The elimination of these eddy currents, which can be a substantial heat source in tokamak poloidal coils, is the principal reason that interest in advanced composites is more than speculative. Also, a nonconductive structure may reduce or eliminate the need for insulation as a discrete part of the winding. The fact that the other elements of the winding are, in a sense, geometrically linear raises interesting possibilities of special designs to take advantage of the essentially linear nature of composites.

Against these advantages must be counted a number of problems, some of which seem inherent in the material and some of which may be ameliorated

as composites come into more common use. Those areas in which improvement seems most likely are unconventionality and high cost. Engineering experience with composites is limited at all temperatures and almost nonexistent in the range near 4 K. Designers are justifiably hesitant about using a material with which they have no experience and which, moreover, is qualitatively different from its predecessors. The presently high cost of advanced composites may also be expected to decrease as production rates increase and techniques are developed. Their current cost restricts production use to devices where the light weight of the composites relative to their mechanical properties engenders substantial advantages elsewhere in the system, as in aircraft and some sporting goods. It should be noted here that for comparing the cost of two otherwise identical, directly substitutable materials, the appropriate parameter is cost per unit volume rather than per unit weight. A given load must be transmitted across a given distance and if stresses are the same (as we assumed above) then the volume of structural material, rather than the weight, remains constant. Because advanced composites weigh $1/6$ to $1/4$ as much as stainless steel, their cost per kilogram could be 4 to 6 times as high, given the simplistic assumptions used here. Fabrication cost must, of course, also be considered.

Advanced composites also present a number of problems which may be reduced by research but are not likely to be eliminated. They are severely anisotropic in both physical and mechanical properties. Part of the reason anisotropy is a problem is that designers are accustomed to metals, which are substantially isotropic and uniform. In a unidirectionally reinforced composite, both elastic modulus and yield strength may be less in the transverse than in the longitudinal directions by more than an order of magnitude. Crossplying of the fiber can improve properties in the second in-plane direction at the expense of the first. It is very difficult to improve properties in the direction perpendicular to the plane but stresses in this direction would appear to be small except for special circumstances. The trade-off between the first two directions presents an interesting problem for the designer, but composites developed so far are comparable with stainless steels only when optimized uniaxially and loaded uniaxially. The thermal contraction shows similar

amounts of anisotropy; the coefficient of thermal expansion in the fiber direction may actually be negative, as with graphite- and Kevlar-reinforced epoxies.⁷ Another characteristic of advanced composites for the designer to contend with is their lack of toughness and ductility. Although they are strong, composites are quite brittle below the glass transition temperature of the matrix; yield stress and ultimate tensile strength are virtually identical. They are therefore less forgiving of local over-stresses than are the metals we have been considering. The low strain to failure also reduces the amount of energy absorbed in failure, so that composites do poorly in impact-type toughness measurements. The more sophisticated crack growth approach, typified in metals by critical stress intensity factor measurements, has not yet been generalized to composites. The multitude of interfaces normal to the crack plane adds considerable complication to the theory of crack propagation. The last problem presented by organic-matrix composites is an expected lack of radiation resistance. Presumably, the composite would not have a substantially higher lifetime in a radiation flux than its matrix; most polymers degrade at about the fluences expected in the toroidal coils of a fusion reactor.⁴² Fortunately, the poloidal coils are farther away from the plasma than the toroidal coils and therefore experience less flux; it is these coils where the electrical resistivity of the composites is most important. There is some hope, therefore, that even if organic-matrix composites' radiation resistance is inadequate for the TF coils, they will be usable in the PF system.

Because a composite is made of two distinct materials, the fiber and the matrix, a number of permutations are possible and it will be useful to consider candidate fiber materials and candidate matrix materials separately. The high-modulus fibers which have been used in organic matrices are graphite, boron, and a duPont proprietary organic called "Kevlar 49."

Graphite fibers are manufactured by pyrolysis of organic fibers. Fiber elastic modulus is not constant but varies according to fabrication techniques; values up to about 500 GPa (75×10^6 psi) are available. The composite, of course, will have a net modulus in the fiber direction which is less by the packing factor. Transverse moduli will be

considerably lower. Graphite is the most frequently used high modulus fiber and the one about which the largest amount of data has been accumulated. It is also the least expensive.

Amorphous boron fibers are produced by chemical vapor deposition onto a wire (usually tungsten) substrate. Because of the more complicated production process, they cost more than graphite fibers. The advantage boron offers is a higher breaking stress than the high modulus graphites, but about the same modulus. The combination is probably the cause of boron composites' higher toughness,⁷ at least at room temperatures. Because of its cost, however, boron has been pursued less aggressively as a reinforcement for polymers than graphite and would require more development for use in magnets.

Kevlar 49 is a duPont proprietary aromatic polyamide fiber. Its strength is comparable to that of graphite or boron but the elastic modulus is less, about 130 GPa (19×10^6 psi). For this reason it probably cannot be substituted for the other fibers in structures whose elastic stiffness is important, but it does offer an interesting alternative to glass fibers of modulus 70-85 GPa ($10-12 \times 10^6$ psi).

As a class, epoxies are used far more often than any other organic as the matrix material in advanced composites. Epoxies share a common polymerization reaction but vary widely in monomer chemistry and additives and therefore in mechanical and physical properties. Most epoxies not optimized for cryogenic service are quite brittle at low temperatures, while formulations for low temperatures creep at temperatures above ambient. Epoxy matrix composites for low temperatures may have to be made with cryogenic-optimized epoxies, such as that used in the LN₂-cooled ORMAK toroidal field coils or the "NASA 2" resin, rather than those presently used; further development would then be necessary to adapt the laminating process and low-temperature matrix materials to each other. This does not appear to be a major problem, but it should be dealt with before epoxy-matrix advanced composites are committed for use in a superconducting magnet.

Several other polymeric materials, including polyurethane, polyamide, and epoxy/phenolic, have been used as advanced-composite matrices. These would be attractive to us if it were demonstrated that their

cryogenic mechanical properties were superior to those of the epoxies, without too much extra cost or difficulty of fabrication.

METAL-MATRIX ADVANCED COMPOSITES

We discuss metal-matrix composites separately because their high electrical conductivity means that they offer no reduction in eddy currents over conventional metallic structure. (In fact, resistivity is lower and eddy currents higher in the composites than in stainless.) The metal-matrix composites must therefore justify themselves compared to stainless steel through mechanical properties, design considerations, or fabrication convenience. They have some interesting attributes, but at the moment are both less developed and more expensive than the stainless steels; their future prospects are better than current realities.

Metal-matrix composites are reliably paramagnetic; they show neither phase transformations nor any of the magnetic transitions peculiar to iron- and nickel-base austenitic alloys. In addition, the composites show reasonably low densities, about a third that of steel, which are useful although not critical. A number of conventional structural alloys, such as those based on aluminum, which have these advantages might be adduced; the point that makes these composites worth considering is that they have strength and stiffness comparable to those of stainless steels. The metal-matrix composites are anisotropic, but not nearly as much so as organic-matrix composites. Transverse moduli are more than half the longitudinal modulus, simplifying structural design.

Obviously metal-matrix composites have disadvantages as well, or the tone of our discussion would be different. The biggest one is their novelty. Organic-matrix advanced composites can to some extent use experience developed in fiberglass, but the metal-matrix materials are produced in an entirely different manner. Methods for fabricating them into complex, three dimensional structures are presently undeveloped. Metal-matrix composites are expensive, even compared with such advanced composites as graphite-epoxy. These problems — lack of experience, fabrication questions, and cost — are likely to be alleviated with development and use. Others, however, seem to be inherent in the nature of certain

classes of composites. All the commercial metal-matrix composites to date use an aluminum alloy (typically 6061). Even alloyed aluminum is more electrically conductive than stainless steel by more than an order of magnitude, and since the matrix is continuous in the composite the composite will be similarly conductive. For pulse coils, then, the metal-matrix composites are even less suitable in this respect than stainless steel. The other problem is peculiar to composites with boron fibers, but since these are the most common in metal-matrix composites the difficulty is important. Boron's exceptionally high cross section for thermal neutrons causes apprehension about both structural damage to the filament and heat input to the cryogenic system. More study will certainly be necessary to evaluate the importance of radiation effects on boron-reinforced composites of any matrix.

All current metal-matrix composites use an aluminum-alloy matrix, but a remarkable variety of reinforcing materials has been used as both fibers and sheets. The most common is boron fibers, either plain or coated with silicon carbide (Borsic filaments). The transverse mechanical properties of B-Al, already high for composites, may be improved at some sacrifice in longitudinal properties by including sheets of titanium or steel in the composite. Stainless-steel wires have also been used to reinforce aluminum. An interesting composite under development by Alcoa and DuPont consists of continuous alumina (Al_2O_3) fibers in an aluminum matrix; it remains to be seen whether this will become a commercial product.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

OTHER STRUCTURAL ALLOYS AND MATERIALS SYSTEMS

There are a number of materials which have been used or proposed as structural materials in superconducting magnets, but for various reasons seem inappropriate to large high field coils of the sort needed for tokamaks. We will deal with these here. It should be recognized that reasonable persons might differ on several judgments below, but that the issues raised must be dealt with in any magnet design using these materials structurally.

COPPER AND COPPER ALLOYS

Most designers of electrical machinery are familiar with copper from using it at room temperature. Its mechanical properties at liquid helium temperatures will give them few surprises. It remains usefully tough and ductile, but also comparatively weak and soft (not stiff). The low stresses that could be applied to copper alloys would force the use of an excessive volume of structural reinforcement in a magnet. Wilson and Walters⁴³ have pointed out that copper which is used for stabilization may also provide significant mechanical support. They believe that in some magnets (of which they give an example) the optimum amount of stainless steel for a fixed stabilizer resistance and mechanical strain may be zero. Their analysis will, however, require careful consideration before it is applied to other magnet systems, especially those where space is limited. Because copper and its alloys are good electrical conductors, increased eddy current losses must also be expected if copper is added to carry loads.

ALUMINUM AND ALUMINUM ALLOYS

Aluminum and its alloys display a low elastic modulus (85 GPa or 12.5×10^6 psi) and either low strength or low toughness, depending on the alloy and condition. Some of the heat-treated alloys, such as 6061-T6, have yield stresses comparable to that of stainless steel 304, but the aluminum alloy has only a fraction of the notch toughness of the 304 whether measured by Charpy or crack growth techniques. The low modulus

will be reflected in substantially greater deflection at a given stress. The low modulus also means that the suggestion of Wilson and Walters (above) to substitute stabilizer for purely structural material is less applicable to aluminum than to copper-stabilized conductors. Like copper, aluminum alloys are good electrical conductors and may present problems with eddy currents.

FERRITIC STEELS

In general, ferritic (body-centered-cubic) steels become brittle when cooled to low temperatures and are therefore unsuitable for cryogenic service. The addition of nickel in amounts from 5 to 12% can lower the ductile-to-brittle transition temperature (DBTT) into the cryogenic range. Commercial alloys are available with 5 wt% Ni (for liquefied natural gas service, 110 K) and 9 wt% Ni (for service down to 77 K, liquid nitrogen temperature). There is no commercial ferritic alloy with a DBTT as low as 20 K (LH_2), but a group at the Lawrence Berkeley Laboratory^{40,41} is investigating a 12 wt% Ni, 0.25 wt% Ti steel with reasonable toughness at temperatures as low as 6 K. Because it (like all ferritic alloys) is ferromagnetic, it can be used only in applications where such behavior is useful or at least tolerable. In such applications, the Berkeley alloy will be worth consideration when commercial lots become available. To date only laboratory sized heats have been made, using better-than-commercial starting materials and a complicated and expensive heat treatment. It remains to be seen what material properties can be achieved reliably in production. For the moment, however, the 12 Ni-0.25 Ti steel must be regarded as more speculative than even some of the advanced composites. The lower nickel content alloys are generally regarded as having inadequate toughness for service much below 77 K.

LOW-EXPANSION IRON-NICKEL ALLOYS

Iron-nickel alloys containing about 36 wt% Ni have, among other odd characteristics, unusually low coefficients of thermal expansion. The best known of these alloys is Invar. There may be specific points in a magnet where a minimum coefficient of expansion is desirable, but in

general it would make more sense to match the expansion of the structural material to that of other magnet materials. Conventional stainless steels are reasonably close to Nb-Ti/Cu conductor in expansion coefficient, and other materials in magnets are still higher. Designers who wish to use the Invar-class alloys should be aware that they are ferromagnetic at room temperature and below, and that their modulus is about 135 GPa⁴⁶ (20×10^6 psi), exceptionally low for iron- and nickel-base alloys. The metallurgical control necessary for predictable properties⁴⁷ and the high nickel content are both likely to make for an expensive alloy.

GLASS-REINFORCED COMPOSITES

Glass-fiber reinforced polymers (fiberglass or GRP) have been in use for a variety of purposes at ambient and cryogenic temperatures for some years, usually as thermal or electrical insulation at modest stresses. They are well suited to such applications. A number of glass-fiber composites made specifically for electrical insulation are available; one commonly used at cryogenic temperatures is G-10,⁴⁸ a glass-epoxy composite. Epoxy is the matrix most often used with glass fibers, but a variety of other organics, such as polyurethanes, phenolics, and silicones, have been used. Glass-reinforced composites do not appear to be acceptable as principal magnet structural materials, however, because of their general lack of stiffness. GRP's with uniaxial reinforcement have elastic moduli of 70-85 GPa ($10-12 \times 10^6$ psi)³⁷ in the fiber direction and a good deal less transversely; 0°/90° crossply has a modulus of 30-45 GPa ($4-6 \times 10^6$ psi).⁴¹ These values imply a good deal of elastic deflection at reasonable stress. If nonconductive structure is necessary for the pulse coils, then glass-reinforced composites might be an alternative to more advanced ones, but fairly extensive design changes would be necessary to use the lower-modulus material.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

SPECIAL-PURPOSE MATERIALS

POTTING MATERIALS

In a number of magnet designs a fluid or semifluid material is emplaced in the coil and then converted to a solid for the purpose of supporting individual elements of the conductor. These materials are known collectively as potting compounds. Those proposed include epoxies, hydrocarbons (oil and paraffin), water, and nitrogen.⁴⁹ The choice among them depends in part on the layout of the particular magnet being designed.

The most universal potting compound is epoxy, formulated and applied in a variety of ways. It may be applied during winding (wet lay-up); after winding (impregnation); or in the form of a tape, usually glass fiber, which is impregnated with epoxy, partially cured, and then emplaced (prepreg). After application, the epoxy is polymerized ("cured") at either room or elevated temperature before service. To avoid damage to other magnet components, the curing temperature should be below 170°C. The general brittleness of epoxies has been implicated⁴⁹ in unpredictable coil behavior, such as training, and other materials have been suggested and used. These are intended to serve as filler materials within a structural case and are not expected to transmit tensile loads. The fillers which are fluid at room temperature, such as transformer oil, water, and nitrogen, offer as advantages easy emplacement at the time of construction and easy replacement afterwards if radiation degradation should occur. The choice of filler material is likely to be made when the construction of the magnet is decided; different fillers are appropriate to different application methods and magnet designs.

LOAD-CARRYING THERMAL INSULATION

At several points in the magnet, it is necessary to transmit mechanical loads across the thermal barrier. Because superinsulation has negligible mechanical strength, another component must be used to carry this load. Its design must be such as to minimize the thermal flux along it. This is achieved by maximizing length and minimizing cross-section and thermal conductivity. For a given mechanical load, the way to reduce the

cross section is to use a stronger support material at higher stresses. The load bearing thermal insulation should, then, have a low thermal conductivity from 300 K to 4 K and permit a high working stress. The currently preferred material is epoxy uniaxially reinforced with glass fiber, loaded in tension because thin members loaded in compression tend to buckle. Some advanced composites offer higher working stress, but because both their cost and their thermal conductivities⁴¹ are higher, they do not appear to be preferable to fiberglass.

FURTHER WORK

At this point it seems useful to discuss the further research which is necessary to confidently choose and design structural materials for superconducting magnets for tokamaks. There is a temptation to describe an ideal material and to regard the description as a challenge to material producers. Unfortunately, even if such a material were invented tomorrow, it would not be available as a commercial product for several early devices. Work on entirely new materials designed for structural service at 4 K would be useful and should be pursued, but must not be regarded as a substitute for efforts aimed at qualifying existing materials for use in LHe. Devices for at least the next 10 years will have to use materials which are presently either commercially available or at an advanced stage of development. Research efforts in these materials can be closely planned to address specific problem areas.

The alloys which seem best suited to superconducting magnets, the stainless steels and the superalloys, share a common need for work on joining techniques and characterization with respect to melting practice and heat treatment. The work which has been done so far^{34,39,40} demonstrates the wide variation which may occur in the mechanical behavior of apparently similar materials. Designers must be provided with data on the minimum properties they can expect when they choose a particular alloy and specify it in a particular way. Typical property values are fairly abundant, but a good measure of the range of each parameter is lacking. Minimum value data will be particularly necessary if magnet structures are to be designed in the spirit of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code. Such data can only be generated from a substantial number of well understood tests which measure those properties relevant to magnet performance.

One of the few things most magnet designs using metallic structures seem to have in common is that they are fabricated by welds which are difficult to make. Constrained welds are quite common; a number of layouts use continuous welds of one sort or another. Enough work has been done welding 304 stainless that it should be relatively straightforward to weld, but the others are either inherently difficult to weld or novel

and not thoroughly developed. In general, most of the problems with each alloy have been identified and welding development efforts need not be shots in the dark. Particular issues known from the outset can be studied. Once sound welds have been achieved, their mechanical properties must be characterized sufficiently well for use in design. Presumably the same organization could measure the properties of both the base metal and the weldments.

The first question which must be answered about the use of advanced composites in large magnets is, "Are they necessary?" An answer will require a good estimate of the losses produced by eddy currents in a reasonable metallic poloidal coil structure and a judgment of whether such losses can be tolerated. If they are tolerable, work on advanced composites may be an unwise diversion of resources. If, however, the eddy current losses seem to be substantial, then a good deal of work will be necessary to learn enough about these relatively new materials to use them safely. The same joining and characterization questions which affect the alloys apply here as well, but with much less technological background. Use of composites is likely to call for changes in magnet design which must yet be assessed. The radiation resistance of the organic-matrix composites must also be evaluated. If there is a reasonable chance that advanced composites will be needed, work should be started as early as possible because a number of areas require investigation.

SUMMARY

Structural materials for large superconducting magnets for tokamak-type fusion reactors can be evaluated in terms of their allowable working stress, their radiation resistance, their electromagnetic interaction, and their general feasibility. For general use, it appears that the most suitable material is either an austenitic stainless steel such as AISI 304, AISI 310S, or 21-6-9 or a nickel-chromium-iron precipitation-hardening alloy. In situations where eddy currents from pulsed magnetic fields are a major problem, graphite- or boron-reinforced composites may be necessary. Characterization and joining studies will be necessary to put magnet structural design on a firm basis.

Representative material properties at 4 Kelvin.

	E, Young's modulus, GPa	σ_y , yield stress, MPa ^c	Toughness ^d	Radiation ^d resistance	Magnetic character	Electrical resistivity $\Omega \cdot m$	Availability	Ease of fabrication	Engineering experience at 4 K
Austenitic stainless steels	200	400-1200	F-G	G	Para-ferro-magnetic	5×10^{-7}	G	F-G	G
Fe- and Ni-base superalloys	200	750-1400	F-G	G	Ferro-magnetic	1×10^{-6}	F	F	F
Polymer-matrix advanced composites	135-225/ ^a 7-35	1100-1500/ 40 ^a	P	P	Para-ferro-magnetic	Very high	P	P	P
Metal-matrix advanced composites	250/150 ^a	1400/ 130 ^a	P	F ?	Para-ferro-magnetic	2×10^{-8}	P	P	P
Copper alloys	140	60-1000	F	G	Dia-magnetic	1.1×10^{-11} 6×10^{-8}	G	F	F
Aluminum alloys	70	65-570	P-G	G	Para-ferro-magnetic	5.6×10^{-11} 2×10^{-8}	G	F	F
Ferritic steels	200	1400-2200	P	G	Strongly ferro-magnetic	3×10^{-5}	G	G	P
Low-expansion Ni alloys	140	850-1300	F	G	Ferro-magnetic	5×10^{-7}	P	F	P
Glass-reinforced composites	70 ^b	20 ^b	P	P	Para-ferro-magnetic	Very high	G	G	G

NOTES:

1 GPa = 1.45×10^5 psi1 MPa = 1.45×10^2 psi^aLongitudinal/transverse.^bAnisotropic material; value given is longitudinal.^cFailure stress for composites.^dP-Poor, F-Fair, G-Good.

ACKNOWLEDGMENTS

I acknowledge with thanks the help of my colleagues in the Superconducting Magnet Development Program, especially J. K. Ballou, R. W. Derby, W. H. Gray, and W.C.T. Stoddart; review of this paper by R. K. Nanstad of the Metals and Ceramics Division, ORNL; and the advice and early data given me by R. P. Reed of the National Bureau of Standards, Boulder, and J. M. Wells of Westinghouse Research Laboratories, Pittsburgh.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

REFERENCES

1. W. M. Stacey, Jr. et al., Tokamak Experimental Power Reactor Studies, ANL/CTR-75-2, Argonne National Laboratory, Argonne, Illinois (1975).
2. GAC Fusion Engineering Staff, Experimental Power Reactor Conceptual Design Study, GA-A13534, General Atomic Company, San Diego, California (1976).
3. M. Roberts et al., Oak Ridge Tokamak Experimental Power Reactor Study Reference Design, ORNL/TM-5042, Oak Ridge (1975).
4. E. S. Fisher and S. H. Kim, "Critical Current Changes and Fatigue Damage after 4.2 K Strain Cycling of Superconducting Composites," paper presented at the 1976 Applied Superconductivity Conference, Palo Alto, California, August 1976.
5. H. I. McHenry, "Fracture Mechanics and Its Application to Cryogenic Structures," paper presented at the International Cryogenic Materials Conference, Kingston, Ontario, July 1975.
6. J. Eftis and H. Liebowitz, "On Fracture Toughness Evaluation for Semi-Brittle Fracture," Eng. Fracture Mechanics 7: 101-135 (1975).
7. M. B. Kasen, "Mechanical and Thermal Properties of Filamentary-Reinforced Structural Composites at Cryogenic Temperatures. 2: Advanced Composites," Cryogenics 15: 701-722 (1975).
8. T. Lyman (ed.), Metals Handbook, 8th edition, Vol. 1, p. 14, American Society for Metals, Cleveland, Ohio, 1961.
9. C. A. Flanagan (ORNL) to J. K. Ballou (ORNL), private communication, 1976.
10. C. D. Henning, "New Directions in Fusion Magnet Development," abstract, Applied Superconductivity Conf., Palo Alto, California, 1976.
11. See, for example, Science 191: 4228 (1976).
12. H. E. Goeller and A. M. Weinberg, "The Age of Substitutability," Science 191: 683-689 (1976).
13. R. C. Kirby and A. S. Prokopovitch, "Technological Insurance against Shortages in Minerals and Metals," Science 191: 713-719 (1976).
14. R. P. Reed and J. F. Breedis, "Low-Temperature Phase Transformations," in Behavior of Metals at Cryogenic Temperatures, ASTM Spec. Tech. Pub. 387, p. 60, Philadelphia, 1966.

15. J. M. Wells et al., "Structural Materials for Cryogenic Applications," Materials Research for Superconducting Machinery-V, National Bureau of Standards, Boulder, Colorado, 1976.
16. D. C. Larbalestier and H. W. King, "Austenitic Stainless Steels at Cryogenic Temperatures 1 - Structural Stability and Magnetic Properties," Cryogenics 13: 160-168 (1973).
17. Handbook on Materials for Superconducting Machinery, 2nd ed., p. 8.2.3-1, Metals and Ceramics Information Center, Columbus, Ohio, 1975.
18. R. L. Tobler and R. P. Reed, "Tensile and Fracture Behavior of a Nitrogen-Strengthened, Chromium-Nickel-Manganese Stainless Steel at Cryogenic Temperatures," Materials Research for Superconducting Machinery-IV, National Bureau of Standards, Boulder, Colorado, 1975.
19. R. L. Tobler et al., "Fatigue and Fracture Toughness Testing at Cryogenic Temperatures," Materials Research for Superconducting Machinery-II, National Bureau of Standards, Boulder, Colorado, 1974.
20. R. L. Tobler (National Bureau of Standards) to C. J. Long (ORNL), personal communication, 1975.
21. W. S. Bennett and G. S. Mills, "GTA Weldability Studies on High Manganese Stainless Steel," Welding J., 53: 548-S-553-S (1974).
22. A412-75, Standard Spec. for Stainless and Heat-Resisting Chromium-Nickel-Manganese Steel Plate, Sheet and Strip, 1976 Annual Book of ASTM Standards, Part 3, Philadelphia, Pennsylvania, 1976.
23. Handbook on Materials for Superconducting Machinery, p. 8.1.4-1, Metals and Ceramics Information Center, Columbus, Ohio, 1975.
24. R. P. Reed and R. P. Mikesell, "The Stability of Austenitic Stainless Steels at Low Temperatures as Determined by Magnetic Measurements," Adv. Cryogenic Eng. 4: 84-100 (1960).
25. Handbook on Materials for Superconducting Machinery, p. 8.1.8-7 - 8.1.8-9, Metals and Ceramics Information Center, Columbus, Ohio, 1975.
26. Handbook on Materials for Superconducting Machinery, p. 8.1.3-0.2, Metals and Ceramics Information Center, Columbus, Ohio, 1975.
27. Handbook on Materials for Superconducting Machinery, p. 8.1.3-8, Metals and Ceramics Information Center, Columbus, Ohio, 1975.

28. A240-75a, "Standard Spec. for Heat-Resisting Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Fusion-Welded Unfired Pressure Vessels," 1976 Annual Book of ASTM Standards, Part 3, Philadelphia, Pennsylvania, 1976.
29. "Specification for Stainless and Heat-Resisting Chromium and Chromium-Nickel Steel Plate, Sheet, and Strip for Fusion-Welded Unfired Pressure Vessels," SA-240, Sect. II, Part A, ASME Boiler and Pressure Vessel Code, New York, 1974.
30. "Protection Against Nonductile Failure," Sect. III, Subsect. NA, App. G., ASME Boiler and Pressure Vessel Code, New York, 1975.
31. "Fracture Toughness Requirements for Materials," Sect. III, Subsect. NB2300, ASME Boiler and Pressure Vessel Code, New York, 1975.
32. W. M. Stacey, Jr. et al., Tokamak Engineering Technology Facility Scoping Study, ANL/CTR 76-1, Argonne National Laboratory, Argonne, Illinois (1976).
33. Handbook on Materials for Superconducting Machinery, p. 8.2.2-1 - 8.2.2-12, Metals and Ceramics Information Center, Columbus, Ohio, 1975.
34. G. G. Lessman et al., "Structural Materials for Cryogenic Applications," in Materials Research for Superconducting Machinery-II, National Bureau of Standards, Boulder, Colorado, 1974.
35. Handbook on Materials for Superconducting Machinery, p. 6.2.2-16.2 - 6.2.2-16.4, 6.2.3-22.1, Metals and Ceramics Information Center, Columbus, Ohio, 1975.
36. A 453-75, "Standard Spec. for Bolting Materials, High-Temperature, 50 to 120 ksi Yield Strength, with Expansion Coefficients Comparable to Austenitic Stainless Steels," 1976 Annual Book of ASTM Standards, Part 1, Philadelphia, Pennsylvania, 1976.
37. Handbook on Materials for Superconducting Machinery, p. 8.2.1-1 - 8.2.1-10.5, Metals and Ceramics Information Center, Columbus, Ohio, 1975.
38. S. L. Hoyt (ed.), ASME Handbook - Metals Properties, 1st edition, p. 424, Amer. Soc. Mech. Eng., New York, 1954.

39. J. M. Wells et al., "Structural Materials for Cryogenic Applications," Materials Research for Superconducting Machinery-IV, National Bureau of Standards, Boulder, Colorado, 1975.
40. J. M. Wells et al., "Structural Materials for Cryogenic Applications," Materials Research for Superconducting Machinery-III, National Bureau of Standards, Boulder, Colorado, 1975.
41. M. B. Kasen, "Properties of Filamentary-Reinforced Composites at Cryogenic Temperatures," in Composite Reliability, ASTM Spec. Tech. Pub. 580, p. 586-611, Philadelphia, Pennsylvania, 1975.
42. J. F. Guess et al., A Survey of Radiation Damage Effects in Superconducting Magnet Components and Systems, ORNL/TM-5187, Oak Ridge (1975).
43. M. N. Wilson and C. R. Walters, Development of Superconductors for Fusion Technology, RL-76-038, Rutherford Laboratory, Chilton, Berkshire, U. K. (1976).
44. S. Jin, J. W. Morris, Jr., and V. F. Zackay, "Grain Refinement Through Thermal Cycling in an Fe-Ni-Ti Cryogenic Alloy," Met. Trans. A 6A: 141-149 (1975).
45. Sungho Jin, S. K. Hwang, and J. W. Morris, Jr., "Comparative Fracture Toughness of an Ultrafine Grained Fe-Ni Alloy at Liquid Helium Temperature," Met. Trans. A 6A: 1569-1575 (1975).
46. Handbook on Materials for Superconducting Machinery, p. 6.3.1-2, Metals and Ceramics Information Center, Columbus, Ohio, 1975.
47. M. A. Hunter, "Low-Expansion Alloys," p. 816-818 in Metals Handbook, 8th edition, Vol. 1, ed. by T. Lyman, American Society for Metals, Cleveland, Ohio, 1961.
48. "Industrial Laminated Thermosetting Products," Standards Publication No. LI 1-1971 (revised 1972 and 1975), National Electrical Manufacturers Association, New York, 1975.
49. P. F. Smith and B. Colyer, "A Solution to the 'Training' Problem in Superconducting Magnets," Cryogenics 15: 201-207 (1975).

INTERNAL DISTRIBUTION

1. W. C. Anderson	37. H. E. McCoy
2. J. K. Ballou	38. H. C. McCurdy
3. C. R. Brinkman	39. J. R. Miller
4. R. L. Brown	40. R. V. Miskell
5. E. H. Bryant	41. A. J. Moorhead
6. P. B. Burn	42. O. B. Morgan
7. W. D. Cain	43. R. K. Nanstad
8. D. D. Cannon	44. H. Pih
9. D. A. Canonico	45. H. Postma
10. J. F. Clarke	46. M. Roberts
11. F. L. Culler	47. M. W. Rosenthal
12. L. Dresner	48. J. L. Scott
13. J. F. Ellis	49. R. E. Schwall
14. W. A. Fietz	50. T. E. Shannon
15. A. P. Fraas	51. S. S. Shen
16. K. J. Froelich	52. J. E. Simpkins
17. W. H. Gray	53. D. Steiner
18. P. N. Haubenreich	54. W. C. T. Stoddart
19. J. P. Kois	55. P. B. Thompson
20. G. G. Kelley	56. P. L. Walstrom
21. C. G. Lawson	57. J. R. Weir
22-27. C. J. Long	58. H. T. Yeh
28. H. M. Long	59. A. Zucker
29. J. K. Lovin	60-61. C. R. Library
30-32. M. S. Lubell	62. CTR Reports Office
33. K. C. Liu	63. Document Ref. Section
34. J. W. Lue	64-65. Lab. Records Dept.
35. J. N. Luton	66. Lab. Records, ORNL, R.C.
36. W. R. Martin	67. Patent Office
	68-69. F. E. D. Library

EXTERNAL DISTRIBUTION

70. E. Adam, Airco, 100 Mountain Avenue, Murray Hill, NJ 07974.
71. J. W. Beal, DCTR, ERDA, Mail Stop G-234, Washington, DC 20545.
72. R. W. Boom, 513 Engineering Research Building, University of Wisconsin, Madison, WI 53706.
73. J. L. Christian, General Dynamics/Convair, San Diego, CA 92112.
74. A. F. Clark, National Bureau of Standards, Boulder, CO 80302.
75. D. L. Coffey, American Magnetics Inc., P. O. Box R, Oak Ridge, TN 37830.
76. D. N. Cornish, Lawrence Livermore Laboratory, P. O. Box 808, Livermore, CA 94550.
77. M. D'Agostino, Grumman Aerospace Corp., Bethpage, NY 11714.
78. E. N. C. Dalder, DMFE, ERDA, Mail Stop G-234, Washington, D.C. 20545.
79. J. E. Darby, Jr., CTR Program D208, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439.
80. R. W. Derby, 247 Third Street, Cambridge, MA 02141.
81. Director, Research & Technical Services Division, ERDA, Oak Ridge Operations, Oak Ridge, TN 37830.

82. R. W. Fast, Manager, Experimental Facilities, National Accelerator Laboratory, P. O. Box 500, Batavia, IL 60510.
83. J. J. Ferrante, General Electric Co., Schenectady, NY 12345.
84. J. File, Princeton University, Plasma Physics Laboratory, Princeton, NJ 08540.
85. R. J. Foley, DMFE, ERDA, Mail Stop G-234, Washington, D.C., 20545.
86. W. S. Gilbert, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94120.
87. R. W. Gould, Dept. of Applied Physics, California Institute of Technology, Pasadena, CA 91109.
88. H. Grad, Courant Institute, New York University, 251 Mercer Street, New York, NY 10012.
89. E. Gregory, Airco, 100 Mountain Avenue, Murray Hill, NJ 07974.
90. W. V. Hassenzahl, Los Alamos Scientific Laboratory, P. O. Box 1663, Los Alamos, NM 87544.
91. C. D. Henning, DMFE, ERDA, Mail Stop G-234, Washington, DC 20545.
92. G. K. Hess, DMFE, ERDA, Mail Stop G-234, Washington, DC 20545.
93. C. F. Hickey, U.S. Army Materials & Mechanics Research Center, Watertown, NY 02172.
94. C. K. Jones, Manager, Cryogenic Research Laboratory, Westinghouse Electric Corporation, R & D Center, Pittsburgh, PA 15235.
95. E. E. Kintner, DMFE, ERDA, Mail Stop G-234, Washington, DC 20545.
96. H. L. Laquer, Los Alamos Scientific Laboratory, P. O. Box 1663, Los Alamos, NM 87544.
97. C. Laverick, 543 Hampshire Lane, Boling Brook, IL 60439.
98. J. A. Mayhall, Lockheed, P. O. Box 1103, Huntsville, AL 35807.
99. D. B. Montgomery, MIT, National Magnet Laboratory, 170 Albany Street, Cambridge, MA 02139.
100. F. Moon, Dept. of Theoretical & Applied Mechanics, Cornell University, Ithaca, NY 14850.
101. R. W. Moses, Jr., University of Wisconsin, Madison, WI 53706.
102. Jacques Parain, Stipe Saclay, B.P. No. 2, 91190 Gif sur Yvette, France.
103. J. R. Powell, Brookhaven National Laboratory, Upton, NY 11973.
104. J. R. Purcell, General Atomic Company, P. O. Box 81608, San Diego, CA 92138.
105. P. Reardon, PPPL, Princeton Univ., P. O. Box 451, Princeton, NJ 08540.
106. R. P. Reed, National Bureau of Standards, Boulder, CO 80302.
107. J. D. Rogers, Q-26, Los Alamos Scientific Laboratory, P. O. Box 1663, Los Alamos, NM 87544.
108. D. J. Rose, Dept. of Nuclear Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139.
109. C. H. Rosner, Intermagnetics General Corp., Charles Industrial Park, New Karner Road, Guilderland, NY 12084.
110. W. B. Sampson, Brookhaven National Laboratory, Upton, Long Island, NY 11973.
111. Z. J. J. Stekly, Magnetic Corporation of America, 179 Bear Hill Road, Waltham, MA 02154.
112. B. P. Strauss, Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, IL 60510.

- 113-139. TIC, Oak Ridge, TN 37830. (27)
- 140. C. E. Taylor, Lawrence Livermore Laboratory, P. O. Box 808, L-384, Livermore, CA 94551.
- 141. R. Thomas, General Atomic Company, P. O. Box 81608, San Diego, CA 92138.
- 142. C. von Keszycski, Grumman Aerospace Corp., Research Center, Building 26, Bethpage, NY 11714.
- 143. S. T. Wang, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439.
- 144. J. M. Wells, Westinghouse Research Laboratories, Pittsburgh, PA 15235.
- 145. J. M. Williams, DMFE, ERDA, Mail Stop G-234, Washington, DC 20545.
- 146. S. L. Wipf, Los Alamos Scientific Laboratory, Los Alamos, NM 87544.
- 147. J. Wong, Supercon, Inc., 9 Erie Drive, Natick, MA 01760.
- 148. H. H. Woodson, Chairman, Dept. of Electrical Engineering, University of Texas at Austin, Austin, TX 78712.
- 149. E. J. Ziurys, DMFE, ERDA, Mail Stop G-234, Washington, DC 20545.
- 150. K. M. Zwilsky, DMFE, ERDA, Mail Stop G-234, Washington, DC 20545.