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EFFECT OF IRRADIATION ON THE CRITICAL CURRENTS OF
ALLOY AND COMPOUND SUPERCONDUCTORS

S. T. Sekula

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EFFECT OF IRRADIATION ON THE CRITICAL CURRENTS OF
ALLOY AND COMPOUND SUPERCONDUCTORS*

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ABSTRACT

The effects of energetic-particle irradiation on the critical-current density $J_c(H)$ of several superconducting compounds and Nb-Ti alloys have been examined by a number of workers. The irradiations used in the investigations include electrons, fast neutrons, ions, and fission fragments. The results of these studies are reviewed and summarized. In the alloys, changes in $J_c(H)$ on irradiation depend on the metallurgical history of the material and indicate that radiation defects modify the strength of the interaction between the fluxoid array and the sample microstructure. Radiation defects in alloys can also affect $J_c(H)$ through small decreases in T_c , the transition temperature and ρ , the normal-state resistivity. Irradiations of Al5 compounds up to moderate fluences (dependent on the type and energy of irradiating particle) lead to decreases in T_c of $\sim 1^\circ\text{K}$ and increases in $J_c(H)$ with dose for most of the samples investigated. This result can be qualitatively understood as resulting from radiation-induced changes in ρ and the pinning force acting on the fluxoids. At higher dose levels, significant depressions of T_c and possibly γ , the electronic specific heat coefficient, lead to drastic reductions in $J_c(H)$. The effect of various energetic particles and irradiation temperature on changes in $J_c(H)$ are discussed.

*Research sponsored by Energy Research and Development Administration under contract with Union Carbide Corporation.

EFFECT OF IRRADIATION ON THE CRITICAL CURRENTS OF ALLOY AND COMPOUND SUPERCONDUCTORS

S. T. Sekula

INTRODUCTION

It is the intent of this review to summarize existing experimental information on the effect of energetic-particle irradiation on the critical-current density $J_c(H)$ of superconducting alloys and compounds. The production of radiation defects in metals has been discussed in detail by Schilling,⁽¹⁾ while Sweedler has described the influence of damage on T_c , the transition temperature, and H_{c2} , the upper critical field.⁽²⁾ The topics of elementary interactions between a single pinning defect and the fluxoid array and also the summation of these individual pinning forces to calculate a volume-pinning-force density, F_p , have been treated by Kramer.⁽³⁾ The critical-current density $J_c(H)$ is intimately related to these parameters, and indeed a large number of investigations have shown that fast-particle irradiation leads to changes in $J_c(H)$ of superconductors as reflected in measurements of lossless dc transport current, magnetization and ac losses. Discussions of radiation effects in elemental, alloy, and compound superconductors have been presented in earlier reviews.⁽⁴⁻⁶⁾

An examination of published reports on radiation effects in superconductors reveals that the materials studied were irradiated using various energetic particles (fast neutrons, fission fragments, electrons, and ions). It is convenient to consider the effect of radiation on alloys

and compounds as two distinct classes, since in the alloys the transition temperature is not as drastically altered by irradiation as is the case for Al5-structure superconductors.⁽²⁾ In addition, it has been pointed out that the damage per incident particle and the resultant configuration of defects are highly dependent on the type and energy of incoming particle as well as the temperature during irradiation.⁽¹⁾ For this reason, in the following discussion, a grouping is made as to the type of irradiating particle employed for the investigation, as well as the temperature during irradiation. Radiation-damage experiments on alloy and compound superconductors have been carried out primarily on materials of technological interest which usually contain one or more types of fluxoid-pinning defects; e.g., dislocations, dislocation cell walls, and second-phase precipitates. The influence of radiation damage on $J_c(H)$ of these materials has been found to be highly dependent on the previous metallurgical history and at present is understood only qualitatively. Consequently, in the ensuing summary, some regard is given to the initial condition of the samples.

A necessary framework for a discussion of radiation effects in superconductors includes an understanding of features of the type-II superconductors and the mechanisms of pinning of fluxoids in the mixed state by defects. These topics have been treated by Kramer^(3,7,8) and by others⁽⁹⁻¹¹⁾ in detail. In this review, only salient features of the current understanding are presented which qualitatively indicate how $J_c(H)$ can be altered by radiation damage through interaction of the radiation defects with existing sample imperfections and fluxoids, and also through

alteration of parameters of the superconductor (the transition temperature T_c , the low-temperature electronic specific heat coefficient γ , and the normal-state resistivity ρ).

In the critical-state model of a type-II superconductor in the mixed state, the pinning of the fluxoid lattice by imperfections leads to a critical-pinning-force density $\vec{F}_p(B, T)$ given by

$$\vec{F}_p(B, T) = \vec{B} \times \vec{J}_c(B, T), \quad (1)$$

where $J_c(B, T)$ is the critical-current density and B is the local value of the magnetic induction. $J_c(B, T)$ can be determined experimentally by a number of techniques, and one common way is to measure the maximum transport current density that can flow in a wire sample without power dissipation. For the simple case of transport current flow transverse to an applied magnetic field H and for superconductors with large values of the Ginzburg-Landau (G-L) parameter κ at sufficiently large values of H so that $B \approx \mu_0 H$ (μ_0 is the permeability of free space), Eq. 1 can be written as approximately

$$F_p(H, T) = B J_c(H, T). \quad (2)$$

$F_p(H, T)$, and hence $J_c(H, T)$, is temperature dependent and is also known to be dependent on the defect microstructure and on superconducting constants of the material (e.g., T_c and H_{c2}). Additional insight may be obtained into how radiation damage might affect F_p if one observes as Brown et al.⁽¹²⁾ that for many superconductors F_p obeys a scaling law⁽⁸⁻¹¹⁾ of the form

$$F_p(H, T) = \frac{H_{c2}^m(T)}{\kappa^n(T)} A(d) f(h) \quad (3)$$

In this expression $\kappa(T)$ is the G-L parameter and $A(d)$ is a geometrical function of the pinning microstructure. The coefficients m and n are also dependent on the type of pinning defect and usually are in the range 2 to 3. The function $f(h)$ expresses the magnetic-field dependence of F_p in reduced units $h = H/H_{c2}$. The exact form of $f(h)$ is dependent on the pinning mechanism but has the general features of being temperature independent with $f(h) = 0$ for $h = 0$ and $h = 1$, and having a maximum value at some intermediate value of h . Figure 1 shows the scaling behavior of a cold-worked Nb-66 at.% Ti alloy as determined by Wohllleben.⁽¹³⁾ From Eq. 3, the maximum pinning force $F_{PM}(T)$ can be defined as

$$F_{PM}(T) = C_1 \frac{H_{c2}^m(T)}{\kappa^n(T)} A(d) \quad (4)$$

where $C_1 = (f[h])_{\max}$. In Eq. 4, $H_{c2}(T)$ and $\kappa(T)$ can be recast in terms of electronic parameters of the superconductor. Using BCS values, the thermodynamic critical field $H_c(T)$, in the well-known expression $H_{c2}(T) = \sqrt{2}\kappa(T)H_c(T)$, can be written as $H_c(t) = 2.42 \gamma^{1/2} T_c B(t)$, where γ is the electronic specific heat coefficient and $B(t)$ describes the temperature dependence of H_c in terms of the reduced temperature $t = T/T_c$. In the dirty limit, the Gorkov-Goodman relation for the G-L parameter can be approximated as $\kappa(T=T_c) = 7.5 \times 10^{-3} \gamma^{1/2} \rho$ where ρ is the normal-state resistivity in $\mu\Omega\text{-cm}$ and γ is in units of $\text{ergs/cm}^3\text{deg}^2$. Then $H_{c2}(t)$ (in Oe) is given by

$$H_{c2}(t) = 4.67 \times 10^{-2} \gamma \rho T_c h^*(t) \quad (5)$$

where we have used the BCS expression $-\left(\frac{dH_c}{dt}\right) = 1.82 H_c(0)$. The quantity

$h^*(t)$ describes the temperature dependence of H_{c2} , which can include electron-spin and spin-orbit effects and has been calculated previously.^(14,15) Consequently, Eq. 4 can be written as

$$F_{PM}(T) = C_2 \gamma^{\left(m-\frac{n}{2}\right)} T_c^m \rho^{m-n} A(d) \left[h^*(t) \right]^{m-n} B^n(t) \quad (6)$$

where C_2 is a constant. $F_{PM}(T)$ is seen to be related to the material parameters γ , T_c , ρ , and the function $A(d)$, which is dependent on the fluxoid-pinning microstructure. The function in brackets expresses the dependence of $F_{PM}(T)$ on the reduced temperature.

To examine the influence of radiation damage by energetic-particle irradiation on $F_{PM}(T)$, we assume for illustrative purposes that the scaling law is not substantially altered by irradiation; i.e., the coefficients m and n , as well as C_1 , remain unchanged. In the limiting case at $T = 0$, it can be shown that

$$\frac{\Delta F_{PM}(0)}{F_{PM}(0)} = \left(\left(m - \frac{n}{2} \right) \frac{\partial(\ln \gamma)}{\partial \phi} + m \frac{\partial(\ln T_c)}{\partial \phi} + (m-n) \frac{\partial(\ln \rho)}{\partial \phi} + \frac{\partial[\ln A(d)]}{\partial \phi} \right) \Delta \phi \quad (7)$$

where $\Delta F_{PM}/F_{PM}$ is the fractional change in $F_{PM}(0)$ due to irradiation by a fluence increment $\Delta \phi$. At higher temperatures, the coefficient of the $\partial(\ln T_c)/\partial \phi$ term will include a function of temperature, but for brevity that will not be explored. Kramer⁽⁸⁾ has shown that a large number of superconducting alloys and compounds obey a scaling law based on a flux-line lattice shear model for which $m = 5/2$ and $n = 2$. Equation 7, which is based on a simple scaling-law model, shows that F_p and J_c can be altered by radiation through changes in γ , T_c , ρ , and $A(d)$. The degree

to which the quantities in Eq. 7 vary with irradiation depends on a number of factors including the metallurgical condition of the sample, type of irradiating particle, and the type of superconductor (alloy or compound). Thus, as Sweedler⁽²⁾ has pointed out, T_c is observed to decrease slightly on irradiating solid-solution alloys, and γ is usually taken to be unchanged, since the effect of radiation in this case can be thought of as a slight alloying influence. (However, recent work⁽¹⁶⁾ on an irradiated Nb-Ti alloy suggests a decrease in γ .) The reasons for the small decrease in T_c on irradiating alloys remain somewhat obscure. On the other hand, T_c can be drastically reduced in A15 materials by radiation damage, and studies relating to possible radiation effects on γ in A15 compounds have only recently been reported.⁽¹⁷⁻¹⁹⁾ Muller et al.⁽²⁰⁾ have shown that both T_c and γ are quite dependent on the heat treatment given the A15 compounds V_3Au and $Nb_3(Au_{0.7}Pt_{0.3})$, and the results were interpreted in terms of long-range order. One can also expect an increase in the normal-state resistivity ρ in both solid-solution alloys and compounds on irradiation, since the radiation-produced defects will decrease the electron mean free path. In ordered systems, a contribution to the resistivity increase will occur due to the destruction of long-range order.

In addition to changes in F_{PM} due to radiation defects on γ , T_c , and ρ , the pinning strength of the microstructure can be modified by radiation damage. Defect microstructures such as point defects, dislocations, dislocation cell walls, precipitates, stacking faults, and grain boundaries lead to local fluctuations in crystalline properties, and the free energy of the type-II superconductor then depends on the positions of the fluxoids relative to these fluctuations. The variation in free

energy with relative spacing between a fluxoid and a given defect gives rise to an elementary pinning force. The magnitude of the elementary pinning force depends on characteristic dimensions of the defects and fluxoids and the spacing of fluxoids, as well as the specific type of defect. Discussions of elementary pinning forces for various defect structures mentioned above have been given elsewhere.^(3,8-11) As discussed by Kramer,⁽³⁾ it is then necessary to take into account the elastic properties of the fluxoid lattice in conjunction with the elementary pinning force for a distribution of defects to arrive at a pinning-force density $F_p(H,T)$ which can be connected with the critical-current density $J_{co}(H)$ through Eq. 1.

To the list of fluxoid-pinning defects above, we may add those produced by energetic-particle irradiations that have been used in the experimental investigations of alloys and compounds and are briefly described in the following. Irradiation with electrons of several MeV produces damage in metals in the form of isolated Frenkel defects; i.e., interstitials and vacancies, distributed randomly throughout the sample. While these Frenkel defects increase the normal-state resistivity and might pin fluxoids at low defect concentrations (where the average spacing is larger than the superconducting coherence length ξ , which for high-field superconductors lies in the range 25 Å to 50 Å), at higher fluences the spacing between defects becomes comparable to or less than ξ and reduces the pinning. Flux-pinning effects due to Frenkel defects have as yet not been investigated in a systematic fashion in well-annealed alloys or compounds, although electron-irradiation studies of Nb and thermal-neutron-damage studies of V (where $\xi \sim 350$ Å) indicate that Frenkel pairs weakly pin fluxoids.⁽⁶⁾

In contrast, the damage produced by elastic collisions of fast neutrons with target atoms (with neutron energies $E > 0.1$ MeV) is in the form of defect cascades and can be thought of as regions of vacancies surrounded by an interstitial-rich cloud. At low temperatures ($\sim 4.2^\circ\text{K}$), the defects in the cascades are immobile, and the cascades range in overall diameter from about $50 \text{ \AA}$ to $200 \text{ \AA}$. The superconducting properties are locally changed in the highly damaged cascades, so that the defect cascades can interact with the fluxoid array. Defect cascades are initially created in about 10^{-10} sec, and at higher temperatures the defects may be quite mobile and undergo rearrangements and annihilation processes in times of about 10^{-6} sec. As a consequence, during irradiation at ambient reactor temperatures, the defects can form defect clusters such as vacancy or interstitial loops and voids. The processes are quite complex and depend on the temperature, the impurity concentrations (substitutional and interstitial), and dislocation content. The importance of the temperature during irradiation is best illustrated by pointing out the differences observed in the superconducting behavior of Nb on irradiating at low temperatures and at temperatures $\sim 300^\circ\text{K}$. Irradiation of single-crystal Nb at 4.6°K with fast neutrons^(21,22) shows that the pinning of fluxoids by defect cascades increases at low fluences and then begins to decrease (due to the overlap of cascades) at fluences of $\sim 2 \times 10^{18} \text{ n/cm}^2$ ($E > 0.1$ MeV). H_{c2} was observed to increase from about 2600 Oe to 3600 Oe, reflecting a large increase in the normal-state resistivity ρ . On the other hand, fast-neutron irradiations of high-purity single-crystal Nb at about 60°C ⁽²³⁾ produced dislocation loops with an average diameter of about $100 \text{ \AA}$. Even at high-dose levels (10^{19} n/cm^2 $E > 0.1$ MeV), there is no evidence for saturation or

decrease in flux pinning, since the defects are mobile and the dislocation-loop size can increase to increase flux pinning. The pinning mechanism in this case has been interpreted as arising from the interaction of the dislocation-loop stress fields with the fluxoid lattice.^(24,25) In addition, H_{c2} was observed to increase only ~ 100 Oe for a dose of 3×10^{18} n/cm² ($E > 0.1$ MeV), indicating a relatively small increase in ρ . Some investigations have also been reported showing that the dislocation-loop size in neutron-irradiated Nb is dependent on interstitial impurity content.^(25,26)

Damage production in metals by energetic-light-ion bombardment arises by Rutherford scattering. Consequently, the number of events which transfer kinetic energy to the primary knock-on target atoms are heavily biased toward low-energy events.⁽²⁷⁾ For comparison, the mean recoil energy of a primary knock-on (the target material is assumed to have an atomic mass of 50) is ~ 200 eV for a 1-MeV proton, while for a 1-MeV neutron the mean recoil energy is about 40 keV. In passing thru the target medium, the proton expends most of its energy in electronic excitation, and in the early stages of traversal of the projectile the damage production at low temperatures is in the form of isolated Frenkel pairs distributed along the particle track. As the particle nears the end of its range, the concentration of Frenkel pairs produced per unit length increases, resulting in a nonuniform distribution of Frenkel pairs along the track length. For a given ion energy, the range of an ion will decrease with mass, and more energy can be transferred to the target atoms as the masses of the target and projectile atoms become comparable. As the mass of the projectile increases, the semblance of the defect structures produced by

the ion irradiation approaches that of fast-neutron damage. Thus, a 40-keV ion with a mass of 50 will produce a defect cascade at the surface (a range of $\sim 10^{-6}$ cm) of a target with the same mass which is similar to that which can be produced by a 1-MeV neutron. At higher temperatures, heavy- and light-ion irradiations produce defect clustering as in the case of neutron irradiation at ambient reactor temperatures. The relatively short range of ions in metals points out the necessity for thin foil specimens in ion-damage studies where chemical contamination effects are to be avoided or where uniform defect distributions are desired.

Fission-fragment damage may be obtained by irradiating samples doped with fissionable impurities with thermal neutrons. The energies of the fission fragments of ^{235}U are ~ 100 MeV with a range of $10^{-3} - 10^{-4}$ cm. This results in a high rate of damage production, and at low temperatures the damage is a mixture of isolated defects and cascades; at high fluences it has been shown to be similar to fast-neutron damage. (28)

Irradiation of samples doped with ^{10}B with thermal neutrons produces lithium nuclei and α particles with a total kinetic energy of ~ 2.5 MeV, most of which is given to the α particle. In this case, the damage produced is primarily isolated Frenkel defects, as has been discussed for light ions.

Except for the elemental superconductors, investigations of fluxoid pinning by radiation defects in superconductors without additional pinning defects have not been carried out in a thorough fashion. The practical superconductors we discuss here generally contain one or more types of fluxoid-pinning defects (e.g., precipitates and dislocation structures). Our present understanding of fundamental fluxoid-defect interactions and

the difficult problem of the summation of these forces acting on a fluxoid-lattice array preclude an *a priori* prediction as to whether radiation defects enhance F_p or weaken it in these materials. Consequently, a major objective of radiation-damage experiments on alloys and compounds has been to measure $J_c(H)$ as a function of fluence over an available range of magnetic-field values and temperatures. These are compared with values of $J_c(H)$ prior to irradiation, $J_{co}(H)$, in order to determine changes in F_p due to radiation damage. In some instances, related measurements of $H_{c2}(T)$, ρ , and T_c were made, and it was possible to infer whether the pinning strength of the microstructure changed as a result of defect production. These investigations are discussed in the following sections.

I. Nb-Ti ALLOYS

Schweitzer et al.⁽²⁹⁾ irradiated commercial Nb-64 at.% Ti material with 1-MeV electrons at 3°K. The sample was a multifilamentary (MF) composite (402 twisted filaments clad in a Cu matrix [Cu:SC ratio 1:1]). Measurements at 4.2°K showed that the critical-current density of the sample (studied in fields up to 40 kOe) was unaffected after irradiation to a dose of 1×10^{19} electrons/cm². These results indicate that the isolated Frenkel defects introduced by the electron irradiation to this fluence did not increase the normal-state resistivity of the sample sufficiently to alter appreciably the pinning of fluxoids by the existing microstructure.

The effect of low-temperature fast-neutron irradiation on Nb-66 at.% Ti alloys in which the predominant flux-pinning mechanism is believed to be dislocation cell walls was investigated by Söll et al.^(30,31)

Cold-worked wire samples about 11 μm were prepared, and some of these were heat treated at various temperatures. Measurements were then made of $J_c(H)$ vs H at $\sim 5^\circ\text{K}$, which are shown in Fig. 2. The samples labeled 1 through 4 contained varying dislocation cell wall densities, while sample 5 contained α -phase Ti-rich precipitates in addition to dislocation walls. The maximum in the pinning force was found for each of these samples (Eq. 1), giving a value of J_{c0} at values of reduced magnetic induction $b(F_{\text{Pmax}}) = H_m/H_{c2}$. The value of $b(F_{\text{Pmax}})$ was found to depend on the dislocation cell wall density and served as a convenient index for the irradiation studies; samples with low dislocation cell wall densities had low values of $b(F_{\text{Pmax}})$. These samples, which showed a wide range of values of J_{c0} , were irradiated at $\sim 5^\circ\text{K}$ with reactor-spectrum neutrons to a fluence of $\sim 3.5 \times 10^{16} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$). The ratio of $J_c(H_m)$ after irradiation to J_{c0} (before irradiation) is shown in Fig. 3 plotted against $b(F_{\text{Pmax}})$. Figure 3 shows that fast-neutron irradiation led to increases in J_c for the material with the smallest wall density (sample 4), while $J_c(H_m)$ decreased for sample 1, which had a larger wall density. The increase in $J_c(H_m)$ of sample 4 by irradiation indicates that the defect cascades can pin fluxoids. The magnitude of the increase of $J_c(H_m)$, however, does not appear to be large enough to make $J_c(H)$ for sample 4 after irradiation comparable to that for the cold-worked unirradiated sample (sample 1).

The samples with small J_{c0} were not investigated at lower fluences. The question then arises as to the extent of defect-cascade overlap that might occur in these samples after irradiation to a dose of $3.5 \times 10^{16} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$). Brown^(6,22) has shown for Nb irradiated with fast

neutrons at 6°K that above a dose of $\sim 2 \times 10^{18}$ n/cm² ($E > 0.1$ MeV), $J_c(H)$ decreases with further irradiation as a result of the increasing overlap of defect cascades. It is possible that in the irradiations of Söll et al. that, although enhancement of $J_c(H_m)$ (in low- J_{co} materials) was observed, there may have been a significant overlapping of cascades in the samples. In this event, the decrease in $J_c(H_m)$ on irradiation of materials with large J_{co} might be understood in part as a decrease in the magnetic interaction; i.e., the interaction caused by the difference of the magnetic energy of fluxoids in the dislocation cells and in the cell walls. We assume that the pinning force due to the defect cascades is negligible in comparison with the pinning force of a dislocation cell core-dislocation cell wall interface. This will be especially true at large neutron doses due to cascade overlap. In this case, the net effect of the irradiation might be to increase the resistivity of the sample by an amount $\Delta\rho$.

Ullmaier⁽⁵⁾ has presented a model to account semiquantitatively for a decrease in $J_c(H)$ in materials irradiated with ions. The defects produced are isolated Frenkel pairs and do not interact strongly with the fluxoid lattice. This model characterizes the dislocation cell cores with a resistivity ρ_0 and the dislocation cell walls with a resistivity ρ' before irradiation such that $\rho' \gtrsim \rho_0$. On irradiation, the resistivities of both regions increase by an amount $\Delta\rho$ where $\Delta\rho \ll \rho_0$. Employing these features in an expression for the elementary pinning force due to a magnetic interaction, Ullmaier was able to show that a relative reduction in the volume pinning force $\Delta F_p/F_p \approx 5 \Delta\rho/\rho_0$ resulted from the ion irradiation. In view of our assumption, this result may be directly applied to understand qualitatively the reduction of $J_c(H)$ by fast-neutron irradiation of Nb-Ti

alloys with large $J_{co}(H)$. Further studies of pinning effects in a variety of Nb-Ti samples would be useful.

As may be seen in Fig. 2, the Nb-Ti sample having the largest $J_{co}(H)$ contained α -precipitates (sample 5). Irradiation to a fluence of 3.5×10^{18} n/cm² ($E > 0.1$ MeV) demonstrated a smaller fractional decrease in $J_c(H)$ for this sample than for the cold-worked sample without precipitates (sample 1). This difference suggests that the defect cascades have less effect on the pinning of fluxoids by precipitates than by dislocation cell walls.

Brown et al.⁽³²⁾ irradiated a cold-worked Nb-44 at.% Ti sample at 4.5°K to a fluence of 3.2×10^{18} n/cm² ($E > 0.1$ MeV) and observed a reduction in J_c . Couach et al.⁽³³⁾ found that J_c decreased in commercial Nb-Ti material on irradiating with fast neutrons at 77°K, with a different dose dependence for single-core (SC) and multifilament (MF) materials. A summary of the results for various low-temperature fast-neutron irradiations is given in Table 1. In addition to listing the fluence and the approximate temperature during irradiation, a brief description of the samples is given. Values of the initial critical-current density $J_{co}(H)$ are given at the measurement temperature T_M . Values of $\Delta J_c / J_{co} = (J_c - J_{co}) / J_{co}$, where J_c is the critical-current density following irradiation, are given along with some comments on annealing behavior or other features as reported by the various investigators.

A number of fast-neutron irradiations of superconducting alloys have been carried out at ambient reactor temperatures (60°C to 100°C). The increase in mobility of radiation defects at elevated temperatures not only causes defect clustering as discussed previously, but can also increase metallurgical reaction rates. Söll et al.⁽³⁰⁾ demonstrated in Nb-Ti samples

containing α -phase precipitates (sample 5 in Figs. 1 and 2) that $J_c(H)$ is somewhat resistant to low-temperature fast-neutron damage, whereas Tsubakihara et al.⁽³⁴⁾ indicate that the decrease in $J_c(H)$ of an aged Nb-60 at.% Ti sample after fast-neutron irradiation at about 70°C may be due to re-solution of α -phase precipitates.

A cold-worked sample of single-phase Nb-52 at.% Ti and one that had been partially annealed by heat treatment at 1100°C were irradiated at about 50°C in the Oak Ridge Research Reactor,⁽³⁵⁾ and measurements were made of $J_c(H)$ prior to and after fast-neutron irradiation. Irradiating to a dose of 4.8×10^{19} n/cm² ($E > 1$ MeV) increased the current density of the annealed material with low J_{co} and decreased the current density of the cold-worked sample with relatively large J_{co} . These results are qualitatively similar to those obtained by Söll et al. after low-temperature irradiation and indicate that the defect clusters can pin fluxoids in low $J_{co}(H)$ materials. The magnitude of the increase in $J_c(H)$, however, was not very large and would indicate that dislocation cell walls are a more effective pinning mechanism than defect clusters in Nb-Ti alloys. For materials with higher $J_{co}(H)$, the defect clusters weaken the pinning strength of the microstructure. Table 2 presents, in summary form, irradiation studies that have been carried out on Nb-Ti alloys at ambient temperatures. The data of Tsubakihara et al.⁽³⁴⁾ and Okada et al.⁽³⁶⁾ indicate that fast-neutron irradiation of Nb-60 at.% Ti alloys containing α -Ti precipitates results in a reduction of J_c . For Nb-48 at.% Ti alloys with large J_{co} , Okada et al.⁽³⁶⁾ show small nonsystematic changes in J_c after irradiating to a fluence of 4.2×10^{18} n/cm² ($E > 1$ MeV). Parkin et al.^(37,38) irradiated commercial multifilamentary Nb-64 at.% Ti to

fluences of 1.2×10^{20} n/cm² ($E > 1$ MeV). A reduction in J_{c0} of about 18% at $H = 40$ kOe was observed after neutron irradiation to a dose of $\sim 4 \times 10^{18}$ n/cm². Continuing irradiations above this level did not cause any further decrease in J_c . Pollock et al.⁽⁴⁰⁾ studied effects of fast-neutron irradiation on the superconducting properties of a series of cold-worked Nb-Ti-V ternary alloys. They noted reductions in T_c of about 0.3°K following irradiation to a fluence of 3.7×10^{19} n/cm² ($E > 1$ MeV). The critical current $J_c(H)$ was also observed to decrease on irradiation. These experiments have all shown that the defect clusters produced by ambient-temperature reactor irradiation modify the fluxoid pinning force due to the microstructure.

Wohlleben⁽¹³⁾ studied the effect of 3.1-MeV proton irradiation at 25°K to a fluence of 1×10^{17} p/cm². The wire sample consisted of a cold-worked Nb-66 at.% Ti core 46 μ m in diameter with a copper jacket 5 μ m thick. Since the range of the 3.1-MeV protons in Nb-Ti is approximately 48 μ m, the distribution of Frenkel defects was very likely concentrated toward the rear of the sample. Measurements were made of J_c as a function of proton dose, applied field in the range $10 \text{ kOe} < H < 80 \text{ kOe}$, and temperature in the range $2.5^\circ\text{K} < T < T_c$. Irradiation to a dose of $1 \times 10^{17}/\text{cm}^2$ led to a uniform degradation of $J_c(H)$ at a given T of about 19% over most of the magnetic-field range and led to a decrease in T_c of 0.17°K. This reduction in J_c is shown in Fig. 4, where J_c is plotted logarithmically vs the temperature prior to and after irradiation. Annealing the irradiated sample for 1 hr at 285°K restored J_c to about 92% of J_{c0} . Wohlleben found that the experimental results obeyed a scaling law

$$F_p(H, T) = A(d) H_{c2}^2(T) h(1-h) \quad (8)$$

where $A(d)$ is a material parameter dependent on the microstructure and composition. The dependence of F_p on h did not change following irradiation, showing that the predominant pinning mechanism (presumably dislocation cell walls) was relatively unaffected by the irradiation. The decrease in F_p is then related to changes in the quantities A and $H_{c2}(T)$. From Eq. 5, it can be seen that $H_{c2}(T)$ can be sensitive to radiation through the factors γ , ρ , and T_c . In the present case, γ is not expected to change significantly, and the normal-state resistivity ($\rho[10^\circ K] = 73 \mu\Omega\text{-cm}$) was not increased by the irradiation. A decrease in H_{c2} could then be ascribed to the reduction in T_c . From an analysis of his experimental data, Wohlleben was able to conclude that about 30% of the decrease in $J_{co}(H)$ was due to a decrease in T_c and 70% to a decrease in $F_{PM}(T)$, the maximum pinning-force density. Wohlleben attributes the decrease in $F_{PM}(T)$ to the production of isolated defects in the cell cores that do not act as pinning sites but decrease the cell-wall pinning in the manner suggested by Ullmaier⁽⁵⁾ and discussed previously. However, we note Wohlleben found no increase in the normal-state resistivity of his samples on irradiation, so that an interpretation of his results in terms of the magnetic interaction would necessarily be based on changes in T_c in the cell cores and walls by the irradiation.

Seibt⁽⁴¹⁾ irradiated a Nb-60 at.% Ti wire sample 12 μm in diameter with 50-MeV deuterons at $10^\circ K$. The range of 50-MeV deuterons in Nb is estimated to be $\sim 3 \text{ mm}$. For doses to $3.5 \times 10^{16} \text{ d/cm}^2$, no change in $J_c(H)$ was observed. To understand qualitatively these results in comparison with

the work of Wohleben, we can roughly estimate the concentration of Frenkel pairs produced by deuterons and protons in a sample whose thickness is small compared to the range of the ions. It can be shown that,⁽⁴²⁾ for a given target material, the concentration of Frenkel pairs generated by unit length of projectile track, C_{FP} is related to the mass of the projectile M , its energy E and atomic number Z , and constants of the target material. For the present purpose, we use the proportionality

$$C_{FP} \propto \frac{M_1}{E} \ln (\gamma E/E_D) \quad . \quad (9)$$

E_D is the threshold energy for target-atom displacement, which is taken to be 36 eV for the Nb-Ti alloys, while

$$\gamma = \frac{4M_1M_2}{(M_1 + M_2)^2} \quad , \quad (10)$$

where M_2 is the mass of the target atom. From Eq. 9, a 50-MeV deuteron produces about 17% of the Frenkel pairs generated by a 3.1-MeV proton in traversing a thin sample. Since the fluence of deuterons cited by Seibt et al.⁽⁴¹⁾ was 35% of the proton fluence used by Wohleben, the concentrations of point defects for deuteron irradiation would be only $\sim 6\%$ of that for proton irradiation in our example. In directly comparing the results of Seibt et al. and Wohleben, the relative concentration of Frenkel pairs generated in the experiments would be even smaller, since Eq. 9 underestimates the damage production of ions nearing the end of their range and which would apply to Wohleben's study. The estimated decrease in $J_c(H)$ for the 50-MeV-deuteron-irradiated Nb-Ti sample is less than 1%.

Coffey et al.⁽⁴³⁾ irradiated a Nb-61 at.% Ti specimen with 15-MeV deuterons at a temperature of $\sim 30^\circ\text{K}$ to fluences of $1 \times 10^{17}/\text{cm}^2$, the

sample thickness being about a factor of two smaller than the deuteron range. Measurements of J_c vs H were then made at 7.0°K before and after irradiation and demonstrated an overall reduction in J_c due to radiation damage. J_{c0} at $H = 25$ kOe (corresponding approximately to the maximum in the pinning force) was about 5.2×10^4 A/cm² and following irradiation decreased by about 35%. The estimated reduction in J_{c0} by the deuteron irradiation (using Eq. 9 in comparison with the results of proton irradiation) is considerably less than 35%, and the reason for this is not understood.

Ischenko and his co-workers^(16,44) recently irradiated Nb-66 at.% Ti samples with 25-MeV oxygen ions at a temperature of less than 30°K up to a dose of 3×10^{16} /cm², the sample being about 5 μ m thick, or about half the range of the ions. Electron microscopy revealed that the sample contained precipitates and a high dislocation density, but no distinct cell structure. At low fluences, the damage production is primarily in the form of Frenkel defects, and, using the more exact form of Eq. 9, we can estimate that a 25-MeV oxygen ion is 80 - 160 times more effective in producing Frenkel pairs than a 3.1-MeV proton. In a similar calculation, Söll et al.^(46,47) estimate that a 25-MeV oxygen ion is roughly equivalent to ~ 4000 fast neutrons with the energy spectrum at the Munich Research Reactor. Measurements were made of T_c and J_c as a function of oxygen-ion dose, magnetic field ($10 \text{ kOe} < H < 50 \text{ kOe}$) and temperature ($6^\circ\text{K} \leq T \leq T_c$). The pinning-force density was found to fit a scaling law given by

$$F_p(H, T) = F_{PM}(T)h^{0.6}(1-h)^{1.2} \quad . \quad (11)$$

The temperature-independent portion of the scaling was little affected by the irradiation. At low fluences (up to $4 \times 10^{15}/\text{cm}^2$), $F_{\text{PM}}(T)$ could be approximately described by the relation

$$F_{\text{PM}}(T) = A(d)H_{c2}^{\frac{3}{2}}/\kappa^2 \quad (12)$$

At a low dose of $4 \times 10^{15}/\text{cm}^2$, T_c decreased by 0.14°K from its initial value of $T_{c0} = 9.4^\circ\text{K}$, and a reduction in F_{PM} at $T = 6^\circ\text{K}$ of about 11% was noted. By extrapolating their upper-critical-field data, the investigators estimated a reduction in $H_{c2}(0)$ of 3 to 4%. Using Eq. 5 and the experimental results $\Delta T_c/T_c \approx -1\%$ and $\Delta\rho/\rho \approx +6\%$, it was concluded that $\Delta\gamma/\gamma \approx -8\%$. The reason for this significant decrease in γ is not understood and may bear further study. The reduction in F_{PM} in this investigation was attributed to changes in T_c , γ , and ρ , although one might expect, as in the case of proton irradiation,⁽³⁸⁾ some effects of radiation on $A(d)$ as well. At higher fluences, Eq. 12 did not remain valid, which suggested an additional mechanism in the reduction of F_{PM} , perhaps changes in the configuration of the pinning centers due to defect clustering. This suggestion is supported by their observation that T_c begins to increase above the $4 \times 10^{15}/\text{cm}^2$ irradiation level, so that after a dose of $3 \times 10^{16}/\text{cm}^2$ the reduction in T_c was only 0.09°K . Further evidence for this was obtained from studies of damage production as measured by resistivity changes and the annealing behavior of T_c . After irradiation to a fluence of $3 \times 10^{16}/\text{cm}^2$, F_{PM} at 6°K decreased by 20%.

A study of the results reported in this study and other ion-irradiation investigations, including recovery of J_c on annealing is given

in Table 3. On examination of Tables 1 and 3, it appears that about a 60% recovery of J_c occurs at annealing temperatures of $\sim 250^\circ\text{K}$, regardless of the irradiating particle.

The radiation-damage studies of Nb-Ti alloys using fast neutrons and ions discussed in this section indicate that reductions in $J_c(H)$ occur on irradiation of materials with large $J_{co}(H)$. These results suggest that the primary factor in decreasing $J_c(H)$ is not the morphology of the defects but is more related to the increase in resistivity, ρ , and possibly the decrease of T_c in the cell cores and dislocation cell walls due to defect production. This suggestion is supported by the observations of Schmelz et al.,⁽¹⁶⁾ who compared reductions in $J_c(H)$ of Nb-Ti materials with large J_{co} for various low-temperature ion and fast-neutron irradiations. They have shown that a correlation exists between the reduction in $J_c(H)$ and the particle fluence for which the defect concentrations, produced by various energetic-particle irradiations were approximately normalized through damage-energy calculations in which defect morphology is not considered. The decrease in J_c can then be qualitatively understood as a decrease in the pinning of fluxoids by dislocation cell walls as a result of the production of defects in the sample. In this regard, a comparison study of fast-neutron irradiations of Nb-Ti materials carried out at low temperatures and ambient reactor temperatures would be useful, since the defect configurations would be different, and the results could be examined in terms of increases in ρ .

Fast-neutron irradiations of materials with low J_{co} result in an increase of $J_c(H)$ due to flux pinning by defect cascades or defect clusters. The magnitude of the increases in $J_c(H)$ due to radiation defects

in this case does not appear to be very large, suggesting that dislocation cell walls are more effective for flux-pinning than the radiation-produced defects. At present, there are no data for which the pinning by cascades and clusters can be directly compared.

II. COMPOUNDS

A number of compound superconductors with the A15 crystal structure (composition A_3B) have higher transition temperatures and larger values of the upper critical field⁽⁴⁸⁾ than the Nb-Ti alloys that have been discussed. Studies have also shown that larger critical-current densities are attainable in these materials so that, for both technological and fundamental reasons, radiation-damage investigations of the A15 compounds are of great interest.

A brief discussion of several general aspects of radiation-damage effects in A15 compounds seems worthwhile prior to a review of the experimental work in more detail. Söll et al.⁽⁴⁶⁾ have examined experimental data on the reduction in T_c of Nb_3Sn by various types of irradiating particles and irradiation temperatures. They find a meaningful parameter for comparison of these results by translating the particle dose ϕ to the quantity $\bar{E}_p$ defined as the mean energy transfer per lattice atom due to irradiation to a particle dose ϕ . The results of their comparison study are shown in Fig. 5 and indicate a good correlation between ΔT_c and $\bar{E}_p$. In independent work, Parkin and Snead⁽⁴⁹⁾ found good correlation between the reduction of T_c observed in irradiated Nb_3Sn with the calculated damage energy per atom (dea), which is similar in concept to $\bar{E}_p$. The dea method takes into account the electronic-energy losses of the cascade atoms

in the calculation of radiation-defect production. The value of $\bar{E}_p$ (or $\bar{E}_p$) is proportional to the concentration of Frenkel pairs created by an energetic particle-target atom interaction and disregards rearrangement of the defects after the collision event. Good correlation, shown in Fig. 5, then suggests that the reduction in T_c is primarily brought about by disordering in the early stages of the collision event and is independent of the irradiation temperature. At low values of $\bar{E}_p$ (or low dose), ΔT_c is small. In this case, changes in $J_c(H)$ by radiation damage will be primarily influenced by a decrease in electron mean free path due to scattering by the defects and a change in the fluxoid pinning by the defects. As mentioned previously, these factors depend strongly on the mobility of the defects, so that comparison of low-temperature-irradiation data with that obtained at higher temperatures is not straightforward. On the other hand, at higher fluences we may reasonably expect that the large reductions in T_c and the associated decrease in $H_{c2}(T)$ will be the major factors in decreasing $J_c(H)$. For these fluences, the influence of radiation temperatures could be disregarded.

The work of Söll et al.⁽⁴⁶⁾ suggests that decreases in T_c occur through disordering in collision events. An additional means for disordering, which appears attractive at first sight, is the replacement-collision sequence⁽⁵⁰⁾ in which the radiation-induced defect can be produced large distances from the primary event by focused-collision sequences. This would provide an efficient mechanism for producing long-range disorder. Robinson⁽⁵¹⁾ notes that a replacement collision traveling along a $\langle 102 \rangle$ direction (see Fig. 6) could decrease the long-range order, but that propagation of the focused-collision sequence over large distances in this

direction is unlikely because of an interposing void between atomic sequences ABA. Long-distance propagation of a focused-collision sequence in the $\langle 100 \rangle$ direction is highly probable, but this would not be a disordering mechanism. Thus it does not seem likely that replacement-collision sequences are an important factor in radiation-induced disordering of Al5 materials.

Brown et al.⁽¹²⁾ irradiated a multifilamentary Nb₃Sn sample prepared in a tin-bronze matrix with fast neutrons at 6°K up to a dose of 1.8×10^{18} n/cm² ($E > 0.1$ MeV). At this fluence, they estimated a decrease in T_c of less than 1°K, which is in essential agreement with the value $\Delta T_c = -0.7^\circ\text{K}$ that can be estimated from other low-temperature fast-neutron studies.⁽⁴⁶⁾ $J_c(H)$ was measured as a function of dose in magnetic fields up to 33 kOe at a temperature of 4.5°K. Some of their results are shown in Fig. 7, where J_c/J_{c0} is plotted vs the fast-neutron dose for several fixed values of H . At the lowest fields, J_c/J_{c0} is seen to decrease with fluence. At higher magnetic fields, J/J_{c0} initially increases with dose, the rate of increase being dependent on the magnetic field. For larger doses, J_c/J_{c0} appears to saturate and then decrease. The fluence at which this occurs is also field dependent; the lower the applied magnetic field, the lower is the dose required to achieve saturation in J_c/J_{c0} . The effect of annealing at temperatures of 83°K and 295°K on the recovery of J_c is also shown in Fig. 7. At the highest field, the results indicate that about 11% of the change in J_c produced by an irradiation of 1.82×10^{18} n/cm² ($E > 0.1$ MeV) recovers on an anneal at 83°K, while about 30% recovers after annealing at 295°K. J_{c0} for the unirradiated sample at $H = 33$ kOe is about 1.5×10^6 A/cm², which is comparable to current

densities in commercial material. The results shown here suggest that $J_c(H)$ at $H \sim 100$ kOe might increase on irradiation to doses in the range $1 - 2 \times 10^{18}$ n/cm². This suggestion was made plausible by qualitative arguments developed by Brown et al. which are discussed in the following paragraph and experimentally verified by the work of Colucci et al.⁽⁵²⁾ Brown et al. considered the scaling law

$$F_p(H, T) = A(d) H_c^m h^n (1-h)^2, \quad (13)$$

where m and n are numerical constants (see Eq. 3). We assume, as Brown et al., that the numerical constants m and n remain unchanged by irradiation; and, to simplify the discussion, we treat as negligible the small decrease in T_c over the dose range they studied. In this case, $\partial(\ln H_c)/\partial\phi = 0$ and, from Eq. 5, $\partial(\ln H_{c2})/\partial\phi = \partial(\ln \rho)/\partial\phi$. This leads to the expression

$$\frac{\Delta F_p(H, T)}{F_p(H, T)} = \left(\frac{(2+n)(h-h_p)}{(1-h)} \frac{\partial(\ln \rho)}{\partial\phi} + \frac{\partial(\ln A[d])}{\partial\phi} \right) \Delta\phi \quad (14)$$

where $h_p = n/(2+n)$ is the reduced field giving the maximum value of $F_p(H, T)$ in Eq. 13. While there are no reported studies of resistivity changes in Nb₃Sn due to fast-neutron damage, many materials show a positive value of $\partial\rho/\partial\phi$ at these fluences.⁽⁵⁴⁾ It can be seen in Eq. 14 that the coefficient of the $\partial(\ln \rho)/\partial\phi$ term is negative for $h < h_p$ and positive for $h > h_p$. At moderate fast-neutron doses, the factor $A(d)$ increases, but at low fields this positive contribution to $\Delta F_p(H)/F_p(H)$ in Eq. 14 is more than compensated by the negative term. At fields $h > h_p$, both contributions are positive, so that $\Delta F_p(H)/F_p(H)$ increases. At larger doses, however, the experimental data suggest that the density of defect cascades

increases sufficiently to reduce the value of the quantity $\partial \left(\ln A(d) \right) / \partial \phi$ with an eventual reversal in sign of $\Delta F_p(H)/F_p(H)$. Equation 14, which qualitatively describes their observations, suggests that $J_c(H)$ at fields considerably above the experimental limit (33 kOe) would be considerably increased by fast-neutron irradiation in the range $1 \sim 2 \times 10^{18}$ n/cm². These results also show that defect cascades in conjunction with the existing microstructure enhance the pinning of fluxoids in contrast to the observations on Nb-Ti previously discussed. Evidence that grain boundaries are the predominant flux-pinning mechanism in Nb₃Sn has been reported.⁽⁵⁵⁾

Colucci et al.^(52,53) irradiated Nb₃Sn samples (with J_{co} values similar to those of Ref. 12) at 6°K with fast neutrons. The samples were then transferred under liquid nitrogen to an experimental apparatus in which $J_c(H)$ could be measured in fields up to 100 kOe. Previous work⁽¹²⁾ has shown that less than 15% recovery of $J_c(H)$ of irradiated Nb₃Sn occurs at 77°K. The recovery below 77°K is due to point-defect migration, and the remaining damage is in the form of more stable defect structures. Colucci et al. measured $J_c(H)$ vs H at 4.2°K for a pair of samples irradiated to fluences of 4.8×10^{17} n/cm² and 1.1×10^{18} n/cm² ($E > 0.1$ MeV), and plotted experimental values of $F_p(H)$. Prior to irradiation, $F_{PM}(H)$ had a value of 4×10^9 dynes/cm³ at $H = 27.5$ kOe. Irradiation to a dose of 4.8×10^{17} n/cm² led to a 22% increase in $F_{PM}(H)$, and the field at which the maximum in $F_p(H)$ occurred shifted from 27.5 kOe to 42.5 kOe. $\Delta J_c/J_{co}$ at $H = 32$ kOe can be estimated from these data to be about 25%, which is in good agreement with the value obtained by Brown et al.⁽¹²⁾ Colucci et al. have shown that $\Delta J_c/J_{co} = +45\%$ at $H = 100$ kOe following

irradiation to 4.8×10^{17} n/cm² ($E > 1$ MeV). Annealing of this sample at 295°K led to about a 50% recovery of the radiation-produced increase at field values greater than 40 kOe. On irradiating to a dose of 1.1×10^{18} n/cm², these workers found that the increase in $J_c(H)$ was not as large as observed on irradiating to a dose of 4.8×10^{17} n/cm². This observation suggests a saturation in the pinning effect of defect cascades at a fluence between these levels. This is somewhat contradictory with the results of Brown et al.,⁽¹²⁾ who found $J_c(H)$ increasing with dose in this range; further study will be required to understand the discrepancy.

Söll et al.⁽⁵⁶⁾ irradiated Nb₃Sn wires, prepared by diffusion, at 4.6°K to a fast-neutron dose of 3.9×10^{18} n/cm² ($E > 0.7$ MeV). At 4.2°K, $J_{co}(H)$ at $H = 50$ kOe was 3×10^5 A/cm², which is about a factor of two lower than the corresponding values for the materials previously discussed. After irradiation, an increase in $J_c(H)$ of about a factor of 2.5 and a decrease in T_c of about 0.8°K was noted. The values of $J_c(H)$ in this case are comparable to the values of $J_{co}(H)$ observed by Brown et al.⁽¹²⁾ and Colucci et al.⁽⁵²⁾ for their unirradiated samples, suggesting that appreciable flux pinning by defect cascades is possible in Nb₃Sn. These workers also found that annealing at 250°K led to a further decrease of T_c of about 0.2°K, while about 50% of the increase in $J_c(H)$ due to irradiation was recovered. A summary of the results obtained in the several low-temperature fast-neutron investigations is given in Table 4.

The measurements of Colucci et al.⁽⁵²⁾ indicate a saturation in the pinning effect of defect cascades at a fluence of $\sim 1 \times 10^{18}$ n/cm² ($E > 0.1$ MeV), which is about a factor of four less than the neutron exposure in the work of Söll et al.⁽⁵⁶⁾ It is not clear as to whether larger

increases in J_{co} could have been observed by Söll et al. at lower doses or whether larger fluences are required to achieve a maximum in the pinning as a consequence of the low J_{co} . Söll et al. propose the latter alternative; the smaller J_{co} , the greater the dose required to produce a saturation in the pinning.

Fast-neutron irradiations of Nb₃Sn samples, similar to those investigated by Brown and Colucci, were carried out at ambient reactor temperatures ($60^\circ\text{C} < t_{irr} < 140^\circ\text{C}$) with subsequent study of $J_c(H)$ at 4.2°K as a function of dose. Parkin and Sweedler⁽⁵⁸⁾ noted little or no reduction in $J_c(H)$ for $H \leq 40$ kOe for fluences below 1×10^{18} n/cm² ($E > 1$ MeV). These results differ from those of Brown and Colucci and indicate that the resultant defect structures produced by low temperature and ambient reactor temperature irradiation may have different flux-pinning effects. (For purposes of comparison, we note that a fluence of 10^{18} n/cm² ($E > 1$ MeV) is roughly equivalent to $\sim 3 \times 10^{18}$ n/cm² ($E > 0.1$ MeV) in Frenkel-pair production, neglecting subsequent rearrangements by migration). At higher fluences, a rapid reduction in J_c was observed, so that at $\phi = 1.1 \times 10^{19}$ n/cm² ($E > 1$ MeV) J_c at $H = 40$ kOe was reduced to about 4% of J_{co} .

Extension of these studies to higher fields ($40 \text{ kOe} < H < 160 \text{ kOe}$)^(57,58) demonstrated that $J_c(H)$ increased with dose up to a fluence of 5×10^{17} n/cm² ($E > 1$ MeV), the degree of enhancement being greater at higher field values, as may be seen in Fig. 8. Up to this fluence, the change in T_c is negligible, and the increases in $J_c(H)$ were interpreted as being due to an increase in H_{c2} as a result of an increase in ρ . However, it is not clear how important the effect of defect clusters may be on fluxoid pinning at these lower doses. At larger neutron fluences,

reductions in T_c become significant, leading to precipitous decreases in J_c/J_{c0} , particularly at the higher-field values, as seen in Fig. 8.

These results are consistent with the observations of Bauer et al.,⁽⁵⁹⁾ who irradiated Nb_3Sn wires, prepared by diffusion, to fast-neutron fluences up to 5×10^{18} n/cm² ($E > 0.8$ MeV) at $\sim 80^\circ\text{C}$. The initial critical-current density of these samples was somewhat lower than those previously discussed (at $H = 30$ kOe, J_{c0} is estimated to be $\sim 5 \times 10^5$ A/cm²). Measurements of $J_c(H)$ in fields up to 100 kOe revealed a field-dependent increase of $J_c(H)$ for doses up to 1×10^{18} n/cm² ($E > 0.8$ MeV), with larger relative increase at the higher fields. After exposure to 1×10^{18} n/cm², J_c at $H = 100$ kOe increased by 460%. Irradiating to 5×10^{18} n/cm² ($E > 0.8$ MeV) led to a reduction in T_c from 18°K to 13.7°K and a general decrease in $J_c(H)$ from the enhanced values obtained by irradiation to 1×10^{18} n/cm². Above $H = 50$ kOe, $J_c(H)$ was still greater than $J_{c0}(H)$. Similar effects were reported by these investigators for Nb_3Al and $Nb_3(Al, Ge)$, although only decreases of $J_c(H)$ for V_3Si could be observed, even at lower doses. In earlier work, Bett^(60,61) studied Nb_3Sn samples prepared by reacting Nb tapes coated with Sn at temperatures of about 980°C . Fast-neutron irradiations at 70°C were carried out to fluences of about 10^{20} n/cm² ($E > 0.7$ MeV), with subsequent measurements of $J_c(H)$ made at 4.2°K in fields up to 40 kOe. These studies also showed an enhancement in $J_c(H)$ by irradiation, with larger increases at higher-field values. For doses above $\sim 1 \times 10^{18}$ n/cm² ($E > 0.7$ MeV), $J_c(H)$ decreased for materials with larger $J_{c0}(H)$.

Snead et al.⁽⁶²⁾ irradiated Nb_3Sn samples at room temperature with 14-MeV neutrons. These samples, prepared in a tin-bronze matrix, had a

large $J_{co}(H)$. (At 40 kOe, $J_{co} \sim 2 \times 10^6$ A/cm².) Measurements of $J_c(H)$ in the field range 20 kOe < H < 160 kOe at 4.2°K demonstrated reductions in $J_c(H)$ at all values of H following irradiation to doses of 1×10^{18} n/cm², respectively. In terms of damage-energy production, Snead et al. estimate from the experimental data that a fluence of 1×10^{18} n/cm² of 14-MeV neutrons is equivalent to $\sim 6.3 \times 10^{18}$ n/cm² ($E > 1$ MeV) reactor-spectrum neutrons, while, using the estimate given by Parkin et al.,⁽⁴⁹⁾ one obtains $\sim 3 \times 10^{18}$ n/cm² ($E > 1$ MeV). These results are then consistent with the ambient reactor irradiation studies where large reductions in $J_c(H)$ were observed above a fluence of $\sim 1 \times 10^{18}$ n/cm² ($E > 1$ MeV).

Besslein et al.⁽⁴⁴⁾ irradiated a Nb₃Sn layer about 5 μ m thick deposited on a Hastelloy strip with 25-MeV oxygen ions at temperatures less than 30°K. The critical current was studied as a function of dose, in the temperature interval $0.5 < T/T_c \leq 1.0$, and in fields up to 60 kOe. The maximum in the volume-pinning-force density, $F_{PM}(T)$ was observed to increase with dose and appeared to saturate at a dose of $\sim 4 \times 10^{14}$ ions/cm². At this fluence, T_c decreased about 1°K. With further irradiation, T_c decreases precipitously, resulting in rapid decrease in $F_{PM}(T)$. At 10^{16} ions/cm², T_c has decreased to $\sim 6^\circ$ K and $F_{PM}(T)$ was small. These workers extrapolated their results to 4.2°K, using a scaling law (Eq. 4). The extrapolated value of F_{PM} prior to irradiation was about 4×10^8 dynes/cm², which is roughly ten times smaller than the value for the samples studied by Colucci et al.⁽⁵²⁾ This extrapolated value of F_{PM} increased to $\sim 3.5 \times 10^9$ dynes/cm² on irradiating to a dose of 4×10^{14} oxygen ions/cm². This value of F_{PM} is comparable to F_{PM} for Colucci's sample prior to irradiation, which was $\sim 4 \times 10^9$ dynes/cm². Similar studies with higher

J_{co} materials would be worthwhile. Annealing the irradiated samples at 300°K demonstrated a 3% recovery of the decrease in T_c , and only a small recovery of radiation-induced changes in $J_c(H)$ was noted.

The measurements of Becker et al.,⁽⁶³⁾ who irradiated Nb_3Sn with 50-MeV deuterons at 18°K, show radiation effects similar to those observed for fast-neutron and oxygen-ion irradiations. Up to a fluence of $5 \times 10^{16}/cm^2$, $\Delta J_c/J_{co}$ was observed to increase with dose, with larger increases at higher fields. At this dose, $\Delta J_c/J_{co} = 75\%$ at $H = 70$ kOe. With further irradiation up to a fluence of $1.9 \times 10^{17}/cm^2$, $\Delta J_c/J_{co}$ slowly decreased at all field values ($10 \text{ kOe} < H < 70 \text{ kOe}$), but the critical-current densities were still larger than the values prior to irradiation. T_c was observed to decrease by 1.3°K from its initial value of 17.8°K following the exposure to $1.9 \times 10^{17}/cm^2$. Annealing studies of the irradiated materials also showed only small recovery effects in $\Delta J_c/J_{co}$ on annealing the samples to 300°K and 370°K. In earlier work, Coffey et al.⁽⁴³⁾ studied 15-MeV deuteron irradiation of Nb_3Sn samples at $\sim 30^\circ K$. Their results indicate an increase in $\Delta J_c/J_{co}$ with irradiation of material with low J_{co} and a decrease in $\Delta J_c/J_{co}$ in materials with high J_{co} .

While damage production in these low-temperature ion-irradiation studies of Nb_3Sn was primarily in the form of isolated Frenkel pairs, about 10% of the damage can be characterized as defect clustering as a result of higher-energy collision events. The distribution of cluster sizes will be accentuated toward small clusters, but on the average they will contain about 40 Frenkel pairs. Robinson⁽⁵¹⁾ can estimate from his calculations of damage effects in Cu that the Frenkel pairs will be spread through ~ 1400 atomic volumes, resulting in structure having a "length"

of $\sim 65 \text{ \AA}$ and a "diameter" of $\sim 36 \text{ \AA}$. These dimensions are comparable to the superconducting coherence length $\xi \sim 40 \text{ \AA}$ for Nb_3Sn , and significant pinning might be attributed to such defect cascades.

The effects of ion irradiations at $\sim 100^\circ\text{C}$ on $J_c(H)$ of Nb_3Sn have also been investigated.^(64,65) At these temperatures, the isolated Frenkel defects and small defect clusters initially created by Rutherford scattering will undergo partial annihilation and clustering rearrangements. Wohleben⁽⁶⁴⁾ conducted a comparison study of $\Delta J_c/J_{co}$ at 4.2°K in the field range $10 \text{ kOe} < H < 50 \text{ kOe}$, using 1-, 2-, and 3-MeV protons and 3-MeV deuterons at $\sim 150^\circ\text{C}$. At low fluences, $\Delta J_c/J_{co}$ increased with irradiation, the enhancement being largest at the larger field values. J_{co} values for the Nb_3Sn -diffusion-layer samples were moderate, amounting to $4.4 \times 10^5 \text{ A/cm}^2$ at $H = 30 \text{ kOe}$. A saturation in the increase of $\Delta J_c/J_{co}$ was observed at doses depending on the energy and mass of the energetic particles, and for all particles at larger doses $\Delta J_c/J_{co}$ rapidly decreased. In the analysis of his data, Wohleben was able to show that the saturation in ΔJ_c occurred at approximately the same normalized fluence $\phi_x = (MZ^2/E)\phi$ where M and Z are the atomic weight and number of the ion with the average energy E in the $3.1\text{-}\mu\text{m}$ -thick sample and ϕ is the experimentally determined fluence. The maximum value of ΔJ_c was seen to differ with the particle energy and mass, and this varying enhancement of ΔJ_c was discussed in terms of the formation of different densities of pinning defects by the various ions. Ischenko et al.⁽⁶⁵⁾ compared the results of their 24-MeV oxygen-ion irradiations of Nb_3Sn with Wohleben's data and found good agreement in the value ϕ_x . In this case, the fluence at saturation in ΔJ_c was about $4 \times 10^{14}/\text{cm}^2$. Assuming that the reduction in T_c by irradiation

is independent of irradiation temperature and depends only on the mean energy transferred per lattice atom $\bar{E}_p$,⁽⁴⁶⁾ we can infer from the low-temperature studies of Besslein et al.⁽⁶⁶⁾ that oxygen-ion irradiation at $\sim 100^\circ\text{C}$ to a dose of $\sim 4 \times 10^{14}/\text{cm}^2$ decreases T_c by about 0.6°K . Using Eq. 9, one can then estimate that at the fluences observed by Wohllieben to give a maximum in ΔJ_c , the transition temperature has been reduced at most by 1°K . The decrease in ΔJ_c observed for fluences above ϕ_x might be due to a combination of a saturation in the pinning of fluxoids by the defects and further decreases in T_c .

Some investigators have studied Nb_3Sn and other materials doped with ^{235}U or ^{10}B and irradiated with thermal neutrons.^(59,67) Brown et al.⁽⁶⁷⁾ irradiated Nb_3Sn in a tin-bronze matrix containing 0.1 at.% ^{235}U with thermal neutrons at a temperature of less than 8°K and measured the critical-current density at 4.5°K as a function of dose in fields up to 33 kOe. As may be seen in Fig. 9, large reductions in T_c were obtained on irradiation. By comparing their results for changes in T_c with the corresponding low-temperature fast-neutron data of Söll et al.,⁽⁴⁶⁾ these workers were able to translate their thermal-neutron fluences into equivalent fast-neutron fluences, as is shown in Fig. 9. Irradiation to a fluence of $1.5 \times 10^{18} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) led to a behavior previously observed by Brown et al.⁽¹²⁾; viz., a decrease in J_c at low-field values and an increase at higher fields. At this fluence, the transition temperature decreased by 0.6°K to 17.4°K . The enhancement of J_c at their highest-field value (33 kOe) does not appear to be as large as they observed in their fast-neutron-damage studies and may be related to differences in the damage structure. For doses above $3.3 \times 10^{18} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$), large reductions in $J_c(H)$ were observed because of the large depressions of T_c .

Bauer et al.⁽⁵⁹⁾ irradiated Nb₃Sn, doped with ¹⁰B, with thermal neutrons at 80°C and measured $J_c(H)$ at 4.2°K as a function of dose over a magnetic-field range 20 kOe < H < 100 kOe. Initially, as the thermal-neutron dose was increased, an enhancement in $J_c(H)$ was observed, with the relative enhancement being larger at higher fields, which results in a critical-current behavior that is less field dependent than for the unirradiated material. A maximum enhancement of $J_c(H)$ occurred after exposure to 5×10^{17} n/cm² and amounted to an increase in J_c at 100 kOe of almost a factor of four. With further irradiation, $J_c(H)$ decreased as a result of significant decreases in T_c . At a fluence of 1×10^{19} n/cm² (thermal), a reduction in T_c from 18°K to 14.6°K was noted. Samples doped with ²³⁵U showed similar results, although the maximum enhancement of J_c was considerably less than that observed in the boron-doped sample. Moreover, exposure to 1×10^{18} n/cm² resulted in a decrease of T_c of about 6.4°K and depressed the critical-current density by almost two orders of magnitude, reflecting the greater production of damage by ²³⁵U fission fragments. Studies were also carried out on Nb(Al, Ge) doped with boron or uranium, with observations similar to those for Nb₃Sn.

Snead⁽⁶⁸⁾ irradiated a V₃Ga single-core wire, prepared in a Cu-Ga bronze jacket, with reactor-spectrum neutrons at a temperature of about 100°C. Measurements were then made at 4.2°K of $J_c(H)$ as a function of dose in the magnetic-field range 20 kOe < H < 185 kOe. The value of $J_{co}(H)$ at H = 40 kOe is estimated to be about 5.4×10^5 A/cm². Snead noted that radiation-induced changes in V₃Ga were similar to those seen in Nb₃Sn irradiated at ambient reactor temperatures.⁽⁵⁸⁾ $J_c(H)$ increased with dose up to a fluence of $\sim 1 \times 10^{18}$ n/cm² (E > 1 MeV), with larger

relative enhancement of $J_c(H)$ at higher-field values. At larger doses, $J_c(H)$ decreased, primarily as a result of significant depressions of T_c by radiation damage. Snead also pointed out that an analysis of his measurements in terms of a unique scaling law is not possible, perhaps because of paramagnetic limiting effects in this material. (69)

Irradiations of V_3Ga single-core wire in a Cu-Ga matrix with 50-MeV deuterons at $\sim 15^\circ K$ have been reported by Becker et al. (63) In this case, $J_{co}(H)$ at 40 kOe was about 5×10^5 A/cm². Measurements of $J_c(H)$ in the field range $10 \text{ kOe} < H < 70 \text{ kOe}$ at $4.2^\circ K$ revealed a rapid enhancement of $\Delta J/J_{co}$ at higher fields for doses up to $5 \times 10^{16}/\text{cm}^2$, and $\Delta J_c/J_{co}$ at 70 kOe was 175%. At lower fields, $H \sim 10 \text{ kOe}$, the change in $J_c(H)$ was negative, indicating a behavior similar to that seen by Brown et al. (12) in fast-neutron-irradiated Nb_3Sn . A continuation of the deuteron irradiation to larger fluences showed that only small increases in $J_c(H)$ at $H = 70 \text{ kOe}$ occurred for doses up to $2 \times 10^{17}/\text{cm}^2$. Above this level, $J_c(H)$ decreased with dose. The essential features of the effects of 50-MeV deuteron irradiation on $J_c(H)$ of V_3Ga appear to be quite similar to that observed by these workers in their study of Nb_3Sn .

Couach et al. (70) irradiated multifilamentary V_3Ga in a Cu-Ga matrix with reactor-spectrum neutrons at a temperature of $27^\circ K$. Studies were made of radiation-induced changes in T_c , $H_{c2}(T)$, and $J_c(H)$ in the temperature interval $4.2^\circ K < T < T_c$ and in magnetic fields up to 80 kOe. These workers found a reduction in critical current at all temperatures and for the entire range of available magnetic fields following irradiation to a fluence of $5 \times 10^{17} \text{ n/cm}^2$ (energy not specified). This result is somewhat unexpected, although one might speculate that the material

studied was "optimized" and possessed the largest possible values of $J_{co}(H)$, so that irradiation would reduce $J_c(H)$ even at low fluences. However, it is not possible to infer absolute values of $J_{co}(H)$ from the available data. A possible alternative explanation is suggested by noting that Couach et al. find a reduction in T_c of V_3Ga from $14.40^\circ K$ to $12.10^\circ K$ on irradiating to a fluence of $3 \times 10^{18} \text{ n/cm}^2$, while Francavilla et al.⁽⁷¹⁾ observed a decrease of T_c from $14.7^\circ K$ to $12.3^\circ K$ after irradiating bulk V_3Ga at $60^\circ C$ to a dose of $6 \times 10^{18} \text{ n/cm}^2$ ($E > 1 \text{ MeV}$). Assuming reductions in T_c are independent of the temperature during irradiation, the disparities in these fluences indicate that damage production corresponding to the fluences given by Couach et al. is twice as large as that for fluences given by Francavilla et al. This could suggest that for the lowest fluence reported by Couach et al. a saturation in the increase of $J_c(H)$ by irradiation has been exceeded, since Snead⁽⁶⁸⁾ observed reductions in $J_c(H)$ following fast-neutron irradiation at doses $\sim 1 \times 10^{18} \text{ n/cm}^2$ ($E > 1 \text{ MeV}$). In view of the difficulties and uncertainties in comparing fluences from different reactors, this explanation is conjectural, and further work is required to clarify the discrepancies. Couach et al.⁽⁷⁰⁾ found a 20% recovery of the decrease in T_c due to irradiation on annealing at $300^\circ K$ and also noted from an analysis of their data that a unique scaling law was inadequate to explain their result.

The experimental investigations of radiation effects in Al5 compounds using a variety of energetic particles and irradiation temperatures suggest that radiation defects interact more strongly with the fluxoids in these materials than in Nb-Ti alloys. For moderate fluences, $J_c(H)$ can be enhanced significantly, while T_c decreases slightly. At higher fluences, $J_c(H)$ decreases because of the large depression in T_c .

Some work on radiation-damage effects on the critical-current density $J_c(H)$ of superconductors with the B1 structure has been reported. NbN samples studied by Sadagopan et al.⁽⁷²⁾ had low values of $J_{co}(H)$, and on irradiating these with fast neutrons at $\sim 70^\circ\text{C}$ they found an enhancement of $J_c(H)$ in the field range 30 kOe to 80 kOe, indicating that the defect clusters were able to pin fluxoids. Bauer et al.⁽⁷³⁾ doped NbN and Nb(Co_{0.24}No_{0.74}) samples with 0.5 at.% ²³⁵U and 0.5 at.% ¹⁰B and investigated the changes in T_c , H_{c2} , and $J_c(H)$ following thermal-neutron irradiations at about 80°C . No changes in T_c were observed with irradiations to a dose of 1×10^{18} n/cm² for the ²³⁵U-doped samples or 5×10^{18} n/cm² for the ¹⁰B-doped samples. The changes in $J_c(H)$ in these materials after irradiation were observed to be small in comparison with the results obtained by these workers in similar studies of Al5 materials.⁽⁵⁹⁾ For reasons as yet not understood, $J_c(H)$ was decreased in NbN and increased in Nb(C,N) by the irradiation.

SUMMARY AND CONCLUSIONS

The experimental studies discussed here indicate that radiation effects on $J_c(H)$ of superconducting alloys and compounds are dependent on a number of variables related to material parameters and the conditions of irradiation, so that it is difficult to present a summary in a completely concise and unified manner. All the materials investigated possessed complicated microstructures; and, although a microscopic analysis of the pinning of fluxoids in these cases is not possible, a number of investigations have shown empirical scaling laws relating $J_c(H)$ to the bulk pinning force

per unit volume $F_p(H,T)$ to be valid for some alloys and compounds,^(8,13) and analysis of data in this manner would be desirable. However, with few exceptions, only limited ranges of magnetic fields were available to the investigators in their studies of these materials with high transition temperatures and large upper critical fields. In most cases, then, a major objective of the radiation-damage experiments was to measure $J_c(H)$ as a function of dose over an available range of magnetic-field values and temperatures for comparison with $J_{co}(H)$, the critical-current density prior to irradiation.

Alloys

Irradiation of cold-worked Nb-Ti alloys having large values of $J_{co}(H)$ with fast neutrons or energetic ions results in decreases of $J_c(H)$. Dislocation cell walls are believed to be the predominant flux-pinning mechanism in these materials, so that the decrease in $J_c(H)$ by irradiation is attributed to the production of radiation defects in the relatively defect-free cells which are surrounded by dislocation walls. This increase in defect density in the cells effectively lowers the pinning forces on the fluxoids due to dislocation cell walls. It should be noted that, although the effects of ion irradiation, fast-neutron irradiation at low temperature, and fast-neutron irradiation at 60°C are qualitatively similar, the defect structures produced are quite different, and these differences may be made manifest when explored in greater depth. For materials with low J_{co} , fast-neutron irradiations lead to an increase in J_c , indicating that radiation defects can interact with fluxoid arrays in the absence of other pinning factors.

Al5 Compounds

For moderate fluences (dependent on the type and energy of irradiating particle), decreases in T_c of about 1°K are observed, while in most cases $J_c(H)$ was observed to decrease. To this fluence level, changes in $J_c(H)$ appear to be dominated by increases in ρ , the normal-state resistivity, and by increases in the fluxoid-pinning force by the microstructure modified by the radiation-defect structures. Some differences in pinning behavior between defect cascades produced by fast-neutron irradiation at low temperature and defect clusters produced by irradiation at ambient reactor temperatures were observed. At higher doses, the large reductions in T_c , which do not appear to depend strongly on irradiation temperature, drastically reduce $J_c(H)$.

It is worthwhile, in concluding this review, to discuss briefly a specific aspect of radiation-damage effects in Al5 compounds in terms of CTR requirements. As has been commonly asserted, Nb_3Sn and V_3Ga would appear to be adequate materials (as far as radiation effects are concerned), since estimates of fast-neutron exposure range from ~ 0.5 to 1×10^{18} n/cm² ($E > 1$ MeV) over a ten-year period of CTR application. However, it should be pointed out that some portions of the superconducting magnet system may receive less radiation shielding as a result of device-design considerations. For this reason, further damage studies in Al5 compounds and other materials which might be less susceptible to radiation effects appear to be worthwhile.

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TABLE CAPTIONS

- Table 1. Low-Temperature, Fast-Neutron Irradiation of Nb-Ti Alloys.
- Table 2. Ambient-Reactor-Temperature, Fast-Neutron Irradiation of Nb-Ti Alloys.
- Table 3. Low-Temperature Ion Irradiation of Nb-Ti Alloys.
- Table 4. Low-Temperature, Fast-Neutron Irradiation of Nb₃Sn and V₃Ga.

Reference	Fluence, Irradiation Temp.	Sample Description	$J_{c0} (A/cm^2)$	$\Delta J/J_{c0} (\%)$	Comments
Söll et al. (30)	$4 \times 10^{18} \text{ n/cm}^2$, $E > 0.1 \text{ MeV}$ 4.6 K	Nb 66 at. % Ti, cold worked and heat treated	$H = 50 \text{ kOe}$ $T_M = 5.3 \text{ K}$ 7×10^3 1.7×10^4 1.5×10^5	+20 0 -10	No recovery of J_c on anneal below 60 K
Couach et al. (23)	$1 \times 10^{19} \text{ n/cm}^2$, $E > 1 \text{ MeV}$ 77 K	Commercial Nb-Ti, Cu/SC = 1/2 Single core	$H = 50 \text{ kOe}$ $T_M = 4.2 \text{ K}$ 1.4×10^5	-15	No further decrease in J_c above fluence of $4 \times 10^{18} \text{ n/cm}^2$
Couach et al. (33)	$1 \times 10^{19} \text{ n/cm}^2$, $E > 1 \text{ MeV}$ 77 K	Commercial Nb-Ti, Cu/SC = 2/1 Multifilament (MF)	$H = 50 \text{ kOe}$ $T_M = 4.2 \text{ K}$ 2×10^5	-25	60% recovery of J_c on anneal at 300°K
Brown et al. (32)	$3.2 \times 10^{18} \text{ n/cm}^2$, $E > 0.1 \text{ MeV}$ 4.5 K	Nb 44 at. % Ti, cold worked	$H = 8 \text{ kOe}$ $H = 4.5 \text{ K}$ 6×10^4	-8	50% recovery of J_c on anneal at 270°K
Söll et al. (31)	$7.5 \times 10^{18} \text{ n/cm}^2$, $E > 0.1 \text{ MeV}$ ~ 5 K	Nb 66 at. % Ti, cold worked	$H = 27 \text{ kOe}$ $T_M = 5.3 \text{ K}$ 1.1×10^5	-50	70% recovery of J_c on anneal at 270°K

Table 1

Reference	Fluence (n/cm^2)	Sample Description	J_{co} (A/cm ²) $T_M = 4.2$ K	$\Delta J_c / J_{co}$ (%)	Comments
Okada et al. (36)	4.2×10^{18} $E > 0.1$ MeV	Nb 60 at. % Ti	$1.7 - 7.8 \times 10^4$ $H = 50$ kOe	-12	T_c decreased 6% by irradiation.
		Nb 48 at. % Ti	$0.5 - 6.0 \times 10^4$	No systematic change	No change in T_c .
Parkin et al. (37,38)	1.2×10^{20} $E > 1$ MeV	Commercial Nb 64 at. % Ti (MF)	$H = 40$ kOe 1.3×10^5	-18	For fluences above 4×10^{18} , $\Delta J_c / J_{co}$ tends to saturate at -18%.
Tsubakihara et al. (34)	1.3×10^{18} $E > 0.1$ MeV	Nb 60 at. % Ti	$0.5 \times 8.0 \times 10^4$ $H = 50$ kOe	Decreases for high J_{co}	T_c decreased 6% by irradiation.
		Nb 48 at. % Ti	$1.0 - 7.0 \times 10^4$	No systematic change	No change in T_c .
Sugisaki et al. (39)	3.5×10^{18} $E > 0.1$ MeV	Nb 66 at. % Ti	$H = 50$ kOe 3×10^5	+100	Not consistent with other experiments.

Table 2

Reference	Energy-Particle Fluence Rad. Temp.	At. % Ti	J_{co} (A/cm ²) Meas. Field Meas. temp.	T_{co}	$\Delta J_c/J_{co}$ (%)	ΔT_c	Comments
Schmelz et al. (16)	25 MeV Oxygen $3.6 \times 10^{14}/cm^2$ ~ 30 K	66	1.5×10^5 A/cm ² 40 kOe 4.2 K	9.4 K	-20	-0.1 K	60% recovery in J_c on anneal at 220 K
Seibt (41)	50 MeV Deuteron $3.5 \times 10^{14}/cm^2$ 10 K	60	1.5×10^5 A/cm ² 50 kOe 4.2 K	-	0	-	-
Wohleben (13)	3.1 MeV Proton $1 \times 10^{17}/cm^2$ 25 K	66	1.3×10^5 A/cm ² 40 kOe 4.2 K	8.85 K	-19	-0.2 K	60% recovery in J_c on anneal 1 hr. at 285 K
Hassenzahl et al. (45)	13 - 15 MeV Proton $7 \times 10^{17}/cm^2$ < 30 K	60	1.5×10^5 A/cm ² 50 kOe 4.2 K	-	-3	-	-
Coffey et al. (43)	15 MeV Deuteron $1 \times 10^{17}/cm^2$ 30 K	61	5.2×10^4 A/cm ² 25 kOe 7 K	8.95 K	-35	-0.3 K	90% recovery in J_c on anneal at 300 K

Table 3

Reference	Fluence Irradiation Temperature	Sample Description	Meas. Field Meas. Temp.	J_{co} (A/cm ²)	T_{co} (K)	$\frac{\Delta J_c}{J_{co}}$ (%)	ΔT_c (K)	Comments
Brown et al. (12,67)	1.82×10^{18} n/cm ² E > 0.1 MeV 6 K	Nb-Sn bronze composite 19 filaments	H = 33 kOe $T_M = 4.5$ K	1.5×10^5	17	+31	<1.0 K	$\Delta J_c/J_{co} = +22\%$ on anneal at 295 K
			H = 6.3 kOe $T_M = 4.5$ K	4.7×10^5	17	-7	<1.0 K	$\Delta J_c/J_{co} = -12\%$ on anneal at 295 K
Colucci et al. (52,53)	1.1×10^{18} n/cm ² E > 0.1 MeV 6 K (annealed at 77 K)	Nb-Sn bronze composite 19 filaments	H = 40 kOe $T_M = 4.2$ K	1.0×10^5	17	+20	-	$\Delta J_c/J_{co} = +10\%$ on anneal at 295 K
			H = 100 kOe $T_M = 4.2$ K	1.2×10^5	17	+40	-	$\Delta J_c/J_{co} = +20\%$ on anneal at 295 K
Söll et al. (56)	4×10^{18} n/cm ² E > 0.1 MeV 4.6 K	Nb ₃ -Sn diffusion wire	H = 50 kOe $T_M = 4.6$ K	3×10^5	17.9	+150	-0.8	$\Delta J_c/J_{co} = +125\%$ on anneal at 250 K
Couach et al. (70)	3×10^{18} n/cm ² E > 1 MeV 27 K	V-Ca bronze composite (61 filaments)	30 < H < 80 kOe 4.2 < T < T _c	(not given)	14.4	-30	-2.3	T _c recovers to 12.5 K on anneal at 300 K

Table 4

FIGURE CAPTIONS

- Fig. 1. Normalized pinning-force density of unirradiated Nb-Ti vs the reduced magnetic-flux density $b \approx h = H/H_{c2}$. The solid line is given by the function $4h(1-h)$.⁽¹³⁾
- Fig. 2. The critical-current density $J_c(H)$ vs H for several unirradiated Nb-66 at.% Ti samples that had been cold drawn and subjected to various heat treatments (see Fig. 3).⁽³⁰⁾
- Fig. 3. Ratio of critical-current densities of several Nb-Ti alloys prior to and after irradiation to a fluence of 3.5×10^{18} n/cm² ($E > 0.1$ MeV) at 4.5°K vs the normalized magnetic induction corresponding to the maximum in the pinning-force density before irradiation.⁽³⁰⁾
- Fig. 4. The logarithm of the critical-current density of a Nb-66 at.% Ti sample vs the temperature for several field values before and after irradiation with 3.1-MeV protons at 25°K.⁽¹³⁾
- Fig. 5. Decrease of the transition temperature T_c of Nb₃Sn vs mean energy transfer per lattice atom $\bar{E}_p$ for several types of energetic-particle irradiation at low and high temperatures.⁽⁴⁶⁾
- Fig. 6. A focused replacement collision sequence in the $\langle 102 \rangle$ direction that could disorder the Al5 lattice.

Fig. 7. Fractional change in $J_c(H)$ of a Nb_3Sn sample irradiated at 6°K vs the fast-neutron fluence ($E > 0.1$ MeV) at several values of the magnetic field. Also shown are the results of annealing after irradiation to a fluence of 1.8×10^{18} n/cm² ($E > 0.1$ MeV).⁽¹²⁾

Fig. 8. Fractional change in the critical current I_c of a Nb_3Sn sample irradiated at ambient reactor temperatures vs the fast-neutron fluence at several values of the magnetic field.⁽⁵⁷⁾

Fig. 9. The critical-current density $J_c(H)$ for a Nb_3Sn sample doped with 0.1 at.% ^{235}U vs the applied field after several thermal-neutron irradiations at 8°K. The fluences given here correspond to a calculated fast-neutron ($E > 0.1$ MeV) dose equivalent.⁽⁶⁷⁾

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

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Figure 6

Figure 7

Figure 8

Figure 9