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Stored Energy in Fusion Magnet Materials Irradiated at Low Temperatures

R. L. Chaplin
H. R. Kerchner
C. E. Klabunde
R. R. Coltman

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R. L. Chaplin
Department of Physics and Astronomy, Clemson University
Clemson, South Carolina

H. R. Kerchner and C. E. Klabunde
Solid State Division, Oak Ridge National Laboratory

R. R. Coltman
Private Consultant, Knoxville, Tennessee

Date of Issue–August 1989

Research Funded by the U.S. Department of Energy
Division of Materials Sciences

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R. L. Chaplin
Department of Physics and Astronomy
Clemson University, Clemson, South Carolina

H. R. Kerchner and C. E. Klabunde
Solid State Division
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

R. R. Coltman
Private Consultant, Knoxville, Tennessee

ABSTRACT

During the power cycle of a fusion reactor, the radiation reaching the superconducting magnet system will produce an accumulation of immobile defects in the magnet materials. During a subsequent warm-up cycle of the magnet system, the defects will become mobile and interact to produce new defect configurations as well as some mutual defect annihilations which generate heat—the release of stored energy. This report presents a brief qualitative discussion of the mechanisms for the production and release of stored energy in irradiated materials, a theoretical analysis of the thermal response of irradiated materials during warm-up, and a discussion of the possible impact of stored energy release on fusion magnet operation.

*Research sponsored by the Division of Materials Sciences, U.S. Department of Energy under contract DE-AC05-840R21400 with Martin Marietta Energy Systems Inc.

1. INTRODUCTION

This report presents a brief discussion of the mechanisms of production and release of stored energy in irradiated materials, a theoretical analysis of the thermal response of irradiated materials during warm-up, and a discussion of the possible impact of stored energy on the design and operation of composite superconducting magnets for fusion reactors. Nuclear energy radiation impinging solids held at low temperature produces metastable defects. These defects can remain in place due to the absence of sufficient thermal energy needed for diffusion. Studies of elementary defect production and their annealing have been carried out since 1958 at temperatures as low as 3.5 K in various facilities around the world. Such studies reveal a complex series of annealing peaks at a variety of cryogenic temperatures. The inherent release of energy with the decay or reconfiguration of elementary metastable defects has been investigated in detail only for a handful of materials. The inhomogeneous, sudden temperature excursions to be expected during warming of a fusion-reactor, superconducting magnet is a natural concern of the designers of future reactors. Part of the basis for this report is experimental data and analyses obtained through the use of a new low temperature neutron irradiation facility (LTNIF)[1] in service at ORNL 1986–87.

2. THE MECHANISMS OF PRODUCTION AND RELEASE OF STORED ENERGY IN SOLIDS

Stored energy is produced in solids when, as the result of impinging energetic radiation, host atoms are raised from their normal to elevated energy states. The nature of the elevated energy state depends upon the type of solid

and the type of incoming radiation. In general, atoms can remain in an elevated energy state until the temperature of the solid is raised to some characteristic range which activates their return to the lower normal energy state. The difference in energy between the two states is released, and it ultimately appears as heat in the solid. If the temperature of the solid is within or above the "characteristic" range during irradiation, the lifetime of atoms in elevated energy states is very short, and no energy is stored.

Stored energy effects are of interest to fusion technology for both crystalline materials, such as pure metals and alloys, and noncrystalline materials, such as organics in the form of composite insulators. As far as we know, however, stored energy studies of irradiated materials have been made only for graphite[2] and six pure metals.[3,4] We know of no studies for metal alloys or organic insulators. Fortunately, in the case of metals, there is an abundance of other radiation effects theory and experimental data which can serve as a basis for scoping their behavior with respect to stored energy. By comparison there is no such reservoir of knowledge for organic insulators. The elevated energy states of affected atoms in metals are known to be related to localized distortions in the periodic structure of the atomic lattice. In contrast, those in organics are chemical and electronic in nature. As a result, our abundant knowledge of metals is of little use in predicting the behavior of stored energy in organics. For this reason, the description given in this report of the mechanisms of production and release of stored energy is focused mainly upon metals.

By direct collision an incident neutron or a charged particle can displace an atom from its normal or equilibrium position. When the "knocked-on" atom comes to rest in a metal it is called an interstitial, and the lattice position

from which it came is called a vacancy. Examples are seen in Fig. 2.1. A minimum or threshold knock-on energy is required to displace an atom permanently. The combination of an interstitial and a vacancy is called a Frenkel pair or Frenkel defect, and the separation of the partners can vary widely depending upon the knock-on energy transferred to the struck atom.

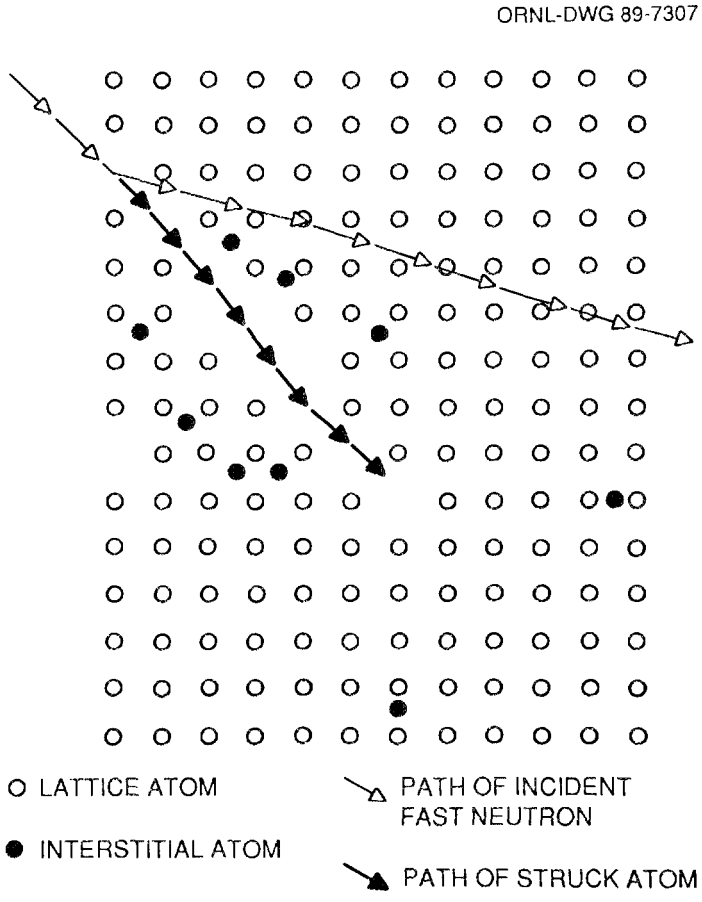

Fig. 2.1. A two-dimensional representation of interstitial and vacancy defect configurations produced by irradiation in a crystalline solid.

The concentration and distribution of Frenkel pairs can vary widely depending upon the irradiation dose and the energy spectrum of the incoming

radiation. The defect distributions produced by each of the three types of radiation reaching a fusion reactor magnet are qualitatively described below.

2.1 Thermal and Epithermal Neutrons

The spectrum of gamma rays emitted by the nucleus of an atom within about 1×10^{-13} second after the capture of a neutron (n,γ reaction) can cause the capturing atom to recoil with sufficient energy (50–500 eV) to produce from one to a few Frenkel pairs in metals. When multiple pairs are produced they lie in close to each other. While the contribution of the n,γ reaction to the total defect production depends upon the neutron energy spectrum (ratio of thermal and epithermal neutrons to fast neutrons) it also depends strongly upon the capture cross section of the host material. For most elements with modest cross sections (up to 10 barns) the contribution by the n,γ reaction is small compared to that by fast neutrons for most reactor spectra. For some elements with higher cross sections such as B, Co, Cd, In, Ag, Au, etc., however, the contributions may be comparable. In the case of organics, all of the constituent elements have small n,γ cross sections which yield a small fraction of the total defect production. One exception is B present in the glass fibers of some composite insulators. The high capture cross section of B and the resulting high energy (2.8 MeV) of the recoiling fragments ($B^{10} + n \rightarrow Li^7 + \alpha$) can produce greater damage than that from all other sources.[5] For this reason, consideration is given to the use of B-free glass.

2.2 Fast Neutrons

Fast neutrons can produce radiation defects by direct collision with host atoms. The "knock-on" or transferred atom energies can cover a wide range of

values (hundreds of eV to tens of keV) depending upon the energy spectrum of the impinging fast neutrons and the mass of the target atoms. In contrast to the wide range of capture cross sections for thermal neutrons, the scattering cross sections for most elements span a narrower range of about 3 to 6 barns. In the case of metals, one primary knock-on (PKO) atom can produce secondary, tertiary etc. knock-ons to create a "displacement cascade" of Frenkel pairs. The number of pairs in a cascade can cover a wide range depending upon the energy of the PKO. Typically, a 1 MeV neutron can produce about 100 Frenkel pairs in a mid-weight element roughly (40–100 amu). In such a cascade, the central region tends to be rich in vacancies while the outer regions are rich in interstitials. The average defect concentration within the cascade is about 1 atomic percent.

When the energy of the PKO exceeds a threshold value the atom becomes ionized. Electrostatic interactions between the moving ion and the stationary host atoms dissipate energy and slow the knock-on. When the knock-on in an organic insulator is ionized and then comes to rest, the ion and its partner electron can remain "frozen in" at low temperatures. Likewise, will any free radical and newly made and broken bonds remain stable until the assembly is warmed. The presence of free electrons in metals precludes the presence of "frozen" inhomogeneities in electrical charge. While some radiation effects are known for organics, such as the breaking of chemical bonds which can result in mechanical, electrical, and optical property changes,[6] the stored energy is speculative at the present time.

2.3 Gamma Rays

Gamma rays produce defects in solids indirectly by first producing energetic Compton electrons which can, in turn, collide with atoms to produce Frenkel pairs in metals[7] and produce the ionization effects in organics described above. In the case of metals, the production of radiation defects by gamma rays is very inefficient since most of the Compton electron energy is dissipated as heat. For a typical mix of neutrons and gamma rays expected in a fusion reactor spectrum, we expect the defect production by gamma rays in metals to be roughly no more than 1% of the total. In contrast, the ionization effects of gamma rays are very effective in producing property changes in organics,[8] and we can only speculate that they are accompanied by stored energy effects as well. For a typical mix, neutrons and gamma rays are expected to do comparable amounts of damage in organics.

In the foregoing discussion, we have given only a brief qualitative discussion of the production mechanisms of radiation defects and the resulting stored energy. Nevertheless, it can be seen that the "typical reactor mix" of radiation components will produce a wide range of defect configurations within fusion reactor materials. Any analysis of a practical reactor case is further complicated by the fact that the radiation intensity and spectrum vary greatly throughout the structure of the reactor. Another complication is the change in defect structures which results from saturation as the radiation dose is increased. The main effects are the spontaneous recombination of interstitials with vacancies and the formation of vacancy and interstitial clusters which occur when new defects are produced very close to existing defects.

The thermally activated motion of a defect naturally leads to exothermic reactions--deionizations, H_2-gas releases, formation of free radicals and linkage changes in polymers, and the conceptually simpler mating of Frenkel pairs and clustering of interstitials and vacancies in metals. All such reactions provide stored energy release. Because of the lack of low-temperature radiation effects information on organics, our discussion of the release of stored energy can be focused only on metals. Both gas release[9] and some property changes[10] have been studied during warmup after low temperature irradiations; however, we can only speculate that substantial release of stored energy accompanies these changes in organics.

Many or all of the defects produced in metals can be "frozen in" depending upon the irradiation temperature. During warm-up after irradiation the defects become thermally activated and move randomly through the material. In nearly all cases, the interstitial moves at lower temperatures than the vacancy. When the interstitial encounters a vacancy they annihilate each other and release typically 3–5 eV per event as heat.[3] Often the radiation produces a variety of interstitial-vacancy configurations each of which has a specific activation energy for movement and eventual annihilation. During a warm-up after irradiation, the multiple activation energy values result in partial releases of the total stored energy which appear as heat pulses centered about particular temperatures. An example of this response for copper is seen in Fig. 2.2, which shows the rate of stored energy release as a function of temperature during warm-up after a fast neutron irradiation at 4.7 K in the LTNIF.[11] The peaks correspond to the partial releases of the stored energy. Graphs of temperature vs time during warm-up, which have applications for fusion reactors, are given in the next section.

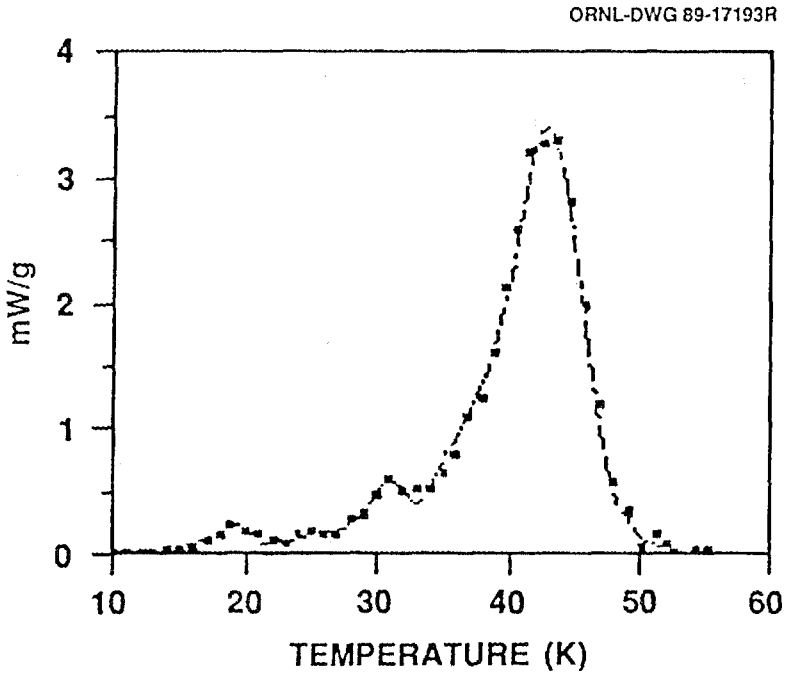

Fig. 2.2. The rate of stored energy release in copper as a function of temperature during warm-up after fast neutron irradiation at 4.7 K in the LTNIF to a dose of 3.8×10^{18} n cm^{-2} (E > 0.1 MeV).

The temperature distribution of stored energy heat pulses released during warm-up depends upon the particular element, any impurity or alloy content, and the energy spectrum of the incoming radiation. Figure 2.3 shows the fractional decreases (upper curves) of the radiation-induced electrical resistivity which occur in copper during warm-up after three different types of irradiation at < 5 K. The lower curves are derivatives which show more clearly the population of particular species of defect configurations for each type of radiation.[12] Both the derivative resistivity and the energy release rate curves reflect the same processes of defect annihilation. For this reason, we can use resistivity data like that in Fig. 2.3 to predict the general behavior of stored energy release for comparable irradiation conditions.

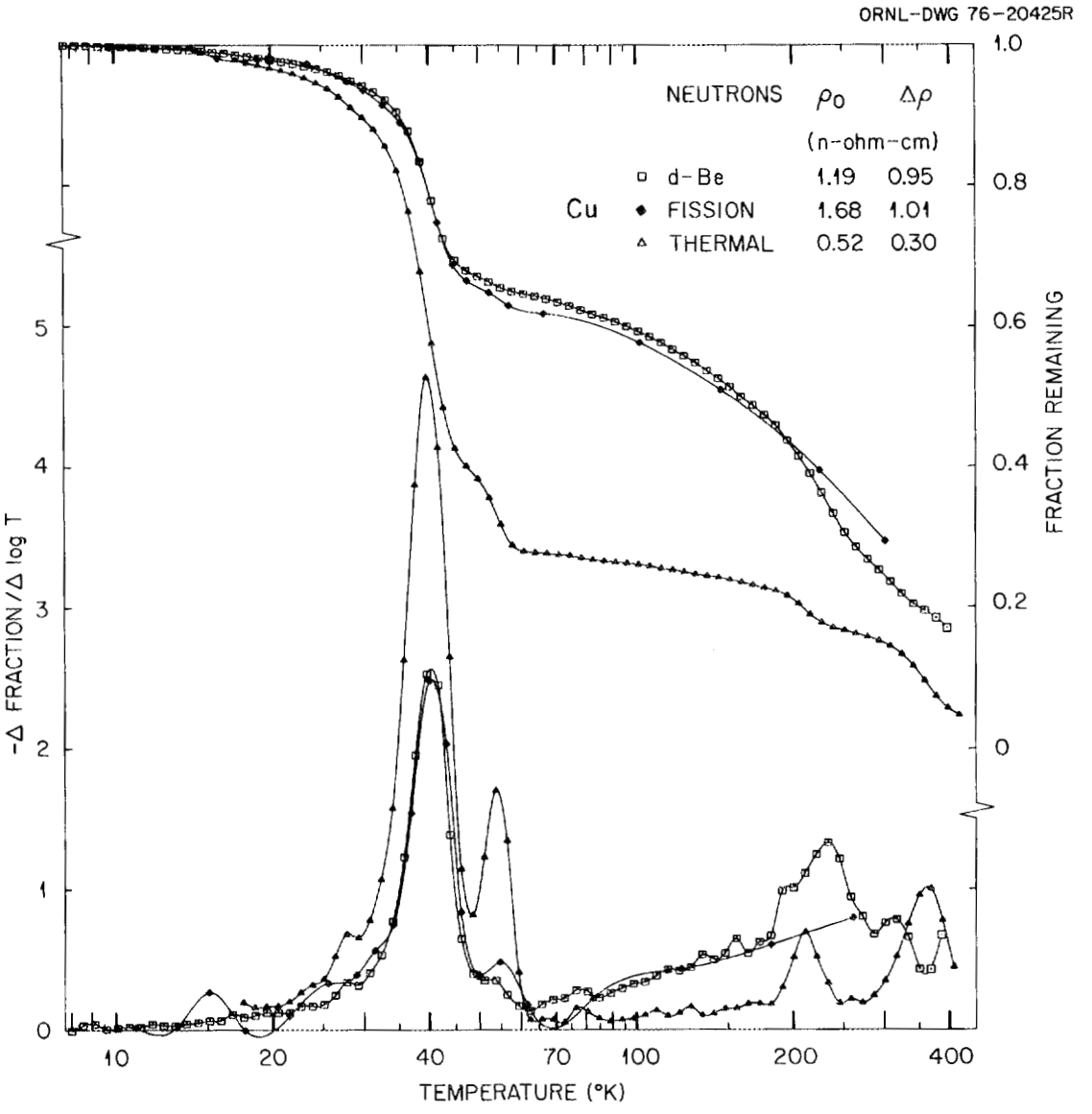

Fig. 2.3 The fractional decreases of the radiation-induced electrical resistivity in copper specimens during warm-up from 5 K after three different types of neutron irradiation.

In addition to the mutual annihilation of interstitials with vacancies, there are other defect reactions which can influence the course of recovery and hence the release of stored energy during warm-up after irradiation. One of

these is the formation of multiple defects (multi-interstitials and multi-vacancies) which are more stable thermally (higher activation energies) than the single defects. This tends to shift recovery and hence stored energy release during warm-up from lower to higher temperatures. Multiple defects can be formed directly during irradiation in the large displacement cascades produced by the high energy knock-ons from fast or fission neutron collision. In contrast the relatively low energy recoils produced by thermal neutron capture create few multiple defects. The fractional recovery data for thermal and fission neutron damage seen in Fig. 2.3 reflect the differences in initial defect configuration produced by each neutron species. Multiple interstitials and vacancies can also be produced by the random encounter of like defects as they become mobile during warm-up.

In addition to the formation of multiple defects, the trapping of defects[13] by extended defects (e.g., dislocations) or by impurities (or minor constituents in an alloy) can also influence the course of recovery and hence stored energy release during warm-up after irradiation. Foreign atoms can trap migrating defects and delay their further movement. Additional warming of the trapped defects is needed to overcome their binding energy to the trap and allow them to move on to annihilation or, not uncommonly, to be trapped by another type of impurity.

While we have a general understanding of many of the underlying mechanisms of recovery, it is clear that the wide range of possible defect reactions and their related activation energy values make it difficult to predict recovery behavior precisely for alloys and impure metals. This is evidenced by the complex recovery rate structure seen for Cu in Fig. 2.3 over the temperature range from 70 to 400 K.

3. THEORETICAL ANALYSIS

The release of stored energy by irradiation defects can, in some cases, produce an uncontrollable rate of temperature rise during an otherwise planned warm-up of an irradiated body. For this reason, it is recommended that the possible impact of the values of stored energy on the safe and efficient operation of fusion reactors be given further study. To help identify the scope of such a study, this section presents a theoretical analysis of the thermal responses of a characteristic material for a variety of irradiation and warm-up conditions.

Nearly all experimental and theoretical information available on the annealing of defects has been derived from property change measurements of samples which were thermally controllable (nonadiabatic) during warm-up. Simple temperature-time warm-up schedules were used because they were amenable to theoretical analysis. For the study of stored energy, however, the warm-up must be made under nearly adiabatic conditions since its release can only be observed by the resulting temperature increases. As a result of the difficult-to-predict temperature-time response of the sample during a stored energy release, the warm-up results are best analyzed by a differential equation which includes the applied heating rate and the thermal properties of the material.

For the model to be used in this analysis, we first assume that a constant power P is applied to a 1-gram sample which contains an annealable defect concentration n_0 expressed as atomic fraction. The recovery of defects during warm-up releases energy at the rate de/dt. According to the conservation of energy principle, the response of the sample is given by

$$P + de/dt = c(T)\, dT/dt + dL/dt, \tag{1}$$

where c(T) is the temperature dependent specific heat, T is the instantaneous temperature, t is the time and L is the energy lost from the surface of the sample. To apply a specific property of the defects to Eq. (1) we write $de = (EN_0/M)\, dn$ where E is the energy released per Frenkel pair (5 eV is chosen as typical for this analysis), N_0 is Avogadro's number, M is the atomic weight, and dn is the change in defect concentration. After substituting for de, Eq. (1) can be rearranged to obtain.

$$dT = \frac{EN_0}{Mc(T)}\, dn + \frac{P - dL/dt}{c(T)}\, dt \quad . \tag{2}$$

The first term on the right side of Eq. (2) relates to temperature change due to the release of stored energy, while the second term relates to changes due to applied and lost heat. As a simplifying assumption for this analysis, we hold the net applied heating rate, P - dL/dt, constant throughout the course of the warmup.

3.1 Annealing Kinetics of Defects

It has been shown that, in many cases, the migration and recovery of irradiation defects obey specific kinetic processes[13] which often occur in successive stages over particular temperature ranges. Three commonly occurring kinetic processes are first- and second-order annealing and correlated diffusion. The first-order annealing process produces somewhat faster annealing rates. Since the difference in the warm-up response for the three processes is only in the relatively fine details, we have selected the first-order process for use in this analysis. The first-order process is given by[13]

$$dn = -Bn\, e^{-U/kT}\, dt, \tag{3}$$

where B is a constant related to the characteristics of the atomic lattice (2.5×10^{12} s^{-1}), U is the activation energy for defect migration, and k is Boltzman's constant (0.8625×10^{-4} eV/K).

The simultaneous equations (2) and (3) are solved by reiterated computations for values of dt using assigned increments of dT and values of T along with a value for the initial defect concentration, n_o. Values of t are found by summing the computed values of dt. The computation is continued until n is sufficiently small (all defects are annealed). From the resulting field of data, plots of sample temperature vs. warm-up time can be made.

3.2 Dependence of Warm-up Upon Defect Concentration

Figure 3.1 shows the computer results for the warm-up of copper with defect concentrations ranging from $n_o = 0$ to 1×10^{-3} atomic fraction. The warm-up rate (P - dL/dt) is 5 mW/g, and U = 0.1 eV. The first visible departure of the warm-up rates from those for the zero-dose case begins at about 33 K. It can also be seen in these curves that, with increasing irradiation dose, the excursions increase to higher temperatures and require shorter times.

A further clarification of the energy release behavior can be seen in Fig. 3.2 which shows the derivative (dT/dt) vs. T of the lower set of curves for Fig. 3.1. The zero-dose heating-rate curve is not visible. The maximum heating rate for a defect concentration of $n_o = 1 \times 10^{-4}$ is 33 K/s at 45 K. The corresponding rate at the same temperature due to the net applied heating (5 mW/g) is only 0.1 K/s; 330 times smaller.

As the dose increases during low temperature irradiation where the defects are immobile the probability of spontaneous (athermal) recombination between vacancies and interstitials also increases (see Sect. 2 above). As a result

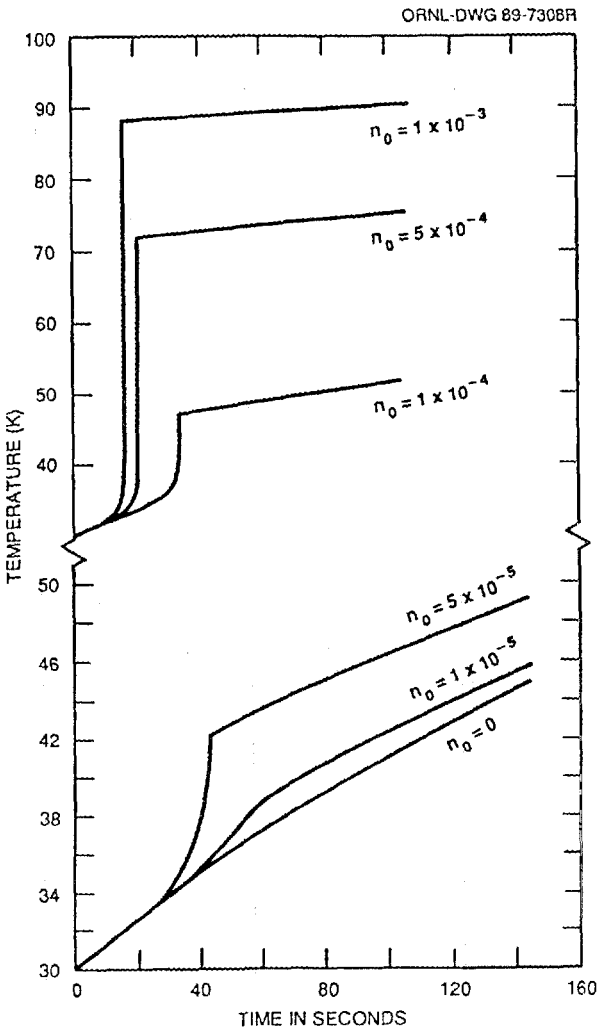

Fig. 3.1. The warm-up response of copper for various defect concentrations. The applied heating rate is 5 mW/g, and the assumed activation energy for the migration of the defects is U = 0.10 eV which is close to the known experimental value.

the defect concentration approaches a saturated value[14] which is estimated at 1.5×10^{-3} for copper. Values close to this could be reached at radiation "hot spots" in fusion magnets (see Sect. 4). The upper set of curves in Fig. 3.1 shows the warm-up response of copper for the higher doses of 1×10^{-4}, 5×10^{-4}, and 1×10^{-3}. The respective temperature excursions are 12, 38, and 55 K. For the last case the maximum heating rate exceeds 10^4 K/s.

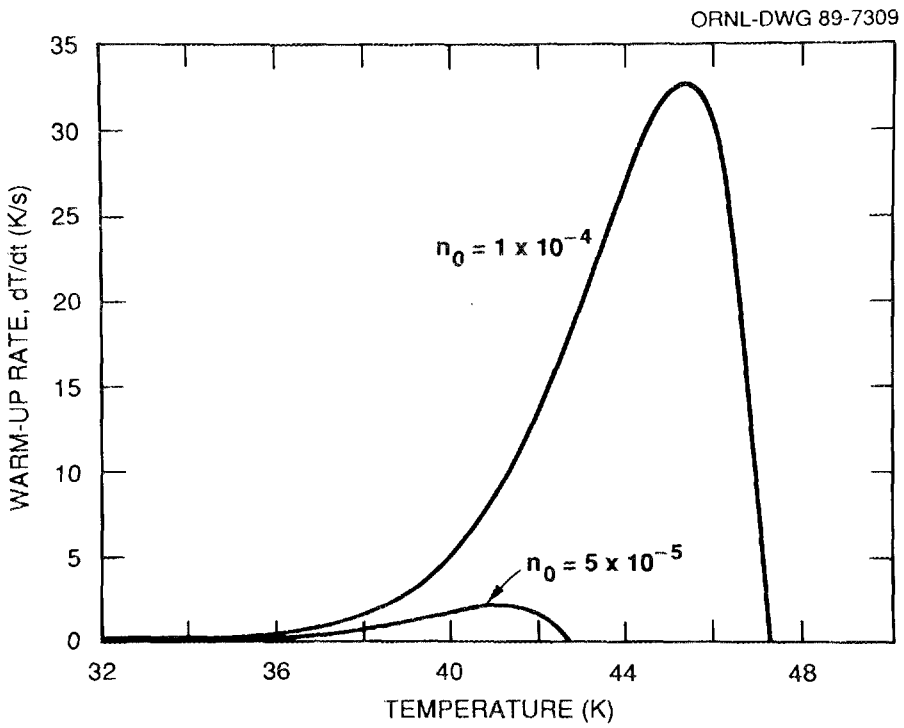

Fig. 3.2. The time derivatives of the lower set of curves in Fig. 3.1 are given as a function of warm-up temperature. The curves for the defect concentrations $n_0 = 0$ and 1×10^{-5} are barely visible above the abscissa.

3.3 Variations of the Applied Heating Rate

Figure 3.3 shows the response of copper with $n_0 = 1 \times 10^{-4}$ for two applied net heating rates; (P - dL/dt) = 1 and 10 mW/g. Notice that the enhancement of the temperature rise caused by the release of stored energy and the temperature range over which it takes place are not influenced by the applied heating rate. These results show that when the total release of the stored energy is large compared to that expended by the applied power over the same temperature span, any variations in the latter cannot serve as a controlling factor in the warm-up response.

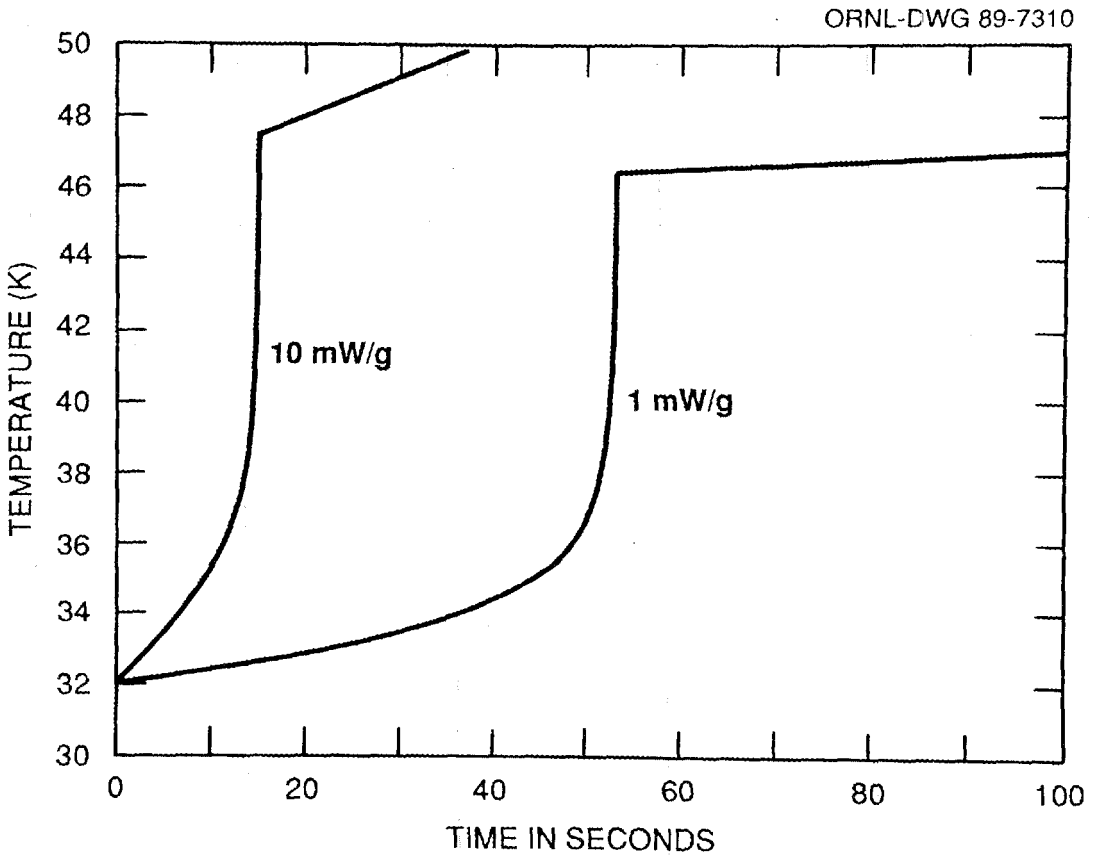

Fig. 3.3. The warm-up response of copper for different applied heating rates, (P - dL/dt), with $n_0 = 1 \times 10^{-4}$ and U = 0.10 eV.

3.4 Dependence Upon Specific Heat

It can be inferred from Eq. (2) that the temperature dependence of the specific heat can play a significant role in the thermal response of a material during the release of stored energy. Figure 3.4 shows the warm-up behavior for three materials with a common defect concentration of 10^{-4}; copper, constantan, and magnesium oxide (MgO). The parameters of E = 5 eV and U = 0.1 eV were chosen for all materials for the sake of comparison since they are not otherwise known for constantan and MgO. Constantan was selected from available specific heat data on alloys because of its relatively large difference from copper.

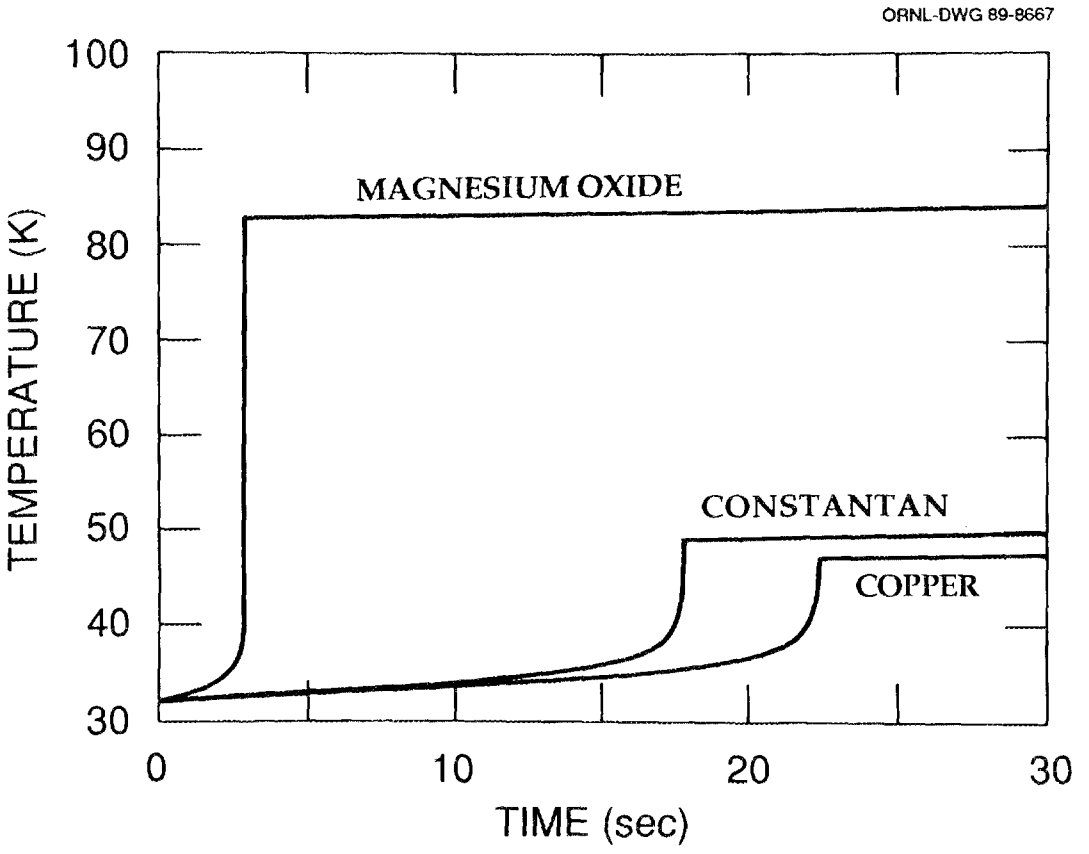

Fig. 3.4. The warm-up response for copper, constantan, and magnesium oxide. The common parameters of $n_0 = 1 \times 10^{-4}$, E = 5 eV, U = 0.10 eV, and P - dL/dt = 5 mW/g are utilized.

While data on stainless steel would be more appropriate, it was not available. MgO was chosen because of its large variation from metals. For the sake of comparison, the specific heats at 40 K, which is about midway through the energy release, are 3.75×10^{17} for copper, 2.98×10^{17} for constantan, and 8.19×10^{16} eV/gK for MgO. Notice that the value for copper is 4.6 times that of MgO. As a result, the temperature rise under these conditions is 4.6 times greater for MgO than for copper. Predictions of the thermal behavior of a material during the stored energy release from a known defect concentration can be made if both the temperature dependence of the specific heat and the defect parameters E and U are known. It is pointed out, however, that E can only be determined

by applying known specific heat data to the results of stored energy experiments.

3.5 Temperature Dependence of Releases - the Influence of U

The temperature range over which stored energy is released is governed by the thermal activation energy U for the movement or migration of the responsible defects. Figure 3.5 shows warm-up curves for copper containing a defect concentration of 10^{-4} which have activation energy values of U = 0.10 and 0.13 eV. Note that the onset of recovery for U = 0.10 eV is about 33 K while

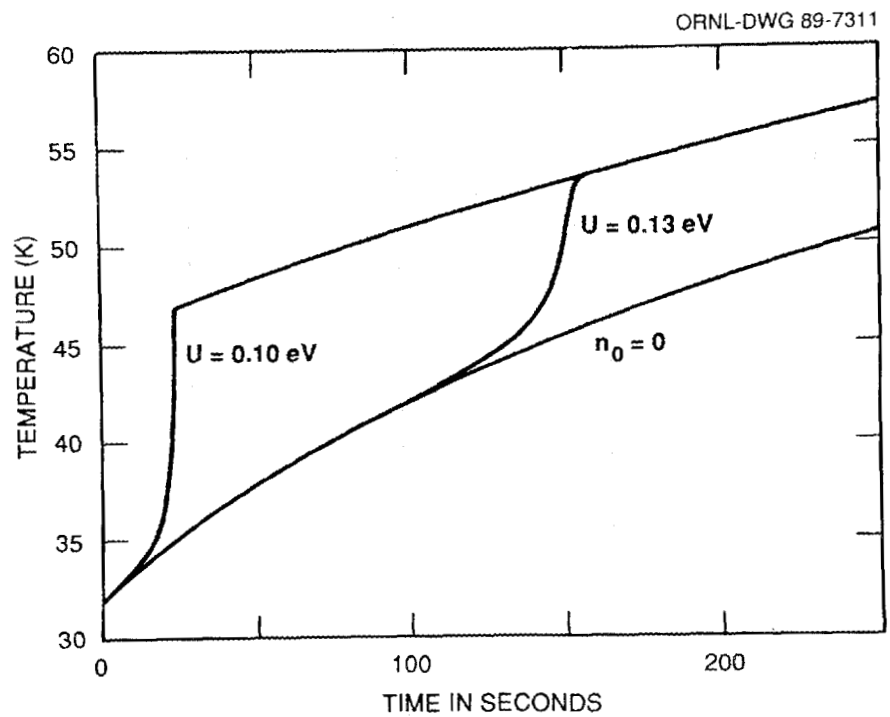

Fig. 3.5. The warm-up response of copper for two different values of the activation energy for defect migration; U = 0.10 and 0.13 eV. The common defect concentration for each stage is $n_o = 1 \times 10^{-4}$, and P - dL/dt = 5 mW/g. A curve for $n_o = 0$ is shown for reference purposes.

that for U = 0.13 eV is about 42 K. Note also that, while the total release of energy is the same for the two cases, the rise in temperature for U = 0.13 eV is less than for U = 0.10 eV. This is accounted for by the increasing specific heat with increasing temperature.

All studies have shown that there are always multiple stages of defect recovery and corresponding releases of energy. Figure 3.6 shows the warm-up response of copper containing two equal concentrations of defects with activation energies of 0.10 and 0.13 eV, respectively. The values chosen for the defect concentrations are 0, 2×10^{-5}, 5×10^{-5}, and 1×10^{-4}. For the smaller defect concentrations, the recovery stages remain relatively isolated from each other

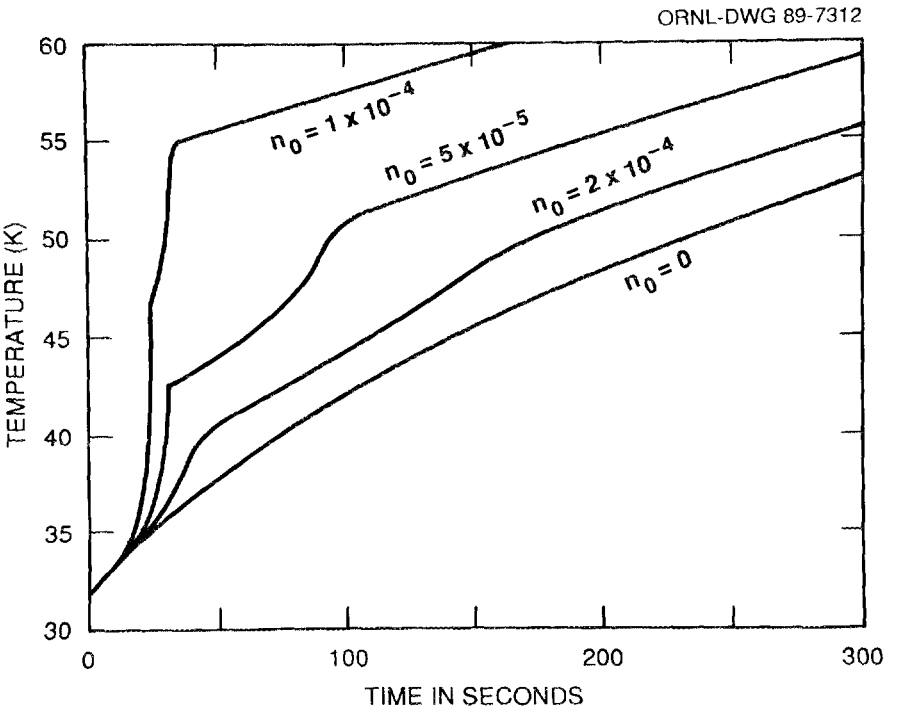

Fig. 3.6. The warm-up response of copper containing two equal concentrations of defects with activation energy values of U = 0.10 and 0.13 eV. Values of n_0 are indicated, and P - dL/dt = 5 mW/g.

on the temperature scale. In contrast, the first stage release in the high concentration case rapidly carries the temperature into the release range of the second stage bypassing any return to the applied heating rate as seen in the other two cases. This sequentially activated behavior is basically a "domino" effect wherein the release from a lower temperature stage triggers the release from a higher temperature stage.

3.6 Controlling the Rate of Energy Release

If, during the course of a planned warm-up of a system the release of stored energy produces an unwanted temperature rise, then an attempt might be made to control the rise by reducing the applied warming rate. Figure 3.7 shows the effect of reducing the applied warm-up rate to zero after the onset of a release of stored energy from a concentration of 10^{-4} defects in copper. Notice that once the release is initiated, a removal of the applied heating rate has virtually no effect on the remainder of the release. The release continues until all defects have been annihilated. The possibility of attaining control by applying cooling ($P - dL/dt < 0$) leads to a complex heat flow problem in real systems which is discussed qualitatively in the next section.

4. APPLICATIONS FOR FUSION REACTOR MAGNETS

Designers generally agree that superconducting magnets for fusion reactors may periodically be warmed to room temperature to remove radiation-induced increases in the electrical resistivity of the copper stabilizer and to perform any needed maintenance. The maximum number of such cycles over the lifetime of the reactor which is considered to be economically feasible is

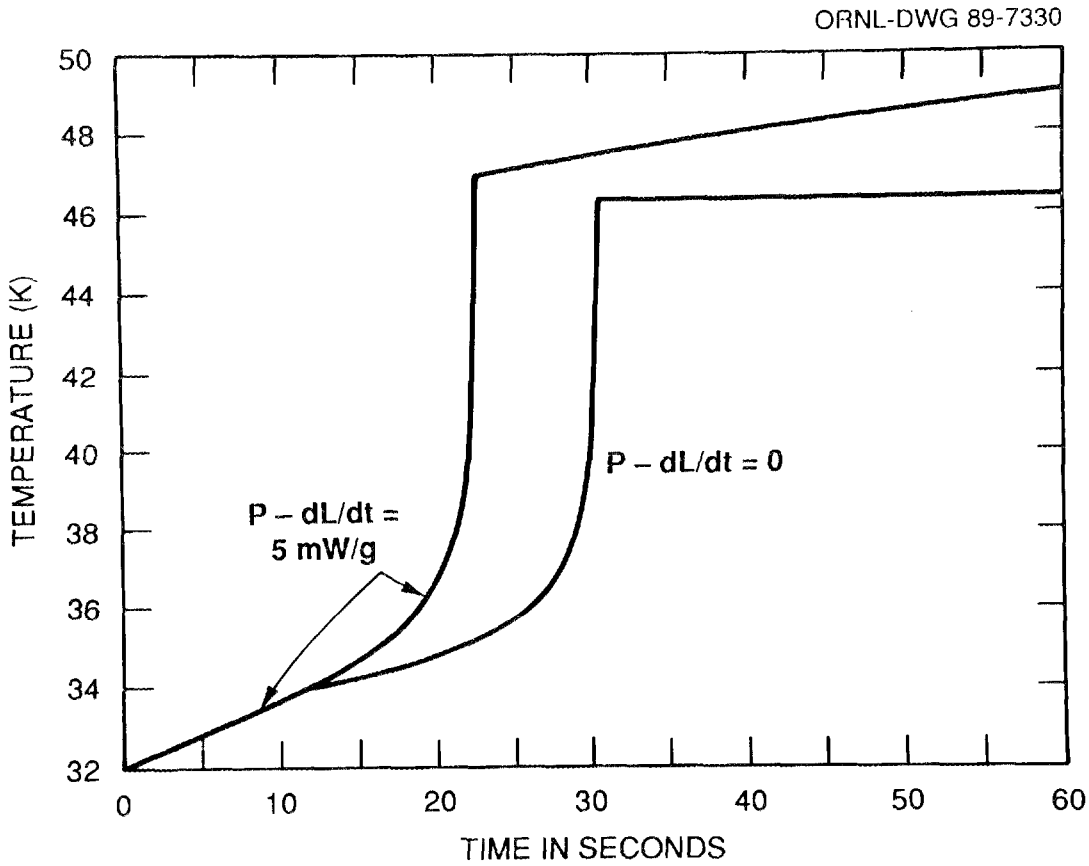

Fig. 3.7. The response of copper when the applied warm-up rate is reduced to zero close to the onset of a stored energy release (34 K). The parameters $n_0 = 1 \times 10^{-4}$, U = 0.10 eV, and P - dL/dt = 5 mW/g were utilized.

about ten for the ITER[15] and five for commercial reactors. We presume that during performance testing, the magnet will be studied to insure that its integrity is maintained during temperature cycling. Such a study would likely include the extensive use of temperature monitors to detect any unwanted stress-inducing temperature gradients in critical members and the use of vacuum sensors to detect any gas bursts which could disrupt planned warm-up rates. Until more information becomes available, it is reasonable to suppose that any unsuspected releases of stored energy during a planned postirradiation

warm-up of a fusion magnet system could produce deleterious temperature excursions.

Any calculation of the response of a fusion magnet system to the release of stored energy during a warm-up cycle would require detailed stored-energy-release information on each component material (the dose dependence of releases over the temperature range of the warm-up) and a detailed neutronics analysis of the system to calculate the distribution of stored energy. While our present neutronics data bank, along with state-of-the-art computer-based computational methods can provide the needed neutronics analysis, the serious lack of data on stored energy precludes even a semiquantitative estimate of the magnet system's response to stored energy releases.

Future research on stored energy can take, on the one hand, a completely empirical approach (temperature vs. time response of irradiated materials during warm-up) without concern for specific values of stored energy; i.e., cal/g. On the other hand, if an analytical approach is considered more economical it must utilize specific values of stored energy which require, in turn, data on the enthalpy or specific heat of materials at low temperatures. While such data are available for pure metals,[16] much is lacking for the superconducting materials, stainless steels, and organic composites anticipated for use in fusion magnet construction. In addition, any comprehensive analysis of a fusion magnet system must take into account the gradients to be expected in stored energy content (discussed below). The response of the magnet to the resulting temperature gradients developed during the release of the stored energy will require information on the temperature dependence of the thermal conductivity[17] which is also lacking for some of the component materials.

While the current lack of stored energy and thermodynamic data prevents any detailed analysis of magnet systems at the present time, there is sufficient information to identify particular aspects which should be considered in future analyses.

4.1 Maximum Dose to the Main Body of a Magnet

Over the years of fusion technology's growth the maximum allowable neutron fluence and gamma-ray dose to magnet materials has steadily increased toward an upper limit imposed, in turn, by limitations on the liquid helium refrigeration system needed to remove nuclear and ambient heat loads on the magnets. In more recent years, two developments have pushed allowable doses close to the upper limit. First, the discovery of the high radiation resistance of polyimide composites compared to commonly used epoxies[8] makes them good insulator candidates for the high dose rate regions of a magnet. Second, the possible use of super fluid He and the development of the "cable-in-conduit" concept[18] for cooling composite superconductors provides greater heat removal rates from the copper stabilizer which, in turn, allows greater radiation-induced resistivity increases therein. The limiting lifetime fast neutron fluence based on heat load considerations is estimated at 2×10^{23} n/m^2 (E > 0.1 MeV).[19] For a lifetime service program of five warm-up cycles, the incremental dose would be 5×10^{22} n/m^2 which is close to that used to obtain the copper results shown in Fig. 2.2.

4.2 Temperature Gradients Induced by Stored Energy Release

As a result of geometrical factors, the intensity of the radiation arriving at the surface of a magnet will vary widely over its surface. In addition, the self attenuation by the magnet materials will produce internal variations in

radiation intensity. Together, these effects will produce gradients in defect concentration and, in turn, gradients in the stored energy to be released. During warm-up the inhomogeneous distribution of stored energy will produce temperature gradients within a component material. The effect of the internal stress produced by such gradients in a particular magnet component may be an important matter for future consideration.

The rate at which such temperature gradients equilibrate will depend upon the thermal conductivity and geometry of the material. In the case of the copper stabilizer, the rates can be estimated using the known thermal conductivity data. The temperature equilibration is expected to occur quickly for copper. In the case of stainless steel and the composite insulators, new thermal conductivity data may be needed. The equilibration rate for stainless steel will be markedly slower than that for copper and the rate for composite insulators will be even slower than that for stainless steel. Any predictive information on the temperature behavior of a magnet during warm-up may serve to guide operators in making any needed adjustments to the warm-up program.

4.3 Radiation "Hot Spots"

Needed penetrations through the blanket and shield of a fusion reactor will allow intense gamma ray and neutron radiation to stream outward and strike relatively small areas of the superconducting magnets. In addition to greater intensity, the neutron spectrum will contain a larger population with the characteristic 14 MeV energy than that impinging on the main body of a magnet. The production rate of defects at the "hot spots" can be from a few to ten times greater than the highest main-body values. As a result, defect

concentrations in metals at "hot spots" can approach the theoretical saturated values after only one operating cycle.

The stored energy that could be released in a metal nearly saturated with defects can be roughly estimated by assuming an atomic defect concentration of 5×10^{-3}, 4 eV per Frenkel pair, and that half of the defects recover during warm-up. The released energy then is 1×10^{-2} eV/atom. For an alloy, a typical release might commence at about 150 K. Above that temperature, the specific heats of most metals are nearly constant. Applying the lattice heat capacity of three times Boltzman's constant per atom (almost universally applicable to crystalline solids in this intermediate temperature range) leads to a resulting temperature rise of 120 K. It is speculated that even for a highly structured recovery spectrum, a high stored energy content could release the energy of various defect configurations in domino fashion. As a result, the temperature rise could occur rapidly, possibly in seconds or less based on results seen for copper in Fig. 3.1. Until new stored energy data are obtained the possibility of a temperature excursion even above room temperature cannot be ruled out.

4.4 Expectations and Uncertainties During the Warm-up Cycle

Even aside from any consideration of stored energy release, it is expected that the warm-up of a fusion magnet system after a reactor power cycle will be carried out according to a procedure intended to protect the system from possible thermal damage. The details of the warm-up procedure will depend upon the magnet design and especially upon the method by which the magnets are cooled during operation, since the cooling system can be used to implement the warm-up. In addition, it is supposed that the exchange-gas pressure in the

insulating vacuum space surrounding a magnet may also be controlled to further implement the warm-up.

In addition to the possible release of stored energy by organic composite insulators during warm-up, these materials can also be expected to release a variety of gases.[8] The gaseous emissions from such composites used as electrical insulators and mechanical spacers and supports within the refrigerated space, may be great enough to contaminate the helium refrigerant. Further, emissions from any composites that may be used as thermal insulating supports within the surrounding vacuum space have the possibility of disrupting any control of exchange gas pressure during warm-up. While gas releases from irradiated composites are known to occur below room temperature, the temperature dependence is not known, although there is indirect evidence for emission as low as 20 K.

The first major release of stored energy during a warm-up cycle is expected to originate in the copper stabilizer at about 30 K. The magnitude and speed of the resulting temperature excursion will depend upon the irradiation dose in a fashion comparable to the theoretical results shown in Fig. 3.4 or 3.6. As an example, consider a high-dose region of the proposed ITER facility.[15] Approximately 1 Joule could be released from each gram of copper stabilizer in less than one second, requiring the impractical He gas refrigeration of 5 kW/m in the 6-cm^2 conduit, or producing a 20-K temperature rise during that second according to the data in Fig. 3.1. Stored energy is released throughout the bulk of a material, but the resulting heat can be removed only through the surface of a body. The rate at which the heat can be conducted into the temperature controlled coolant depends upon the thermal conductivity of the solid and the film resistance at the He-solid interface. In the case of the copper stabilizer the

thermal conductivity is relatively high, however, it is expected to be substantially reduced below unirradiated values depending upon the concentration of radiation defects. The film resistance will, in turn, depend upon the parameters of the warm-up procedure such as the coolant pressure and flow rate. With these uncertainties it is difficult to predict the magnitude of a temperature excursion in the stabilizer and the rate at which the resulting temperature gradient will equilibrate.

At the site of "radiation hot spots" temperature excursions are expected to occur at substantially faster rates and go to higher temperatures than in the main body of the magnet. By the domino effect the release centered at 42 K seen in Fig. 2.2 could, in turn, release energy associated with defects which recover in a structureless fashion between 80 and 300 K as seen in Fig. 2.3.

Nothing is known about stored energy in the candidate superconductors. Since they are highly alloyed materials, it is speculated that the onset of stored energy release will occur at relatively high temperatures—possibly above 100 K. It is speculated further that defect recovery is likely to be structureless in character, although the possibility of a discretely activated release cannot be discarded. Since the superconductor is contiguously dispersed in the copper stabilizer, it is likely that, if stored energy is present in the superconductor, domino effects between the two will take place.

The recovery of defects in stainless steel is known to occur well below room temperature, although the details are not well known,[20] and there are likely to be variations from one alloy type to another. Because of stainless steel's much lower thermal conductivity compared to copper, it is expected that internal temperature increases will more closely approach values that the materials would attain under adiabatic conditions, and that equilibration times

will be much longer. The same type of response is expected for composite organic insulators, but since their thermal conductivities are even less than those for the stainless steels, the resulting effects will be enhanced.

4.5 Energy Release During a Magnet Quench

It is expected that the design of a fusion magnet system intends to safely accommodate the unplanned quench and resulting release of the stored magnetic energy. Provided that magnet temperatures do not exceed approximately 20 K during such an event, it is unlikely that any release of radiation-induced stored energy would be triggered. If, however, a quench initiates in a region where sizable radiation damage and resulting stored energy has accumulated, then the synergistic effects of magnetic and radiation-induced, stored-energy release will produce a local temperature excursion larger than that predicted for a simple magnet quench. The most likely site for such an event will be at a radiation "hot spot," where radiation damage is high and cooling demands imposed by nuclear heating are greatest. Superconducting magnet assemblies will likely be designed to limit the local thermal pulse at the start of a quench to the low thermal expansion range below 150 K. Unfortunately, a 150-K temperature excursion will cover the range where radiation damage anneals sharply (approximately 40 K for pure copper and up to 150 K for alloys). The thermal resistance to heat flow out of the affected region, combined with cooling from the refrigerant stream and with electronic switching to dump magnetic field energy externally, will limit radiation damage annealing to a small part of the magnet.

5. CONCLUSIONS

Even if the needed stored energy data for the component materials of a magnet were available, the wide range of the materials' thermal conductivities and the variety of their thermal interconnections makes it difficult to predict an overall warm-up response. If the low-temperature irradiation facilities become available, consideration could be given to the study of the warm-up response of a possibly miniaturized magnet section as a fruitful element in an investigative program. Even with better predictive information than we now have, it would seem prudent to use additional temperature sensors sited at high flux and "hot spot" regions in the first reactors. The resulting data would be valuable for making later advancements.

The broad purpose of this report is to identify stored energy release in irradiated materials as a possible concern for fusion reactor development. It is our recommendation that further research and study should be made to give a more realistic perspective to this concern than we now have. It is our hope that further study of stored energy release will show that its effects can be accommodated with little or no effort into present conceptual designs, and that progress in the development of fusion energy will continue unimpeded by this concern.

6. ACKNOWLEDGMENTS

This research was funded by the Division of Materials Sciences, Office of Basic Energy Sciences, U.S. Department of Energy, under Contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. The authors are grateful to M. T. Robinson, T. E. Shannon, and John Lyons for discussions and their helpful, elucidating comments.

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160. Office of Assistant Manager for Research and Development, DOE-ORO, PO Box 2201, Oak Ridge, Tennessee 37831-8600
161. T. Okada, Institute of Science and Industrial Research, Osaka University, 8-1 Mihogaoka Ibaragi, Osaka 567, Japan

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