RADIATION DAMAGE IN SOLIDS II

PART OF THE PROCEEDINGS OF THE SYMPOSIUM ON RADIATION DAMAGE IN SOLIDS AND REACTOR MATERIALS

VENICE, 7-11 MAY 1962

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA 1962

PROCEEDINGS SERIES

RADIATION DAMAGE IN SOLIDS

II

PART OF THE PROCEEDINGS OF THE SYMPOSIUM
ON RADIATION DAMAGE IN SOLIDS AND REACTOR MATERIALS
HELD BY THE INTERNATIONAL ATOMIC ENERGY AGENCY
AT THE FONDAZIONE CINI,
S. GIORGIO MAGGIORE, VENICE, 7-11 MAY 1962

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA 1962

RADIATION DAMAGE IN SOLIDS, IAEA, VIENNA, 1962
STI/PUB/56

FOREWORD

Radiation damage has presented a new design parameter for the selection of materials to be used in fuel and cladding elements, moderators, structural components and pressure vessels in nuclear reactors. The severe and novel requirements for certain optimum combinations of physical and nuclear properties have emphasized the need for a better understanding of the basic mechanisms of radiation damage. This knowledge is not only essential for progress in the field of nuclear energy, but has direct applications to space technology and semi-conductor research as well. The IAEA, as part of its programme of promoting nuclear technology, therefore convened the Symposium on Radiation Damage in Solids and Reactor Materials at Venice 7-11 May 1962.

The Symposium was primarily concerned with the investigation of the fundamental processes of radiation that underlie the behaviour of metals, alloys and ceramics that are actually useful or potentially useful reactor materials. Two sessions were devoted to studies of irradiation effects on simple metals, as these effects are easiest to interpret. Other topics included general theory, alloys, fissionable and moderator materials and special experimental techniques for radiation damage studies. The properties influenced by irradiation which were of main concern were those of primary importance to the behaviour of solids as reactor materials (e.g. dimensional stability, phase transformation, radiation hardening, fracture, fission-gas escape from uranium and its compounds). Other properties, such as optical, electrical and magnetic properties, and effects on semiconductors, ionic and other non-metallic crystals are also of interest in that these studies can increase our knowledge of the mechanism of radiation damage in solids and provide a tool for investigation into the physics of the solid state by offering a means of introducing controlled radiation damage. The subjects of corrosion and radiation chemistry were excluded.

The Symposium was attended by 220 participants from 24 Member States and one international organization. Of the 78 papers before the Symposium, 35 on radiation damage in solids generally and 3 on reactor materials were presented and discussed in full, while 35 papers formed the background for five panel discussions, which were introduced by five survey papers.

The two volumes now being published contain all the 35 papers on radiation damage in solids actually presented and discussed individually at the Symposium. The material relating to panel discussions on radiation damage in semiconductors and in ionic and other non-metallic crystals will be published as a third volume later in the year. It is hoped that the panel discussions and papers on radiation damage in reactor materials will also be published at a later date.

SIGVARD EKLUND
Director General

July 1962

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ALLOYS

(Session 4)

EFFECTS OF NEUTRON IRRADIATION ON NON-FISSIONABLE ALLOYS*

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Abstract — Résumé — Аннотация — Resumen

EFFECTS OF NEUTRON IRRADIATION ON NON-FISSIONABLE ALLOYS. Neutron irradiation can cause three major effects in non-fissionable alloys: (1) the excess vacancies produced by irradiation can accelerate diffusion; (2) point defects and regions of strain can serve as additional nucleation sites for phase changes; and (3) the displacement of atoms may cause a break-up of ordered or precipitated regions. By the proper choice of alloy systems, the first two effects have been isolated and examined in detail.

Essentially pure enhanced diffusion can be achieved in short-range ordering alloys such as the α-phase of Cu-Zn and Cu-Al. A quantitative theory was developed which shows that the temperature and flux dependence of enhanced diffusion varies with the relative amounts of excess vacancies and of their trapping sites in the solid. The predictions of the theory for high trapping-site concentration have been verified in Cu-Zn by neutron irradiation, and these for the low trapping-site concentration by positive ion bombardment. Experiments on Cu-Al indicate that the low trapping-site case can be achieved in this alloy with neutrons. These experiments also show that by controlled irradiation an alloy can be put into a low-temperature state which cannot be achieved by thermal means alone.

The change in the number of nucleation sites has been studied in the iron-carbon system. Since the carbon diffuses interstitially, the diffusion rate cannot be accelerated, and no precipitated regions exist in freshly quenched specimens. Therefore, all changes in the rate of disappearance of carbon from solution must be related to trapping, viz., nucleation phenomena. After a few hours' irradiation at ambient temperature, internal friction measurements of the carbon peak showed that it disappears ten times faster than the thermal rate. The implication that ten times the nuclei are present is confirmed by electron microscope studies. After several days of irradiation at low temperature, however, the rate of disappearance of carbon from solution is 1000 times the thermal rate and is governed precisely by the activation energy for diffusion of carbon in iron. Detailed studies of this phenomenon with electrical resistivity measurements show several decay steps which are related to the interaction of the carbon atoms with point defects.

EFFETS DE L'IRRADIATION NEUTRONIQUE DANS LES ALLIAGES DE MÉTAUX NON FISSILES. L'irradiation neutronique peut causer trois principaux types d'effets dans les alliages de métaux non fissiles: 1) Les lacunes supplémentaires produites par l'irradiation peuvent accélerer la diffusion; 2) Les défauts ponctuels et les zônes déformées peuvent devenir des centres de nucléation supplémentaires pour les changements de phase; 3) Le déplacement d'atomes peut provoquer la désagrégation de zônes de cristallisation ou de précipitation. En choisissant judicieusement les alliages, l'auteur a pu isoler les deux premiers effets et les étudier en détail.

Il est possible d'augmenter la diffusion essentiellement pure dans des alliages ordonnés à courte distance, tels que Cu-Zn et Cu-Al en phase alpha. On a élaboré une théorie quantitative montrant que l'influence de la température et de l'intensité du flux sur l'augmentation de la diffusion varie suivant la quantité des lacunes excédentaires et de leurs lieux de piégeage dans le solide. Les prévisions de la théorie concernant la forte concentration des lieux de piégeage ont été vérifiées dans l'alliage Cu-Zn, à la suite d'une irradiation neutronique et celles concernant la faible concentration des lieux de piégeage, à la suite d'une irradiation par des ions positifs. Des expériences faites sur l'alliage Cu-Al montrent que le cas de la faible concentration des lieux de piégeage peut être réalisé dans cet alliage par irradiation neutronique. Ces expériences montrent que par une irradiation contrôlée, on peut placer un alliage dans un état correspondant à une basse température, ce qui ne peut pas être obtenu par des moyens thermiques seuls. Le changement du nombre des centres de nucléation a été étudié dans l'alliage Fe-C. Comme le carbone diffuse dans les interstices, la vitesse de

* Work supported in part by the United States Atomic Energy Commission.

diffusion ne peut être accélérée et il n'existe pas de zônes de précipitation dans les échantillons fraîchement trempés. Toute modification du taux de disparition du carbone de la solution doit donc être attribuée à des phénomènes de piégeage, c'est-à-dire de nucléation. Après quelques heures d'irradiation à la température ambiante, des mesures de la friction interne de la «pointe de carbone» montrent que le carbone disparaît dix fois plus vite que par des moyens thermiques. Des études faites au microscope électronique confirment qu'il y a dix fois plus de noyaux. Toutefois, après plusieurs jours d'irradiation à basse température, le taux de disparition du carbone de la solution est égal à mille fois le taux thermique et dépend précisément de l'énergie d'activation pour la diffusion du carbone dans le fer. Des études détaillées de ce phénomène à l'aide de mesures de la résistivité montrent plusieurs étapes d'altération qui dépendent de l'interaction des atomes de carbones et des défauts ponctuels.

ДЕЙСТВИЕ НЕЙТРОННОГО ОБЛУЧЕНИЯ НА НЕРАСЩЕПЛЯЮЩИЕСЯ СПЛАВЫ. Нейтронное облучение может обусловить три главных вида воздействия на нерасщепляющиеся сплавы: 1) наведенные облучением избыточные вакансии могут ускорить диффузию; 2) точечные дефекты и зоны напряжения могут служить дополнительными местами зарождения новых фаз; 3) смещение атомов может вызвать разрушение упорядоченных зон или зон, полученных в результате осаждения. Благодаря надлежащему выбору систем сплавов удалось выделить первые два вида воздействия и подробно их изучить.

Существенно чистая усиленная диффузия может быть достигнута в сплавах с коротким упорядочением, как например альфа-фаза Cu-Zn и Cu-Al. Была разработана количественная теория, которая показывает, что зависимость усиленной диффузии от температуры и потока изменяется сообразно с относительными количествами избыточных вакансий и мест их улавливания в твердом теле. Теоретический прогноз относительно сильной концентрации мест улавливания был подтвержден при нейтронном облучении Cu-Zn, а прогноз относительно слабой концентрации мест улавливания – при бомбардировке положительными ионами. Опыты на сплаве Cu-Al указывают, что слабые концентрации мест улавливания могут быть достигнуты в этом сплаве при помощи нейтронов. Эти опыты показывают также, что посредством контролируемого облучения сплава его можно привести в состояние, соответствующее низкой температуре, что не может быть достигнуто одними только термическими способами.

Изменение числа мест зарождения было изучено на системах железо-углерод. Так как углерод диффундирует между слоями, то скорость диффузии не может быть ускорена, и в свеже-закаленных образцах не существует зон, образованных осаждением. Поэтому все изменения в скорости исчезновения углерода из раствора должны быть связаны с явлениями захвата, то есть зарождения. После облучения при комнатной температуре в течение нескольких часов измерения внутреннего трения углеродного пика показали, что его исчезновение в десять раз быстрее термической скорости. Предположение о наличии в десять раз большего числа нуклидов подтверждается исследованиями при помощи электронного микроскопа. Однако при облучении при низкой температуре в течение нескольких дней скорость исчезновения углерода из раствора превышает в 1000 раз термическую скорость и определяется как раз энергией активации диффузии углерода в железе. Подробное изучение этого явления при помощи измерения электрического сопротивления указывает на наличие нескольких стадий распада, которые связаны со взаимодействием атомов углерода с точечными дефектами.

EFECTOS DE LA IRRADIACION NEUTRONICA EN ALEACIONES NO FISIONABLES. La irradiación neutrónica puede causar tres efectos principales en las aleaciones no fisionables: 1) el aumento del número de

huecos producidos por la irradiación puede acelerar la difusión; 2) los defectos puntiformes y las zonas de deformación pueden actuar como puntos suplementarios de nucleación para los cambios de fase; 3) el desplazamiento de los átomos puede originar la disgregación de las zonas ordenadas o precipitadas. El autor ha aislado y estudiado con detalle los dos primeros efectos, utilizando para ello aleaciones adecuadamente escogidas.

En aleaciones de ordenamiento compacto, tales como Cu-Zn y Cu-Al en fase α es posible obtener una difusión acrecentada prácticamente pura. Se ha elaborado una teoría cuantitativa según la cual la difusión

acrecentada depende de la temperatura y del flujo, y que esta dependencia varía según la cantidad relativa de huecos y de sus lugares de captura en el sólido. Las predicciones en cuanto a la concentración elevada de lugares de captura, basadas en esta teoría, se han verificado en aleaciones de Cu-Zn por irradiación neutrónica, y las relativas a concentración baja, por bombardeo con iones positivos. Los experimentos realizados con Cu-Al indican que en esta aleación es posible lograr la concentración baja de lugares de captura con ayuda de neutrones. También muestran que gracias a la irradiación controlada, se puede disminuir la temperatura de una aleación hasta un punto imposible de alcanzar con medios exclusivamente térmicos.

La variación del número de puntos de nucleación se ha estudiado en el sistema hierro-carbono. Como el carbono se difunde intersticialmente, no es posible acelerar su difusión, y no existen zonas precipitadas en muestras recién templadas. Por tanto, todas las alteraciones de la velocidad de desaparición del carbono de la solución deben atribuirse a fenómenos de captura o de nucleación. Después de unas horas de irradiación a temperatura ambiente, las mediciones por fricción interna del pico correspondiente al carbono muestran que la velocidad de desaparición de éste es diez veces superior a la velocidad térmica. La deducción de que debe haber un número de núcleos diez veces mayor es confirmada por estudios efectuados con el microscopio electrónico. Sin embargo, después de varios días de irradiación a baja temperatura, la velocidad de desaparición del carbono de la solución es mil veces superior a la velocidad térmica, y depende precisamente de la energía de activación necesaria para la difusión del carbono en el hierro. Estudios detallados de este fenómeno con medición de la resistividad eléctrica indican la existencia de varias etapas de desintegración que se atribuyen a la interacción de los átomos de carbono con defectos puntiformes.

A. EFFECTS OF RADIATION OF ALLOYS

The study of radiation damage in solids was originally motivated by a concern for the property changes to be expected in reactor materials. However, in recent years this type of study has been of increasing importance to the investigation of solid-state phenomena in non-reactor materials, since fast particle bombardment is an excellent method for the introduction of controlled numbers of defects into a solid. The control over the type and distribution of the defects is particularly important in alloys, because any given thermodynamic state of an alloy is characterized by a positional relationship of the atoms. This relationship can be altered in three important ways by heavy-particle bombardment.

(1) Destruction of ordered or precipitated regions

Theoretical studies of the details of damage in a solid by a highly energetic primary knock-on indicate that near the end of its path the knock-on displaces a large number of atoms [1], and also causes interchange of atoms by replacement collisions. Although many of these displaced atoms may relax back to their original positions, the periodicity of any ordered structure which may have existed in this region will have been partially destroyed. If severe local damage occurs near a precipitate some of the clustered atoms should be driven back into solution. The destruction of order by neutron irradiation has been studied in Cu_3Au [2] and Ni_3Mn [3] alloys, and the break-up of precipitates has been reported for both proton [4] and neutron [5] bombardment of Fe-Cu.

(2) Enhanced nucleation

The local damage region at the end of the path of the primary knock-on might be expected to serve as a nucleation site for phase changes. Either the large strains arising from the displaced atoms could be relieved by the formation of a new phase in the vicinity, or the voids which must also be present in this same region of large damage could release the lattice strains surrounding a precipitating atom. A study of the white to grey tin transformation has demonstrated the enhancement of nucleation [6]. White tin is unstable below 12° C but the transformation to grey tin is exceedingly slow unless the white tin is either seeded or severely cold-worked. Prior low-temperature irradiation of the white tin in a reactor will also induce the transformation, which indicates that either the strains of the damaged regions are equivalent to cold-work strains or that some of the damaged regions have rearranged themselves into the grey tin structure. Regardless of the details of the mechanism, neutron radiation has enhanced the nucleation of the phase charge.

(3) Enhanced diffusion

In a large class of metals and alloys atomic diffusion takes place by the vacancy mechanism. The addition by irradiation of vacancies in excess of the number present in thermal equilibrium will, therefore, accelerate diffusion. It has been shown that the diffusion coefficient associated with irradiation in the average reactor is only of the order of 10^{-20} cm²/sec [7]. Since such small diffusion coefficients of tracer atoms cannot as yet be observed, enhanced diffusion is not yet accessible to measurement in pure metals. However, the migration of vacancies in an alloy can cause a large number of local atomic interchanges which can be detected in the changes of some physical properties such as electrical resistivity. This type of measurement has been made on several alloy systems, some of which are reviewed by M. Wechsler in a paper presented at this Symposium.

If the bombarding particle either has a low energy or is light in mass (electrons or gamma-rays), the severe local damage and replacement collisions discussed above are not expected. Only the simple displacement of atoms occurs and, therefore, only single vacancy-interstitial pairs are created. As far as is known, no destruction of order or creation of nucleation centres occurs with electron or gamma irradiation and, therefore, only the enhanced diffusion effect is expected. Since during the irradiation of many alloys at least two of the above effects are occurring simultaneously, it is important to find ways of isolating the individual effects for a quantitative study of each. Two of these effects, enhanced diffusion and enhanced nucleation, have been isolated and studied separately. Investigations of these two effects are discussed in this paper.

B. ENHANCED DIFFUSION

Enhanced diffusion can be studied either by using only electron or gamma-ray radiation or by choosing an alloy system in which enhanced diffusion is the dominating factor. We wanted to make a quantitative study of

enhanced diffusion under all types of radiation and, therefore, chose an alloy, alpha-brass, in which this is the major effect. This alloy has proved to be a fortunate choice for these studies in many respects [8]. It does not become unmanageably radioactive after neutron irradiation; the slight preference of the Cu-Zn bond causes short-range ordering without the development of long-range order; equilibrium short-range order is achieved in reasonable lengths of time in the temperature range of 170-300° C; small changes in short-range order cause large changes in the electrical resistivity; the rate of change of short-range order obeys essentially first-order kinetics; measurements have shown that short-range order is not noticeably destroyed by a few hours of heavy-particle radiation. Three deleterious features are the large thermal coefficient of electrical resistivity, the very similar X-ray scattering of copper and zinc, and a tendency to de-zincify at high temperatures. The first requires the measurement of resistivity at liquid-nitrogen temperature, the second prevents the direct determination of the degree of short-range order, and the third makes annealing at high temperature risky. However, the good features outweigh the bad and this alloy has been used extensively for radiation studies. Details of some of the experiments will now be given.

The black circles of Fig. 1 illustrate the relative equilibrium resistivities of alpha-brass (30% Zn) measured at liquid-nitrogen temperature.

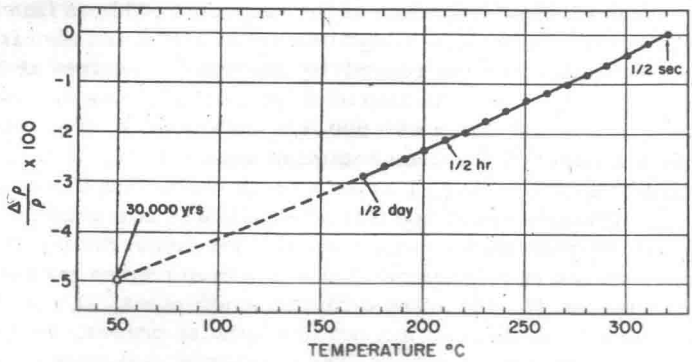

Fig. 1
Equilibrium resistivities of alpha-brass measured at liquid nitrogen temperature
Arrows are example times to achieve equilibrium. Open circle at 50° C is value obtained by electron irradiation. (Reference [9].)

Typical times required to achieve these equilibria are indicated. A study of the times required to achieve equilibrium at several temperatures showed that these characteristic times obey an Arrhenius equation [8] and allow the activation energy for the diffusion process to be determined. The energy obtained in this manner is in excellent agreement with that obtained by other techniques. Knowing this, one can calculate the time to achieve equilibrium at any temperature and, as shown in Fig. 1, at 50° C this time would be 30 000 years. When the brass is equilibrated at one of the higher temperatures and then placed in a radiation field at a lower temperature,

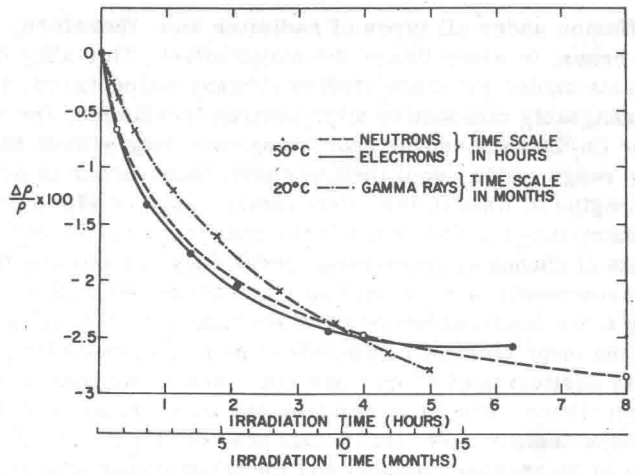

Fig. 2

Change in electrical resistivity of alpha-brass with neutron, electron, and gamma irradiation [9] Fluxes: neutron = 10^{12} nv (fast), electron = 2.6 x 10^{14} electrons/cm² sec, Co^{60}-gamma = 850 000 R/h.

the enhanced-diffusion effect will allow the alloy to achieve equilibrium much faster than under thermal conditions alone, provided the temperature is still high enough to allow migration of the vacancies. This is illustrated in Fig. 2. The brass was brought to equilibrium at 210° C and then irradiated at 50° C in the reactor and the resistivity decrease measured at intervals in liquid nitrogen [9]. This was also done on other samples in a 2-MeV electron beam and at 20° C in a 850 000 R/h Co^{60} source. The final value achieved by six hours of electron radiation shown in Fig. 2 is plotted as the open circle at 50° C in Fig. 1. This clearly shows that a very large enhancement of diffusion occurs and that a technique is now available for putting alloys into thermodynamic equilibrium at low temperatures.

The phenomenon of enhanced diffusion has been treated mathematically with some success [7, 10]. The diffusion coefficient, D, is given as $D = V_t \nu_V \lambda^2$ where V_t is the total number of vacancies present, ν_V their jump frequency, and λ the jump distance. The number of vacancies present in a radiation field is the sum of V_o, the thermal vacancies, and V, the radiation- produced vacancies, and the central problem in the determination of the diffusion coefficient is the calculation of the total number of vacancies under varying conditions. Three possibilities were considered:

(1) The vacancies may anneal to internal and external surfaces. The corresponding differential equation is

$$dV/dt = K - K_V V \qquad (1)$$

where K is the rate of vacancy production and is proportional to the radiation flux, and K_V is the constant of vacancy escape and is proportional to the vacancy sink concentration, α, and, therefore, $K_V = \alpha \nu_V \lambda^2$.

(2) The vacancies may encounter the interstitials and be annihilated before reaching a sink. The corresponding differential equation is

$$dV/dt = K - Vi\nu_i \tag{2}$$

where i is the concentration of interstitials and ν_i is the jump frequency of the interstitials, used here because the interstitial is believed to migrate faster than the vacancy and is, therefore, the rate-controlling factor.

(3) The vacancies may be removed by both of these processes at the same time, then

$$dV/dt = K - K_V V - Vi\nu_i. \tag{3}$$

When the alloy is placed in a radiation field there is a transient condition until a new steady-state concentration of vacancies is established. Then, at steady state, $dV/dt = 0$ for each of the above equations. The solution to the first, Eq. (1) is $V = K/K_V = K/\alpha\nu_V\lambda^2$. The diffusion coefficient in the radiation field, D', contains terms for both the thermal concentration of vacancies, V_o, and the irradiation-produced vacancies, V. Thus

$$D' = (V_o + V)\nu_V\lambda^2 = V_o\nu_V\lambda^2 + \frac{K\nu_V\lambda^2}{\alpha\nu_V\lambda^2} = D + \frac{K}{\alpha} \tag{4}$$

where D is the diffusion coefficient under thermal conditions alone. The natural measure of diffusion enhancement, D' - D, is seen to be the temperature-independent constant K/α. The solution to this and the other conditions appears in Table I.

TABLE I

ACTIVATION ENERGY AND FLUX DEPENDENCE OF RADIATION-ENHANCED DIFFUSION AS DETERMINED BY THE ANNEALING MECHANISM

Annealing mechanism	Activation energy for enhanced diffusion	Flux-dependence of enhanced diffusion
Linear	0	Linear
Recombination	$E_m^V - (1/2)E_m^i$	Square root
Recombination plus linear	$(1/2)E_m^V$	Square root

In this Table E_m^V and E_m^i are the migration energies of the vacancies and interstitials respectively. A plot of Eq. (4) is shown by the dashed curve of Fig. 3; the solid line is the thermal diffusion. The ordinate of this figure is $1/\tau$ where τ is the mean atomic jump time, and is related to the diffusion coefficient in FCC. metals by

$$D = \lambda^2/12\ (1/\tau) \tag{5}$$

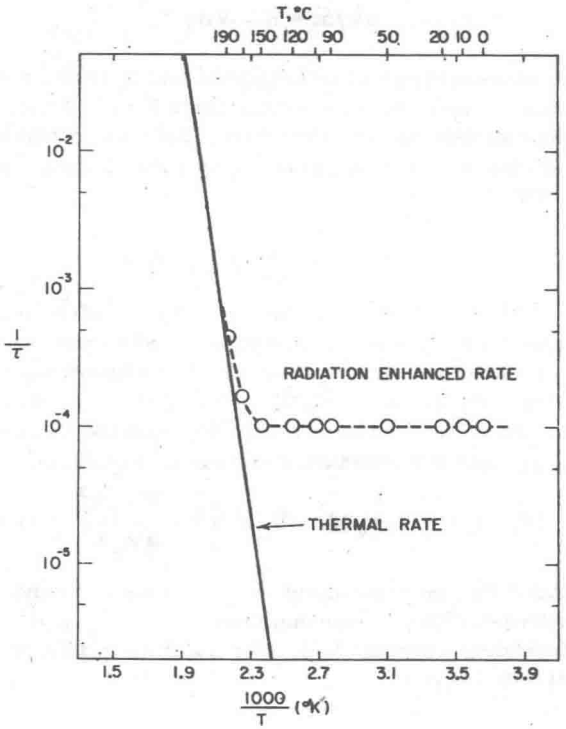

Fig. 3
Rate of ordering ($1/\tau$), vs. $1/T$ for neutron irradiation of alpha-brass
Solid line - thermal rate. Dashed line - theoretical radiation enhanced rate for linear annealing of vacancies. Circles - experimental points [7].

Data similar to those of Fig. 2 were taken in the Brookhaven reactor at a variety of temperatures. The reciprocal of the characteristic decay time τ, of the curves, where τ is also the mean atomic jump time, is plotted in Fig. 3 with open circles. It is seen that the behaviour predicted by Eq. (4) for the linear annealing of vacancies to sinks is obeyed and, by use of Eq. (5), $D' - D = D' \cong K/\alpha \cong 10^{-20}$ cm^2/sec.

The validity of this simple theory has been further demonstrated by DIETZ and BALTHESEN in the iron-silicon system [11]. They quenched iron containing 3% silicon from 1000° C, where it is soluble, and irradiated it in a reactor at a series of lower temperatures. They studied the precipitation rate by measuring the magnetic after-effect. Their results are illustrated in Fig. 4 where the plotted variable $n_0 D$ is proportional to the $1/\tau$ used in Fig. 3. It is seen that there is a plateau similar to that observed in alpha-brass between 300 and 400° C. The rapidly decreasing curve below 300° C probably arises from the decreasing mobility of the vacancies where the steady-state approximations to Eqs. (1-3) are not valid. The slight slope in the plateau region is attributed by the authors to a small contribution from recombination of vacancies and interstitials as shown in Eq. (2) and Table I. From the value of their plateau region, $K/\alpha \cong 10^{-20}$, which is in

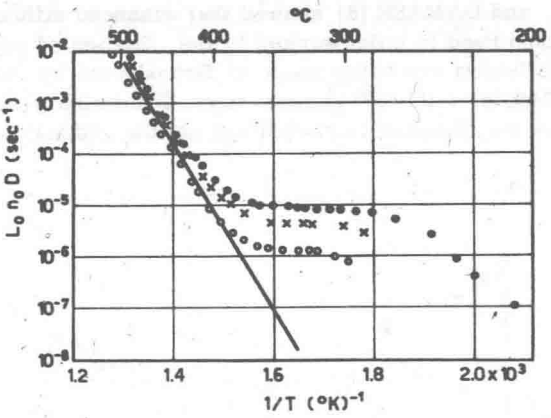

Fig. 4
Rate of diffusion (n_oD) vs. 1/T for reactor irradiation of iron-silicon [11]

agreement with the alpha-brass results. The difference in values between the two 4-cm-distance specimens of Fig. 4 is probably caused by a differing α, dislocation concentration, in them. The agreement of their results with the theory also indicates that very little disturbance was caused by the break-up of precipitate clusters.

ARNDT and HINES [12] have succeeded in obtaining the case governed by Eq. (3) in which both the linear annealing and the recombination mechanisms are large. They performed experiments on alpha-brass (10%Zn) subjected to 30-keV Ne^+ bombardment. They employed the de-zincafication phenomenon exhibited by alpha-brass by relating the zinc lost at the surface to the diffusion coefficient. Thus, by observing the comparative rate of change of the optical reflection coefficient of the surface for irradiated and unirradiated samples they were able to measure the enhancement of diffusion by radiation at a series of temperatures. They found that the temperature-dependence was not zero as in the linear annealing case, but that the resulting curve could be fitted by the solution of Eq. (3).

As seen in Table I, the slope for this case is $(i/2)E_m^V$. By this relation their data give 18 ± 2 kcal/mol for the activation energy of vacancy motion. They further verified that the enhanced diffusion was proportional to the square root of the bombarding flux as required in the solution of Eq. (3).

The bombardment of the surface of a metal with neon ions produced 4.5×10^{-2} atomic fractions of defects/sec compared with about 10^{-10} atomic fractions/sec produced in a reactor [7]. Such a large concentration of vacancies and interstitials might be expected to permit considerable recombination. It is presumed, therefore, that a light bombardment would produce too low a concentration for recombination and the loss of vacancies would be caused primarily by linear annealing to sinks. Linear annealing should also be favoured when the concentration of sinks is increased. If the sink concentration is too high, then the mean-free-path of the vacancy is too small to cause much atomic interchange and little or no enhanced diffusion is observed. Arndt and Hines reported that their samples had to be