The Reduction of Irradiation-Induced Creep
by Point Defect Trapping

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ABSTRACT

The theory of point defect trapping as developed by Mansur and Yoo has been applied to predict the effect of solutes on the steady-state dislocation climb creep rate. A range of parameters of experimental relevance is considered. Vacancy loops generated in the cascades of point defect production by heavy particles are also included in the formalism. It is shown that the effect of vacancy loops on the creep rate is mathematically equivalent to a simultaneous reduction in the vacancy trapping rate at solutes as well as in the free point defect generation rate and recombination coefficient. These parameters are reduced by the ratio of the sink strength without vacancy loops to the total sink strength. It is found that solute trapping and vacancy loops do not reduce the unperturbed creep rates by more than an order of magnitude for the parametric range considered.

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INTRODUCTION

In an earlier paper [1] the theory of vacancy and interstitial trapping at solutes was developed. The effects of trapping on void nucleation, void growth, and irradiation creep were formulated. It was predicted that while void nucleation would be extremely sensitive to the presence of point defect traps and that void growth and climb-glide creep would be proportional to each other and moderately sensitive, the creep rate by dislocation climb* would be less sensitive to the presence of point defect traps. Experimental observations seem to confirm this predicted trend. Swelling varies by many orders of magnitude with relatively minor solute additions. Creep rates, on the other hand, often are more similar after minor changes in solute content and even for vastly different alloys [2]. The expected behavior of swelling with trapping parameters of interest under attainable experimental conditions has been explored in detail [1]. In view of the demonstrated trend, it is the purpose of the present paper to examine the predicted behavior of the dislocation climb creep rate under a range of experimental conditions.

This paper will also include the vacancy loops formed during the collapse of damage cascades produced by energetic particles. In view of the increased attention accorded this subject in recent years [3-7] the simultaneous effect of vacancy loops and solute traps on the point defect concentrations and in particular on the dislocation climb creep rate will be

*The irradiation creep rate due to dislocation climb has also been referred to as creep by stress-induced preferred absorption of point defects (SIPA) and creep by orientation-dependent capture efficiencies of dislocations for point defects.

determined. The following section gives the theoretical basis for the trapping and creep calculations. The next section gives predicted results in regimes of experimental interest. The work is summarized in the last section.

THEORY

Point Defect Trapping at Solutes

A simplified set of equations describing conservation of point defects in the presence of one vacancy and one interstitial type solute trap in an infinite medium may be obtained from reference [1]

Free Vacancies

$$G_v + \tau_v^{-1} C_v' - R C_i C_v - C_v R_i C_i' - C_v K_v (C^t - C_v' - C_i') - K_v^0 C_v = 0 \quad (1)$$

Free Interstitials

$$G_i + \tau_i^{-1} C_i' - R C_i C_v - C_i R_v C_v' - C_i K_i (C^t - C_v' - C_i') - K_i^0 C_i = 0 \quad (2)$$

Trapped Vacancies at Solutes

$$C_v K_v (C^t - C_v' - C_i') - \tau_v^{-1} C_v' - C_i R_v C_v' = 0 \quad (3)$$

Trapped Interstitials at Solutes

$$C_i K_i (C^t - C_v' - C_i') - \tau_i^{-1} C_i' - C_v R_i C_i' = 0 \quad (4)$$

Equations (1) and (2) describe conservation of free vacancies and interstitials while Eqs. (3) and (4) describe conservation of trapped vacancies and interstitials, respectively. Subscripts v and i denote vacancies and interstitials. The superscript 0 indicates that we have not yet included vacancy loops in these terms. We set* $G_i = G$ and $G_v = G + G_T^0$, where G is

*Here we neglect the effects of interstitials injected during self-ion bombardment. This has been treated in an earlier report [8].

the radiation-induced point defect generation rate and G_T is the thermal generation rate of vacancies, $G_T = K_V^0 \bar{C}_V^S$, where $\bar{C}_V^S$ is the average thermal vacancy concentration at all sinks. C and C' denote the (physical) concentrations of free and trapped point defects. $R = 4\pi r_0 (D_i + D_v)$ is the coefficient of recombination where r_0 is the radius of the recombination volume and the D 's denote the diffusion coefficients. $R_i = 4\pi r_i D_v$ and $R_v = 4\pi r_v D_i$ denote the recombination coefficients of free vacancies with trapped interstitials and free interstitials with trapped vacancies, respectively, where r_i and r_v denote the corresponding radii of the recombination volumes. The mean time a defect is trapped is given by $\tau = (b^2/D^0) \exp[(E^b + E^m)/kT]$ where D^0 is the pre-exponential of the diffusion coefficient, $D = D^0 \exp[-E^m/kT]$, b is the order of an atomic distance, E^m is the free defect migration energy, E^b is the binding energy of a defect to the trap, k is Boltzmann's constant, and T is absolute temperature. $\kappa_v = 4\pi r_v' D_v$ and $\kappa_i = 4\pi r_i' D_i$ denote the capture coefficients of traps for free vacancies and interstitials, respectively, where r_v' and r_i' are the corresponding radii of the capture volumes. K is the rate per free defect for absorption at all internal sinks such as voids, dislocations, etc., i.e., $K = \sum_j K^j$ where j runs over each type of sink. K is simply the sink strength, S , times the diffusion coefficient. For vacancies or interstitials, i or v , $K_{i,v} = D_{i,v} S_{i,v} = \sum_j K_{i,v}^j = D_{i,v} \sum_j S_{i,v}^j$. The sink strengths for voids and dislocations, respectively, are given by $S_{i,v}^V = 4\pi \int r_{i,v}^V Z_{i,v}^V n(r_V) dr_V = 4\pi \bar{r}_V \bar{Z}_{i,v} N_V$ and $S_{i,v}^d = Z_{i,v}^d L$. Here the Z 's are the sink efficiencies of the sink identified by the superscript for the defect identified by the subscript, $n(r_V) dr_V$ is the number of voids per unit volume in the range of radii r_V to $r_V + dr_V$, N_V is the total number of voids, $\bar{r}_V \bar{Z}_V$ is the average value used when all voids are considered to

be of average size and L is the dislocation density. The Z 's are described in more detail in ref. 9.

In the previous paper [1], it was shown that vacancy trapping with a binding energy to traps of E_v^b is equivalent* to interstitial trapping with binding energy $E_i^b \sim E_v^m - E_i^m + E_v^b$. In the remainder of this paper we may treat only vacancy trapping with the understanding that the results apply equally well to interstitial trapping. For the remaining development we therefore set $r_i = r_i' = c_i' = 0$.

Point Defect Trapping at Solutes and Vacancy Loops

To include vacancy loops in our description we replace $G_v = G + G_T^0$ in Eq. (1) with $G_v = G - G \epsilon_v + G_T^0 + G_T^{vl}$, where ϵ_v is that fraction of vacancies generated which is retained in vacancy loops and $G_T^{vl} = Z_v^{vl} D_v C_v^{vl} L^{vl}$ is the thermal generation rate of vacancies emitted from vacancy loops with capture efficiency for vacancies Z_v^{vl} (Z_i^{vl} for interstitials), thermal equilibrium vacancy concentration C_v^{vl} and effective dislocation line length per unit volume L^{vl} . We must also include the loss rate of point defects to vacancy loops so that the loss rate terms become $K_v = K_v^0 + K_v^{vl}$ and $K_i = K_i^0 + K_i^{vl}$ where $K_v^{vl} = Z_v^{vl} D_v L^{vl}$ and $K_i^{vl} = Z_i^{vl} D_i L^{vl}$. Finally, we must

*Equivalent in the sense of producing the same increase in the fraction of point defects recombining. At the November 1977 meeting of the American Nuclear Society in San Francisco a disagreement arose concerning this point. We maintained that vacancy binding at *atomic* solute traps with an energy E_v^b would produce the same effect as interstitial binding with the larger energy $E_i^b \sim E_v^m - E_i^m + E_v^b$. However, M. R. Hayns of AERE Harwell maintained that vacancy binding and interstitial binding at atomic traps produce the same effect when $E_i^b = E_v^b$. We have recently learned, however, that Hayns now agrees with us (M. R. Hayns, private communication). This issue should not be confused with the argument that (only) for large precipitate type traps equivalent effects will be produced when $E_i^b \sim E_v^b$ (A. D. Brailsford, to be published).

add an equation describing conservation of vacancies at vacancy loops.

The system of equations then becomes

Free Vacancies

$$G - G_{\epsilon_v} + G_T + G_T^{vl} + \tau_v^{-1} C_v - R C_v C_i - C_v K_v (C^t - C_v) - (K_v^0 + K_v^{vl}) C_v = 0 \quad (5)$$

Free Interstitials

$$G - R C_v C_i - C_i R_v C_v' - (K_i^0 + K_i^{vl}) C_i = 0 \quad (6)$$

Trapped Vacancies (at Solutes)

$$C_v K_v (C^t - C_v) - \tau_v^{-1} C_v' - C_i R_v C_v' = 0 \quad (7)$$

Trapped Vacancies (at Vacancy Loops)

$$G \epsilon_v + K_v^{vl} C_v - G_T^{vl} - K_i^{vl} C_i = 0 \quad (8)$$

In Eq. (8) the first two terms denote the creation rate of vacancies "trapped" in vacancy loops. These two terms are analogous to the first term of Eq. (7). The third term of Eq. (8) describes loss of "trapped" vacancies by thermal release, the analog of the second term of Eq. (7), and the last term of Eq. (8) describes the flux of interstitials to vacancy loops and is the term analogous to the last term of Eq. (7),* the recombination term.

* In equations (5)–(8) the time derivative of the respective free and trapped-at-solute and trapped-at-vacancy loop point defect concentrations are set equal to zero. This is justified in the absence of vacancy loops by the fact that C_i and C_v have much smaller relaxation times than those for changes in the sink strengths [9], so that C_i and C_v are in a steady state relative to the instantaneous sink strengths. It has been assumed [5,6] and recently shown [7] that the vacancy loop distribution relaxation times are also short and hence that the vacancy loop distribution is in a steady state with respect to the instantaneous sink strength.

After some algebra these equations (5) through (8) may be combined to yield a cubic equation for C_i .

$$C_i^3 (R_V \tau_V K_i^0 R^*) + C_i^2 [R^* R_V \tau_V G_T^0 + K_i^0 K_V^0 R_V \tau_V + K_i^0 K_V^* R_V \tau_V (C^T - C^I) + K_i^0 R^*] \\ + C_i [G_T^0 R^* + R_V K_V^* (C^T - C^I) \tau_V G_T^0 + K_i^0 K_V^0 - R_V \tau_V G^* K_V^0] - G^* K_V = 0 \quad , \quad (9)$$

where

$$\frac{R^*}{R} = \frac{G^*}{G} = \frac{K_V^*}{K_V} = \frac{K_i^0}{K_i^0 + K_i^{V\ell}} \quad . \quad (10)$$

Comparing Eq. (9) with Eq. (40) of ref. 1 reveals that these equations are formally identical. (There is a typographical error in Eq. (40) of ref. 1. All R_i in that equation should be changed to R_V .) Here, however, R^* , G^* , and K_V^* appear instead of R , G , and K_V . Equation (40) of ref. 1 applies to vacancy trapping with no vacancy loops. Therefore, we have shown that the only effect of vacancy loops in conjunction with vacancy trapping at solutes is precisely described by a simultaneous reduction in the free vacancy capture coefficient, in the generation rate of free defects, and in the free defect recombination coefficient by the ratio of the interstitial loss rate to all sinks excluding vacancy loops to the interstitial loss rate to all sinks, as given by Eq. (10). This important result will be used later to study the effect of simultaneous trapping of vacancies at solutes and retention of vacancies in vacancy loops.

Heald and Speight [5] studied the effect of vacancy loops on swelling and creep in the absence of trapping and arrived at the conclusion that the presence of vacancy loops is equivalent to reducing the free defect generation rate and recombination coefficient as in Eq. (10). Our work confirms their result and makes extension to the case where point defect trapping at solutes is taking place simultaneously.

Creep by Preferred Absorption of Point Defects

Creep by stress-induced preferred absorption of point defects results from the induced inhomogeneity interaction between point defects and dislocations [10-12]. The interaction varies with the orientation of the dislocation Burgers vector and the point defect relaxation volume and elastic polarizability. Because the polarizability and relaxation volume of the interstitial are much larger than those of the vacancy, the effect arises essentially by perturbation of the interstitial fluxes. The interstitial flux is enhanced for dislocations having Burgers vector near parallel to the stress axis and decreased for dislocations having Burgers vector near perpendicular to the stress axis. Thus a net interstitial absorption occurs on planes near perpendicular to the stress axis while a net vacancy absorption occurs on planes parallel to the stress axis. The creep rate can be expressed as [13]

$$\dot{\epsilon} = \frac{2\Omega L}{9} \left(\Delta Z_i^d D_i C_i - \Delta Z_v^d D_v C_v \right), \quad (11)$$

where L is the dislocation density and ΔZ_i^d and ΔZ_v^d denote the difference between capture efficiencies for the subscript defect of dislocations with Burgers vectors parallel and perpendicular to the stress axis and are linear in the stress as described below. As mentioned above $\Delta Z_v^d \ll \Delta Z_i^d$ for the vacancy parameters usually employed, meaning that there is no stress-induced preferred absorption of vacancies [1]. The thermal counterpart of Eq. (11), which describes creep due to dislocation climb resulting from stress-induced preferred *emission* of thermal vacancies (Herring-Nabarro creep) is given by

$$\dot{\epsilon} = \frac{2\Omega L D_v C_v^e Z_v^d}{9} \frac{\sigma_E \Omega}{kT} \quad (12)$$

where σ_E is the effective stress and

$$c_V^e = \Omega^{-1} \exp\left(S_V^f/k\right) \exp\left(-E_V^f/kT\right) \quad (13)$$

is the bulk thermal vacancy concentration with S_V^f the entropy and E_V^f the energy of vacancy formation.

The expression given by Heald [13] for ΔZ_i^d is

$$\Delta Z_i^d = \frac{3(1-\nu) \left\{ 2\pi / \ln \left[2R_d \left| \frac{(1+\nu) \mu b \Delta V_i}{3\pi(1-\nu) kT} \right| \right] \right\}^2 \sigma V_i a_i}{4\pi(1+\nu)^2 \Delta V_i \mu} \quad (14)$$

while the expression obtained from Wolfer et al. may be written [14]

$$\Delta Z_i^d = - \left[\frac{b}{4a \ln(R_d/a)} \right]^2 \frac{(1+\nu)}{120 \pi} \frac{(5-4\nu)}{[(1-\nu)kT]^2} \sigma \alpha_i^\mu \Delta V_i \bar{Z}_V^{-1} \quad (15)$$

Here $a_i = -15(1+\nu) \Delta \mu_i / [15(1-\nu) \mu + 2(4-5\nu) \Delta \mu_i]$, $R_d = (\pi L)^{-1/2}$ is one-half the mean dislocation spacing, a is the dislocation core radius, ν is Poisson's ratio, μ is the shear modulus, ΔV_i is the interstitial relaxation volume, α_i^μ is the interstitial shear polarizability, and $\bar{Z}_V$ is the average vacancy capture efficiency of all sinks in the system. Equations (14) and (15) could be written in more similar form when we realize that

$$\alpha_i^\mu = \mu \Omega \quad 15(1-\nu) \Delta \mu_i / [15(1-\nu) \mu + 2(4-5\nu) \Delta \mu_i] \quad .$$

However, we retain the present forms since [13] gives a set of recommended parameters which includes a value for $\Delta \mu_i$ while [14] gives a set which includes α_i^μ . In Fig. 1 we show that Eqs. (14) and (15) give similar numerical results using the parameters recommended for each. However, it should be pointed out that if we use the $\Delta \mu_i$ recommended in [13]

this gives an interstitial shear polarizability of ~ -10 eV as compared to the more reasonable value of -150 eV recommended in ref. [14]. Thus, if we were to use the same sets of parameters in Eq. (14) and (15) the predicted creep rates would differ by an order of magnitude. In general, the predicted creep rates are sensitive to the assumptions made for parameters which are not well known. Another example would be the dislocation core radii. If this were doubled then Eq. (15) would give roughly a factor of 4 lower creep rate.

Fortunately, the results we present in the next section for the effect of trapping on creep rate are independent of the ΔZ 's given by Eqs. (14) and (15). They only depend on the fact that ΔZ_i^d is non-zero. This obtains since we are interested in the reduction in creep rate with trapping. The creep rates are proportional to the free interstitial concentrations by Eq. (11) since $\Delta Z_v^d \ll \Delta Z_i^d$. Thus the quantity of interest in this paper is the ratio of the interstitial concentration with trapping to that without trapping, which is independent of ΔZ_i^d , the value of the difference in interstitial capture efficiencies of dislocations aligned parallel and perpendicular to the stress axis.

For completeness, we also recall that for dilute alloys, the effect of trapping on thermal creep, [Eq. (12)], is negligible, no matter how large the effect on irradiation creep. Thus, at a fixed temperature, the thermal component of creep becomes a larger fraction of the total creep as trapping becomes more important. This arises because the number of free thermal vacancies remains essentially unchanged even though the total number of thermal vacancies in the system increases due to an increase in the number of trapped vacancies as the vacancy binding energy increases. From equilibrium statistics [15]

$$c_v^{e'} = 12 c^t \exp \left(S_v^f / k \right) \exp \left(-S_v^b / k \right) \exp \left[- \left(E_v^f - E_v^b \right) / kT \right] \quad (16)$$

and

$$c_v^e = \left[\Omega^{-1} - c_v^{e'} - 12 c^t \left(1 - c_v^{e'} / c^t \right) \right] \exp \left(S_v^f / k \right) \exp \left(-E_v^f / kT \right) \quad (17)$$

Here $c_v^{e'}$ is the concentration of trapped vacancies and S_v^b is the change in entropy on binding a vacancy. Since E_v^f is greater than 1 eV and E_v^b is less than 0.5 eV in metals of interest, we see that $c_v^{e'} \ll c^t$, and in a dilute alloy by definition $c^t \ll \Omega^{-1}$. Thus c_v^e in Eq. (12) is affected little by vacancy trapping and the thermal creep rate is essentially unchanged.

RESULTS

In this section the effects of trapping on the creep rate by dislocation climb are explored. For reference, we first examine the creep rate without trapping as a function of dose rate and temperature. Table 1 gives the parameter values used in these calculations. Figure 2 shows the creep rate as a function of dose rate. This figure shows that creep rate is proportional to the square root of dose rate at low temperature (300°C) and linear in dose rate at high temperature (700°C) with a transition from linear to square root at intermediate temperature (500°C) above about 10^{-5} dpa/s. This is to be expected since we have shown in the previous section that the creep rate is essentially proportional to the free interstitial population. It has been shown [9] that the point defect concentrations are proportional to the square root of the dose rate where most point defects are lost by recombination (low temperature or high dose rate) and to the first power of the dose rate where most point defects are lost to sinks (high temperature or low dose rate).

Figure 3 shows the predicted creep rate as a function of temperature for typical reactor and charged particle dose rates. At reactor dose rates the irradiation induced creep rate is insensitive to temperature above about 425°C. At the higher charged particle dose rate, however, the creep rate is an increasing function of temperature. This is because at the lower dose rates the loss of point defects to recombination is not dominating above about 425°C, while at the higher dose rate the loss to recombination is still decreasing substantially with increasing temperature at 650°C. For a fixed sink structure the interstitial concentration is insensitive to temperature where recombination is minor, since D_i in this temperature range increases only slightly with increasing temperature. Figure 3 also shows for comparison the thermal dislocation climb component of creep.

Figures 4 through 6 show the effects of vacancy trapping on the irradiation induced creep rate as functions of dose rate, sink strength, solute concentration, and temperature. A vacancy binding energy of 0.5 eV is used in these computations. This is a relatively high binding energy and thus the results may be thought of as upper limits to the effects of trapping on irradiation-induced creep. Figure 4 shows the reduction in creep rate as a function of solute concentration for typical reactor and charged particle dose rates and temperatures. We note that at the highest solute level the effect of trapping is to reduce the creep rate about a factor of 5 for charged particle and about a factor of 2 for reactor conditions. Reactor creep simulation by charged particles usually takes place at near reactor dose rates and temperatures. However, it is interesting to find that at the much higher dose rates and temperatures where swelling simulation takes

place (the high dose rate, high-temperature case of Fig. 4) the creep rate is expected to be more strongly reduced by trapping. Thus the buildup of stress due to nonuniform swelling would be enhanced compared to reactor conditions.

Figures 5 and 6 show the effect of varying the sink strength, solute concentration, and dose rate. Figure 5 shows that even with the lowest usual sink strength in an irradiated material, 10^{13} m^{-2} , the creep rate is only reduced by a factor of 4 at 0.1% solute. At the very high level of $5 \times 10^{15} \text{ m}^{-2}$, corresponding roughly to a highly cold-worked stainless steel, the effect of trapping on creep rate is negligible. Figure 6 shows the effect of trapping on creep rate with variation in sink strength in the range of reactor dose rates. At a sink strength of 10^{14} m^{-2} , corresponding say to lightly irradiated nickel, the reduction in creep rate over most of the range is approximately a factor of 3 at 0.1% solute while again at $5 \times 10^{15} \text{ m}^{-2}$, corresponding say to cold-worked stainless steel, the effect of trapping is negligible. However, even at the lower sink strengths the effect of trapping is insignificant at dose rates of the order of 10^{-7} dpa/s , corresponding to the outer regions of a reactor core assembly. The reason for this is that the free interstitial concentration is so low at this dose rate that the probability of recombination of an interstitial with either free or trapped vacancies is small.

Figures 7 and 8 display the effects of vacancy trapping and vacancy loops on creep rate. Figure 7 represents a typical dose rate and temperature for reactor irradiation and Fig. 8 for self-ion bombardment. The relative creep rate is plotted as a function of $K_i^{VL}/K_i^0 = S_i^{VL}/S_i^0$, the ratio of vacancy loop sink strength for interstitials to that for all sinks

excluding vacancy loops. The plots cover the range from where the sink strength of vacancy loops is small compared to the sink strength of other sinks to where the vacancy loop sink strength is five times the sink strength of other sinks. Since vacancy loops are thought to be formed at a size of near $10 \text{ \AA}$ [3-7] and the average size at any instant in the steady state must be smaller than this due to decay and net interstitial absorption, they are generally not resolved in postirradiation electron microscopic examinations. Thus their actual density and therefore sink strength is uncertain. Without trapping, the reduction in creep rate is substantial at large vacancy loop sink strengths, about a factor of 5 for reactor conditions and a factor of 3 for ion bombardment conditions when $K_i^{v2}/K_i^0 = 5$. However, with trapping, the further reduction in creep rate due to vacancy loops is more modest. For vacancy trapping with a binding energy of 0.5 eV and solute concentration of 1%, the additional reduction in the creep rate due to vacancy loops is less than a factor of 2 up to a vacancy loop sink strength ratio $K_i^{v2}/K_i^0 = 5$. From these curves we also observe that as the vacancy loop sink strength increases the effect of trapping becomes less important as evidenced by the fact that the curves approach each other at high vacancy loop sink strength ratios. This is as required physically. As the sink strength is increased the loss rate of interstitials by recombination with both free and trapped vacancies is decreased, and in the limit of large K_i^{v2}/K_i^0 the curves with free recombination (upper curve in Figs. 7 and 8) and with free and trapped recombination (lower two curves in Figs. 7 and 8) should approach each other since they also must approach the same value that would be obtained by neglecting bulk recombination and trapping altogether.

SUMMARY

In this paper the effects of point defect trapping at solutes on the dislocation climb creep rate are explored with a range of variables of experimental interest. The basis of the negligible role of point defect trapping on the thermal dislocation climb creep rate is described. It is due to the fact that the self-diffusion coefficient $D_v C_v^e$ is essentially unchanged by dilute concentrations of alloying elements. It is shown that vacancy loops, generated by the collapse of point defect production cascades, may be included in the formalism together with point defect trapping at solutes. The effect of these vacancy loops on the creep rate is shown to be mathematically equivalent to a simultaneous reduction in the point defect generation rate, the free point defect recombination coefficient, and the capture coefficient of solute traps for free vacancies by a factor S_i^0/S_i in equations which apply to a system without vacancy loops. This latter factor is the ratio of the sink strength for interstitials of all sinks excluding the vacancy loops to the sink strength for interstitials of all sinks. The combined effects of solute trapping and vacancy loops on the creep rate under several conditions are illustrated. The reduction of the creep rate due to both solute trapping and vacancy loops is never found to be more than an order of magnitude in the parametric range explored here. Two conclusions may be based on these findings:

1. Steady-state creep rates are not expected to be greatly different in alloys with differences in solute content and binding energy, i.e., chemical identity, of solutes at the levels of order 1% examined here.

2. The possibly different steady-state vacancy loop distributions, resulting from neutrons on the one hand and the charged particles used to simulate reactor irradiation-induced creep on the other hand, are not

expected to produce greatly different creep rates. The differences are expected to be even smaller where point defect trapping is operating simultaneously. This follows since the difference in steady-state distributions of vacancy loops produced by one type of particle and another must be smaller than the difference between including and omitting vacancy loops. We have examined this and found it to give a factor of 5 reduction in the most extreme case (Fig. 7, upper curve).

This general reduction of the creep rate by several-fold with point defect trapping which we predict for reasonable conditions may provide one possible interpretation of a phenomenon which has recently been pointed out. In ref. [16], Straalsund shows results for stainless steels where the creep rate increases by a factor of 2 or 3 from low dose to high dose. In these materials, in general the precipitate volume fraction increases over this dose range, thus resulting in a depletion of solute traps. The increase in creep rate observed is of the order predicted here when a substantial fraction of solute, initially of concentrations of the order of 1%, is taken up in precipitates.

The present theory will be compared in detail to experimental results which are becoming available. At present it is possible to say that the predicted lack of strong sensitivity of steady-state creep rate to point defect trapping and vacancy loop content is in agreement with experimentally observed trends.

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TABLE 1

Parameter Values Used in Obtaining Results
Shown in the Figures

Parameter	Value
σ , MPa	100
μ , MPa	7.75×10^4
ν ,	0.312
$\Delta\mu_v$, MPa	0
$\Delta\mu_i$, MPa	-7.75×10^4
b , m	2.1×10^{-10}
ΔV_v , m ³	-5.06×10^{-30}
ΔV_i , m ³	1.4×10^{-29}
V_v , m ³	5.06×10^{-30}
V_i , m ³	1.4×10^{-29}
a , units of b	4
L , m ⁻²	5×10^{14}

FIGURE CAPTIONS

Fig. 1. Comparison of ΔZ_i^d Expressions given by Heald [13] and Wolfer et al. [14] Versus Temperature. The ordinate is equal to $2\Omega L \Delta Z_i^d / 9$ by Eq. (11).

Fig. 2. Dislocation Climb Creep Rate Versus Dose Rate at Several Temperatures Spanning the Range of Engineering Applications.

Fig. 3. Dislocation Climb Creep Rate Versus Temperature for Typical Reactor Dose rates (10^{-7} – 10^{-6}) and Charged Particle Dose Rate (10^{-3}).

Fig. 4. Effect of Trapping on the Creep Rate with Increasing Solute Content. Solid curve is typical for reactor irradiation and dotted curve is typical for charged particle bombardment.

Fig. 5. Effect of Trapping on the Creep Rate with Increasing Solute Content and for Different Sink Strengths at 500°C and 10^{-6} dpa/s. The dashed, dashed-dotted, solid and coincident-with-border curves represent the lowest through highest sink strengths of experimental interest.

Fig. 6. Effect of Trapping on the Creep Rate over the Range of Reactor Dose Rates of Interest, for $T = 500^\circ\text{C}$ and for a Range of Sink Strengths.

Fig. 7. Combined Effect of Trapping and Vacancy Loops on the Creep Rate as a Function of the Vacancy Loop Sink Strength for Interstitials Normalized to the Sink Strength for All Other Sinks, under Typical Reactor Irradiation Conditions.

Fig. 8. Combined Effect of Trapping and Vacancy Loops on the Creep Rate as a Function of the Vacancy Loop Sink Strength for Interstitials Normalized to the Sink Strength for All Other Sinks, under Typical Charged Particle Bombardment Conditions.

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Fig. 1. Mansur and Wolfer

Fig. 2, Mansur and Wolfer

Fig. 3, Mansur and Wolfer

Fig. 4, Mansur and Wolfer

Fig. 6, Mansur and Wolfer

Fig. 7, Mansur and Wolfer

Fig. 8, Mansur and Wolfer