UNCLASSIFIED

C. C. Bigelow

FKM- 3549
April 1, 1958This document is
PUBLICLY RELEASABLE

FROM: D. P. Gregory

Authorizing Official

Date: 3-27-2013

SUBJECT: Creep of Columbium in a
High Fast Neutron Flux
FieldCC: R. I. Strough M. Cooper
E. R. Dytko Ray Kennedy
A. I. Chalfant S. E. Moore
G. H. Rowe M. Zeisser
R. E. ClearyClassification Cancelled or Changed
TO

By Authority of D.O.C

Circ: B. A. Schmickrath
C. E. Holtsinger
G. E. Beardsley
R. N. WallaceName Title Date
K. O. Bapatich 5/14/70

Classification

Authorized Classifier

4-3-58
Date

Recent reactor designs consider fast fluxes in excess of 10^{16} neutrons/cm²/sec. There is the possibility that the radiation damage of structural materials, especially the creep rates, could be accelerated in such high neutron flux fields. The purpose of this report is to examine the theory of radiation damage to obtain an idea of the extent of this damage.

Bruch and McHugh discuss the effect of neutron flux on the magnitude of radiation damage. They conclude on very meager data that if there is an effect of flux, the direction is toward a decrease in magnitude of radiation damage with increasing flux. The variation in flux from which this conclusion was drawn is from 10^{11} to 5.5×10^{13} . As stated before, neutron fluxes a thousandfold larger than the maximum one above are anticipated. Thus, more experimental work at higher fluxes needs to be done in order to substantiate this trend.

A previous report, FKM-3389, discusses the theory of radiation creep. The calculations below follow the procedure given in this memo.

When a 2-Mev neutron strikes a columbium nucleus in a head-on collision, it imparts a kinetic energy to the nucleus of the order of 0.085 Mev. For collisions at other angles, the average energy transferred is half this amount, or

UNCLASSIFIED

DISCLAIMER

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

DISCLAIMER

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

C. C. Bigelow

FXM-3549

0.0425 Mev. The energy required to knock an atom out of its lattice site to form a separated interstitial and vacancy is 25 ev for copper. For columbium, a value of twice this amount seems realistic. Thus, the number of displaced atoms produced from each fast neutron collision is approximately 425. The total concentration of displaced atoms produced in a time t by a fast neutron flux ϕ in a material with a scattering cross-section σ_s is given by:

$$C \approx n \sigma_s \phi t$$

For columbium, $n = 425$, $\sigma_s = 5 \times 10^{-24}$, and if $\phi = 10^{16}$ and $t = 150 \text{ hours} = 5.4 \times 10^5 \text{ sec.}$, $C = 12.6$, or each atom will be knocked out of its lattice site to form a separated interstitial and vacancy on the average of 12.6 times during this period. Due to diffusion in the high-temperature thermal spikes, many of these point defects will anneal out immediately and Cottrell predicts that only about $n^{2/3}$ survive. Thus if 425 are produced per fast neutron collision, 53 survive. In the calculations that follow, values of 10 and 100 will be used for the number of survivors of a thermal spike.

The thermal migration of the point defects that survive the spike may produce self-diffusion in the metal at temperatures below the normal recrystallization temperature as explained in FXM-3389. If this diffusion rate is large, a creep problem may exist at normal reactor operating conditions.

The critical condition where the excess concentration of point defects equals the concentration of initial trapping sites, assuming that dislocations are the principal trapping sites, gives the time for a defect to jump from one site to the next, τ , as $8 \times 10^{-8} \text{ sec.}$ for $n = 10$ and $8 \times 10^{-9} \text{ sec.}$ for $n = 100$. If the point defect takes much longer than this to jump, its contribution to the diffusion coefficient will diminish appreciably because

C. C. Bigelow

FIM -3549

it will disappear by recombination after making only a small number of jumps.

The time for a vacancy to jump is temperature dependant according to the relation:

$$\tau = \nu^{-1} e^{\frac{E_m}{kT}}$$

for columbium, $\nu = 10^{13}$ vibrations/sec. The value of E_m , the energy for movement of a vacancy has been calculated as 0.9 ev. for copper, and experimental evidence places this value at 0.7 ev. A rough estimate of the value of E_m for columbium may be obtained by multiplying the value for copper by the ratio of the activation energies for self diffusion of the two metals. This gives a value of 1.24 ev for E_m in columbium. Using these values of ν and E_m , the critical temperature is 1430°F for $n = 10$ and 1832°F for $n = 100$. At temperatures below these values, the defects will not have the thermal energy to move about. At temperatures above this range, but below those at which self-diffusion predominates, the diffusion coefficient during irradiation is determined mainly by the density of trapping sites on dislocations, grain boundaries, etc.

The number of jumps per atom per second is given by:

$$f = 2\alpha j \frac{dc}{dt} = \begin{matrix} 2.5 & (n = 10) \\ 25 & (n = 100) \end{matrix}$$

Taking $D = 1/6 a^2 f$ for the diffusion coefficient, where a is the atomic spacing, gives $D = 4.15 \times 10^{-16}$ cm²/sec. when $n = 10$, and $D = 4.15 \times 10^{-15}$ when $n = 100$.

The value of $j = 10^7$ assumed a pure material with dislocations acting as the main sinks for defects. In a polycrystalline metal, the grain boundaries and also impurity atoms can trap the point defects. If we assume the metal is

0315587030

C. C. Bigelow

CONFIDENTIAL

FXM-3549

polycrystalline with 1000 grains per cm^2 and that the grains are square, 0.01 cm. per side, each side contains approximately 3×10^5 atoms. The total number of atoms adjoining grain boundaries in 1 cm^2 of the metal is approximately 6×10^8 atoms.

If there are 10^{15} atoms per cm^2 and 10^8 dislocation lines per cm^2 , the number of atoms at the center of a dislocation line is approximately 10^7 .

The total number of trapping sites in this polycrystalline metal is thus $6 \times 10^8 + 10^7 = 6.1 \times 10^8$ neglecting impurity atoms. To take the effect of impurities into account, assume that this number is 10^9 , therefore, one atom in 10^6 lies on a trapping site, or $j = 10^6$.

Performing the same calculations as before gives $\tau = 8 \times 10^{-6}$ for $n = 10$ and 8×10^{-7} for $n = 100$. The critical temperatures are 951° and 1163°F for $n = 10$ and $n = 100$ respectively. The diffusion coefficients are likewise 4.15×10^{-17} and 4.15×10^{-16} .

Most creep-resistant alloys lose their useful strength at temperatures greater than about 0.55 - 0.6 of their absolute melting point (2290°F - 2540°F for columbium) where the diffusion coefficient is greater than about 10^{-16} - $10^{-14} \text{ cm}^2/\text{sec}$. The table below summarizes the calculations for the radiation induced self diffusion:

	n = 10		n = 100	
	$D - \frac{\text{cm}^2}{\text{sec}}$	Temp. $^\circ\text{F}$ Range	D	Temp Range
$j = 10^7$	4.15×10^{-16}	1130-2290	4.15×10^{-15}	1830-2400
$j = 10^6$	4.15×10^{-17}	951-2000	4.15×10^{-16}	1163-2290

CONFIDENTIAL

0315587030

0315587030

C. C. Bigelow

CONFIDENTIAL

FXM-3549

From this table it is seen that diffusion coefficients of the same order of magnitude as those for rapid creep are found at low temperature.

Thus, these values of the self-diffusion coefficient are large enough to pose a definite creep problem because the temperatures are in the range at which the reactors of interest will be operated.

The above analysis assumes that the point defects migrate as separate entities. Kunz and Holden have proposed a model for radiation damage which consists of the agglomeration of the dispersed interstitial atoms. This theory explains the phenomena of radiation strengthening of metals by a process similar to precipitation hardening. Bruch and McHugh present data on radiation effects of molybdenum which meet the requirements of the Kunz and Holden theory. This data was obtained at a flux of approximately 10^{11} , however.

Cottrell discusses the various explanations of radiation hardening. He states that the alternate view from the Kunz and Holden theory that the point defects segregate to dislocations has several points in its favor. It has been shown that large numbers of defects can be absorbed onto dislocations, thus changing the position of the dislocation in the crystal. The nucleation of slip by movement of dislocations is thus difficult. The observed shape of the stress-strain curve, the coarse slip lines, the yield drop, the overshoot effect and the dependence of yield stress on temperature and strain rate, all favor a mechanism in which the nucleation of slip, rather than the propagation of slip, is made difficult by radiation damage.

CONFIDENTIAL

-5-

03170291030

0315047030

C. C. Bigelow

~~CONFIDENTIAL~~

FXM-3549

Makin, et al, suggest that some point defects migrate to dislocations and there produce the pinning and yield effects, but that others form small clusters distributed homogeneously throughout the lattice. These clusters provide barriers to dislocations which are responsible for the general hardening that persists after the initial yield point has been overcome.

If the vacancies migrate as separate entities at reactor operating temperatures, the diffusion coefficients calculated are realistic and will give rise to a creep problem. This problem should be experimentally studied as quickly as possible.

D. P. Gregory
D. P. Gregory

DPG:pk

~~CONFIDENTIAL~~

-6-

03170201030

UNCLASSIFIED

0315087030

C. C. Bigelow

~~CONFIDENTIAL~~

FXM-3549

1. Gregory, D. P., "Radiation Creep", FXM-3389
2. Bruch & McHugh "Radiation Damage Studies of Seven Non-Fissionable Metals"
Preprint 37, Session XVI, Nuclear Engineering & Science
Conference, March 17-21, 1958.
3. Kunz, F. W. & Holden, A. N., "The Effect of Short-Time Moderate Flux
Neutron Irradiation On the Mechanical Properties of
Some Metals", Acta Met. 2, Pg. 816.
4. Cottrell, A. H., "Effects of Neutron Irradiation On Metals & Alloys,"
Metallurgical Reviews, 1, 479
5. Makin, M. J., U. K. Atomic Energy Research Estab. Report to be published.

UNCLASSIFIED

~~CONFIDENTIAL~~

0317201030