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To: Mr. L. M. Raring

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FXM-4220

Date: September 2, 1959

From: D. P. Gregory

Subject: Radiation Enhanced Creep
in Columbium

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Calculations have been performed to determine the effect of fast neutron flux on the creep rate of the PWAR-11 and 11C structures under reactor operating conditions. New experimentally determined values for some of the parameters are used in the calculations. The theory of radiation enhanced diffusion rate has been experimentally verified by G. J. Dienes at Brookhaven. The calculations and Dienes' experimental verification for low neutron fluxes are discussed in the attached appendix.

The results of the calculations for the PWAR-11 and 11C are shown in Table I where the "effective temperature" of the fuel element cladding and the upper head of the pressure vessel are tabulated for various values of the parameter η , the density of vacancy trapping sites in the metal. The "effective temperature" is that corresponding to the radiation-enhanced creep rate.

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Table I

Regions of radiation-enhanced creep rate for FWAR-11 and 11C for various values of the parameter η . Temperatures shown are the "effective temperature" at which each component will operate during irradiation.

FWAR-11

	$\eta = 10^9$	$\eta = 10^8$	$\eta = 10^7$	$\eta = 10^6$
Fuel element cladding	*	all of clad at 2000	all of clad at 2200	*
Upper head of pressure vessel	*	*	1900	2050

* No change in "effective temperature"

FWAR-11C

	$\eta = 10^9$	$\eta = 10^8$	$\eta = 10^7$	$\eta = 10^6$
Fuel element cladding	*	1900-2000	all of clad at 2040	all of clad at 2210
Upper head of pressure vessel	*	*	*	1900

Dienes found a value of $\eta = 10^8$ for his experiments with alpha brass. Brass has a different crystal structure from Cb and is in other respects quite different, therefore, we should not consider η to be the same. The parameter η for Cb should, however, lie between 10^6 and 10^9 . Table I shows that no difficulty would be experienced in either the FWAR-11 or 11C as far as creep rate is concerned if $\eta = 10^9$. If $\eta = 10^6$, the cladding in the FWAR-11C would effectively be at 2200°F and the upper head would effectively be at 1900°F. A similar problem exists for the FWAR-11 if $\eta = 10^7$. Deformations under these temperature conditions would seriously violate our present reactor design criteria. The magnitude of η can only be determined experimentally by inpile creep tests. It is essential that this information be obtained as soon as possible.

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The calculations show that a 1300°F tube-burst test in the MTR or ETR (assuming a fast flux of 10^{13}) would show no effect of flux on creep rate if the density of trapping sites is 10^8 or 10^9 . However, if $\eta = 10^6$ or 10^7 , the "effective temperatures" would be 1920°F and 1800°F, respectively and a large effect would be noticed.

It is recommended that a 1300°F tube-burst test be run in the MTR or ETR as soon as possible.

Appendix

FXM-3389 discussed the theory of radiation-enhanced creep and FXM-3549 applied this theory to the creep of columbium structures in the presence of a fast flux of 10^{16} . Briefly, the theory states that since diffusion occurs by a vacancy mechanism in cubic metals, the generation of vacancies by fast neutron collisions with metal atoms during irradiation should enhance the diffusion rates as a result of the excess vacancies in the metal. High-temperature creep of cubic metals also occurs by a vacancy mechanism. Thus, if the high-temperature diffusion rate is enhanced, the creep rate will also be enhanced by the same amount.

Recently the self diffusion coefficient for columbium has been measured by Seigle at Sylvania as

$$D = 12.4 \pm .08 e^{-\frac{105,000 \pm 3,000}{RT}}$$

Harvey Brooks at Harvard has calculated the formation energy of a lattice vacancy in a number of metals, including two bcc metals, tungsten and alpha iron. The results of his calculations show that E_f , the energy required to form a lattice vacancy, in a bcc metal is about $0.85 H$, where H is the activation energy for self diffusion. The formation energy for a vacancy in a fcc metal is only $0.6 H$.

The theory of radiation-enhanced diffusion rates has been experimentally verified by G. J. Dienes of Brookhaven. Dienes examined the rate of ordering in alpha brass during fast neutron irradiation in the Brookhaven reactor at a fast flux of about 10^{12} . Fig. 1 shows the excellent agreement between the theory and Dienes' experimental data.

Diffusion calculations similar to those of Dienes have been made for columbium-1% Zr alloy as a function of fast neutron flux and η , the density of vacancy trapping sites, using the new values for E_f , and H . The data for columbium is plotted in the following way. In Fig. 1, the constant radiation-enhanced diffusion coefficient, D_e , is found in the temperature range T_1 to T_2 as shown in the following figure.

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The magnitude of D_e is governed mainly by the fast neutron flux, ϕ , and η . The D_e curve intersects the thermal rate curve at M (at T_2) where the concentration of radiation-produced vacancies equals the concentration of thermally-produced vacancies. Thus, at temperatures higher than T_2 , the thermal rate will control diffusion. There is a low-temperature cut-off point where the D_e curve falls to the thermal rate curve at N (at T_1). This is the temperature where thermal energy cannot supply enough energy to move a radiation-produced vacancy. If we plot T_1 and T_2 as functions of fast neutron flux, the following curve results.

Thus, any point within the shaded region has a diffusion coefficient equal to the thermal rate at the temperature of the upper curve for a given flux.

Figures 2 to 5 show the calculated results for columbium plotted in this way for various values of η . At 1800F, the mechanism of creep in columbium-1% zirconium alloy begins to change from a slip to a diffusion controlled mechanism. This 1800F line is drawn in the figures to show the conditions of flux and temperature under which radiation-enhanced creep rates may be expected. Thus, in Fig. 2, radiation will not affect creep rate until a fast flux of 10^{15} is reached, where the upper boundary of the diffusion-enhanced region crosses the 1800F line. However, at this flux, a specimen at a temperature as low as 240F would be at an effective temperature of 1800F!

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The physical meaning of the term "effective temperature" used in the discussion is as follows. Temperature, such as we measure with a thermocouple, is the result of the vibration amplitude of the metal atoms. If the amplitude is large, the material is hot. Irradiation does not affect this thermal vibrational amplitude except in the regions of thermal spikes which only last for about 10^{-10} second. Diffusion-controlled creep of metals in the absence of radiation depends on this large thermal vibration amplitude to create lattice vacancies so that dislocation climb can take place. Thus, the "effective temperature" during irradiation is the temperature where the number of thermally-produced vacancies in the absence of irradiation is equal to the number of radiation-produced vacancies in the presence of radiation.

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FIG. 2
EFFECTIVE TEMP., °F, VS.
FAST NEUTRON FLUX, ϕ , neut/cm²-sec
FOR $\eta = 10^9$

$\eta = 10^9$

FIG. 2,

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$\eta = 10^8$

FIG. 3

EFFECTIVE TEMP., °F, VS.
FAST NEUTRON FLUX, ϕ , neutrons/cm²-sec
FOR $\eta = 10^8$

FIG. 3

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FIG. 4

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