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Fusion-Neutron-Irradiated Metals
at 4.2K

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RESISTIVITY DAMAGE RATES IN FUSION-NEUTRON-IRRADIATED METALS AT 4.2K*

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ABSTRACT

Changes in electrical resistivity at liquid helium temperature have been used to monitor the production of damage in dilute alloys of vanadium, niobium and molybdenum, and pure tungsten, aluminum and copper irradiated with high energy neutrons. The neutrons were produced at the Livermore rotating-target neutron sources (RTNS-I and RTNS-II). Further experiments on V, Nb and Mo were carried out with 30 MeV d-Be neutrons and slightly degraded fission-spectra neutrons. The results for all six materials are compared to those obtained in a pure fission spectrum. The relative damage production rates are in agreement with predictions based on damage energy calculations.

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RESISTIVITY DAMAGE RATES IN FUSION-NEUTRON IRRADIATED METALS AT 4.2K

M. W. Guinan and J. H. Kinney

1. INTRODUCTION

The measurement of damage rates at low temperatures using resistivity or other techniques can provide a basis for comparison of total defect production in a variety of irradiation sources. Experiments covering a wide range of materials in diverse but well-characterized sources will produce a firm data base against which models of the displacement can be compared.

This work is part of an interlaboratory program to study low-temperature damage rates in dilute alloys of vanadium, niobium and molybdenum with electrons, energetic light ions, fission neutrons, and high energy neutrons. The samples were prepared by R. E. Reed of Oak Ridge National Laboratory. A list of participants and a detailed description of alloy preparation are given elsewhere [1].

Dilute alloys rather than high purity materials were chosen to suppress transient variations in the damage rates sometimes observed at low dose in high purity bcc materials. All three alloys contained 300 appm Zr. The results of electron [2] and fission neutron [3] irradiations of identical alloys have previously been published. In the present work we report the results of irradiations at the Livermore rotating-target neutron source [4] (RTNS-1), d-Be neutrons at the University of California, Davis cyclotron and fission neutrons at the

Livermore Pool Type Reactor (LPTR) fast fission plate [5] (FNIF-10).

A primary purpose of this study is to begin to provide a data base from which fusion neutron irradiation effects can be correlated with fission spectra irradiations. In order to extend this comparison, recent results on tungsten, aluminum and copper irradiated at RTNS-II [6] are included.

2. EXPERIMENTAL DETAILS

Vanadium, niobium and molybdenum samples were received from ORNL in the form of foils 28-35 microns in thickness, 100 mm in length and 10 mm wide. Ribbon specimens 100 mm x 150 μ m were cut from the foils using a precision shear. Three ribbons, one of each alloy, were wound onto a sample holder to form a helix 3.3 mm in diameter by 6 mm long. Copper potential and current leads were spot welded to the samples and the assembly secured by varnish.

To suppress the superconductivity of vanadium and niobium at 4.2K the sample holder was inserted in a superconducting solenoid with a critical current of 12.35 amperes at about 10 kOe. During irradiations the assembly was immersed in liquid helium. Fields of 2.3 kOe and 9.2 kOe respectively were applied to the vanadium and niobium during measurement. The sample holder and solenoid were placed in a conventional upright cryostat with a specially designed 1" diameter tail piece. To ensure uniformity of flux, the samples and solenoid were continuously oscillated 360° about their axis during irradiation.

Conventional DC potentiometric techniques were employed with a sensitivity of ± 10 nV. The measuring current was 100 ma. Noise levels were typically 30-50 nV at both neutron sources. Typical sample resistances at 4.2K were Nb(45m Ω), V(35m Ω), and Mo(20m Ω) respectively. Resistivities, ρ , and room temperature resistivity ratios for a typical set of samples are given in Table 1. All sets were within 2% of these values. Further details are given in an earlier report [7].

Tungsten, aluminum, and copper samples were cut from 25.4 mm wide foil stocks. They were annealed prior to spot welding Cu leads and mounted flat on the end of a commercial heli-tran continuous flow cryostat. The aluminum and copper samples were only partially annealed in an attempt to produce samples with RRRs of ~ 200 .

The resistances of the samples were measured by a computerized data acquisition system which incorporated a Vidar Model 520 Digital Voltmeter and a Digital Equipment Corp. LSI-11 computer. This system was programmed to measure the resistance of each sample ten times in both current directions and average the results. It also measured an internal standard, as well as the temperature sensors and the neutron count during irradiation. Resistivities and resistivity ratios are given in Table 1. Further details of RTNS-11 irradiations are given elsewhere [8], [9].

Resistivities were determined from a combination of length measurements using a microscope with a 2. μ m resolution, sample weights using a micro-balance with .2 μ g resolution and handbook density values.

The largest uncertainty (1%) arises from the finite width (.08 mm) of the potential leads. At 4.2K the resistivities, based on room temperature dimensions, were reduced to account for thermal contraction. These factors are .985 (V), .970 (Nb), .992 (Mo), .992 (W), .960 (Al), and .969 (Cu).

3. IRRADIATIONS

Following irradiations of V, Nb and Mo at both the Livermore rotating target neutron source (RTNS-I) and at the University of California Davis cyclotron using 30 MeV deuterons on a thick beryllium target [10] the cryostat was moved without warmup to the LPTR (FNIF-10) facility for incremental irradiations.

At the RTNS the cryostat was positioned as close as possible to the neutron source, which located the sample axis 16 mm away. At this position the neutron flux is of the order of $4-6 \times 10^{14}$ n/m²-s with an average energy of 14.8 MeV. An initial run of 11 hours was made to check operation in which only the vanadium and molybdenum were measured. In a later run of 55 hours all three samples were measured. The relative fluence received by the samples during the runs was monitored by the use of a proton recoil counter. Absolute fluences were determined from the activation of the niobium samples through the $^{93}\text{Nb}(n,2n)^{92m}\text{Nb}$ reaction for which a cross-section of 458 mb was used [11]. Corrections were made for decay during the runs.

At the Davis cyclotron the cryostat was positioned so the sample axis was located 40 mm behind the beryllium target where the neutron

spectrum had been previously determined [12]. This spectrum was corrected for attenuation through the cryostat and a room temperature experiment located closer to the target by using the total cross-sections given in ENDL [13]. The resulting spectrum is given in Ref. 7. One run of 19.5 hours was made at a deuteron energy of 30 MeV. The average beam current was 26 μ a. At the sample position the neutron flux ($E > 1$ MeV) was 1.8×10^{15} n/m²-s. The relative fluence during this run was monitored by the integrated beam current of 1.809 C. This is about 6% less than that determined from the activity of the Nb sample using a spectrum averaged cross-section for $\text{Nb}^{93}(n,2n)\text{Nb}^{92m}$ of 169 mb [11].

At the LPTR the cryostat was positioned so that the samples were located 10" from the fission plate where the spectrum was known [5]. Iron foils, placed outside the cryotip near the position of the samples, were used for fluence monitors through the $\text{Fe}^{54}(n,p)\text{Mn}^{54}$ reaction. Relative fluences were monitored by integrated reactor power output.

At the RTNS-II niobium dosimetry foils were placed on each side of the gauge section of the samples. See Ref. 9 for a typical configuration. Here the specimens were located only 5 mm from the source. This, coupled with the higher beam current at RTNS-II, produces fluxes of up to 20 times those in the RTNS-I experiments. Table 2 lists the average fluxes observed in each experiment as well as the total fluence determined from the indicated foil dosimeters. The spectrum averaged cross-sections are also indicated.

4. RESULTS

The results of all the experiments are summarized in Table 3. For each experiment, the total observed change in resistivity $\Delta\rho$, and the average damage production rate, $\Delta\rho/\Delta\phi$, are given for each sample. The data for vanadium and molybdenum exhibit a small but definite decrease in rate in the two longer irradiations. In both cases however, the change is less than 3% over the total range of $\Delta\rho$ covered. Niobium exhibits no measurable change in slope in either experiment. The low fluence and relative paucity of data points in these earlier experiments precluded any determination of $d\rho/d\phi$ as a function of $\Delta\rho$.

Unfortunately, at RTNS-II the situation is no better. By moving the samples closer to the source, the flux on a given sample is very sensitive to small shifts in beam position [9]. As a result, when the beam is shut down by the experimenter or due to a spark, discontinuous shifts of up to 20% in the apparent damage rate can occur. Thus, again only values of $\Delta\rho/\Delta\phi$ can be determined with any precision.

We note that the values of $\Delta\rho$ given in Table 3 are referred to the room temperature dimensions of the samples. They are thus higher than values previously reported [7], [8] by the inverse of the factors given in section 2. This was done to facilitate comparison with other published values.

Relative uncertainties in $\Delta\rho$ are Nb (5%), V(3%), Mo(1%), Al(1%), and Cu(1%), respectively. The absolute uncertainty in $\Delta\rho/\Delta\phi$ is dominated by the fluence determination, 5% for RTNS-I and RTNS-II and 15% for D-Be and LPIR.

In order to compare the results given in Table 3 with other measurements several adjustments need to be made to determine values for the initial damage rates, $(d\rho/d\phi)_{\Delta\rho=0}$, from the average rates, $\Delta\rho/\Delta\phi$, reported here. Since the correlation of fission and fusion neutrons was a major objective of the present work, we have used the results of Coltman, Klabunde and Williams [14] in a pure fission spectrum to make these adjustments. They report results for the same alloys of V, Nb and Mo used here, as well as Al and Cu.

Apart from initial transients the damage rate can be written as a function of damage, $\Delta\rho$, as

$$d\rho/d\phi = (d\rho/d\phi)_{\Delta\rho=0} (1 - \Delta\rho/\Delta\rho_s), \quad (1)$$

where $\Delta\rho_s$ is the saturation value of the resistivity determined by extrapolating $d\rho/d\phi$ to zero.

Integrating eq. (1) gives the desired relationship,

$$(d\rho/d\phi)_{\Delta\rho=0} = -(\Delta\rho/\Delta\phi) (\Delta\rho_s/\Delta\rho) \ln(1 - \Delta\rho/\Delta\rho_s) \quad (2)$$

For the high energy neutron irradiations of Nb, W, Al and Cu eq. (2) was used to determine initial damage rates with values of $\Delta\rho_s$ inferred from the slopes of $d\rho/d\phi$ vs. $\Delta\rho$ given by Coltman et al [14] (Nb, Al, Cu) and Klabunde et al [15] (W). For V and Mo the range of $\Delta\rho$ in the high energy neutron irradiations were entirely in the transient region observed [14]. For these materials eq. (2) was used with an effective value of $\Delta\rho_s$ determined from the transient region. The values of $(d\rho/d\phi)_{\Delta\rho=0}$ obtained were then reduced by the ratios of observed

initial rates to those extrapolated from the higher-damage linear portions of the curves. These factors were .880 for V and .902 for Mo.

For the LPTR irradiations the values of d_0/d_0^* given in Table 3 actually represent the value of d_0/d_0^* at the damage levels obtained in the previous RTNS-I and D-Be irradiations. Values for $(d_0/d_0^*)_{d_0=0}$ were obtained by taking ratios of d_0/d_0^* observed, at the appropriate value of d_0 , by Coltman et al [14] to their extrapolated initial damage rates. The values in Table 3 were then reduced (V and Mo) or increased (Nb) by these ratios. In addition to the modification of the fission spectrum by the fission plate and room return neutrons, a significant thermal flux is present at the LPTR(FNIF-10). Following Coltman et al [14] we have corrected the initial damage rates for thermal neutron damage. At the FNIF-10 position the thermal flux is .528 of the fast flux ($E > .1$ MeV) compared to the about equal fluxes at the BSR(LTIF) facility [16] used by Coltman. Using the same values of d_0/d_0^* for thermal neutrons [14] the reductions for initial damage rates are 2.0 for V, 0.4 for Nb, and 0.7 for Mo.

The resulting values for $(d_0/d_0^*)_{d_0=0}$ are compiled in Table 4. Where two experiments were indicated in Table 3, the average is tabulated. In all cases, repeated values were within 2% of the average. Included for comparison are the results of Coltman, Klabunde and Williams [14] in the BSR(LTIF) facility, those of Kirk and Greenwood [18] in the CP5(VI53) facility. In addition, the results of Roberto, Klabunde, Williams and Coltman in a 40 MeV d-Be spectrum are included. The results of Table 4 currently represent the total data base obtained in well

characterized facilities for the correlation of fission and fusion neutron damage at 4.2K.

5. DISCUSSION

We will first compare the relative damage production from neutron sources to that predicted from damage energy calculations. We will then consider the question of absolute defect production rates.

The experimental damage rates $dp/d\phi$ can be expressed as

$$dp/d\phi = \rho_f \sigma_d \quad (3)$$

where ρ_f is the resistivity increment per atomic fraction of Frenkel pairs and σ_d is the displacement cross-section. If we assume that the number of defects produced in energetic cascades is proportional to the damage energy, i.e., the energy of the primary recoil less the energy lost from all generations of recoils to electron excitation, then the ratio of two experimental damage rates should be equal to the ratio of the corresponding damage energy cross-sections, σ_{DE} .

5.1 Damage Energy Cross-Sections

Codes for the calculation of damage energy cross-sections have been available for a number of years. In Table 5 we have tabulated recent values for Nb, V, and Mo in both the RTNS and LPTR spectra. Both the ENDF/B-IV and the 1978 ENDL evaluated neutron cross-section files have been used. All used the LSS model [20] for electronic stopping and Robinsons [21] analytical approximation for the resulting energy

partition. The present versions of the codes were all written about 1975 and have since undergone minor modifications and all are loosely based on the earlier work of Sheely [22] and Jenkins [23]. The authors' initials and the laboratory at which each code [24]-[28] is maintained is also given.

While the maximum spread in cross-section in Table 5 is 12% (for Nb at RTNS), when ratios of cross-sections using the same code are taken the spread is somewhat reduced. The ratio of RTNS to LPTR cross-section is $4.48^{+.08}_{-.16}$ for V, $5.78^{+.22}_{-.18}$ for Nb and $5.08^{+.25}_{-.22}$ for Mo. In this case the maximum spread of 9% is for Mo. On the other hand, ratios can vary as much as 20% when different codes are used. At high energies the differences arise primarily in the details of n multiple n and charged particle reactions. At low energies differences arise primarily from group averaging methods employed in the resonance range.

With the above in mind, damage energy cross-sections are listed in Table 6 for each of the entries in Table 4. The ANL code maintained by Greenwood [28] was used for all but W and Pt which are not available on the ENDF/IV-B file. For these the LLNL code and the 1978 ENOL file were used. For V and Mo in the 30 MeV D-Be spectrum extended ($E_n > 20$ MeV) files were not available and the method described in Ref. [7] was used.

Doran and Graves [24] estimate that errors in damage energy cross-sections may be as high as 20% in the high energy ranges considered here. For all the materials, and particularly vanadium, the values may be systematically high by up to 10% due to the use of LSS electronic stopping as discussed by Robinson [29]. However, when ratios are taken

the uncertainty will still be of the order of 10% or less.

5.2 Damage Ratios: Fission-Fusion Correlation

The experimental ratios of damage from all the neutron sources to that from pure fission neutrons (Table 4) are given in Table 7. They are compared to the ratios of damage energy cross-sections from Table 6. The results are also displayed graphically in Fig. 1.

Overall the agreement seems well within uncertainties in both theory and experiment. The LPTR experiments are consistently higher by 17% than predicted while the CP-5 data are consistently lower by 16%. The RTNS results are mixed, averaging 5% lower than predicted, but all within 10% if W at -13% is excluded. The D-Be experiments are both consistently low by 13%. It appears that within present uncertainties damage production scales with damage energy at least over the recoil energy range of from below 10 keV to above 200 keV.

5.3 Damage Production Efficiency

To convert damage energy cross-sections to the displacement cross-sections needed to evaluate eq. 1, we must specify the constant of proportionality. Following Robinson [29] we can write

$$\sigma_d = K \sigma_{DE} / 2 T_A \quad (4)$$

where K is the displacement efficiency and T_A is an effective displacement energy which accounts for the anisotropy of the displacement threshold. If $K = 1$ and $T_A = T_0$, the measured threshold displacement energy, we have the Kinchin and Pease model [30]. Lucasson [31] has reviewed both experimental and computer data on the anisotropy of dis-

placement thresholds in fcc, bcc and hcp metals. His suggested values have been the basis of a number of comparisons of production efficiencies by high energy neutrons [7], [15], [18]. Once ϵ_f and T_A are specified, the displacement efficiency can be obtained for a given experiment by substituting eq. 2 in eq. 1 and solving for K, i.e.

$$K = (dn/d\phi)^{-1} T_A / \epsilon_f \quad (5)$$

For ease of comparison we have used the values of ϵ_f and T_A tabulated by Klabunde et al [15] to determine K for the RTNS irradiations with the exception of W for which $T_A = 84$ eV and $\epsilon_f = 14 \times 10^{-6}$ cm [31] was used. The resulting values are given in Table 8. For platinum the 40 MeV D-Be irradiation was used.

Both the analytic theory of random cascades and binary collision calculations predict that $K = 0.8$ at energies well above threshold. The values in Table 8 cluster near 1/3 this value for the f.c.c. metals and 1/2 this value for b.c.c. metals independent of Z, as previously noted [18]. Jung [32] has recently derived considerably different values for T_A by integrating damage production data from electron irradiation of polycrystalline materials. Using his values for ϵ_f and T_A we obtain the values of K given in the second column of Table 8. Here K tends to decrease with increasing Z. An additional comparison can be made with polycrystalline electron data [31] by using a Mott scattering code to generate recoil spectra for electrons, correcting for LSS energy partitioning just as with neutrons to determine damage energy cross-sections. In all cases considered, K peaks

or is still rising as a function of electron energy [33]. If we arbitrarily scale this value to $K = 1$ the corresponding K for high energy neutrons is independent of assumed values for ϵ_f and T_A . These values are given in the third column of Table 5. In this case there is a decrease with Z for f.c.c. metals and no apparent trend for b.c.c. metals. Finally, in the last column of Table 3, we list values of K assuming $T_A = T_0$. Here the values are remarkably constant as previously noted [18]. Tungsten appears to be unusual in all schemes. For both structures this, perhaps, indicates that displacement processes in energetic cascades are only dependent to a large extent on the minimum energy required to displace an atom.

6. CONCLUSIONS

Total defect production in both f.c.c. and b.c.c. metals as measured by electrical resistivity at 4.2 K scales with damage energy. When fission and fusion neutron sources with well characterized spectra are compared, damage energy scaling is accurate to about 10%, well within present experimental and theoretical uncertainties.

The values taken for directional averaged displacement threshold energies are, at present, somewhat subjective. Further work is required to determine the utility of this concept.

Table 1
Sample Specifications

Sample	Source Purity	Thickness (um)	Anneal after Shearing (hr-°C) (Torr-Gas)	Initial Resistivity ^a $\rho_0(4.2K)$ (n·m)	Residual Resistance Ratio ^b ($\rho_{RT}/\rho_{4.2}$)
V	ORNL 300ppm Zr	29.5	None	1.865 ^c	111
Nb	ORNL 300ppm Zr	30.1	None	2.173 ^d	68
Mo	ORNL 300ppm Zr	29.0	None	.7170	78
W	MRC 99.95%	25.3	2 - 1800°C 5 x 10 ⁻⁹ -Air	.6921	80
Al	MRC MARZ-5N	44.5	1 - 60°C 400 - He	.3778 (.3716) ^e	75 (76)
Cu	A.D. Mackay 99.999%	24.6	1 - 200°C 400 - He	.1068 (.0949) ^e	157 (177)

^aValues calculated from RT measurements corrected for thermal contraction.

^bRT varied from 292K to 297K.

^cAt .23 Tesla transverse field.

^dAt .92 Tesla transverse field.

^eSize-effect corrected (see text).

Table 2

Summary of Irradiations

Source	Flux(n/m^2-s)	Sample	Fluence $\Delta\phi(n/m^2)$	Dosimeter Cross-section $\sigma(mb)$
RTNS-I	5.8×10^{14}	V, Mo	2.30×10^{19}	458^a
RTNS-I	4.4×10^{14}	V, Mo Nb	8.49×10^{19} 8.63×10^{19}	458^a
LPTR(FNIF-10) ^c	7.11×10^{13}	V, Nb, Mo	7.46×10^{18}	23.2^b
D-Be(30 MeV)	1.78×10^{15}	V, Nb, Mo	13.13×10^{19}	169^a
LPTR(FNIF-10) ^c	7.11×10^{13}	V, Nb, Mo	8.66×10^{18}	23.2^b
RTNS-II	4.76×10^{15}	Al	8.20×10^{20}	458^a
	4.85×10^{15}	Cu	8.36×10^{20}	
RTNS-II	1.07×10^{16}	W	16.01×10^{20}	458^a

^a $^{92}_{Nb}(n,2n)^{93m}_{Nb}$ [11]

^b $^{54}_{Fe}(n,p)^{54}_{Mn}$ [13]

^c $E = .54$ eV, for $E = .1$ MeV flux is $5.33 \times 10^{13} n/m^2-s$

Table 3
Experimental Damage Production^a

Sample	RTNS-I/II		D-Be(30 MeV)		LPTR(FNIF-10) ^b	
	$\Delta\rho$	$\Delta\rho/\Delta\phi$	$\Delta\rho$	$\Delta\rho/\Delta\phi$	$\Delta\rho$	$\Delta\rho/\Delta\phi$
V	16.70	19.66	----	----	0.39	5.23
	4.70	20.37	20.21	15.39	0.47	5.39
Nb	9.82	11.61	----	----	0.20	2.66
	----	----	9.61	7.36	0.22	2.54
Mo	8.72	10.23	----	----	0.18	2.38
	2.41	10.32	8.60	6.67	0.21	2.39
W	171.30	10.70	----	----	----	----
Al	33.57	4.09	----	----	----	----
Cu	19.14	2.29	----	----	----	----

^a $\Delta\rho$ ($10^{-11} \Omega \cdot m$), $\Delta\rho/\Delta\phi$ ($10^{-31} \Omega \cdot m^3$).

^bIncremental irradiations following preceeding entry,
E = 0.54 eV; to convert to E = 1 MeV multiply $\Delta\rho/\Delta\phi$ by 1.337

Table 4
Comparison of Initial Damage Rates, $(d\phi/d\phi)_{\Lambda_0}^a = 0$

Sample	RTNS-I or II	D-Be (30 MeV) U.C. Davis	D-Be (40 MeV) ORNL	BSR(LTIF) (Fission)	LPTR(FNIF-10) (E>.1MeV)	CP-5(VT53) (E>.1MeV)
V	18.01	14.03	---	7.17	6.56	---
Nb	11.44	7.38	10.1	3.43	3.47	2.19
Mo	9.47	6.10	---	3.38	3.00	1.36
W	11.55	---	---	3.27 ^b	---	---
Al	4.18	---	---	2.19	---	1.49
Cu	2.48	---	2.11	.723	---	.424
Pt	---	---	4.72	1.58	---	.818

^aIn units of 10^{-31} g - m³

^bRate in a pure fission spectrum inferred from Nakagawa et al. [17] by Klabunde [15].

Table 5
DAMAGE ENERGY CROSS-SECTIONS (b-keV)^a

RTNS-II (14.5-15.0 MeV)				
Authors	Laboratory	Nb	V	Mo
DG [24]	HEDL	274	265	263
GAG [25]	ORNL	294	274	284
LRK [26]	LLNL	289/270 ^b	262/265 ^b	246/246 ^b
PG [27]	BNL	285 ^b	260	---
GOD [28]	ANL	263	267	263

LPTR (Moderated Fission) (E> .54 eV) ^c				
DG [24]	HEDL	48.9	59.0	49.3
GAG [25]	ORNL	50.2	60.1	53.9
LRK [26]	LLNL	48.2/48.2 ^b	57.6/59.5 ^b	50.6/50.3 ^b
PG [27]	BNL	49.3 ^b	60.2	---
GOD [28]	ANL	45.1	59.2	52.0

^aENDF/IV-B

^b1978 ENDL

^cFor E> .1 MeV multiply by 1.337

Table 6
Damage Energy Cross-Sections^a

Sample	RTNS-I or II	D-Be (30 MeV) U.C. Davis	D-Be (40 MeV) ORNL	BSR(LTIF) (Fission)	LPTR(FNIF-10) (E>.1MeV)	CP-5(VT53) (E>.1MeV)
V	267	200	---	97.1	79.2	---
Nb	263	197	243	79.5	60.3	55.7
Mo	263	192	---	83.4	69.5	61.2
W	201 ^b	---	---	49.8 ^b	---	---
Al	178	---	---	98.3	---	76.2
Cu	288	---	265	81.3	---	56.3
Pt	---	---	182 ^b	45.8 ^b	---	29.6 ^b

^aFrom GOD [28] using ENDF/IV-B

^bFrom LRK [26] using 1978 ENDL

Table 7

Experimental and Theoretical Damage Ratios with Respect to a Pure Fission Spectrum^a

Sample	RTNS-I or II	D-Be(30 MeV)	D-Be(40 MeV)	LPTR(FNIF-10)	CP-5(VT53)
V	2.51 (2.75)	1.96 (2.06)	---	0.91 (0.82)	---
Nb	3.34 (3.31)	2.15 (2.48)	2.95 (3.06)	1.01 (0.76)	0.64 (0.70)
Mo	2.80 (3.15)	1.81 (2.30)	---	0.89 (0.83)	0.55 (0.73)
W	3.53 (4.04)	---	---	---	---
Al	1.91 (1.81)	---	---	---	0.68 (0.78)
Cu	3.43 (3.54)	---	2.92 (3.26)	---	0.59 (0.69)
Pt	---	---	2.97 (3.97)	---	0.51 (0.65)

^aValues are for the ratio of initial damage rates followed by the ratio of damage energies in parenthesis.

Table 8

Damage Efficiency of Fusion Neutrons^a

Sample	$K(\rho_f, T_A \text{ from [15]})^b$	$K(\rho_f, T_A \text{ from [32]})$	$K(e^- = 1)$	$K(T_A = T_0)$
V	.43	.54	.47	.147
Nb	.42	.47	<.47	.134
Mo	.39	.39	.32	.162
W	.69	---	<.56	.345
Al	.33	.77	.48	.187
Cu	.25	.37	.23	.163
Pt ^c	.23	.24	.17	.185

^ad:/d: from RTNS irradiations

^b $T_A = 84 \text{ eV}$, $\rho_f = 14 \times 10^{-6} \text{ cm}$ for W

^cd:/d: from D-Be(40 MeV) irradiation [19]

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FIGURE CAPTION

Fig. 1. Ratios of experimental damage rates to those found in a pure fission spectra are compared to the ratios of corresponding theoretical damage energy cross-sections. The results given in Table 7 for ^{235}U , ^{239}Pu , ^{241}Am , ^{241}Pu and moderated fission (^{235}U) neutrons are plotted. The dashed lines indicate deviations of 10%.