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DAMAGE PARAMETER COMPARISON FOR
CANDIDATE INTENSE NEUTRON TEST
FACILITIES FOR FUSION MATERIALS

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It is recognized worldwide that an intense source of fusion energy neutrons is needed to evaluate candidate fusion materials. At an International Energy Agency (IEA) workshop held in San Diego in February 1989, an Evaluation Panel recommended that three neutron source concepts be developed further. The panel also recommended that further comparisons were needed of their irradiation environments. In this paper, a comparison is made of damage parameters for beryllium, carbon, silicon, vanadium, iron, copper, molybdenum, and tungsten irradiated in spectra characteristic of d-Li, spallation, and beam-plasma (d-t) neutron sources and in a reference DEMO first wall spectrum. The treatment of neutron-induced displacement reactions is confined to the region below 20 MeV and transmutation reactions to below 50 MeV by the limited availability of calculational tools. The spallation spectrum is relatively soft; less than 2% of the neutrons are above 50 MeV. The transmutation results emphasize the need to define the neutron spectra at low, as well as high, energies; only the DEMO spectrum is adequate in this respect. Recommendations are given for further work to be performed under an international working group.

INTRODUCTION

It is recognized worldwide that an intense source of fusion energy neutrons is needed to evaluate candidate fusion materials. Several concepts for an International Fusion Materials Irradiation Facility (IFMIF) were described and evaluated at an IEA workshop held in San Diego in February 1989.[1] The Evaluation Panel recommended that three neutron source concepts--beam-plasma, d-Li, and spallation--be developed further.[2]

The beam-plasma concept, developed by Lawrence Livermore National Laboratory (LLNL), is based on a mirror-type plasma machine fueled with tritium and subjected to intense deuteron beams injected perpendicular to its axis.[3] The d-Li source, proposed by the Los Alamos National Laboratory (LANL), is an upgrade of the Fusion Materials Irradiation Test (FMIT) facility designed at Hanford and Los Alamos but never constructed.[4] Neutrons are produced by one

or more 35 MeV deuteron beams incident on one or more flowing lithium targets. The conceptual spallation source, EURAC (European Accelerator), proposed at the workshop by the Institute of Nuclear Fusion (INF) of the Polytechnic University of Madrid, generates neutrons with a 600 MeV proton beam incident on a liquid lead target. Both of the accelerator-based sources, d-Li and spallation, are characterized by "high-energy tails", i.e., they produce neutrons above the 15 MeV upper limit of a fusion device.

The Evaluation Panel also recommended that the radiation effects community develop descriptions, on a consistent basis, of the radiation environments of these sources as a prelude to a critical examination of how well each source can simulate the environment of a fusion reactor. The IEA subsequently requested one of the authors (DGD) to begin to implement this recommendation. This paper describes the status of this work.

This study is concerned only with the comparison of damage parameters among the several sources; facility comparisons in terms of test volume, accessibility, reliability, etc., are outside its scope.

BASES FOR NEUTRON SOURCE COMPARISONS

The Evaluation Panel concluded that each of the three sources is capable, in principle, of generating sufficient flux for fusion materials studies, so flux and damage rates, i.e., source strengths, will not be compared in the present study. We will concentrate on spectral comparisons, using spectral-averaged damage energy, transmutations, and recoil spectra.

The neutron spectra (see Fig. 1) used in this study and some of their characteristics are described briefly in Tables 1a and 1b.

The beam-plasma spectrum is at the edge of the plasma (8 cm radius); an aluminum reflector extends from 21.5 cm to 51.5 cm.

The d-Li spectrum is for a configuration featuring two 250 mA deuteron beams incident on two targets oriented at 90 degrees to one another. The beams strike the targets 10 cm from the targets common apex. Spectra were calculated for several locations in the plane of the beams along the plane of symmetry. The point used in this study is 8.5 cm from the apex. The flux is nearly a maximum here, but the spectrum is somewhat softer than at the virtual intersection of the beams (14 cm from the apex) because the highest energy neutrons are emitted in the forward direction.

The spallation spectrum (recommended by M. Victoria of the Paul Scherrer Institute) is from a published calculation by Pepin [5] for an experimentally realizable configuration. It is the neutron spectrum at, and 90 degrees to, the curved surface of a 15 cm diameter cylindrical lead target bombarded by 520 MeV protons.

K. Ehrlich, Kernforschungszentrum Karlsruhe, provided the first wall spectrum for the conceptual Culham DEMO reactor [6] used here as a reference case.

A primary source of difficulty in comparing spallation spectra with d-t and d-Li spectra is that the neutron energy range extends from thermal to hundreds of MeV. The low-energy region, from thermal to tens of keV, is of interest because neutron absorption cross sections can become very large with decreasing neutron energy, leading to high transmutation rates. Furthermore, this region produces low-energy displacement cascades for which residual defect production efficiencies are high relative to higher energy cascades. This may accelerate some property changes per calculated displacement. Only the DEMO spectrum was defined below a few tenths MeV.

Neutron reactions in the MeV range are dominated by elastic and inelastic events that produce neutrons or nuclei of hydrogen and helium. A wealth of nuclear data in this range ensures that uncertainties are relatively small. Above a few tens of MeV, on the other hand, spallation and fission reactions occur that produce many more atomic species, ranging up to the atomic number of the target nucleus. Few data exist in this region and model calculations are computer intensive, hence expensive.

The approach for this study was to combine the several neutron spectra with appropriate cross sections to determine spectrum-averaged primary recoil spectra, displacement damage cross sections, and transmutation production. It was necessary to estimate the displacement damage energy for neutrons above 20 MeV, the upper limit of the Evaluated Nuclear Data Files (ENDF/B) [7] used in the U.S. and in many other countries. Transmutation files, on the other hand, are available to 50 MeV in the transmutation and activation code REAC*2 [8], developed originally for FMIT applications. The high energy data for iron have been evaluated so are probably more accurate than those for the other elements.

CALCULATIONS

Displacement Damage

The code SPECTER [9] was used to calculate damage energy cross sections. The cross section was assumed constant above 20 MeV, generally leading to a small underestimate. Better approximations could be made, but this is the least serious computational limitation at present.

Transmutations

The code REAC*2 was used to calculate transmutation production; the few neutrons above 50 MeV (see Table 1b) in the spallation spectrum were ignored. Because transmutation production may be nonlinear due to the production of daughter nuclides, the calculations were carried out to 1000 days for the DEMO case, with output at 100-day intervals. The other spectra were run to the same total damage energy, 8 keV-b, corresponding to 80 displacements per atom (dpa) in iron, in 10 equal time steps.

Recoil Spectra

Recoil spectra files (based on ENDF/B-V nuclear data and the DISCS code [10]) are contained in SPECTER for neutrons below 20 MeV. SPECTER was used here to calculate complete recoil spectra in Fe, Mo, and C for the DEMO and Beam-Plasma cases. It was also used to estimate recoil spectra for the d-Li and spallation spectra, ignoring neutrons above 20 MeV. Although the number of neutrons above 20 MeV is small (see Table 1b), this distorts the shape of the recoil spectrum somewhat and, of course, fails to show the highest energy recoils. It is of interest to note that the consensus of a recent workshop [11] was that the major concern regarding high-energy tails in neutron spectra used for fusion studies is unwanted transmutations, not effects of high-energy recoils. The authors did not have access, in the time available, to an operating version of a code incorporating intranuclear cascade and fission models that would permit the calculation of recoil spectra (and transmutation production) at high neutron energies.

RESULTS

Displacement Damage

Spectral-averaged damage energy cross sections are summarized in Table 2. (Values of ED, the effective displacement energy, are included; the damage energy was converted to displacements by multiplying by $0.8/2 \cdot ED$.) At low Z, the cross section tends to decrease less (or even increase) with decreasing energy below a few MeV, which keeps the variation among neutron sources small. The cross section for V through Mo is nearly constant.

Transmutations

The results of transmutation calculations are summarized in Table 3, including the ratios of appm He/dpa and appm H/dpa. Only for carbon are these ratios affected significantly by the variation in dpa values.

The most significant lesson to be learned from these results is that generalizations are difficult to make. For example, charged particle emission reactions become less important with increasing atomic number, Z, as expected, but only tungsten clearly illustrates this effect. At low Z charged particle emission cross sections can be high, but differences in reaction thresholds lead to large variations in hydrogen and helium production among the elements and among the spectra. These gas-producing reactions lead then, in the low Z regime, to solid transmutants that are predominantly of lower Z than the matrix.

At higher Z we find neutron absorption reactions becoming increasingly important. Through subsequent beta decay, they produce elements of higher Z than the matrix. The relevant cross sections generally increase rapidly at low energy so production is highest in the low-energy regime of DEMO. This illustrates the importance of careful definition of the low-energy portion of

source spectra. Furthermore, this region will be sensitive to the configuration of material in and near the test volume.

Of primary interest is the comparison of the candidate source results with DEMO. As would be expected, the beam-plasma (d-t) source provides at least as good a simulation as the other sources. The d-Li source, however, produces similar transmutation rates except that it overemphasizes some high-threshold reactions at low Z. Some of these are also overemphasized by the weak high-energy tail of the spallation spectrum, although more commonly this spectrum is too soft to produce rates as high as in DEMO.

Recoil Spectra

Two examples of calculated recoil spectra are shown in Fig. 2. The shape of the d-Li (Point 2) recoil spectrum for iron agrees rather well with DEMO from a few tenths MeV to the upper limit of DEMO, but carbon exhibits a high energy deviation. A proper calculation for the d-Li spectrum would extend the high energy tail to perhaps 6 MeV, but at very low magnitude. The corresponding neutron spectrum has 11% neutrons above 20 MeV, and only 2 % above 30 MeV.

INTERIM CONCLUSIONS

It is no surprise to find that the beam-plasma source promises the best simulation of a D-T reactor. Large discrepancies with certain DEMO transmutation rates may exist, however, depending on the shape of the very low energy end of the neutron spectrum. Of course, first wall spectra vary also, depending on the choice of coolant and blanket materials, which suggests that a range of reference spectra might be appropriate for future calculations.

While only a few elements have been examined, some interesting differences among transmutation rates in the various sources have been revealed, emphasizing that these comparisons are element specific. For this comparative study, it is important to determine which region of the neutron spectrum is producing a particular transmutation product.

All candidate source spectra need better definition at low energies.

The specific spallation spectrum reported on here is generally too soft to provide the high gas production rates required of an IFMIF; harder spectra can be obtained, however, from a spallation source. (Other spallation spectra provided to us for study were even softer than the Pepin spectrum.)

RECOMMENDATIONS

1. It is important to determine whether the spallation spectrum used here is representative of a well-defined spallation neutron irradiation facility. It remains to be seen whether an appropriate compromise exists between an overly hard spectrum, producing unwanted spallation products, and an overly soft spectrum that produces too little of the desired transmutation products.

2. The inadequate treatment of neutrons above 20 MeV, including the lack of evaluated nuclear data in this region, is the most obvious shortcoming of the present calculations. If a spallation source is to be evaluated, calculations with the HETC code [12] (or equivalent) are needed. Transmutation calculations need to be tested against data from recent irradiations at the Los Alamos Spallation Radiation Effects Facility.

3. While such a code would be applied to d-Li spectra also, it is not considered essential in this case. More important is to make sure that cross sections in the 20-to-40 MeV range in REAC*2 (or equivalent) are of the highest accuracy possible and that any important missing datum is supplied by calculation or experiment.

4. Better definition of candidate IFMIF neutron source spectra is needed in the thermal and epithermal region if meaningful transmutation calculations are to be made.

5. More realistic beam-plasma spectra are needed, although it seems clear that such a source can satisfactorily mimic neutron environments in a d-t reactor.

6. A range of reference fusion reactor spectra should be considered to allow for different cooling and blanket materials.

A small international working group is currently being organized under IEA auspices to pursue source characterizations and their comparisons. It will include specialists in neutronics, nuclear data, damage parameters, code verification, and reactor experimentation.

ACKNOWLEDGEMENT

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TABLE 1A NEUTRON SPECTRA USED IN THIS WORK

SPECTRUM	CALC. BY	REFERENCE	CODE USED	NO. OF GROUPS	TOTAL FLUX	PROVIDED BY
DEMO, 1ST WALL	Culham	CLM-R-254 1985	?	100	1.41e+15 n/cm2-s	Ehrlich, KfK
BEAM-PLASMA Plasma edge, 8 cm Al, 21.5-51.5 cm	Kawabe & Sagawa Tsukuba U.	none	AMISH	27	14.9e+14 n/cm2-s?	Coensgen, LLNL
D-Li: 2-250 mA beams at 90 deg; 8.5 cm from apex of targets	Varsamis, LANL	IFMIF rept.; TBP Nucl. Sci. Eng.	FMITSP (Mann)	50 (1 MeV)	5.45e+14 n/cm2-s	Lawrence, LANL
SPALLATION: 520 MeV p on Pb, 90 deg	Pepin, 1982	ANL-82-80 1982	HET, 05R	28	0.846 n/sr-p	Victoria, PSI

TABLE 1B CHARACTERISTICS OF NEUTRON SPECTRA USED IN THIS WORK

SPECTRUM	FRACTION OF FLUX ABOVE:						Lowest Energy Group
	100 MeV	20 MeV	15 MeV	13.5 MeV	1.0 MeV	0.1 MeV	
DEMO	0	0	0	0.126	0.28	0.56	0 - 0.41 eV
BEAM-PLASMA, w/refl.	0	0	0	0.56	0.66	0.84	0 - 0.02 MeV
D-Li, point 2	0	0.10	0.37	-	.90	?	0 - 1 MeV
SPALLATION (Pepin)	.004	0.04	0.05	-	0.52	0.95	0.001 - .01 MeV

TABLE 2--SPECTRUM-AVERAGED DAMAGE ENERGY CROSS SECTIONS (KEV-BARNS)

SPECTRUM/ELEMENT	Be	C	Si	V	Fe	Cu	Mo	W
ED (eV)	31	31	25	40	40	30	60	90
DEMO	23	30	59	71	65	67	67	43
B-P w/refl.	26	37	129	169	171	179	166	118
D-Li, 8.5 cm	28	44	150	197	198	202	187	137
SPALL.-Pepin	35	50	92	95	84	83	87	54
20 MeV	21	47	200	303	316	347	321	255

TABLE 3A--TRANSMUTATIONS (APPM) IN BERYLLIUM FOR 1000 DAY
DEMO EQUIVALENT EXPOSURE (80 DPA IRON)

	DEMO 1st WALL	B-P W/REFL.	D-Li 8.5 cm	SPALL. PEPIN
DPA	36	41	44	55
H	380	400	2300	1300
H/DPA	10	10	52	24
He	17000	23000	22000	14000
He/DPA	470	570	500	250
Li	1100	970	2400	3000
Be				

TABLE 3B--TRANSMUTATIONS (APPM) IN CARBON FOR 1000 DAY DEMO
EQUIVALENT EXPOSURE (80 DPA IRON)

	DEMO 1st WALL	B-P W/REFL.	D-Li 8.5 cm	SPALL. PEPIN
DPA	50	23	22	67
H	8.4	7.3	1500	920
H/DPA	0.2	0.3	69	14
He	12000	17000	14000	440
He/DPA	240	740	640	7
Li	0.8	0.8	4.2	8.9
Be	1600	2100	1900	660
B	-	-	1500	910
C				

TABLE 3C--TRANSMUTATIONS (APPM) IN SILICON FOR 1000 DAY DEMO EQUIVALENT EXPOSURE (80 DPA IRON)

	DEMO 1st WALL	B-P W/REFL.	D-Li 8.5 cm	SPALL. PEPIN
DPA	115	112	92	146
H	8800	14000	10000	4000
H/DPA	77	120	110	27
He	1900	3400	2200	770
He/DPA	17	30	24	5
F	0.0002	0.0010	0.0007	<1E-4
Ne	1.1	3.4	1.6	0.3
Na	1.6	4.7	3.0	0.5
Mg	1900	3300	2900	1200
Al	3200	5100	4500	1800
Si				
P	10.0	2.1	0.6	2.2
S	0.0024	0.0001	<1E-4	0.0002

TABLE 3D--TRANSMUTATIONS (APPM) IN VANADIUM FOR 1000 DAY DEMO EQUIVALENT EXPOSURE (80 DPA IRON)

	DEMO 1st WALL	B-P W/REFL.	D-Li 8.5 cm	SPALL. PEPIN
DPA	86	92	76	95
H	1700	3100	2400	1000
H/DPA	20	34	32	11
He	340	530	750	380
He/DPA	4	6	10	4
Ar				
K				
Ca	0	0.1	0.5	0.1
Sc	0	0	1	0
Ti	1500	2600	3500	1900
V				
Cr	3100	290	42	260
Mn				

TABLE 3E--TRANSMUTATIONS (APPM) IN IRON FOR 1000 DAY DEMO EXPOSURE

	DEMO 1st WALL	B-P W/REFL.	D-Li 8.5 cm	SPALL. PEPIN
DPA	80	80	80	80
H	4900	6100	5800	2200
H/DPA	61	76	73	28
He	700	930	1000	460
He/DPA	8.8	12	13	5.8
Ti	0.3	0.4	4.1	1.4
V	70	86	110	76
Cr	930	1000	1400	500
Mn	4600	3600	5300	1700
Fe				
Co	10	0.9	0.6	0.5
Ni	0.1	-	-	

TABLE 3F--TRANSMUTATIONS (APPM) IN COPPER FOR 1000 DAY DEMO EQUIVALENT EXPOSURE (80 DPA IRON)

	DEMO 1st WALL	B-P W/REFL.	D-Li 8.5 cm	SPALL. PEPIN
DPA	108	129	104	110
H	4300	7200	4800	2300
H/DPA	40	56	46	21
He	1300	2300	1800	700
He/DPA	12	18	17	6
Cr				
Mn			0.06	0.01
Fe	2	4.5	7.0	1.3
Co	1300	2500	1600	650
Ni	29000	24000	14000	6000
Cu				
Zn	2600	270	50	300
Ga				

TABLE 3G--TRANSMUTATIONS (APPM) FOR MOLYBDENUM FOR 1000 DAY
EQUIVALENT EXPOSURE (80 DPA IRON)

	DEMO 1st WALL	B-P W/REFL.	D-Li 8.5 cm	SPALL. PEPIN
DPA	54	49	54	59
H	2000	2500	3800	1800
H/DPA	37	52	70	31
He	530	710	710	300
He/DPA	10	15	13	5
Sr	46	19	50	3.8
Y	320	450	320	130
Zr	520	730	910	480
Nb	2400	2600	3900	1800
Mo				
Tc	26000	5700	2500	1700
Ru	2100	150	24	200
Rh	2.1			

TABLE 3H--TRANSMUTATIONS (APPM) IN TUNGSTEN FOR 1000 DAY
DEMO EQUIVALENT EXPOSURE (80 DPA IRON)

	DEMO 1st WALL	B-P W/REFL.	D-Li 8.5 cm	SPALL. PEPIN
DPA	23	28	23	24
H	75	120	750	550
H/DPA	3	4	32	23
He	75	110	420	240
He/DPA	3	4	18	10
Tm				
Yb	0.002	0.004	0.039	0.015
Lu	0.005	0.016	0.039	0.008
Hf	140	240	600	330
Ta	5800	17000	8600	2300
W				
Re	150000	41000	15000	8200
Os	20000	360	20	30

Fig. 1--Comparison of neutron spectra; curves have been shifted arbitrary amounts for clarity.

Fig. 2--Comparison of iron and carbon PKA spectra for the d-Li source (point 2) with that for the DEMO first wall.

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