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FACILITIES

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ABSTRACT

A comparison was made of damage parameters for carbon, iron, and molybdenum irradiated in spectra for d-Li, spallation, and beam-plasma (d-t) neutron sources and a reference DEMO first wall spectrum. The transmutation results emphasize the need to define the neutron spectra at low energies; only the DEMO spectrum was so defined. The spallation spectra were also poorly defined at high neutron energies; they were too soft to produce the desired gas production rates. The treatments of neutron-induced displacement reactions were limited to below 20 MeV and transmutation reactions to below 50 MeV by the limited availability of calculational tools. 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

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evaluated at a workshop held in San Diego in Feb. 1989.[1] This workshop was held at the request of the Executive Committee of the IEA Implementing Agreement on R & D on Radiation Damage to Fusion Reactor Materials. 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 FMIT (Fusion Materials Irradiation Test facility designed at Hanford and Los Alamos but never constructed [4]) design in which neutrons are produced by one or more 25 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, produce neutrons above the 15 MeV upper limit of a fusion device, i.e., "high energy tails".

The Evaluation Panel also recommended that the radiation effects community develop descriptions of the radiation environments of these sources "on a consistent basis" as a prelude to a critical examination of how well each source can simulate the environment of a fusion reactor. The Executive Committee subsequently requested one of the authors (DGD) to attempt to

implement this recommendation. The objective of this report is to discuss 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

Neutron source comparisons can be made on the basis of neutron fluxes, neutron spectra, primary recoil spectra, damage energy or displacement rates, and transmutation species and rates. However, the Evaluation Panel concluded that each source 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, in terms of the neutron spectra themselves or the following derived spectral-averaged quantities: damage energy or displacement cross sections, transmutation cross sections, and recoil spectra. In addition, the fluence dependence of transmutation production will be examined.

The sources of the neutron spectra used in this study and some of their characteristics are described briefly in Tables 1a and 1b. Some comparisons are given in Fig. 1. Neutron spectra were solicited from LLNL for the beam-plasma source, from LANL for the D-Li source, and from the Paul Scherrer Institute (PSI) and the INF for a spallation source.

Two beam-plasma spectra at the edge of the plasma (8 cm radius), with and without an aluminum reflector (inner radius 21.5 cm, outer radius 51.5 cm) were received from Livermore; they were calculated at Tsukuba University.

Two D-Li spectra, both uncollided but for different locations in a configuration featuring two accelerator/target systems at 90 deg, were received from Los Alamos. The locations are in the plane of the two beams and along the axis of symmetry between the two targets. Point 1 is 14 cm from the vertex, which is at the virtual intersection of the two beams. Since the highest energy neutrons are emitted in the forward direction, this location illustrates a hard spectrum. Point 2 is 8.5 cm from the vertex, illustrating a somewhat softer, higher flux location.

Two spallation spectra have been examined to date. One, provided by M. Victoria, PSI, is from a published calculation by Pepin (using the HET and 05R codes) [5] for an experimentally realizable configuration. It is for the neutron spectrum at, and 90 degrees to, the curved face of a 15 cm diameter cylindrical lead target bombarded by 520 MeV protons. The other, one of several provided by J. M. Perlado, INF, is from a calculation with HETC for the proposed EURAC in which a finely focused beam of 600 MeV protons is incident on a one cm wide lead target surrounded by a lead reflector. It corresponds to a specimen located within a centimeter of the liquid lead target. The spectrum is quite soft as shown in Table 1b.

At the IFMIF workshop, the suggestion (attributed to S. Cierjacks) was made that a facility based on a triton beam impinging on a hydrogenous target

should be considered, referred to hereafter as a T-H source. A triton energy of 21 MeV would produce a neutron spectrum with a maximum energy of 14 MeV. A T-H source spectrum provided by Kernforschungszentrum Karlsruhe (KfK) has been included in this study.

KfK also provided a first wall spectrum for the conceptual Culham DEMO reactor [6] to be used as a reference case.

None of the spectra received, other than DEMO, provide spectral definition below a few tenths MeV. None of the calculations take account of spectral perturbations by test assemblies. Because each spectrum (or set of spectra) was provided by a different source, no uniformity of accuracy can be assumed.

A primary source of difficulty in making the desired source comparisons is that the neutron energy range covered by the sources extends from thermal to hundreds of MeV. It is convenient here to identify three energy regions: thermal to a few tens of keV, less than 20 MeV, and greater than 20 MeV. The lowest energy range 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.

Twenty MeV is the upper limit of the Evaluated Nuclear Data Files (ENDF/B) used in the U.S. and many other countries (major data files developed in other countries are also limited to 20 MeV or lower). Evaluated cross sections above 20 MeV are rare, so most high energy applications require the use of

calculated nuclear data. This introduces uncertainties in both the calculation of neutron spectra at high energies, and the calculation of derived damage parameters at high energies.

More importantly, the nuclear interaction processes change in character as the energy is increased above 20 MeV to hundreds of 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 means most uncertainties are relatively small. At 100 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 planned approach for this study was to combine the various spectra with appropriate cross sections to determine spectral-averaged cross sections for the production of primary recoil spectra, displacement damage, and transmutations. Recent nuclear model calculations at Los Alamos to 100 MeV for iron, molybdenum, and carbon were originally thought to be available for this study. However, we found that the complete data needed to calculate displacement damage was not available. Therefore, it was necessary to estimate the displacement damage energy due to neutrons above 20 MeV.

Transmutation files, on the other hand, are available to 50 MeV in the transmutation and activation code REAC*2 [7], developed originally for FMIT applications. The high energy data for Fe have been subject to evaluation so are probably more accurate than those for Mo and C.

CALCULATIONS

Displacement Damage

The codes NJOY [8] and SPECTER [9], both well known, were used to calculate displacement damage and primary recoil spectra, respectively. For the former, the displacement cross section above 20 MeV, the upper limit of the evaluated nuclear data files, was assumed constant leading to a small underestimate. Better approximations could be made, but this is the least serious computational limitation at present. In calculating recoil spectra, the neutron spectra were truncated at 20 MeV. This distorts the shape of the recoil spectrum somewhat and, of course, fails to indicate the highest energy recoils. Although the number of neutrons above 20 MeV is small (see Table 1b), this calculation should be redone with a different code as suggested below. However, it is of interest to note that the consensus of the present workshop was that the major concern regarding high energy tails is transmutations, not effects of high energy recoils.

Transmutations

The code REAC*2 was used to calculate transmutations for iron, molybdenum, and carbon. The few neutrons above 50 MeV (see Table 1b) in the spallation spectra 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, corresponding to 80 displacements per atom (dpa) in iron.

Recoil Spectra

Recoil spectra files (based on ENDF/B-V nuclear data [10] and the DISCS code [11]) 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, Beam-Plasma, and H-T cases, i.e., those having no neutrons above 20 MeV. It was also used to estimate recoil spectra for one D-Li and one spallation spectrum, ignoring neutrons above 20 MeV. The authors did not have access, in the time available, to an operating version of a code incorporating intranuclear cascade and fission models that in principle is capable of calculating recoil spectra (and transmutation production) at high neutron energies. (Both recoil and transmutation results are included in published descriptions of EURAC, but documentation of the calculations has not been available to the authors.)

RESULTS

Displacement Damage

Spectral-averaged damage energy cross sections are summarized in Table 2. At low Z (carbon), the cross section increases with decreasing energy below a few MeV which keeps the variation among neutron sources small. The cross sections

for Fe and Mo are essentially the same, leading to one-third fewer displacements for Mo at a given fluence if effective displacement threshold values of 40 eV and 60 eV are used for Fe and Mo, respectively.

Transmutations

The results of transmutation calculations, carried to a level of damage energy equivalent to 1000 days in DEMO (8 keV-barn or 80 dpa for Fe) for each spectrum, are summarized in Table 3. The ratios of appm He/dpa and appm H/dpa are included.

Hydrogen and helium production show similar trends for Fe and Mo. In carbon, however, we find a large increase in hydrogen production in the higher energy spectra where (n,px) reaction thresholds are exceeded. Such spectral effects are, of course, element specific.

The major solid transmutation products in iron are Mn and Cr, which reflect the dominance of (n,p) and (n,alpha) threshold reactions and the softness of several of the spectra. The production of Co is unexpectedly high in DEMO because of neutron capture in the low energy tail (although the quantity is negligible). In Mo, these low energy neutrons produce a rather large concentration of Tc. This illustrates the importance of careful definition of the low energy portion of the source spectra. Furthermore, this region will be sensitive to the configuration of material in and near the test volume. (When such characterization is done, a further problem may be revealed with

spallation spectra that range from hundreds of MeV down to eV. This is the production of nuclides by the high energy neutrons for which thermal and epithermal absorption cross sections are unknown and extremely difficult to calculate. This would create further uncertainties in transmutation rates.)

In this work, only the DEMO first wall spectrum is well characterized at low energies. No spectral detail below a few tenths MeV was provided for most of the other cases (see Table 1b).

In carbon, the high production of boron in the high energy spectra corresponds to the high production of hydrogen mentioned earlier by above-threshold neutrons.

Recoil Spectra

Some examples of calculated recoil spectra for various neutron spectra are compared in Figs. 2-6. Only the energy dependence, i.e., the shapes of the curves, is relevant; the magnitudes are quite arbitrary. The Beam-Plasma w/Reflector case (Fig. 2) agrees well with DEMO above a few tenths MeV for all three elements, as would be expected. A modification of the reflector could probably increase the low energy tail to give better agreement at lower energies.

The shape of the D-Li (Point 2) recoil spectra also agree rather well with DEMO from a few tenths MeV to the upper limit of DEMO (see Fig. 3 for Fe),

except for a high energy deviation for carbon (Fig. 4). 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, only 2% above 30 MeV.

To help illustrate the energy dependence, recoil spectra for monoenergetic neutrons at 14 and 20 MeV are compared in Fig. 5. From a damage simulation perspective, the main difference is the 2-3 MeV recoils that are present only in the 20 MeV case. But these constitute less than 0.1% of the total number of recoils and account for only a few tenths percent of the displacements.

We are unable to make good comparisons of spallation recoil spectra at this time, as explained above. The result of a SPECTER calculation for Fe for Pepin's spectrum, ignoring neutrons above 20 MeV, is shown in Fig. 6. The recoil spectra for Fe and Mo decrease more rapidly with energy than the DEMO spectra. The agreement is somewhat better for C.

The T-H case also agrees well with DEMO above 0.4 MeV. At lower energies, it decreases with decreasing energy much faster than DEMO.

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.

All candidate spectra need better definition at low energies.

While only three elements have been examined (the transmutation calculations are presently being extended to other elements), some interesting discrepancies among transmutation rates in the various sources have been revealed, emphasizing that these comparisons may be very element specific. For this comparative study, it is important to determine which region of the neutron spectrum is producing a particular transmutation product.

Both of the specific spallation spectra studied are too soft to provide the high gas production rates required of an IFMIF; harder spectra can be obtained, however, from a spallation source.

RECOMMENDATIONS

1. It is important to determine whether either of the spallation spectra used here are representative of those expected from 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. Some relevant experiments at LAMPF have been performed by a PSI/Risø/LAMPF collaboration and analyses are in progress. These results, and earlier results obtained in an ANL/LAMPF collaboration, should be compared with concentrations predicted by a state-of-the-art code.
3. While such a code would be applied to D-Li spectra also, it is not considered essential. More important is to make sure that current knowledge of cross sections in the 20 to 40 MeV range is incorporated into NJOY (or equivalent), and any important missing data 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 decision on the feasibility of a T-H source is needed to justify continued inclusion of this interesting concept in these comparative studies. If positive, more rigorous spectra are needed.

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

8. A small international working group should be established to pursue source characterizations/comparisons. This group would be concerned with the spectral definition phase through the calculation of various damage parameters. It should include those responsible for neutronics calculations for each candidate source, and specialists on nuclear data, damage parameters, code verification, and reactor experimentation.

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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	Kawabe & Sagawa Tsukuba U.	none	ANISN	27		Coensgen, LLNL
Plasma edge, 8 cm						
Al, 21.5-22.3 cm					9.8e+14 n/cm2-s?	
Al, 21.5-51.5 cm					14.9e+14 n/cm2-s?	
D-Li, 2-250 mA beams at 90 deg.	Varsamis, LANL	IFMIF rept. TBP Nucl. Sci. Eng.	FMITSP (Mann)	50 (1 MeV)		Lawrence, LANL
8.5 cm from vertex					5.45e+14 n/cm2-s	
14 cm from vertex					5.27e+14 n/cm2-s	
T-H (21 MeV tritons)	Cierjacks, KfK	IFMIF rept. TBP Nucl. Sci. Eng.	?	28	1.04e+13 n/cm2-s	Ehrlich, KfK
SPALLATION						
520 MeV p on Pb, 90 deg at targ. face	Pepin, 1982	ANL-82-80 1982	HET, 05R	28	0.846 n/sr-p	Victoria, PSI
600 MeV p on Pb w/ Pb reflector Z=3.75, R=1.3 cm	Atchison & Fischer, PSI	none	HETC	35	0.127 n/cm2-p	Perlado, Madrid

TABLE 1R 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		
DEMO	0	0	0	0.126	0.28	0.56	0 - 0.41 eV
BEAM-PLASMA							
w/o reflector	0	0	0	0.95	0.98	0.997	0 - 0.02 Mev
w/reflector	0	0	0	0.56	0.66	0.84	0 - 0.02 Mev
D-Li							
14.0 cm from vertex	0	0.12	0.49	-	.94	?	0 - 1 Mev
8.5 cm from vertex	0	0.10	0.37	-	.90	?	0 - 1 Mev
T-H	0	0	0	0.23	0.90	?	0 - 1 Mev
SPALLATION							
520 Mev (Pepin)	.004	0.04	0.05	-	0.52	0.95	0.001 - .01 Mev
600 Mev (Perlado)	<.003	0.008	0.014	-	0.42	?	0.4 - 0.6 Mev

R = 1.3 cm

R = 1.3 cm

Table 2
Spectral-Averaged Damage Energy Cross Sections (keV-barns)

SPECTRUM	C	Fe	Mo
DEMO	31	66	67
B-P	41	271	245
B-P w/refl.	40	188	171
D-Li, Pt.1	44	240	241
D-Li, Pt.2	45	220	223
Spall (Pepin)	51	81	89
Spall (Perlado)	49	55	63
T-H	41	182	182
14 MeV	41	293	265
20 MeV	49	319	351

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

MOLYBDENUM

ELEMENT	DEMO 1st WALL	BEAM-PLASMA W/O REFL.	BEAM-PLASMA W/REFL.	D-Li 14 cm	D-Li 8.5 cm	T-H	SPALL- PEPIN	SPALL- PERLADO
DPA	54	48	49	54	54	53	59	61
H	2000	3200	2500	4400	3800	780	1800	760
H/DPA	37	66	52	82	70	15	31	12
He	530	890	710	810	710	190	300	130
He/DPA	10	18	15	15	13	4	5	2
Sr	46	29	19	55	50	8	3.8	2.7
Y	320	570	450	370	320	95	130	53
Zr	520	900	730	1000	910	300	480	200
Nb	2400	3200	2600	4500	3900	530	1800	760
Mo								
Tc	26000	6300	5700	2900	2500	1900	1700	3100
Ru	2100	6.6	150	16	24	32	200	480
Rh	2.1							

FIGURE CAPTIONS

1. Comparison of neutron spectra; curves have been shifted arbitrary amounts for clarity.
2. Comparison of the iron PKA spectrum for the Beam-Plasma source (with Al reflector) with that for the DEMO first wall.
3. Comparison of the iron PKA spectrum for the D-Li source (pt. 2 at 8.5 cm) with that for the DEMO first wall.
4. Comparison of the carbon PKA spectrum for the D-Li source (pt. 2 at 8.5 cm) with that for the DEMO first wall.
5. Comparison of iron PKA spectra for 14 and 20 MeV monoenergetic neutrons.
6. Comparison of the iron PKA spectrum for Pepin's spallation source with that for the DEMO first wall.

IRON PKA SPECTRA (SPECTER)
BEAM-PLASMA W/REFL. COMPARED WITH DEMO

IRON PKA SPECTRA (SPECTER)

D-Li, PT.2 COMPARED WITH DEMO

CARBON PKA SPECTRA (SPECTER)

D-Li, PT.2 COMPARED WITH DEMO

IRON PKA SPECTRA (SPECTER)
COMPARING 14 MEV AND 20 MEV NEUTRONS

IRON PKA SPECTRA (SPECTER)

PEPIN'S SPALLATION COMPARED WITH DEMO

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