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PNNL-12200

Radiation Damage Calculations for the FUBR and BEATRIX Irradiations of Lithium Compounds in EBR-II and FFTF

L. R. Greenwood

May 1999

Prepared for the U. S. Department of Energy
under Contract DE-AC06-76RLO 1830
Pacific Northwest National Laboratory
Richland, Washington 99352

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Summary

The Fusion Breeder Reactor (FUBR) and Breeder Exchange Matrix (BEATRIX) experiments were cooperative efforts by members of the International Energy Agency to investigate the irradiation behavior of solid breeder materials for tritium production to support future fusion reactors. Lithium ceramic materials including Li_2O, $LiAlO_2$, Li_4SiO_4, and Li_2ZrO_3 with varying ^6Li enrichments from 0 to 95% were irradiated in a series of experiments in the Experimental Breeder Reactor (EBR II) and in the Fast Flux Test Facility (FFTF) over a period of about 10 years from 1982 to 1992. These experiments were characterized in terms of the nominal fast neutron fluences and measured ^6Li burnup factors, as determined by either mass spectrometry or helium measurements. Radiation damage in these compounds is caused by both the ^6Li-burnup reaction and by all other possible neutron reactions with the atoms in the compound materials. In this report, displacements per atom (dpa) values have been calculated for each type of material in each of the various irradiations that were conducted. Values up to 11% ^6Li-burnup and 130 dpa are predicted for the longest irradiations. The dpa cross sections were calculated for each compound using the SPECOMP computer code. Details of the dpa calculations are presented in the report. Total dpa factors were determined with the SPECTER computer code by averaging the dpa cross sections over the measured or calculated neutron flux spectra for each series of irradiations. Using these new calculations, previously measured radiation damage effects in these lithium compounds can be compared or correlated with other irradiation data on the basis of the dpa factor as well as ^6Li-burnup.

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G. W. Hollenberg (Pacific Northwest National Laboratory) and C. E. Johnson (Argonne National Laboratory - East) provided guidance and technical assistance with assembling the information concerning these experiments. D. G. Porter (Argonne National Laboratory - West) was very helpful in providing information regarding the irradiation history of these experiments in the EBR II reactor. Funding for this work was provided by the U. S. Department of Energy, Office of Fusion Energy.

Contents

Introduction

Fusion reactors based on the D-T reaction need a large and continuous supply of tritium. Lithium metal or lithium containing ceramic materials are proposed for breeding the tritium via the $^{6}Li(n,\alpha)^{3}H$, $^{7}Li(n,nt)^{4}He$, and $^{7}Li(n,2n)^{6}Li$ nuclear reactions. The ^{6}Li reaction has a high thermal neutron cross section of 941 barns and an average of about 1 barn in fast reactors. Fusion reactor designs may include Be moderators to enhance the ^{6}Li reaction. The ^{7}Li threshold reactions mainly occur with the 14 MeV neutrons produced by the D-T reaction. The recoiling alpha and triton from the $^{6}Li(n,\alpha)^{3}H$ reaction create a cascade of secondary recoil atoms from their interactions with atoms in the compound material. Fast neutron interactions with atoms in the compounds can also cause primary recoil atoms that also lead to a cascade of secondary recoil atoms. Both of these processes lead to radiation damage characterized by the total number of displacements per atom (dpa). This report documents the calculation of dpa for various lithium ceramic compounds that were irradiated in the FUBR and BEATRIX experiments in EBR II and FFTF. Although dpa is not in itself a measurable effect, it has proven useful as an exposure parameter for correlating material effects for different materials and radiation environments. The purpose of this report is to document the calculation of dpa for the Li breeder compounds in the FUBR and BEATRIX series of irradiations.

It should be noted, however, that other effects besides dpa will also be important for characterizing the irradiation performance of these materials, especially transmutation which leads to the creation of Li vacancies and the buildup of transmutant product interstitials. The absolute value of the calculated dpa is somewhat irrelevant due to the very high rate of atomic recombination in most materials. As an example, the longest exposures in this study lead to the prediction of about 11% burnup of ^{6}Li and 130 dpa. However, if 99% of the displaced atoms recombine, then burnup (transmutation) effects may be a factor of ten more important than stable product dpa in the evolution of material property changes. Irradiation experiments performed on these lithium ceramics do not indicate any significant property changes at these burnup or dpa levels that would seriously degrade the usefulness of these materials for tritium breeding in fusion reactor applications. Ultimately, it is the measured performance of lithium ceramic breeder materials as a function of irradiation exposure that determines their applicability in fusion reactor designs. Comparisons with dpa levels in structural materials such as stainless steel may thus be irrelevant.

Material Characterization

The lithium containing ceramic materials were prepared by members of an International Energy Agency collaborative program, as documented in several publications (see references with each table). In EBR-II, ceramic pellets were irradiated in canisters placed in several pins located in row 7 at different radial and axial locations. The irradiations in the FFTF MOTA were designed to measure tritium release. The lithium was enriched in ^{6}Li in varying amounts from 0 to 95%. Principal details of the materials are given in the following tables. The references with each table provide more detailed documentation.

Table 1 – Test Matrix for FUBR-1A in EBR-II[1,2,3,4]

Material	^{6}Li Enrichment %	Column Length cm	Column Diameter cm	Theoretical Density %
Li_2O	56	5.7	0.95	85
$LiAlO_2$	95	5.7	0.95	60, 85, 95
Li_2ZrO_3	95	5.7	0.95	85
Li_4SiO_4	95	5.7	0.95	85

Table 2 – Test Matrix for FUBR-1B/BEATRIX-I in EBR-II[5,6,7,89]

Material	^{6}Li Enrichment	Column Length cm	Column Diameter cm	Theoretical Density %
Li_2O	0.07, 7.5, 56	5.0, 5.7	0.95, 1.7, 2.4	80, 85, 100
$LiAlO_2$	95	5.0, 5.7	0.95, 2.3	75, 80
Li_2ZrO_3	95	5.7	0.95	80
Li_4SiO_4	95	5.7	0.95	80, 95

Table 3 – Test Matrix for BEATRIX-II in FFTF-MOTA-2A[10,11,12]

Material	^{6}Li Enrichment %	MOTA Canisters	Diameter cm	Theoretical Density %
Li_2O	61	1E	1.65-1.85[a]	87
Li_2O	61	1C	Pellets	80
Li_2O	0.07, 61	1B,1D	Crystals	80-95
$LiAlO_2$	0.2,95	5E,8B	Disks	80
Li_2ZrO_3	0.2,95	5E,8B	Disks	80
Li_4SiO_4	0.2,95	5E,8B	Disks	80, 95

[a] Li_2O ring specimen for tritium release studies.

Table 4 – Test Matrix for BEATRIX-II in FFTF-MOTA-2B[13]

Material	^{6}Li Enrichment %	MOTA Canisters	Diameter cm	Theoretical Density %
Li_2O	95	1B	1.65-1.85[a]	87
Li_2ZrO_3	85	2C	b	80
$LiAlO_2$	0.2	5F,8B	Disks	80
Li_4SiO_4	0.2	5F,8B	Disks	80, 95

[a] Li_2O ring specimen for tritium release studies.
[b] Li_2ZrO_3 sphere bed for tritium release studies.

Table 5 – Summary of the FUBR and BEATRIX Irradiation Histories

Experiment	Subassembly	Subcapsules	Runs	MWd	EFPD
	EBR-II				**@62.5 MW**
FUBR-1A	X370	1,2,3,4	119-120	6041	96.7
	X370A	5,6,7,8	123-126	11101	177.6
	In both runs	9,10,11	119-126	17142	274.3
FUBR-1B	X415	B1,B3,B6,B7	135A-141C[a]	21344	341.5
BEATRIX-I	X415A	B8,B9,B10,B11	144A-151	37455	599.3
	In both runs	B2,B4,B5	135A-151	58799	940.8
FUBR-1B	X416	S1,S2	135A-141C[a]	21104	337.7
BEATRIX-I	X416A	S4,S5	144A-151	37455	599.3
	In both runs	S3	135A-151	58559	936.9
	FFTF				**@291 MW**
BEATRIX-II	MOTA-2A	1B,1C,1D,1E, 5E,8B	11	87213	299.7
BEATRIX-II	MOTA-2B	1B,2C,5F,8B	12	59160	203.3

[a] X415 was removed for runs 137E and 138B; X416 was removed for 137E, 138B, and 138C.

Irradiation Histories

All of the irradiation histories are summarized in Table 5. Details of the EBR-II irradiations were provided in a private communication from D. G. Porter (Argonne National Laboratory – West, 1999.) Details of the FFTF-MOTA irradiations are documented in references 9 -12. Irradiations referred to as FUBR-1A were started in the EBR II reactor in 1982. These experiments lasted for about a year and materials were irradiated for three different exposure times of 96.7, 117.6, and 274.3 full power days at 62.5 MW reactor power. A second series of experiments referred to as FUBR-1B was initiated in 1985. Two assemblies were irradiated for about a year resulting in exposures of 337.7 or 341.5 full power days. The small difference in exposure resulted from the brief removal of one of the two assemblies during run 138C. Some materials were then removed and the rest continued irradiation along with some additional materials in a third experiment referred to as BEATRIX-I for an exposure of 599.3 full power days. Materials that were irradiated in both the FUBR-1B and BEATRIX-I experiments thus had net exposures of 936.9 or 940.8 full power days. Neutron dosimetry was not performed for these particular irradiations in EBR-II. However, dosimetry measurements were performed for similar irradiations in row 7.[14,15]

A fourth experiment referred to as BEATRIX-II was conducted in the Materials Open Test Assembly (MOTA) in two irradiations in FFTF labeled 2A and 2B. MOTA-2A was irradiated from January 1990 to December 1990 for 299.7 full power days at 291 MW reactor power. MOTA-2B operated from May 1991 to March 1992 for 203.3 full power days at 291 MW reactor power. Neutron dosimetry was included with these irradiations and the neutron flux spectra and radiation damage calculations for a variety of elements have been published.[16,17]

Radiation Damage Cross Sections and dpa Calculations

The $^6Li(n,\alpha)^3H$ reaction releases 4.782 MeV of energy (Q value) resulting in energetic tritium (2.733 MeV) and alpha (2.050 MeV) particle recoils. These high-energy recoils lose energy and are stopped within a short distance in the lithium compounds. A small fraction of the time, the recoiling particles hit a nucleus of one of the atoms in the compound leading to either an elastic scattering event or a nuclear reaction. These nuclear events cause secondary atoms to be displaced from their lattice sites. If we use the Lindhard model of energy loss and a modified Kinchin-Pease model for secondary displacements, then we can calculate the total number of displaced atoms for each $^6Li(n,\alpha)^3H$ reaction. This leads to a fixed relationship between burnup of ^6Li atoms and dpa (for this reaction only). Each compound will have a different ratio of burnup to dpa due to the differences in lithium content and energy loss characteristics. In the modified Kinchin-Pease model, constant displacement energy is assigned to each atom in a given compound. Unfortunately, these values are not readily available for these compounds. Efforts are underway to use a better model for these compounds; however, these results are not currently available. If we assign values of 10 eV for Li, 30 eV for O, 27 eV for Al, 25 eV for Si, and 40 eV both for Ti and Zr, then the calculated conversion of ^6Li burnup to dpa is given in Table 6, assuming 100% enrichment of ^6Li. For a measured level of ^6Li burnup and enrichment, the dpa can be calculated by multiplying the values in Table 6 times these two factors. For example, if we start with 56% enriched Li_2O and the ^6Li burnup is measured to be 8%, then the dpa due to this reaction will be 117 x 0.56 x 0.08 = 5.2. Once the ^6Li is fully burned out, this process will stop and no further dpa can be generated from this reaction. It should be noted that the conversion factors in Table 6 are technically only correct at low neutron energies since at higher energies the energy of the incident neutron will raise the recoil energies slightly. However, since this reaction mainly occurs with neutrons well below 1 MeV, this correction for the neutron spectra of interest is negligible. Due to the burnup of ^6Li as well as the variations in the ^6Li enrichment, dpa cross sections for these compounds depend on both of these factors and change with irradiation as the ^6Li burns up. Both of these effects were taken into account in these calculations. Due to the high cross section of ^6Li at lower neutron energies, neutron self-shielding can also be an important time-dependent effect. Simple approximations to the neutron self-shielding effects for the materials and neutron spectra used in these experiments indicate that the corrections would typically be on the order of 5%. Due to the complicated geometries of these experimental assemblies and the relatively small order of these corrections, neutron self-shielding corrections were not included. The calculated ^6Li burnup values presented in the tables below agree favorably with measurements made for these materials, as documented in various references in this report.

Table 6 – Conversion of ^6Li Burnup to dpa
(Multiply times ^6Li enrichment)

Material	Dpa / % ^6Li Burnup
Li_2O	117.0
$LiAlO_2$	33.7
Li_2ZrO_3	44.9
Li_4SiO_4	67.8

Of course, this is only part of the dpa story. All other possible nuclear reactions will also cause dpa. The SPECOMP[18] computer code was used to calculate these more conventional dpa cross sections as a function of neutron energy for each type of lithium compound. These dpa cross sections were then added to the SPECTER[19] computer code for integration over the neutron flux spectra in each series of irradiations.

The calculated dpa values for each series of irradiations are discussed below. Specific comments describe each experiment. In all of these irradiations, the reactor power and hence dpa rates are essentially constant (< 10% variation over the run cycles) except during reactor downtimes. For all of the irradiations, the Li compounds were encapsulated in 316 stainless steel containers. The dpa values for the 316 SS cladding are also presented below along with the total neutron fluences. The composition of 316 SS was taken as Ni(0.13), Cr(0.18), Mn(0.019), Mo(0.026), and Fe(balance).

FUBR-1A Irradiation in EBR-II

Eleven pins were fabricated for irradiation designated PIN-1 through PIN-11. Solid pellets as described in Table 1 were irradiated at four different elevations in each pin. Canisters were placed symmetrically about the reactor centerline at 1.2 to 7.9 cm and at 15.2 to 21.6 cm. As shown in Table 5, pins 1, 2, 3, and 4 were irradiated in experiment X370 for a total of 96.7 EFPD (Effective Full Power Days) at a nominal power of 62.5 MW. Pins 5, 6, 7, and 8 were irradiated in X370A for 177.6 EFPD. Pins 9, 10, and 11 were in for both irradiations for a total exposure of 274.3 EFPD. The dpa calculations for these positions and exposures are given in Tables 7-9. Exact locations for specific pellets were not available. However, as seen in Tables 7-9s, the variations in dpa between these locations are rather small. It should be noted that the different pins were irradiated in different radial locations and hence had slightly different flux and damage values. The dpa values in the table are average values for the assemblies and radial variations are < 10%. Axial flux variations are also relatively small (< 10%) near core midplane.

Table 7 - dpa Calculations for FUBR-1A - Capsules 1, 2, 3, 4 - 96.7 EFPD

Fluence ($x10^{22}$ n/cm^2)		1.39	1.45	1.34
Dpa, 316 SS		5.6	5.9	5.4
^{6}Li Burnup, % :		1.20%	1.23%	1.12%
Height,cm:		-20	0	+20
Material	^{6}Li Enrichment, %	dpa	dpa	dpa
Li_2O	56	12.5	13.1	12.0
$LiAlO_2$	95	13.1	13.8	12.6
Li_2ZrO_3	95	13.2	13.9	12.7
Li_4SiO_4	95	12.2	12.9	11.7

Table 8 – dpa Calculations for FUBR-1A – Capsules 5, 6, 7, 8 – 177.6 EFPD

Fluence ($x10^{22}$ n/cm^2)		2.55	2.66	2.46
Dpa, 316 SS		10.3	10.9	9.9
^{6}Li Burnup, % :		2.20%	2.25%	2.05%
Height,cm:		-20	0	+20
Material	^{6}Li Enrichment, %	dpa	dpa	dpa
Li_2O	56	22.9	24.1	22.0
$LiAlO_2$	95	24.0	25.3	23.1
Li_2ZrO_3	95	24.3	25.6	23.3
Li_4SiO_4	95	22.4	23.6	21.5

Table 9 – dpa Calculations for FUBR-1A – Capsules 9, 10, 11 – 274.3 EFPD

Fluence ($x10^{22}$ n/cm^2)		3.94	4.11	3.79
Dpa, 316 SS		15.9	16.8	15.2
^{6}Li Burnup, % :		3.38%	3.46%	3.14%
Height,cm:		-20	0	+20
Material	^{6}Li Enrichment, %	dpa	dpa	dpa
Li_2O	56	35.4	37.3	34.0
$LiAlO_2$	95	37.1	39.1	35.6
Li_2ZrO_3	95	37.6	39.5	36.0
Li_4SiO_4	95	34.6	36.4	33.1

FUBR-1B/BEATRIX-I Irradiations in EBR-II

Two different types of pins were fabricated for these irradiations. B7A pins labeled B1 through B11 contained canisters with Li ceramic pellets at three different elevations, -15.5 to -21.6 cm, -7.6 to -13.2 cm, and +16.8 to +22.4 cm. S pins labeled S1, S2, and S3 contained canisters with Li ceramic pellets at two elevations symmetrically around midplane at 1.3 to 7.9 cm. Exact locations for specific pellets were not readily available. However, the variations in dpa are not very large for all of the different positions. As shown in Table 5, the B7A pins B1, B3, B6, and B7 were irradiated in run X415 for 341.5 EFPD. These pins were then replaced by pins B8, B9, B10, and B11 in run X415A for an irradiation of 599.3 EFPD. Pins B2, B4, and B5 were present for both irradiations resulting in a net exposure of 940.8 EFPD. Pins S1 and S2 were similarly irradiated in run X416 for 337.7 EFPD. These pins were replaced by pins S4 and S5 for an irradiation of 599.3 EFPD in run X416A. Pin S3 was present for both of these irradiations for a net exposure of 936.9 EFPD. The dpa values in the table are average values for the assemblies and radial variations are $<10\%$. Axial flux variations are also relatively small ($<10\%$) near core midplane.

Table 10 – dpa Calculations for FUBR-1B – Capsules 1, 3, 6, 7 – 341.5 EFPD

Fluence ($x10^{22}$ n/cm^2)		4.91	5.12	4.72
Dpa, 316 SS		19.8	20.9	19.0
^{6}Li Burnup, % :		4.19%	4.28%	3.90%
Height, cm:		-20	0	+20
Material	^{6}Li Enrichment, %	dpa	dpa	dpa
Li_2O	56	44.0	46.3	42.2
Li_2O	7.5	41.6	43.8	39.9
Li_2O	0.07	41.3	43.4	39.5
$LiAlO_2$	95	46.2	48.7	44.3
Li_2ZrO_3	95	46.7	49.1	44.8
Li_4SiO_4	95	43.0	45.3	41.2

Table 11 – dpa Calculations for BEATRIX-I – Capsules 8, 9, 10, 11 – 599.3 EFPD

Fluence ($x10^{22}$ n/cm^2)		8.62	8.98	8.29
Dpa, 316 SS		34.7	36.7	33.3
^{6}Li Burnup, % :		7.23%	7.40%	6.74%
Height, cm:		-20	0	+20
Material	^{6}Li Enrichment, %	dpa	dpa	dpa
Li_2O	56	77.1	81.2	74.0
Li_2O	7.5	73.1	77.0	70.1
Li_2O	0.07	72.4	76.4	69.5
$LiAlO_2$	95	81.0	85.4	77.7
Li_2ZrO_3	95	82.0	86.3	78.5
Li_4SiO_4	95	75.3	79.4	72.2

Table 12 – dpa Calculations for FUBR-1B/BEATRIX-I – Capsules 2, 4, 5 – 940.8 EFPD

Fluence ($x10^{22}$ n/cm^2)		13.5	14.1	13.0
Dpa, 316 SS		54.5	57.6	52.2
^{6}Li Burnup, % :		11.11%	11.36%	10.38%
Height, cm:		-20	0	+20
Material	^{6}Li Enrichment, %	dpa	dpa	dpa
Li_2O	56	121.0	127.3	116.1
Li_2O	7.5	114.6	120.8	110.0
Li_2O	0.07	113.7	119.9	109.1
$LiAlO_2$	95	127.1	134.0	122.0
Li_2ZrO_3	95	128.6	135.2	123.2
Li_4SiO_4	95	118.1	124.5	113.2

Table 13 – dpa Calculations for FUBR-1B – Capsules S1, S2 – 337.7 EFPD

Fluence ($x10^{22}$ n/cm^2)		4.86	5.06	4.67
Dpa, 316 SS		19.6	20.7	18.7
^{6}Li Burnup, % :		4.14%	4.24%	3.86%
Height,cm:		-20	0	+20
Material	^{6}Li Enrichment, %	dpa	dpa	dpa
Li_2O	56	43.5	45.8	41.8
Li_2O	7.5	41.2	43.4	39.5
Li_2O	0.07	40.8	43.0	39.1
$LiAlO_2$	95	45.7	48.2	43.8
Li_2ZrO_3	95	46.2	48.6	44.3
Li_4SiO_4	95	42.5	44.8	40.7

Table 14 – dpa Calculations for BEATRIX-I – Capsules S4, S5 – 599.3 EFPD

Fluence ($x10^{22}$ n/cm^2)		8.62	8.98	8.29
Dpa, 316 SS		34.8	36.7	33.3
^{6}Li Burnup, % :		7.23%	7.40%	6.74%
Height,cm:		-20	0	+20
Material	^{6}Li Enrichment, %	dpa	dpa	dpa
Li_2O	56	77.1	81.2	74.0
Li_2O	7.5	73.0	77.0	70.1
Li_2O	0.07	72.4	76.4	69.5
$LiAlO_2$	95	81.0	85.4	77.7
Li_2ZrO_3	95	82.0	86.2	78.5
Li_4SiO_4	95	75.3	79.4	72.2

Table 15 – dpa Calculations for FUBR-1B/BEATRIX-I – Capsule S3 – 936.9 EFPD

Fluence ($x10^{22}$ n/cm^2)		13.5	14.0	13.0
Dpa, 316 SS		54.3	57.4	52.0
^{6}Li Burnup, % :		11.07%	11.32%	10.34%
Height,cm:		-20	0	+20
Material	^{6}Li Enrichment, %	dpa	dpa	dpa
Li_2O	56	120.4	126.8	115.6
Li_2O	7.5	114.2	120.3	109.6
Li_2O	0.07	113.2	119.3	108.6
$LiAlO_2$	95	126.6	133.5	121.4
Li_2ZrO_3	95	128.0	134.7	122.6
Li_4SiO_4	95	117.6	124.0	112.7

BEATRIX-II Irradiations in FFTF

The BEATRIX-II experiments were conducted in the MOTA-2A and MOTA-2B irradiations in FFTF. These experiments were primarily designed to evaluate the rate of recovery of tritium during irradiation. The experimental assemblies consisted of solid pellets or tubes (rings) of lithium ceramics with flowing gas in the center or sphere beds. In MOTA-2A, the Li_2O ring canister was in position 1E and solid pellets and single crystals were in positions 1B, 1C, 1D, and 1E. In MOTA-2B, the Li_2O ring canister was located in position 1B and a Li_2ZrO_3 sphere bed was located in position 2C. $LiAlO_2$, Li_2ZrO_3 and Li_4SiO_4 disc samples were also irradiated in both experiments. MOTA-2A reached an exposure of 299.7 EFPD whereas the MOTA-2B exposure was 203.3 EFPD at an operating power of 291 MW. The dpa calculations listed in Tables 16 and 17 are quoted for positions where the neutron flux spectra were determined from neutron dosimetry measurements. Radial flux gradients are relatively small (< 10%). Axial flux gradients are relatively small near midplane where the main testing was done, but become quite steep at the top of the core 8B position. However, the dpa values are so low at these out-of-core positions that the materials damage effects are probably negligible.

Table 16 – dpa Calculations for BEATRIX-II – MOTA-2A – 299.7 EFPD

Fluence ($x10^{22}$ n/cm^2)		8.89	7.44	0.24
Dpa, 316 SS		24.9	21.8	0.25
^{6}Li Burnup, % :		9.96%	7.60%	1.68%
Reactor Position:		1-B,C,D,E	5E	8B
Height,cm:		-42.7	+37.7	+122.4
Material	^{6}Li Enrichment, %	dpa	dpa	dpa
Li_2O	61	68.1	56.6	1.93
Li_2O	0.07	60.8	51.2	0.72
$LiAlO_2$	95	68.3	57.5	1.27
Li_2ZrO_3	95	63.9	53.7	1.39
Li_4SiO_4	95	70.4	58.8	1.81

Table 17 – dpa Calculations for BEATRIX-II – MOTA-2B – 203.3 EFPD

Fluence ($x10^{22}$ n/cm^2)		5.63	7.91	4.77	0.20
Dpa, 316 SS		14.2	21.1	12.9	0.23
^{6}Li Burnup, % :		6.68%	7.92%	5.29%	1.27%
Reactor Position:		1B	2C	5F	8B
Height,cm:		-41.2	-27.3	+44.3	+121.3
Material	^{6}Li Enrichment, %	dpa	dpa	dpa	dpa
Li_2O	95	41.5	59.9	36.9	2.07
Li_2ZrO_3	85	35.5	52.4	32.3	1.08
Li_2ZrO_3	0.2	32.9	49.4	30.3	0.59
Li_4SiO_4	0.2	35.3	53.1	32.4	0.64

Conclusions

The tables included in this report document the dpa damage to solid lithium tritium-breeder materials irradiated in the FUBR and BEATRIX series of irradiations in EBR-II and FFTF reactors. The calculations clearly show that most of the dpa damage arises from fast neutron reactions such as elastic and inelastic scattering rather than from the $^{6}Li(n,\alpha)t$ reaction. This effect can be seen most clearly in the tables that include materials that were both enriched and depleted. For example, in Table 15 at midplane the dpa for Li_2O with 56% enrichment is 126.8 compared to 119.3 for depleted Li_2O. This means that with 56% enrichment, only 6% of the dpa is coming from the $^{6}Li(n,\alpha)t$ reaction. Using the dpa to burnup conversion factors in Table 6, it is easy to estimate the contribution to the dpa from the $^{6}Li(n,\alpha)t$ reaction for any entry in the dpa tables. The dpa values in this report were calculated using the conventional dpa model. Newer calculations are in progress using improved models. When these cross sections become available, it would be straightforward to recalculate the dpa factors for these experiments. However, the current dpa values are compatible with the conventional dpa calculations that are widely used and quoted in the literature. For example, the dpa values for the 316 SS cladding is also given for each of the irradiations. The dpa is only an estimate of the total energy available for creating displacements in a compound and does not directly relate to observable damage effects due to the high probability of recombination effects. Transmutation effects due both to the $^{6}Li(n,\alpha)t$ reaction as well as other nuclear reactions may be very important in influencing the degradation of materials since these effects produce a permanent change in the irradiated material.

In the comparison of these fast neutron experiments on lithium ceramics to similar experiments in thermal or mixed-spectrum reactors, it is likely that the fast neutron dpa rates are much lower in the mixed-spectrum reactors. Fusion reactors will also exhibit differences from fast reactors in the neutron spectra due to both the 14 MeV neutrons and increased lower-energy neutron flux due to Be blankets and other moderating materials.

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