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STUDIES OF D-Li NEUTRON SOURCE - AN OVERVIEW

by

Itacil Gomes and Dale L. Smith
Fusion Power Program/Technology Development Division

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STUDIES OF D-Li NEUTRON SOURCE - AN OVERVIEW

I. C. Gomes and D. L. Smith

ABSTRACT

The construction of a neutron source facility able to reproduce the radiation environment predicted for a fusion reactor can be considered a very important milestone for the fusion program. Such a neutron source should allow materials testing over a wide range of neutron flux and neutron fluence. To date, none of the existing facilities reproduce the neutron flux with the energy spectrum of a fusion reactor. As a result, the major part of the required material database is obtained by extrapolations which may not be as reliable as needed to predict the real performance of those materials under fusion reactor conditions. As an example, the effect of the gas production, transmutation, atomic displacement, and other nuclear responses on the ductility and swelling and perhaps other properties as well, must be analyzed in samples which have undergone reactor conditions environment.

This study is focused on the neutronics analysis of a D-Li neutron source. Neutron induced nuclear responses and neutron transport are calculated with the aim at defining the expected performance of a D-Li neutron source. The first section describes the differences in the magnitude of the neutron flux when material is present or not inside the test cell. The second section deals with nuclear responses such as DPA, helium production, and nuclear heating. In the third section, calculations of the available volume above a threshold DPA value are presented. Section four presents results for the gamma-ray flux distribution. A brief discussion about tritium generation in the lithium jet is given in section five, and the conclusions are summarized in section six.

1. NEUTRON FLUX WITH MATERIAL PRESENT INSIDE THE TEST CELL

This and the following sections present results considering the presence of material inside the test cell. All the analysis performed in these sections are for a single beam configuration with the beam cross sectional area at the lithium jet as a parameter. Description of the model and computer code used in this analysis can be found elsewhere [1].

During normal operation of a neutron source the test assembly region will be filled with samples of materials and the surrounding regions will be occupied by structural materials and support equipment. Under these circumstances, the neutrons will interact with materials present in test assembly and surrounding structure and will either be absorbed, or will collide and lose part of their energy. These processes will generate changes in the neutron energy spectrum as well as in the magnitude of the neutron flux (through reflection and absorption). At this time, it is not possible to predict accurately the composition of the materials inside the test cell. However, an approximate material composition and distribution can be assumed to evaluate the impact of the presence of material inside the test cell. In this work, SS-316 was chosen as the reference material and it was placed inside the test cell at a 30% density for the first 15 cm and at a 100% density from 15 to 50 cm. The remaining volume of the test cell was considered to be a black absorber such that no neutrons nor gamma-rays are reflected back from those regions. The cooling material, probably NaK or lithium-7, was not included in the test assembly region for the sake of simplification and because of their low attenuation power for neutrons.

Figure 1 presents the comparison of the total neutron flux distribution with and without material (SS-316) inside the test cell in the beam direction for a 20x20 cm beam cross sectional area. The cases presented in this figure are the neutron flux distribution along the center line of the beam and at 9 cm from the center of the beam on the y-axis. The point $x=0$ corresponds to the beginning of the test assembly. Negative values for x refer to the lithium jet and the jet backing plate. As indicated, the total neutron flux with material inside the test cell is higher than the uncollided neutron flux throughout the 30 cm depth of the cell (for this particular geometric and material model). Figure 2 presents the same information as Figure 1 for neutron energies below 1 MeV. It can be seen that the neutron flux, for neutron energies below 1 MeV with material inside the test cell, is much higher, mainly at positions far inside the test cell, than the correspondent uncollided neutron flux. When material is present inside the test cell, the neutron flux below 1 MeV is attenuated by roughly only a factor of 2 (from 0 cm to 30 cm in the direction of the beam) compared with a factor of roughly 30 for the uncollided flux. At 30 cm depth inside the test cell, for this particular material and geometric configuration, the neutron flux for energies below 1 MeV is the major component of the total neutron flux.

2. NUCLEAR RESPONSES ON THE BACKPLATE AND INSIDE THE TEST CELL

During this work several nuclear responses were analyzed for both, the backplate and inside the test cell. Responses as nuclear heating, DPA rate, and production of helium, protium, deuterium, and tritium were analyzed. These nuclear responses are a function of the neutron flux and materials but are also dependent on the neutron energy spectra which change from location to location inside the test cell. The use of SS-316 inside the test assembly volume provides, if not an exact answer, at least a general idea of the kind of responses that one would expect from the neutron irradiation facility.

2.1 Nuclear Responses at the Backplate

The main reasons to place a plate backing the lithium jet is to improve the stability of the lithium jet, and to establish a vacuum boundary for the beam accelerator vacuum. There are arguments about the advantages and disadvantages of having a backplate. The analysis of the merits of those arguments is beyond the scope of this work, but if a backplate is used, concerns about its lifetime must be addressed.

The radiation field will be at a maximum on the backplate as will DPA and gas production rates. Since it is highly desirable to have an irradiation facility with the highest duty factor possible, analysis of the radiation damage to the backplate is needed to estimate the frequency of the backplate replacement.

Figure 3 presents a plot of the DPA rate in a SS-316 backplate as a function of the beam spot area for 35 and 40 MeV deuteron beams, with 250 mA current. It can be seen that displacement rates can be as high as 950 DPA/yr (for 3x1 cm² beam spot area with 40 MeV deuterons) or as low as 15 DPA/yr (for the 20x20 cm² beam spot area with 35 MeV deuterons). It is clear that the stainless steel would not last long under a DPA rate of 950 DPA/yr (an average DPA rate, among fusion reactor designs, for stainless steel at the first wall is about 10 DPA/yr). On the other hand, a maximum DPA rate of 15 DPA/yr may not be enough to perform accelerated material testing. Figure 4 presents similar results but for helium-4 production in the backplate. Similar comments to those for Figure 3 can be made for this figure. Figure 5 shows the nuclear heating due to neutrons and gamma-rays on the backplate as a function of the beam spot area. This figure shows that a nuclear heating deposition as high as 400 Watts/cm³ and 220 Watts/cm³ for a 40 MeV and 35 MeV deuteron beams, respectively, can be expected using a 3x1 cm² beam cross sectional area. For a 20x20 cm² beam size only 10 Watts/cm³ and 7.5 Watts/cm³, respectively, would be deposited.

2.2 Nuclear Responses Inside the Test Cell

Nuclear responses have a distribution similar but not identical to the neutron flux. Analysis of distribution of responses as DPA, helium production, nuclear heating, and others, is more useful than analysis of the neutron flux distribution. As an example, the DPA gradient inside the test cell is as or more meaningful than the neutron flux gradient.

Figure 6 displays the SS-316 DPA profile along the beam axis for six different beam cross sectional areas ($3 \times 1 \text{ cm}^2$, $12.5 \times 2 \text{ cm}^2$, $7 \times 7 \text{ cm}^2$, $17 \times 3 \text{ cm}^2$, $10 \times 10 \text{ cm}^2$, and $20 \times 20 \text{ cm}^2$). The values plotted in this figure refer to the calculations with material (SS-316) inside the test assembly volume. As can be observed, the highest gradient of the DPA rate is for the $3 \times 1 \text{ cm}^2$ beam size which exhibits an average slope of 36% per centimeter in the first 10 cm of the test assembly region. The $10 \times 10 \text{ cm}^2$ and $20 \times 20 \text{ cm}^2$ beams present a much more modest average slope for the first 10 cm with only 17% and 12% per centimeter, respectively. Figure 7 displays the DPA gradient in the direction perpendicular to both, beam and jet flow directions for the same beam cross sectional areas as Figure 6 and computed at the position $x=0$, which corresponds to the beginning of the test assembly region. The $3 \times 1 \text{ cm}^2$ beam has a very sharp distribution which results in a very high gradient (84% per centimeter in a 15 cm span) in this direction. The $10 \times 10 \text{ cm}^2$ and $20 \times 20 \text{ cm}^2$ beams present an essentially flat profile in this direction over the 10 cm² and 20 cm² span of the beams, respectively. Because a single material sample will be exposed during irradiation to both gradients (parallel and perpendicular to the beam) it is important to have the minimum gradient in both directions. This is successfully accomplished by using beams of large cross sectional areas.

Another critical parameter that must be considered when performing irradiation for materials testing is the helium to DPA ratio (ratio of the helium production in atoms part per million per unit time to the number of displacements per atom per unit time.) In fusion reactors, at the first wall, this ratio is about 10 to 15 for SS-316. In fission reactors, this ratio is much smaller and, as a result, material responses to irradiation such as ductility, swelling, and other properties, may not be the same as in a fusion reactor. Figure 8 and 9 show the helium to DPA ratio (for SS-316) profile along the beam direction and perpendicular to the beam direction, respectively, for a $10 \times 10 \text{ cm}^2$ beam with 35 MeV deuterons and 250 mA of current. The value for the helium to DPA ratio does not vary too much inside the volume analyzed (what is good for irradiation purposes), having a maximum value of roughly 12.5 and a minimum about 5. Along the direction perpendicular to the beam, the helium to DPA ratio is maintained almost constant over a 20 cm span.

2.3 Nuclear Responses for Several Materials

The behavior, under irradiation, of each element may differ considerably for different neutron energy spectra. In this section different materials are considered and their nuclear responses under D-Li and ITER (lithium as coolant) neutron energy spectra are evaluated and compared. The four materials analyzed are: 1) stainless steel (65.5% Fe, 19.% Cr, 14.5% Ni, and 1% Si); 2) vanadium; 3) niobium; and 4) iron.

Table 1 presents the calculated value for DPA per year using the neutron energy spectrum from a 35 MeV, 250 mA deuteron beam with six different cross sectional areas at several positions inside the test assembly region and an ITER first wall neutron energy spectrum (for a design using lithium as a coolant and 1.6 GW of fusion power). In all cases one full power year of irradiation is assumed. Table 2 presents results for helium production using the same irradiation scenarios as Table 1. Table 3 presents similar DPA results as Table 1 for a 40 MeV deuteron beam. Table 4 shows helium production results for a 40 MeV deuteron beam. As can be noticed from these results, (from Table 1 to 4) the beam cross sectional area has a much stronger impact on the maximum value of the nuclear response than on the value of the response a few centimeters inside the test assembly region. Thus, nuclear responses have about the same order of magnitude after several centimeters inside the test assembly region, independently of the beam cross sectional area. This allows one to choose DPA and helium production profile to suit requirements for backplate lifetime and nuclear responses gradient within a sample.

Tables 5 and 6 present results for helium production (appm/year) to DPA (dpa/year) ratio for 35 MeV and 40 MeV deuteron beams, respectively. These results show that the helium to DPA ratio is weakly dependent on the beam cross sectional area and that differences up to 15% can be expected when the beam cross sectional area varies from 3 cm² to 100 or 400 cm². Also, it can be seen that helium to DPA ratio is weakly dependent on the deuteron energy, despite each particular response being strongly dependent on the deuteron energy. Comparing with the ITER first wall helium to DPA ratio for the different materials used in this analysis, one can say that helium to DPA ratios, similar to those expected in a fusion reactor, are easily obtainable with a D-Li neutron source.

3. VOLUME WITH NUCLEAR RESPONSES ABOVE A SPECIFIED THRESHOLD

The available volume with nuclear response above a specified threshold is a vital parameter that defines the performance of an irradiation facility. To evaluate the volume provided to the experimenter with nuclear responses above a threshold value, it is important to perform calculations with material inside the test assembly area. The most reliable quantity to describe

similarities or differences among irradiation facilities is the DPA rate, which is a measure of the damage suffered by the material and incorporates the information about the intensity of the radiation field as well as of the neutron energy spectrum.

Table 1. DPA rate per year for stainless steel, vanadium, niobium, and iron under D-Li neutron energy spectrum at different positions inside the test cell for a 35 MeV, 250 mA deuteron beam compared with the ITER first-wall DPA rate.

Material/ Beam Cross Section Area	DPA (dpa/year) Position Inside the Test Assembly Region					ITER
	(-.16,0,0)	(0,0,0)	(1,0,0)	(5,0,0)	(10,0,0)	1st-Wall
SS-316						
3x1 cm	535.	472.	256.	66.	24.	--
12.5x2 cm	119.	107.	73.	26.	12.	--
7x7 cm	89.	82.	62.	26.	12.	--
17x3 cm	72.	65.	47.	20.	9.	--
10x10 cm	50.	46.	36.	18.	10.	--
20x20 cm	16.	14.	12.	8.	5.	--
ITER	--	--	--	--	--	17.
Vanadium						
3x1 cm	534.	470.	252.	65.	24.	--
12.5x2 cm	120.	107.	73.	27.	12.	--
7x7 cm	91.	83.	62.	26.	12.	--
17x3 cm	74.	66.	47.	20.	9.	--
10x10 cm	51.	47.	36.	18.	10.	--
20x20 cm	16.	14.	13.	8.	5.	--
ITER	--	--	--	--	--	17.
Niobium						
3x1 cm	504.	446.	246.	64.	24.	--
12.5x2 cm	111.	100.	69.	25.	12.	--
7x7 cm	83.	76.	58.	25.	12.	--
17x3 cm	67.	61.	44.	19.	9.	--
10x10 cm	46.	42.	33.	17.	9.	--
20x20 cm	15.	13.	11.	7.	4.	--
ITER	--	--	--	--	--	16.
Iron						
3x1 cm	528.	465.	253.	65.	24.	--
12.5x2 cm	117.	105.	72.	26.	12.	--
7x7 cm	88.	80.	61.	26.	12.	--
17x3 cm	71.	64.	46.	20.	9.	--
10x10 cm	49.	44.	35.	17.	9.	--
20x20 cm	15.	14.	12.	7.	5.	--
ITER	--	--	--	--	--	17.

Table 2. Helium production for stainless steel, vanadium, niobium, and iron under D-Li neutron energy spectrum at different positions inside the test cell for a 35 MeV, 250 mA deuteron beam compared with the ITER first-wall helium production.

Material/ Beam Cross Section Area	Helium Production (appm/year) Position Inside the Test Assembly Region					ITER
	(-16,0,0)	(0,0,0)	(1,0,0)	(5,0,0)	(10,0,0)	1st-Wall
SS-316						
3x1 cm	7414.	6657.	3966.	1072.	404.	--
12.5x2 cm	1508.	1395.	1010.	383.	187.	--
7x7 cm	1047.	992.	802.	389.	183.	--
17x3 cm	866.	800.	624.	275.	134.	--
10x10 cm	560.	532.	440.	245.	139.	--
20x20 cm	169.	152.	134.	88.	56.	--
ITER	--	--	--	--	--	240.
Vanadium						
3x1 cm	2262.	2045.	1280.	346.	127.	--
12.5x2 cm	441.	411.	313.	123.	65.	--
7x7 cm	306.	289.	238.	133.	62.	--
17x3 cm	245.	231.	188.	91.	48.	--
10x10 cm	156.	152.	129.	80.	47.	--
20x20 cm	46.	42.	38.	26.	18.	--
ITER	--	--	--	--	--	54.
Niobium						
3x1 cm	885.	797.	482.	134.	52.	--
12.5x2 cm	179.	166.	121.	47.	23.	--
7x7 cm	122.	116.	96.	46.	22.	--
17x3 cm	102.	94.	74.	33.	16.	--
10x10 cm	65.	62.	52.	29.	17.	--
20x20 cm	20.	18.	16.	10.	7.	--
ITER	--	--	--	--	--	38.
Iron						
3x1 cm	4834.	4347.	2624.	555.	24.	--
12.5x2 cm	974.	903.	661.	26.	12.	--
7x7 cm	670.	637.	520.	26.	12.	--
17x3 cm	555.	514.	406.	20.	9.	--
10x10 cm	356.	340.	284.	17.	9.	--
20x20 cm	107.	97.	86.	7.	5.	--
ITER	--	--	--	--	--	170.

Table 3. DPA rate per year for stainless steel, vanadium, niobium, and iron under D-Li neutron energy spectrum at different positions inside the test cell for a 40 MeV, 250 mA deuteron beam compared with the ITER first-wall DPA rate.

Material/ Beam Cross Section Area	DPA rate (dpa/year)					ITER
	Position Inside the Test Assembly Region					
	(-16,0,0)	(0,0,0)	(1,0,0)	(5,0,0)	(10,0,0)	1st-Wall
SS-316						
3x1 cm	966.	788.	399.	100.	36.	--
12.5x2 cm	192.	163.	105.	38.	18.	--
7x7 cm	135.	118.	86.	38.	18.	--
17x3 cm	111.	94.	67.	27.	13.	--
10x10 cm	74.	65.	50.	25.	14.	--
20x20 cm	22.	20.	16.	10.	7.	--
ITER	--	--	--	--	--	17.
Vanadium						
3x1 cm	977.	789.	394.	98.	35.	--
12.5x2 cm	195.	164.	105.	38.	18.	--
7x7 cm	138.	120.	87.	38.	18.	--
17x3 cm	113.	95.	67.	27.	13.	--
10x10 cm	76.	66.	51.	25.	14.	--
20x20 cm	23.	20.	16.	10.	7.	--
ITER	--	--	--	--	--	17.
Niobium						
3x1 cm	909.	749.	388.	99.	35.	--
12.5x2 cm	180.	154.	100.	37.	18.	--
7x7 cm	126.	110.	82.	37.	17.	--
17x3 cm	103.	88.	64.	26.	13.	--
10x10 cm	68.	60.	47.	24.	13.	--
20x20 cm	20.	18.	15.	9.	6.	--
ITER	--	--	--	--	--	16.
Iron						
3x1 cm	952.	777.	395.	99.	35.	--
12.5x2 cm	189.	160.	104.	38.	18.	--
7x7 cm	133.	116.	85.	38.	18.	--
17x3 cm	109.	93.	66.	27.	13.	--
10x10 cm	73.	63.	49.	25.	13.	--
20x20 cm	22.	19.	15.	10.	6.	--
ITER	--	--	--	--	--	17.

Table 4. Helium production for stainless steel, vanadium, niobium, and iron under D-Li neutron energy spectrum at different positions inside the test cell for a 40 MeV, 250 mA deuteron beam compared with the ITER first-wall helium production.

Material/ Beam Cross Section Area	Helium Production (appm/year) Position Inside the Test Assembly Region					ITER
	(-.16,0,0)	(0,0,0)	(1,0,0)	(5,0,0)	(10,0,0)	1st-Wall
SS-316						
3x1 cm	12640.	11165.	6444.	1757.	638.	--
12.5x2 cm	2394.	2170.	1560.	600.	300.	--
7x7 cm	1603.	1491.	1186.	598.	281.	--
17x3 cm	1361.	1212.	946.	415.	204.	--
10x10 cm	860.	800.	648.	369.	210.	--
20x20 cm	250.	231.	190.	125.	84.	--
ITER	--	--	--	--	--	240.
Vanadium						
3x1 cm	4096.	3714.	2291.	639.	228.	--
12.5x2 cm	750.	697.	533.	218.	116.	--
7x7 cm	497.	473.	390.	223.	106.	--
17x3 cm	423.	387.	321.	152.	79.	--
10x10 cm	261.	251.	210.	131.	80.	--
20x20 cm	74.	70.	60.	42.	30.	--
ITER	--	--	--	--	--	54.
Niobium						
3x1 cm	1491.	1322.	776.	216.	81.	--
12.5x2 cm	281.	256.	186.	72.	36.	--
7x7 cm	186.	175.	141.	71.	34.	--
17x3 cm	158.	142.	112.	50.	24.	--
10x10 cm	100.	94.	76.	44.	25.	--
20x20 cm	29.	27.	22.	15.	10.	--
ITER	--	--	--	--	--	38.
Iron						
3x1 cm	8238.	7325.	4294.	1184.	432.	--
12.5x2 cm	1550.	1414.	1030.	400.	201.	--
7x7 cm	1032.	967.	777.	400.	188.	--
17x3 cm	877.	787.	622.	277.	137.	--
10x10 cm	552.	518.	422.	245.	141.	--
20x20 cm	159.	149.	123.	82.	55.	--
ITER	--	--	--	--	--	170.

Table 5. Helium production (appm/yr) to DPA rate (dpa/yr) ratio for stainless steel, vanadium, niobium, and iron under D-Li neutron energy spectrum at different positions inside the test cell for a 35 MeV, 250 mA deuteron beam compared with the ITER first-wall helium to DPA ratio.

Material/ Beam Cross Section Area	Helium to DPA ratio (appm/dpa) Position Inside the Test Assembly Region				ITER
	(-.16,0,0)	(1,0,0)	(5,0,0)	(10,0,0)	1st-Wall
SS-316					
3x1 cm	13.8	15.5	16.3	16.7	--
12.5x2 cm	12.7	13.9	14.5	15.3	--
7x7 cm	11.7	13.0	14.7	14.9	--
17x3 cm	12.0	13.3	13.8	14.7	--
10x10 cm	11.2	12.4	13.8	14.4	--
20x20 cm	10.8	11.0	11.7	12.3	--
ITER	--	--	--	--	14.
Vanadium					
3x1 cm	4.2	5.1	5.4	5.4	--
12.5x2 cm	3.7	4.3	4.6	5.3	--
7x7 cm	3.4	3.8	5.0	5.0	--
17x3 cm	3.3	4.0	4.5	5.2	--
10x10 cm	3.1	3.6	4.5	4.8	--
20x20 cm	2.8	3.0	3.3	3.9	--
ITER	--	--	--	--	3.2
Niobium					
3x1 cm	1.8	2.0	2.1	2.2	--
12.5x2 cm	1.6	1.8	1.9	1.9	--
7x7 cm	1.5	1.7	1.8	1.9	--
17x3 cm	1.5	1.7	1.8	1.9	--
10x10 cm	1.4	1.6	1.7	1.8	--
20x20 cm	1.4	1.4	1.5	1.6	--
ITER	--	--	--	--	2.4
Iron					
3x1 cm	9.2	10.4	11.0	11.3	--
12.5x2 cm	8.3	9.2	9.7	10.4	--
7x7 cm	7.6	8.5	9.9	10.0	--
17x3 cm	7.8	8.8	9.3	10.0	--
10x10 cm	7.3	8.1	9.2	9.7	--
20x20 cm	7.0	7.2	7.7	8.2	--
ITER	--	--	--	--	10.

Table 6. Helium production (appm/year) to DPA rate (dpa/year) ratio for stainless steel, vanadium, niobium, and iron under D-Li neutron energy spectrum at different positions inside the test cell for a 40 MeV, 250 mA deuteron beam compared with the ITER first-wall helium to DPA ratio.

Material/ Beam Cross Section Area	Helium to DPA ratio (appm/dpa) Position Inside the Test Assembly Region				ITER
	(-16,0,0)	(1,0,0)	(5,0,0)	(10,0,0)	1st-Wall
<u>SS-316</u>					
3x1 cm	13.0	16.2	17.6	18.0	--
12.5x2 cm	12.5	14.8	15.7	16.5	--
7x7 cm	11.9	13.8	16.0	16.1	--
17x3 cm	12.3	14.2	15.2	15.5	--
10x10 cm	11.6	13.0	14.6	15.3	--
20x20 cm	11.3	12.1	12.6	12.9	--
ITER	--	--	--	--	14.1
<u>Vanadium</u>					
3x1 cm	4.2	5.8	6.5	6.6	--
12.5x2 cm	3.9	5.1	5.7	6.4	--
7x7 cm	3.6	4.5	5.8	5.9	--
17x3 cm	3.8	4.8	5.5	6.0	--
10x10 cm	3.5	4.2	5.2	5.8	--
20x20 cm	3.3	3.7	4.1	4.5	--
ITER	--	--	--	--	3.2
<u>Niobium</u>					
3x1 cm	1.6	2.0	2.2	2.3	--
12.5x2 cm	1.6	1.8	2.0	2.0	--
7x7 cm	1.5	1.7	1.9	1.9	--
17x3 cm	1.5	1.8	1.9	1.9	--
10x10 cm	1.5	1.6	1.8	1.9	--
20x20 cm	1.4	1.5	1.6	1.6	--
ITER	--	--	--	--	2.4
<u>Iron</u>					
3x1 cm	8.7	10.9	12.0	12.2	--
12.5x2 cm	8.2	9.9	10.6	11.2	--
7x7 cm	7.8	9.2	10.6	10.7	--
17x3 cm	8.0	9.4	10.3	10.5	--
10x10 cm	7.6	8.6	9.8	10.4	--
20x20 cm	7.3	8.0	8.4	8.7	--
ITER	--	--	--	--	10.

When irradiating materials for testing purposes, it is crucial to have not only a similar number of neutrons, or DPA rate, or helium production alone, but similar value of DPA with about the same ratio of helium production to DPA, similar transmutation rates (which is not addressed in this report) and temperatures of interest for the fusion application. The D-Li neutron source does not produce exactly the same spectrum as a "fusion reactor spectrum" but it does result in a very similar helium to DPA ratio. Because the temperature in an experiment can be controlled, the D-Li neutron source is indeed a good option for a material testing irradiation facility. The question that arises at this point is related to the available volume for material tests. Doran [2] estimates that a volume of 1 liter with DPA rate above 20 DPA/year would be enough to perform all required material testing for ITER and Demo designs. Figures 10 and 11 display the available volume above a DPA threshold value as a function of the DPA threshold value for beams with deuterons of 35 MeV and 40 MeV, respectively. The beam current is 250 mA and six different cross sectional areas are analyzed. It can be seen that none of the cases presented in these figures meets the requirement of one liter with DPA rate above 20 DPA/year. With a beam current of 250 mA it is possible to get about 300 cm³ of volume above 20 dpa for a 35 MeV deuteron energy and about 500 cm³ for a 40 MeV deuteron energy. The cases presented are for a single beam configuration and are not far from the target value of 1 liter. Improved configurations, such as the curved target and two-beams at an angle on the same target may result in increased volumes and are the subject of further analyses [3].

4. GAMMA-RAY FLUX DISTRIBUTION INSIDE THE TEST CELL

The gamma-ray production and transport is significant mainly for heating deposition in the sample and structural materials. The presence of material inside the test cell will trigger a considerable gamma-ray production due to the interaction of the neutrons with samples, structural materials, and coolant. Since the gamma production is heavily dependent on the material present inside the test assembly and on the neutron energy spectrum below 1 MeV, the numbers presented here should be taken as a preliminary estimate, because the material composition of the test assembly may differ considerably from the one used here and the neutron flux spectrum between 0 and 1 MeV is not well defined at the source. Also, the gamma-ray production due to the interaction of the deuteron beam with the lithium jet is not included. This gamma-ray source is estimated to be of the same order of magnitude as the one included in this study. Figure 12 presents results for the gamma-ray flux distribution along the axis of a 250 mA, 35 MeV deuteron beam for six different deuteron beam cross-sectional areas. Figure 13 presents similar results for 40 MeV beams. Figures 14 and 15 display the gamma-ray flux distribution perpendicular to the beam (at the backplate) for the same cases as Figures 12 and 13. Figure 16 presents results for the nuclear heating distribution on the backplate due to gamma-rays.

5. TRITIUM PRODUCTION IN THE LITHIUM JET

The tritium production in the lithium jet is due mainly to two major mechanisms. The first is the interaction of deuterons and protons with the lithium atoms, reactions which have several branches with tritium production [4]. The second mechanism is the neutron interaction with the lithium. The former mechanism is mainly important if a substantial amount of lithium-6 is present in the lithium jet (above a few percent of atoms). The tritium production from the D-Li reaction can be estimated assuming that the tritium yield from this reaction is 0.03 [5]. The tritium production from the neutron interaction with lithium can be easily estimated by any transport code. A problem arises from the fact that the cross section for generating neutrons is given in a neutron group structure that has just one energy group between zero and 1 MeV. Since the lithium-6 neutron cross section for tritium production is very much energy dependent in the interval 0 to 1 MeV, only a first order estimation for the tritium production can be performed.

The tritium production from the D-Li reaction was calculated to be approximately 7.5 grams per year (using a 0.03 yield value and 250 mA deuteron current). The tritium production from neutron reaction with lithium, considering natural lithium (7.5% Li-6) was estimated at 6 grams per year. If depleted lithium is used (less than 1% abundance of lithium-6), the former value is reduced almost directly by the ratio of the actual abundance of lithium-6 to the natural abundance. Based on this, it is recommended to use depleted lithium in the jet to reduce as much as possible the tritium production.

6. CONCLUSIONS

It has been shown that a D-Li neutron source has significant potential to be seriously considered for an irradiation facility. The potential flexibility of being able to produce different levels of nuclear responses through the reduction or enlargement of the beam cross sectional area is an important advantage of the D-Li source compared with other neutron source candidates.

The neutron energy spectrum, a subject that was raised as an issue for the D-Li neutron source, has been shown to produce nuclear responses similar to those expected at a fusion reactor. The neutron yield of the D-Li reaction is quite high compared with other nuclear reactions and the accelerator and target technology has been, to some extent, previously developed for the FMIT facility. The conceptual simplicity, well demonstrated technological basis, neutron induced nuclear responses similar to a fusion reactor, and easy accessibility to the test volume make the D-Li neutron source well suited as a fusion material testing irradiation facility.

Figure 1 Comparison of the total neutron flux with and without material inside the test assembly volume for a 20x20 cm² beam with a current of 250 mA and a deuteron energy of 35 MeV.

Figure 2 Comparison of the neutron flux distribution with and without material inside the test assembly for neutron energies below 1 MeV for a 20x20 cm² beam with 250 mA of current and 35 MeV deuteron energy.

Figure 3 DPA rate at the backplate as a function of the beam cross sectional area for 35 MeV and 40 MeV deuterons with a beam current of 250 mA.

Figure 4 Helium-4 production rate at the backplate as a function of the beam cross sectional area for 35 and 40 MeV deuteron beams with 250 mA of current.

Figure 5 Nuclear heating due to neutrons and gamma-rays at the backplate as a function of the beam cross sectional area for a 35 and 40 MeV deuteron beams with 250 mA of current.

Figure 6 SS 316 DPA rate profile along the beam direction for four different beam cross sectional areas with 250 mA of current and 35 MeV deuteron energy.

Figure 7 SS 316 DPA profile in the direction perpendicular to the beam and to the jet for four beam cross sectional areas with 250 mA of current and 35 MeV deuterons.

Figure 8 Helium production (appm/yr) to DPA rate (dpa/yr) ratio. Profile along the beam direction for a 250 mA, 35 MeV, 10 x 10 cm² deuteron beam.

Figure 9 Helium production (appm/yr) to DPA rate (DPA/yr) ratio. Profile perpendicular to the beam and to the Jet for a 250 mA, 35 MeV, 10 x 10 cm² deuteron beam.

Figure 10 Volume above a threshold valve as a function of the threshold valve for 6 beams spot areas. Considering beams with 35 MeV deuterons and 250 mA of current.

Figure 11 Volume above a threshold valve as a function of the threshold valve for 6 beam spot areas, considering beams with 40 MeV deuterons and 250 mA of current.

Figure 12 Gamma-ray flux distribution in the beam direction for 6 different beam cross sectional areas for a 250 mA, 35 MeV deuteron beam.

Figure 13 Gamma-ray flux distribution in the beam direction for 6 different beam cross sectional areas for a 250 mA and 40 MeV deuteron beam.

Figure 14 Gamma-ray flux distribution in the direction perpendicular to the beam for 6 different beam cross sectional areas for a 250 mA, 35 MeV deuteron beam.

Figure 15 Gamma-ray flux distribution in the direction perpendicular to the beam for 6 different beam cross sectional areas for a 250 mA and 40 MeV deuteron beam.

Figure 16 Nuclear heating due to gamma-rays on the backplate for 6 different beam cross sectional areas for 250 mA beams with 35 and 40 MeV deuteron energy.

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