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NEUTRON ENVIRONMENT IN $d + Li$ FACILITIES

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ABSTRACT

A microscopic d + Li neutron yield model has been developed based upon classical models and experimental data. Using equations suggested by the Serber and evaporation models, a generalized least squares adjustment procedure generated angular yields for E_d to 40 MeV using the available experimental data. The HEDL-UCD experiment at $E_d=35$ was used to adjust parameters describing the neutron spectra. The model is used to predict yields, spectra, and damage responses in the FMIT Test Cell.

I. INTRODUCTION

With the continuing progress toward breakeven fusion facilities, more thought is being directed toward the materials that will be used in power-producing fusion reactors. Unfortunately, there presently does not exist any facility capable of producing very large peak fluxes ($>10^{15}$ n/cm²-s) of high energy neutrons (~ 14 MeV) or of large fluxes ($>10^{14}$ n/cm²-s) of high energy neutrons over large volumes (500 cm³). Because of the severe limitation of producing dense targets of deuterium or tritium, the RTNS (Rotating Target Neutron Source) or any other d+t source is restricted to much lower fluxes ($\sim 10^{13}$ n/cm²-s) in small volumes (~ 1 cm³).

Such high fluxes are necessary as can be seen from previous material programs. Materials must be tested to end-of-life conditions because material property changes are not only nonlinear with neutron dose, but also can be nonmonotonic. Thus, displacements of 75 to 300 dpa (displacements per atom) and helium productions of 500 to 2500 appm (atomic parts per million) must be achieved before the first fusion engineering test reactor is constructed. Fission reactors can produce the desired displacements but cannot match the helium production to displacement rate. Ion bombardment is also suspect because of its concentration of damage near the surface.

High fluxes of high energy neutrons can be produced from d+Li reactions. The Fusion Material Irradiation Test Facility (FMIT)[1] now being designed at the Hanford Engineering Development Laboratory for the U.S. Department of Energy will produce high energy neutrons with sufficient fluxes in large volumes. This paper describes, using relatively simple yet accurate models, the neutron environment (including expected displacement and helium production rates) of such d+Li facilities [2,3] with particular attention to the nominal operating parameters of FMIT. The effects of changing various FMIT design parameters will also be described as well as the perturbing effects of samples. A preliminary report has been published elsewhere [4].

II. BACKGROUND

FMIT will have 35 MeV deuterons striking a flowing liquid lithium target 1.9 cm thick. In order to reduce heating problems in the lithium jet, the beam will be disbursed with present designs being Gaussian in shape with full widths at half maximum values (FWHM) of 3 cm in width and 1 cm in height. Over 99.9% of the beam will hit the Li jet. A stainless steel backing plate of ~.16 cm will constrain the Li and will separate the target space from the experimental volume in the test cell.

Since the peak fluxes of greater than 10^{15} n/cm²-s will occur within 3 cm of the rear of the backing plate, the source of neutrons cannot be modeled as a point. Persiani [5] has analyzed the neutron environment using the experimental data of Daruga et al., [6] and of Saltmarsh et al., [7] but treating the source as a point. For a more accurate description, the cross sections for producing neutrons are needed as a function of distance into the lithium and of the angle between the incident beam direction and the neutron's path. Since the position within the lithium is related to the deuterons' instantaneous energy (ignoring small straggling effects), the dependence of cross section on position can be converted into a dependence on deuteron energy. In addition, since most material property changes will depend on the energy distribution of the neutrons striking the material, the dependence of the cross section on neutron energy must also be known. Thus, the unperturbed energy dependent neutron flux as a function of neutron energy at a point in the test cell can be found from

$$\frac{d\phi}{dE_n} = \int_0^{E_{d-inc}} dE_d \int \frac{d^2\sigma}{d\Omega dE_n} \frac{I(y,z)}{(dE_d/dx) r^2} dydz \quad (1)$$

where $d^2\sigma/d\Omega dE_n$ is the differential cross section for producing neutrons, E_{d-inc} is the incident deuteron energy, dE_d/dx is the relationship between energy loss and the position parallel to the beam (x), $I(y,z)$ is the deuteron current distribution, and r is the distance between the neutron source point and the point of interest in the test volume. Note that Equation 1 ignores scat-

tering (both neutron and deuteron) within the target as well as neutron scattering outside the target. The equation also ignores the slight loss of deuteron intensity (less than 5%) as they pass through the lithium due to nuclear reactions and the extremely slight divergence of the deuteron beam.

III. NEUTRON SOURCE TERM

a. Introduction

All the quantities in Equation 1, except the differential cross sections, are known from geometry, target design, or well established physics. Unfortunately, there is not enough experimental data to determine these cross sections. Instead, models tested against experiment must be used.

The d+Li interaction can be modeled in four ways, stripping of the deuteron's proton, formation of a compound nucleus followed by the evaporation of neutrons, the breaking up of the deuteron by the long range Coulomb potential, and the interaction of the deuteron with only one of the neutrons in the lithium nucleus. Fortunately, because of the low atomic number of lithium and the relatively low deuteron energies used in FMIT, the latter two processes are relatively unimportant.[8] However, over 40 reactions are possible for the deuteron energies of interest, thus requiring a simplified approach. The approach taken here is to use two semi-classical models, the Serber stripping model and the evaporation model, and adjust their parameters to obtain agreement with experiment.

b. Angular Yields

Although for most applications the energy dependent neutron flux is needed, there are several important applications where only the energy integrated flux (or angular yield) is needed, such as total neutron yield either of the source as a whole or at points in the FMIT Test Cell. Also it is easier to incorporate experimental data into angular yield models since these are the quantities experimenters normally report.

Using the least squares adjustment computer code FERRET [9] the energy dependence of 5 angular functions forming the angular yields were determined using all the experimental data for deuterons on lithium with $14 < E_d < 45$ MeV. A major problem in using experimental data is that the data do not span all neutron energies; rather only neutrons above some threshold energy are observed. Therefore, using a preliminary version of the model and the energy dependence from the very low energy measurement of the HEDL-UCD (threshold = .4 MeV at $E_d = 35$ MeV), all the data were corrected to zero neutron energy.

In addition, in order to compare the experimental data, the

data were put onto a common angle and deuteron energy grid ($\theta = 0, 4, 7, 12, 20, 30, 45, 70, 90^\circ$ and $E_d = 5, 10, 15, 19, 22, 25, 30, 35, \text{ and } 40 \text{ MeV}$). For measurements where no uncertainties were given a normalization uncertainty of 20% and a statistical uncertainty of 10% were used. Other experimental uncertainties were increased by uncertainties because of data modifications to the standard grid. The uncertainties due to the use of a standard grid were unimportant, but the corrections for neutron energy thresholds were important, especially at large angles. The input data is summarized in Table I and Figure 1. The data of Goland, et al, [15] were not used because their inclusion caused a lack of convergence in the adjustment procedure. For the data of Saltmarsh, et al, [7] the time-of-flight data were used instead of the dosimetry corrected data as it is now thought that the correction is wrong. [16]

To explain the neutron yield and spectra from 160 MeV deuteron bombardment of thin targets, Serber [17] in 1947 treated the deuteron as very weakly bound with the energy and angle of the spectator neutron being determined by the average internal motion of the target nucleus. Although slight differences exist depending upon whether the target nucleus is opaque or transparent, these differences are relatively minor. The resulting formula is

$$\left. \frac{d\sigma}{d\Omega} \right|_{\text{Serber}} = \frac{1.}{[1 + (\theta/\theta_s)^2]^{3/2}} \quad (2)$$

where $\theta_s = (5720/E_d)^{1/2}$. However, the theory presupposes that $E_d \gg E_B$, the deuteron binding energy ($\sim 2.2 \text{ MeV}$). Thus it is not surprising that a slightly different formula was more successful in the preliminary model.

$$\left. \frac{d\sigma}{d\Omega} \right|_{\text{Pre}} = \frac{1.}{1 + (\theta/\theta_p)^2} \quad (3)$$

where $\theta_p = (1800/E_d)^{1/2}$. For an isotropic angular distribution in the center of mass system for a given neutron energy, the laboratory angular distribution would be a linear combination of unity and cosine (θ). However, an analysis of the HEDL-UCD data for $E_n = 1 \text{ to } 2 \text{ MeV}$ shows a $1 + \cos^5 \theta$ dependence. Therefore, maximum ($\cos^5 \theta, 0$) was added to form the five angular functions. Functions peaking at $\sim 20^\circ$ and 90° were also tried but their parameters were too uncertain to be meaningful.

So as not to presuppose the deuteron energy dependence of each of the six angular functions, the energy range was broken into 9 groups, 0 - 5 MeV, 5 - 10 MeV, 10 - 15, 15 - 19, 19 - 22, 22 - 25, 25 - 30, 30 - 35, and 35 - 40 MeV. Thus 45 parameters were adjusted by FERRET, which at the same time kept track of the 32 data points. By requiring a smooth variation as a function of deuteron energy, the parameters and their covariance matrix were found.

The most important result of this analysis is the total number of neutrons produced in the $d + Li$ reaction. For example, the volume having flux greater than 10^{15} n/cm²-s for the current FMIT design is 7.6 ± 1.8 cm³, while the volume having an average flux of 10^{15} n/cm² is 21 ± 4 cm³. Figure 2 shows the volume with flux greater than ϕ as a function of ϕ as well as the volume with an average flux of ϕ . Since flux is linearly related to deuteron current, Figure 2 can be used to determine such relations as a function of deuteron current as well. Not only may the deuteron current be different when the FMIT facility begins operation, but other design variables may also change.

c. Neutron Spectra

The determination of the neutron spectra is much more difficult because so much more data are required. Even if experimental neutron spectra were available, the magnitude of the quantity of the data and the need to use non-linear parameters make the use of a code like FERRET unadvisable. Instead, simple models for stripping and for evaporation are used with their parameters being adjusted to fit the HEDL-UCD experiment at $E_d = 35$ MeV.

The model for stripping relies mainly on the Serber model. As noted above, the Serber model pictures the deuteron as weakly bound with the energy and angular dependence of the emerging neutron dependent on the average motion of nucleons in the target nucleus. August, et al, [18] have shown that this model which was developed to explain results using 160 MeV deuterons gives the proper shape of the high energy distribution ($E_n > E_d/2$) at 0° for a thick target for incident deuteron energies of interest at FMIT. The equations used are

$$\frac{d^2\sigma}{d\Omega dE_n} = \frac{d\sigma(E_d, \theta)}{d\Omega} S(E_d, E_n) \quad 0 < E_n < E_d$$

$$\frac{d\sigma}{d\Omega}(E_d, \theta) = a(E_d) \left. \frac{d\sigma}{d\Omega} \right|_{\text{Serber}} + b(E_d) \left. \frac{d\sigma}{d\Omega} \right|_{\text{Pre}}$$

$$a(E_d) = K_1 * \text{Max}(41.4, 24.6 + E_d) * 6.426$$

$$b(E_d) = K_2 * \text{Max}(106., 87 + E_d) * 2.761$$

$$S(E_d, E_n) = Nf(E_n, E_d) \frac{E_d E_B}{[(E_n - E_d/2)^2 + E_B E_d]^{3/2}}$$

$$f(E_n, E_d) = \text{MIN} \left(\frac{E_n^2}{(.35 E_d)^2}, 1 \right)$$

where $d\sigma/d\Omega|_{\text{Serber}}$ is defined in Equation 2, $d\sigma/d\Omega|_{\text{pre}}$ is defined in Equation 3, E_B is the binding energy of the deuteron. The functions $a(E_d)$ and $b(E_d)$ come from smoothing the results from the angular yields analysis and are not part of the Serber model which assumes a cross section independent of deuteron energy. Neither is the function $f(E_n, E_d)$ which ensures that the cross section for zero or negative energy neutrons is zero, not finite as predicted by the Serber model. Remember that the Serber model assumed $E_n > E_B$. The form of f was chosen to match the low energy ($E_n < E_d/2$) part of HEDL-UCD data. The normalization constant N is chosen so that

$$\int_0^{E_d} \frac{S(E_d, E_n)}{f(E_d, E_n)} dE_n = 1$$

For the highest neutron energies ($E_n > E_d$) the Serber model breaks down for $d + \text{Li}$. Here the dominant reaction is the stripping of ${}^7\text{Li}$ to the ground and first excited states of ${}^8\text{Be}$. Because only two states are involved (and both are unbound), the classical picture fails and one must resort to a quantum mechanically treatment or to experiment. The latter choice is taken with a deuteron energy independent microscopic cross section $\sigma(\theta)$ used for each state for $E_d < E_n < E_d + Q(\theta)$.

The evaporation part of the model is also in two parts. The first part is the classical evaporation model [19] which predicts the energy spectrum of the neutrons which are boiled off as the first particle out after a compound nucleus is formed. The second part, a linear term in neutron energy, represents all succeeding evaporations. Thus the formulas that result are

$$\frac{d\sigma}{dE_d d\Omega dE_n} = \frac{d\sigma}{d\Omega}(E_d, \theta) * S(E_d, E_n)$$

$$\frac{d\sigma}{d\Omega}(E_d, \theta) = a(E_d) + b(E_d)\cos\theta + d(E_d)\cos^5\theta$$

$$a(E_d) = K_3 * (282. - E_d) * .875$$

$$b(E_d) = K_4 * (342. + E_d) * .881$$

$$d(E_d) = K_6 * \text{MIN}(125., 105. + E_d) * (.06.191)$$

$$S(E_d, E_n) = \frac{1}{T} \exp(-E_n/T) + f(E_d, E_n)$$

$$T = .55 * E_d^{1/2}$$

$$f(E_d, E_n) = \left[.1 * E_d - 2 * \text{MIN}(E_n, .05 E_d) \right] * .1$$

d. Comparison with Experiment

Figure 3 presents a comparison between the model results (corrected for the experimental neutron detection threshold) and the measurements between 15 and 40 MeV. The calculation passes through the data of Nelson, et al., [11] Daruga, et al., [6] Amols et al., [13] Johnson, et al., [14] and Saltmarsh, et al. [7]. The calculations are lower than the measurements of Lone, et al., [10] and Weaver, et al., [12] but higher than those of Goland et al. It should be noted that the data of Lone, et al., show a very large yield for low energy neutrons ($E < 2$), which is very uncertain due to uncertainties in detection efficiency. If the 2.3 MeV detection threshold of Lone, et al., is used instead of their 0.3 MeV threshold, the C/E's change to .89, .92, .85 respectively. The data of Goland, et al., on the other hand, show a drastic fall off for neutrons below 5 MeV, maybe explaining why the model predicts more neutrons than they observed. Overall, there seems to be little deuteron energy dependence or angular dependence in the differences between the model and the measurements.

The HEDL-UCD experiment is the most detailed and precise experiment for the deuteron energy of FMIT. Figure 4 shows a comparison of the neutron spectrum for the 12° HEDL-UCD measurements using a logarithmic axis. Table I displays a summary of the comparisons for the HEDL-UCD measurements. It should be noted that the 0 - 1 MeV experimental value is assumed to be (1.5 ± 1.5) of the values between 1 and 2 MeV in agreement with the trend of the HEDL-UCD data below 1 MeV. In general, the model accurately describes the measurement.

IV. APPLICATIONS

a. Unperturbed Neutron Spectra

Two different methods are used to determine the unperturbed neutron spectra in the FMIT test cell. The first method which

treats the source volume as a set of discrete sources is very fast and flexible, allowing not only spectra, but also displacement rates, helium production rates, and volumes involving such quantities, to be inexpensively calculated. The other method, based on the Monte Carlo technique [20] allows an easy extension to the calculation of perturbed fluxes. The difference in the calculated unperturbed fluxes by the two methods is less than 1%.

The discrete method uses planes corresponding to equal ΔE_d steps, with surface elements on the planes chosen to have equal beam density. The source is assumed to be concentrated at the midpoint of the surface element. Typically 35 planes ($\Delta E_d = 1\text{MeV}$) planes with 80 surface elements are used to evaluate the integral in Equation 1. Experience has shown that the calculated flux values are not sensitive if the number of source elements in each plane is above 50 but are very sensitive if only one direction in the plane is used. The calculations of volumes having flux greater than a given value are insensitive to the treatment of the vertical (1cm FWHM) direction, while the value of flux at a given point is quite sensitive.

The source for the Monte Carlo method is treated as 6 separate volumes corresponding to $E_d = 0$ to 15MeV, 15MeV to 20MeV, 20 to 25, 25 to 30, 30 to 33, and 33 to 35MeV, whose source strength was calculated using the discrete model. Neutrons are assumed to be born uniformly in the direction parallel to the beam and according to the beam profile in directions perpendicular to the beam. Both plane and point detectors have been used. However, great care must be exercised in the use of planar detectors near the source because of the rapid variation of the flux near the source.

Figure 5 shows the predicted unperturbed spectra for four representative points, the point of the highest flux, a point further along the axis of the deuteron beam, a point on the backing plate which is off-axis, but in the midplane, and finally a point on the backing plate but off midplane. The shapes of the spectra above 15MeV are remarkably similar. Also there is a significant number of neutrons below 10MeV for points near the backing plate resulting from neutrons from wide-angle effects.

b. Damage Parameters

Although much attention is paid to flux, the experimentalists who will use FMIT will be more interested in predicting damage rates, such as displacement and helium production.

Unfortunately, the nuclear data needed for such calculations are in very poor shape. Data is needed past 40MeV, but ENDF/B, [21] the main U.S. nuclear data library, extends only to 20MeV. Therefore, data for isolated materials but not for iron or stainless steel, have been obtained over the desired energy range. To provide an idea of the usefulness of FMIT, damage parameters for Cu, the evaluated material closest to iron, have been used. The displacement cross sections are from ORNL [22] with $E_{\text{damage}} = 30\text{eV}$.

Because the ORNL calculations for helium production do not agree with measured values [23,24] and do not include processes such as $(n,2n\alpha)$, new calculations using the computer code HAUSER*5 [25] were performed.

Since the main reason for the FMIT facility is to expand the damage data base from fission reactors to fusion reactors, the damage response in FMIT should peak around 14MeV. Figures 6 and 7 show the predicted damage rates (displacement and helium productions, respectively) for the four points of Figure 5. As can be seen, there is relatively little response at low energies and that the damage rates do peak in the region of interest.

V. CONCLUSION

The unperturbed neutron spectra, displacement rate, and helium production in the FMIT test cell have been calculated using a source term which agrees well with experimental results. The predicted values show that there exists significant volumes having damage rates greater than that of the first wall of a fusion reactor.

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TABLE I
NEUTRON YIELDS FROM d + Li

Experimenter	As Measured				As Used in Fit		
	E_d	E_{n-min}	θ	Value	E_d	θ	Value ^{e)}
Lone, et al.	14.8	0.3	0	3.1	15	0	3.70 ^{a)}
	18.0	0.3	0	4.9	19	0	5.87 ^{a)}
	23.0	0.3	0	10.3	22	0	9.20 ^{a)}
Nelson, et al.	15.0	1.0	0	2.5	15	0	2.9 ^{a)}
	15.0	1.0	10	2.0	15	12	2.1 ^{a)}
	15.0	1.0	20	1.3	15	20	1.6 ^{a)}
	15.0	1.0	30	.82	15	30	1.02 ^{a)}
	15.0	1.0	45	.58	15	45	.75 ^{a)}
Weaver, et al.	16.0	3.0	3.5	3.6 $\pm$.6	15	4	3.9 ^{b)}
	19.0	3.0	3.5	5.8 $\pm$.9	19	4	7.2 ^{b)}
	19.0	3.0	10	4.3 $\pm$.7	19	12	5.0 ^{b)}
	19.0	3.0	18	2.9 $\pm$.5	19	20	3.7 ^{b)}
	19.0	3.0	25	2.0 $\pm$.3	19	20	3.5 ^{b)}
	19.0	3.0	32	1.5 $\pm$.2	19	30	2.4 ^{b)}
Daruga, et al.	22.0	0.0	0	7.3 $\pm$ 1.2	22	0	7.3 ^{c)}
	22.0	1.8	90	.6 $\pm$.1	22	90	.9 ^{c)}
Amols, et al.	35.0	5.0	0	21 $\pm$ 5	35	0	24.9 ^{a)}
Johnson, et al.	35	1.0	0	23.5 $\pm$ 3.8	35	0	24.5 ^{d)}
	35	1.0	4	21.0 $\pm$ 3.4	35	4	22.0 ^{d)}
	35	1.0	8	16.5 $\pm$ 2.7	35	7	18.5 ^{d)}
	35	1.0	12	12.1 $\pm$ 2.0	35	12	12.9 ^{d)}
	35	1.0	20	7.13 $\pm$ 1.17	35	20	7.80 ^{d)}
	35	1.0	30	5.08 $\pm$.83	35	30	5.70 ^{d)}
	35	1.0	45	3.12 $\pm$.51	35	45	3.61 ^{d)}
	35	1.0	70	1.85 $\pm$.30	35	70	2.22 ^{d)}
Saltmarsh, et al. (TOF data)	40	2.0	0	36.7 $\pm$ 5.5	40	0	39.0 ^{c)}
	40	2.0	7	24.7 $\pm$ 3.7	40	7	26.6 ^{c)}
	40	2.0	15	11.4 $\pm$ 1.7	40	12	15.8 ^{c)}
	40	2.0	30	6.28 $\pm$.9	40	30	7.55 ^{c)}
	40	2.0	45	3.61 $\pm$.5	40	45	4.57 ^{c)}
	40	2.0	60	2.41 $\pm$.4	40	70	2.83 ^{c)}
	40	2.0	90	1.43 $\pm$.22	40	90	2.01 ^{c)}

Yield from 0-1 MeV assumed 1.5 Yield 1-2 MeV

a) Normalization uncertainty = 20%, statistical uncertainty = 10%

b) Normalization uncertainty = 16%, statistical uncertainty = 10%

c) Normalization uncertainty = 15%, statistical uncertainty = 5%

d) Normalization uncertainty = 15%, statistical uncertainty = 6.5%

e) Uncertainties due to corrections are 100% of E_{n-min} correction for $E_n \leq 2.0$ MeV, 50% for $E_n \geq 2.0$ MeV, 10% of E_d and θ correction are added to above uncertainties

TABLE II

Comparison of HEDL-UCD Experiment and Model

Yield^a (10^{16} n/sec-A)

Angle	Exp. ⁶	Model	Ratio	Maximum Deviation ^{b,c}
0	24.3 $\pm$ 1.1	25.6	1.06 $\pm$.05	1.00 $\pm$.03 - 1.08 $\pm$.05
4	20.8 $\pm$ 1.3	22.4	1.08 $\pm$.07	1.00 $\pm$.05 - 1.11 $\pm$.06
12	12.0 $\pm$ 0.8	12.8	1.07 $\pm$.07	1.04 $\pm$.05 - 1.08 $\pm$.06
20	7.13 $\pm$ 0.43	8.07	1.13 $\pm$.07	1.11 $\pm$.06 - 1.20 $\pm$.06
30	5.07 $\pm$ 0.30	5.35	1.05 $\pm$.06	1.01 $\pm$.06 - 1.16 $\pm$.04
45	3.11 $\pm$ 0.19	3.32	1.07 $\pm$.07	1.02 $\pm$.07 - 1.15 $\pm$.04
70	1.85 $\pm$ 0.11	2.10	1.14 $\pm$.07	1.11 $\pm$.03 - 1.18 $\pm$.06
105	1.31 $\pm$ 0.08	1.38	1.06 $\pm$.07	1.04 $\pm$.03 - 1.07 $\pm$.04
150	0.65 $\pm$ 0.04	0.73	1.13 $\pm$.07	1.08 $\pm$.06 - 1.25 $\pm$.12

^aThe yield is for $E_n > 1$ MeV.^bThere is a 15% normalization uncertainty in the experimental data.^cOnly that energy range having Yield (θ) $> .05 \times \text{MAX Yield } (\theta)$ is considered.

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INPUT DATA

Relationship Between Flux and Volume

Comparison between Model and Measurement

Comparison between Model and UCD-HEDL Experiment 12 DEGREES

Predicted Unperturbed Neutron Spectra
E-d=35 MeV, I-d=0.1 A
3 cm $\times$ 1 cm FWHM Gaussian Source

Predicted Displacement Response for Copper
E-d=35 MeV, I-d=0.1 Å
3 cm × 1 cm FWHM Gaussian Source

Predicted Helium Production Response
E-d=35 MeV, I-d=0.1 A
3 cm $\times$ 1 cm FWHM Gaussian Source