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LA-UR -88-3272

LA-UR--88-3272

DE89 000307

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SUBMITTED TO 15th Symposium on Fusion Technology
September 19-23, 1988
Utrecht, The Netherlands

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Two dimensional Cross-Section Sensitivity and Uncertainty Analysis of the LBM Experiments at LOTUS

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In recent years, the LOTUS fusion blanket facility at IGA-EPF in Lausanne provided a series of irradiation experiments with the Lithium Blanket Module (LBM). The LBM has both realistic fusion blanket materials and configuration. It is approximately an 80 cm cube, and the breeding material is Li_2O. Using as the D-T neutron source the Haefely Neutron Generator (HNG) with an intensity of about $5 \cdot 10^{12}$ n/s, a series of experiments with the bare LBM as well as with the LBM preceded by Pb, Be and ThO_2 multipliers were carried out.

In a recent common Los Alamos/PSI effort, a sensitivity and nuclear data uncertainty path for the modular code system AARE (Advanced Analysis for Reactor Engineering) was developed. This path includes the cross section code TRAMIX, the one dimensional finite difference S_N transport code ONEDANT, the two-dimensional finite element S_N transport code TRISM, and the one- and two-dimensional sensitivity and nuclear data uncertainty code SENSIBL.

For the nucleonic transport calculations, three 187 neutron group libraries are presently available: MATXS8A and MATXS8F based on ENDF/B-V evaluations and MAT187 based on JEF/EFF evaluations. COVFILS-2, a 74 group library of neutron cross sections, scattering matrices and covariances, is the data source for SENSIBL; the 74 group structure of COVFILS-2 is a subset of the Los Alamos 187 group structure.

Within the framework of the present work a complete set of forward and adjoint two dimensional TRISM calculations were performed both for the bare, as well as for the Pb- and Be-preceded, LBM using MATXS8 libraries. Then a two dimensional sensitivity and uncertainty analysis for all cases was performed. The goal of this analysis was the determination of the uncertainties of a calculated tritium production per source neutron from lithium along the central Li_2O rod in the LBM. Considered were the contributions from ^{1}H, ^{6}Li, ^{7}Li, ^{9}Be, ^{nat}C, ^{14}N, ^{16}O, ^{23}Na, ^{27}Al, ^{nat}Si, ^{nat}Cr, ^{nat}Fe, ^{nat}Ni, and ^{nat}Pb. The total uncertainties obtained lie between 1.71% and 2.63%. The largest contributors were ^{7}Li (1.15%) and ^{16}O (1.[illegible]5%) for the bare LBM, ^{9}Be (2.21%) for the Be-preceded LBM, and ^{nat}Pb (2.25%) for the Pb-preceded LBM.

1 INTRODUCTION

The Lithium Blanket Module (LBM) was constructed for testing on the toroidal D-T neutron source of the Princeton Tokamak Fusion Test Reactor (TFTR).[1] The LBM has both realistic fusion blanket materials and configuration and has been designed for detailed experimental analysis of tritium breeding and neutron flux spatial/spectral distributions. It is approximately an 80 cm cube, and the breeding material is Li_2O. Li_2O pellets are placed in the leading 60 cm of stainless steel rods (the back 20 cm of each rod is solid stainless steel) which are arranged in a hexagonal array.

Due to a delay in undertaking D-T operation of TFTR, it was decided that the LOTUS facility at the IGA-EPFL in Lausanne (Switzerland) could provide a very valuable resolution of basic technological uncertainties in fusion reactor blanket physics.[2] The LOTUS experiments use the Haefely Neutron Generator (HNG) with a source intensity of $5 \cdot 10^{12}$ n/s; this source has a well defined spatial/spectral distribution with a potential for a highly accurate analysis. Using this source a series of experiments with the bare LBM as well as with the LBM preceded by Pb, Be and ThO_2 multipliers were carried out.

A collaborative Los Alamos/PSI effort is underway to analyze the LOTUS/LBM experiments being performed by EPFL. The goals of the analysis are first, to investigate the accuracy of the most recent nuclear data on the part of the U.S. (ENDF/B, versions V and VI) and the European Community (JEF-1/EFF); and second, the adequacy of the common 1-, 2- and 3-D neutron transport and 1- and 2-D sensitivity and uncertainty methods.[3,4]

The first 2-D cross section sensitivity and uncertainty analysis of the bare LBM presented in reference 3 indicated suprisingly large uncertainties in the calculated tritium production per source neutron from lithium in the central Li_2O rod near the LBM steell reflector. This was caused mainly by ^{7}Li, ^{16}O and ^{nat}Cr. This lead to the assumption that ^{7}Li, ^{16}O and ^{nat}Cr evaluations would need to be improved. Latter, in a further analysis, it was found that the higher uncertainties were caused mainly by incompletely included cancelling effects in the sensitivity profiles, when the COVFILS-2[5,6] covariance data library was used.

In parallel, also within the framework of a collaborative Los Alamos/PSI effort, is the development of a one- and two-dimensional cross section sensitivity and uncertainty path of the AARE modular code system.[7,8] The main effort concentrated on the further development of the cross section sensitivity and uncertainty code SENSIT 2.[9] Additional features were incorporated, such as the capability to calculate complex reactions (such as KERMA, dpa or He production) when the covariance data becomes available, and the reduction of the user's input using the geometry file GEOMTY produced by TRISM, and extensions to consider all contributions to the sensitivity profiles in relation to the covariances from the COVFILS-2 library. A strategy was also developed for the one-dimensional capability. This resulted in the new cross section sensitivity and uncertainty code SENSIBL.[4,10]

The lack of suitable benchmark problems made it difficult to test sensitivity codes with a covariance library. Therefore a benchmark problem for one and two-dimensional sensitivity and uncertainty analysis representative of a fusion reactor blanket, was recently defined and SENSIBL was extensively tested using this benchmark (See reference 11).

As part of the recent effort, a detailed cross-section sensitivity and uncertainty analysis has been performed for experiments using the HNG with the LBM bare and also preceded with lead and beryllium multiplier plates. The work reported here is the cross-section sensitivity and uncertainty analysis performed at Los Alamos using the U.S. nuclear data base. A companion analysis will be performed at PSI using the European Fusion File (EFF)[12] when the cross section covariance file is available.

2 CROSS SECTION DATA LIBRARIES

The transport and reaction cross sections were obtained from libraries in the MATXS8 187 neutron group format.[13] MATXS8A, a library containing 31 isotopes and MATXS8F, containing 21 isotopes, all based on ENDF/B-V evaluations, were used for all materials. Neutron spectra (187-group) were calculated for ten regions of a 3-D model of the LBM using the Monte Carlo code MCNP.[14] The transport and reaction cross section data were collapsed into the 74 neutron group structure of the COVFILS-2[5,6] covariance data library using the calculated neutron spectra. The generation of the collapsed transport libraries from the MATXS libraries was accomplished with the code TRANSX-CTR.[13]

COVFILS-2 is a library of multigroup neutron cross sections, scattering matrices, and covariances (uncertainties and their correlations). The 14 ma terials included in the first version of COVFILS-2 are ^1H, ^6Li, ^7Li, ^9Be, ^{nat}C, ^{14}N, ^{16}O, ^{23}Na, ^{27}Al, ^{nat}Si, ^{nat}Cr, ^{nat}Fe, ^{nat}Ni, and ^{nat}Pb. COVFILS-2 was produced using various modules of the NJOY nuclear data processing system.[15,16] It is largely based on data evaluations from the ENDF/B-V library, although some minor corrections and improvements are incorporated. In cases where the covariance evaluation is missing (as in the case of Be) or judged to be inadequate, private Los Alamos evaluations are employed.[17] The 74-group structure was chosen for compatibility with the extensive, general-purpose MATXS8 187-group library which was produced including scattering reactions for which covariance evaluations are available.

3 CALCULATIONAL METHODS AND HNG/LBM MODEL

Cross-section processing, neutron transport, and the cross-section sensitivity and uncertainty analyses were performed with the cross-section sensitivity and uncertainty path of the modular code system AARE (Advanced Analysis for Reactor Engineering).[7,8] This path includes the cross-section processing code TRAMIX[8] (the code based on TRANSX CTR[13]), the one dimensional finite difference S_N-transport code ONEDANT,[19] the two-dimensional finite element S_N transport code TRISM,[18] and the one- and two dimensional cross section sensitivity and uncertainty code SENSIBL.[10] Neutron transport calculations were performed with TRISM, a computer program for solving the two dimensional neutral particle transport equation in rectangular (x y) and cylindrical (r z) geometries using triangular finite elements within a general domain having curved or other nonorthogonal boundaries. The code SENSIBL was used to perform the cross section sensitivity and uncertainty analyses. The algorithms used are based on first order generalized perturbation theory. SENSIBL is coupled to TRISM and ONEDANT via interface files. The forward and adjoint angular fluxes as well as the geometry from TRISM (or ONEDANT) are transferred as input to SENSIBL on these files.

In the model of the HNG/LBM used for the calculations with TRISM, all of the rectangular geometry of the LBM and HNG was represented by equivalent r-z geometry. The Haefely neutron source was positioned 10 cm from the front of the LBM grill plate (or multiplier plate face) the axis. The HNG has been the model for several studies in both two- and three- dimensions[20,21]; the HNG was modeled for TRISM using 44 bands with as many as 11 material regions per band.

The LBM was subdivided along the axis into 28 bands, one in the grill plate, 22 in the Li_2O breeding zone and 5 in the reflector. In the radial direction the zones are Li_2O, cladding, the cooling channel, one zone with smeared Li_2O and cladding, and one zone with smeared Li_2O, cladding and cooling channels. The plexiglass surrounding the LBM was omitted for simplicity. In the axial direction the zones were subdivided into regions between 0.23 to 30.73 and 30.73 to 60.23 cm for the precalculation of weighting spectra with MCNP The lead and beryllium multiplier plates were modeled as 5- and 6-cm-thick zones, respectively, adjacent to the front of the grill plate.

All TRISM forward and adjoint calculations were performed in the 74-neutron-group structure with a P_3S_8 approximation and converged to within 10^{-3}. The forward source was distributed in the copper region of the Haefely generator using a Gaussian shape on the copper surface representing the target area. A calculated source spectrum[22] was distributed into the appropriate (nine highest) energy groups. The adjoint sources for the five detector regions were specifed as the macroscopic tritium production cross section for lithium in the Li_2O detector volumes. The LBM calculational model is shown schematically in Fig. 1. The zone designations are as follows: 1 and 2, Li_2O; 3 and 4, stainless steel cladding; 5 and 6, homogenized Li_2O and cladding; 7 and 8, homogenized Li_2O, cladding, and void; 9, grill plate stainless steel; 10, reflector steel; 11, reflector steel with void; and 12, void.

A total of 18 TRISM calculations were required, three forward calculations (for the bare LBM and for the lead and beryllium multiplier plates) and 15 adjoint calculations (five detector volumes for each of the LBM multiplier configurations) The

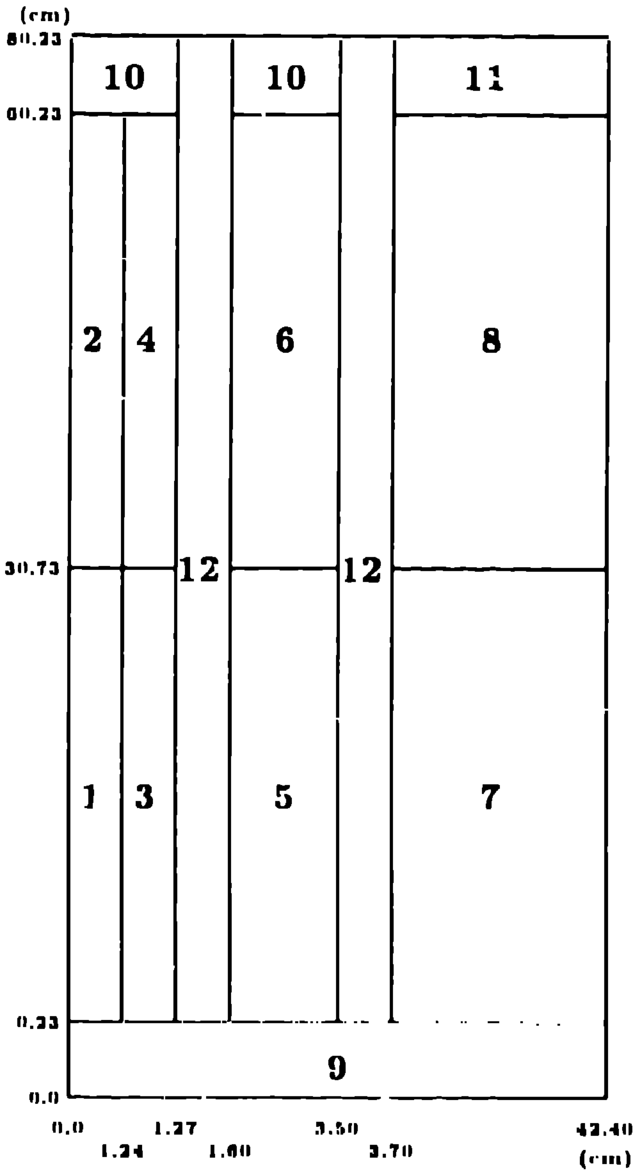

FIGURE 1: Material divisions and detector regions specified in the TRISM geometry model for the LBM.

LBM Detector Volume		Tritium Production per Source Neutron — Multiplier Plate: Bare	Lead	Beryllium
1	T_6	$3.102 \cdot 10^{5}$	$2.515 \cdot 10^{5}$	$4.587 \cdot 10^{5}$
	T_7	$1.660 \cdot 10^{5}$	$8.381 \cdot 10^{6}$	$1.073 \cdot 10^{5}$
2	T_6	$1.070 \cdot 10^{5}$	$1.010 \cdot 10^{5}$	$1.138 \cdot 10^{5}$
	T_7	$6.958 \cdot 10^{6}$	$3.173 \cdot 10^{6}$	$3.145 \cdot 10^{6}$
3	T_6	$7.015 \cdot 10^{6}$	$6.070 \cdot 10^{6}$	$5.782 \cdot 10^{-6}$
	T_7	$2.600 \cdot 10^{6}$	$1.183 \cdot 10^{6}$	$1.119 \cdot 10^{6}$
4	T_6	$3.620 \cdot 10^{-6}$	$2.797 \cdot 10^{6}$	$2.481 \cdot 10^{6}$
	T_7	$7.838 \cdot 10^{7}$	$3.690 \cdot 10^{7}$	$3.398 \cdot 10^{7}$
5	T_6	$1.766 \cdot 10^{6}$	$1.272 \cdot 10^{-6}$	$1.103 \cdot 10^{6}$
	T_7	$2.227 \cdot 10^{-7}$	$1.061 \cdot 10^{7}$	$9.602 \cdot 10^{8}$

TABLE I: Calculated tritium production per source neutron in the five LBM detector volumes for each multiplier configruation.

calculated forward response, the tritium production per source neutron, is given in Table I for each of the LBM detector volumes and multiplier configurations.

4 SENSITIVITY AND UNCERTAINTY CALCULATIONS

The goal of the cross-section sensitivity and uncertainty analysis is to determine the uncertainties of a calculated response function, tritium production per source neutron from lithium. In the analysis reported here, the uncertainties in the calculated tritium production at five different positions along the central Li_2O rod in the LBM (see Fig. 1) were computed using SENSIBL. The detector region mid points are at 1.0, 15.75, 29.0, 44.25, and 58.25 cm along the central rod from the rear of the grill plate. The detector volumes were 2.48 cm diameter cylinders of length 2.0, 2.5, 3.0, 3.5, and 3.5 cm, respectively. For each of five investigated positions mentioned above, an adjoint calculation with TRISM was performed using the macroscopic tritium production cross section as the adjoint source. To check the consistency of the forward and adjoint calculations, a comparison was made between the tritium production per source neutron computed in the forward calcula

LBM Detector Volume	Relative difference between inner products (%)		
	Multiplier Configuration		
	Bare	Lead	Beryllium
1	0.593	0.372	0.302
2	0.341	0.101	0.068
3	0.022	0.050	0.034
4	0.093	0.087	0.073
5	0.070	0.022	0.024

TABLE II: Comparison of the inner products of the forward $< \Phi, R >$ and adjoint $< S, \Phi^* >$ calculations for each LBM detector region and multiplier configuration.

tion for the detector region, $< \Phi, R >$, and the integral over the HNG source region of the product of the forward source and the adjoint flux for that detector, $< S, \Phi^* >$. Perturbation theory predicts that the inner product relationship $< \Phi, R > = < S, \Phi^* >$ should hold. The results of this comparison are given in Table II.

A total of 15 SENSIBL calculations were required for the sensitivity and uncertainty analysis; five for the bare LBM calculations and five each for the lead and beryllium multiplier plate calculations. These calculations required as input the forward (three sets) and adjoint (15 sets) angular fluxes calculated by TRISM. In the calculation for the beryllium multiplier plate, the MAT number 1302 was specified for ^{9}Bel (the "l" denotes the Los Alamos evaluation). There are four MAT numbers for this nuclide on COVFILS 2; 1301, 1302, 1303,and 1304. The covariance data for the (n,2n) reaction is represented as 1, 3, 9, and 27 (all) inelastic "lumps" for these MAT numbers, respectively. The response input was the macroscopic tritium production cross section for natural lithium in Li_2O collapsed from 187 to 71 groups using the weighting spectra calculated for the region in which the detector volume was located and including the appropriate ^{7}Li cross section.

A possible large source of uncertainty in the calculated response is the cross sections for the copper in the HNG. Because this material is not available in COVFILS-2 and since aluminum is not a HNG/LBM material, ^{27}Al was substituted for ^{nat}Cu in the SENSIBL calculations. With some knowledge of the relative covariance data for ^{nat}Cu and ^{27}Al cross sections, an estimate can be made of the contribution to the uncertainty in the calculated response from copper cross sections. The contributions to the uncertainty in the calculated tritium production in the five LBM detector volumes calculated with SENSIBL are given in Table III for all of the materials present which have data in COVFILS-2. Materials used in the calculation which did not have data on COVFILS-2 are ^{10}B, ^{11}B, ^{nat}K, ^{55}Mn, ^{nat}Cu, ^{64}Zn, ^{nat}Zr, and ^{nat}Mo; in all cases except copper, these are trace constituents.

The total uncertainties obtained lie between 1.74% and 2.63%. The largest contributors were ^{7}Li (1.15%) and ^{16}O (1.35%) for the bare LBM; ^{9}Be (2.21%) for the Be-preceded LBM; and ^{nat}Pb (2.25%) for the Pb-preceded LBM.

The larger contributions from ^{7}Li in front of the LBM, where the 14-MeV spectrum occurs, indicates bigger uncertainties in the threshold reactions, such as the inelastic scattering levels and/or in the $(n, n't)$ reaction, in comparison to other "whole-energy-range" reactions. The (n, xn) down-scattering of the source neutrons in lead or beryllium (when the LBM is preceded by lead or beryllium) makes the threshold reactions of ^{7}Li less important and leads to a decrease of the relative standard deviation.

Also, (n, xn) reactions in lead and beryllium show bigger cross section uncertainties than other "whole energy-range" reactions from those two materials. This leads to a larger uncertainty in the ^{7}Li tritium production in front of the LBM, where the first and second collision neutrons are important. Due to the neutron thermalization on the other nuclides in the LBM, the importance of the (n, xn) reactions of lead and beryllium and their contribution to the total relative standard deviation decrease towards the back of LBM.

The contributions from ^{nat}Fe are very small even at the back of LBM where ^{nat}Fe has a high concentration in the stainless-steel reflector. The same can be concluded with respect to ^{nat}Ni. The contributions from ^{nat}Cr are not large, yet still higher when conpared to those from ^{nat}Fe and considering much smaller isotopic densities of ^{nat}Cr as compared to ^{nat}Fe in the stainless-steel reflector.

5 CONCLUSIONS

The obtained uncertainties in the calculated tritium production per source neutron caused by the cross-section uncertainties are acceptable considering the uncertainties still coming from the calculational scheme and from the methods.

The obtained low uncertainties does not imply that there are no systematic errors in the evaluations. Therefore, in a next step, the calculated reaction rates will be compared with the newest measured values in the LOTUS experiments.

Also, a companion analysis will be performed at PSI using the European Fusion File (EFF) when the cross-section covariance file is completed.

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Material	Multiplier	LBM detector volume 1	2	3	4	5
		Relative standard deviation (%)				
^{1}H	Bare	.22	.04	.02	.01	.02
	Lead	.17	.04	.02	.02	.05
	Beryllium	.11	.03	.02	.02	.04
^{6}Li	Bare	.31	.28	.15	.06	.13
	Lead	.47	.26	.09	.08	.18
	Beryllium	.23	.19	.07	.07	.17
^{7}Li	Bare	1.15	1.09	.87	.74	.80
	Lead	.80	.80	.71	.48	.80
	Beryllium	.68	.73	.E5	.47	.89
^{9}Bel	Bare					
	Lead					
	Beryllium	2.21	1.08	.94	.68	.50
^{nat}C	Bare	.07	.03	.02	.01	.01
	Lead	.06	.02	.01	.01	.01
	Beryllium	.04	.01	.01	.02	.02
^{16}O	Bare	.29	.90	1.14	1.30	1.35
	Lead	.32	.65	.75	.88	1.08
	Beryllium	.38	.54	.68	.89	1.12
^{nat}Cu (^{27}Al)	Bare	.87	.27	.18	.13	.13
	Lead	.68	.23	.17	.15	.18
	Beryllium	.59	.16	.15	.19	.22
^{nat}Cr	Bare	.08	.16	.18	.23	1.03
	Lead	.07	.17	.15	.15	.87
	Beryllium	.13	.12	.11	.12	.84
^{nat}Fe	Bare	.85	.35	.31	.30	.55
	Lead	.61	.32	.29	.29	.50
	Beryllium	.53	.25	.25	.32	.59
^{nat}Ni	Bare	.04	.11	.12	.13	.14
	Lead	.05	.08	.09	.10	.11
	Beryllium	.04	.08	.09	.11	.12
^{nat}Pb	Bare					
	Lead	2.25	1.24	.52	.37	.58
	Beryllium					
Total*	Bare	1.74	1.52	1.51	1.55	1.97
	Lead	2.63	1.73	1.27	1.14	1.82
	Beryllium	2.48	1.40	1.32	1.28	1.88

* Totals include contributions from Nitrogen, Natrium and Silicon

TABLE III: Contributions to the Uncertainty in the Calculated Tritium Production per Source Neutron in the LBM Detector Volumes for Each Multiplier Configuration.

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