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INTEGRAL EXPERIMENTS FOR FUSION REACTORS

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Abstract: Recent works in the area of integral experiments for fusion reactors are reviewed categorizing them into three classes. An emphasis is put on the experiments for neutron multiplying materials, Beryllium and Lead. Introduction of activities is made on the examination of the tentative version for JENDL-3 and new design-oriented experiments. A comment is given on the accuracies in experiment and analysis.

(fusion reactor, integral experiment, tritium breeding, data validation)

Introduction

The neutronics plays a fundamental role on the nuclear technology of the D-T fusion reactors. This comes from the fact that 80 % of the primary energy generated in the burning plasma is released to the surrounding blanket region as the kinetic energy of 14 MeV neutrons. The neutrons, in turn, regenerate tritium, not existent in nature, to complete a closed fuel-cycle and at the same time produce heat, an easier form of energy to handle, in the blanket. Through the nuclear reactions in the course, neutrons induce various phenomena: generation of secondary radiation, production of radio-activities and various primary processes leading to radiation damage.

All the neutron induced phenomena including tritium breeding and nuclear heating are estimated using the nuclear data of materials in the blanket/shield and radiation transport calculation methods for various blanket concepts. The accuracies of nuclear data and related transport calculations are of prime importance because they resultantly affects all the reactor design parameters. The integral experiment has an important role to validate the reliability of the nuclear data evaluated from various differential cross section measurements and theoretical predictions. The requirements for nuclear data and the status of integral experiments for examining them are well covered in the previous reviews[1-9].

Recent trend in the fusion integral experiments is increasing interest in neutron multiplying materials. One of the reason is the problem of Li(n,n') T cross section has almost solved. The other reason is that since the practical blanket designs contain various factors to degrade the energy of primary neutrons, reliance on Li only for neutron multiplication is no more sufficient for achieving enough tritium breeding. Blanket design concepts incorporating neutron multiplier have been eagerly investigated in the scoping studies like the Blanket Comparison and Selection Study[10,11].

The integral experiment for fusion reactors are not confined to the validation of nuclear data. It extends to the assessment of overall uncertainties associated to the prediction from nuclear calculations. As blanket design study proceeds, accurate estimation of neutronic parameters in the complex configuration is getting important to narrow the margins in related design factors. Integral experiments directing this are newly requested from the design people.

Another point to be noted is increased contributions from Japan, especially as an outcome of intensive activities at powerful 14 MeV neutron source facilities, FNS and OKTAVIAN. They cover wide area from differential cross section measurements to large scale integral experiments for design support.

In this report, we categorized the integral experiments into three classes depending on their objectives: Class 1 for nuclear data verification, Class 2 for examining cross section sets and transport methods to predict neutronic parameters, and Class 3 for assessing the overall uncertainty in nuclear prediction in complex systems The recent activities in the three classes are reviewed, putting an emphasis in introducing the work done in Japan. Some remarks are given on the points that affect on the accuracy of the experiments and analysis.

Class 1: Integral Experiments for Nuclear Data Verification

The objective of the experiments in this class is to provide data for examining the validity of the evaluated values in nuclear data libraries for individual elements by integral means. All elements contained in the materials for reactor components surrounding plasma are candidates for the experiments.

There are various experiment types depending on the nuclear data to be examined. Common to all types, the quantity to be measured should have a well-defined physical meaning. And the experimental system should, basically, consist of uniform single element in composition, and have simple and symmetric shape. These are important to provide unambiguous interpretation for the nuclear data in interest and to minimize the uncertainties that might be introduced in system-modeling and neutron transport calculation. The neutron spectrum concerned is characterstic to the medium studied but is system size/shape dependent.

Widely conducted are leakage neutron spectra measurements from the experimental systems of various materials with thicknesses ranging in 0.5 - 4 mean free paths for 14 MeV neutrons. When the amount of leakage neutrons relative to the primary source neutrons are determined by integration or direct total absorption method, the neutron multiplication factor is obtained.

The recent works in the class are shown in Table 1.

Table 1
Recently reported experiments in the class 1

Leakage neutron spectra measurements

- Pulsed Sphere Program at LLNL (Pb)[12]
- A series of experiments at OKTAVIAN, Osaka University, KURRI, U. of Tokyo (Li, Pb, Fe, Cr, Si, Co, Mn, Cu, Nb)[7,13-18]
- Technical University Dresden (Pb)[19]
- Anglewise measurements at FNS, JAERI (Be, Li, Li_2O, C)[20-22]

Total neutron multiplication experiments

- I.V. Kurchatov IAE (Be, Pb, ^{238}U, ^{232}Th)[23-25]
- Bhabha ARC (Be, Pb)[26,27]

Neutron multiplication experiments

Reflecting the common interest on neutron multiplication, new experiments and re-evaluation on lead and beryllium were reported by several laboratories.

(a) Lead

Figure 1 summarizes the results of experiments on the neutron multiplication factors of the lead assemblies with the shell thicknesses of 3 - 22.5 cm. There are 10 - 20 % difference among the experiments, while the calculation results show reasonable agreements among the evaluated files[28,29]. As a general trend, the measured results suggest a little bit higher value for the (n, 2n) cross section at 14 MeV. Iwasaki's recent work[30] also supports this observation. To draw a finite conclusion from integral experiments, however, additional data with good experimental accuracies are requested. The apparent defference between absorption method (BARC and KIAE) and integration of leakage spectra (OKATVIAN and TUD) needs to be examined from the assessment of error components associated to each technique. It is expected that the on-going IAEA supported international benchmark experiment and calculation program on lead would answer to the problem.

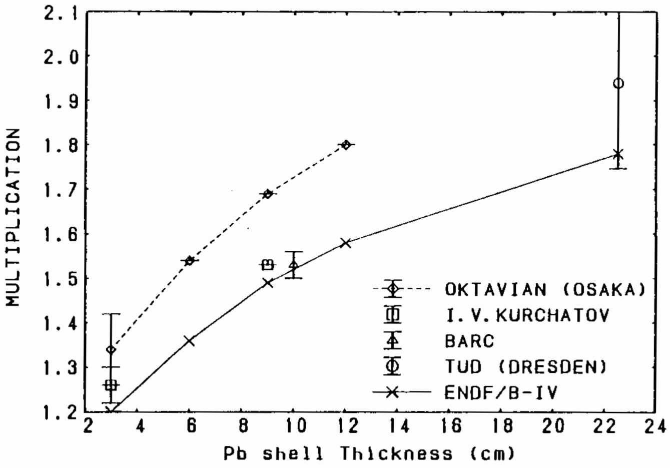

Fig. 1 Neutron Multiplication Factors in Pb Shells

(b) Beryllium

Table 2 lists the neutron multiplication experiments on beryllium. BARC and KAIE experiments are the absorption method, while LLNL experiment measured leakage neutron spectrum. In the latter, the measured time spectra was compared with the calculation and no integrated result was reported. Hence direct comparison in the form of neutron multiplication factor is not given. The comparisons of the measured data with the calculations show large discrepancies ranging in 0.9 - 1.2. Different from lead, the evaluated values of (n, 2n) cross sections themselves have 10 % variation at 14 MeV. The shapes of cross section curve also affect the neutron multiplications due to the secondary neutron contribution from its low threshold energy for (n,2n) reaction. This introduces complexity in interpreting the calculated to measured ratios based on the various evaluated data. The present integral data are sparse and seem not mutually consistent. Hence, additional experiments with good geometry and high accuracy are keenly needed to judge the adequacies of the new evaluations. Since beryllium is the most promisive neutron multiplier, a change in (n, 2n) cross section data would affect the tritium breeding evaluation in many design concepts.

Table 2 Experiments on Neutron Multiplicatin of Beryllium

Author	System Geometry	Shell Thickness (cm)	Experiment	Error (%)	Calculation / Experiment	
					Alice ENDL-84	
Wong (LLNL)	Sphere	13.8	Time Spectrum Integration	± 10%	0.91	
		19.9			0.97	
			Apparent Mult.		Claw-IV ENDFB/IV	
Nargundkar (Bhabha ARC)	Rectangular Prism	8	1.33	± 3%	1.23	
		12	1.70	± 3%	1.19	
	Absorption Polyethylene	20	1.68	± 12%	1.23	
			Total Mult.		BLANK ENDL-75,	ENDFB/IV
Zagryadsij (Kurchatov)	Sphere	5	1.36	± 3%	1.02	1.09
	Absorption Boron Tank	8	1.53		1.05	1.15

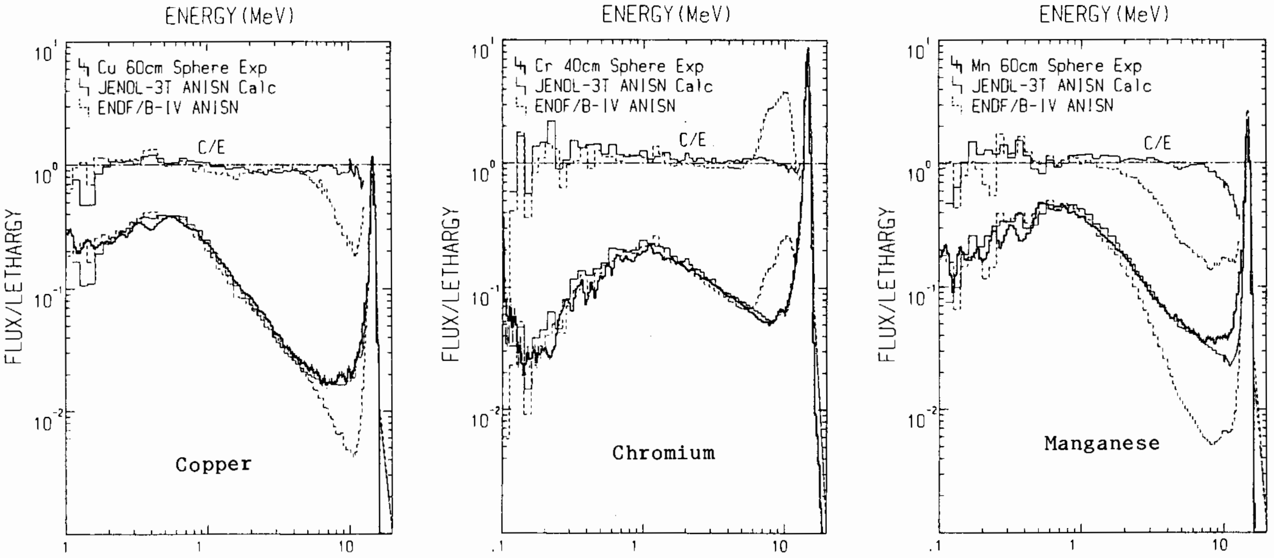

Fig. 2 Experimental and Calculated Spectra from Spherical Shells of Copper, Chromium and Manganese

Leakage neutron spectrum experiments

The absorption method for neutron multiplication factor measurements only gives, from its nature, the overall neutron gain of the system. Fischer[29], however, pointed out from a comparison study of the evaluated nuclear data on lead that there was considerable difference in second neutron angle/energy distributions among them. The leakage neutron spectrum measurement using time-of-flight technique can provides information on these quantities keeping a good correlation with differential cross section data. From this reason a number of experiments have been conducted on many materials besides neutron multiplier. Here, two recently reported experiments are introduced.

(a) KURRI-OKTAVIAN leakage neutron spectra mea-measurements

Adding to a series of leakage neutron spectrum measurements of Osaka University at OKTAVIAN, Ichihara et al.[18]of KURRI(Reactor Research Insti-Institute, Kyoto University) measured spectra from spherical shells of various materials using the same neutron source and time-of-flight technique. The materials were: LiF, Teflon(CF_2), Si, Cr, Mn, Co, Cu, Nb, Mo and W. They had thicknesses ranging in 0.4 to 4.7 mean free paths for 14 MeV neutrons. The results were compared with the calculations by ANISN or MCNP and data files, JENDL-3T, ENDF/B-IV and ENDL 73. Some of the results are shown in Fig. 2. They indicates ENDF/B IV and ENDL-73 data have some deficiencies leading to considerably large disagreements in spectra, while JENDL-3T gives better results in MeV region. Thus, this experiments, along with the previous works of OKTAVIAN group, provide a unified set of effective integral data to evaluate the accuracies of existing and new data files.

(b) Angular neutron flux spectra measurements

Angle dependent leakage neutron flux spectra from cylindrical slabs of different thicknesses were measured for Li, Li_2O, C and Be by Oyama et al. using FNS at JAERI[20~22]. The thicknesses ranged typically 0.5 - 5 mean free paths for 14 MeV neutrons and the measuring angles were five from 0 to 67 degrees relative to incident neutrons. The features of this experiment are that the scattering characteristics of the medium is more clearly represented by the systematic measuring of well defined angular fluxes, while in the ordinary spherical shell experiments, all angular components are integrated in different weighting with a strong bias in forward direction.

Figures 3 and 4 show a part of the results with those calculated by MCNP code. It can be seen a good deal of information on the cross section data is obtained from the present results. Note that there are considerably large difference among the evaluated data of beryllium. To make the comparison between the calculated and measured results more visible, Oyama devised a diagram by range-wize integration on neutron energy and discussed the problems in the nuclear data. The diagram for beryllium is shown in Fig. 5

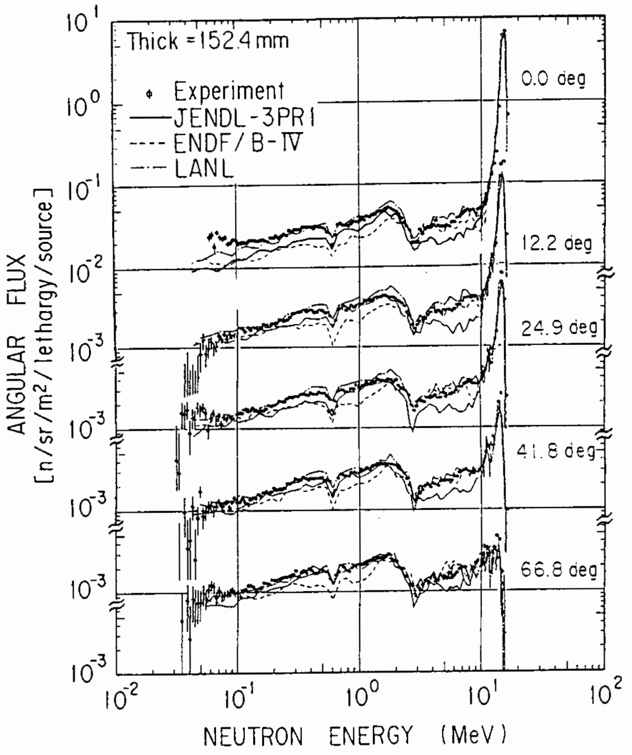

Fig. 3. Angular Fluxes from 152 mm-thick Beryllium Cylindrical Slab

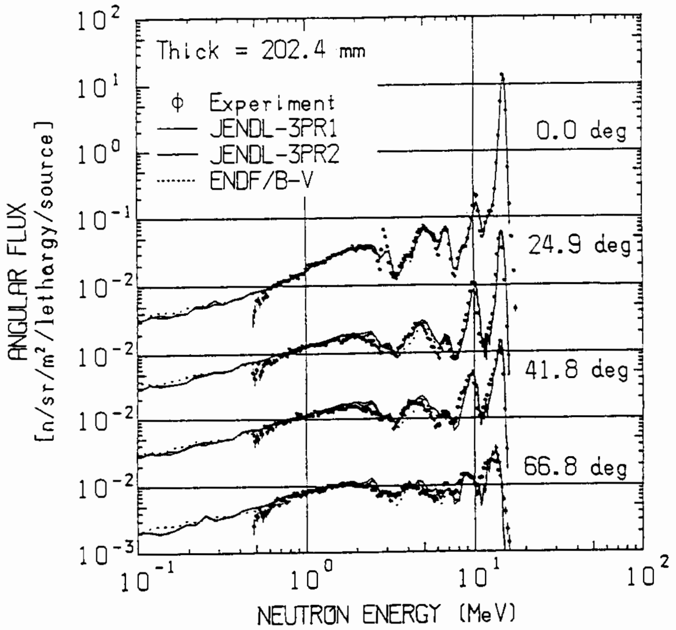

Fig. 4 Angular Fluxes from 202 mm-thick Graphite Cylindrical Slab

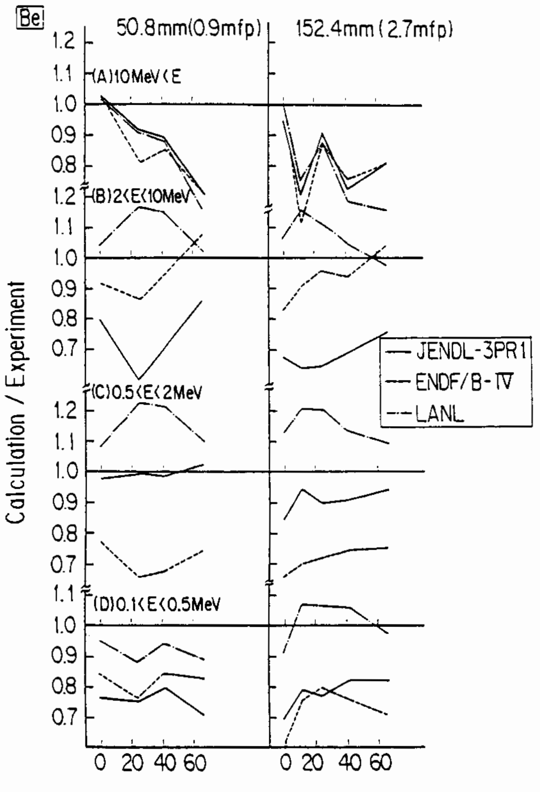

Fig. 5 Calculated to Measured Ratios of Bunched Angular Fluxes from Be Slabs as Functions of Thickness and Angle

Class 2: Integral Experiments for Examination of Cross Section data and Neutron Transport Codes

The objective of the experiments in this class is to examine the accuracies of cross section data and neutron transport codes used in the nuclear designs by measuring the reactor-relevant neutronic parameters such as tritium production rate. The experimental system in this class is dependent on the issues to be pursued. Generally, it is simple in geometry and in composition to make comparison with calculations straightforward, yet, is designed to emphasize the expected cause of disprepancy as clearly observable as possible. It is not always directly related to reactor designs. Measured parameters are typically tritium production, various reaction rates for activation/dosimetry and in-system neutron spectra as well as those escaping from the system.

The recent works in this class are shown in Table 3.

Table 3

Recently reported experiments in the class 2

- A series of benchmark experiments on cylindrical assemblies at FNS, JAERI (Li_2O, C, Li_2O/C, Be/Li_2O, Fe)[31-35]
- Sphere and slab experiments at OKTAVIAN, Osaka University, Joint Study of Universities (Li, Pb-Li, SS 316, Teflon)[7,13-17,36,37]
- Neutron spectrum measurements at Tokyo Institute of Technol. (LiF, LiF-C, H_2O, C)[38,39]
- Slab experiment at LOTUS, IGA, EPFL[40,41]
- TPR measurement at Lucas Heights Research Lab., Australia[42]

There have been so many experimental data on various items that it is hard to survey them in a limitted space, though every are valuable as benchmark data to check the calculation results. Here, only a brief description is given on the tritium production measurements, the most interesting item in fusion neutronics, at FNS and OKTAVIAN.

(a) FNS cylindrical slab experiment

Tritium production rate(TPR) distributions both from ^{6}Li and ^{7}Li were measured for the cylindrical assemblies of natural lithium-oxide, lithium-oxide followed by graphite reflector and lithium-oxide sandwiching a beryllium layer by Maekawa et al. Neutron source was put outside. Measuring methods are on-line counting by paired Li-glass scintillators for ^{6}Li and Li_2O irradiation samples with liquid scintillation counting technique(LSC) for both ^{6}Li and ^{7}Li. The on-line and irradiation methods gave an agreement within experimental errors. The calculations with the JENDL 3 temporary version predicted the TPRs in 5-10 % accuracies except for the boundaries of beryllium, where larger discrepancies were observed.

(b) OKTAVIAN sphere and slab expeliments

The breeder material at OKTAVIAN experiment was natural Li metal both in sphere and slab geometries. The sphere system consisted of two shells with the neutron source at the center. The inner shell was removed or substituted with Pb neutron multiplier to confirm the contribution. Slab experiment was with Pb multiplier and graphite reflector. Tritium was measured by Li_2CO_3 pellet and LSC (Dierckx method). Two groups in the joint activities of Universities independently measured TPRs to ascertain consistency. The calculations with JENDL 3 temporary version and ENDF/B-IV gave reasonable agreement with the measured values except for old version of ^{7}Li(n, n')^{3}T reaction in the latter. They integrated the TPR over the sphere systems both for Li and Pb-Li to obtain TBRs. The effect of Pb neutron multiplication was clearly observed, but apparent TBR decreased due to the suppression of ^{7}Li(n,n')^{3}T reaction that had a dominant contribution in the present configuration.

Integral Test of JENDL-3T

As a practical example for the utilization of integral experiments, a quick summary is given on the recent tests and its results on the nuclear data of JENDL 3T for fusion use. JNEDL 3T is the test version of JENDL 3 before its publication. New generation of the evaluated nuclear data files ENDF/B-VI, EFF-2, JENDL-3 etc. will line up in 1988-1989. Preparing for this, an intensive work has been put on for the test of will-be JENDL-3 to pick up possible deficiencies in the evaluation and to amend them.

The examination program in the area of fusion use was couducted as a joint effort of sub-committees of the Nuclear Data Committee and Committee on Reactor Physics. This program used the integral experiments included in the Classes 1 and 2 available in Japan and some from the other countries. In the multigroup calculations the unified set was used to keep a good correlation among different experiments on the same elements and to minimize the deviations due to the difference in group structure or data prosessing. The results summarized by Maekawa[35] is shown in Table 4. Note that the neutron multiplying materials, beryllium and lead, were pointed out to contain problems and re-examination were recommended.

Table 4
Results of the Test on JENDL-3T^{+}Using Integral Experiments*

^{1}H:	Good agreement for water and polyethylene leakage spectra.
^{6}Li:	Good. Deviation in 7 - 12 MeV region for leakage spectrum.
^{7}Li:	Generally good for leakage spectra and reaction rate experiment. Slight change suggested in (n,2n) and total.
^{9}Be:	Discrepancy persists. Deviation observed below 10 MeV. Detailed examination needed, especially, in energy-angle correlation.
^{12}C:	Good agreement. Minor discrepancy observed corresponding to 2nd and 3rd levels.
^{16}O:	Good agreements both for leakage spectrum and reaction rates in O containing composites.
Si:	Poor agreement. Ten to 30 % deviation observed in leakage spectrum.
Cr:	Fairly good for leakage spectrum. Discrepansy exsist below 8 MeV. The (n,2n) cross section to be checked.
Fe:	Fairly good for leakage spectrum. Underestimation observed in 8 - 13 MeV.
Mn:	Fairly good. Discrepancy observed near 10 MeV for leakage spectrum. The elastic and (n,2n) to be checked.
Cu:	Fairly good. Discrepancy observed near 10 MeV for leakage spectrum
Pb:	Discrepancies in leakage spectra and neutron multiplication. Examination recommended.

+: Temporary library for the examination before publication of JENDL-3

*: Summarized from the report of Subworking Group

Class 3: Design-oriented Integral Experiments

The objective of the experiments in this class is to provide data on neutronic parameters to examine the overall uncertainty included in calculational prediction for nuclear designs.
To obtain neutronics parameters for a certain blanket concept by an integral experiment, we need a close matching of neutron spectrum to that encountered in the reactor blanket, because the parameters are often spectrum sensitive. Hence, the experimental system should represent typical features of the blanket configuration in interest. Necessarily, the system is large in size and complicated compared to the Class 2 systems. Yet, it is necessary to be simple as possible as to allow accurate modeling in the calculations. The parameters to be measured are also diverse depending on the design request, but the tritium breeding characteristics are of major interest at the moment.

The number of experiments is very limited, because an intense 14 MeV neutron source and a large size test blanket are absolutely needed. The followings are in this class.

- JAERI/USDOE Collaborative Program at FNS, JAERI
  Li_2O, Be/Li_2O blankets, Effects of Be neutron multiplier and first wall on TPR[43-47]
- Universities' Joint Experiment Program at OKTAVIAN
  Li, Pb/Li , Pb/Li/C blankets[17,37]
- Hybrid, LBM Cooperation Program[40,41] at LOTUS, IGA, EPFL

OKTAVIAN and LOTUS experiments have some difficulties to attain fully the objective of this class due to hard spectra of neutrons entering into test blankets as the results of the close distances between the neutron sources and the experimental assemblies.

Figure 6 illustrates the basic structure of the system used in the JAERI/USDOE Collaborative Experiment Program. A large distance from the neutron source to the blanket test zone and the neutron-reflecting enclosure produce a well-simulated neutron field uniformly on the wide area around the central axis of the test blanket zone. The test zone is composed by assembling unit-sized blocks. This arrangement facilitates the change of the test zone for different compo-

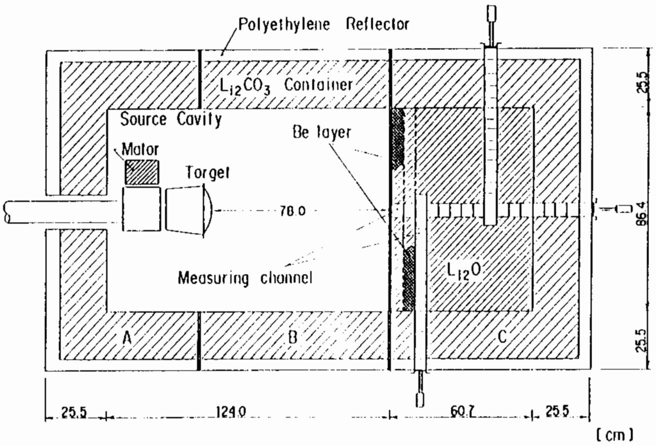

Fig. 6 Experimental Arrangements in a Closed-geometry for JAERI/USDOE Joint Experiment Program

sitions such as the substitution of a part of reeder by Be neutron multiplier. Tritium production rates, activation reaction rates and neutron spectrum distributions were measured along the central axis. The TPR distributions from ^{6}Li are compared for three test blanket configurations: Li_2O reference, Be layer in front of Li_2O and Be layer sandwiched between two Li_2O regions in Fig. 7. The effect of Be neutron multiplication are clearly observed.

The measured data on various items are analyzed independently at both parties with common experimental conditions. An example of the comparison is given in Table 4. Here, TPRs from natural Li are integrated over the test blanket depth along the central axis. The measured values obtained by zonal extraction method of tritium produced in the Li_2O blocks which constitute the breeder region of the assembly. The agreement between calculated and measured values is good for this case within 3 %, but systematic about 4 % differeces are observed between JAERI and U.S. results by Monte Carlo calculations. Note that both calculations underestimate Be effect. This program provide various productive and practical results that Class 2 experiments have not furnished.

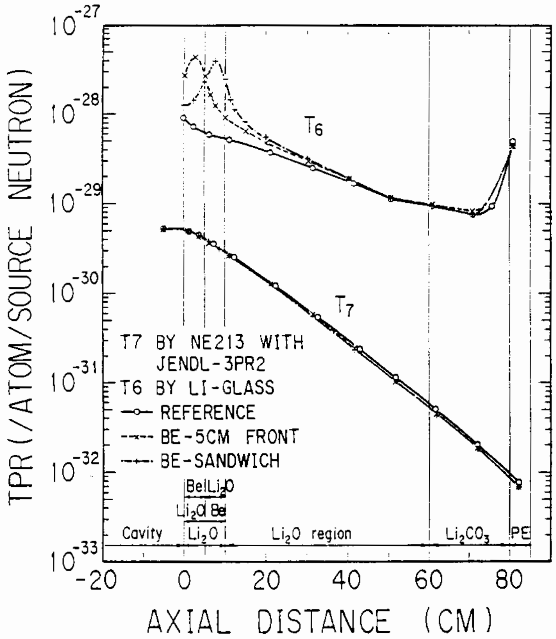

Fig. 7 Tritium Production Rate Distributions from ^{6}Li, in Three Test Blanket Assemblies: Li_2O, Be/Li_2O, $Li_2O/Be/Li_2O$

Comments on the Accuracies in Integral Experiments

Since the recent required accuracies for the nuclear data of important elements are high, the integral experiments to validate them should be correspondingly accurate enough. There are some factors that should be treated carefully in reporting experimental data and using them in recent experiments to assure good accuracy. These are neutron source characteristics and modeling of the experimental system and detector probes. Brief comments on them are given below.

Neutron source characteristics

Since the fusion neutronics experiments are essentially "source problem" where all measured data are correlated to the source neutrons, the source characterization: neutron angular/energy distribution and absolute neutron yield is most essential part of the experiment.

The neutron source anisotropy due to target structure is more enhanced, compared with that of small source, in a high-intensity target system used in modern experiments for good statistics. It is heavier and more complicated in structure to assure good cooling capability. This anisotropy should be well confirmed by experimental means and suitably taken in the related calculations of the analysis as the input conditions.

The measurd values are usually expressed per unit source neutron by absolute normalization, because the corresponding calculated value is

Table 5 Comparison of Integrated Zonal Tritium Production Rates in Li_2O and $Li_2O/Be/Li_2O$ Test Blankets.

a. Increase in the Tritium Breeding Potential

Method	Reference	Be-Sandwiched	Be-Sand./Ref.
MCNP(U.S.)	2.442-28*	2.644-28+	1.083
DOT(U.S.)	2.657-28	2.832-28	1.066
MORSE-DD(JAERI)	2.538-28	2.733-28	1.077
Measurement	2.477-28	2.732-28	1.103

b.C/E Values

Method	Reference	Be-Sandwiched	Be-Sand./Ref.
MCNP(U.S.)	0.986	0.968	0.982
DOT(U.S.)	1.073	1.037	0.966
MORSE-DD(JAERI)	1.025	1.000	0.976

* Units: tritium atom/source neutron. Nat.Li atom. sec.

\+ Tritium produced in the beryllium zone is excluded obtaind as such quantity. In high intensity operation, however, from the hazard of radiation damage one can not directly depend on the associated α particle method that is reliable technique in absolute neutron counting compared with the external monitors.

In the accurate experiments, the detailed measurement of source neutron profile and complicated procedures in the determination of absolute normalization factor are indispensable.

Modeling of the experimental assembly and detector probes

Many of neutronics parameters are very sensitive to both the geometrical relation because of $1/r^2$ effect of the point source, and large spectrum change due to directional incidence of neutrons. Hence, experimental system and detector probes should be rigorously positioned to keep symmetry and exact dimensions be reproduced in the modeling of the system for the input data of the calculation for analysis. Sometime also the geometry of the experimental channel and finite size of detector probes should be treated exactly. Otherwise, systematic deviations may be introduced that affect the accuracy in the comparison study.

Conclusions

We reviewed the recent activities in integral experiments for fusion reactors grouping them into three classes from their objectives.

Integral data for nuclear data validation have been accumulated for various elements. Especially several works have been conducted on lead and beryllium from increased interest in neutron multipliers. The results suggest the necessity of improvements, more or less, for the current evaluated data files for (n,2n) cross section and secondary energy/angular distributions. On the other hand, further experimental efforts with improved accuracy are necessary to narrow the gaps observed among the reported data. More measurements for other elements are also needed for cross-checking by independent experimenters, from the basic nature of the experiments in this class.

As for the basic integral experiments, tritium production rates from ^{6,7}Li, activation reaction rates and neutron spectra have been obtained in FNS, OKTAVIAN experiments and others. These data have been used as benchmarks to examine the accuracies in predicting neutronic parameters by current various nuclear data and calculation methods. As an example, accuracies of latest evaluations of ^{7}Li (n,n'α)T cross section have been successfully confirmed from tritium production measurements, showing that they have converged to satisfy the required level. More systematic investigation by using sensitivity analysis will be required, if the basic integral experiments are extended to such as cross section adjustment for major elements.

The integral experiment to assist in the design concept of blanket provides practical data to examine the overall accuracies of the nuclear calculations in simulated spectrum field. Since there are many competing reactions in the energy range where neutron multiplying reactions occur, simulation of the system composition as well as the input neutron spectrum are very important for an exact evaluation of tritium production of such system. As design study of the breeding blanket proceeds, the needs for the experiments in this class would increase. The effect of Be in Li_2O breeder is being investigated under the collaboration between JAERI and USDOE. Similar experiment on Li-Pb system will be demanded, since it is one of the promisive blanket concepts yet supporting experimental data on the composite sistem is lacking.

There are many factors to affect the final results of experiments and their analyses, when the target accuracy is high. Enough attention should be paid on the source characteristics, detector characteristics and modeling of the experimental system in order to avoid possible systematic biases characteristic to experimenters/facilities. Some of these could be reduced by cross-examinations of neutron yield monitoring, measuring techniques and analytical means among different experimenters/facilities. This also serves to take good correlations among their data. In this meaning, the international cooperation is encouraged.

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