SUMMARY OF RECENT RESULTS FROM THE JAERI/U.S. FUSION NEUTRONICS PHASE I EXPERIMENTS

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ABSTRACT

A series of integral neutronics experiments is in progress as a collaborative program between Japan Atomic Energy Research Institute (JAERI) and U.S. Department of Energy(DOE) on fusion blanket engineering. Three types of experiments were conducted on lithium oxide as the Phase I of the program. Measured parameters are tritium production rates and neutron spectrum in test blanket modules. The results obtained in the collaboration are described along with the features of this program.

INTRODUCTION

The tritium breeding ratio(TBR) in a fusion blanket is one of the most important parameters to be considered in the conceptual design of fuel-self-feeding D-T reactors. There are many factors, both physics and engineering, that affect the TBR value in a design.[1,2] Various studies have been undertaken on first wall/ blanket systems to take balance among the multiple requirements from materials, thermo-mechanics, plasma control, tritium production and its recovery.[3,4,5] In those studies it was disclosed that it is not so easy to achieve a TBR value of 1.05 that is considered as a lower limit for fuel self-sufficiency in conceptual designs.

Efforts in neutronics area are to provide data needed for identifying and selecting materials and configurations that achieve an optimal TBR, and to improve the accuracy of predictions on nuclear parameters. There has been a number of calculational activities to estimate the achievable TBR in many concepts. To assure reliable prediction on TBR values, however, experimental support would be required to verify the accuracies of the nuclear data, numerical methods on neutron transport and adopted calculation modeling which were used in the predictions. So far, the number of experimental data available for this purpose is very limited.

At the moment, a plasma-based neutron source is not yet in practical use; an accelerator-based source plays a main role in the experiments for fusion reactor neutronics. The JAERI installed an intense D-T neutron source for fusion neutronics studies (FNS)[6] taking the above-mentioned situation into account, and started an extensive experimental program that include integral experiments both on breeding blanket and shielding, fusion dosimetry and cross section measurements.

The experimental program on tritium breeding blanket was planned in two categories: one is "clean benchmark" experiments[7] and the other is "engineering-oriented benchmark" experiments. The latter incorporates the key factors of a breeding blanket of composite configuration yet is simple enough to be accurately analyzed so that the overall accuracies of nuclear data, calculation methods and calculational modeling are estimated, while the former focuses on the examination of nuclear data and/or transport methods in simple systems.

The "engineering-oriented" experiment was proposed in 1982 as an item for the joint planning activities between JAERI and U.S.DOE on fusion reactor engineering. A collaboration program on joint experiments and the analysis was agreed upon in October 1984 with using effectively resources available in both parties. The objectives of the program are:

1) to provide experimental data needed to determine the accuracy, guide the development and establish the validity of the calculational methods and nuclear data bases, and
2) to provide experimental data to assist in the selection, from a neutronics point of view, of configurations and materials for candidate blanket designs.

The collaboration program is planned in two phases. Phase I experiments that have just been completed aimed to establish a methodology for engineering-oriented benchmark using fairly simple configurations. Phase II experiments, scheduled to start during summer of 1986, will direct at complex material arrangements and geometrical configurations with a better simulation to the neutron spectrum found in reactor environment.

BASIC CONCEPT IN PHASE I EXPERIMENT

A unique feature of the Phase I program is the incorporation of the rotating neutron target(RNT) and the target room enclosure to the experimental arrangement. The 2nd target room of FNS is presumed as the plasma chamber of a fusion reactor and the concrete enclosure as the blanket region surrounding the core plasma. Neutrons from the burning plasma are simulated by those from the RNT located around the center of the room. By loading a blanket test module in a large experimental port, a part of the enclosure is substituted by a breeding blanket composition as is shown in Fig. 1.

If the spectrum of neutrons impinging into the test module were close to that encountered in a reactor blanket, neutron parameters measured along its central axis would approximate those in the radial direction of a reactor blanket of same composition. A survey work[8] with simplified calculation models showed that distributions of tritium production rate(TPR) from both ^{6}Li(T6) and ^{7}Li(T7) gave fairly close shapes to those of a reactor model of FER (experimental reactor concept at JAERI) class, except for the vicinity of the front edge of the module. Based on this analysis, it was concluded that experiments in this arrangement could provide useful information on blanket design.

The source characterization is an important part of this program.[9] Once source characteristics is established for this experimental arrangement, a systematic examination can be performed on the effect of blanket configuration upon the neutronics parameters. Some examples of candidate configurations for experiments are shown in Fig. 2. Since test materials are prepared in the form of blocks in a unit size to set up the experimental system, configurational change is very easy and flexible.

At FNS, the neutron yield is monitored by the associated alpha particle method. Hence, all measured values are obtained per source neutron. In the analysis that includes the target, the room and the test assembly, calculated values are normalized to unit source. Thus, comparison between calculations and experimental values can be made on absolute basis in the present arrangement.

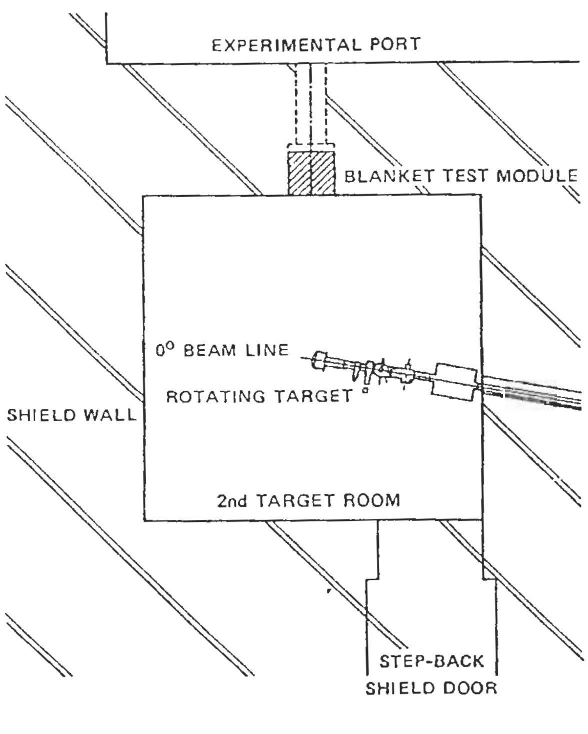

Fig. 1. Layout of Phase I experiment

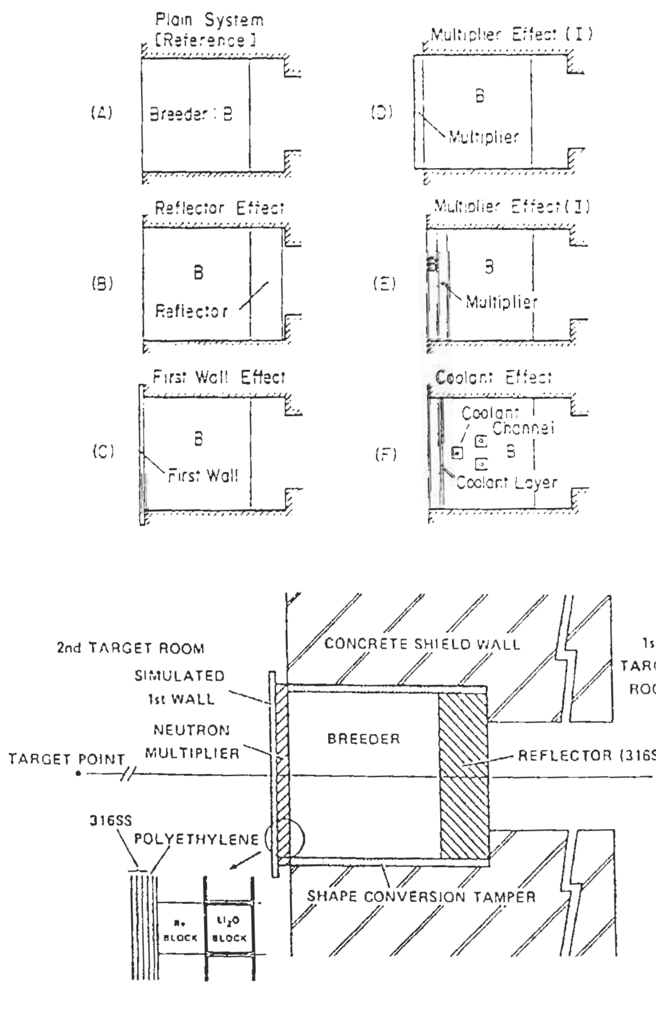

Fig. 2. Schematic drawing of candidate experimental configurations

DESCRIPTION OF EXPERIMENTS

Experimental systems

Three types of test modules have been assembled in the experimental series. They were: a) the reference, b) first-walled, c) beryllium neutron multiplier systems. In all cases, the breeding material was lithium oxide. The basic dimensions of test module were 63 cm in equivalent diameter and 61 cm in length. The distance from the RNT to the front end of module was 248 cm.

The reference system was a single-zoned breeder made up of Li_2O blocks alone. Since the system has the simplest composition, it serves as the base in estimating the effect that is introduced by adding or inserting a region of other material to the basic system.

The first-walled system had a simulated wall layer in front of the reference assembly. It was intended to confirm the sensitivity of measuring methods to the perturbation introduced by the layer in a parametric way. Measurements were performed on four different wall configurations.

In the Be neutron multiplier system, a Be zone was added to the reference. Three different configurations were composed in this series. The main concern was to examine the impact of Be neutron multiplier inclusion on the neutronics parameters studied. In two experiments of this series, the Be layer was placed in front of the breeder, while it was sandwiched between two breeder regions in the third experiment.

BLANKET TEST ASSEMBLIES INVESTIGATED

- Reference System
  - Single-region Li_2O breeder
    - 60cm Li_2O
- First Walled System
  - No first wall /60cm Li_2O*
  - 0.5cm SS^{+} /60cm Li_2O
  - 0.5cm SS/0.5cm PE^{++} /60cm Li_2O
  - 1.5cm SS /60cm Li_2O
  - 1.5cm SS/0.5cm PE /60cm Li_2O
- Be Neutron Multiplier System
  - 5cm Be /60cm Li_2O
  - 10cm Be /60cm Li_2O
  - 5cm Li_2O/5cm Be/60cm Li_2O**
  - 10cm Li_2O /60cm Li_2O

*: Identical with reference system
**: Be sandwiched system
+: Type 316 stainless steel
++: Polyethylene as simulant of water

Table 1. Test assemblies in Phase I experiment

The compositions of all assemblies in the three systems mentioned above are summarized in Table 1. An illustration of the Be sandwiched system is shown in Fig. 3 as an example of the loading pattern applied. Descriptions of the RNT, target room, experimental port and materials in block form used in these modules are given in Refs. 9 and 10.

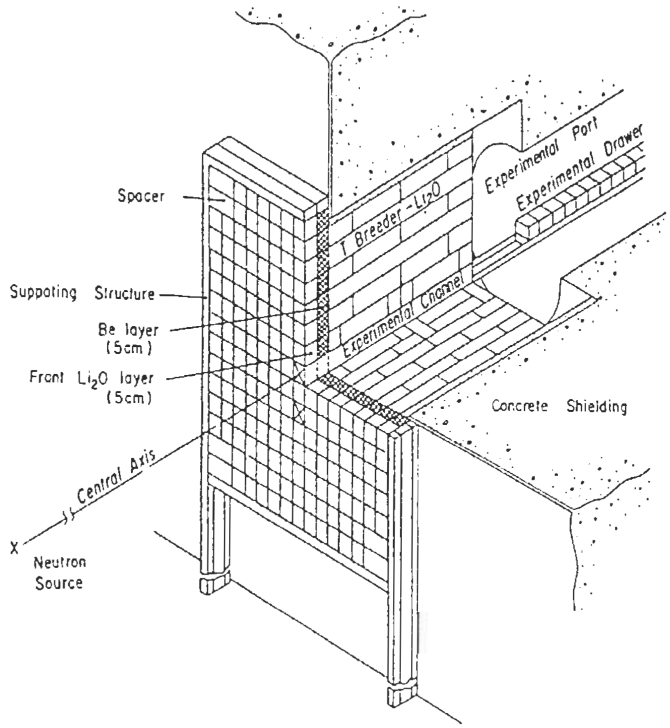

Fig. 3. Beryllium sandwiched assembly

Measured Parameters and Methods Applied

The main efforts in this program have been directed to the measurements of the TPR and neutron spectrum. These parameters were measured along the central axis of the test assembly in most cases. Two types of experimental approach have been undertaken: a) on-line method by radiation counters and b) irradiation method by counting the activities accumulated in small samples inserted in the experimental system.

The on-line method utilizes small-sized scintillation detectors which are suitable for parametric survey for the TPR in different configurations. Since the method has high detection efficiency, it is applicable at low neutron fluence with reasonablly short measuring time. This results in less radiational problem in quick access for the configurational change of the system. By this reason, the on-line method was applied to all of the assemblies.

The irradiation method is adopted for the determination of reaction rates on absolute basis. Another feature of this method is the smaller perturbation to the neutron field compared with the case of counter method. As it requires, however, intense and long neutron exposure, the consumption of tritium target and the high dose rate resulted from the activation of the target assembly limit the number of irradiation runs. In the present program, this method was adopted in selected cases: the reference and Be sandwiched systems.

The measured items and the methods applied are summarized in Table 2. On the TPR measurement of irradiation type approach, two methods were developed separately at JAERI and Argonne National Laboratory(ANL) for Li-containing sample and liquid scintillation counting technique. These two methods were applied in parallel to make a cross-check on the accuracies of measured values. Since liquid scintillation counting method is widely used as basic technique for determination of tritium in small amount in neutronics experiments, the inter-organization comparison was one of the most important items in this collaboration to confirm the reliability of this method. Measurement of neutron spectrum at the front face of the experimental assembly by two methods - the proton recoil proportional counter(U.S.) and NE213 scintillation counter(JAERI) - that cover a wide range of energy is another shared item between JAERI and U.S. Details on measuring methods are described in Refs. 10 and 11.

MEASURED ITEMS AND METHODS APPLIED

TRITIUM PRODUCTION RATES

On-line Type (JAERI)
- T6 : Paired Li Glass Scintillation Counters
- T7 : Micro Spherical NE213 Spectrometer
  - Indirect method -

Irradiation Type
- T6, T7 : Li_2O Pellet/Liq. Scint.* (JAERI)
- TN : Li Metal Foil/Liq. Scint. (U.S.)

NEUTRON SPECTRUM

On-line Type
- Fast Neutron : NE213 Spectrometer
  0.5MeV < E < 15MeV (JAERI)
- Slow Neutron : Proton Recoil Spectrometer**
  5keV < E < 2MeV (U.S.)

Irradiation Type (JAERI)
- Activation Foils : Al, Au, Co, In, Nb, Ni
- Spectral Indeces : Ti, Zn, Zr

* Liquid Scintillation Counting Method
** Input Source Spectrum to the Test Module

Table 2. Measured items and methods applied

EXPERIMENTAL RESULTS

Reference System

The experiment in Phase I program was initiated with the most basic and simple system, the reference. All measuring techniques referred to in the preceding section were applied to this system in order to confirm their applicability. The measured spatial distribution of TPR from ^{6}Li is shown in Fig. 4. A sharp spike is observed at the front edge of the breeder region; the high values of TPR at the surface are caused by thermal neutrons from the concrete room wall. They are, however, absorbed near the surface, and the TPR value falls rapidly. The contribution of this very soft component in the incident neutron spectrum gets small in the region deeper than about 2.5 cm. At the rear edge there is also an observed jump in the TPR values due to thermal neutrons from the wall located at the back. Except for these two ends, the measured TPR curve can simulate fairly well the shape of the TPR distribution in a blanket

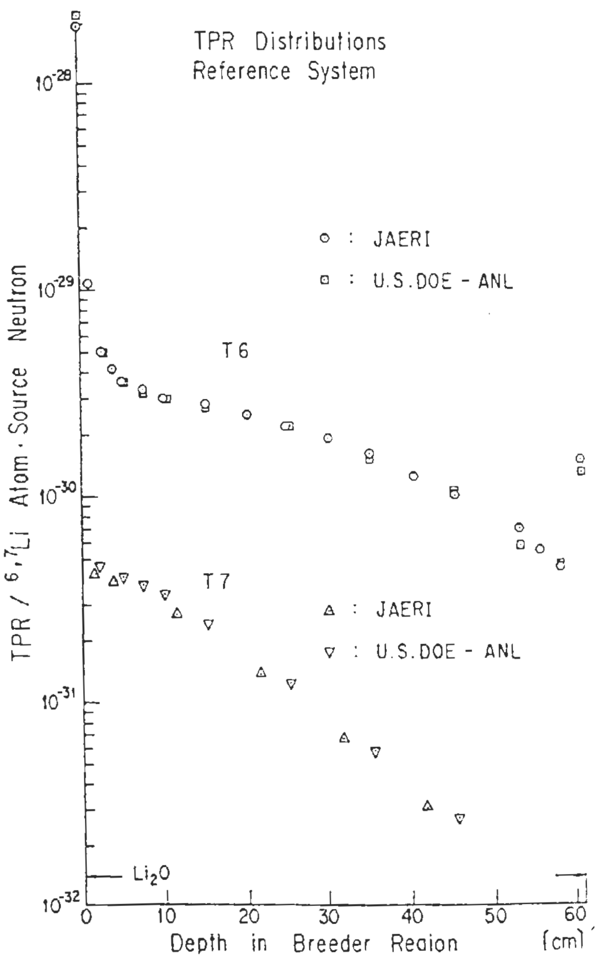

Fig. 4. The measured tritium production rate (TPR) in the reference system

having the same composition. The TPR from ^{6}Li measurements as obtained by JAERI and U.S. gave good agreement over the whole region within the experimental errors. Discussion on the results obtained by the different measuring techniques can be found elsewhere.[10] The TPR from ^{7}Li is also shown in the same figure. There is a systematic difference in absolute values between JAERI and U.S. results, though the relative shapes are the same. The reason for the difference is partly attributed to the ^{7}Li(n,n'α) cross section data used in the indirect method applied by JAERI. Neutron spectra were measured along the central axis by using a small NE213 spectrometer. The spectra at two different locations are shown in Fig. 5 to demonstrate the change above 1 Mev in the system. Reaction rate distributions of activation foils were also measured and compared with the analytical predictions to provide spectral information in the system (see Ref.10).

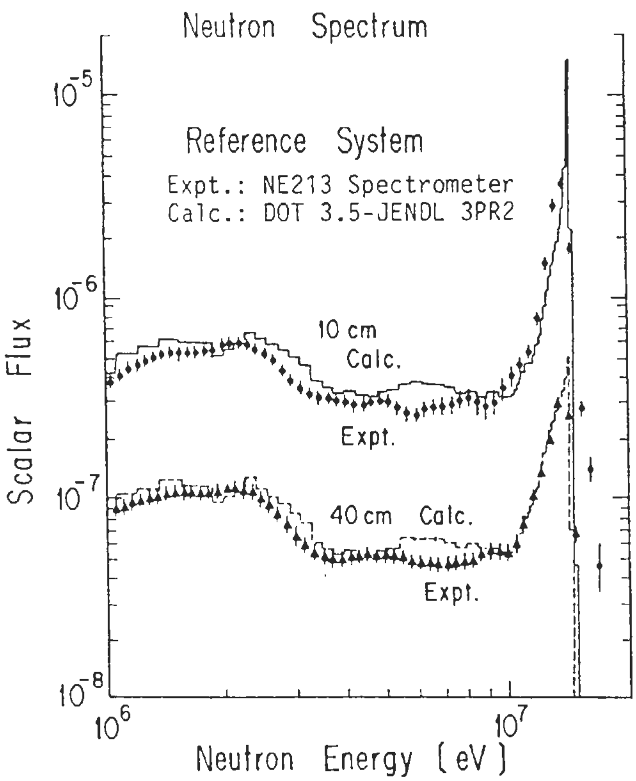

Fig.5. Fast neutron spectra in the reference system

First-walled System

The effect of first wall inclusion in different configurations was studied systematically by measuring the TPR with the on-line counter methods. The TPR was measured at a fixed location in the reference case, then the same paremeter was measured with the first wall layer of each configuration in place, in turn. This sequence was repeated successively for other detector locations. By this means, relative changes in TPR can be accurately determined. Since the changes in TPRs are not large in this experiment, the results shown in Fig.7 are presented in relative form:

$$(TPR_{f-w}-TPR_{ref})/\ TPR_{ref},$$

where TPR_{f-w} and TPR_{ref} are tritium production rates in the first-walled and non-walled system, respectively. A systematic trend is clearly observed for each TPR from ^{6}Li or ^{7}Li demonstrating the measuring technigue applied have good sensitivity to configurational changes. The insertion of 0.5 mm thick polyethylene layer - a simulant of cooling water - enhances the TPR from ^{6}Li considerably in the first 15 cm in the breeder region.

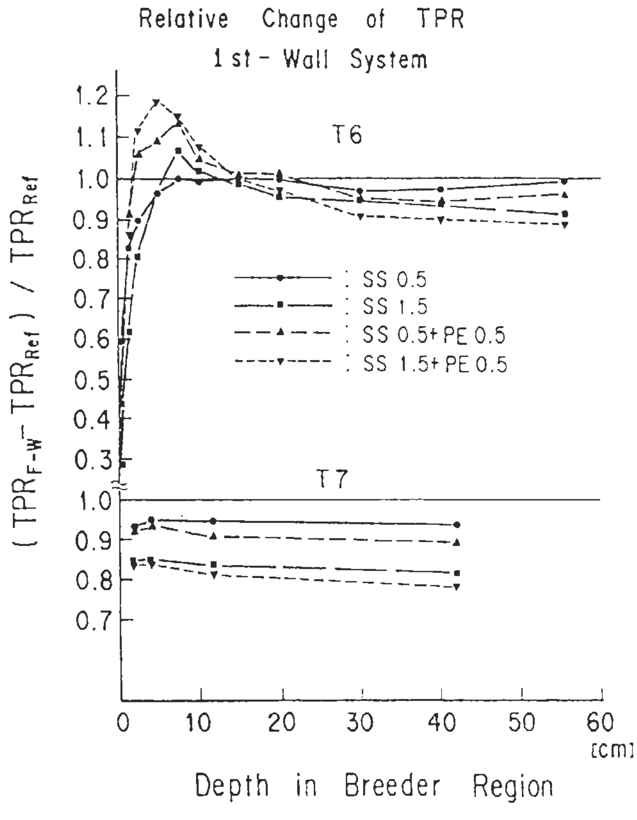

Fig. 6. Relative change in TPRs for first walled system

Be Neutron Multiplier System

The TPRs were measured by the on-line counter methods in all of three different dispositions of the Be neutron multipler zone. The TPR from ^{6}Li in the Be 10cm case is shown in Fig. 7 along with that of the reference. It can be seen that the addition of Be layer in front of the reference assembly increses the TPR considerably in the front half of the breeder region by the multiplication and moderation of incident source neutrons, while the TPR decreases in the rear half. The Fig. 10 of Ref. 11

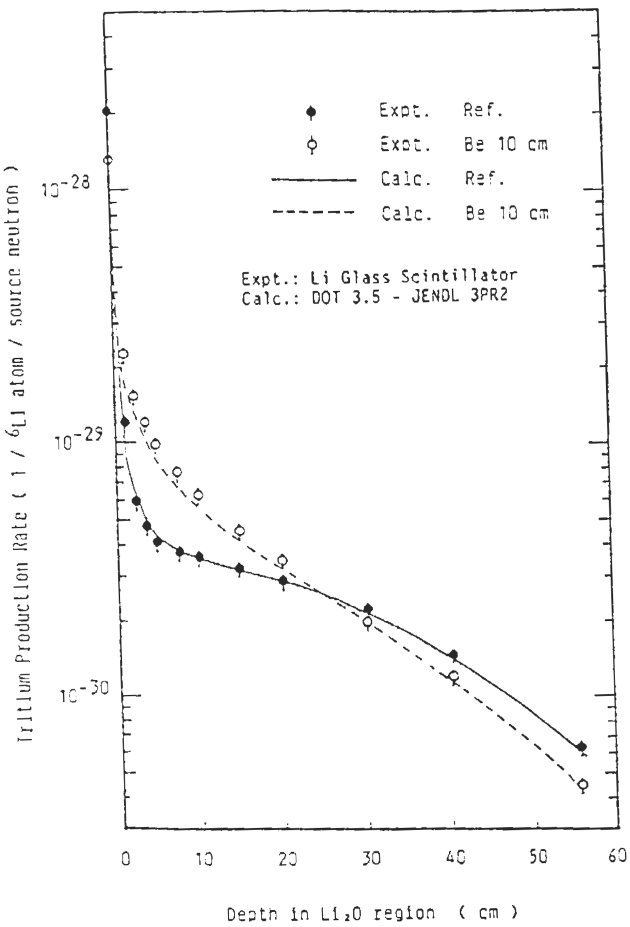

Fig. 7 Tritium Production rate from ^{6}Li in Be 10 cm system measured by on-line method

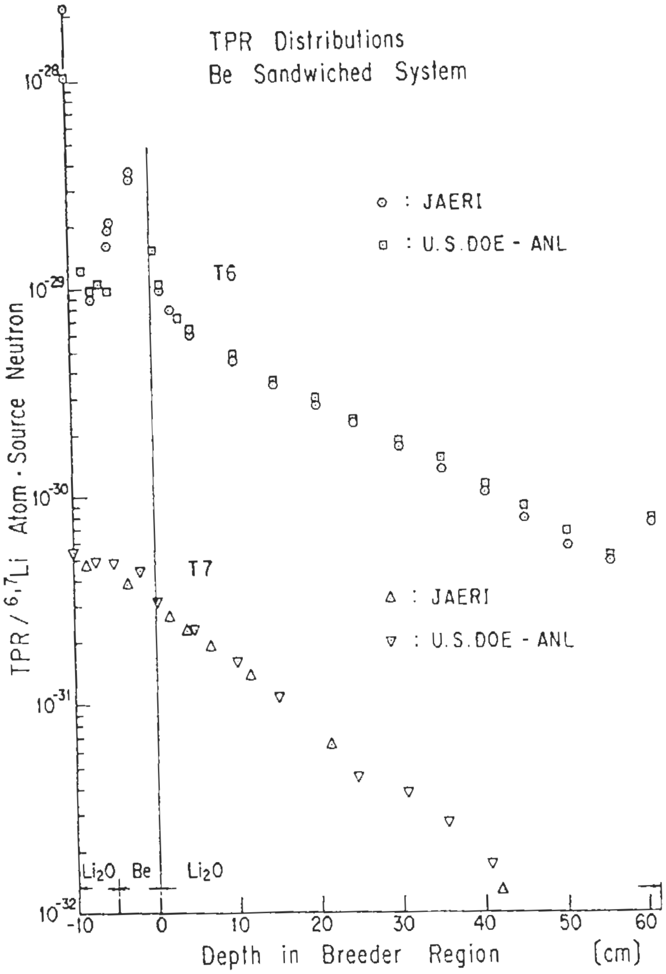

Fig. 8 Measured tritium production rates in the Be sandwiched system

shows the TPR dependence on the Be thickness. Within the range measured, the thicker Be layer gives the larger effects. The TPR values from ^{7}Li shows a decrease correspondingly. The irradiation method was applied to the Be sandwiched system. The reason for the choice of this assembly was to examine closely the issues associated with a composite system where reaction rate distributions were predicted to show complex shapes.

The TPRs in the Be sandwiched system are shown in Fig. 8 both for ^{6}Li and ^{7}Li. As the same scale is used in Figs. 4 and 8, the changes due to the insertion of the Be layer can be seen by the direct comparison of two figures. The contribution of the front breeder layer as a means to enhance the tritium production was experimentally confirmed in this experiment. The agreement between JAERI and U.S. results was also generally good. From the comparison of measured values of different means, it turned out that the TPR from ^{6}Li have larger uncertainties at the region boundaries because the neutron spectrum , hence the TPR, varies drastically with position. The results of activation foils as spectral indices are given in Fig. 10 of Ref. 10.

ANALYSES AND DISCUSSION

The analyses of the experiments have been independently carried out both at JAERI and U.S.DOE-UCLA using the different nuclear data and transport codes with common input conditions on the neutron source, room and experimental systems. The nuclear data and calculation codes used in the analyses are summarized in Table 4. As the details on the analysis and the intercomparison appear in Ref. 12 in this issue, a brief comment on TPRs in typical case will be given here.

In Fig. 9, the C/E values for TPR from ^{6}Li measured by Li-glass on-line method in the reference system are shown both for deterministic and Monte Carlo methods as an example of the intercomparison. It is noted that there are large differences among the calculational values even in a simple assembly. In the calculations by DOT codes, fairly constant C/E values ranging within 1.13 - 1.28 are obtained throughout the breeder region except at front two locations. The C/E values obtained by U.S. give larger deviations from unity and the difference between

	JAERI	U.S.
• Discrete ordinates (2-D, r-z model)	DOT3.5 + GRTUNCL JENDL-3PR1&2 JACKAS (P5, 125G)	DOT4.3 + GRTUNCL ENDF/B-V* MATXS6 (P5, 80G)
• Monte Carlo	MORSE-DD JENDL-3PR1 DDL/J3P1 (125G)	MCNP ENDF/B-V* BMCCS3 (continuous energy/ Angle)

*: Young's evaluation for $^7Li(n,n'\alpha t)$ was used. Latest and Previous evaluation for Be were compared.

Table 4 Calculational method, nuclear data and cross-section libraries

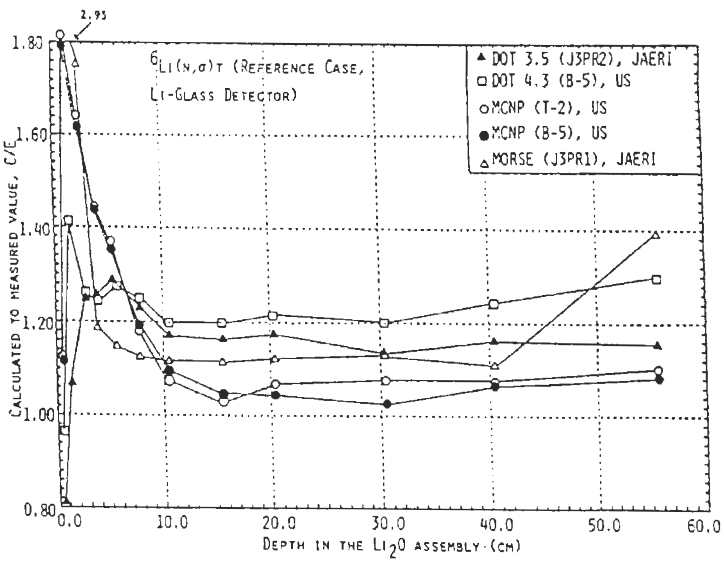

Fig. 9 Calculated to measured value of tritium production rate from ^{6}Li in the reference system

JAERI and U.S. increases as going deep in the assembly. This trend is the same as that observed in the JAERI/U.S. calculational benchmarks[13] and is attributed partly to the difference in the numbers of groups in the libraries used. The Monte Carlo calculations give better C/E values (MCNP: 1.03 - 1.10, MORSE-DD: 1.10 - 1.14 except the last measuring point) over the DOT calcula- tions in the region deeper than 5 - 10 cm from the front end. In the front part, however, large deviations from unity are observed. The discrepancy is partly attributed to the interpolation scheme in the front region where the TPR distribution curve is steep, and partly to poor statistics of very soft neutrons that have large cross section for tritium production. As for the C/E values for

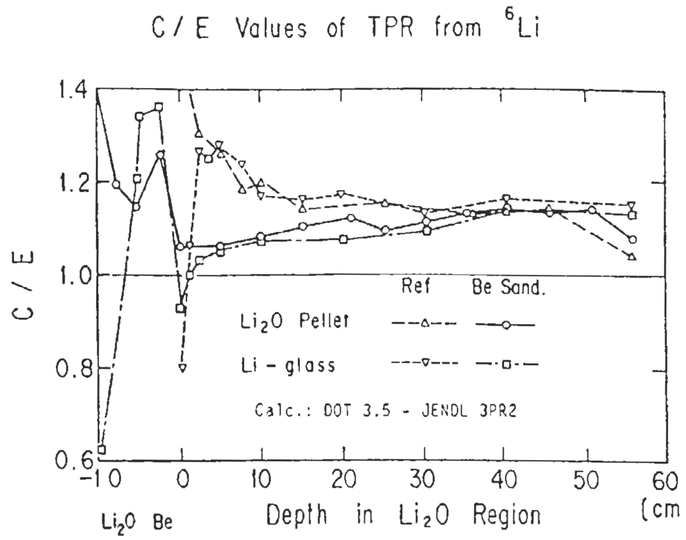

Fig. 10 A comparison of C/E value for ^{6}Li between the reference and Be sandwiched systems

TPR from ^{7}Li, there is a systematic diference of 12-18% between JAERI and U.S. calculations probably due to the difference in the $^7Li(n,n'\alpha)^3T$ cross section data in JENDL 3PR2 and ENDF/B-V.[12] Further examination and improvement in modeling, data and methods is necessary for each analysis mentioned above.

The analyses on the first-walled and Be neutron multiplier systems have been conducted and similar trends were observed.[12] A comparison between the reference and Be sandwiched systems in the C/E values is shown in Fig. 10 for the TPRs from ^{6}Li. The calculation is that of DOT and measured values are those by both on-line and irradiation methods at JAERI. Large fluctuations of the C/E values are observed inside and at the boundaries of Be zone of the Be sandwiched system. This indicates the difficulties both in calculational prediction and experimental determination of the TPR in the system having a heterogeneous configuration. In the rear breeder region of the Be sandwiched assembly, the C/E values are closer to unity than those of the reference case near the Be zone, but gradually increase to the same level at the rear end of the system. The re-examination of Be cross section is in progress to clarify the cause of the C/E difference between the reference and Be sandwiched systems.

SUMMARY

A series of integral neutronics experiments on fusion blanket is being conducted using FNS facility as a collaborative program between JAERI and U.S. DOE. The main objectives of the program is to provide the experimental data needed to determine the accuracy of nuclear calculations and assist the nuclear design of fusion blankets. Experiments on three kinds of systems were carried out as the Phase I of the program: the reference, first-walled and Be neutron multiplier systems. Lithium oxide was used as the breeding material.

Measured parameters were tritium production rate(TPR) and neutron spectrum as a function of position along the central axis in each assembly. Two types of measuring approach were undertaken: on-line counter method and irradiation method. The on-line method was developed to facilitate a parametric study upon different system configurations. In the irradiation method of the TPR, an international comparison was made as a cross-check on the accuracies of the basic measured data.

The characterization of the neutron source - the neutron yield, energy spectrum and spatial distribution - was performed in the first place to establish the input condition for experiments and their analysis. The TPR distributions both from ^{6}Li and ^{7}Li along with the related neutron spectra in the reference system were measured in detail by on-line and irradiation methods. The relative change in TPR due to the attachment of a simulated first wall on the reference assembly were measured for four different configurations. The small changes in TPR values were accurately determined by the on-line methods. The impact of the Be zone addition on the TPR distribution was measured for three different configurations. A considerable increase in the TPR from ^{6}Li was observed in the breeder region around the Be zone. On the TPR values by the irradiation method, good agreement was obtained between JAERI and U.S. both in the reference and Be sandwiched cases.

The analyses of the experiments were carried out independently at JAERI and U.S. by using the deterministic and Monte Carlo methods. Relative shapes in TPR distributions were reasonably well repsented by calculations except for near zone boundaries. Fairly large differences were observed among the analytical results. The calculated to measured value ratios of the TPR range from unity to 1.3 depending on the numerical methods and organizations. The examination on the causes of the differences is in progress. Large differences around the zone boundaries are attributed partly to experimental uncertainties such as self-shielding correction and partly to inadequacy in calculational modeling. Further efforts are required for the improvement on these points.

The Phase I program, a new experimental approach, has provided the means and data effective in examining the accuracies of the nuclear data and methods used to predict the tritium breeding characteristics in blankets.

ACKNOWLEDGMENT

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REFERENCES

1. M. ABDOU, et al., "DT Fuel Self-Sufficiency in Fusion Reactors," *Fusion Technology* 9 [2] 250 (1986)

2. M. ABDOU, "Overview of Analytical and Experimental Efforts on Tritium Breeding," *Fusion Technology* 8 [1] 1525 (1985)

3. D. L. SMITH, et al., "A Blanket Comparison and Selection Study - Final Report," Angonne National Laboratory, ANL/FPP-84/1 (1984)

4. T. TONE, et al., "Conceptual Design of Blanket Structures for Fusion Experimental Reactor (FER)," JAERI-M 83-216 (in Japanese) (1984)

5. F. CARRE, et al., "Status of Fusion Reactor Blanket Evaluation Studies in France," *Fusion Technology* 8 [1] 491 (1985)

6. T. NAKAMURA, et al., "A D-T Neutron Source for Fusion Neutronics Experiments at the JAERI," *Proc. Internationl Ion Engineering Congress -ISIAT '83 & IPAT'83*,Kyoto (1983)

7. H. MAEKAWA, et al., "Blanket Benchmark Experiments on a 60 cm-thick Lithium-Oxide Cylindrical Assembly," to be published in JAERI-M Report

8. T. FUKUMOTO, T. NAKAMURA, Y. SEKI, "Pre-Analysis on Fusion Blanket Neutronics Experiment Utilizing an Experimental Hole of FNS Target Room #2," JAERI-M 83-129, 124 (1983)

9. Y. OYAMA, et al., "Neutron Field Characteristics in a Concrete Cavity Having DT Neutron Source," this proceedings

10. H. MAEKAWA, et al., "Measured Neutron Parameters for Phase I Experiments at the FNS Facility," this proceedings

11. S. YAMAGUCHI, T. NAKAMURA, "Tritium Production Measurements by Lithium-Glass Scintillator Method," this proceedings

12. M. Z. YOUSSEF, et al., "Analysis and Intercomparison for Phase I Experiments at FNS," this proceedings

13. M. Z. YOUSSEF, et al., "U.S./JAERI Fusion Neutronics Calculational Benchmark for Nuclear Data and Codes Intercomparison," PPG-900 UCLA-ENG-85-37/JAERI-M 85-201 (1985)