

Summary of experiments and analyses from the JAERI/USDOE Collaborative Program on Fusion Blanket Neutronics

Hiroshi Maekawa^a, Mohamed A. Abdou^b

^a*Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken, 319-11, Japan*

^b*University of California at Los Angeles, 405 Hilgard Avenue, Los Angeles, CA 90024-1597, USA*

Abstract

The JAERI/USDOE Collaborative Program on Fusion Blanket Neutronics started officially on October 23, 1984 using the intense D–T neutron generator FNS and was concluded in 1993. The program was divided into three phases. The Phase I series was planned for engineering-oriented benchmark experiments and measuring technique development. The Phase II series was characterized by a closed geometry with a slab-type test blanket and the neutron source surrounded by a reflecting enclosure. The experiments provided extensive data on the breeding characteristics of Li₂O and the beryllium neutron multiplication effect in different configurations. The Phase III series was planned to simulate the fusion reactor as practically as possible using a point neutron source. The combination of a pseudo-line source and annular test blanket on the deck can simulate part of tokamak geometry as cylindrical geometry. Since 1988, integral experiments on induced radioactivity and nuclear heating have also been performed under the Collaboration Program. Both Japan and the US have analyzed these benchmark experiments using the latest and/or newly developed data and methods. A novel methodology has been developed to estimate design safety factors and the associated confidence levels.

I. Introduction

In judging the feasibility of D–T fusion power reactors, tritium self-sufficiency using a lithium-containing blanket is one of most severe problems. In the engineering design of a fusion reactor, accuracy of nuclear data, calculational methods, modeling for the details of the structure, etc. strongly affect the estimation of nuclear parameters such as the tritium breeding ratio. It is important in defining the design safety factor to confirm experimentally the reliability of estimated nu-

clear parameters in the design of a fusion reactor under a variety of conditions such as the structure of blanket, selection of lithium-containing material and neutron multiplier, tritium recovery system and so on.

At the Japan–US Workshop on Fusion Neutronics held at JAERI/Tokyo Headquarters in 1982, the discussion was focused on tritium fuel self-sufficiency in D–T fusion reactors. In order to resolve this problem, Japan–US collaborative experiments were recommended. From October 1984, the JAERI/USDOE Collaborative Program on Fusion Blanket Neutronics was

Calendar Year	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
Phase-I RNT,Ref,SS,Be Source Reflection		Pre-WS	IA	IB								
Phase-II Ref, BeS, BeF Be-coverage Hetrogeneous				IIA		IB	IIC					
Phase-III Line source Annular Armor Opening							LS		IIIA	IIIB	IIIC	
Induced Activity Nuclear Heating							↔	↔	↔	↔	↔	
Summary												↔
Contract Period				I			II			III		

Fig. 1. Historical time chart of JAERI/USDOE Collaborative Program on Fusion Blanket Neutronics.

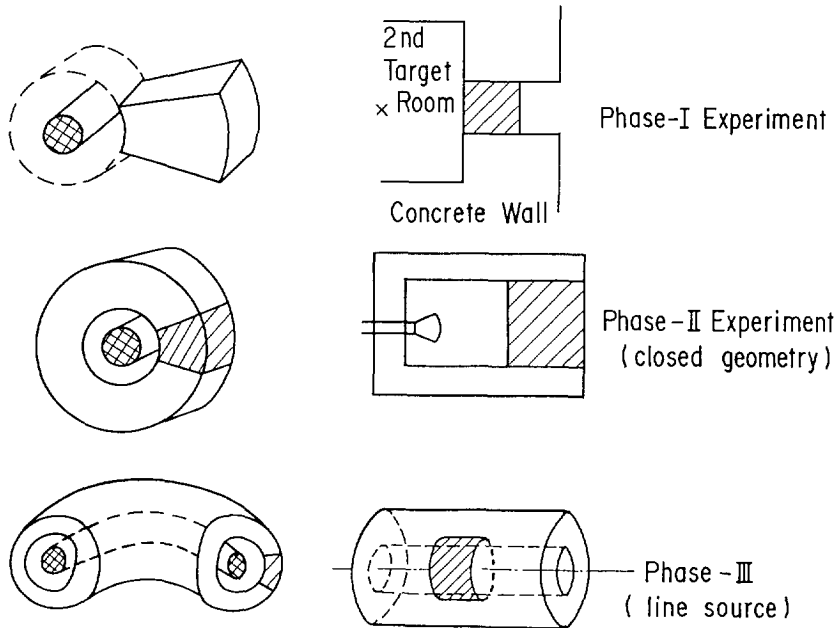


Fig. 2. Stages for the simulation of neutron source and blanket configuration.

started using the Fusion Neutronics Source facility (FNS)[1] as the Annex II to the Implementing Agreement between JAERI and USDOE on Cooperation in Fusion Research and Development. This Annex II was extended twice and completed in October 1993. Many joint reports and papers have been published. Most of

them are shown in the reference list at the end of this paper.

The objectives of this program are:

- (1) to establish new experimental methods for design supportive neutronics experiments;

- (2) to provide experimental data for the assessment of accuracies of nuclear data, calculational methods and response functions (including the kerma factor, etc.) used in the fusion reactor design;
- (3) to develop neutronics technology for the design and testing of next D–T burning fusion devices;
- (4) to provide estimates of uncertainties in satisfying tritium self-sufficiency; and
- (5) to give a guideline of the nuclear design to the fusion reactor designers.

The program was separated into three phases, Phase I, Phase II and Phase III depending on the positioning of the source and test blanket arrangements. Integral experiments on induced radioactivities for both short- and long-lived isotopes, and on total nuclear heating by microcalorimetric techniques were performed in conjunction with Phase III. The historical time chart of this program is shown in Fig. 1. This paper outlines these experiments and summarizes results obtained in this collaborative program.

2. Engineering-oriented blanket benchmark experiments

2.1. Simulation of fusion reactor blanket

For the engineering tests, experiments are usually carried out on a so-called “mock-up” system, namely a test assembly that simulates a design of an actual reactor. In the case of the D–T fusion reactor development, the usage of an accelerator-based D–T source is the only practical way at present for these experiments, since there are no plasma-based fusion devices available with steady neutron production.

It is also almost impossible at present to provide a test system simulating the huge and complex tokamak-type reactor. From the neutronics point of view, a scale-down assembly is equal to the mock-up experiments when a nucleonic simulation is achieved. Therefore partial mock-up experiments would be a realistic solution. From the analysis on a combination of several mock-up experiments, we can estimate the accuracy range of neutronics parameters in the nuclear design of typical fusion reactors.

There are two key variables for the nuclear simulation, namely simulations of geometry and material configuration. Fig. 2 shows the concept of each stage for the simulation of the neutron source and blanket configuration in the JAERI/USDOE collaboration program. The strategy of this program is illustrated in Fig. 3, i.e. how to approach the real fusion reactor. The

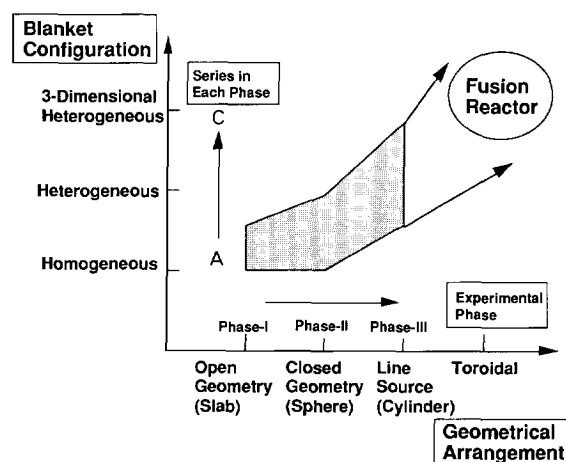


Fig. 3. Strategy for simulation of fusion reactor blanket.

outline of experimental arrangements are summarized in Table 1.

2.2. Phase I experiments [2–4]

A unique feature of the Phase I is the incorporation of the rotating neutron target (RNT) and the target room enclosure into the experimental arrangement. The second 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 at the center of room. By loading a blanket test module in a large experimental port, a part of the enclosure is substituted by a breeding blanket composition shown in Fig. 4.

Neutronics parameters were measured in three series of experiments, i.e. reference, first wall and beryllium (Be) neutron multiplier experiments. Their configurations are summarized in Fig. 5. Lithium oxide (Li_2O) blocks were loaded in the experimental port to form the reference assembly which was the same assembly used in the clean benchmark experiment [5].

For the source neutron characterization, two types of experiments were carried out. One was the measurement of angular distribution and neutron spectrum from the RNT by Th-232 fission counter, NE213 detector and activation foils, and the time-of-flight method, respectively. The second was the incident neutron flux mapping and spectrum at the entrance of port.

Neutronic parameters measured were tritium production rate (TPR) distributions, in-system neutron spectra

Table 1
Outline of experimental arrangement

	Phase I experiments	Phase II experiments	Phase III experiments
Neutron source	Point source $3 \times 10^{12} \text{ n s}^{-1}$	Point source $3 \times 10^{12} \text{ n s}^{-1}$	Line source $1.5 \times 10^9 \text{ n cm}^{-1} \text{ s}^{-1}$
Arrangement	Open geometry	Closed geometry	Annular geometry
Distance between source and test region	250 cm	78 cm	21.3 cm
Test assembly	Lithium oxide 60 cm thick cylinder	Lithium oxide 60 cm thick rectangular	Lithium oxide and lithium carbonate 40 cm thick annulus rectangular
Additional material and arrangement	Be neutron multiplier first wall (SS304, PE)	Be neutron multiplier large opening	Graphite armor
Number of test assembly	9	8	3

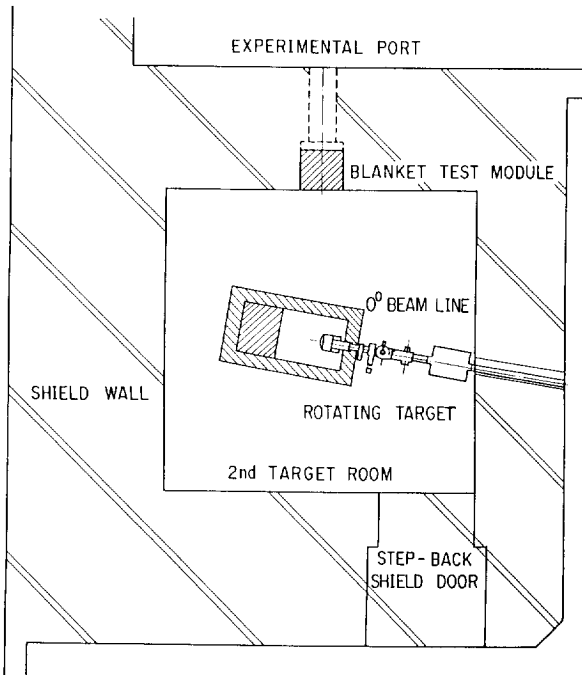


Fig. 4. Experimental arrangements for Phase I and Phase II programs.

and reaction rate distributions by Al, Ni, Zr, In and Au foils. All measurements were performed mainly along the central axis. Techniques used in the three phases are summarized in Table 2. The comparison of TPR of Li-6 (T_6) measured by three different methods is shown in Fig. 6.

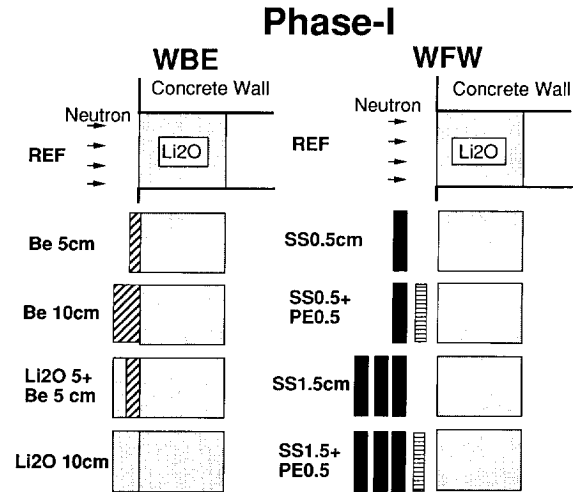


Fig. 5. Configurations for the experiments on first wall effect and neutron multiplier effect.

Our efforts in Phase I were devoted mainly to measuring the TPR. It became clear that the on-line type methods are very powerful technique for survey experiments such as the first-wall experiment. Reasonable agreements are obtained in the TPR data obtained by JAERI and ANL, and also by the on-line and integral type methods. Reaction rates measured by activation foils having various responses are very useful for the evaluation of nuclear data and calculational methods. It has been demonstrated that the neutron spectrum with a wide energy range (from a few keV to 15 MeV) can be measured by use of proton-recoil gas proportional counters and small sphere NE213 spectrometer.

Table 2
Techniques and neutronic parameters measured

Measuring technique	Neutronic parameter measured
<i>On-line detector</i>	
Li-glass scintillator	T production rate of ${}^6\text{Li}$
NE213 liquid scintillator	Neutron spectrum above 2 MeV
Proton-recoil gas proportional counter	T production rate of ${}^7\text{Li}$
	Neutron spectrum of a few keV to 1 MeV
<i>Liquid scintillation counting method</i>	
Zonal method with Li_2O plate/block (extracted by heat-up)	T production rates of ${}^7\text{Li}$ and ${}^{\text{N}}\text{Li}$
Li-metal file (extracted by melting)	T production rates of ${}^6\text{Li}$, ${}^7\text{Li}$ and ${}^{\text{N}}\text{Li}$
Li_2O pellet (resolved in water)	T production rates of ${}^6\text{Li}$, ${}^7\text{Li}$ and ${}^{\text{N}}\text{Li}$
<i>Foil activation method</i>	Reaction rate
<i>Thermoluminescent dosimeter (TLD)</i>	
Self-irradiation method	T production rates of ${}^6\text{Li}$, ${}^7\text{Li}$ and ${}^{\text{N}}\text{Li}$
Interpolation method	Gamma-ray heating rate

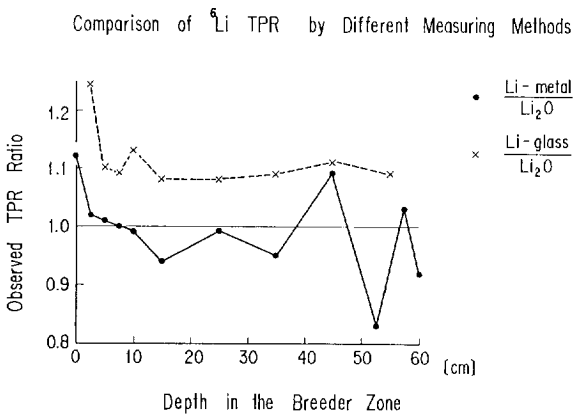


Fig. 6. Comparison of ${}^6\text{Li}$ tritium production rates measured by different methods.

2.3. Phase II experiments [6-11]

The disadvantages inherent in the Phase I series are the room-returned slow neutrons, asymmetric arrangement of the target relative to the test blanket and rather weak intensity of the incident neutron flux. Based on results of detailed analysis, it was concluded that the "closed geometry" was desirable to simulate a fusion reactor environment. Intensive pre-analyses of material arrangements were performed to give better simulation with limited material resources. The re-

sults of the pre-analyses suggested the following for Phase II.

- (1) The rotating neutron target (RNT) should be surrounded by a lithium carbonate (Li_2CO_3) zone to simulate the reflected neutron component.
- (2) The test blanket region should be set at a shorter distance from the target to obtain higher neutron flux.
- (3) The test blanket should be contained in the Li_2CO_3 zone which can work as a buffer region for the room-returned neutrons.
- (4) The outside of Li_2CO_3 should be covered with a polyethylene zone to shield the room-returned neutrons.

Fig. 7 shows the basic concept of the Phase II arrangement. The Phase II series are divided into three periods. The Phase IIA and IIB focused on the neutron multiplication effect of beryllium (Be). In Phase IIA, the Be configuration was changed only for the test region, including the reference system, i.e. lithium oxide (Li_2O) only, while the Phase IIB system had a Be layer as liner on the inner surface of the source cavity, so that the D-T neutron source was fully covered with Be and breeding materials. The Phase IIC examined the heterogeneity and coolant channel effects in the more realistic blanket configuration. Fig. 8 shows the arrangement of Phase II series assemblies.

Three newly developed techniques were applied to the Phase II series in addition to the techniques used in

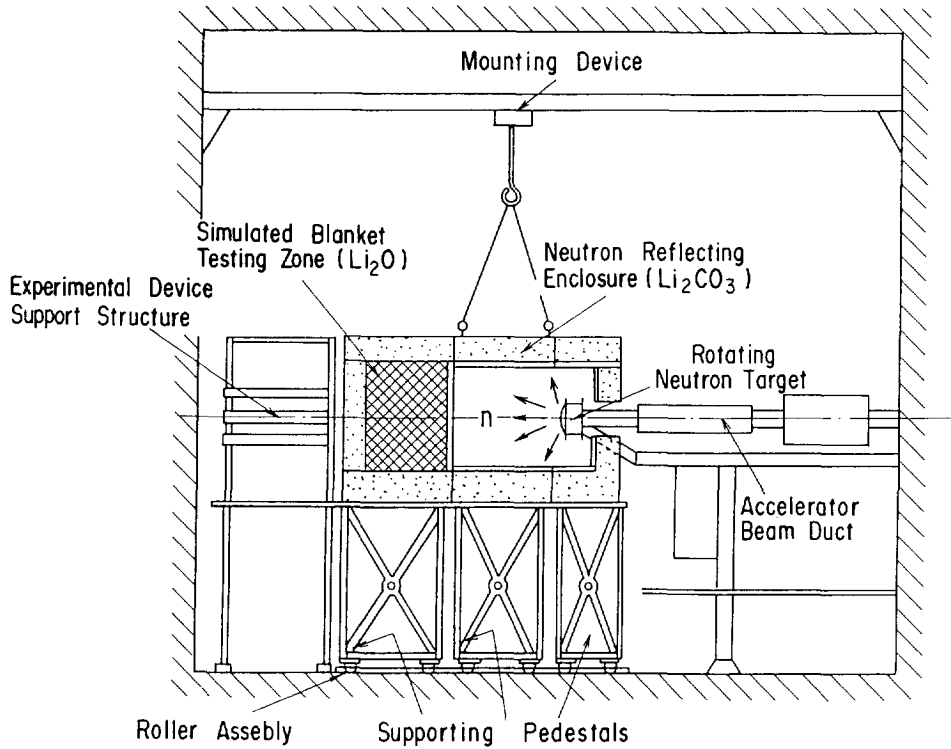


Fig. 7. Basic concept of Phase II arrangement.

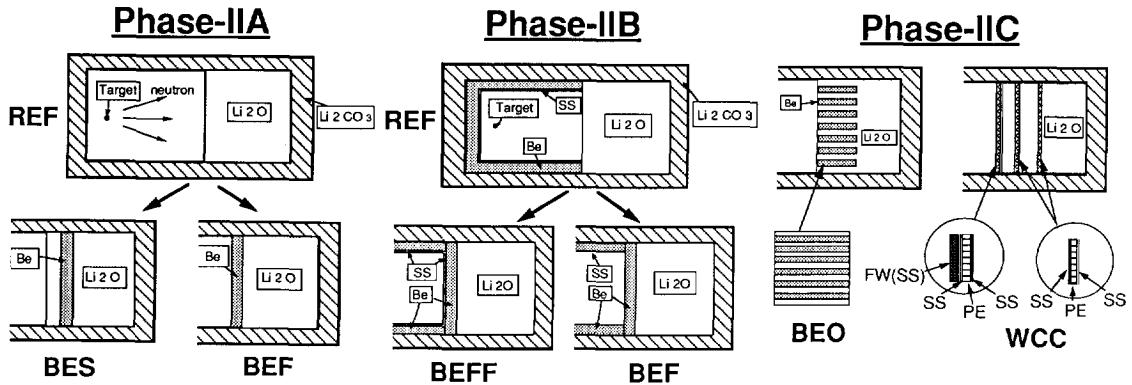


Fig. 8. Arrangement of Phase II series experiments.

Phase I. One is the zonal method for measuring integral TPR of ${}^7\text{Li}$ and ${}^6\text{Li}$ (natural lithium) near the Be and water regions where TPR changes steeply. The other two are the interpolation method with thermoluminescent dosimeters (TLD) and the spectrum weighting function method with the small sphere NE213 spectrometer for the gamma-ray heating rate measurement.

2.4. Phase III experiments [12-15]

The Phase III experiments have been planned to more closely simulate the fusion reactor as practical as possible given the limited resources available.

The objectives of Phase III can be summarized as follows:

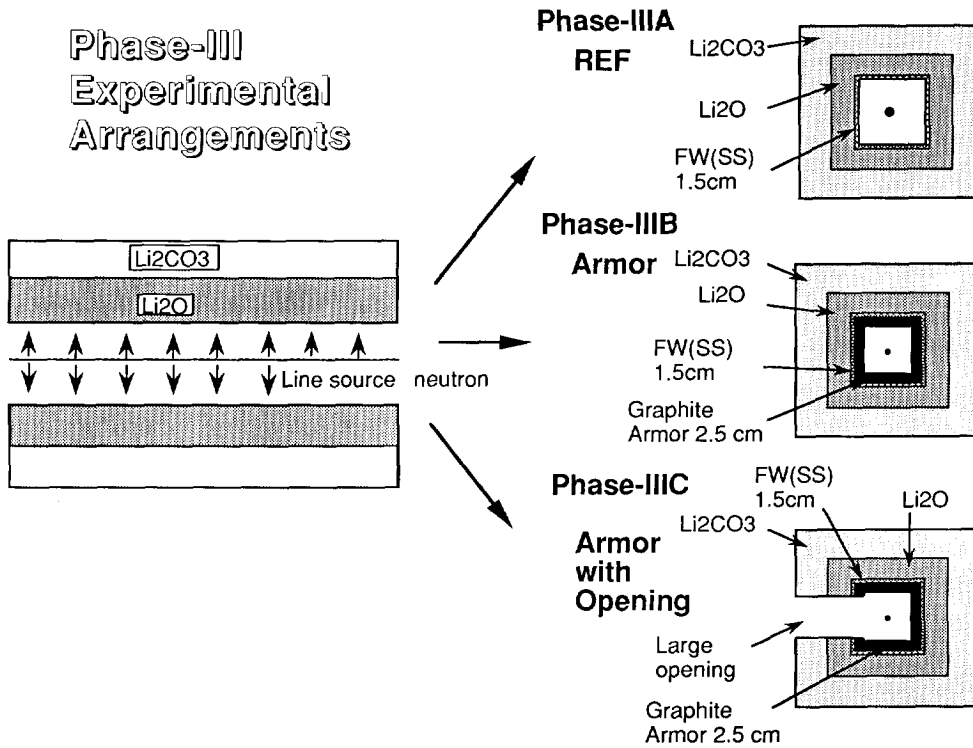


Fig. 9. Arrangement of Phase III series experiments.

- (1) to examine the effect of the source spread;
- (2) to obtain information for annular shape blanket;
- (3) to provide benchmark data for 3-dimensional geometry;
- (4) to examine the effect of graphite armor on tritium breeding;
- (5) to examine the effect of a large opening on tritium breeding.

In order to simulate the source spread, a pseudo line source has been developed using a point D-T neutron source and a moving deck [12,13]. The two modes, "stepwise" and "continuous" were applied to the experiments. In the stepwise mode, the measurements were performed periodically at equal-spaced points over the 2 m length. This mode was applied to the on-line measurements, i.e. the technique using a high sensitive detector such as NE213 spectrometer, proton-recoil proportional counter and Li-glass scintillator. In the continuous mode, the experimental assembly repeated the shuttle motion at the constant speed of 6.2 mm s^{-1} except near the turning points at both ends of 2 m stroke. This mode was adopted in off-line measure-

ments, i.e. irradiation of activation foils, Li_2O samples and thermoluminescent dosimeters (TLD). From the performance test, it was demonstrated that this system gave a good line source. The combination of this line source and annular test blanket can simulate a part of tokamak geometry as a cylindrical geometry. Three types of annular shape fusion test blankets have been examined to install them on the moving deck. They are named Phase IIIA, IIIB and IIIC assemblies, respectively. The Phase IIIA assembly is the reference blanket made of Li_2O and Li_2CO_3 blocks with SS304 first wall region. The Phase IIIB is the Phase IIIA assembly with a graphite armor region in order to investigate the effect of this graphite armor on neutronic parameters such as tritium production rate. The Phase IIIC assembly is the Phase IIIB assembly with a large opening in order to investigate the effect of this opening on the neutronic parameters. These arrangements are shown in Fig. 9.

Most of the techniques used in the Phase III series are followed to the previous Phase I and II series. Some new techniques have been developed and applied to the Phase III experiments using the line source.

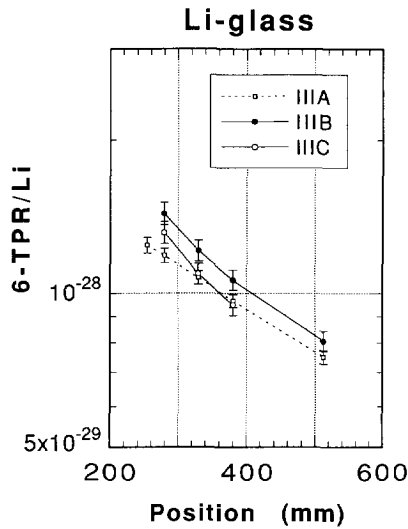


Fig. 10. Tritium production rate distributions of Li-6 in Phase III assemblies.

Useful and reliable benchmark data have been accumulated through the Phase III series experiments. They are TPRs of ${}^6\text{Li}$, ${}^7\text{Li}$ and ${}^9\text{Li}$, various reaction rates measured by activation foils, neutron spectra, gamma-ray spectra, and gamma-ray heating rates. The TPR distributions of ${}^6\text{Li}$ for the three assemblies are shown in Fig. 10. The effect due to the large opening is observed in Phase IIIC result.

2.5. Experiments on induced radioactivities [16–18]

The assessment of decay heat, shutdown dose, radioactive waste and hazard potential is a key issue in the nuclear design of fusion devices. In order to verify the activation codes and associated nuclear data libraries for the nuclear design, benchmark experiments were planned and performed using the D–T neutron fields of Phase IIC, IIIA and IIIC. The irradiated materials were Fe, Ni, Cr, Mn–Cu alloy, Ti, Mo, Zr, Ta, W, Si, Mg, Al, V, Nb, SS316, $\text{YBa}_2\text{Cu}_3\text{O}_7$, $\text{ErBa}_2\text{Cu}_3\text{O}_7$, Sn, Ag, Pb, Zn, In and Au.

Two kinds of analyses on the measured radioactivities were conducted. The first analysis examined the decay gamma-radioactivities integrated over 100 keV to 3 MeV of gamma-ray energy for an irradiated material. This method does not directly look at the role of activation cross-sections in the observed discrepancies between the calculations and measurements. There are other parameters which can contribute to the observed

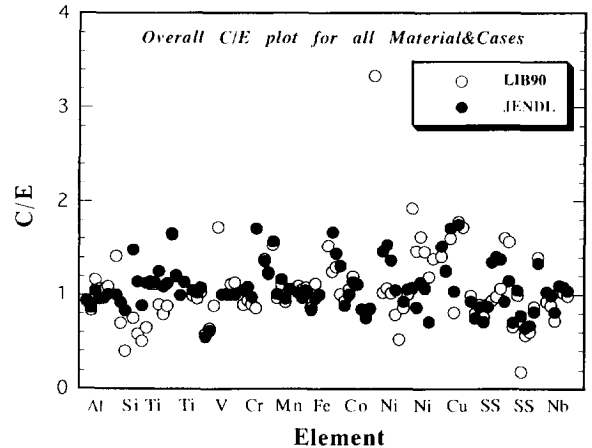


Fig. 11. C/E values for various materials by two versions of THIDA.

C/E discrepancies, i.e. erroneous data of product half-lives, branching ratios and decay gamma-ray yields. The second method was geared to look at each individual isotopic activity measured in the experiments. Activation cross-section libraries of leading radioactivity codes, ACT4/THIDA-2, REAC*2, REAC*3, DKR-ICF and RACC were used to analyze the measured isotopic activities. Fig. 11 shows the improvement of the C/E values for various materials by the new version of THIDA-2.

Major observed facts are as follows.

- (1) Different codes and libraries give large discrepancies in many isotopic radioactivity calculations.
- (2) Serious disagreements between calculation and experiments are observed even for important reaction products, e.g. ${}^{58}\text{Ni}(n,p){}^{58\text{m}}\text{Co}$.
- (3) The JENDL Activation File gives the most preferable results among libraries tested.
- (4) The REAC*3 library with VITAMIN-J structure compatible to EAF-2 have still a number of problems, e.g. ${}^{27}\text{Al}(n,\alpha){}^{24\text{m}}\text{Na}$.

2.6. Experiments on nuclear heating using direct method [19–22]

The nuclear heat deposition rates in a D–T fusion environment have been measured by a newly developed calorimetric technique to provide the data for testing kerma factor libraries. The block-diagram of measuring

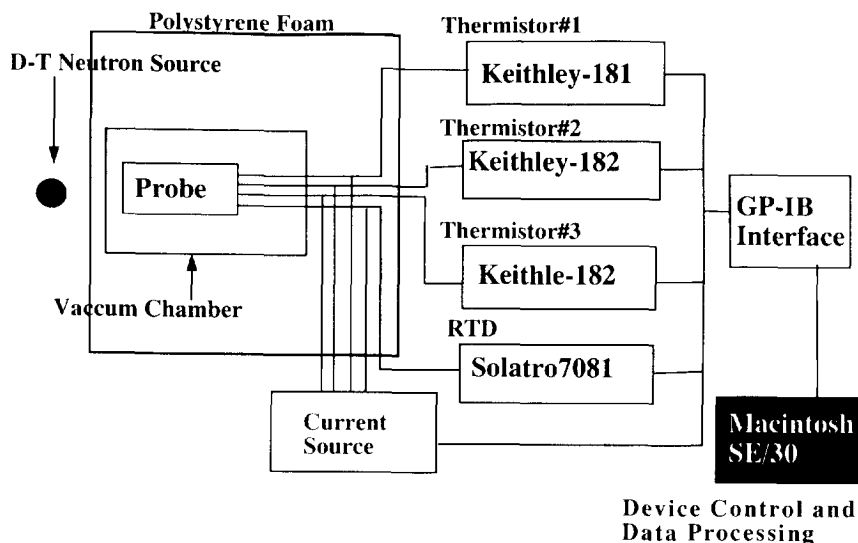


Fig. 12. Block-diagram of direct nuclear heating measurement with micro-calorimeter.

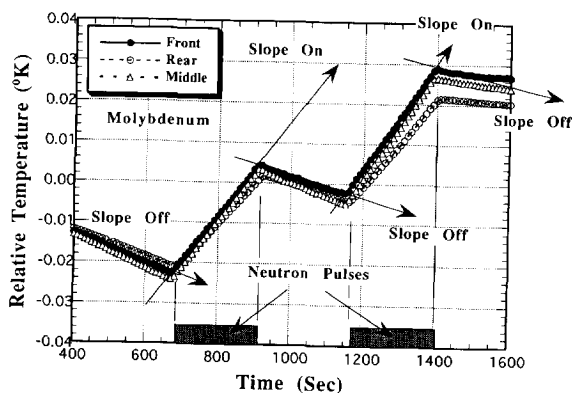


Fig. 13. Row data of temperature change in Mo probe measured by RTD.

system is shown in Fig. 12. Thermistors and platinum RTDs were employed as thermal sensors embedded in calorimeters made of single material (probe). The materials tested were C, Al, Ti, Fe, Cu, Ni, Zn, Zr, Nb, Mo, Sn, W, Pb, SS304 and Li_2CO_3 . Each of these calorimeters was placed inside of a vacuum chamber and set in front of the RNT at the distance of about 80 mm. The calorimeters were subjected to spaced neutron pulses of 3 to 10 minutes duration. Fig. 13 shows a row data of the temperature change in a Mo probe measured by RTD. The measured heat deposition rates ranged from 7 to $30 \mu\text{W g}^{-1}$ for a normalized source strength of 10^{12} n s^{-1} .

The calculations have been performed using both Japanese and US codes and data libraries. Large discrepancies have been found between calculations and measurements. Almost all the C/E values, however, lie in a band extending from 0.5 to 2.0 for all the above materials.

3. Feedback to design of fusion reactors

3.1. Experimental analyses

In JAERI's analysis, the DOT3.5 code [23] was applied in the deterministic method along with the FNSUNCL code [24]. The FUSION-J3 library [25] was used in the DOT3.5 calculations. For the Monte Carlo calculations, the MORSE-DD code [26] or GMVP code [27] was used along with the DDXLIB-J3 library. The GMVP code is the vectorized version of MORSE-DD. Both libraries were based on JENDL-3 [28].

The US group adopted the DOT5.1 code [29] along with the RUFF first collision code [30] for the deterministic treatment. The RUFF code is similar to the FNSUNCL code. In the Monte Carlo treatment, the MCNP-3B code [31] was applied along with continuous energy and angle library based on the ENDF/B-V data.

Calculation methods and nuclear data are summarized in Table 3 for the analyses of these benchmark experiments by both Japan and the US.

The distribution of calculation to experiment ratio (C/E) is very helpful to understand the status of nuclear

Table 3
Calculation codes and nuclear data used in the analyses

	JAERI/Japan	USA
<i>Monte Carlo method</i>		
Code	MORSE-DD, GMVP	MCNP-3A, MCNP-3B
Type of library	DDX, n : 125-group	Point energy
Nuclear data file	JENDL-3PR1 JENDL-3.1	ENDF/B-V
<i>Discrete ordinate (SN) method</i>		
Code	DOT3.5	DOT4.3, DOT5.1
Type of library	n : 125-group, γ : 40-group P-5 or P-7	n : 80-group (MATXS) P-5
Nuclear data file	JENDL-3PR1, -3PR2 JENDL-3.1	ENDF/B-V
Number of quadrature	S-10 or S-16	S-8

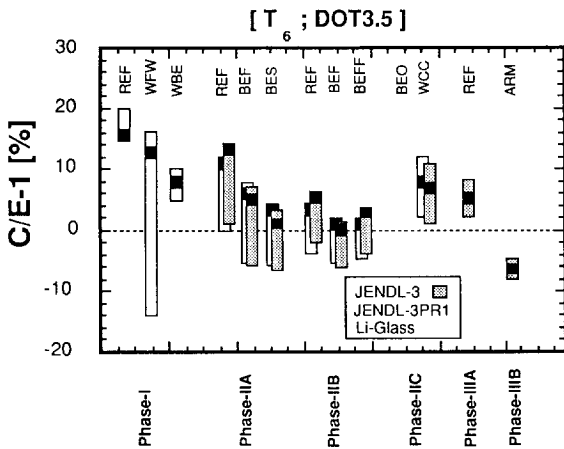


Fig. 14. Gross trend of the C/E of ⁶Li TPR through the whole experiment series for the case of DOT3.5 calculations. (Symbols such as REF are shown in Figs. 5, 8 and 9.)

design accuracy. Fig. 14 shows the C/E distribution of TPR of ⁶Li measured by Li-glass scintillator and DOT3.5 calculation with JENDL-3PR1 and -3.1 for all three phase experiments [32]. The horizontal axis is sort of assembly. The C/E values distribute in the range of bars and the black bars mean the most provable range. The following facts are obtained from this type analysis.

- (1) There is a tendency for underestimation of TPR in the Be-containing systems.

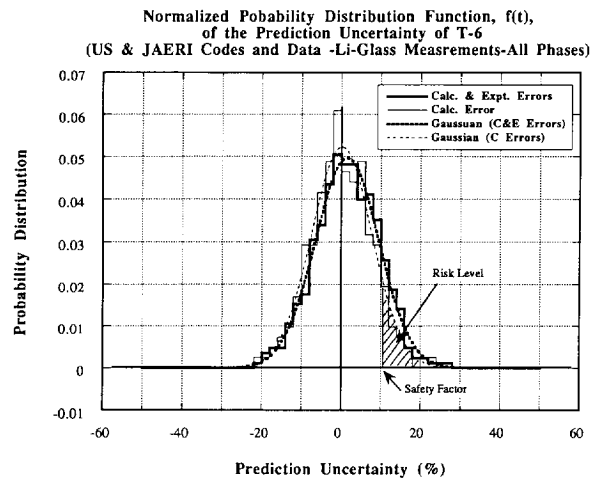


Fig. 15. Probability distribution function of prediction uncertainty (C/E-1) of ⁶Li TPR for all results.

- (2) The accuracy of estimated TPR is within 10% as a whole.

3.2. Estimation of design safety factor and associated confidence level

The experimental and calculational data sets of local tritium production rate (TPR) in each experiment were interpolated to give estimate to the prediction uncer-

tainty of the line-integrated TPR, a quantity that is closely related to the tritium breeding ratio (TBR) in the test assembly. The calculational and experimental uncertainties (errors) in a local TPR (i) in experiment are propagated and thus contributed to the prediction uncertainty, u_i , in the integrated TPR and its standard deviation, σ_i . An approach is also pursued to give estimates to the prediction uncertainty in the volume-integrated TPR based on measurements and calculations of local TPR in the traverse direction. A novel methodology has been developed to arrive at estimates to a kind of design safety factor which assist fusion reactor designers to ensure the achievable TBR in a blanket not falling below unity [33]. For this purpose, a normalized distribution function (NDF) was constructed from the prediction uncertainties, u_i 's, and their associated deviations, σ_i 's calculated for all the experiments carried out during the program. Important statistical parameters were calculated from the NDF such as the global mean prediction uncertainty, \bar{u} , and the possible spread, $\pm \sigma_u$, around it. The design safety factors were then derived from these NDFs and they account for the discrepancies found between various calculational methods and data (e.g. discrete ordinates code, Monte Carlo code, JENDL-3, ENDF/B-V, etc.) and measured values based on various experimental techniques. Associated with each safety factor is the confidence level a designer may choose to have that a calculated TPR will not exceed the actual measured value. Higher confidence levels require larger safety factors. Tabular and graphical forms for these factors were developed as derived independently for TPR from ${}^6\text{Li}$, ${}^7\text{Li}$ and ${}^{\text{N}}\text{Li}$. As a sample of the graphs, the distributions of estimation accuracy are shown in Fig. 15 for the local TBR by Li-glass scintillator and all four calculations [33]. For example, when we design the blanket with 10% margin, i.e. safety factor of 1.1, considering the 10% overestimation in the calculation shown in Fig. 15, the shadowed area (risk probability) suggests a possibility of additional overestimation, i.e. the TBR of a fusion reactor becomes insufficient.

Fusion blanket designers can obtain the required safety factors from the tables and graphs mentioned above for a wide range of confidence levels which could be applied to the calculations of TPR for ${}^6\text{Li}$, ${}^7\text{Li}$ and ${}^{\text{N}}\text{Li}$. It should be emphasized, however, that these safety factors are applicable to TPR in Li_2O breeding material as obtained from the JAERI/USDOE Collaborative Program based on simplified prototypical fusion blanket assemblies under very ideal neutron source conditions. The safety factors obtained in this work are defined for a typical case, so-called "good geometry",

i.e. well-defined geometry, and not for "complex 3-dimensional configuration" such as a real fusion device, ITER. Further efforts are needed to obtain the final safety factors, i.e. the safety factors for real fusion devices and reactors with complex geometry and configuration.

4. Concluding remarks

This Collaborative Program has been completed successfully utilizing resources, techniques and manpower of both sides. Its period is 9 years officially and more than 10 years actually. We believe this Collaboration gave us mutual benefits and it serves as an excellent example for international collaboration.

Major achievements and output can be summarized as follows.

- (1) A valuable benchmark data base such as tritium production rate (TPR) have been accumulated from Phase I, II and III experiments, and induced radio-activities and nuclear heating experiments.
- (2) New techniques have been developed for the measurements of neutron spectra, TPR and other nuclear parameters.
- (3) Experimental analyses were carried out by the latest and/or newly developed data and methods, e.g. GMVP, MCNP, JENDL-3, and ENDF/B.
- (4) A novel methodology has been developed to estimate design safety factors and the associated confidence levels. Fusion blanket designers can use this method to assess tritium self-sufficiency.
- (5) These safety factors are based on the prediction uncertainties of TPR as derived from the numerous calculational and experimental data accumulated during the program.
- (6) For individual radioactive isotope generation, safety factors were also estimated for ~ 20 materials of interest to fusion application. In addition, detailed systematic study has been performed using C/E data to quantify the quality of various activation cross section libraries in predicting level of radioactivity in various blankets.

Acknowledgments

The authors would like to express their great appreciation to the many scientists who have contributed to making the JAERI/USDOE collaborative effort on the fusion blanket neutronics a great success. They also

thank the FNS operator group for their excellent support to the experiments, and the program managers and government officials who have supported this collaborative program. The US activities have been supported by the US Department of Energy, Office of Fusion Energy.

References

- [1] T. Nakamura, H. Maekawa, J. Kusano, Y. Oyama, Y. Ikeda, C. Kutsukake and S. Tanaka, Fusion neutronics source (FNS), Proc. of the 3rd Symp. on Accelerator Science and Technology, August 27–29, 1980, Osaka Univ. Osaka, Japan, pp. 55–56.
- [2] T. Nakamura and M.A. Abdou, Summary of recent results from the JAERI/US fusion neutronics Phase I experiment, *Fusion Technol.* 10 (1988) 541.
- [3] H. Maekawa, T. Nakamura, Y. Oyama, Y. Ikeda, S. Yamaguchi, K. Tsuda, K. Oishi, K. Porges, E. Bennett, T. Yule and G. DiIorio, Measured neutron parameters for Phase I experiments at the FNS facility, *Fusion Technol.* 10 (1988) 564.
- [4] M. Nakagawa, T. Mori, K. Kosako, Y. Ikeda, T. Nakamura, M. Youssef, C. Gung, M. Abdou, R. Santoro, R. Alsmiller, J. Barnes and T. Gabriel, JAERI/US Collaborative Program on Fusion Neutronics, Phase I Fusion Integral Experiments, Analysis, JAERI-M 88-177, Japan Atomic Energy Research Institute, 1988; UCLA-ENG-88-15 University of California at Los Angeles, 1988.
- [5] H. Maekawa, Y. Ikeda, Y. Oyama, S. Yamaguchi, K. Tsuda, T. Fukumoto, K. Kosako, M. Yosizawa and T. Nakamura, Fusion Blanket Benchmark Experiments on a 60 cm-thick Lithium-Oxide Cylindrical Assembly, JAERI-M 86-182, Japan Atomic Energy Research Institute, 1986.
- [6] Y. Oyama, S. Yamaguchi, K. Tsuda, Y. Ikeda, C. Konno, H. Maekawa, T. Nakamura, K.G. Porges, E.F. Bennett and R.F. Mattas, Phase IIA and IIB Experiments of JAERI/USDOE Collaborative Program on Fusion Blanket Neutronics, JAERI-M 89-154, Japan Atomic Energy Research Institute, 1989.
- [7] M. Nakagawa, T. Mori, K. Kosako, Y. Oyama and T. Nakamura, JAERI/USDOE Collaborative Program on Fusion Blanket Neutronics: Analysis of Phase IIA and IIB Experiments, JAERI-M 89-154, Japan Atomic Energy Research Institute, 1989.
- [8] M.Z. Youssef, M.A. Abdou, Y. Watanabe and P.M. Song, US/JAERI Collaborative Program on Fusion Neutronics: Phase IIA and IIB Fusion Integral Experiments: The US Analysis, UCLA-ENG-90-14 FNT-31, University California at Los Angeles, 1989.
- [9] Y. Oyama, C. Konno, Y. Ikeda, S. Yamaguchi, K. Tsuda, H. Maekawa, T. Nakamura, K. Kosako, M. Nakagawa, T. Mori, A. Kumar, M. Youssef, M. Abdou, Y. Watanabe, K. Porges, E. Bennett and R. Mattas, Phase IIC Experiments of the JAERI/USDOE Collaborative Program on Fusion Blanket Neutronics: Experiments and Analysis of the Heterogeneous Fusion Blanket, Volume I: Experimental Results, JAERI-M 92-182, Japan Atomic Energy Research Institute, 1992; UCLA-FNT-63/UCLA-ENG-93-18 University of California at Los Angeles, 1993.
- [10] Y. Oyama, C. Konno, Y. Ikeda, S. Yamaguchi, K. Tsuda, H. Maekawa, T. Nakamura, K. Kosako, M. Nakagawa, T. Mori, A. Kumar, M. Youssef, M. Abdou, Y. Watanabe, K. Porges, E. Bennett and R. Mattas, Phase IIC Experiments of the JAERI/USDOE Collaborative Program on Fusion Blanket Neutronics --- Experiments and Analysis of the Heterogeneous Fusion Blanket, Vol. II: Analysis, JAERI-M 92-183, Japan Atomic Energy Research Institute, 1992; UCLA-FNT-64/UCLA-ENG-93-19 University of California at Los Angeles, 1993.
- [11] Y. Oyama, S. Yamaguchi, K. Tsuda, Y. Ikeda, C. Konno, H. Maekawa, T. Nakamura, K. Porges and E.F. Bennett, Measured characteristics of Be multi-layered and coolant channel blankets: Phase IIC experiments of the JAERI/USDOE Collaborative Program, *Fusion Technol.* 19 (1991) 1955.
- [12] T. Nakamura, Y. Oyama, Y. Ikeda, C. Konno, H. Maekawa et al., A line D–T neutron source facility for annular blanket experiment: Phase III of the JAERI/USDOE Collaborative Program on Fusion Neutronics, *Fusion Technol.* 19 (1991) 1873.
- [13] C. Konno, Y. Oyama, Y. Ikeda, K. Kosako, H. Maekawa et al., Measurements of the source term for annular blanket experiment with a line source, *Fusion Technol.* 19 (1991) 1885.
- [14] Y. Oyama, C. Konno, Y. Ikeda, F. Maekawa, K. Kosako, T. Nakamura, H. Maekawa, A. Kumar, M.Z. Youssef, M.A. Abdou, Y. Watanabe and E.F. Bennett, Phase III Experiments of the JAERI/USDOE Collaborative Program on Fusion Blanket Neutronics-Line Source and Annular Blanket Experiments, Vol. I: Experiment, JAERI-M 94-015, Japan Atomic Energy Research Institute, 1994; UCLA-FNT-75/UCLA-ENG-93-85 University of California at Los Angeles, 1994.
- [15] Y. Oyama, C. Konno, Y. Ikeda, F. Maekawa, K. Kosako, T. Nakamura, H. Maekawa, A. Kumar, M.Z. Youssef, M.A. Abdou, Y. Watanabe and E.F. Bennett, Phase III Experiments of the JAERI/USDOE Collaborative Program on Fusion Blanket Neutronics-Line Source and Annular Blanket Experiments, Vol. II: Analysis, to be published in JAERI-M and UCLA-FNT/UCLA-ENG report.
- [16] Y. Ikeda, A. Kumar, C. Konno, K. Kosako, Y. Oyama, T. Nakamura, H. Maekawa, M.Z. Youssef and M.A. Abdou, Measurements and analyses of decay radioactivity induced in structural materials, to be published in a special issue of *Fusion Technol.*
- [17] A. Kumar, Y. Ikeda, M.A. Abdou, M.Z. Youssef, C. Konno, K. Kosako, Y. Oyama, T. Nakamura and H. Maekawa, Measurements and analyses of decay radioactivity induced in plasma facing component materials, to be published in a special issue of *Fusion Technol.*

- [18] A. Kumar, Y. Ikeda, M.A. Abdou, M.Z. Youssef, C. Konno, K. Kosako, Y. Oyama, T. Nakamura and H. Maekawa, Measurements of D-T neutron induced radioactivity in plasma-facing materials and their role in qualification of activation cross-section libraries and codes, submitted to ISFNT-3.
- [19] Y. Ikeda, A. Kumar, K. Kosako, C. Konno, Y. Oyama, F. Maekawa, M.Z. Youssef, M.A. Abdou and H. Maekawa, Integral test of kerma data for SS304 stainless steel in the D–T fusion neutron environment, submitted to ISFNT-3.
- [20] A. Kumar, Y. Ikeda, M.A. Abdou, M.Z. Youssef, C. Konno, K. Kosako, Y. Oyama, T. Nakamura and H. Maekawa, Calorimetric measurements of nuclear heating in small probes of plasma-facing materials, submitted to ISFNT-3.
- [21] Y. Ikeda, A. Kumar, C. Konno, K. Kosako, Y. Oyama, T. Nakamura, H. Maekawa, M.Z. Youssef and M.A. Abdou, Direct nuclear heating measurements and analyses for C, Fe, Ni, SS304, Al, W, Nb, to be published in a special issue of Fusion Technol.
- [22] A. Kumar, Y. Ikeda, M.A. Abdou, M.Z. Youssef, C. Konno, K. Kosako, Y. Oyama, T. Nakamura and H. Maekawa, Direct nuclear heating measurements and analyses for Ti, Zr, Mo, Pb, Cu, Sn, and Li_2CO_3 , to be published in a special issue of Fusion Technol.
- [23] W.A. Rhoades and F.R. Mynett, The DOT-III, Two-Dimensional Discrete Ordinate Transport Code, ORNL-TM-4280, Oak Ridge National Laboratory, 1973.
- [24] K. Kosako, FNSUNCL, personal communication, 1990.
- [25] K. Maki, K. Kosako, Y. Seki and H. Kawasaki, Nuclear Group Constant Set FUSION-J3 for Fusion Reactor Nuclear Calculations based on JENDL-3, JAERI-M 91-072, 1991 (in Japanese).
- [26] M. Nakagawa and T. Mori, MORSE-DD, A Monte Carlo Code Using Multigroup Double Differential Form Cross Sections, JAERI-M 84-126, Japan Atomic Research Institute, 1984.
- [27] M. Nakagawa, T. Mori and M. Sasaki, Comparison of vectorization methods used in a Monte Carlo code, Nucl. Sci. Eng. 107 (1991) 58.
- [28] K. Shibata, T. Nakagawa, T. Asami, T. Fukahori, T. Narita, S. Chiba, M. Mizumoto, A. Hasegawa, Y. Kikuchi, Y. Nakajima and S. Igarashi, Japanese Evaluated Nuclear Data Library, Version --JENDL-3--, JAERI 1319, Japan Atomic Energy Research Institute, 1990.
- [29] W.A. Rhoades and R.L. Childs, An Updated Version of the DOT4 (Version 4.3) One- and Two-Dimensional Neutron/Photon Transport Code, ORNL-5851, Oak Ridge National Laboratory, 1982.
- [30] L.P. Ku and J. Kolibal, RUFF-A Ray Tracing Program to Generate Uncollided Flux and First Collision Source Moments for DOT4, A User's Manual, EAD-R-16, Plasma Physics Laboratory, Princeton University, 1980.
- [31] Los Alamos Monte Carlo Group, MCNP-A General Monte Carlo Code for Neutron and Photon Transport, Version 3A, LA-7396, Rev. 2, Los Alamos National Laboratory, 1986.
- [32] Y. Oyama, K. Kosako, M. Nakagawa, T. Nakamura, Comparative study of systems and nuclear data in C/E ratio for a series of JAERI/USDOE Collaborative Fusion Blanket Experiment, Fusion Eng. Des. 18 (1991) 281.
- [33] M.Z. Youssef, A. Kumar, M.A. Abdou, Y. Oyama, C. Konno, F. Maekawa, Y. Ikeda, K. Kosako, M. Nakagawa, T. Mori and H. Maekawa, Quantification of design margins/safety factors based on the prediction uncertainty in tritium production rate from the integral experiments of the USDOE/JAERI Collaborative Program on Fusion Blanket Neutronics, to be published in a special issue of Fusion Technol.