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BLANKET ENGINEERING

KEYWORDS: *fusion blanket, tritium breeding, lithium-oxide*

A SUMMARY OF BENCHMARK EXPERIMENTS FOR SIMULATION OF FUSION REACTORS USING AN ANNULAR BLANKET WITH A LINE DEUTERIUM-TRITIUM SOURCE

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The Japan Atomic Energy Research Institute (JAERI)/U.S. Department of Energy collaborative program was performed using the Fusion Neutronics Source facility at JAERI. In Phase III of this program, tritium breeding measurements were conducted in prototypical blankets driven by a simulated deuterium-tritium neutron line source. This phase differed from the earlier two phases in respect to the spatial distribution of the source as the earlier experiments were done with a point neutron source. This series basically consisted of an annular test blanket and a pseudoline source to investigate the effect of source spread on the neutronic performance. A concise description is on the outlines of the simulated line source, the test blanket systems for Phases-IIIA, -IIIB, and -IIIC, measured items, experimental results, and their analyses.

I. INTRODUCTION

The Japan Atomic Energy Research Institute (JAERI)/U.S. Department of Energy (U.S. DOE) collaborative program on fusion blanket neutronics started formally in 1984. The Fusion Neutronics Source (FNS) facility[1] was used for the experiments. The program set out the following objectives:

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

The program developed into three phases based on the source and test blanket arrangements. Figure 1 shows the concept of each stage for simulation of the neutron source and the blanket configuration in the JAERI/U.S. DOE collaborative program, along with the idea of clean benchmark experiments, which provide the benchmark data used for the verification of nuclear data files and calculation methods.

The Phase-I series[2,3] was planned for engineering-oriented benchmark experiments, measuring technique development, and comparison of data and methods used in the fusion neutronics. Slab-type test blanket assemblies were embedded in the experimental port between the first and second target rooms of the FNS facility. The D-T neutrons were generated at the center of the second target room using a rotating target.

The Phase-II series was characterized by a closed geometry with a slab-type test blanket and the neutron source fully covered by a reflecting enclosure. This arrangement provided a good simulation of the neutron spectrum in a typical fusion reactor blanket. The experiments generated extensive data on breeding characteristics of Li_2O and the beryllium neutron multiplication effect in different configurations.[4-8]

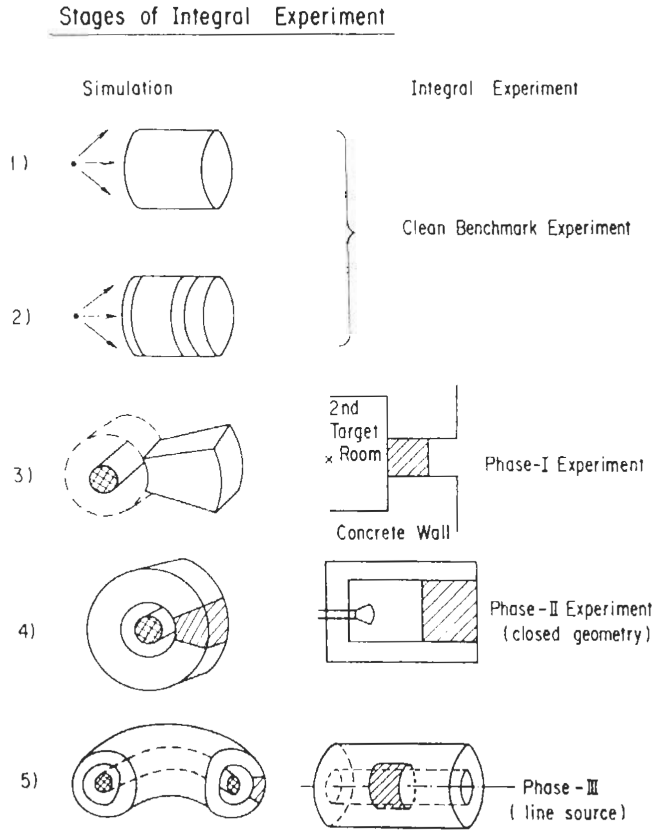

Fig. 1. Stages for the simulation of the neutron source and blanket configuration in the JAERI/U.S. DOE collaborative program along with the idea of a clean benchmark experiment.

This paper presents outlines of the Phase-III experiments and their analyses in the framework of the JAERI/U.S. DOE collaborative program on fusion blanket neutronics, which was completed in October 1993. The time schedule of this collaborative program is illustrated in Fig. 2.

II. PURPOSE OF PHASE-III

The Phase-III program was motivated by a need to investigate the effect of spatial distribution of the source on neutronic performance parameters such as the tritium production rate. Whereas the Phase-II concept is great while examining the spatial distribution across the full blanket thickness, the point source arrangement presents an inherent limitation when it comes to simulating the angular distribution of an extended source. A strategy of the benchmark experiments for the simulation of fusion reactors in this collaborative program is illustrated schematically in Fig. 3. A real tokamak-type fusion reactor has a three-dimensional toroidal shape with a heterogeneous configuration. Namely, a doughnut-shaped plasma region is surrounded by reactor components such as the first wall, divertor, breeding blanket, shielding, and so on.

The Phase-III experiments were planned to simulate the fusion reactor as closely as possible, in the sense of benchmarks, using limited resources. For this purpose a pseudoline source was developed.[9] The combination of this line source and the annular test blanket can simulate a part of the tokamak geometry as a cylindrical geometry.

The aims of Phase-III can be summarized as follows:

1. to examine the effect of source spread
2. to obtain information for the annular shape blanket
3. to provide benchmark data for three-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.

III. DEVELOPMENT OF LINE SOURCE

The pseudoline source was installed in target room number 1 of the FNS. The general concept illustrated in Fig. 4 was planned and incorporated in the floor plan of the FNS building. An annular test blanket was assembled in a frame mounted on a heavy load carriage deck. The carriage shuttled back and forth on the rails so that a titanium-tritium target, mounted on the tip of a specially designed long-sized slim beam line duct, virtually traveled along the central axis of the cavity inside the test blanket from one end to the other. The carriage deck was driven by a computer controlled servomotor. A uniform intensity line source was thus simulated by moving the annular test blanket assembly back and forth a number of times. The following two modes were applied to the experiments:

III.A. Stepwise Mode

In the stepwise mode, the measurement was performed periodically at equal-spaced points over the entire 2-m length. This mode was applied to the on-line measurements, e.g., the technique using a highly sensitive detector such as the NE-213 spectrometer, the proton-recoil proportional counter, and the Li-glass scintillator. Measured data were taken for each source position separately, thus giving the importance of different source positions to the overall result. A personal computer was deployed to position the assembly with an accuracy of 1 mm. These discrete source point measurements were corrected for the effect of neutron yield variation and were synthesized to obtain line source equivalent results.

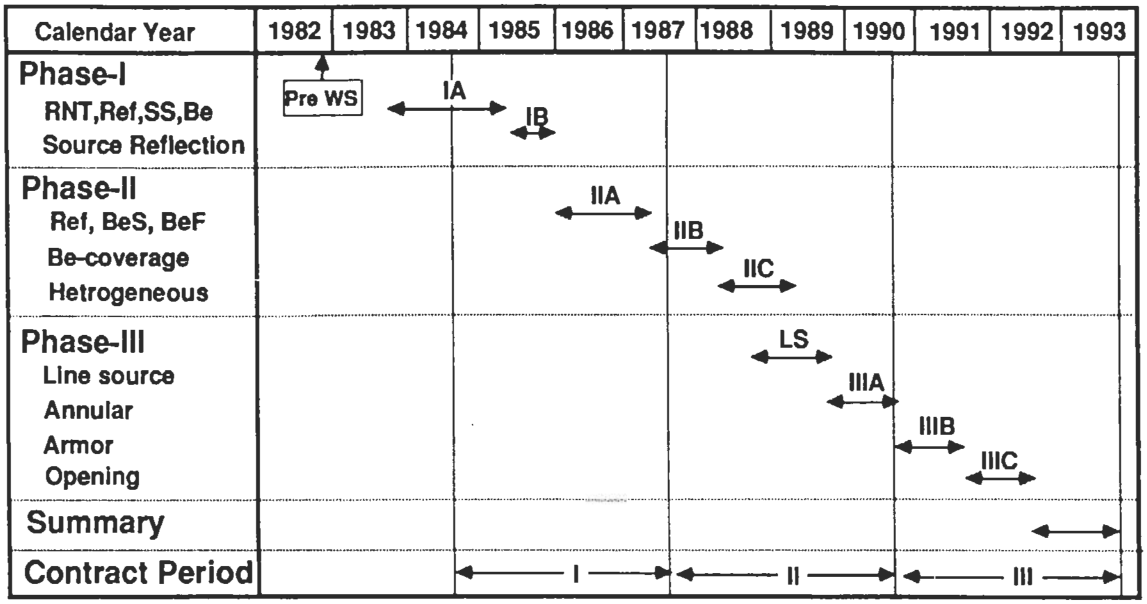

Fig. 2. Historical timetable of the JAERI/U.S. DOE collaborative program.

III.B. Continuous Mode

In the continuous mode, the experimental assembly repeated the shuttle motion at a constant speed of 6.2 mm/s, except near the turning points at both ends of the 2-m stroke. It took 11 min for a complete cycle. This mode was adopted in off-line measurements, i.e., irradiation of activation foils, Li_2O samples, and thermoluminescence dosimeters. Because these methods generally require high neutron fluence, the adoption of

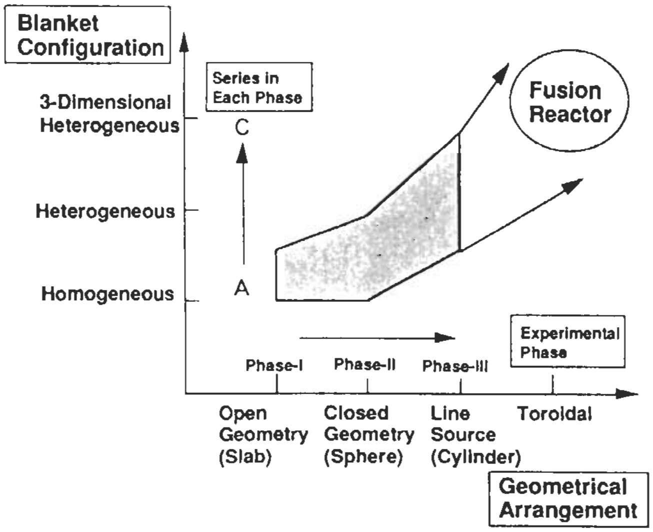

Fig. 3. Strategy for the simulation of a fusion reactor blanket in the JAERI/U.S. DOE collaborative program.

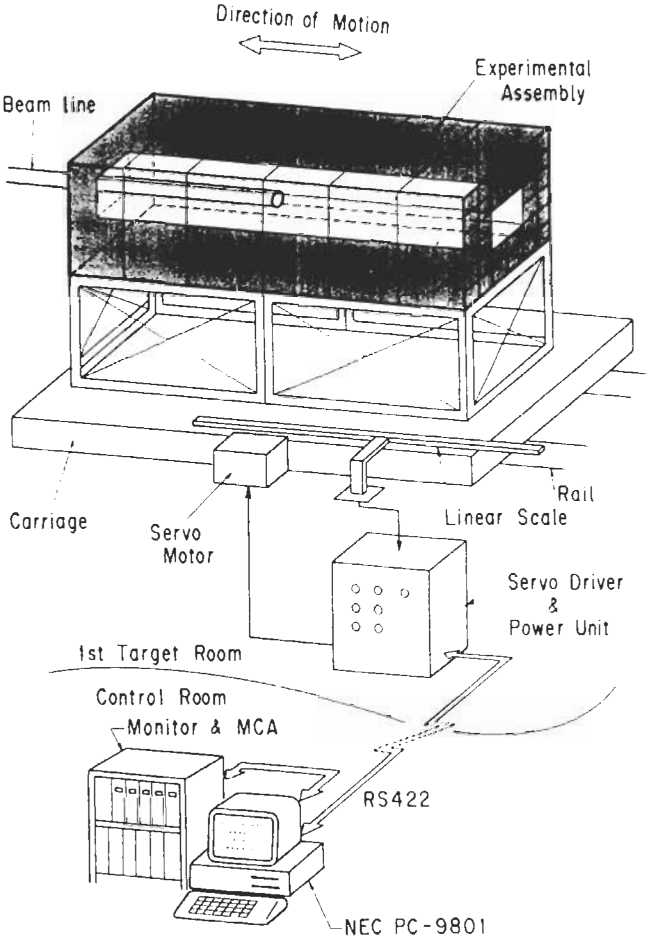

Fig. 4. General concept for the FNS line source arrangement.

the stepwise mode would have unnecessarily lengthened the total experimental time.

IV. OUTLINE OF EXPERIMENTS

In 1988, the deck driving system was modified so as to construct the line source. At the same time, Li_2CO_3 blocks of ~4 t were prepared to complement the insufficient stock of existing Li_2O blocks, weighing 1.2 t. Because of cost considerations, it was unthinkable to buy Li_2O blocks.

IV.A. Source Characterization

Before the start of Phase-III experiments in 1989, the line source performance was measured in both stepwise and continuous operation modes.[10] In the case of the stepwise mode, the fast flux distributions at 200, 400, and 600 mm from the line source were taken at the same time by three equivalent NE-213 detectors. The fast flux above 10 MeV was obtained by the NE-213 detectors using the spectrum weighting function method.

In the case of the continuous mode, reaction rate distributions were measured along a line of 2-m length and parallel to the central axis, by aluminum, titanium, iron, cobalt, nickel, zinc, niobium, indium, and gold foils. The distance between the central axis and the line was 219 mm. Because the line source was simulated by time averaging in the continuous mode, the time dependence of the nuclear response had to be corrected by using the time-dependent source position and neutron yield data. For each activation detector, the neutron flux varies by $1/r^2$ dependence with the source position moving along the pseudoline source.

The neutron flux distribution around the line source was calculated by the FNSUNCL code, which is a modified version of the GRTUNCL code.[11] The FNSUNCL code is able to calculate the first collision source from the distributed source by summing up the contributions from the distributed point sources taking account of the angular distribution of the energy spectrum and the emission probability, which were obtained from a Monte Carlo calculation. The measured fast neutron flux and reaction rate distributions were compared to the calculated ones. A good agreement was observed between them. It was demonstrated that the present line source was flat in the central region over the 1-m length and the source term obtained by FNSUNCL could be applied to a follow-up transport calculation.

IV.B. Phase-IIIA

The Phase-IIIA experiment was performed in 1989 on the square-shaped annular blanket assembly named the "reference test blanket." This assembly had a simple configuration consisting only of a first wall and a breeder zone. The assembly was formed by stacking blocks with the following unit sizes: Li_2O blocks with a 50.6-mm unit size or its multiples covered with 0.3-mm-thick stainless steel and Li_2CO_3 blocks with a 101.2-mm unit size covered with epoxy paint. Both stainless steel and epoxy paint protect the Li_2O or Li_2CO_3 against humidity and CO_2 in air, and they confine the tritium produced in the blocks. A first wall of 15-mm-thick Type 304 stainless steel was added in front of the breeder zone. The outer size of the first wall was 455.5 mm square and 2040 mm long. The breeder zone was made of 203-mm-thick Li_2O and 203-mm Li_2CO_3. Figure 5 shows the concept of Phase-III assemblies. A photograph of the Phase-IIIA assembly is shown in Fig. 6.

Measured items included tritium production rates (TPR), neutron spectra, and reaction rate distributions. The detectors and techniques employed for these measurements are summarized in Table I.

Three techniques were applied to this Phase-III series. The technique of proton-recoil proportional counting was particularly developed to reduce the measurement time and data processing.[12] In the conventional technique, several high-voltage runs are separately needed for getting a neutron spectrum at one measurement point alone, while the developed technique gives the spectrum a single run using a high-voltage sweep with a ramp mode (sawtooth shape.) The second technique was a multidetector acquisition system for ^6Li tritium production rate measurement by Li-glass scintillation detectors. A pair of detectors of ^6Li- and ^7Li-glass scintillators are symmetrically placed in experimental drawers on both sides of the axis. When the neutron source is relatively moving from one end to the other of the assembly, the background contribution due to

TABLE I

Measured Neutronic Parameters and Their Methods

Tritium production rate
- Liquid scintillation counting method with $^6Li_2O$, $^7Li_2O$, and $^NLi_2O$ for T_6, T_7, and T_N
- Subtraction method with a pair of ^6Li- and ^7Li-glass scintillation detectors for T_6
- Spectrum weighting function method with NE-213 scintillation detector for T_7

Neutron spectrum
- NE-213 spectrometer for a neutron spectrum above 2 MeV
- Proton-recoil proportional counters of H_2 and H_2/Ar for a neutron spectrum of a few keV to 1 MeV

Reaction rate distribution
- Foil activation method with niobium, aluminum, nickel, gold, indium, titanium, zirconium, iron, and cobalt

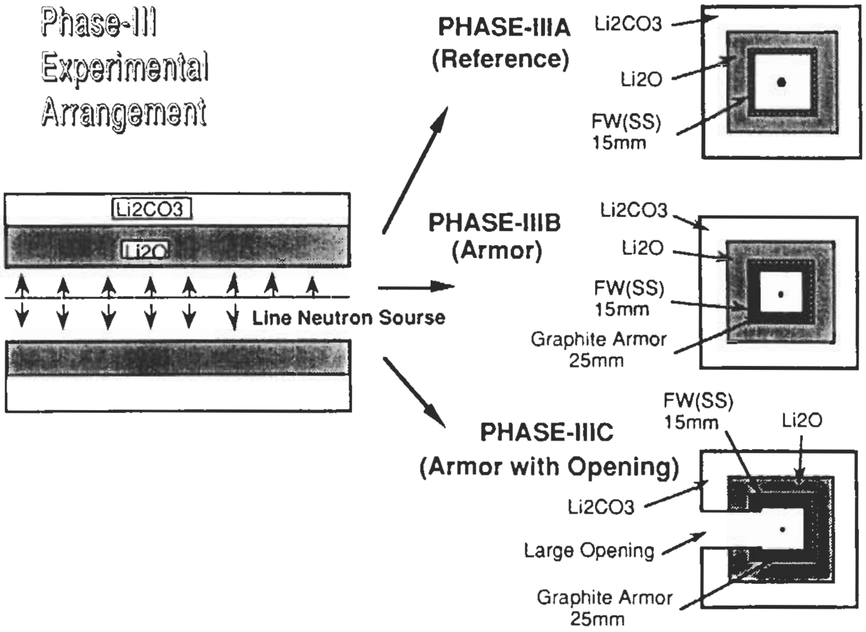

Fig. 5. Layout of the Phase-III series assemblies.

gamma-rays from the materials around the detector increases when the source and detector come close to each other. A set of 20 pulse height spectra with a 100-mm source interval for one measurement point were collected for each detector. The third technique was the spectrum weighting function method for the ^{7}Li tritium production rate measurement using the NE-213 detector. This method gives the tritium production rate directly from the measured recoil-proton spectrum, i.e., pulse height spectrum using a weighting function, while the conventional method requires an unfolded neutron spectrum from the pulse height spectrum and a set of cross-section data of $^7\mathrm{Li}(n,n'\alpha)t$.

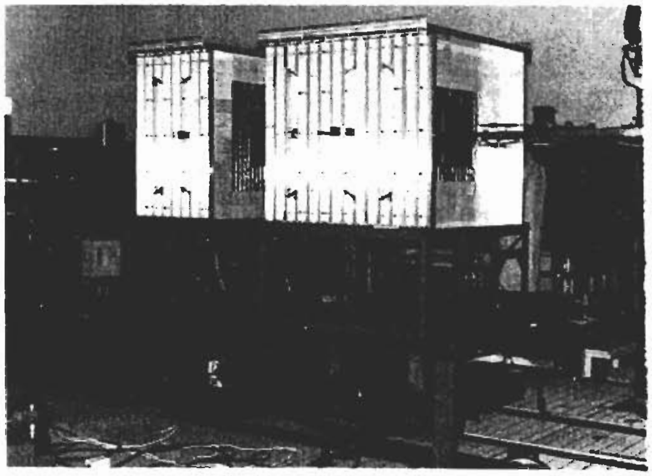

Fig. 6. A view of the Phase-IIIA assembly.

The measured items and their techniques in the follow-up phases, i.e., Phase-IIIB and Phase-IIIC, were almost the same as those in Phase-IIIA.

IV.C. Phase-IIIB

Most fusion reactors in relatively recent designs adopt graphite or carbon fiber composite to protect the first wall from plasma disruptions. The purpose of the Phase-IIIB experiment was to examine the effect of the carbon armor on the neutronic parameters. To simulate the graphite armor, a 25-mm-thick graphite layer was placed in the cavity on the inner surface of the first wall region of the reference blanket, i.e., the Phase-IIIA assembly. Figure 7 shows the simulated graphite armor located in the cavity (Phase-IIIB assembly, armor test blanket). The Phase-IIIB experiment was carried out in 1990.

IV.D. Phase-IIIC

There are many large holes and ducts in a fusion reactor such as a neutral beam injector and a vacuum exhaust duct. The purpose of the Phase-IIIC experiment was to examine the effect of a large opening on the neutronic parameters, especially the TPR. To simulate a large duct, an opening of 376 mm square and 425 mm long was made in the Phase-IIIB arrangement, as shown in Fig. 8. The Phase-IIIC experiment was performed in 1991.

Tritium production-rate distributions in Phase-IIIA and Phase-IIIB were remeasured in 1992. The end of Phase-IIIC marked the end of Phase-III.

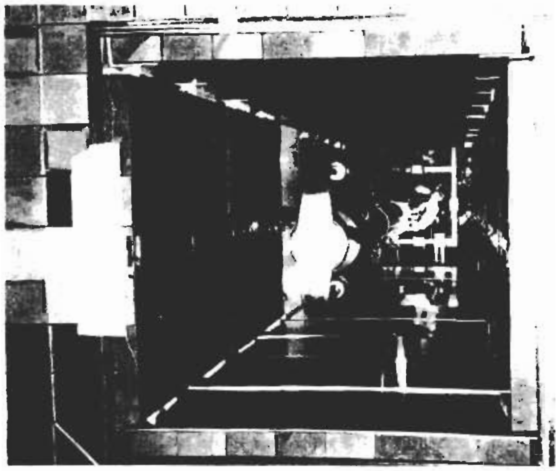

Fig. 7. A view of the Phase-IIIB assembly. The graphite armor is located in front of the first wall of Type 304 stainless steel.

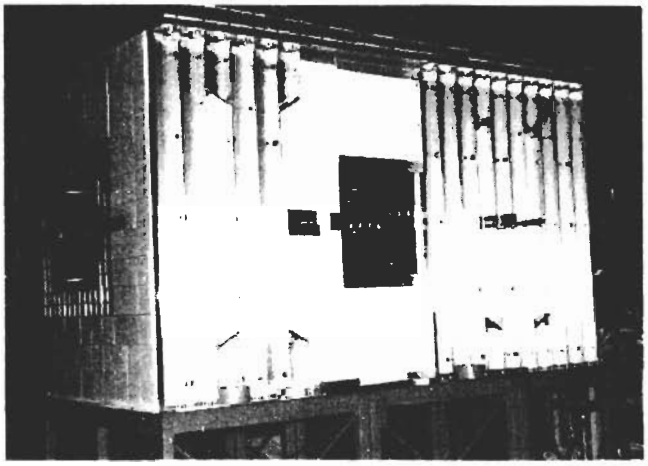

Fig. 8. A view of the Phase-IIIC assembly.

V. OUTLINE OF ANALYSES

V.A. JAERI's Analysis

In JAERI's analysis, the DOT3.5 code[13] was applied, for a deterministic treatment, along with the FNSUNCL code.[11] The FUSION-J3 library[14] was used in the DOT3.5 calculations. For the Monte Carlo calculations, the MORSE-DD code[15] or GMVP code[16] 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 (Ref. 17). They are summarized in Table II.

TABLE II

Methods and Data for the JAERI Analysis

Codes:	DOT3.5 with FNSUNCL	MORSE-DD or GMVP (vectorized MORSE-DD)
Data:	FUSION-J3 (n: 125, γ: 40) Infinite dilution	DDXLIB-J3 (n: 125, γ: 40) Infinite dilution
Model:	*R-Z* Inscribed cylinder P5-S16 Mesh $\leq$ 10 mm	Three dimension Rectangular shape 13 000 000 histories

V.B. United States' Analysis

The United States adopted the DOT5.1 code[18] along with the RUFF first collision code[19] for the deterministic treatment. The RUFF code is similar to the FNSUNCL code. In the Monte Carlo treatment, the MCNP-3B code[20] was applied with continuous energy and angle ENDF/B-V data. They are summarized in Table III.

VI. PREDICTION UNCERTAINTY AND DESIGN FACTORS FOR TPR

The experimental and calculational data sets of local TPR in each experiment were interpolated to give an estimate of prediction uncertainty of 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 in a sample experiment, say, i, propagate and contribute to the prediction uncertainty, u_i, in the integrated TPR with a standard deviation, σ_i. An approach was also pursued to give estimates of the prediction uncertainty in the volume-integrated TPR based on measurements and calculations of local TPR in the transverse direction. A novel methodology was then developed[21] to arrive at estimates of a design safety factor,

TABLE III

Methods and Data for the University of California, Los Angeles Analysis

Codes:	DOT5.1 with RUFF	MCNP-3B
Data:	MATXS5 based on ENDF/B-V.2 (n: 30, γ: 12) Infinite dilution	RMCCS/BMCCS based on ENDF/B-V continuous energy and angle
Model:	*R-Z* Inscribed cylinder P3-S16 Mesh $\leq$ 10 mm	Three dimension Rectangular shape 8 000 000 histories

which could potentially assist fusion reactor designers to ensure that achievable TBR in a blanket would not fall below unity. For this purpose, a normalized density 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.[22,23] 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, derived from these NDFs, 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.), on one hand, and measured values based on various experimental techniques, on the other. Associated with each safety factor, there would be a confidence level, which the designer might choose to have, so that the calculated TPR would not exceed the actual measured value. Higher confidence levels require larger safety factors. Tabular and graphical forms for these factors have been given independently for TPR produced from ^{6}Li, ^{7}Li, and natural-lithium.[22,23]

Fusion blanket designers can obtain the required safety factors from the tables and graphs, as mentioned earlier, for a wide range of confidence levels, which could be applied to the calculations of TPR for ^{6}Li, ^{7}Li, and natural-lithium. It should be emphasized, however, that these safety factors are applicable to TPR in Li_2O breeding material as obtained from the JAERI/U.S. DOE collaborative program, which was essentially based on simplified prototypical fusion blanket assemblies under very ideal neutron source conditions. The safety factors obtained in this work[22] are thus defined for a typical case of "good geometry." Further efforts are needed to obtain more realistic safety factors, i.e., the safety factors for real fusion devises and reactors with complex geometry and configurations such as the International Thermonuclear Experimental Reactor.

VII. CONCLUDING REMARKS

The series of Phase-III experiments of the JAERI/U.S. DOE collaborative program on fusion blanket neutronics was planned to simulate the tokamak-type fusion reactor as closely as possible using the current state-of-the-art. For example, in order to simulate a spatially extended source, a pseudoline source was developed using a point D-T neutron source and a moving deck. It was demonstrated, though, that this system gave a good simulation of a line source.

Three types of annular shape fusion test blankets were chosen for the experiments during three subphases, i.e., Phase-IIIA, Phase-IIIB, and Phase-IIIC. The Phase-IIIA assembly was the reference blanket made of Li_2O and Li_2CO_3 blocks with a Type 304 stainless steel first wall. The Phase-IIIB was obtained from the Phase-IIIA assembly by addition of a graphite armor region in order to investigate the effect of this graphite armor on neutronic parameters such as the TPR. The Phase-IIIC assembly was derived from the Phase-IIIB assembly by making a large opening in order to investigate the effect of this opening on the neutronic parameters.

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

Useful and reliable benchmark data have been accumulated through the Phase-III series experiments.

Both JAERI and the University of California, Los Angeles, analyzed these benchmark experiments.

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