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Evaluation of the prediction uncertainty in tritium production based on results from experiments on an Li_2O annular blanket surrounding a 14 MeV simulated line source

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Abstract

The experimental analysis of phase III experiments of the USDOE/JAERI collaborative Program on Fusion Neutronics is described. The annular Li_2O test assembly totally surrounds a simulated 14 MeV line source of length 2 m. This simulation is achieved by cyclic movement of the assembly relative to the stationary 14 MeV point source. Three phases of experiments were performed and analyzed. In phase IIIA, a stainless steel first wall 1.5 cm thick was used. An additional carbon layer 2.45 cm thick was added in phase IIIB, and a large opening (42.55 cm × 37.6 cm) was made at one side of the annular assembly in phase IIIC. Calculations were performed independently by the USDOE and JAERI for many measured items that included the tritium production rate (TPR) from $^6Li(T_6)$, $^7Li(T_7)$; in-system spectrum measurements; and various activation measurements. In this paper, the calculated-to-measured values (C/E) for the TPR were used to derive qualitative estimates to the mean values of the prediction uncertainty in the line-integrated TPR, and the possible spread around these values. Distinction was made between results based on the discrete ordinates and on the Monte Carlo method. Furthermore, a comparison was made with the pertaining results when all the experiments conducted during the USDOE/JAERI collaborative program were considered.

1. Introduction

Several integral experiments were conducted at the fusion neutronics source (FNS) facility at the Japan Atomic Energy Research Institute (JAERI), within the US Department of Energy (USDOE)–JAERI Collaborative Program on Fusion Blanket Neutronics, and constituted phase III. In this phase, a simulated line source [1,2] was created by moving an annular blanket assembly in a periodic motion relative to a stationary 14 MeV point source. Several measurements were performed for the tritium production rate (TPR), spectra and several reaction rates, and the calculated results were compared with the experimental values to examine the prediction accuracies obtained by various codes and databases.

The aim of this paper is to derive estimates for the prediction uncertainties of the TRP measured in three distinctive experiments, i.e. the reference experiment, the armor experiment and the large-opening experiment (see below). The prediction uncertainties in the local as well as the line-integrated TRP are estimated based on

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the calculational and experimental uncertainties (errors) at each location where TPR is measured. Based on these results, the overall mean prediction uncertainty and the possible spread around these mean values are evaluated. Conservative correction or safety factors were estimated and these, when applied to calculated TPR values, will bring the calculations in agreement with the measurements. A comparison of these derived parameters was also made with results from previous experiments.

2. Experimental and calculational methods

The experimental annular assembly is rectangular in shape (see Fig. 1) of length 2040 mm and has outer dimensions of 1301 mm × 1301 mm. The reference assembly (phase IIIA) consists of an Li_2O zone of thickness 203 mm, followed by an Li_2CO_3 zone 203 mm thick covered by a polyethylene (PE) layer 16 mm thick to isolate the assembly from the room-returned neutrons. The inner cavity has a square shape of dimensions 455.5 mm × 455.5 mm, with a 304 stainless steel first wall (FW) 15 mm thick. The length of the simulated line source is 2000 mm. There are six experimental drawers in the radial direction (three on each side), where measurements of the TPR are performed. In the armor experiment (phase IIIB), a layer of carbon 2.54 cm thick was placed in front of the FW. In the phase IIIC experiment, a large opening of dimensions 376 mm × 425.5 mm was made (at one side at the center of the annular assembly of Phase IIIB) to simulate a duct in a fusion reactor. There are three drawers facing the opening on the other side of the assembly (drawers A&B&C) and drawer (D) next to the opening in the radial direction.

The source was characterized with and without the annular assembly in place, by performing multifoil activation (MFA) and spectrum measurements [3–5] along the axial direction. In-system neutron spectrum measurements were also performed to characterize the nuclear field inside the assembly [4,6,7]. For the TPR, lithium-glass detectors were used to measure the TPR from $^{6}Li(T_6)$, and the NE213 indirect method was used to measure the TPR from $^{7}Li(T_7)$, by folding the measured spectrum with the $^{7}Li(n,n'\alpha)t$ cross-section from JENDL-3PR2.

In the analysis, the USDOE used the DOT5.1 code [8], and the RUFF [9] first collision code for the discrete

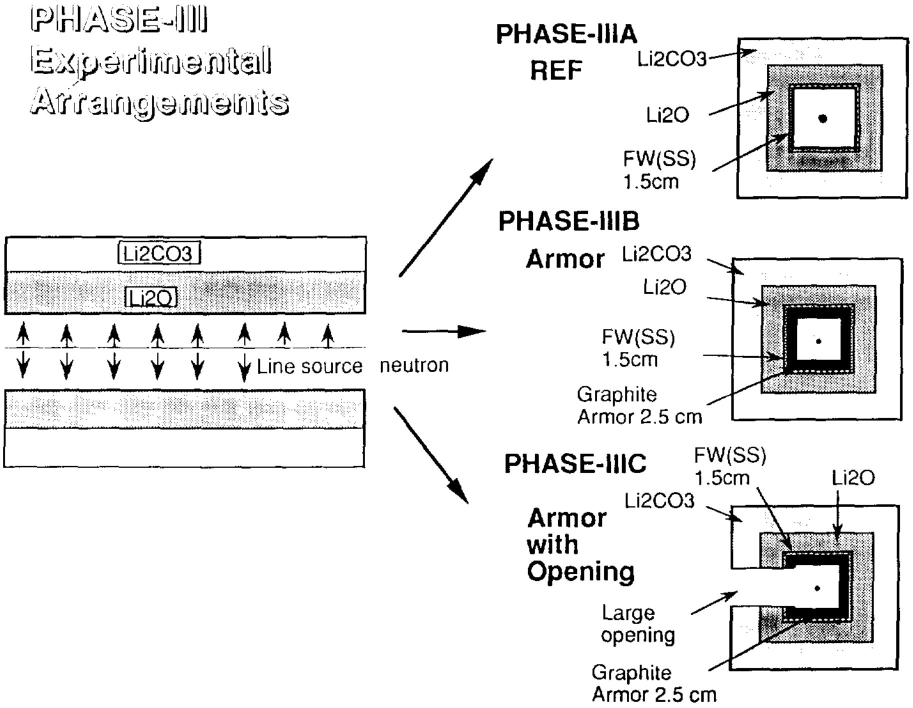

Fig. 1. Experimental arrangement for phase III experiments.

ordinates method and the MCNP-3B code for the Monte Carlo method, along with its continuous energy and angle library RMCCS/BMCCS, based on ENDF/B-V data. The 30-group MATXS5 library [10] (ENDF/B-V, version 2) was used in the DOT5.1 calculations (P_3–S_{16}). In the JAERI analysis, the DOT3.5 code was applied along with the FNSUNCL code, a modified version of GR-TUNCL. The FUSION-J3 library (P_5–S_{16}, 125-n), based on JENDL-3 data, was used. In the analysis performed by the Monte Carlo method, the MORSE-DD [11] code and the GMVP [12] code (a vectorized version of MORSE-DD) were applied. The transport and response calculation of MORSE-DD are based on JENDL-3PR2 data, while the transport calculation of GMVP is based on JENDL-3 data (125-g, DDX library). In the transport calculation, the responses (T_7, T_6, etc.) have been calculated from JENDL-3PR2 (denoted by GMVP(PR2)) and from JENDL-3 (denoted by GMVP(J3)).

3. Prediction uncertainties in local TPR

Based on the experimental data, it was shown [5] that the impact of the inclusion of the armor layer on local T_7 is such that a decrease of about 8%–10% occurred. However, the predicted decrease is larger when calculated by all codes and databases [5]. This was attributed to the difference in the neutron spectra behind the carbon layer between the calculations and measurements [5]. The effect of the large opening on local T_7 in drawer B (located at the middle of the assembly and facing the opening) is such that a decrease occurred in the measured values by 0.5%–0.8% at all locations, while the calculations showed a decrease (by about 1%–2.5%) at some locations and an increase (about 1.5%–3%) at other locations [5].

An example of the calculated-to-experimental (C/E) values of local T_7 in drawer B of phase IIIB is shown in Fig. 2. The prediction uncertainty is the average of the quantity $[(C/E) - 1] \times 100$, estimated at all locations where measured data were taken inside the Li_2O zone. It was shown that the C/E values of local T_7 in phase IIIA are on average lower than unity by about 5% [5]. Since the predicted decrease in local T_7 upon the inclusion of the armor layer is larger than the corresponding decrease detected by NE213, the corresponding C/E curves are lower in absolute values than those of phase IIIA at all locations, by an average value of about 10%–15%, as shown in Fig. 2. In phase IIIC, the average C/E values are still lower than unity (by about 10%), as in phase IIIB. It was shown that the C/E values obtained by GMVP with JENDL-3 data are closer

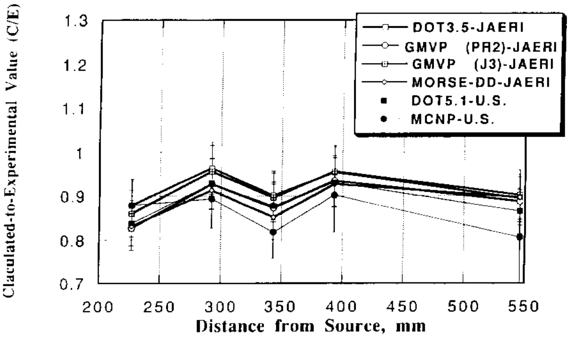

Fig. 2. C/E values of TPR from $^7Li(T_7)$ in the radial direction along drawer B of phase IIIB (NE213 measurements, from ref. [5]).

to unity than those obtained with the response calculated from the J3/PR2 database [5].

For the TRP from $^6Li(T_6)$, the measured increase in local T_6 upon the inclusion of the armor layer is from about 20% (at front locations) to about 10% (at back locations). However, the predicted increase is about 14% (using GMVP, MORSE-DD or DOT5.1), about 17% (MCNP) or about 9% (DOT3.5) at the very front locations but, at a distance greater than about 330 mm from the line source, the results based on MCNP, DOT3.5 and DOT5.1 showed a decrease in local T_6, in contrast to the measured trend [5]. The effect of the opening is such that a decrease in measured T_6 of about 8% occurred at front locations and of about 11% at back locations. The corresponding decreases predicted with GMVP are about 13% and 9%. This decrease is a result of the decrease in the reflected low energy neutrons incident on the no-hole side, resulting from the presence of the opening.

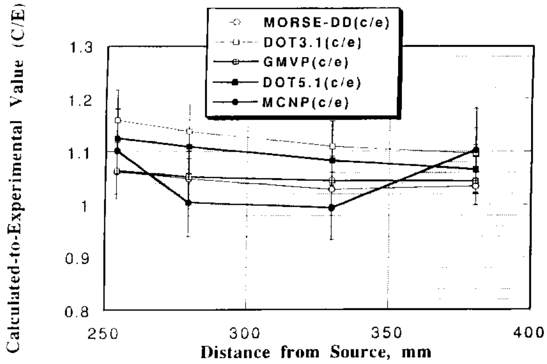

Fig. 3. C/E values of TPR from $^6Li(T_6)$ in the radial direction along drawer B of phase IIIA (lithium-glass measurements, from ref. [5]).

Table 1
Average values of the prediction uncertainty $[(C/E)-1] \times 100$ in local TPR from Li-6 (T_6) and Li-7 (T_7)

Phase	Local T_6 [a]	Local T_7 [b]
IIIA	5%–15%	−5%
IIIB	−5%	−10%–15%
IIIC	−5%	−10%

[a] Measured by lithium-glass detectors.
[b] Measured by NE213 method.

It was shown that such a decrease is confined to a width in the axial direction corresponding to the width of the opening [7] (42.5 cm).

An example of the C/E values of local T_6 in drawer B of phase IIIA is shown in Fig. 3. In this phase, the average C/E values are generally larger than unity by 5%–15%. Since the predicted increase in local T_6 when the armor layer is added is less pronounced than those obtained from measurements, the overestimation in T_6 is compensated for in phase IIIB, leading to local C/E values that are on average lower than unity by about 5% [5]. Table 1 summarizes the prediction uncertainties in the local TPRs.

4. Prediction uncertainty in the line-integrated TPR

In the present work, estimates were made of the overall prediction uncertainty in the line-integrated TPR from ^{6}Li and ^{7}Li, following the methodology described in refs. [13–15]. Briefly, the best fitting curve (by the least-squares method) for the measured data is integrated in the radial direction, and the uncertainty (error) in the integrated value E_{int} is estimated from the

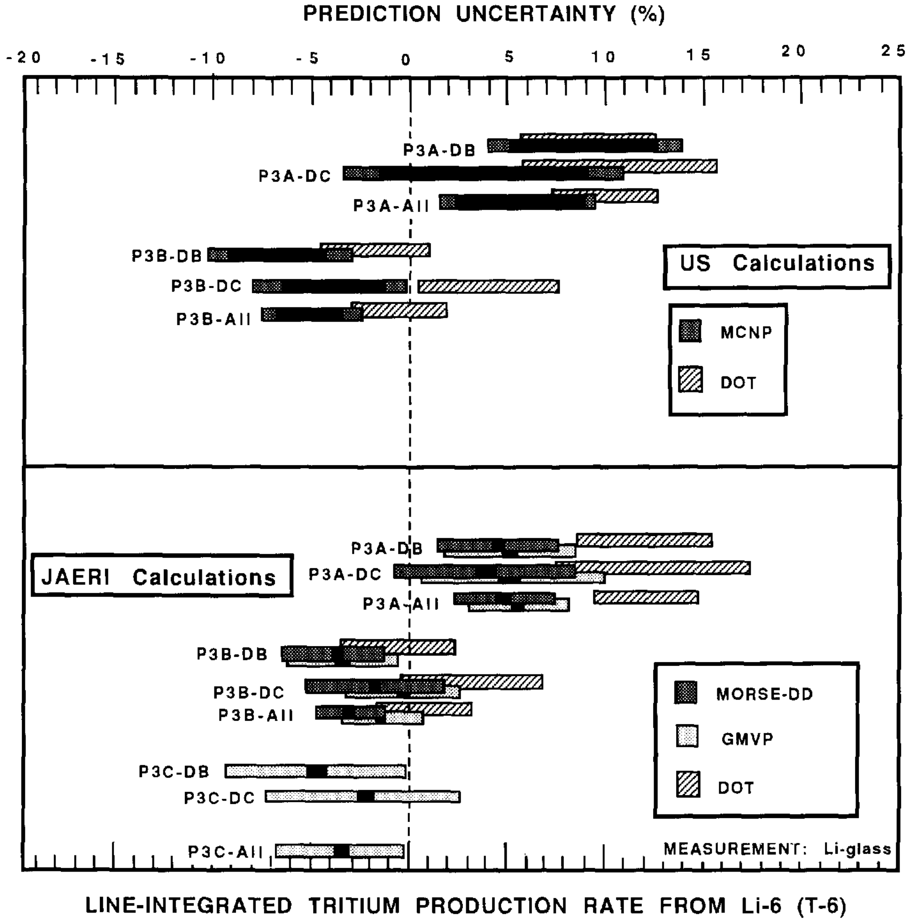

Fig. 4. Prediction uncertainty in the line-integrated TPR from Li-6 (T_6) (lithium-glass measurements, phase III).

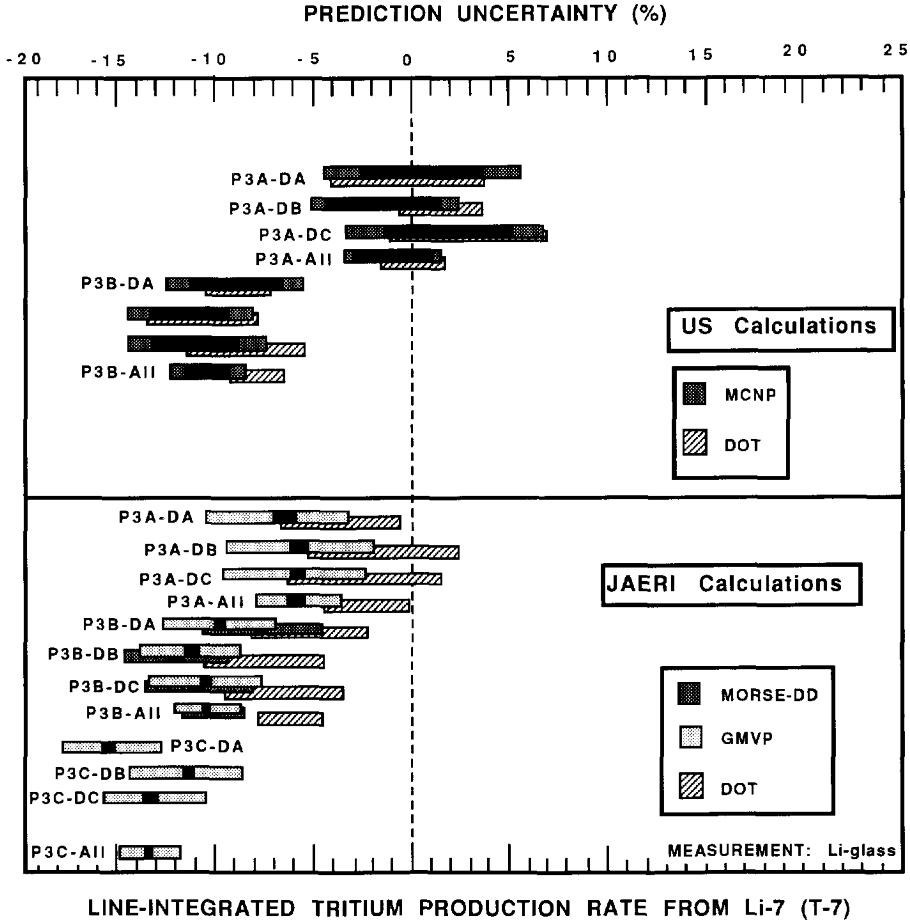

Fig. 5. Prediction uncertainty in the line-integrated TPR from Li-7 (T_7) (NE213 measurements, phase III).

uncertainties in the fitting coefficients which account for the uncertainty in the measured data. The same procedures are applied to the calculated data at the locations where measurements are taken. An estimate is then made to the value, i.e. $u_i = [(C/E)_{\rm int} - 1] \times 100$, and the associated relative standard deviation σ_i. These prediction uncertainties and standard deviations are given in Figs. 4 and 5 for each experiment and each drawer. The notation "All" represents the case when u_i and σ_i are derived from the local TPR in all the drawers in a given experiment. The black bars represent the deviations, when only the calculational errors are accounted for in the Monte Carlo calculations. As can be seen, the prediction uncertainty in line-integrated T_6 is similar to the average prediction uncertainty in local values, i.e. overprediction in phase IIIA by 5%–15%, and general underprediction in phases IIIB and IIIC by about 2%–6%. Also, line-integrated T_7 is underpredicted in all the drawers of phases IIIB and IIIC by 8%–15% and by about 6% in phase IIIA, particularly in the GMVP case.

To quantify the overall prediction uncertainties in the three phases, the methodology described in ref. [13] was applied to construct normalized distribution functions (NDFs) from the uncertainty ranges shown in Figs. 4 and 5. From these normalized distribution (probability density) functions, the overall mean prediction uncertainties ($\bar{u}$) and standard deviations (σ_u) were derived for line-integrated T_6 and T_7. Figs. 6 and 7 show the NDFs of T_6 based on the US and JAERI calculations, respectively, where distinction is made between the discrete ordinate (DO) and Monte Carlo (MC) results. The corresponding NDFs for T_7 are shown in Figs. 8 and 9. The gaussian curves that approximate these NDFs (having the same $\bar{u}$ and σ_u values) are also shown for comparison. Table 2 gives these statistical parameters when the calculational methods are distin-

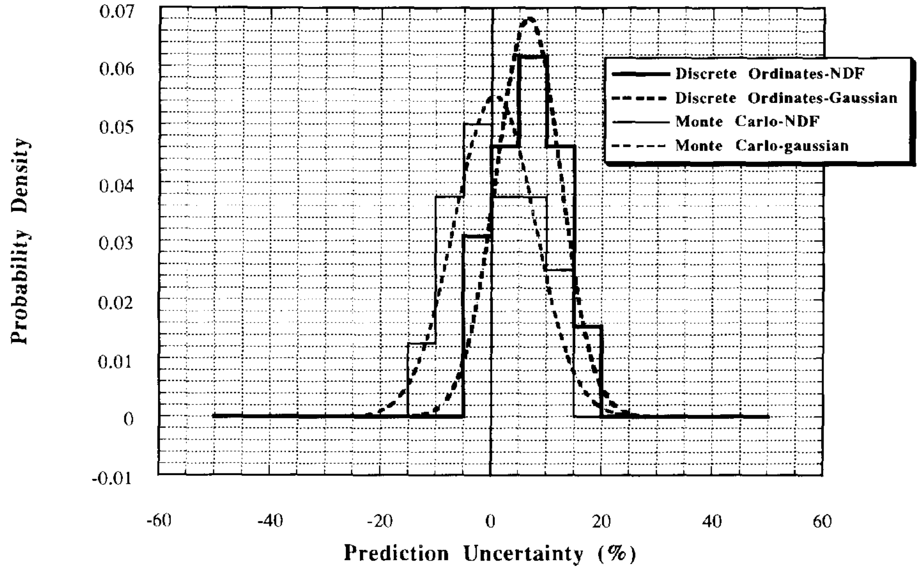

Fig. 6. Normalized distribution (probability density) function of the prediction uncertainties in T_6 (US calculations, (lithium-glass measurements, phase III).

guished and when their cases are treated simultaneously (denoted by "Both") is deriving the NDFs.

Based on the US calculations, the mean prediction uncertainties in line-integrated T_6 are about 6.8% (DO) and about 0.6% (MC) (as opposed to about 3.4% when the results from the two calculational methods are combined), with a spread $\pm\sigma_u$ of 6%–7%. In the JAERI calculations, these uncertainties are similar (about 6.8% (DO) and about 0.4% (MC); as opposed to about 2.4% when results from the DO and MC methods are combined), with a spread of $\pm\sigma_u$ of 5%–7%. The uncertainties based on the US calculations are

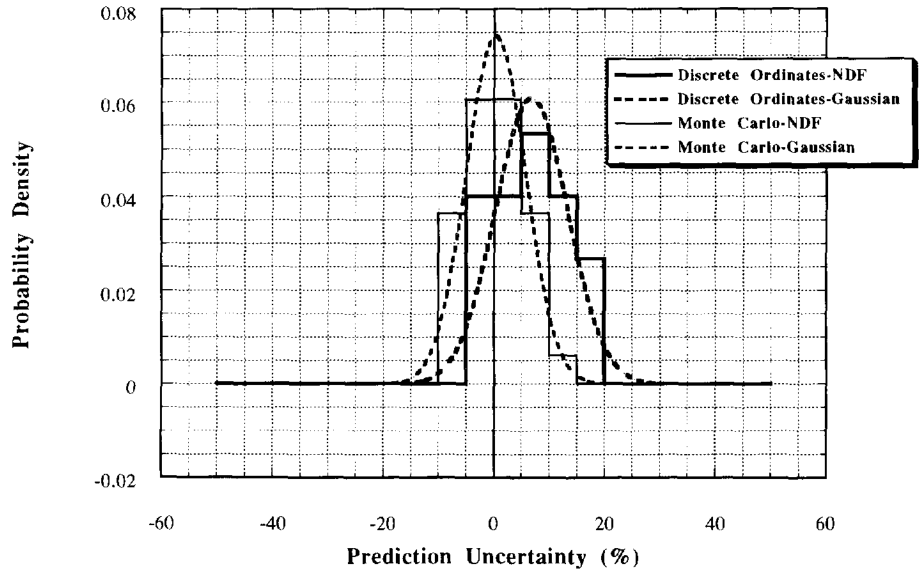

Fig. 7. Normalized distribution (probability density) function of the prediction uncertainties in T_6 (JAERI calculations, lithium-glass measurements, phase III).

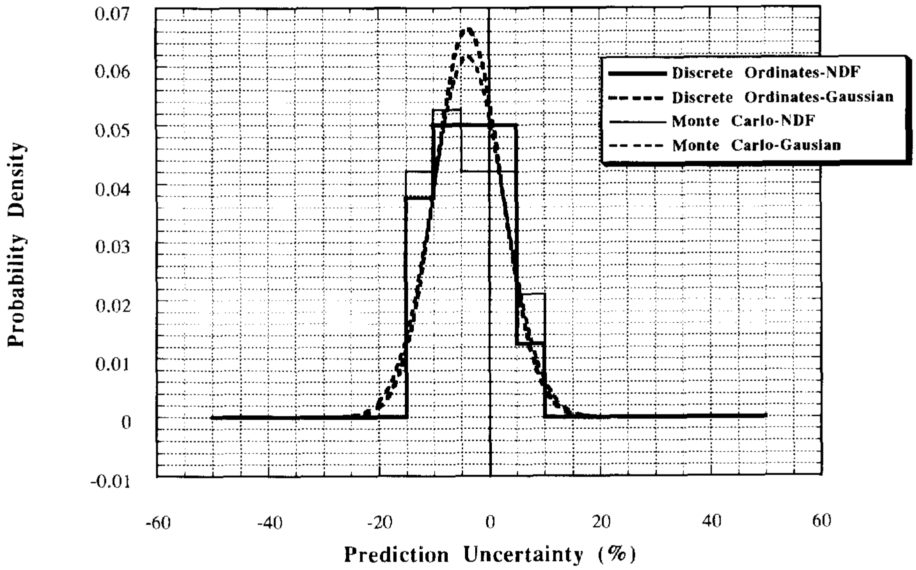

Fig. 8. Normalized distribution (probability density) function of the prediction uncertainties in T_7 (US calculations, NE 213 measurements, phase III).

about 1% larger than those of JAERI. It is clear also that results based on the DO method give larger uncertainties than those based on the MC method by about 6%.

For T_7, the mean prediction uncertainties $\bar{u}$ based on the US calculations, are about −3.8% (DO and MC), with a spread $\pm\sigma_u$ of 6%. The corresponding uncertainties based on the JAERI calculations are about −4%

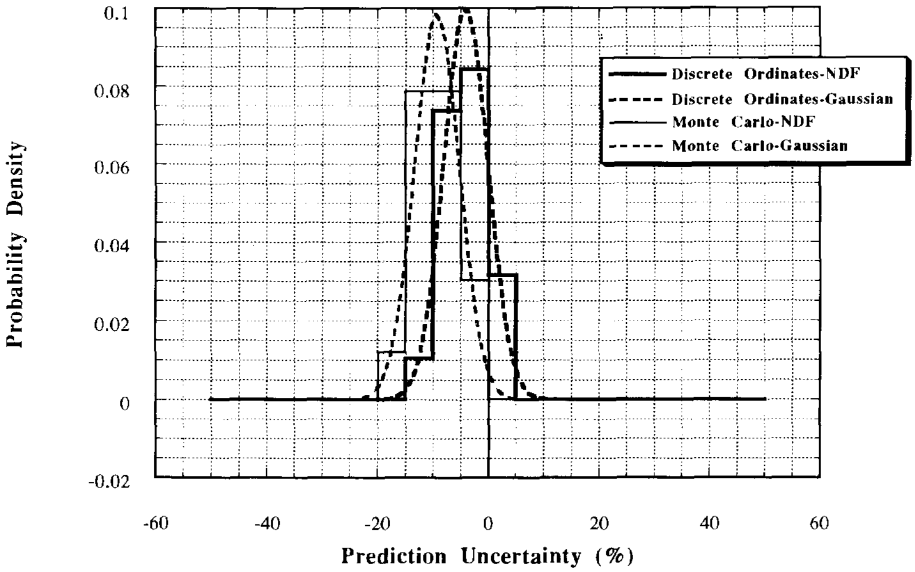

Fig. 9. Normalized distribution (probability density) function of the prediction uncertainties in T_7 (JAERI calculations, NE213 measurements, phase III).

Table 2
Statistical parameters of the prediction uncertainty u(%) of TPR as obtained from various calculational methods

Method	US						JAERI					
	Discrete ordinates		Monte Carlo		Both		Discrete ordinates		Monte Carlo		Both	
T6 (lithium glass)												
Number of cases considered	6	(26) [a]	6	(24)	12	(50)	6	(26)	15	(32)	21	(58)
$\bar{u}$ (average)	6.73	(7.6)	0.63	(−0.8)	3.36	(3.2)	6.83	(3.6)	0.38	(−2.5)	2.39	(0.2)
σ_u (standard deviation)	5.83	(7.7)	7.26	(7.6)	7.32	(8.8)	6.55	(7.1)	5.40	(7.4)	6.49	(7.9)
Most conservative correction or safety factor	1.20	(1.3)	1.15	(1.2)	1.20	(1.3)	1.20	(1.2)	1.15	(1.2)	1.20	(1.2)
T7 (NE213)												
Number of cases considered	8	(26)	8	(23)	16	(49)	8	(26)	16	(30)	24	(56)
$\bar{u}$ (average)	−3.75	(10.3)	−3.82	(4.8)	−3.79	(7.6)	−4.10	(−1.1)	−9.32	(−2.8)	−7.50	(−2.0)
σ_u (standard deviation)	6.00	(10.5)	6.46	(9.9)	6.25	(10.5)	4.00	(6.5)	4.04	(7.8)	4.75	(7.3)
Most conservative correction or safety factor	1.10	(1.3)	1.10	(1.4)	1.10	(1.4)	1.05	(1.1)	1.00	(1.2)	1.05	(1.2)

[a] Values based on all the experiments performed under the USDOE–JAERI Collaborative Program (lithium-glass and NE213 measurements).

(DO) and −9% (MC) (as opposed to about −7.5% when the results from the two calculational methods are combined), with a spread $\pm\sigma_u$ of about 4%. It should be noted that fewer cases were considered in the US calculations. The overall underprediction is consistent with the underprediction observed in each experiment. The uncertainties based on the US calculations are about 1%–4% larger than those for the JAERI. Also, the calculational results based on the DO method are larger than those based on the MC method by about 5% in JAERI calculations.

One can see from Figs. 6–9 that the NDFs vanish at particular values (u_k) in the positive space of the prediction uncertainty u. For example, the NDF for T_6 based on the DO method vanishes at $u_k = 20\%$, i.e. at $S_k = u_k + 1 = (C/E)_k = 1.2$. This means that the probability that the calculated line-integrated TPR from Li-6 is larger than the measured value by more than 20% is null. Since overestimation in the TPR calculation by blanket designers could lead to not meeting the tritium self-sufficiency conditions, the calculated T_6 should be corrected (divided) by the correction factor S_k to account for the overestimation in T_6 evidenced from the results shown in Fig. 6. This would bring the calculations into agreement with the measurements. These factors could be viewed as the most conservative correction or safety factors that can be applied to TPR calculations based on the experimental analysis of phase III. They are given in Table 2 and can be quantitatively used by blanket designers to safeguard against any possible overestimation in the TPR calculations.

The prediction uncertainties in the TPR ($\bar{u}$) and the associated deviations ($\pm\sigma_u$) were estimated for line-integrated T_6 and T_7 based on the lithium-glass and NE213 measurements in all the experiments conducted under other phases of the USDOE–JAERI Collaborative Program [15]: phase I, open geometry [16,17]; phase II, closed geometry [18–20]. Their values are introduced in Table 2 (shown in parentheses) for comparison with the results based only on phase III experiments. This comparison will indicate the effect of differences in the geometrical arrangement and source conditions (line vs. point source), encountered in other phases, on the uncertainties in the TPR prediction.

In the US case, the uncertainties in T_6 are comparable with those of phase III only to within about 1%, in both the DO and MC calculations. In the JAERI case, however, the uncertainties are larger in phase III (by about 3%) than in all phases in both the DO and MC calculations. For T_7, the observed underestimation in all the experiments of phase III was compensated for when all the phases are considered, since positive prediction uncertainties were encountered in phases I and II experiments (see ref. [15]). In the US case, the overall uncertainties in T_7 are positive and larger by about 8%–14% compared with phase III uncertainties. In the JAERI case, the uncertainties are also larger (smaller in absolute values) than the uncertainties of phase III by about 3%–7%, but underprediction can still be observed.

5. Conclusions

Three integral experiments were conducted at the FNS, in which an annular Li_2O blanket totally surrounded a simulated line source, i.e. the reference experiment (with SS 304 FW), the armor experiment (a carbon layer 2.45 cm thick was placed in front of the FW), and the large-opening experiment. The mean values of the prediction uncertainties of the line-integrated TPR from Li-6 (T_6) and Li-7 (T_7) were calculated, along with the associated experimental and calculational errors, and compared with the uncertainties in the local TPR. The uncertainties in the line-integrated TPR were used to construct NDFs, from which the mean prediction uncertainty $\bar{u}$ and standard deviation $\pm\sigma_u$ were calculated for T_6 and T_7. Distinction was made between results based on the DO and MC methods.

Based on the US calculations, the mean prediction uncertainties in line-integrated T_6 are about 6.8% (DO) and about 0.6% (MC), while they are about 6.8% (DO) and about 0.4% (MC) in the JAERI calculations. The spread around these mean values is about 5%–7%. The uncertainties based on the US calculations are about 1% larger than those of the JAERI. The DO method gives larger uncertainties than those based on the MC method by about 6%. For the T_7, the mean prediction uncertainties based on the US calculations are about −3.8% (DO and MC), and are about −4% (DO) and −9% (MC) based on the JAERI calculations, with $\pm\sigma_u$ of about 4%–6%. Conservative correction factors were also derived and these, when applied, will bring the calculations in agreement with the measurements.

The prediction uncertainties in the TPR estimated in the present work were compared with the corresponding values when results from all the experiments conducted under the USDOE–JAERI Collaborative Program were considered. They are within about 1% for T_6 in the US case but they are larger by about 3% in the JAERI case than those estimated when all phases were accounted for. For T_7, the underestimation observed in all experiments of phase III was compensated for when all the phases were considered. In the US case, the overall uncertainties in T_7 are positive and larger by about 8%–14% compared with the phase III uncertainties. In the JAERI case, the uncertainties are also larger than the phase III uncertainties by about 3%–7%, but underprediction was still observed. This emphasizes that the estimation of the prediction uncertainties in the TPR is system dependent.

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