OPERATING AND GEOMETRICAL ARRANGEMENT REQUIREMENTS FOR FUSION NEUTRONICS TESTING

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ABSTRACT

Neutronics tests in a fusion engineering test device will be required to verify the neutronics prediction capabilities (calculational methods and data base). This paper presents the requirements related to the neutronics test. These requirements include those associated with the operational environment (e.g., wall load, fluence, plasma burn time, etc.) and the ones related to the test module configuration (geometrical arrangements, minimum size for meaningful test information, boundary conditions, etc.). Both experimental consideration and neutronic analyses were carried out to quantify these conditions.

INTRODUCTION

As a part of the FINESSE[1] project which attempts to identify and quantify the engineering testing requirements for the development of fusion nuclear components, substantial effort was devoted to quantifying these conditions related to the neutronics tests in a fusion testing device. The objectives of these tests are to verify the neutronics prediction capabilities (calculational methods and data base) and to evaluate the uncertainties in extrapolation to demonstration and commerical reactors.

Integrated tests perform in a test device and aimed especially at verification of neutronics methods and data require specialized modules. In contrast to issues such as thermomechanical behavior, in which look-alike test modules are least useful under scaled-down conditions, neutronics verification tests require that, and are most useful when, the test module is as close to a look-alike as possible. Therefore, neutronics tests should be treated separately from other types of tests. It is necessary to notice that other types of blanket tests (e.g., thermomechanical, tritium recovery) have their own neutronics considerations concerning simulation of bulk heating, tritium production, etc., to simulate the act-alike behavior that is different from those aimed specifically at neutronics tests.

Neutronics testing will involve several types of measurements such as source neutron yield, tritium production rate, neutron and gamma-ray spectra, heating rates during operation, activation, and after-heat. The requirements for neutronics testing fall within two categories: (1) test device operating conditions, and (2) test module conditions. The fusion test device conditions include parameters such as the wall load, fluence, and pulse length. The test module conditions are those related to the minimum size requirement for optimal testing, and requirements on the test module boundary conditions and geometrical arrangement.

TEST DEVICE OPERATING CONDITION REQUIREMENTS

The inherent limitations for measuring a particular parameter govern the optimum operating condition in a test device. The main limitations of the experimental techniques are count rate, counting statistics, detector size, operation environments (temperature, magnetic field, etc.) and accuracy.[2] Especially, count rate and counting statistics give the wall load requirement to various techniques as summarized in Table I. From instrumental considerations, all neutron parameters except induced activation can be measured in one of two fluence modes: either the low fluence mode (~1 $MW.s/m^2$) or the very low fluence mode (~1 $W.s/m^2$). The low fluence mode can be achieved, for example, with a wall load of 1-MW/m^2 and 1-s plasma burn time or, alternatively, 0.01 MW/m^2 and 100 s. Thus, neutronics tests impose only modest requirements on the product of the wall load and plasma burn time with no stringent requirements on the magnitude of either parameter since the neutronics parameters, except in-

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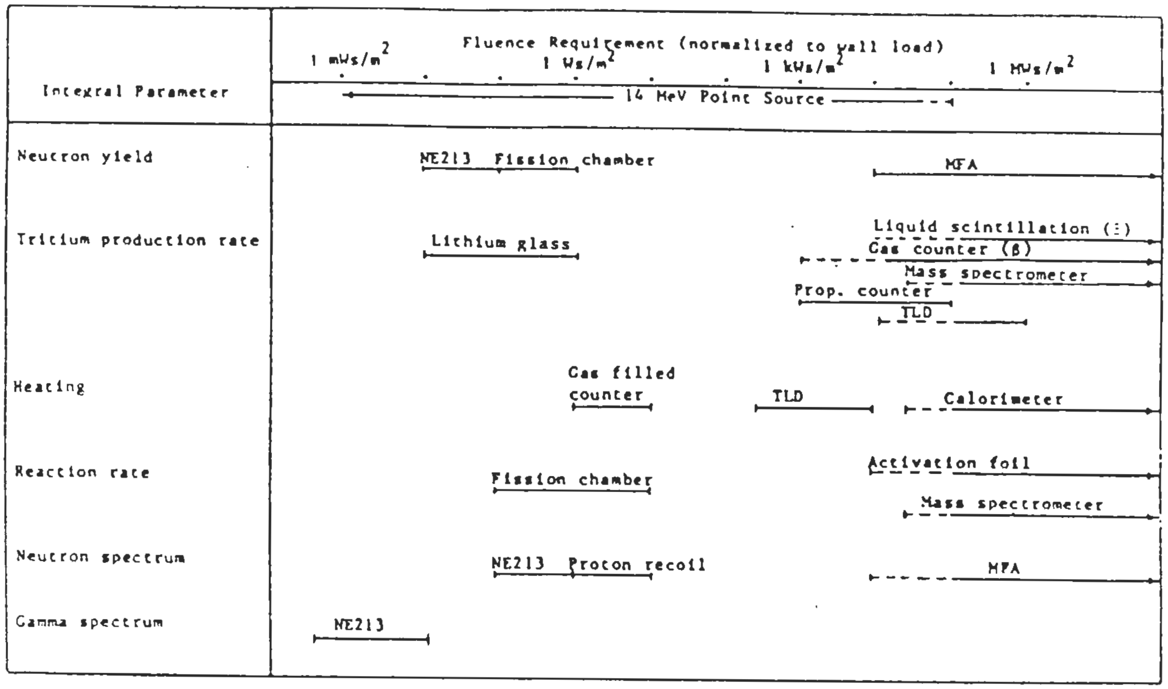
TABLE I

Fluence Requirements for Various Experimental Techniques*



*For counter methods, the measuring time is assumed to be 10 ~ 100 s.

duced activation, vary linearly with both the wall load and operating time. Notice, however that much larger fluences than those considered here will require the use of different, less accurate measurement techniques.

Operating the test device in the very low fluence mode is most suitable for measuring tritium production from ^{6}Li, gamma-ray heating, neutron and gamma-ray spectra, if a low activation level is desired. The main problem associated with the low fluence operating mode is the activation of the test module and device components which may render the device inaccessible just after shutdown. This will necessitate a long cool-down time to handle the reactor components. On the other hand, the main problem related to the very low fluence operation mode is the poor spatial resolution and instability of measurements. The methods used for measurements in the low fluence mode have better accuracy and spatial resolution as compared to those used in the very low fluence operation mode. For source characterization and neutron yield, which is viewed as a part of the plasma diagnostics, measurements can be undertaken in both operational modes.

GEOMETRICAL ARRANGEMENT REQUIREMENTS

The requirements on the test module size and geometry are governed mainly by the objective and the procedure for the particular neutronics test under consideration. If a local measurement of tritium production is intended, for example, then the only useful information that can be obtained from such a neutronics test is to verify the consistency between analytical prediction and experimental measurements. Resolving the question of the adequacy of the nuclear data base can be better achieved in a simple benchmark experiment. However, to improve the analytical prediction and to identify the various sources of uncertainties, one would proceed from a geometrically simple benchmark experiment utilizing a point source to a more complicated one involving a volumetric plasma source in a fusion test device.

On the other hand, if the objective of the neutronics test is to verify an integrated parameter in a given blanket concept such as the tritium breeding ratio (TBR), the test module used in this experimental planning approach should duplicate in great detail the actual blanket module as discussed in the previous work.[3] Verification of achievable breeding ratio require that factors which affect the global TBR (such as actual penetrations for heating and fueling, full coverage geometrical arrangement, and presence of the impurity control system) are included in the fusion test device. Also, extrapolating the results of measuring the local tritium production rate (TPR) in a partial coverage case to demonstration or commercial reactor TBR involves many uncertainties. Since the estimated margin[4] in TBR for candidate blanket concepts is small, very high accuracies in measurements are required, and these sources of uncertainties need to be carefully evaluated.

In a fusion test device, the test area at the first wall is limited by cost considerations. Hence, a near-full-coverage blanket for neutronics verification tests is obviously not practical. Therefore, the neutronics analysis has focused on examining the usefulness of neutronics test information as a function of the test module size. In addition, an effort to improve the usefulness of test information from a given size test module has been attempted. Variables considered in such an improvement included: (1) details of material and geometrical arrangement within the test modules, and (2) conditions at the test module boundaries which are sensitive to factors such as the material and dimensions of the "reflective" zone surrounding the test module.

A. Calculational Model

The fusion test device parameters used in the calculational analysis are shown in Table II. The test module as shown in Fig. 1 was divided into two zones: testing module zone to measure tritium production and reflective zone to adjust the neutron spectrum coming into the testing zone. The reflective zone was examined by 1-D models shown in Fig. 2 using the ANISN code.[5] The testing module region can be characterized by two dimensions in a fusion device which was approximated by a cylinder. The first parameter is the magnitude of the maximum poloidal angle, θ_m, subtended by the test module. The second is the maximum width, L_m of the test module in the axial direction of the device. The importance of θ_m and L_m was examined separately by two 2-D models shown in Fig. 3 using the DOT4.3 code[6] (P_3S_8, 13 neutron groups). The first is an R-θ geometry where R refers to the minor radius of the plasma. The second is an R-Z model where Z is the axial direction for the plasma along which L_m is measured.

TABLE II
Test Device Parameters

Parameter	Size (cm)	Material	Density (%)
Plasma radius	15	Vacuum	
First wall			
Radius	25	Vacuum	
Thickness	6	HT-9	18
Breeder	42	Li_2O	85 x 0.85
		HT-9	8
		Helium	7
Plenum	22	HT-9	15
Shield	30	S.S.	100

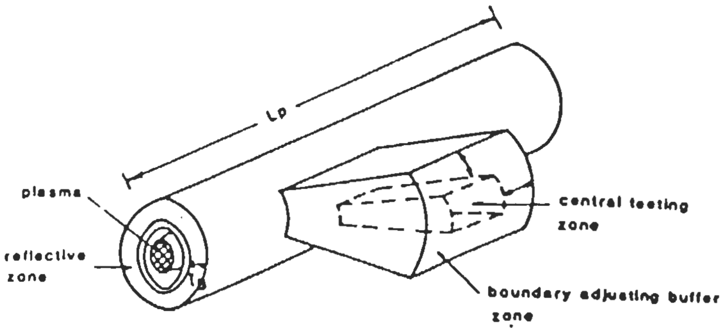


Figure 1. Concept of the Test Module

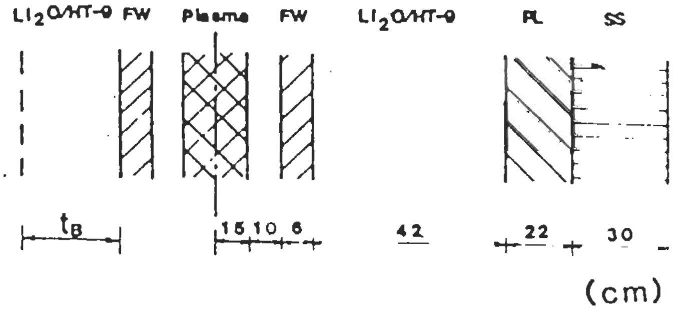


Figure 2. One-Dimensional Slab Model

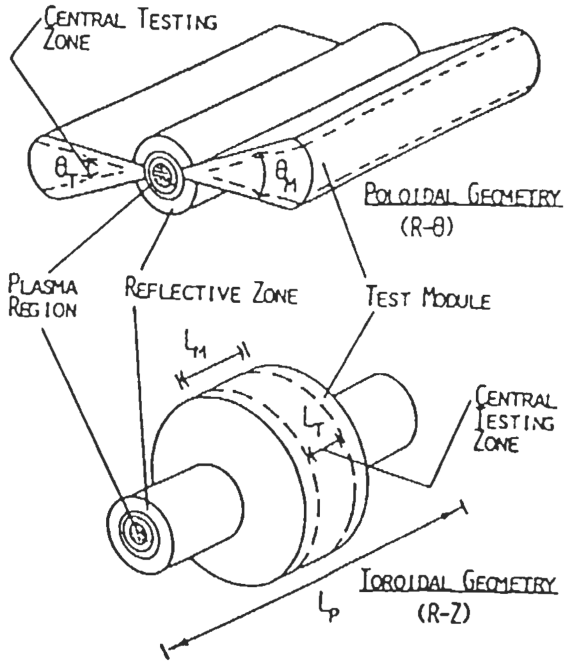


Figure 3. Two-Dimensional Cylinder Model.

B. Reflective Zone

The impact of the type of materials surrounding the test module on the neutron spectrum in the first wall has been investigated in a slab geometrical model. A series of calculations has been carried out to optimize the

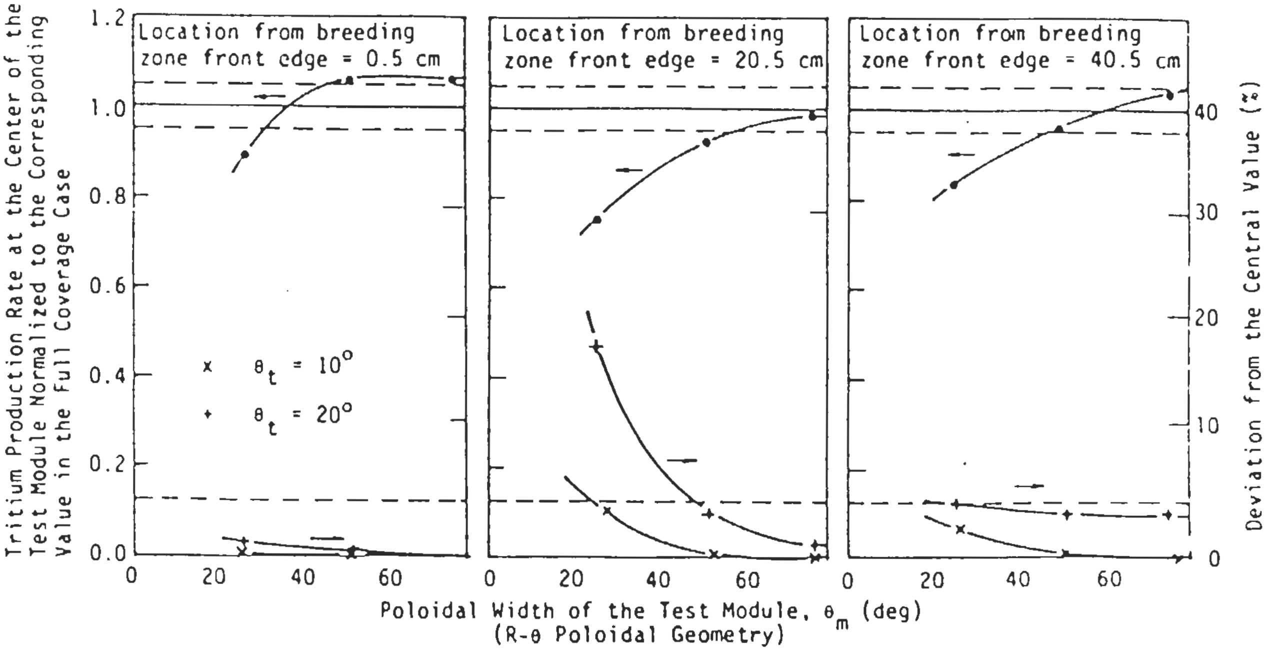


Fig. 4. The total tritium production rate ($T_6 + T_7$) as a function of the test module width (θ_m). Also shown is the deviation (%) from central values as a function of the test module width for two central zone widths, θ_t = 10 and 20 deg.

thickness of the breeding zone located in the reflector side. The fact that the low energy neutrons saturate more slowly as compared to the fast ones indicates that the front part of the breeding zone (in the reflector side) is more efficient in reflecting the high energy neutrons, while a thicker breeding zone is required to simulate the reflected slow energy neutrons. However, an excellent simulation of the tritium production profile can be obtained in the case where B = 5 cm, followed by a 10-cm thick stainless steel zone as can be seen in the results given in Table III.

TABLE III

Total Tritium Production Rate ($T_6 + T_7$) Normalized to the Values in the Reference Case (B:Breeder)

	Depth in the Breeder (cm)		
Case	0.5	20.5	40.5
B = 42 cm (ref.)	1.0	1.0	1.0
B = 0 cm	0.580	0.635	0.711
B = 10 cm	0.871	0.919	0.945
B = 20 cm	0.970	0.984	0.991
B = 0, SS = 10 cm	1.038	0.990	0.991
B = 5, SS = 10 cm	1.006	0.997	0.996
B = 10, SS = 5 cm	0.959	0.974	0.982

C. Poloidal Width of the Test Module

Figure 4 shows the variation in the local tritium production rate (sum of T_6 and T_7) as a function of the poloidal angle θ_m at three locations on the central line of the test module. The value shown is normalized to the corresponding values in the full coverage case. Also shown in this figure is the maximum percentage deviation of the tritium production rate at $\theta_t/2$ = 5 and 10 deg from that at the central line. This deviation depends on the width of the test module, which is characterized by the angle θ_m, and on the location throughout the test module, e.g., top or middle, as shown in Fig. 4. The information contained in this figure is used to specify the minimum test module width (θ_m) that is required to obtain a tritium production rate at a given location inside the test module which is within a desired target percentage of the corresponding value in the full coverage case. For example, if the local tritium production rate at the front edge of the test module central line is required to be within 5% of the corresponding value of the full coverage case, the width of the test module should be the one that corresponds to either θ_m = 22 deg (-5% deviation) or θ_m = 48 deg (+5% deviation). If measurements were to be performed at the back-edge of the test module central line, the corresponding values would be θ_m = 48 or 71 deg for the same target accuracy. The situation is different at the middle location where a test module width that corresponds to $\theta_m{}'$ = 55 deg would give a 5% target accuracy. In addition to this prescribed deviation, it is necessary to add the incremental contribution that comes from performing the measurements within the spatial zone characterized by the angle θ_t.

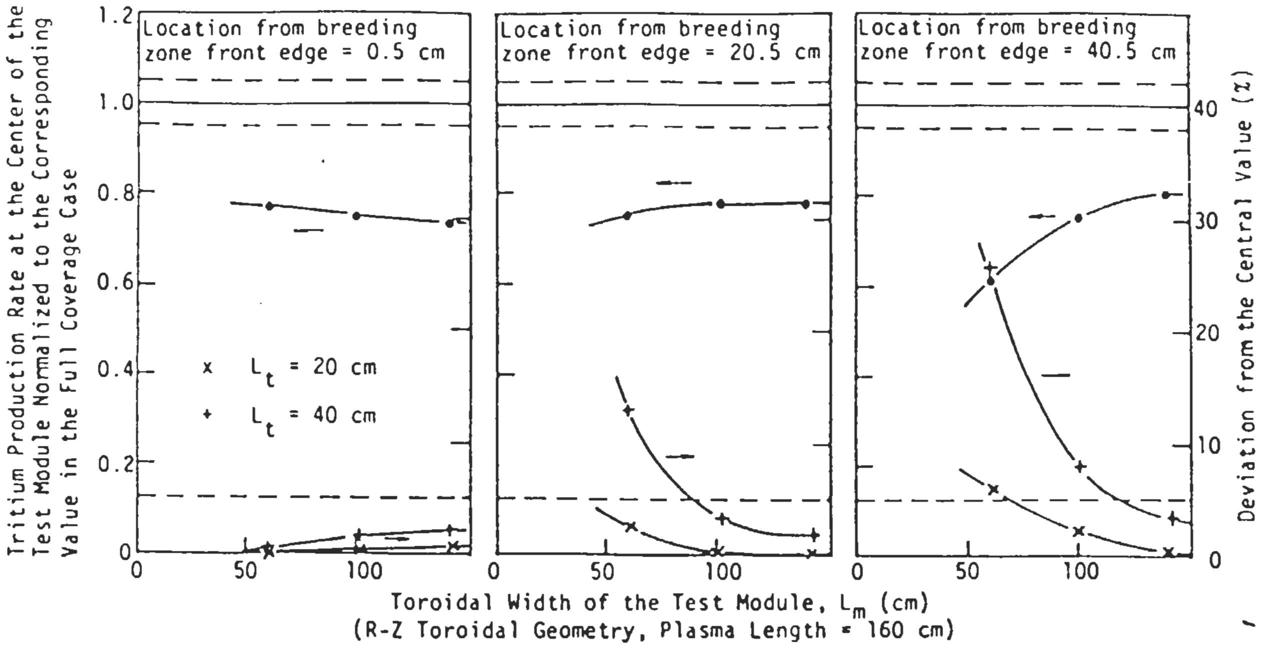


Fig. 5. The total tritium production rate ($T_6 + T_7$) as a function of the test module width (L_m). Also shown is the deviation (%) from the central values as a function of the test module width for two central zone widths, L_t = 20 and 40 cm in the case of the plasma length, L_p = 160 cm.

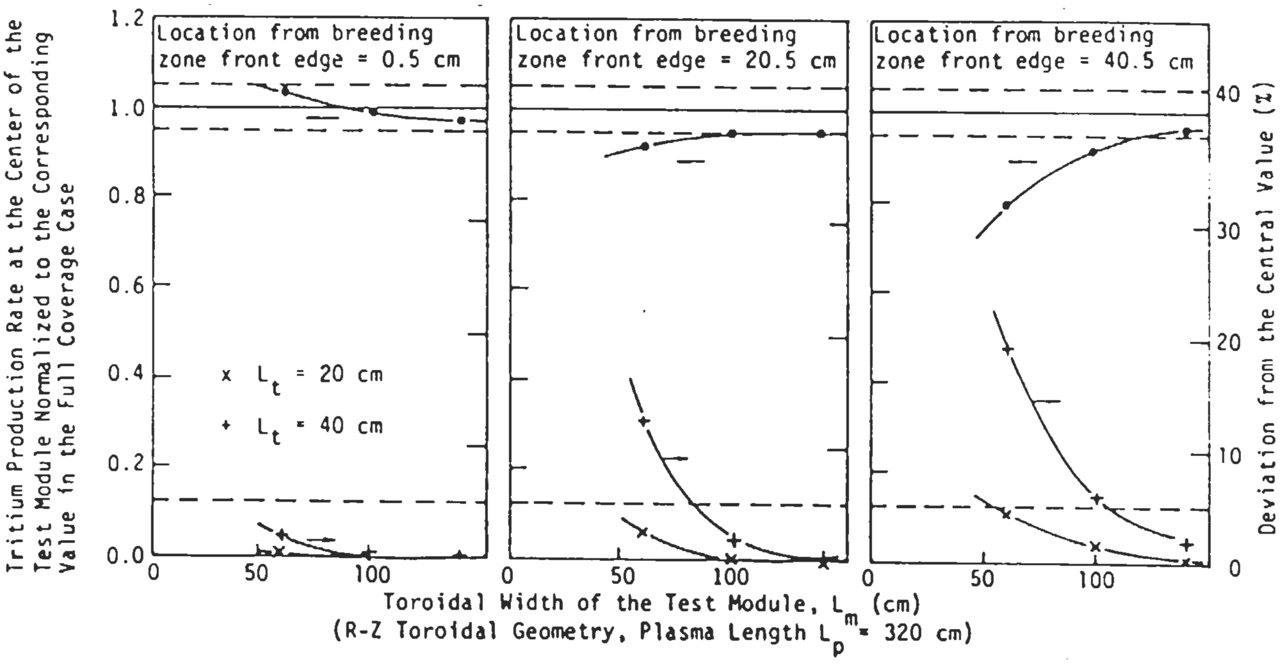


Fig. 6 The total tritium production rate ($T_6 + T_7$) in the case of plasma length, L_p = 320 cm, shown in the same way as Fig. 5.

D. Toroidal Width of the Test Module

Similar curves that specify the minimum test module size in the R-Z geometrical model are shown in Figs. 5 and 6 for the cases where the plasma length is L_p = 160 and 320 cm, respectively. In this geometrical arrangement, the test module width is characterized by the parameter L_m while the test module-central zone where measurements are most likely to be performed is characterized by the parameter L_t. For the case with L_p = 160 cm, the tritium production rate at the front edge of the test module is within 5% of the corresponding value in the full coverage case provided the test module width is either L_m = 50 cm (+5% deviation) or L_m = 150 cm (−5% deviation). For the former case, one should add ~3.4% deviation (total ~8.4%) if measurements were to be carried out within the central zone of L_t = 40 cm at that location.

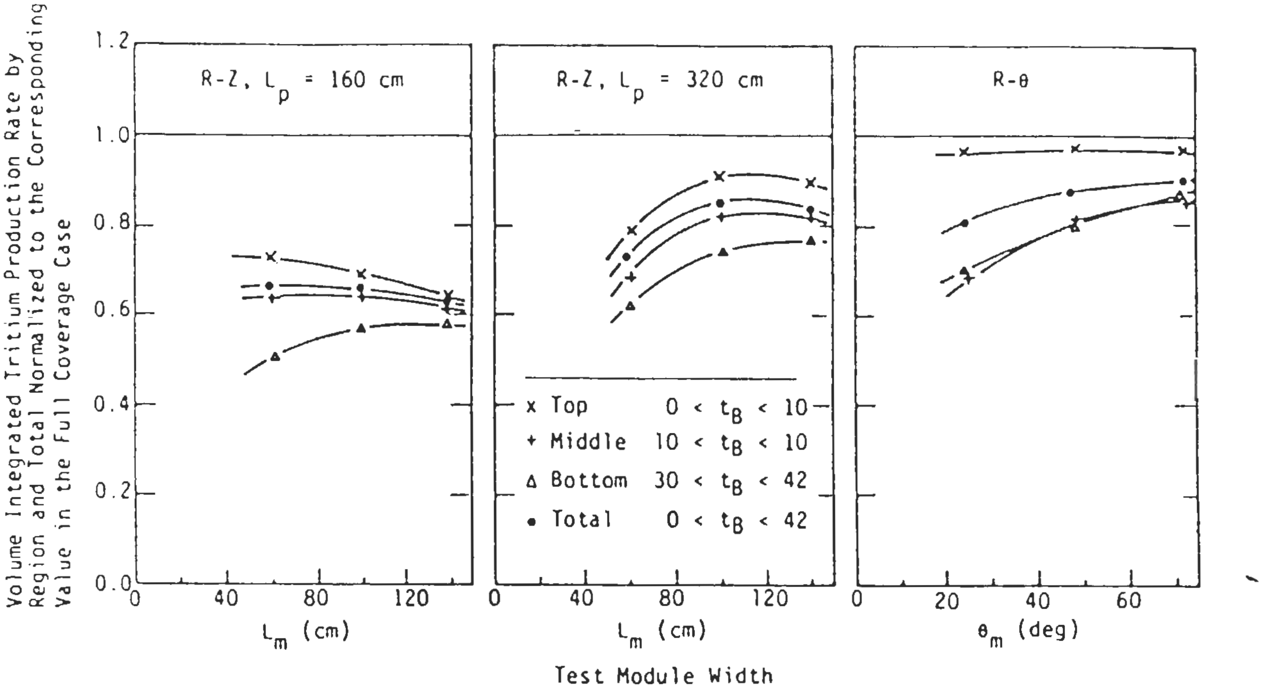


Fig. 7. The total tritium production rate integrated over various spatial segments and the overall tritium breeding rate as a function of the test module width (L_m or θ_m).

E. Integrated Tritium Production Rate

There are several serious problems concerning the usefulness of the integrated TBR verification tests in a fusion test device with a test module that partially covers the plasma source. Figure 7 shows the integratged values of tritium production rate in various segments of the test module (characterized by the parameter t_B) and the overall tritium breeding rate as a function of the test module width. Curves are shown for both the R-θ and R-Z arrangements. The values shown in this figure are normalized to the corresponding values in a volume equivalent to the test module volume in the full coverage case. In all the cases shown, the total tritium breeding ratio in the test module is significantly smaller than the corresponding value in the full coverage case. The uncertainties involved in extrapolating the tritium breeding measurements in a test module to an achievable net tritium breeding ratio in a full-scale reactor are greater than presently estimated margins in the tritium breeding potential for a candidate blanket concept.

CONCLUSIONS

The most serious problems were found in the neutronics analysis which showed that simulating a fusion reactor to extrapolate the full coverage effects was very difficult in the partial coverage arrangement. The reflective zone was also very important regarding the source determination. These lead to two particularly important conclusions. First, blanket neutronics measurements in a test module in any fusion facility, while useful, do not provide the level of accuracy necessary for neutronics verification, particularly resolving the issue of the achievable tritium breeding ratios. Thus, neutronics measuremeasurements do not by themselves provide strong justification for a fusion test facility, but such measurements are useful to perform if such a test facility is justified by other engineering test requirements. Second, the problem of demonstrating D-T fuel sufficiency prior to constructing a full-scale reactor requires further detailed evaluations.

ACKNOWLEDGEMENT

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