Pulsed Activation Analyses of the ITER Blanket Design Options Considered in the Blanket Trade-Off Study

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Abstract

Pulsed activation calculations have been performed on two blanket options considered as part of the ITER home team blanket trade-off study. The objective was to compare the activity, afterheat and waste disposal rating (WDR) results of a composite blanket/shield design for the continuous operation approximation to a pulsed operation case to determine whether the differences are at most the duty factor as predicted by the two nuclide chain model. Up to a cooling period of 100 years, the pulsed activity and afterheat values were below the continuous operation results and well within (except for one afterheat value) the maximum deviation predicted by the two nuclide chain model. No difference in the WDR values were noted as they are, to a large extent, based on long-lived nuclides which are insensitive to short-term changes in the operation history.

1. Introduction

The International Thermonuclear Experimental Reactor (ITER) project began a new design phase in July of 1992 called the Engineering Design Activity (EDA). As part of this activity the U.S. ITER home team initiated a blanket option trade-off study (BOTS) wherein several blanket design options were analyzed. The options considered were a self-cooled Li/V blanket, a helium cooled Li/V blanket and a water cooled 316 SS nonbreeding blanket/shield option. Detailed activation, dose rate and waste disposal rating (WDR) calculations have been performed for these different ITER blanket design options based on a fluence of 3.0 MW/m^2 and an average neutron wall loading of 2.0 MW/m^2. The BOTS blanket analysis was based on a continuous operation assumption. The results of this work are presented in a companion paper in this conference [1].

For many years it was assumed that magnetic fusion energy (MFE) devices would perform on a steady state (continuous) operation basis. Changes in plasma stability and confinement theories have led to changes in the operation mode of the devices. MFE reactors are currently proposed to operate in a pulsed/intermittent mode with pulse widths, t_p, ranging from several minutes up to an hour and off (dwell) times, t_d, of several minutes. During the experimental and startup phases of these devices, the dwell time between pulses can be on the order of several hours. Several papers have been written over the past few years discussing the effect of pulsed/intermittent activation in MFE devices [2-4]. In Refs. 3 and 4, using a two nuclide chain model, it is demonstrated that the continuous operation approximation utilized to model the temporal operation history of MFE reactors can overestimate the activity and hence the activity related parameters for a given radionuclide by as much as the duty factor; $df = \frac{t_p+t_d}{t_p}$. Figure 1 depicts the results of the two nuclide chain model, i.e., the ratio of the number density of the radionuclide computed by the pulsed equation, N (pulsed), to that computed by the steady state approximation, N (steady state), for the homogeneous pulse scheme

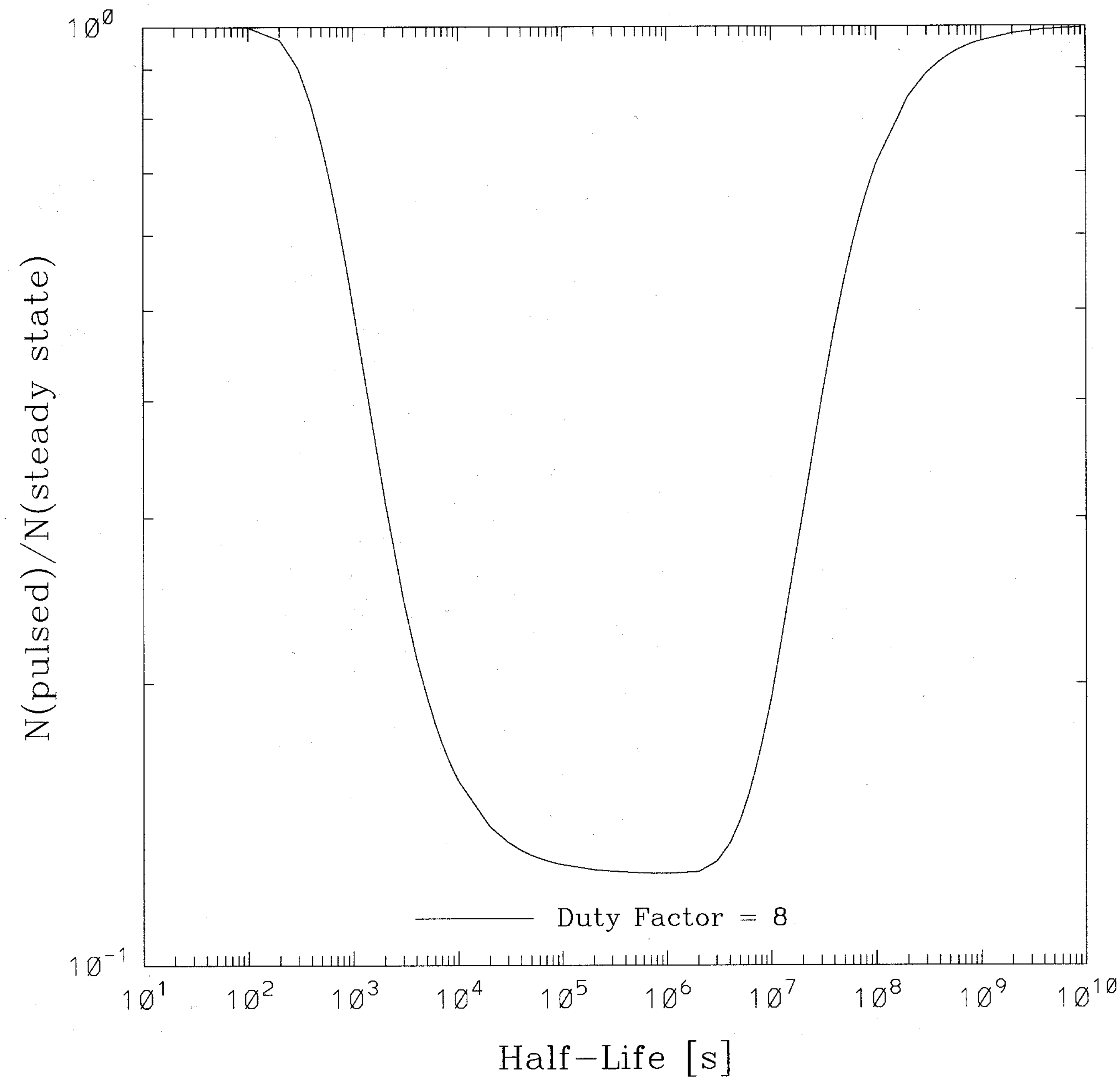

Figure 1. Ratio of the continuous operation approximation activity to the uniform pulse sequence activity for a duty factor of 8.

depicted in Fig. 2. The pulse width and dwell time are consistent with the ITER design parameters of the BOTS analysis. The analysis contained in Refs. 3 and 4 is based on the examination of a single radionuclide. Shielding, blanket and structural materials are composed of a number of constituent nuclides which are affected in varying degrees by the operation history. Thus depending on the influence of the temporal history on the activity of the various radionuclides and the contribution of each radionuclide to the total activity, one can expect that the activity and activity related parameters computed by the continuous operation approximation will be off by at most the duty factor at shutdown and for several months to a year thereafter from the actual pulse case values.

The objective of this paper is to compare the activity, afterheat and WDR results of the continuous operation approximation to an actual pulsed operation case for a composite blanket/shield design to determine whether the differences are at most the duty factor as predicted by the two nuclide chain model. A brief activity comparison of two BOTS blanket designs, the self cooled Li/V and the 316 SS nonbreeding option, is made using three different inhomogeneous pulse histories, a uniform/homogeneous pulse scenario and the continuous operation approximation. The various temporal histories are consistent with the originally proposed ITER design parameters: a nominal fusion power of 3.0 GW, an average wall loading of 2.0 MW/m^2, 10^4 cycles with a power of 3.0 GW and 10^5 cycles with a power of 1.5 GW, a pulse duration of 1000 seconds and a maximum duty cycle of 50%. Following the above general comparison, a more detailed comparison is made between the steady state approximation and one of the inhomogeneous pulse cases.

2. Method of Solution

The multigroup discrete ordinate code package TWODANT [5] was used to perform the one-dimensional toroidal cylindrical geometry neutronics calculations. A 46 neutron – 21 gamma coupled group cross section library containing P_3 Legendre

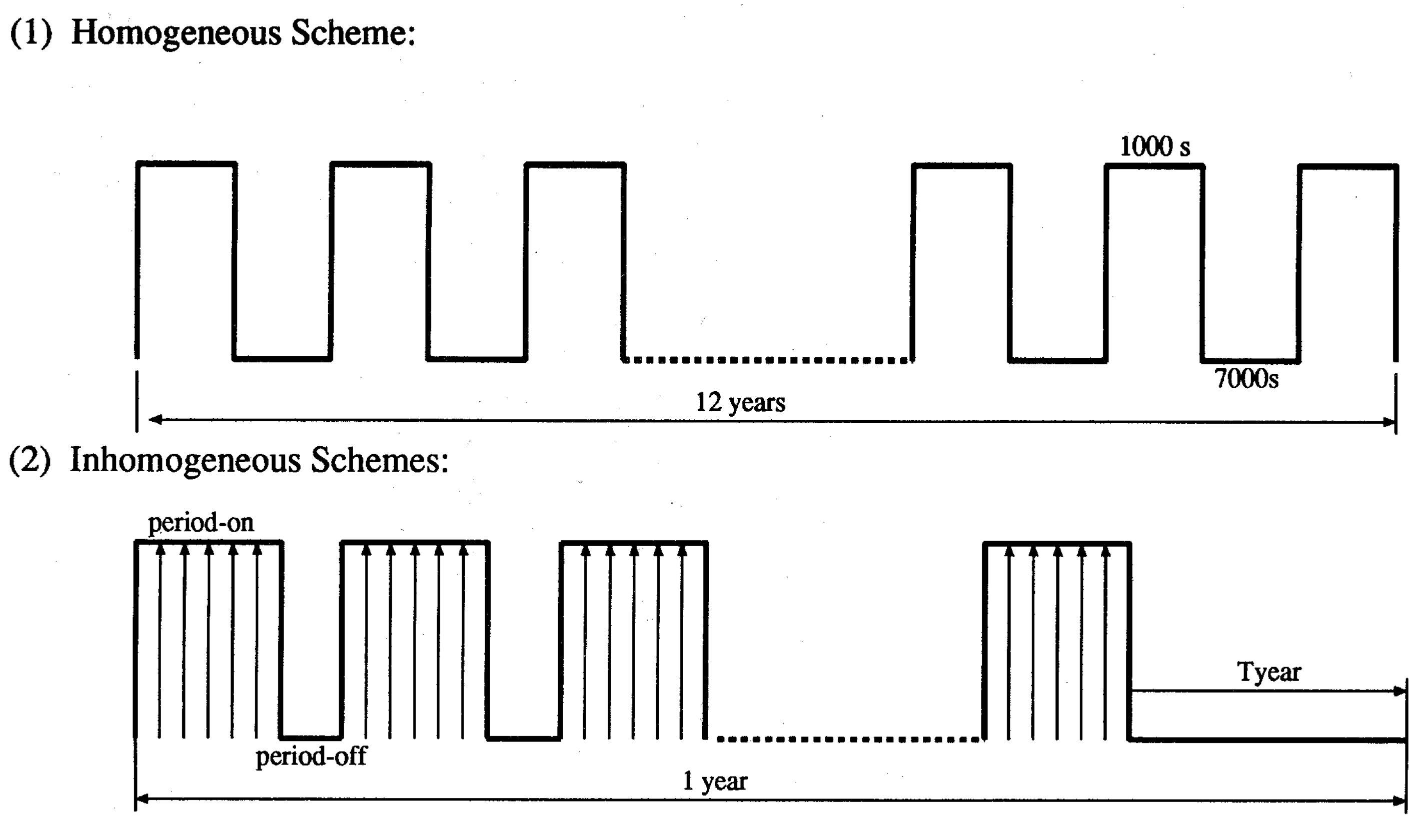

Figure 2. Homogeneous and inhomogeneous pulse operation schemes.

expansions of the scattering cross-section based on the ENDF/B-V basic data files is used in the calculations. The analysis has been performed for a nominal fusion power of 3.0 GW and an average wall loading of 2.0 MW/m^2. The inboard and outboard regions are assumed to extend over a height of 12 meters. The radial builds used for the two blanket options of the BOTS study are given in Figs. 1 and 2 in the companion paper of this conference [1].

The activation calculations were performed with a newly modified version of the DKR-ICF code [6] designated DKR-PULSAR. Various routines from the PULSAR demonstration code [3,7] have been implemented within DKR-ICF to accurately model pulse/intermittent operation histories. The activation cross section library utilized is USACT93 [8] and is based on isotopic radioactive decay and neutron transmutation cross section data from the ENDF/B-VI and EAF3 [9] basic data libraries.

The steady state calculations are based on the standard approximation utilized to model pulsed/intermittent operation histories in MFE devices; all pulses are coalesced into one continuous operation period (the dwell periods are removed and the flux height of the pulses is retained). This approximation preserves the neutron fluence; however, the operation period is reduced. For the general comparison, the pulsed operation histories utilized in this analysis are depicted in Fig. 2 and consist of a homogeneous scheme (uniform series of pulses) and three inhomogeneous schemes (nonuniform series of pulses) for the total twelve year period. A one year operation period is depicted for the inhomogeneous schemes with the pulse history parameters given in Table 1. Successive years have an identical temporal pattern except for the twelfth year; the device is shut down after the last pulse. The pulse width is the same for all cases, 1000 seconds; however, the dwell times differ, ranging from 1000 to 4000 seconds. In all cases the neutron fluence is preserved.

Table 1. Inhomogeneous Pulse Scheme Parameters

Case	Tdwell [s]	Period-on [days]	Period-off [days]	# Pulses/period	# Operation Periods/year	Tyear [day]
1	4000	21	9	359	11	39
2	1860	12	18	359	11	48
3	1000	8	22	359	11	52

The waste disposal rating (WDR) for the blanket and vacuum vessel are computed using the specific activities and the U.S. NRC 10CFR61 waste disposal concentration limits [10].

We note here that the steady state results presented in this paper differ from those presented in the companion paper [1]. The reason for the differences is that a different transmutation cross section library was employed for the activation calculations of each paper.

3. Results and Discussion

A comparison of the total activity of the three inhomogeneous pulsed operation schemes, the homogeneous pulse operation scheme and the continuous operation approximation for the self-cooled Li/V blanket is presented in Fig. 3. The steady state result overestimates the activity results from shutdown to a cooling time of approximately 100 years after shutdown. In the extreme long term after shutdown, the activity results are the same as expected since the long half-life isotopes are unaffected by short term differences in the operating history. The differences in the activity values for short times after shutdown are due to intermediate half-life nuclides (minutes to possibly a few hours) which dominate the overall activity at shutdown. The effect short-lived nuclides, with half-lives on the order of the dwell period, have on the activity can be seen by differences in the pulsed activation results. Since the total fluence in all cases is the same, the

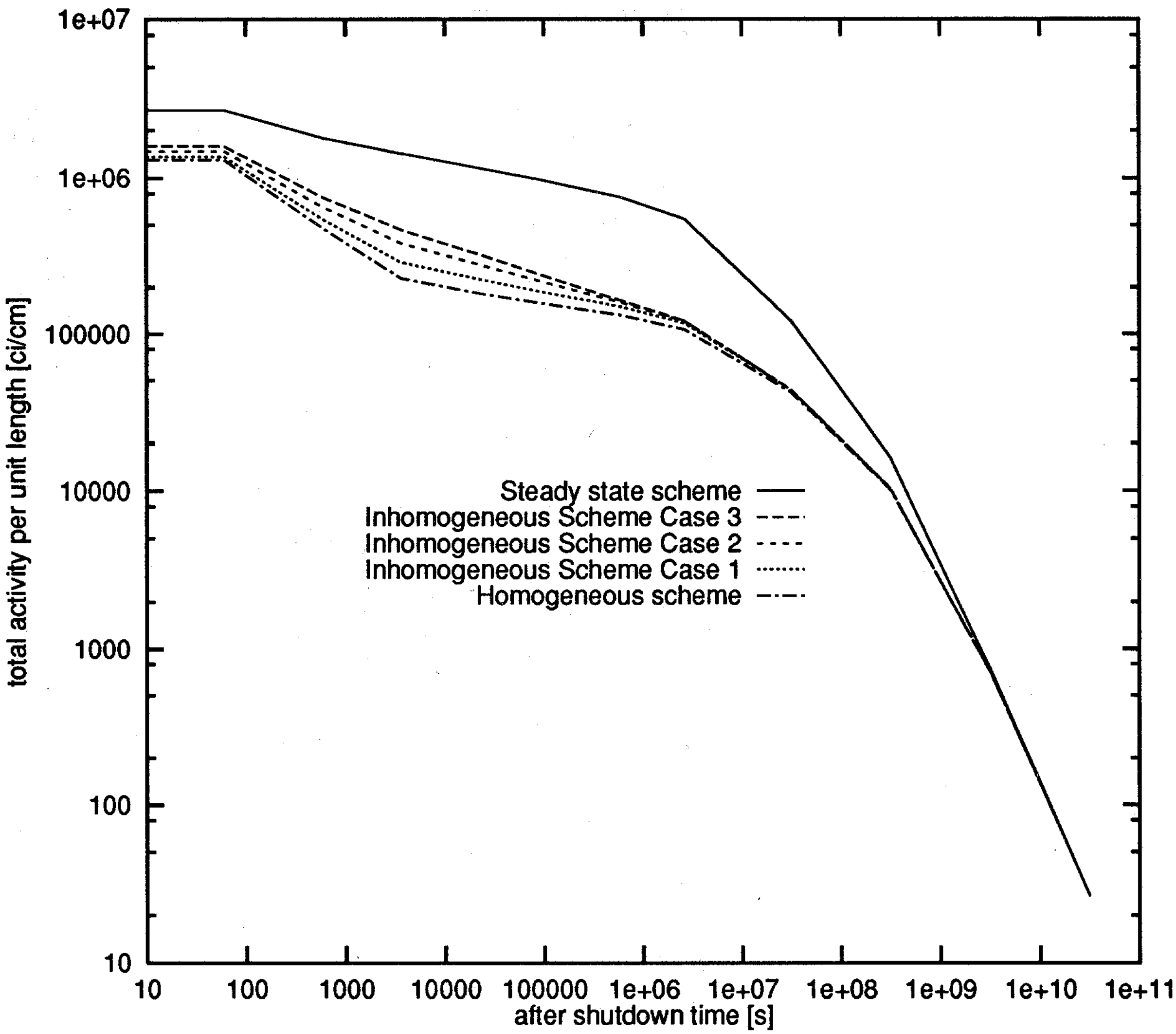

Figure 3. Total activity after shutdown for the self-cooled Li/V blanket option.

differences can only be due to variations in the length of the dwell periods. Note that the homogeneous pulsing scheme has the lowest total activity from approximately 1 minute to 1 year after shutdown. The duty factor for the homogeneous scheme is 8, hence the steady state results should be at most a factor of 8 larger than the pulsed results. The largest difference between the results is a factor of 6.33 at 6 hours after shutdown, which is slightly lower than the maximum deviation of 8 predicted by the two nuclide chain model (see Fig. 1). This is due to the composite effect the various radionuclides have on the total activity as noted previously.

Figures 4 and 5 present specific material activity comparisons for the continuous operation and the Case 1 inhomogeneous operation scheme. The overall trend in the results for the continuous and pulse cases is the same: at shutdown the V5Cr5Ti structure dominates the activity. After approximately a 10 minute cooling period, the activity of the V5Cr5Ti has dropped below that of Inconel and 316 SS which have comparable activities through the remaining after-shutdown period considered. Being positioned outside of the vacuum vessel (see Fig. 1, Ref. 1), the Pb structure, having a smaller volume and being exposed to a lower flux level, produces the least amount of radioactivity of the structural materials in the self-cooled Li/V blanket. As noted in the figures, the pulsed operation scheme affects each structural material differently (the difference between the continuous and pulsed curves depends on the dominant radionuclides) with the beryllium structure affected the least. A detailed isotopic analysis, not presented in this paper, would be necessary to determine the specific radionuclides affected and the extent of the effect. A comparison of the vacuum vessel and blanket structure total activity and decay heat results is presented in Table 2. It is noted that for the pulsed case, the vacuum vessel activity and afterheat values are considerably lower than the blanket values as compared to the same quantities computed for the steady state case. The pulsed operation results for the blanket region are up to a factor of 2.9 for the activity and 4.2 for the afterheat

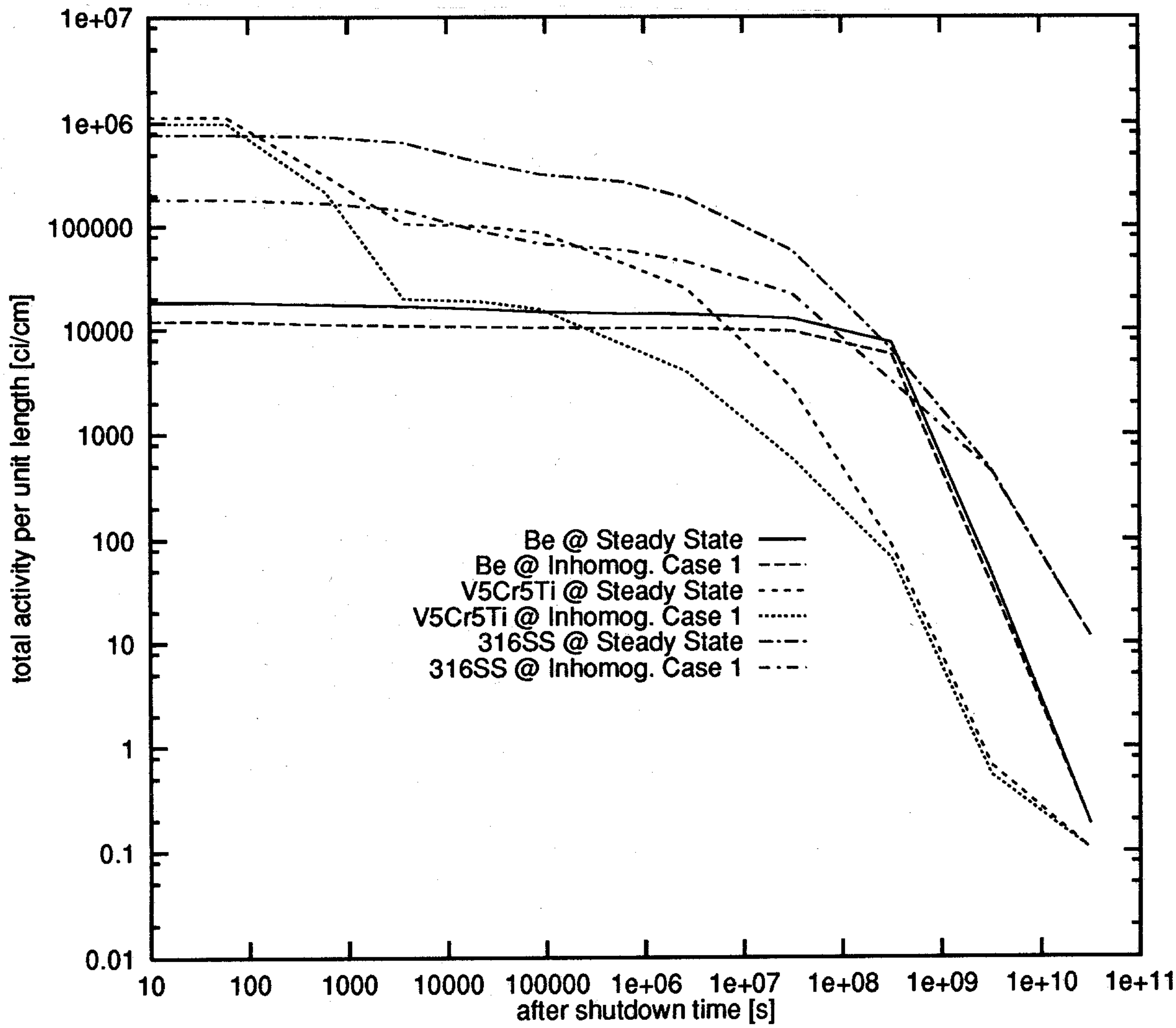

Figure 4. Material activity after shutdown for the self-cooled Li/V blanket option.

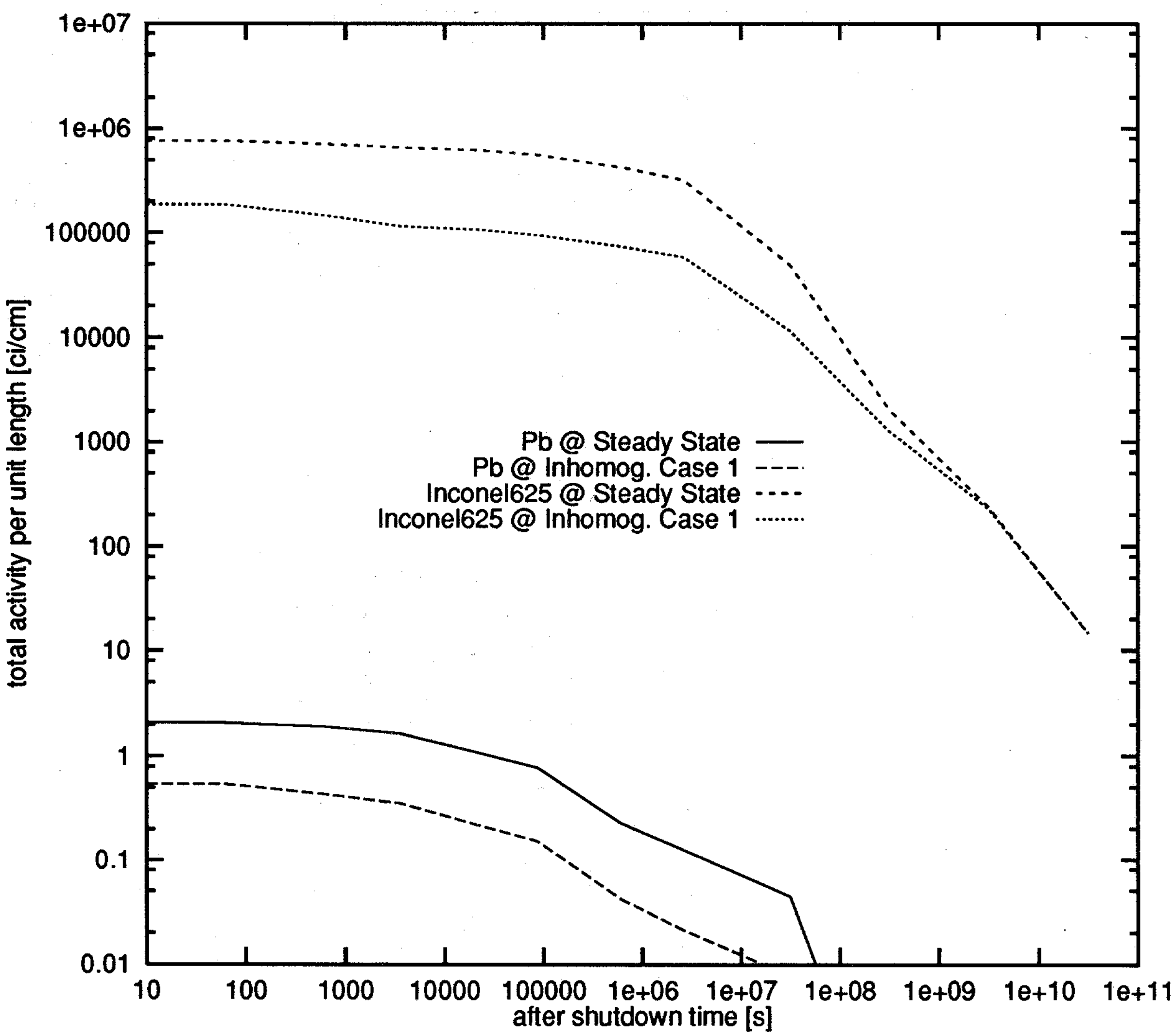

Figure 5. Material activity after shutdown for the self-cooled Li/V blanket option.

Table 2. Total Activity (MCi) and Decay Heat (MW) for the Self-Cooled Li/V Blanket Option

	Steady State Operation Scheme				Pulsed Operation Scheme (Case 1)			
	Blanket		Vacuum Vessel		Blanket		Vacuum Vessel	
	Activity (MCi)	Decay Heat (MW)	Activity (MCi)	Decay Heat (MW)	Activity (MCi)	Decay Heat (MW)	Activity (MCi)	Decay Heat (MW)
0	2913.75	34.39	2061.25	14.15	2723.75	32.19	601.50	3.89
1 min	1436.25	19.39	1923.75	13.23	1252.50	17.33	463.38	2.96
1 hour	152.88	1.50	1641.25	10.80	38.10	0.30	324.75	2.12
l day	126.75	1.05	1106.13	4.74	32.71	0.21	203.38	0.73
1 week	72.13	0.20	871.25	3.82	21.90	0.04	164.50	0.65
1 month	48.25	0.08	636.25	2.85	17.86	0.01	129.00	0.55
1 year	19.33	9.26e-4	132.25	0.45	12.79	2.18e-3	41.50	0.14
10 year	9.51	6.91e-4	10.61	0.04	7.31	4.38e-4	5.60	0.02
100 year	0.06	3.26e-6	0.87	2.13e-4	0.05	2.55e-6	0.84	211e-4

lower than the steady state results. For the vacuum vessel the factors are 4.8 for the activity and 5.7 for the afterheat. These factors are lower than the maximum deviation (8) predicted by the two nuclide chain model.

The total activity comparison for the water cooled 316 SS nonbreeding blanket for the three inhomogeneous pulse operation schemes, the homogeneous scheme and the continuous operation approximation are shown in Fig. 6. The results for the pulsed cases are quite different at shutdown as compared to the Li/V curves indicating that a major contributor to the short-term activity is an isotope with a half-life of a few hours. At approximately one year after shutdown the pulsed schemes produce essentially the same result. As for the case of the self-cooled Li/V blanket, after a cooling period of 100 years the results of the steady state and pulse cases agree. The largest difference between the results is a factor of 4.5 at shutdown.

A specific material activity comparison for the 316 SS nonbreeding blanket for the continuous operation and the Case 1 inhomogeneous operation scheme is shown in Fig. 7. One notes that the activity in the device is dominated by 316 SS. This is because 316 SS structurally dominates the design of the vacuum vessel, blanket and shield (see Fig. 3, Ref. 1). To compare the Inconel and 316 SS structures on an equal basis, the specific activities of the materials would need to be compared and analyzed which is beyond the scope of this paper. As in the Li/V blanket case, the Pb structure produces the least amount of radioactivity. Table 3 presents a comparison of the vacuum vessel and blanket structure total activity and decay heat results. The difference between the pulsed and steady state operation blanket results is a factor of up to 4 for the activity results and 4.8 for the afterheat results. For the vacuum vessel the factors are 5.2 for the activity and 12 for the afterheat. The factor of 12 is surprisingly large but it should be realized that afterheat does not necessarily follow the same behavior as activity.

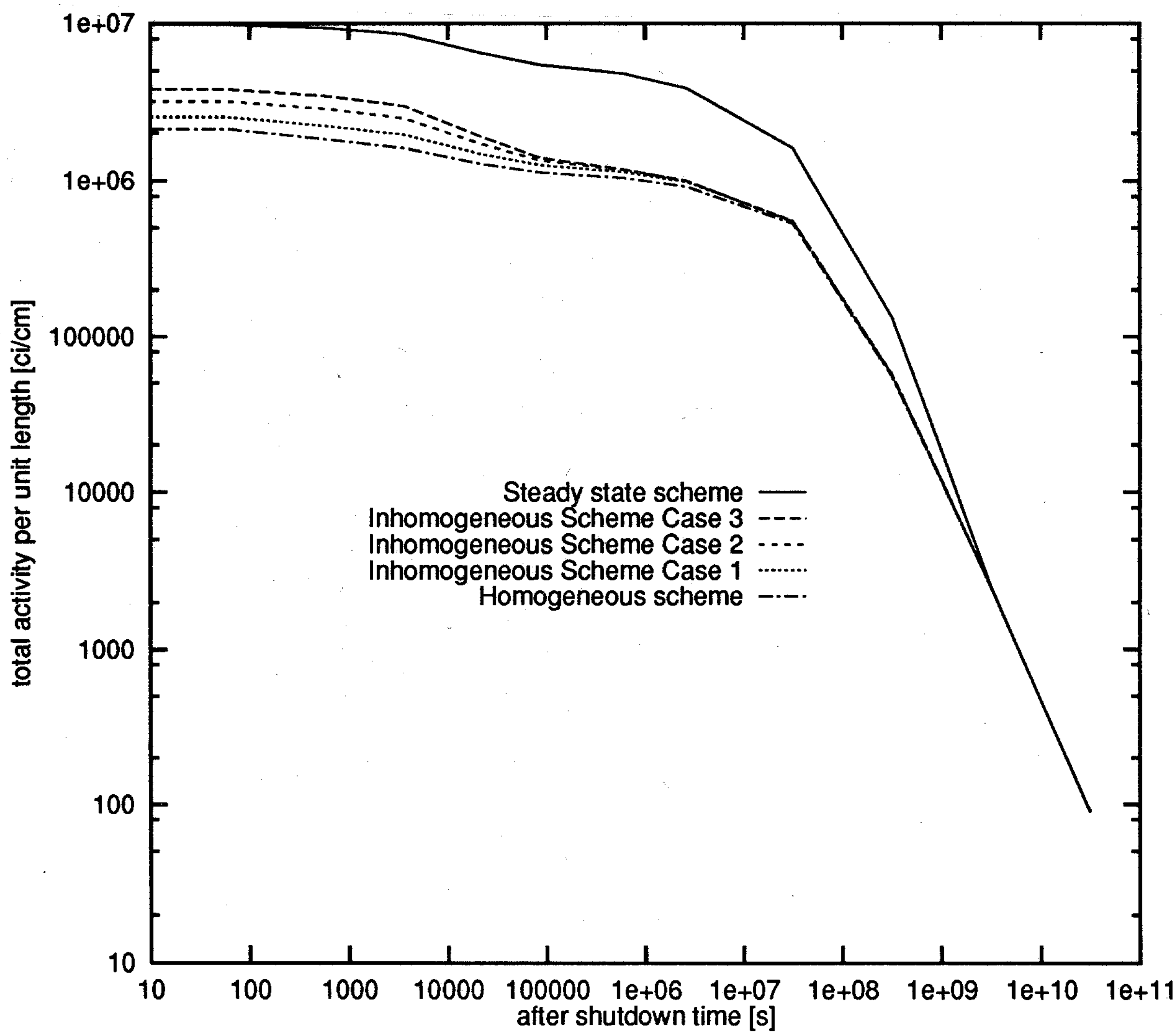

Figure 6. Total activity after shutdown for the 316 SS/H_2O blanket option.

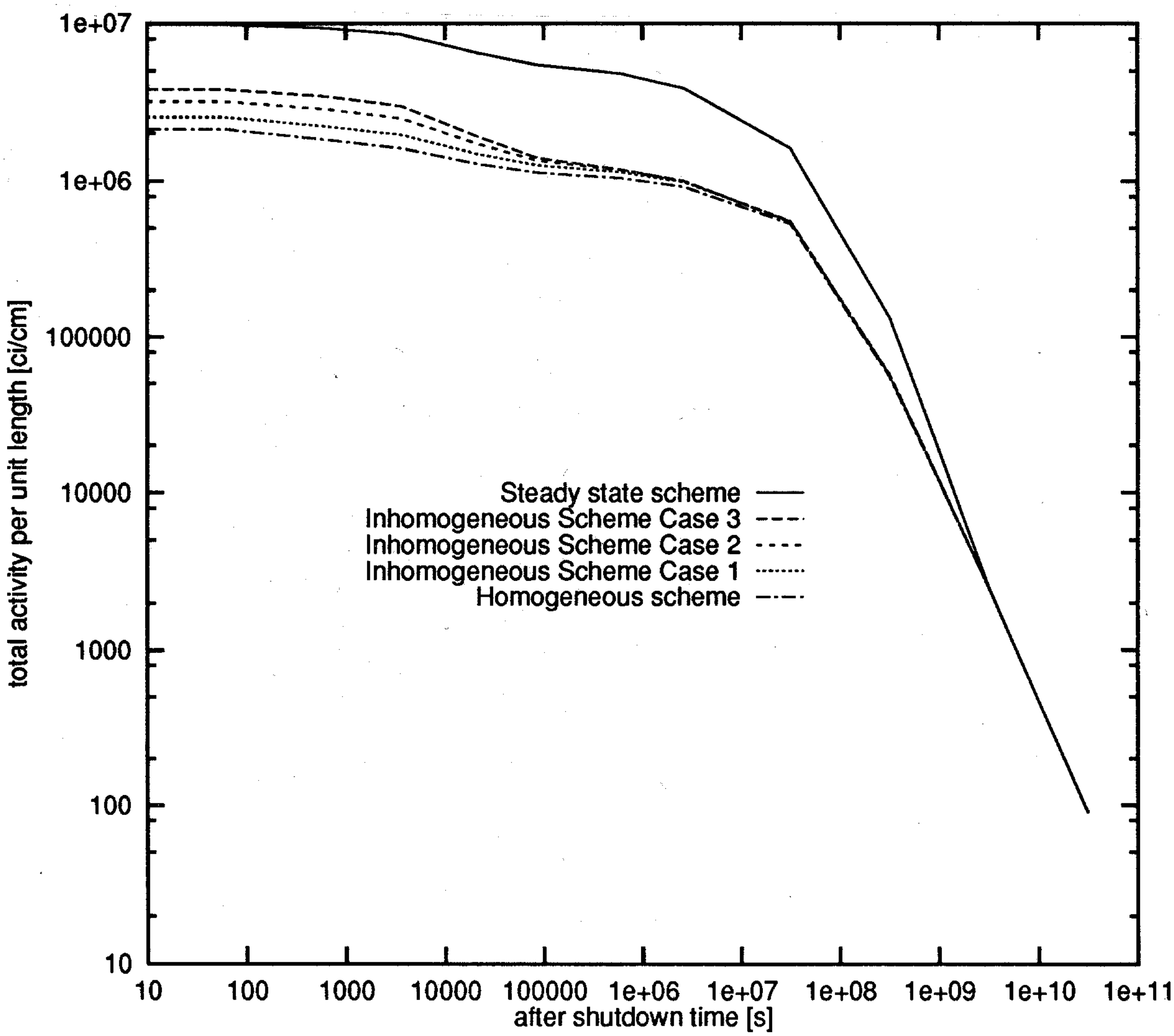

Figure 7. Material activity after shutdown for the 316 SS/H_2O blanket option.

Table 3. Total Activity (MCi) and Decay Heat (MW) for the 316 SS/H_2O Blanket Option

	Steady State Operation Scheme				Pulsed Operation Scheme (Case 1)			
	Blanket		Vacuum Vessel		Blanket		Vacuum Vessel	
	Activity (MCi)	Decay Heat (MW)	Activity (MCi)	Decay Heat (MW)	Activity (MCi)	Decay Heat (MW)	Activity (MCi)	Decay Heat (MW)
0	12335.00	83.18	55.00	0.38	3261.25	23.49	16.25	0.10
1 min	12198.00	81.61	50.00	0.34	3150.00	22.26	11.25	0.075
1 hour	10625.00	61.70	45.00	0.28	2447.50	13.91	8.75	0.063
1 day	6800.00	14.06	32.50	0.15	1570.00	2.79	5.00	0.024
1 week	6000.00	12.45	26.25	0.14	1425.00	2.49	3.75	0.021
1 month	4825.00	10.45	26.25	0.12	1230.00	2.18	2.50	1.9e-2
1 year	2012.50	2.91	6.25	0.01	690.00	0.92	0.75	3.9e-3
10 year	166.25	0.27	0.88	1.13e-3	71.00	0.14	0.01	1.1e-3
100 year	3.11	4.61e-4	0.03	5.88e-6	3.09	4.56e-4	0.002	5.4e-6

A comparison of the NRC Class C WDR results for both blanket options and for the continuous and pulsed operation cases is presented in Table 4. One notes that there is basically no difference between the continuous and pulsed operation results. This should not be unexpected as the majority of the radioactive isotopes listed in the regulatory guide are long-lived and as noted previously, long-lived isotopes are unaffected by short term temporal differences in the operation history.

4. Conclusions

Pulsed activation calculations have been performed on two blanket options considered as part of the ITER home team blanket trade-off study. The objective was to compare the activity, afterheat and WDR results of a composite blanket/shield design for the continuous operation approximation to a pulsed operation case to determine whether differences are at most the duty factor as predicted by the two nuclide chain model. It was found that the two nuclide chain model provided an upper bound for the differences in activity following shutdown. Though the differences in the results are not overly large (ranging up to 6.33), the differences can influence decisions regarding remote handling versus hands-on maintenance. For the activity related parameters considered, it was noted that the difference in the afterheat results, to a large extent, paralleled the activity results fairly well except for one case for which the difference was 12. For the WDR rating it was noted that there was no difference between the values of both operating modes. This is because the WDR values are largely based on long-lived nuclides which are insensitive to short-term changes in the operation history. From the results of this brief analysis it can be stated that the two nuclide chain model predicts the maximum difference between the continuous and pulsed operation cases for the activity and does a fairly good job for the afterheat. However, pulsed operation calculations must be performed to obtain the actual values necessary for a suitable design analysis.

Table 4. Class C NRC Waste Disposal Ratings for the Self-Cooled Li/V and 316 SS/H_2O Blanket Options

	Steady State Operation Scheme				Pulsed Operation Scheme (Case 1)			
	Blanket		Vacuum Vessel		Blanket		Vacuum Vessel	
	Self-Cooled Li/V	316 SS/ H_2O	Self-Cooled Li/V	316 SS/ H_2O	Self-Cooled Li/V	316 SS/ H_2O	Self-Cooled Li/V	316 SS/ H_2O
0	0.15	3.78	5.14	0.93	0.15	3.78	5.20	0.93
1 min	0.15	3.78	5.14	0.93	0.15	3.78	5.20	0.93
1 hour	0.15	3.78	5.14	0.93	0.15	3.78	5.20	0.93
1 day	0.15	3.78	5.14	0.93	0.15	3.78	5.20	0.93
1 week	0.15	3.78	5.14	0.93	0.15	3.78	5.20	0.93
1 month	0.15	3.78	5.14	0.93	0.15	3.78	5.20	0.93
1 year	0.15	3.78	5.14	0.93	0.15	3.78	5.20	0.93
10 year	0.15	3.78	5.14	0.93	0.15	3.78	5.20	0.93
100 year	0.15	3.78	5.14	0.93	0.15	3.78	5.20	0.93

Acknowledgement

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