Validation of the ALARA Activation Code for Arbitrary Irradiation Schedules

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Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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Phiphat Phruksarojanakun, Paul P.H. Wilson
University of Wisconsin-Madison
1500 Engineering Dr.
Madison, WI 53706
wilsonp@engr.wisc.edu

ABSTRACT

The ALARA [Analytic and Laplacian Adaptive Radioactivity Analysis][1] activation code, previously validated for its accuracy and precision [2], has now been validated for arbitrary irradiation schedules. Based on the International Atomic Energy Agency [IAEA] Fusion Evaluated Nuclear Data Library [FENDL] Calculational Activation Benchmark[3], eight irradiation schedules were designed, each conserving the total fluence and schedule duration of the benchmark's pulsing problem. In addition to steady-state approximations and hybrid pulsing schemes, the test schedules included pulsing histories with varied pulse heights and increasing levels of complexity. The total calculated activities in 44 non-void zones at four short (≤ 1 hr) cooling times were used to compare results for the eight different irradiation histories to the exact pulsing benchmark. Overall, agreement between the exact pulsing case and the testing cases was within 1.92% at all zones and within 0.35% in most zones. The results show that ALARA is an effective computational tool for the calculation of induced activity caused by complex irradiation schedules.

1. INTRODUCTION

Increasingly, calculations of induced activity in fusion power systems involve complex irradiation schedules. For example, in some inertial fusion energy systems, target material deposition is expected on the first wall. Following the initial irradiation while that material is part of the target, it will be subjected to lower magnitude pulses during its residence on the first wall, and then removed from the reaction chamber and recycled into another target to repeat the process. Similarly complex irradiation schedules are associated with the complex flow paths of liquid breeders through the blankets of many fusion energy system designs. Therefore, it is important to develop a computational tool that is able to simulate arbitrary pulsed/repeated irradiation schedules.

ALARA [Analytic and Laplacian Adaptive Radioactivity Analysis][1] has already been validated[2] for its general solution methodologies and its ability to handle complex histories of uniform pulses. This work verifies ALARA's implementation of support for complex histories of non-uniform pulses.

2. BENCHMARK SPECIFICATION

The reference problem for this verification is the IAEA FENDL Calculational Activation Benchmark [3] pulsing problem. It is based on the reference steel/water shielding blanket design in the ITER outline design and includes all materials from the inboard magnet to the outboard vacuum vessel. The neutron fluxes are provided by the benchmark in the VITAMIN-J 175 group energy structure for each of the 468 fine mesh intervals. Zones 27 through 29 represent the plasma. These fluxes were calculated using the ONEDANT [4] deterministic neutron source normalized to inboard and outboard neutron wall loadings of 1 and 1.5 MW/m^2, respectively. In all cases the FENDL-2/A activation library and FENDL-2/D decay library were used. The benchmark problem is a typical uniform pulsed operation in a fusion power system with 94500 pulses. Each pulse lasts 1000 seconds with dwell time of 1200 seconds between pulses for a total irradiation time of 3 years and a total operation time of 6.592 years. This problem is one of the two used in the previous validation exercise[2].

This verification exercise includes eight test problems, each of which conserves the total fluence and the total schedule duration (the time between the beginning of the first pulse and the end of the last pulse). The first four test problems rely on commonly used approximations to pulsed irradiation histories. The second four problems are designed to perturb the irradiation schedule in order to stress the methods used in ALARA and are not expected to represent useful engineering approximations of this pulsing scenario. The results for each test problem are compared to the exact pulsing solution by calculating the relative difference of the total activity in each zone:

$$\text{Relative Difference (\%)} = \frac{EXACT - X}{EXACT} \cdot 100 ,$$

where X is a method of interest.

3. PULSING APPROXIMATIONS

The first set of test problems is made up of standard pulsing approximations currently used in fusion activation analysis. This research is not meant to be either a justification or a criticism of those approximations. Instead, they have been chosen because the differences between their results and the exact results are expected to be small and predictable. Thus they will provide a mechanism to test ALARA's capabilities.

3.1. Steady-state Approximation

The first activation calculation was performed with a steady-state approximation in which the flux was averaged over the full lifetime such that the total fluence and total operation time are conserved. This approximation has been shown to be reasonably accurate for most isotopes, with some error expected for short-lived isotopes (half-lives on the order of the dwell time between pulses, and shorter), and has been used often in the past for the analysis of magnetic confinement systems.

The relative difference for the steady state approximation is expected to be highest immediately following shutdown and reduce to nearly zero on the same time scale as the dwell time between pulses. Figure 1 shows the relative differences of the steady-state approximation at a cooling time of 1 hour, 4 hours, 8 hours and 1 day. The results are within 1.92% at all cooling times. As expected, they monotonically decrease as cooling time increases since both the total fluence and the total operating time are conserved. The differences between the results of the exact pulsing history and the steady state approximation are negligible at long cooling times.

3.2. Hybrid Approximation

The hybrid approximation is becoming a commonly used method to better approximate the pulsing problem in certain scenarios [5]. This technique takes advantage of the speed of the steady-state approximation by simulating the majority of pulses with a steady-state operation period, but improves upon that method's error by including a number of exact pulses at the end of operation. In essence, these final pulses represent a correction to the inventories of short-lived isotopes that dominate the error of the steady-state approximation.

The three hybrid irradiation schedules studied in this research had 100, 500 and 5000 exact final pulses, respectively. The relative differences for the hybrid cases are very small in magnitude, approaching the meaningful limit of this analysis. As such, the lack of monotonic behavior in these results as cooling time increases is inconclusive (and perhaps irrelevant). Figure 2 shows the relative difference from the 100-pulse hybrid approximation, relative to the exact pulsing solution. The overall patterns of the relative differences from the 500-pulse and 5000-pulse cases are similar to the 100 pulses with most data points lying below 0.015% and 0.010%, respectively. Table 1 presents the average relative differences for all zones in all hybrid cases.

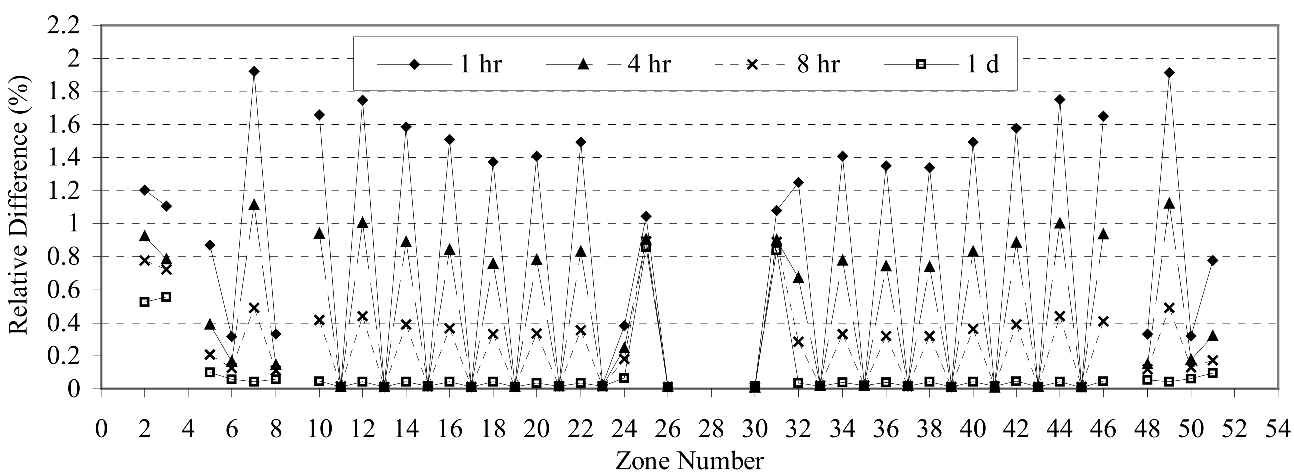

Figure 1. Relative difference (%) between the steady-state approximation and the exact pulse solution at different cooling times.

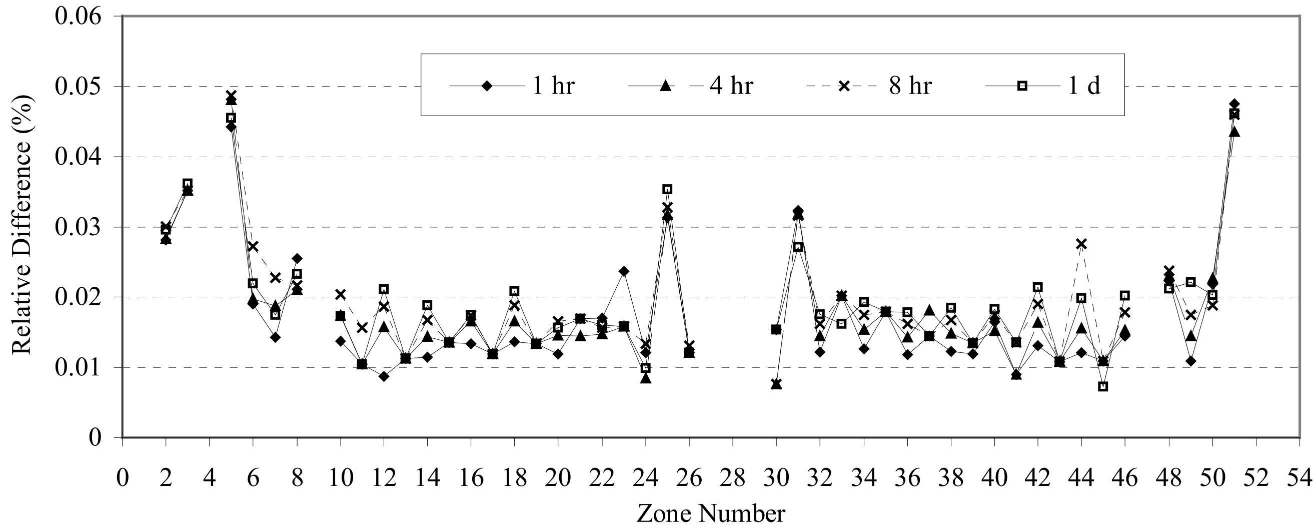

Figure 2. Relative difference (%) between the 100-pulse hybrid approximation and the exact pulsing solution at different cooling times.

Table 1. Average relative difference (%) between hybrid approximations and exact pulsing solution at different cooling times.

Hybrid Approximation (# of pulses)	Cooling Time [h]			
	1	4	8	24
100	0.017	0.018	0.020	0.019
500	0.010	0.011	0.012	0.012
5000	0.007	0.007	0.007	0.008

According to Table 1, the discrepancies are reduced as the number of pulses increases. This confirms that the hybrid approximation more closely resembles the exact pulsed case with increasing number of pulses at the end of operation.

4. PERTURBED SCHEDULES

One of unique features in ALARA is its ability to simulate complex irradiation schedules. Such schedules might arise from the modeling of mobile fusion reactor materials as they proceed through different locations in the system, each with different flux spectra. To test this capability, the exact pulsed schedule has been reformulated into four schedules with increasing levels of complexity. Even though these complex irradiation schedules are not natural approximations to the exact problem, they are of interest in order to study how the code works under extreme circumstances. Furthermore, since they are based on the exact pulsed schedule, we can form reasonable hypotheses about the results.

Each of the first three designed schedules has one sub-schedule that is repeated 47250 times. A group of two uniform pulses (1000 s + 1200 s + 1000 s) is replaced by an alternative set of pulses with the same total fluence and a total operation time of 3200 seconds. The first sub-schedule (case 5) is composed of two pulses with relative heights of 1.5 and 0.5, respectively, and preserving the pulse duration and dwell time. The second one (case 6) is identical to the first one except that the order of the pulse heights is switched. The third formulation (case 7) contains four different pulses with durations of 500 seconds, 1000 seconds, 375 seconds and 125 seconds, and relative heights of 1.5, 0.75, 1.25 and 0.25, respectively. The dwell time between each pulse is 400 seconds. Each sub-schedule is separated by a 1200-second delay.

The last designed schedule (case 8) has four sub-schedules: one block of two (original) uniform pulses followed by the sub-schedules from cases 5, 6, and 7, accordingly. Each sub-schedule is separated by a 1200-second delay. Figure 3 shows graphical representations of four designed schedules.

The results from the complex and exact schedules are not expected to differ substantially at long cooling times since both the total fluence and the total operation time are conserved. These differences are expected to be less than or equal to differences between the steady state approximation's results and the exact pulsing results, and more than the differences between the hybrid approximations' results and the exact pulsing results.

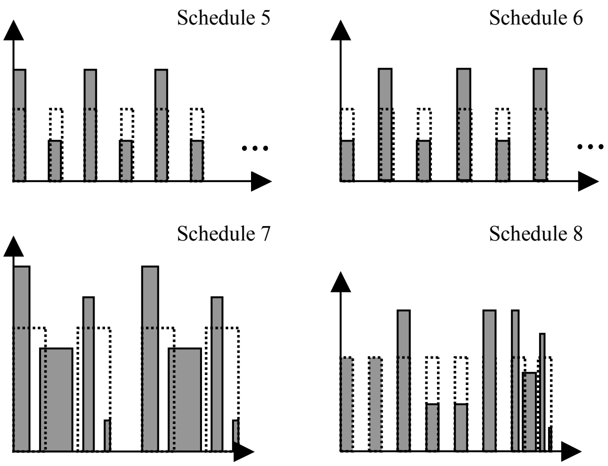

Figure 3. Graphical representations of four perturbed schedules.

Furthermore, since the last pulse dominates the results at short cooling times, schedule 5 and schedule 6 are expected to have relative differences of the same magnitude but opposite sign. Schedule 5 and 6 end with pulses that are 50% lower and 50% higher, respectively, than the standard pulse. As a result, schedule 5 will produce less activity at short cooling times by the same amount that schedule 6 will produce more.

Table 2 summarizes the quantitative nature of the relative differences of each perturbed schedule's results from the exact results. Qualitatively, the plots of relative differences from all perturbed schedules resemble the one from the steady-state approximation. As shown in Figure 4, the relative differences of schedule 8 display the monotonic behaviors as cooling times increase.

Table 2. Average relative difference (%) between complex perturbed schedules and uniform pulsing schedule at different cooling times.

Perturbed Schedules	Cooling Time [h]			
	1	4	8	24
Schedule 5	0.74	0.42	0.23	0.077
Schedule 6	-0.74	-0.42	-0.23	-0.078
Schedule 7	0.50	0.28	0.15	0.050
Schedule 8	0.16	0.075	0.040	0.015

As expected, the relative differences are more noticeable at the beginning of the cooling period than at one day after shutdown. Of all four schedules, schedule 8 has the least overall differences. Arguably, this schedule most closely resembles the exact schedule. As shown in Figure 5, the relative differences from schedule 5 and schedule 6 demonstrate that the last pulse greatly dominates the results at short cooling times. As expected at short cooling times, schedule 6 produces more activity (negative relative difference) than schedule 5 does and the magnitudes of their relative differences are approximately the same.

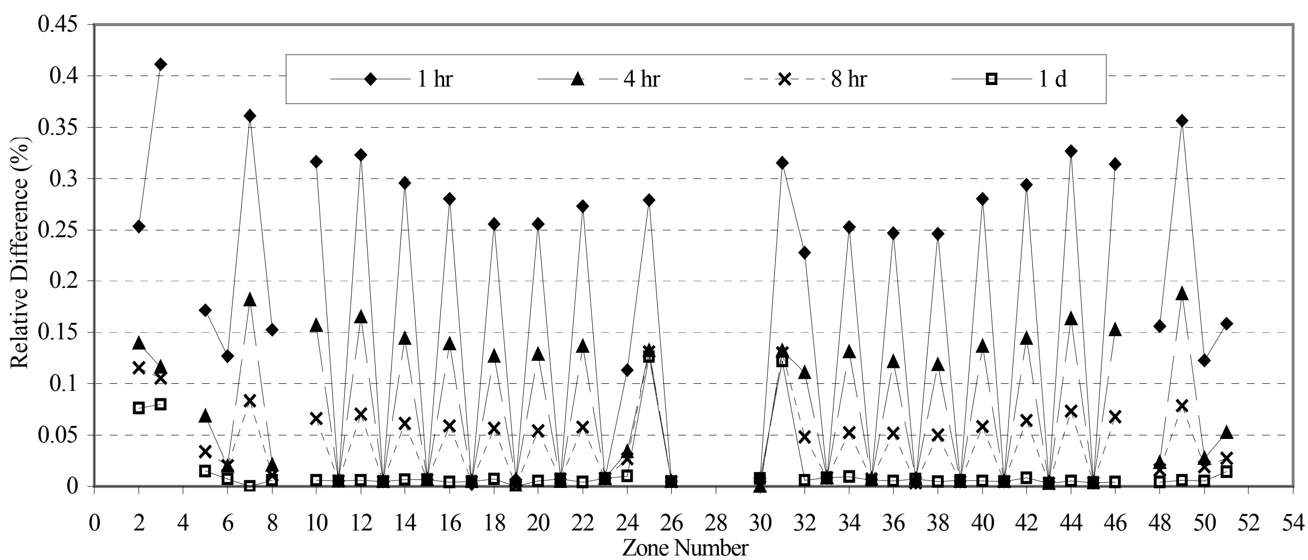

Figure 4. Relative difference (%) between the results from schedule 8 and the exact pulse schedule at different cooling times.

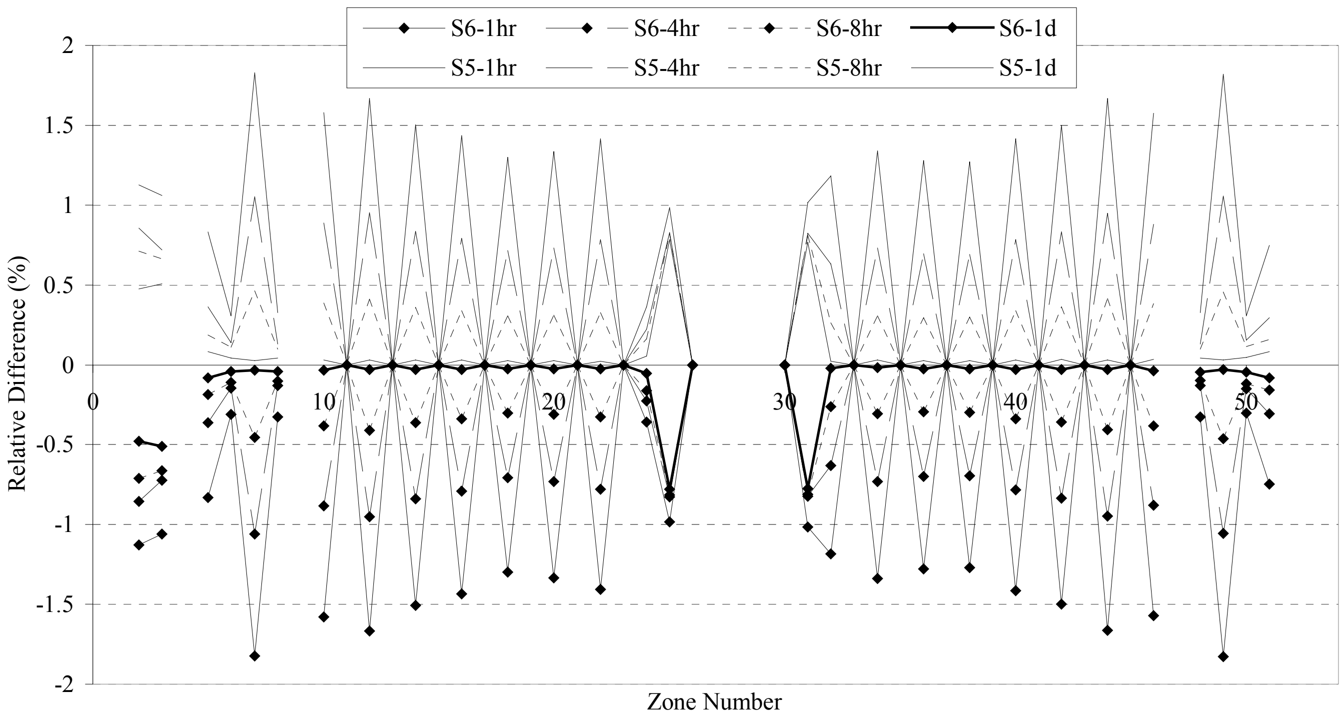

Figure 5. Comparison of relative difference (%) between results of uniform pulsing and results of Schedule 5 (S5) and Schedule 6 (S6), respectively.

It is important to note that the differences between the complex schedule results and the exact pulsing results do not indicate an error in the calculation, but reflect the physical differences among the schedules. Since the differences between the exact pulsing schedule and the various approximate and/or perturbed schedules are qualitatively predictable and quantitatively bound by those of the steady-state approximation, this suite of schedules provides a reasonable base for validating this functionality.

5. CONCLUSIONS

The ALARA activation code has been validated for arbitrary irradiation schedules. The results from eight test problems have been compared to the result from the exact pulsing case. The relative differences of the results are within 1.92% at all zones and cooling times and continue to improve as the cooling times increase. This is consistent with both the quantitative and qualitative behavior expected from these tests. Based on this study, ALARA is recommended for use in the activation analysis of fusion power systems under arbitrary irradiation schedules. ALARA also provides a mechanism to further explore the accuracy and validity of using various approximations to exact pulsing during engineering analysis.

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