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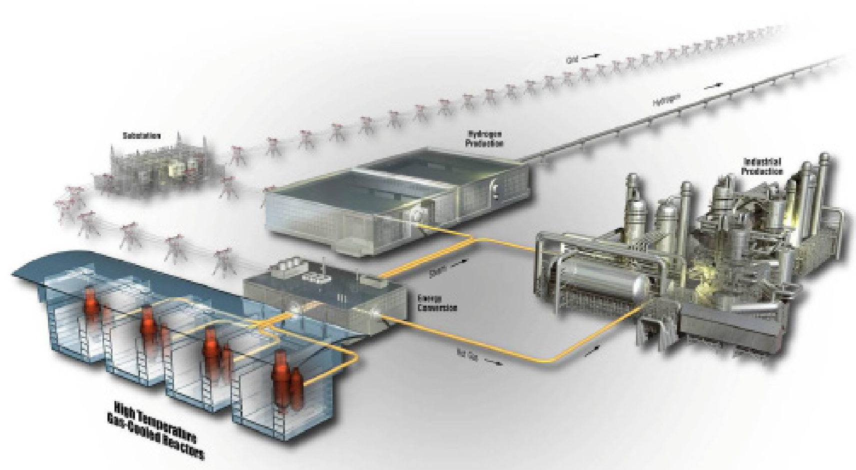
# Analytical Neutronics Studies Correlating Fast Neutron Fluence to Material Damage in Carbon, Silicon, and Silicon Carbide

June 2011

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# Analytical Neutronic Studies Correlating Fast Neutron Fluence to Material Damage in Carbon, Silicon, and Silicon Carbide

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# 1. INTRODUCTION

This study evaluates how fast neutron fluence >0.1 MeV correlates to material damage (i.e., the total fluence spectrum folded with the respective material's displacements-per-atom [dpa] damage response function) for the specific material fluence spectra encountered in Next Generation Nuclear Plant (NGNP) service and the irradiation tests conducted in material test reactors (MTRs) for the fuel materials addressed in the white paper. It also reports how the evaluated correlations of >0.1 MeV fluence to material damage vary between the different spectral conditions encountered in material service versus testing.

## 1.1 Description of the Proposed Issue or System

The damage response functions for carbon, silicon, and silicon carbide (SiC) are presented first followed by calculated neutron spectra from AGR-1, AGR-3/4, and the General Atomics Modular Helium Reactor (MHR). The damage response functions are then multiplied by (folded) the neutron spectra to produce new functions, referred to herein as product damage functions (PDF). Twelve PDFs are calculated for four neutron spectrums and the three materials of interest. The PDFs are further integrated over the lethargy variable corresponding to three specific neutron energy ranges (0.0–0.02, 0.02–0.1, and 0.1–14.0 MeV) in order to develop correlations between material damage and fast fluence for the different spectral conditions encountered in material service versus testing.

## 1.2 Damage Response Functions

Damage response functions for dpa, also referred to and known as dpa neutron cross sections, are derived per Reference [1] for three different materials: natural carbon (graphite), silicon, and SiC. Carbon, or graphite, is an important material in graphite reactors for structural components (fuel blocks, reflector blocks, pedestals, etc.) and an integral part of the TRISO fuel particles as various buffer and pyrolytic carbon coatings. SiC is also an important component of tristructural isotropic (TRISO) fuel particle coatings, specifically the particle pressure vessel containment coating. Silicon in its crystalline or metallic form is not used in graphite reactors, but is included here in the material damage discussion because the SiC compound damage response function (dpa cross section) exhibits behavior intermediate between silicon and carbon.

Figure 1 is a semilog plot of the three material damage functions (dpa cross sections). The dpa cross section data range over the neutron energy interval from $10^{-10}$ to 20 MeV. From $10^{-10}$ to approximately 0.02 MeV, all three cross sections appear to be zero, or at least very small relative to the cross section magnitudes above 0.02 MeV. This strongly indicates that material damage from any neutron spectrum having a fast component will most likely be dominated by that component.

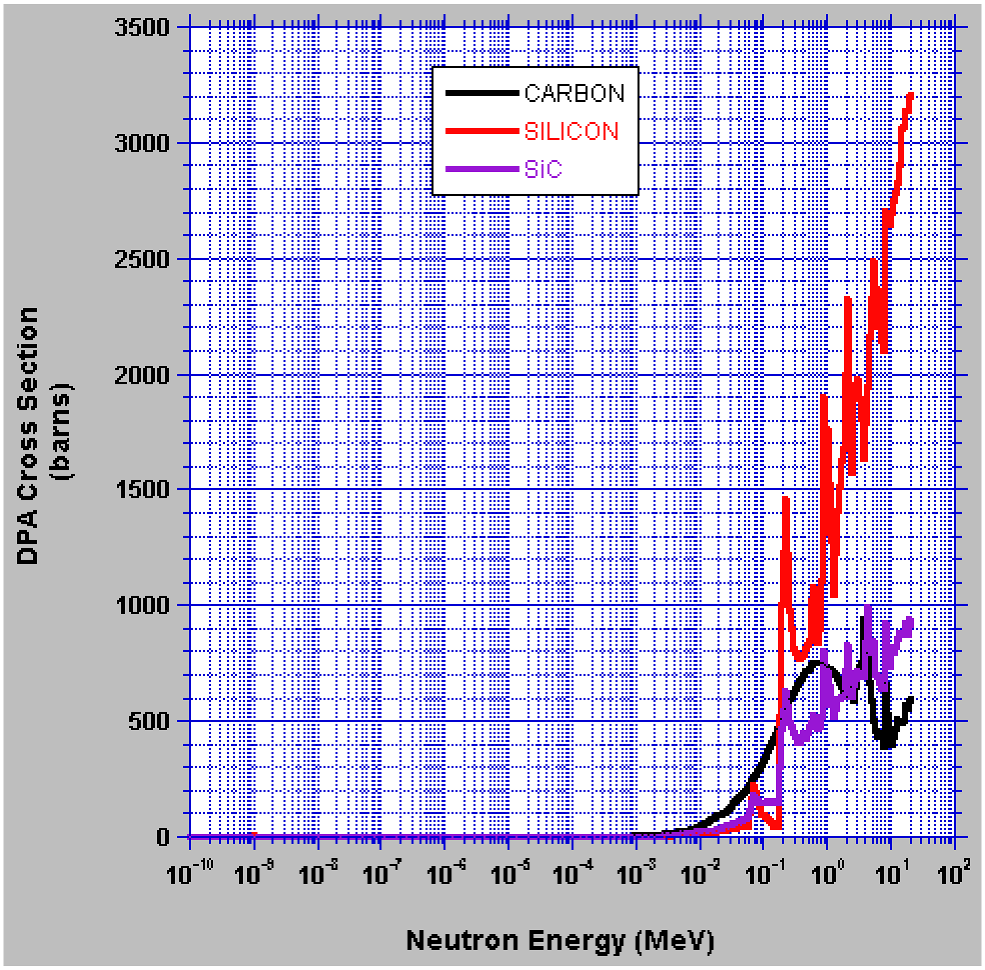


Figure 1. DPA cross sections for natural carbon, silicon, and SiC (semilog scale).

Figure 2 re-plots the same Figure 1 dpa cross-section data, but on a log-log scale. The log-log scale allows us to see the actual variation and magnitude in the dpa cross section data below 0.02 MeV. Below 0.02 MeV, the cross section data are clearly not zero, but are substantially reduced in magnitude relative to the cross section data above 0.02 MeV.

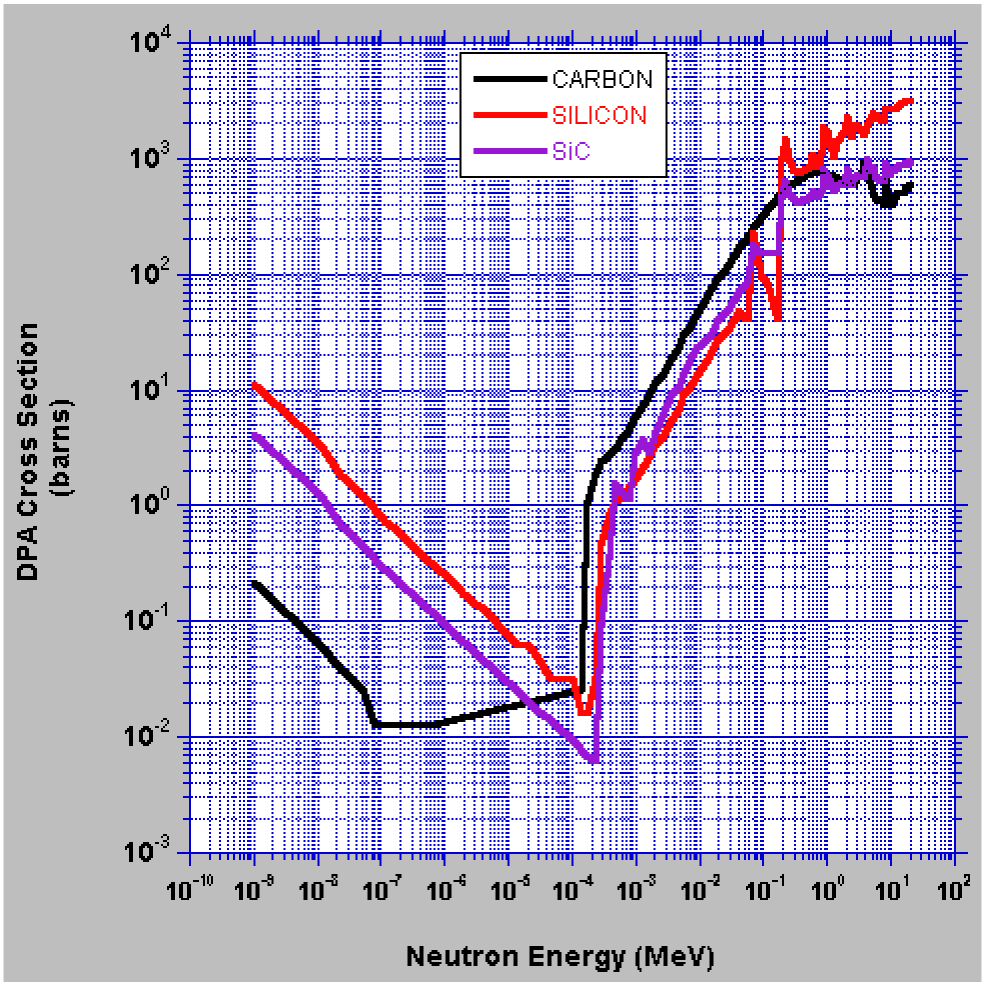


Figure 2. DPA cross sections for natural carbon, silicon, and SiC (log-log scale).

## 1.3 Neutron Spectra

The next step in the study identifies appropriate neutron spectra that can be folded with the above dpa cross section (damage response functions).

For the Advanced Test Reactor (ATR) spectra, spectra from the three TRISO particle tests (AGR-1, AGR-2, and AGR-3/4) were chosen for the analysis. Since the AGR-1 and AGR-2 test are so similar (capsule design, compact loading, and test position in the ATR core), the AGR-1 and AGR-2 spectra are assumed to be the same. Hence, the AGR-1 spectra is also assumed to represent the AGR-2 test spectra. All spectra considered here are normalized to one neutron.

Figure 3 shows calculated AGR-1 normalized spectra in fuel compacts near the ATR core midplane. The AGR-1 test capsules were located in the B-10 ATR test position in the beryllium reflector [2].

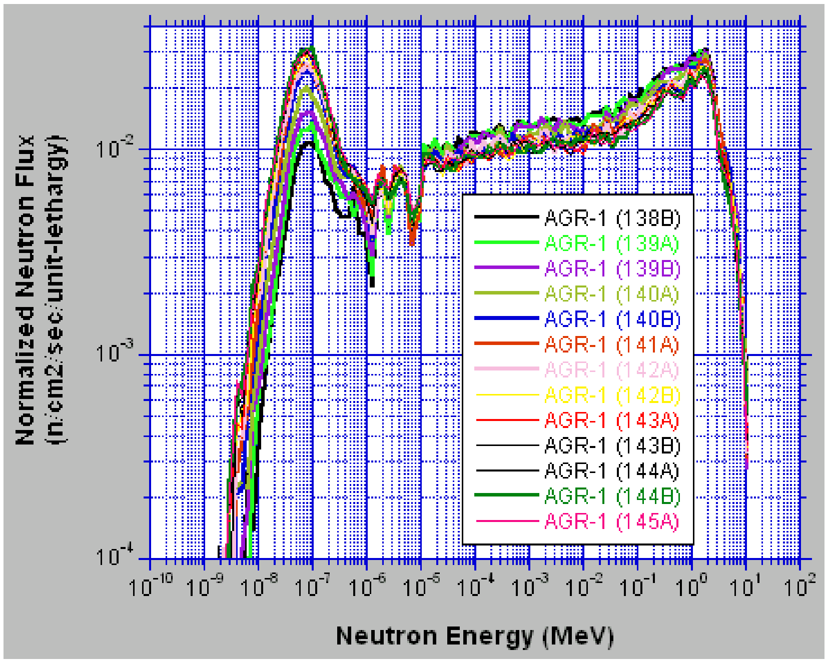


Figure 3. AGR-1 fuel compact normalized neutron flux spectra as a function of ATR cycle (or burnup).

Figure 4 shows a calculated neutron spectrum for the AGR-3/4 test (green line). The AGR-3/4 test capsule is destined to be loaded into the ATR northeast flux trap. The compact fuel stack is located at the center of the flux trap surrounded by a thick annular ring of graphite and light water. The AGR-3/4 spectrum in Figure 4 represents an average over the compact fuel stack and should remain relatively constant over the multiple ATR irradiation cycles, since the graphite annulus in the flux trap is not borated. The graphite holders in AGR-1 and AGR-2 were borated, and as the irradiation cycles progressed, the boron-10 would burnout and the neutron spectrum would change as shown in Figure 3 for the AGR-1 irradiation cycles.

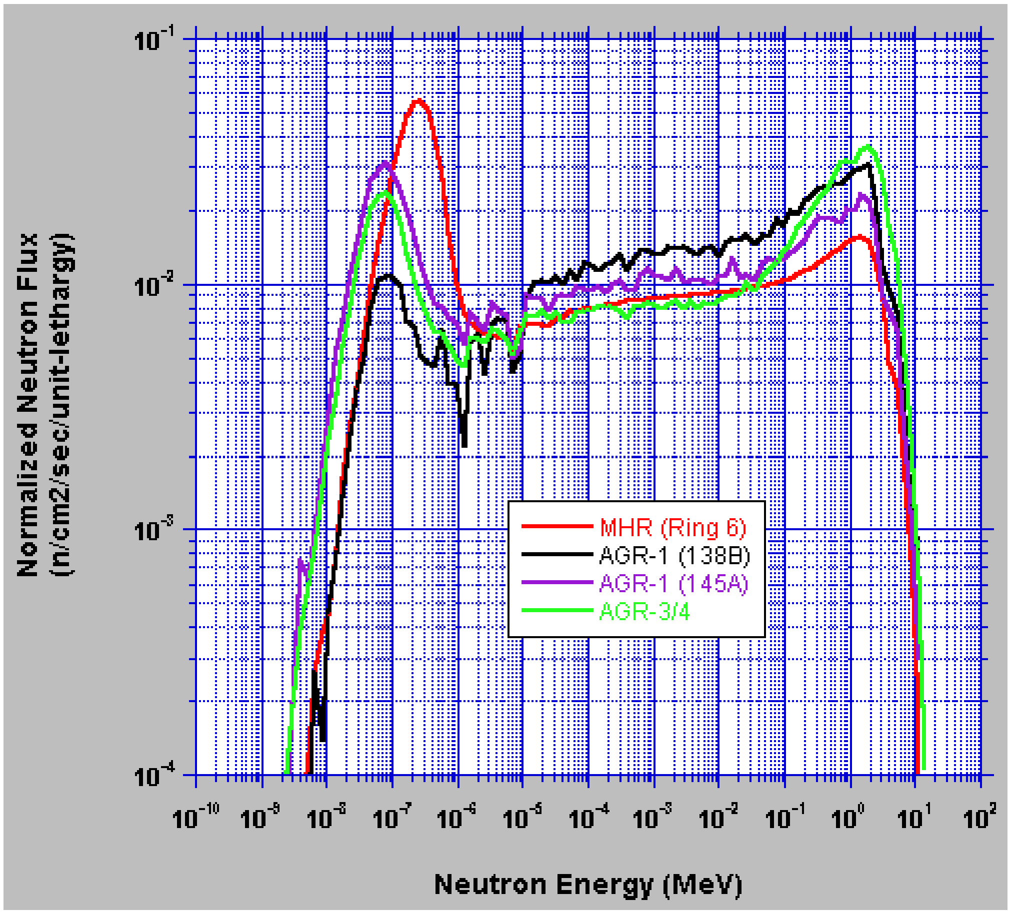


Figure 4. AGR-3/4 fuel compact normalized neutron flux spectrum at beginning-of-cycle.

For the NGNP service fuel spectrum, the calculated neutron spectra for a modular helium reactor (MHR), or a prismatic high-temperature gas-cooled reactor will be used for comparison purposes. These spectra are directly out of reference [2], where the MHR fuel was assumed to be at a uniform temperature of 1100°C and the surrounding block graphite at 927°C. Figure 5 shows the Monte Carlo Neuton Particle (MCNP)-calculated neutron spectra averaged over the fuel rods (compact stacks in each fuel channel) in fuel blocks in the active core rings 6, 7, and 8.

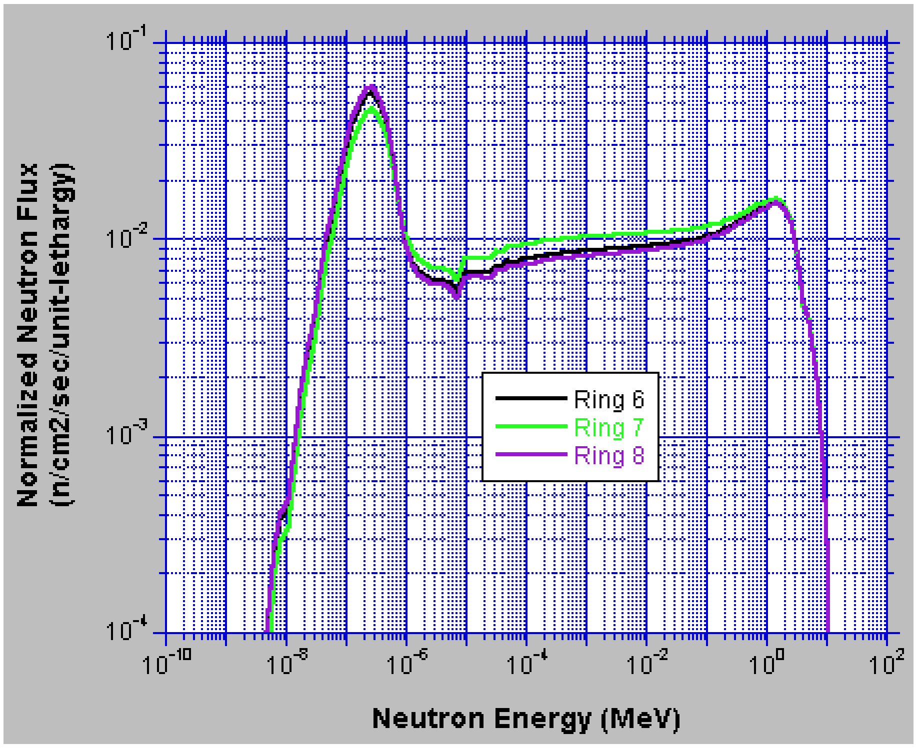


Figure 5. MHR compact neutron flux spectra for the three core annulus fuel element rings.

Note that Figures 3 and 5 are extracted from and calculated per reference [2]. Figure 4 is new and has been calculated in a manner similar to Figures 3 and 5 using the MCNP5 computer code and an ATR model of the AGR-3/4 test in the northeast flux trap.

## 1.4 Product Damage Functions

The normalized neutron spectra in Figures 3, 4, and 5 have been folded with (multiplied by) the appropriate dpa cross section data from Figures 1 and 2 for carbon, silicon, and SiC. The resultant function produced from the folding of the normalized spectra and the dpa cross sections are referred to as the product damage function (PDF). The calculated PDFs are shown in Figures 6, 7, and 8 for carbon, silicon, and silicon-carbide (SiC), respectively.

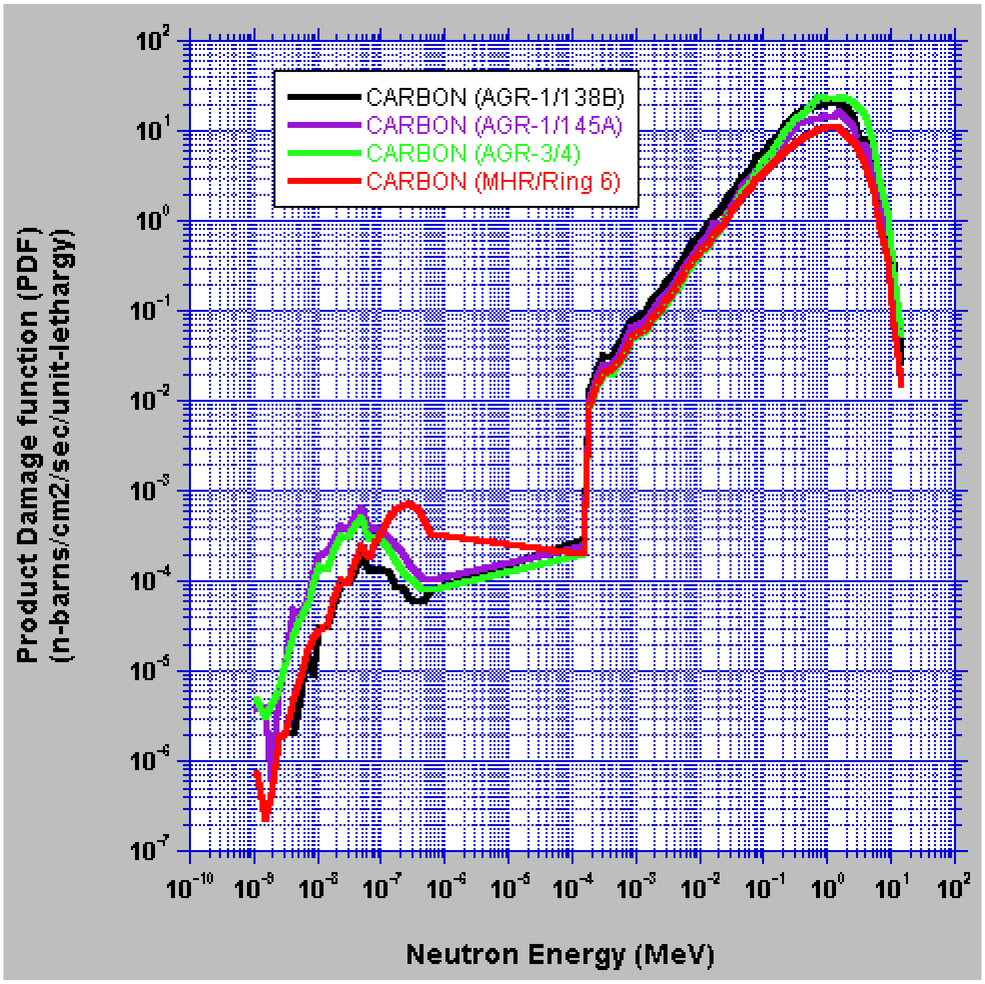


Figure 6. PDF for CARBON in the AGR-1, AGR-3/4, and MHR neutron spectrums.

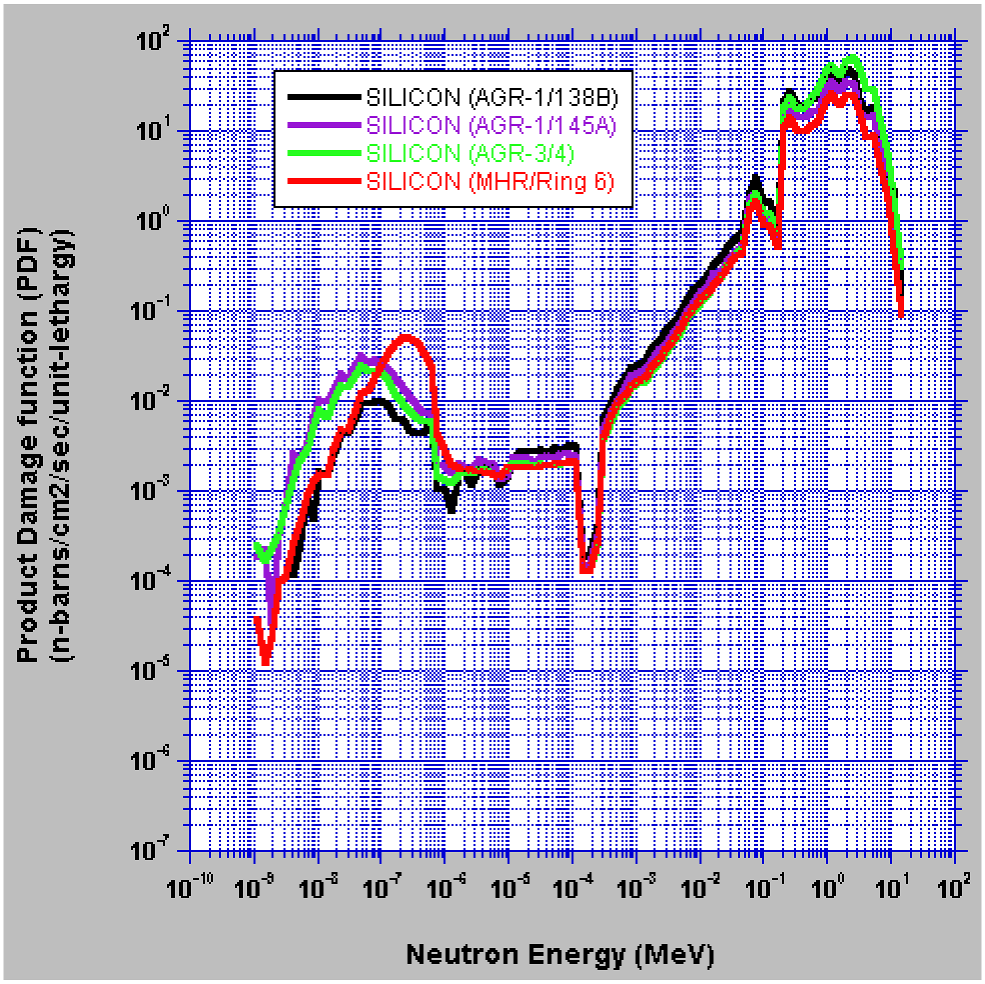


Figure 7. PDF for SILICON in the AGR-1, AGR-3/4, and MHR neutron spectrums.

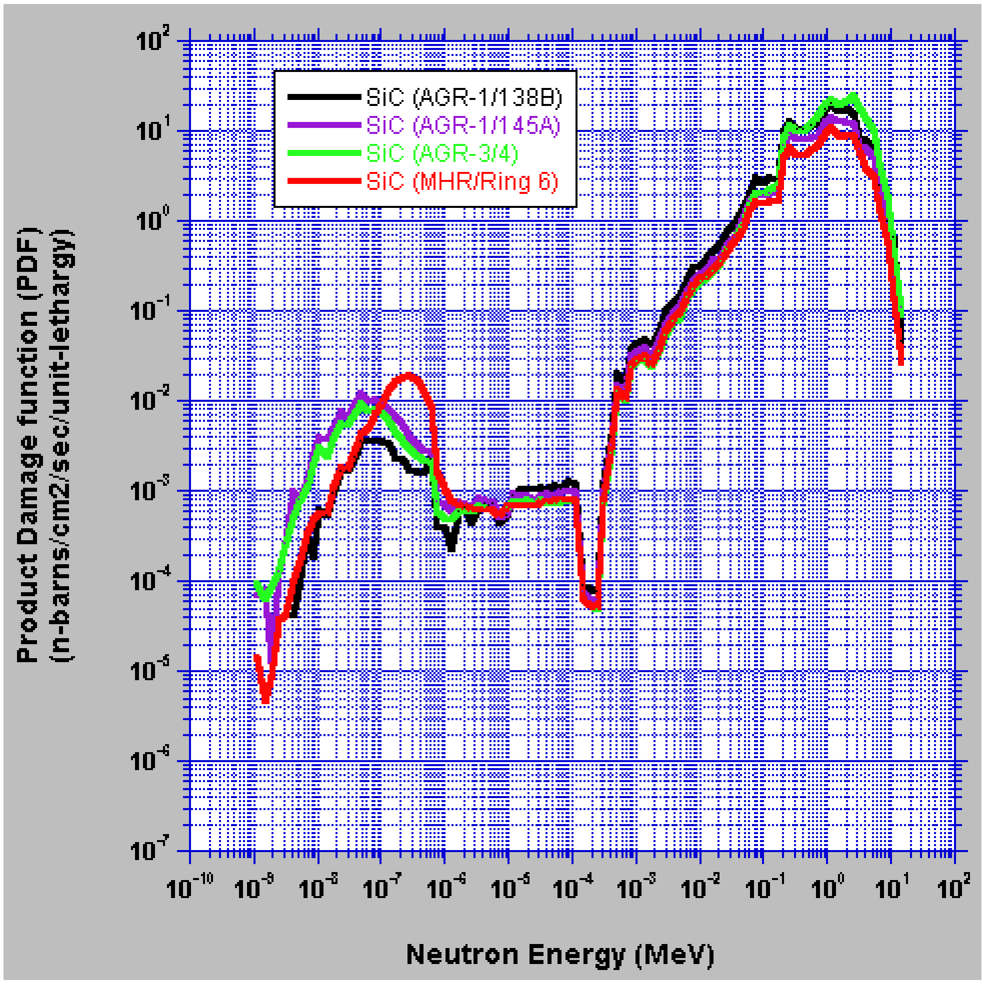


Figure 8. PDF for SiC in the AGR-1, AGR-3/4, and MHR neutron spectrums.

Integrating the PDFs over specific energy ranges allowed the quantifying of relative damage contributions of neutrons of certain energies relative to the total dpa damage. The integrated values divided by the total dpa gives the percent damage relative to the total, hence a relative factor in which comparisons can be made for the three materials and different reactor spectrums.

Although not shown in Figures 6–8, the 13 AGR-1 ATR cycle spectrums actually produce relatively constant integrated percent PDF contributions, despite the thermal neutron peak changing significantly over the 13 cycles as shown in Figure 3. This is because of the very minor thermal neutron contribution to the total dpa damage. Hence, only the 138B (beginning of life [BOL]) and 145A (end of life [EOL]) cycle data is presented here for brevity.

The 12 PDFs in Figures 6–8, or four reactor spectrums folded with the three materials, are each integrated specifically over three neutron energy ranges of

0.0–0.02, 0.02–0.1, and 0.1–14 MeV). These three energy ranges span the entire neutron energy spectrum. The energy ranges were chosen to: (1) show that the thermal and epithermal neutrons in all the neutron spectrums contribute a relatively small amount to the total dpa damage in all cases, (2) demonstrate that the 0.02–0.1 MeV range contributes a relatively significant fraction of the total dpa damage, although it is not included in the usual >0.1 MeV reportable fast flux energy range, and (3) show the relative contribution of the standard 0.1–14 MeV energy damage range as requested in this Request for Additional Information.

The relative dpa contributions (%) by energy range are given in Tables 1, 2, and 3 for the three materials (carbon, silicon, and SiC).

Table 1. Percent of accumulated dpa for carbon (graphite).

| Energy Range | | AGR-1 | | AGR-3/4 | MHR |
|---|---|---|---|---|---|
| (MeV) | (MeV) | 138B | 145A | BOL | BOL |
| 0.0 | 0.02 | **2.57** | **2.65** | **1.40** | **3.08** |
| 0.02 | 0.1 | **11.24** | **10.93** | **7.19** | **12.21** |
| 0.1 | 14.0 | **86.19** | **86.42** | **91.40** | **84.71** |

Table 2. Percent of accumulated dpa for silicon.

| Energy Range | | AGR-1 | | AGR-3/4 | MHR |
|---|---|---|---|---|---|
| (MeV) | (MeV) | 138B | 145A | BOL | BOL |
| 0.0 | 0.02 | **0.47** | **0.55** | **0.26** | **0.71** |
| 0.02 | 0.1 | **2.32** | **2.25** | **1.32** | **2.55** |
| 0.1 | 14.0 | **97.21** | **97.19** | **98.42** | **96.74** |

Table 3. Percent of accumulated dpa for SiC.

| Energy Range | | AGR-1 | | AGR-3/4 | MHR |
|---|---|---|---|---|---|
| (MeV) | (MeV) | 138B | 145A | BOL | BOL |
| 0.0 | 0.02 | **1.47** | **1.56** | **0.78** | **1.88** |
| 0.02 | 0.1 | **6.73** | **6.53** | **4.06** | **7.36** |
| 0.1 | 14.0 | **91.80** | **91.91** | **95.15** | **90.09** |

The fast fluence (0.1–14 MeV) for **carbon** accounts for 86–91% of the total dpa for the three reactor spectrums considered (AGR-1, AGR-3/4, and MHR). The AGR-1 fast neutron spectrum results are in close agreement with the MHR, or 86/91 versus 85%. The AGR-3/4 test, with its relatively larger fast fluence peak at

1–2 MeV, has 91% damage because of the fast fluence. The thermal and epithermal neutrons (<0.02 MeV or <20 keV) contribute only 1.4–3.0% of the total dpa damage for the three spectrums. Neutrons in the 0.02–0.1 MeV range however contribute a significant amount (7–12%).

The fast fluence (0.1–14 MeV) for **silicon** accounts for 97–98% of the total dpa for the three reactor spectrums considered (AGR-1, AGR-3/4, and MHR). Again, the AGR-1 fast neutron spectrum results are in close agreement with the MHR, or 97/98 versus 97%. The AGR-3/4 test with its relatively larger fast fluence peak at 1–2 MeV has 98% damage because of the fast fluence. The thermal and epithermal neutrons (<0.02 MeV or <20 keV) contribute only <1.0% of the total dpa damage. Neutrons in the 0.02–0.1 MeV range contribute only about 1–3%.

The fast fluence (0.1–14 MeV) for **SiC** accounts for 90–95% of the total dpa for the three reactor spectrums considered (AGR-1, AGR-3/4, and MHR). The AGR-1 fast neutron spectrum results are in close agreement with the MHR, or 92 versus 90%. The AGR-3/4 test with its relatively larger fast fluence peak at 1–2 MeV has 95% damage because of the fast fluence. The thermal and epithermal neutrons (<0.02 MeV or <20 keV) contribute only 0.75–2.0% of the total dpa damage. Neutrons in the 0.02–0.1 MeV range contribute 4–7%.

## 1.5 Fast Fluence versus Material Damage

This section provides estimates of fast fluence and total dpa. The three reactor spectrums (AGR-1, AGR-3/4, and MHR) have been scaled to typical operating power levels and folded with the appropriate dpa cross sections (carbon and SiC). The normalized product damage functions were then integrated over four energy ranges to provide an estimate of the material damage in terms of accumulated dpa.

Table 1 gives dpa estimates for the three reactor spectrums along with the corresponding fast fluences for the three energy ranges of >0.1, >0.18, and >1.0 MeV. Assumptions for scaling the reactor power level, irradiation time, and in-core locations of the TRISO fuel compact for each reactor case are provided below the table.

Table 4. Calculated estimates of fast fluence and dpa.

| | AGR-1* | AGR-3/4** | NGNP/MHR*** |
|---|---|---|---|
| CARBON dpa (total) | 3.72 | 3.80 | 3.29 |
| (>0.1 MeV) | 3.32 | 3.55 | 2.88 |
| (>0.18 MeV) | 3.10 | 3.38 | 2.68 |
| (>1.0 MeV) | 1.46 | 1.82 | 1.26 |
| | | | |
| SiC dpa (total) | 2.96 | 3.18 | 2.59 |
| (>0.1 MeV) | 2.76 | 3.06 | 2.39 |
| (>0.18 MeV) | 2.68 | 3.00 | 2.31 |
| (>1.0 MeV) | 1.45 | 1.84 | 1.25 |
| | | | |
| Fast Fluence ($n/m^2$) | | | |
| (>0.1 MeV) | 5.14+25 | 5.39+25 | 4.47+25 |
| (>0.18 MeV) | 4.60+25 | 4.98+25 | 3.97+25 |
| (>1.0 MeV) | 2.15+25 | 2.68+25 | 1.85+25 |

* Mid-plane of the ATR core; Capsule 4, Stack 1, Compact Cell 90504, ATR as-run data, 626.21 EFPDs.

** Average over the full compact stack in the northeast ATR flux trap, 108 MW ATR total core power, 400 EFPDs.

*** Ring 6 active core, maximum irradiation time of 1,600 EFPD (high burnup), 600 MW total core power, 1,020 total fuel blocks, average over fuel compacts in Ring 6 block.

From Table 4, AGR-1 has only slightly lower total dpa and fast fluence relative to AGR-3/4. The very close total dpa and accumulated fast fluence reflect the same design goals of the two experiments. The relatively lower total dpa and fast fluence of the NGNP/MHR versus AGR-1 and AGR-3/4 is primarily because of the softer neutron spectrum (Figure 4).

Table 5 provides a uniform basis, or a fixed fast fluence of 4.0+25 $n/m^2$ (>0.1 MeV), to compare the material damage (total dpa) for the three reactor spectrums. It is clear that the material damage (total dpa) is essentially the same for all three reactors.

Table 5. Calculated estimates of total dpa for a fixed fast fluence (4.0 + 25 n/m$^2$).

| | AGR-1* | AGR-3/4** | NGNP/MHR*** |
|---|---|---|---|
| CARBON dpa (total) | 2.90 | 2.82 | 2.94 |
| SiC dpa (total) | 2.30 | 2.36 | 2.32 |

* Mid-plane of the ATR core; Capsule 4, Stack 1, Compact Cell 90504, ATR as-run data, 626.21 EFPDs.

** Average over the full compact stack in the northeast ATR flux trap, 108 MW ATR total core power, 400 EFPDs.

*** Ring 6 active core, maximum irradiation time of 1,600 EFPD (high burnup), 600 MW total core power, 1,020 total fuel blocks, average over fuel compacts in Ring 6 block.

## 1.6 Conclusions

PDFs are calculated by folding normalized neutron spectra with dpa damage response functions. Calculated PDFs are given in Figures 6–8 for carbon, silicon, and SiC. Three reactor spectra are considered: (1) AGR-1 TRISO particle test in ATR (BOL Cycle 138B and EOL Cycle 145A), (2) the prospective AGR-3/4 TRISO particle test in the ATR northeast flux trap, and (3) the General Atomics MHR concept (NGNP). The neutron spectrum for the current AGR-2 TRISO particle test in the ATR is assumed to be nearly identical to the completed AGR-1 test because of test position similarity.

Integration of the PDFs over the three neutron energy intervals (0.0–0.02, 0.02–0.1, and 0.1–14 MeV) and over the entire 0–14 MeV neutron energy range allows one to calculate the relative contribution of each energy interval to the total dpa, providing a basis to compare different reactor spectra. Tables 1–3 provide the relative contributions as a function of material, energy interval, and reactor spectrum.

For all three materials and all four reactor spectra, the majority of the material damage in dpa is because of fast neutron fluence. The fast fluence (>0.1 MeV) contributes 85–91%, 96–98%, and 90–95% of the total dpa for carbon, silicon, and SiC, respectively. This is clearly a relative basis for the correlation between fast fluence and dpa; the fast fluence does by far the majority of total material damage in terms of dpa.

Interestingly, the neutrons in the 0.02–0.1 MeV do contribute a significant 7–12% of the total dpa for carbon, and 4–7% for SiC. At 0.02 MeV, this appears to be the "actual" threshold where the carbon and SiC material dpa cross sections become significant. Above 0.02 MeV, the dpa cross sections continue to increase. This is in contrast to the >0.1, >0.18, and >1.0 MeV energies usually used to a thresholds to report dpa and fast fluence.

Thermal and epithermal neutrons, or neutrons of energy <0.02 MeV (<20 keV) contribute only a very small 0.5–3.0% of the total dpa damage. Differences in neutron spectra between ATR and NGNP in this energy range will therefore have only a very minor impact on reported total dpa for material damage estimates.

Calculated total dpa for a given irradiation test in one reactor spectrum can be matched by a different reactor spectrum by simply controlling the irradiation times; hence, the total accumulated fast fluence. Matching fast fluence (>0.1 MeV) is an accurate pretest means to estimate the needed irradiation time to achieve a dpa material goal. Matching fast fluence (>0.02 MeV) should provide an even more accurate estimate of the required irradiation time.

# 2. REFERENCES

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[2] TEV-1022, "Response to Questions about the Applicability of the AGR Test Results to NGNP Fuel," Rev. 1, prepared for the U.S. Nuclear Regulatory Commission by Idaho National Laboratory, Project No. 23841, September 23, 2010.

## 2.1 Definitions/Glossary

None

## 2.2 Acronyms

None