# Correlation of Metrics of Clad Damage by Neutrons in Fast Reactors

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## 1. Personal Section

Since a very young age, I have been fascinated by mathematics and science, and throughout my academic life I have enjoyed studying these subjects. During my junior year, my teachers recommended that I apply for the Research Science Institute at MIT, a summer program in scientific and mathematical research for incoming high school seniors. I decided to accept their advice, and I was accepted to the program.

For the application to the Research Science Institute, I was asked about what area I would want to research, and I mentioned alternative energy sources as my primary interest. As a result, I was paired with a nuclear engineer, Professor Driscoll, who conducts research on how nuclear power could become more feasible. Although I had some background knowledge of nuclear energy, conducting research required a more in-depth understanding of the subject. Therefore, my first step was gaining a more advanced knowledge of nuclear energy and of my specific research topic, which dealt with radiation damage within nuclear reactors.

Despite my enthusiasm for science, I was initially nervous about conducting research, and I was hesitant to apply for the Research Science Institute. I had always assumed that meaningful research was in the domain of Ph.D. professors and graduate students, far outside the reach of high school students like me. Given the complexity and dangers of nuclear energy, I thought that this would be especially true for the area in which I was assigned to work. However, while a professor's research in general can be highly complex, there are often parts with which high school students can assist. Research certainly poses challenges and can be difficult, but I advise that you do not discount it simply due to lack of experience.

## 2. Research Section

### 2.1 Introduction

Compared to fossil fuel-powered plants, nuclear reactors can extract a tremendous amount of energy from fuel through a process known as nuclear fission. A conventional nuclear reactor can provide roughly 360,000 kilowatt-hours of electricity per kilogram of uranium used; in comparison, coal-fired plants generate about 3 kilowatt-hours per kilogram of fuel. However, an even larger amount of energy remains unused, as conventional nuclear reactors only use about 5% of their fuel (1). The remainder of the fuel – along with radioactive products of fission – is disposed of as nuclear waste. One reason for this low fuel usage is that only certain isotopes of uranium, primarily uranium-235 (U-235), can be used directly in nuclear fission. Uranium-235 comprises only a small percentage of reactor fuel; this percentage is called the "enrichment." The remainder of the fuel is almost entirely U-238, which cannot typically undergo nuclear fission (2).

However, under the right conditions, U-238 can absorb a neutron to become plutonium-239 (Pu-239), which can undergo fission (2-3). This absorption requires energy, though, so it can only occur with high-energy neutrons, called “fast neutrons” due to their high speed. Neutrons are fast immediately after release during nuclear fission, but most reactors deliberately slow these neutrons down using a moderator (usually water), as slow neutrons are more effective at causing fission of U-235 (2). In contrast, a fast reactor omits the moderator, allowing neutrons to remain moving quickly, and the abundance of fast neutrons can convert a larger amount of U-238 to Pu-239. In fact, some fast reactors, called breeder reactors, create so much Pu-239 that they produce more fissile material (fuel that can undergo fission) than they consume in fission (3).

Unfortunately, in addition to producing Pu-239 and initiating fission, fast neutrons damage the reactor materials, especially the cladding material that encases the fuel rods. There are two main measures associated with cladding damage: fluence, which measures cumulative neutron flow[1] per unit area, and displacements per atom (dpa), which measures how many times, on average, each cladding atom has been knocked out of position. Although only a small fraction of the neutrons strike cladding materials, each collision affects not only the atom struck but also the surrounding atoms, leading to a cascade of collisions (4). Over time, this continuous bombardment weakens the cladding material and eventually renders it unusable. At this point, the entire fuel rod must be removed and disposed of, even if usable fuel remains.

[1] For the purposes of this project, we only counted the neutrons that were moving at high speeds, as these cause the most damage. Thus, strictly speaking, we measured only the “fast fluence” rather than total fluence.

It is known that fluence increases as fuel burnup – the extent to which the fuel is used[2] – increases. However, when comparing fluence and burnup, the enrichment of the fuel is not usually considered a relevant factor. My mentor, Professor Driscoll, proposed that fluence is inversely proportional to enrichment; thus,

$$\Phi = k\frac{B}{x}$$

where $\Phi$ represents fluence, $B$ is the burnup, $x$ is the enrichment, and $k$ is a constant of proportionality[3]. The specific value of $k$ varies somewhat depending on average neutron speed and other reactor conditions, but Professor Driscoll predicted that it would not vary too greatly, especially for a given fuel type[4].

The second prediction was that dpa would vary directly with fluence for any given reactor according to the equation $\text{dpa} = \sigma_d \Phi$. As above, we predicted that the constant of proportionality $\sigma_d$ would depend on reactor conditions, particularly neutron speed. Thus, we predicted the ratio of dpa to fluence would be constant over a reactor's lifespan but would be different for different reactors.

## 2.2 Procedure

Except for a few experimental facilities, fast reactors have not been used in the nuclear industry, so there were few traditional experiments to provide data. Instead, the data came from a computer simulation called ERANOS that was designed specifically for fast reactors.

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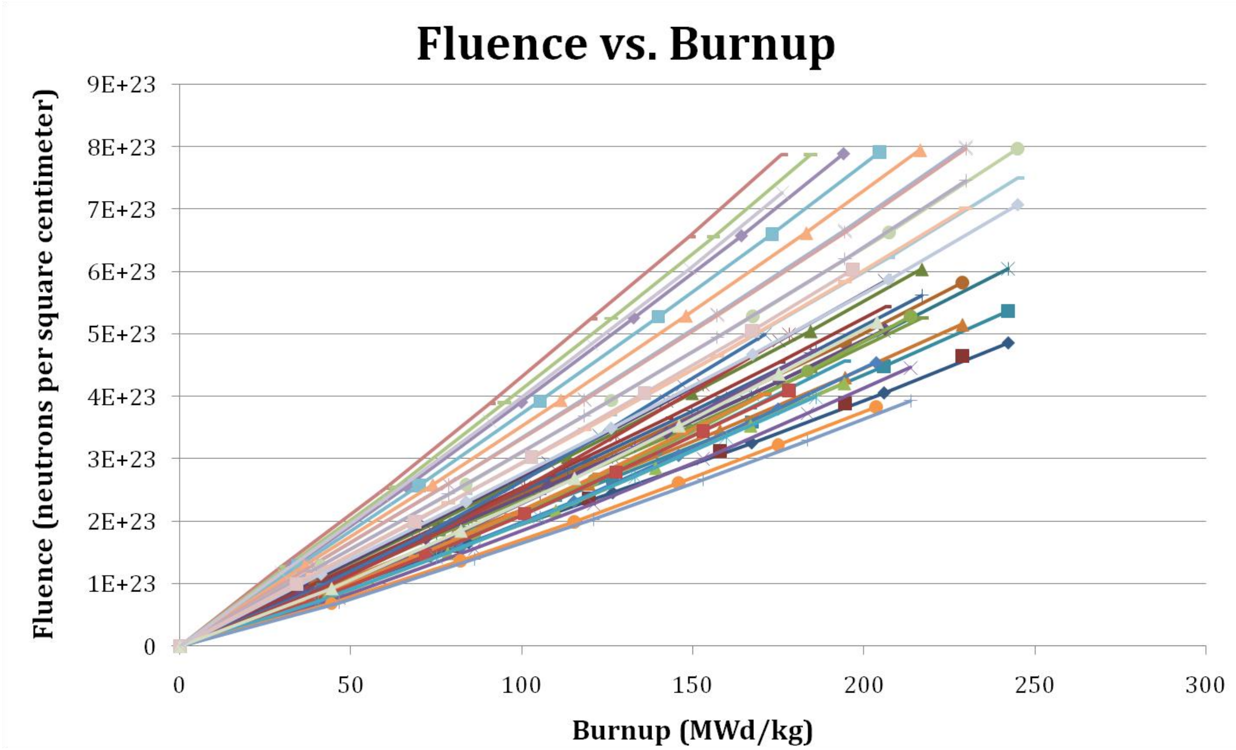
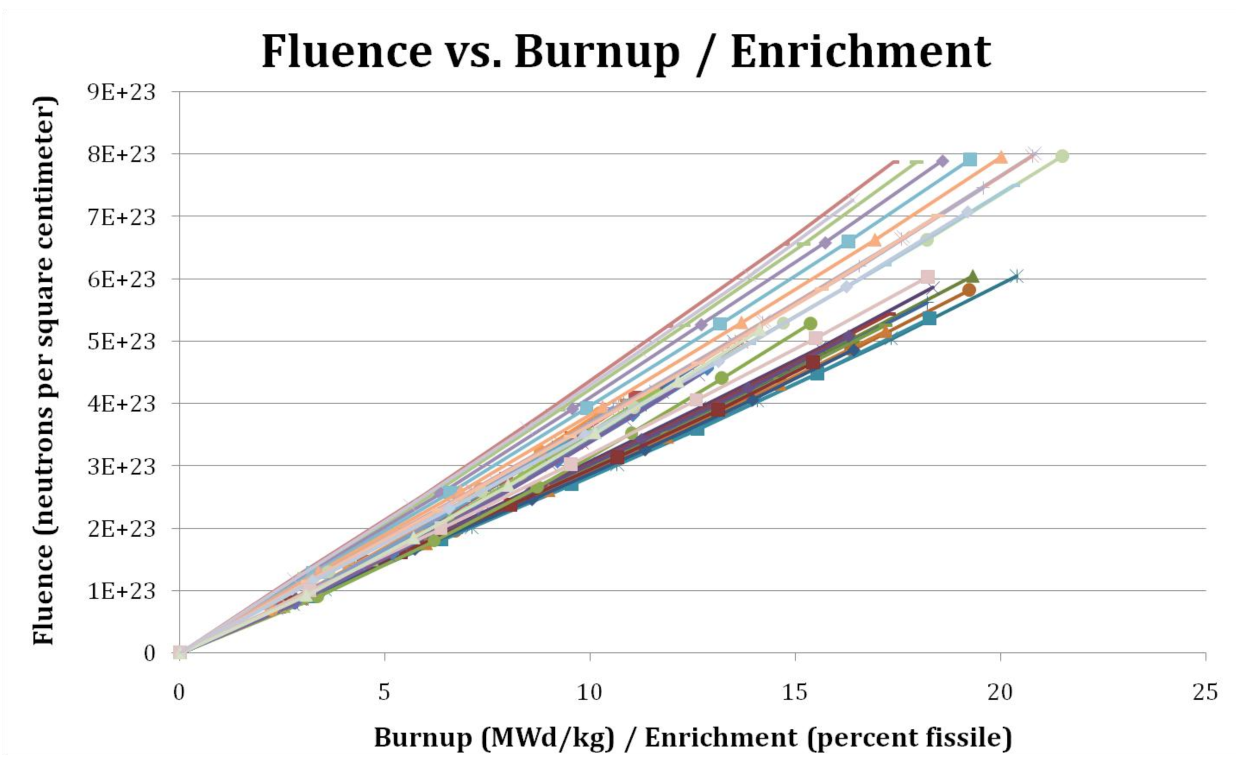
[2] Burnup is officially defined as heat energy produced (usually measured in megawatt-days, or the equivalent of producing 1 million watts for 1 day) divided by the fuel mass (measured in kilograms).
[3] Professor Driscoll's original formula was more complex. For simplicity, I have combined many of the constants into a single term $k$ to emphasize that the main factors are fluence, burnup, and enrichment.
[4] Uranium in fuel rods can either be alloyed with zirconium or chemically bonded with either oxygen (as $UO_2$) or carbon (as UC). Reactors using oxides and carbides tend to have slower neutrons, as the oxygen and carbon atoms can slow down fast neutrons.

For a given set of initial reaction conditions, such as the type of fuel and enrichment, ERANOS can calculate how much fuel has been used and the neutron flow through the cladding materials at various times in the reactor lifespan. However, usable data had to be extricated from extensive files that comprised 84.8 MB in total. Additionally, not all values I needed were reported in the same format or even in the same reactor location; for example, the fuel burnup was given as an average over the entire reactor, while neutron flow was given for the center of the reactor, where it was highest. Since the formulas tested are only valid if fluence and burnup are measured at the same location, it was first necessary to determine the relationship between peak and average burnup and then calculate the peak burnup in each reactor based on its average burnup.

### 2.3 Results

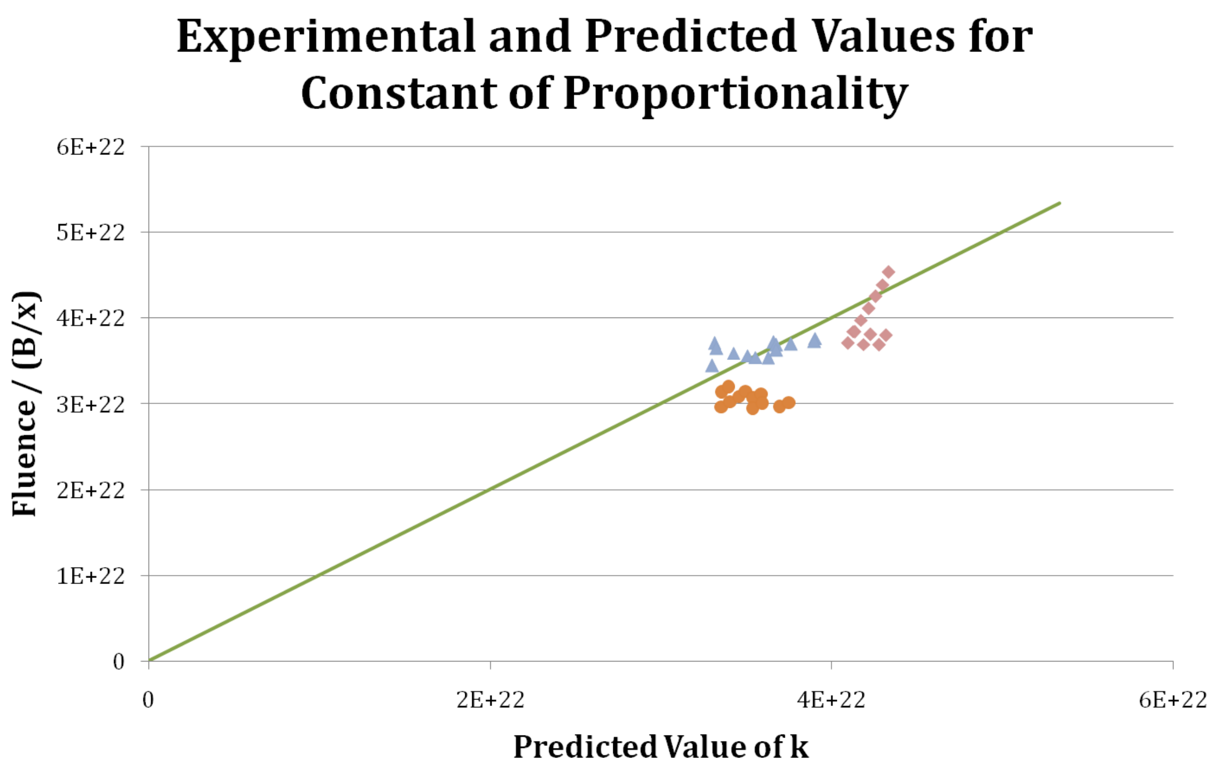
After extracting the data from the ERANOS output files and processing it to obtain the necessary values, it was possible to answer the original two questions. The first one – whether the quotient $B/x$ was better than just burnup at predicting fluence – was examined by plotting the values of fluence and burnup for each of the 40 reactor simulations examined, as well as the values of fluence against the quotient $B/x$. The results are shown in the following two graphs.



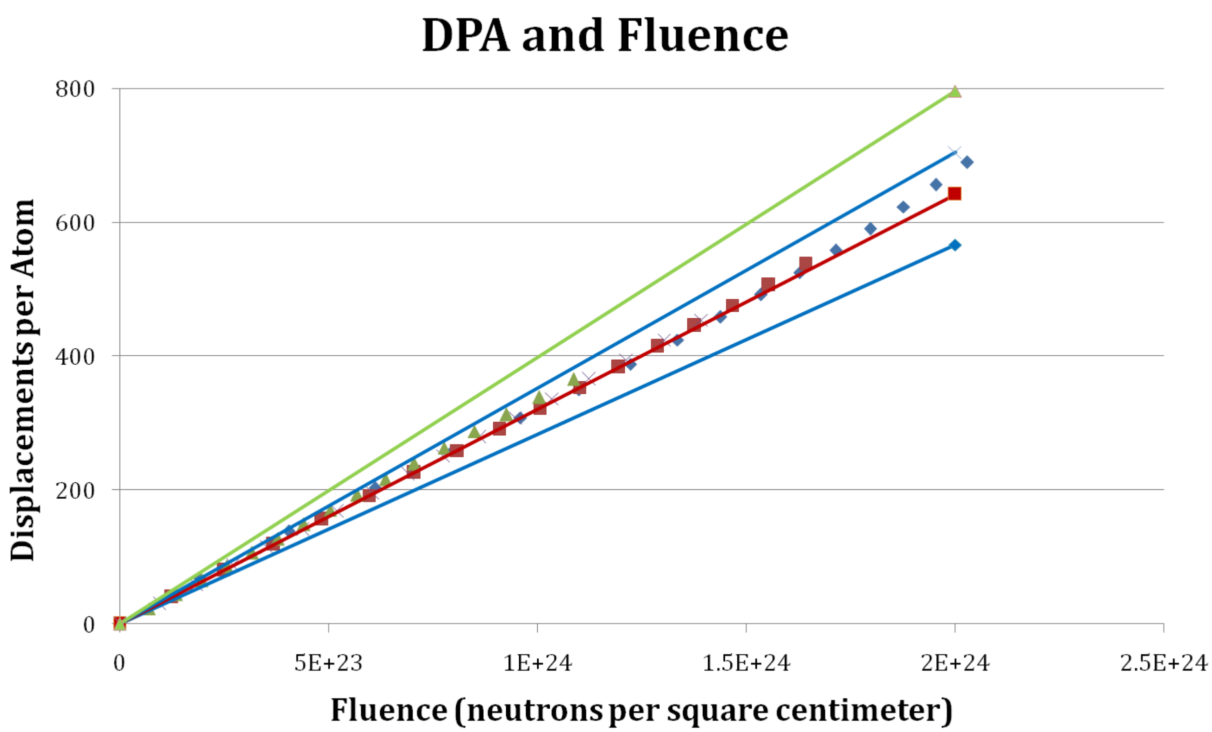




Since there is less variation among the reactor cores in the second graph, burnup divided by enrichment is a better predictor of fluence than burnup is.

The remaining variability can be explained at least partly by the reactor conditions affecting the constant of proportionality $k$. Since $k$ can be calculated based on other variables, it is possible to compare the predicted value of $k$ to the ratio $\frac{\Phi}{B/x}$, which is the slope from the previous graph. According to our prediction, these values should be equal, or at least approximately so. The following graph shows that the experimental and predicted values are in reasonably good agreement. (Perfect agreement is represented by the diagonal line $y = x$.) Furthermore, both the experimental and predicted values seem to cluster based on fuel type: the circles represent uranium carbide cores, the triangles represent uranium oxide, and the diamonds represent metallic uranium.




The other major question considered was whether dpa varied directly with fluence according to the relationship $\text{dpa} = \sigma_d \Phi$. To answer this, I examined four plutonium cores of varying enrichments and calculated values for dpa, $\sigma_d$, and $\Phi$ over the course of each reactor lifespan. For a given reactor, the ratio dpa/Φ was essentially constant, as expected. However, although the four reactors studied had different values for $\sigma_d$, they all surprisingly had almost identical values of the ratio dpa/Φ. The results are shown in the following graph. The four colors represent the four different cores tested at various stages of each reactor lifespan, and the solid lines represent the predicted relationship for each reactor.




Thus, while there does appear to be a linear relationship between fluence and dpa, the relationship seems to be even stronger than predicted, as all four reactors can be modeled by the same line. However, since only four reactor cores were analyzed here, these results might not generalize to other reactor configurations.

### 2.4 Conclusions

In this project two questions were examined: whether fluence is proportional to burnup divided by enrichment, and whether dpa was proportional to fluence. The first hypothesis appears to be mostly correct, as there is a strong relationship between fluence and $B/x$ – stronger than the relationship between fluence and burnup and sufficient to be used as an approximation. The relationship between dpa and fluence seems to be even simpler than we had originally conjectured, so it may also have value as a prediction.

## 3. Acknowledgments

I would like to thank my mentor Professor Driscoll and his graduate students Joshua Richard and Tingzhou Fei for their invaluable assistance in guiding and directing my research. I would also like to thank all the staff, sponsors, and coordinators of the Research Science Institute, particularly the Center for Excellence in Education, for organizing my research experience and helping me to edit my original paper.

## 4. References

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