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Author(s): Hayes-Sterbenz, Anna Catherine

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Analysis of the Reactor Position Independent Monitor (PIM) Diagnostic

Anna Hayes

T-2, Los Alamos National Laboratory, Los Alamos, NM 87544

Abstract

In this note I analyze the physics determining the proposed reactor position independent monitor (PIM), which is the ratio $\left({}^{240}\text{Pu} / {}^{239}\text{Pu} \right)^{1/3} \times \left({}^{135}\text{Cs} / {}^{137}\text{Cs} \right)^{1/2}$. The PIM ratios in any reactor fuel is shown to increase monotonically with the time over which the fuel is irradiated. This is because the Cs ratio determines the neutron flux, while the Pu isotopic ratio is determined by the flux times the irradiation time. If the irradiation time for all fuel rods across the reactor is fixed, the PIM ratio is approximately constant in all rods. However, no information can be extracted from the PIM ratio on Pu isotopics unless both the flux (or Cs ratio) and the irradiation time (from, say, Ru isotopics) are known separately, i.e., the PIM ratio is not a fundamental parameter of any reactor. Thus, unless the PIM ratio has been measured for the specific fuel under interrogation, no information can be deduced from measurements or reactor simulations of PIM ratios in different fuel from the same reactor. However, if a PIM measurement has been in one spent fuel rod from a given reactor, all other rods that are known to have been in the reactor for the same irradiation period can be assumed to have approximately the same PIM ratio.

Introduction: Recently, a reactor position independent monitor (PIM) has been proposed [1] that could potentially be used for plutonium isotopics. Here I provide an independent assessment of this PIM. This is a natural task for this project because the isotope ratios defining the PIM have been evaluated in this project and the detailed physics presented in our publication [2], listed below. The main conclusion of the present analysis is that the proposed PIM only provides information on Pu isotopics if the irradiation time is known independently.

The PIM diagnostic:

The PIM diagnostic was originally defined to be

$$PIM1 = \left({}^{240}\text{Pu} / {}^{239}\text{Pu} \right)^{1/3} \times \left({}^{135}\text{Cs} / {}^{137}\text{Cs} \right)^{1/2} \quad (1)$$

Recent analysis found that this diagnostic was approximately independent of the reactor rod position. Thus, if the PIM1 number were a universal constant for all rods in a given reactor design, a measured ${}^{135}\text{Cs} / {}^{137}\text{Cs}$ ratio for one of the rods could be used to deduce the ${}^{239}\text{Pu} / {}^{240}\text{Pu}$ ratio. However, our earlier analysis [2] showed that the ${}^{135}\text{Cs} / {}^{137}\text{Cs}$ is determined by the average neutron flux used to irradiate the rod and number of reactor shutdowns, while the ${}^{240}\text{Pu} / {}^{239}\text{Pu}$ ratio is dominantly determined by the reactor fluence, with a small correction for the flux. Since the fluence is the flux times irradiation time, the PIM diagnostic could only be constant if every rod was irradiated for the same length of time. Conversely, without independent knowledge of the irradiation time, the PIM diagnostic is not a universal constant or parameter for a given reactor; it varies monotonically with the irradiation time and cannot be used to deduce information about plutonium isotopics or other key isotopics.

To illustrate the dependence of the PIM diagnostic on irradiation time more clearly we first consider a related but simpler diagnostic,

$$PIM2 = (^{240}\text{Pu}/^{239}\text{Pu}) * (^{135}\text{Cs}/^{137}\text{Cs}) \approx \text{constant} * T_{\text{irradiation}} \quad (2)$$

The simple relation between PIM2 and T_{irrad} arises because $^{240}\text{Pu}/^{239}\text{Pu} \propto \phi T_{\text{irrad}}$ and $^{137}\text{Cs}/^{135}\text{Cs} \propto \phi$, where ϕ is the neutron flux. Thus, the PIM2 ratio is approximately independent of flux. Fig.1 displays this point, where it can be seen that the PIM2 diagnostic scales linearly with the irradiation time, while the original PIM diagnostic (eq. (1)) scales with T_{irrad} to the 1/3 power. Both diagnostics are flux dependent, but not strongly so.

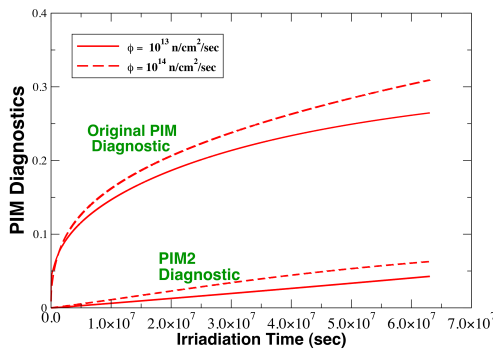


Fig.1 Both the original PIM diagnostic, as defined in eq. 1, and the PIM2 diagnostic increase with irradiation time, for two fluxes, 10^{14} and 10^{13} n/cm²/sec. The non-linear increase of the PIM1 diagnostic comes from including the power of 1/3 in the Pu isotopes, eq. 1. If all rods see the same irradiation times, the PIM diagnostics are only slightly flux (and hence slightly position) dependent. However, without independent knowledge of the irradiation time, the diagnostic cannot be used to deduce Pu isotopics.

The results in Fig.1 can be understood by examining the Pu and Cs ratios separately for different fluxes as a function of irradiation time, as displayed in Fig. 2. As can be seen, once equilibrium burn is reached the Cs ratio is a constant that is flux dependent, while the Pu ratio increases linearly with irradiation time. Across a reactor core the flux can change by about a factor of two, and both the Pu and Cs ratios will change proportionally, one with flux and one inversely with flux. While the Cs ratio can be used to extract the flux, no information can be deduced about the Pu isotopics without independent knowledge of the irradiation time.

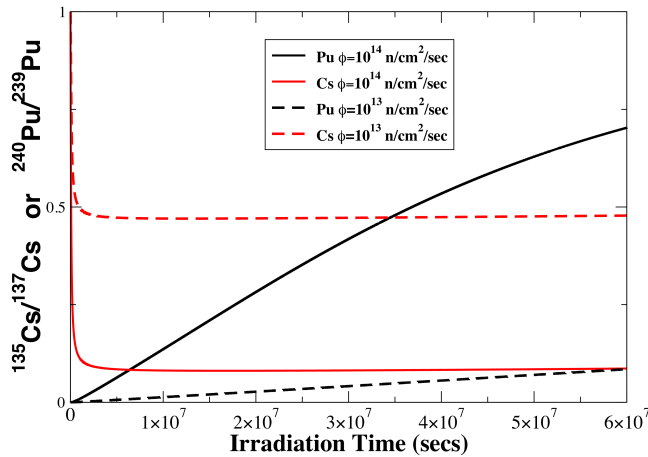


Fig.2 The $^{135}/^{137}\text{Cs}$ and $^{240}/^{239}\text{Pu}$ ratios as a function of the irradiation time. As was shown in ref. [2] the Cs ratio is a constant for a fixed flux, independent of irradiation time. The Pu ratio depends on the fluence, so it increases linearly with time, with a slope that depends on the flux. For these reasons, both PIM ratios (PIM1 and PIM2) increase with irradiation time and are not constants for any reactor design. They are, of course, constant for a fixed irradiation time, which is equivalent to saying that the Pu isotopics is determined by fluence and the Cs ratio by flux, i.e., their product is constant for fixed irradiation time. Reactor shutdowns introduce an additional complication to the Cs ratio.

Analytic expressions for this shutdown effect, as well as for the Cs and Pu ratios determining the PIM ratios are provide in detail in Ref. [2].

Summary: The PIM ratios (eq. 1 or eq. 2) increase with the irradiation time. This is simply because the Cs ratio determines the neutron flux and the Pu isotopic is determined by the flux times the irradiation time. So if the irradiation time seen by all rods across the reactor is fixed, the PIM ratio is approximately constant. However, no information can be extracted on Pu isotopics unless both the flux (or Cs ratio) and the irradiation time (say, from Ru isotopics) are known separately, i.e., the PIM ratio is not a fundamental parameter of any reactor.

Reference

- [1] M. Robel and K. Carney, *Reactor Modeling and Analysis: Using Stable Isotopes for Burn Up and Chronology*, DNN R&D Joint Program Review, Oak Ridge National Laboratory, April 29 – May 1, 2014
- [2] A.C. Hayes and Gerard Jungman, *Determining reactor flux from xenon-136 and cesium-135 in spent fuel*, [Nuclear Instruments and Methods in Physics Research A 690 \(2012\) 68–74](#)