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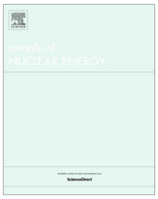

Computationally-generated nuclear forensic characteristics of early production reactors with an emphasis on sensitivity and uncertainty

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ABSTRACT

With nuclear technology and analysis advancements, site access restrictions, and ban on nuclear testing, computationally-generated nuclear forensic signatures are becoming more important in gaining knowledge to a reclusive country's weapon material production capabilities. In particular, graphite-moderated reactors provide an appropriate case study for isotopics relevant in Pu production in a clandestine nuclear program due to the ease of design and low thermal output. We study the production characteristics of the X-10 reactor with a goal to develop statistically-relevant nuclear forensic signatures from early Pu production. In X-10 reactor, a flat flux gradient and low burnup produce exceptionally pure Pu as evident by the ^{240}Pu/^{239}Pu ratio. However, these design aspects also make determining reactor zone attribution, done with the ^{242}Pu/^{240}Pu ratio, uncertain. Alternatively, the same ratios produce statistically differentiable results between Manhattan Project and post-Manhattan Project reactor configurations, allowing for attribution conclusions.

1. Introduction

Expanding nuclear capabilities and the rise of global terrorism have emphasized the need for nuclear forensic science, the main goal of which is to characterize nuclear material. Although considered a new field, nuclear forensic science has origins early in United States' nuclear intelligence campaigns with ^{85}Kr monitoring in the early 1950s for characterizing Soviet nuclear tests and reactor Pu production (Richelson, 2007). Nuclear forensic science is not only a key component in nuclear intelligence, but provides a deterrent in the use of nuclear weapons through attribution (Perry et al., 2009). A growing spectrum of nuclear threats cause concern on the viability of deterrence, while clandestine nuclear programs and terrorism actions have increased awareness of an unattributed domestic nuclear detonation. Post-detonation nuclear forensic science, the main driver of the attribution process, is dictated by pre-detonation processes and methods. In particular, reactor operating characteristics define Pu quality and ultimately the by-products of weapon detonation. Traditionally, the by-products from pre- and post-detonation origins are characterized in a radiochemistry laboratory. However, lack or limited access to nuclear sites and facilities requires the traditional laboratory setting to be supplemented or replaced with computationally derived Technical Nuclear Forensic (TNF) signatures in order to gain insight into the actual activities in a site of interest.

Fundamentally and not exclusively[1], accuracy of the computational TNF method is constrained by the nuclear data used and neutron transport method employed making quantification and understanding of sensitivity and uncertainty (S/U) an obligatory component of data analysis. Two methods of uncertainty propagation commonly used are "bounding" and "best-estimate" techniques (Gauld, 2003). In our analysis, uncertainties in nuclear forensic signatures and production estimates were calculated using best-estimate Monte Carlo sampling method. Sensitivity analysis was performed using forward and adjoint calculations. Quantifying sensitivities and uncertainties using early production reactor data presents required characteristics for weapons material production and highlights the statistically relevant TNF signatures. Production reactor S/U analysis provides the researcher with a twofold benefit: causality of error within modeled system and the effects of error on forensic statements/conclusions related to these systems. A convenient byproduct is further understanding of how the modeled system behaves under certain conditions; thus, providing a way to definitively leverage these differences.

To illustrate relevance, North Korea restarted Pu production operation with a graphite-moderated reactor at the Yongbyon

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[1] Other sources of uncertainty include but are not limited to model dimension, heavy-metal mass, operating power level and cooling time.

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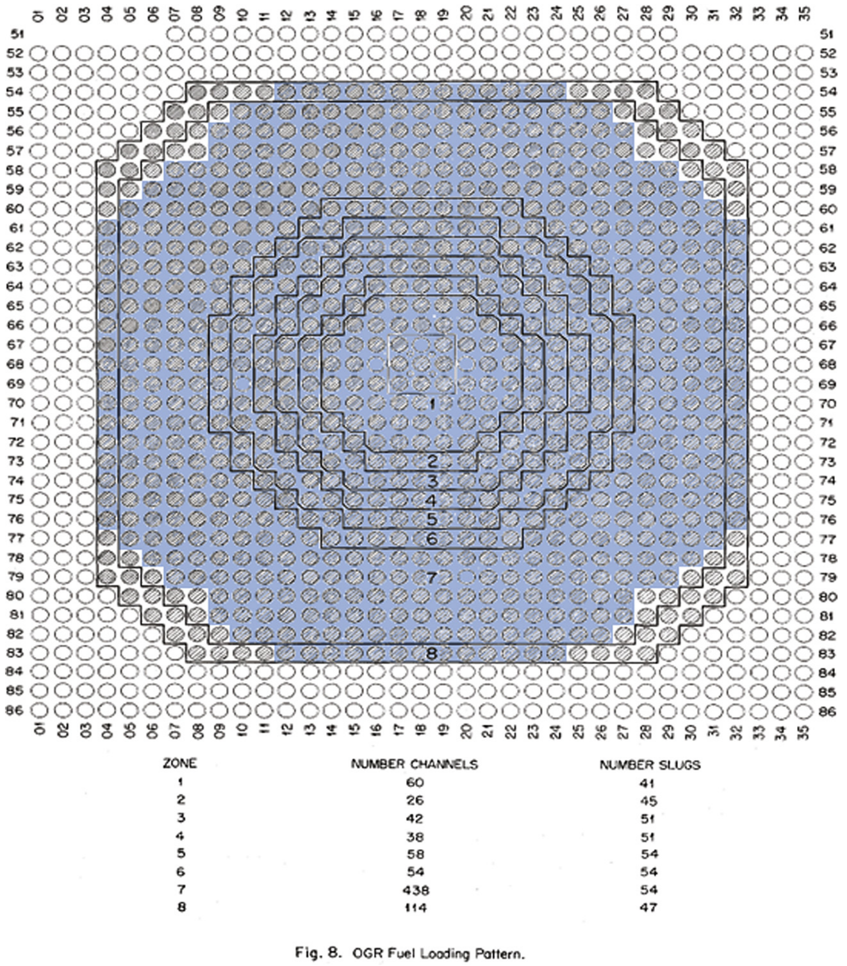

ZONE	NUMBER CHANNELS	NUMBER SLUGS
1	60	41
2	26	45
3	42	51
4	38	51
5	58	54
6	54	54
7	438	54
8	114	47

Fig. 8. OGR Fuel Loading Pattern.

Fig. 1. Fuel loading schematic of Manhattan (709 channel shaded region) and post-Manhattan mission periods (830 channel region) (Jones et al., 1945; Stanford, 1959).

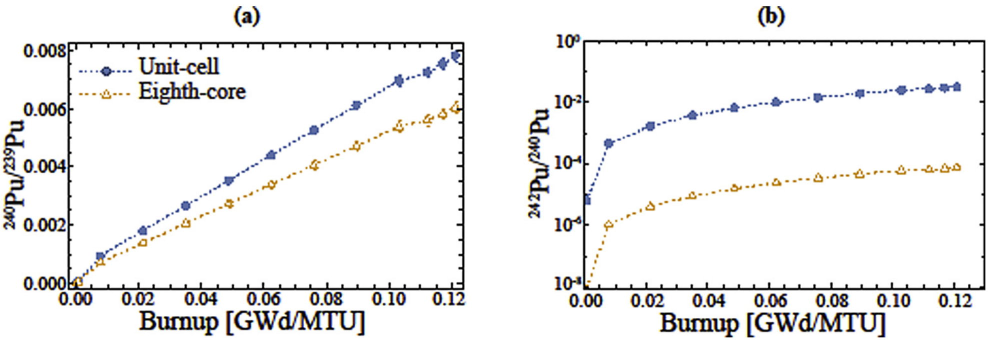

Fig. 2. Unit cell and 1/8th of a core ^{240}Pu/^{239}Pu (a) and ^{242}Pu/^{240}Pu (b) ratios comparison. Log scale removes visibility of error bars, but the difference of two orders of magnitude shows the effect of neutron leakage and flux changes on the ratio.

nuclear site looking to improve “quality and quantity” (Brunnstrom, 2016). Therefore, the X-10 graphite reactor provides an appropriate nuclear forensic case study because of the design, still used today in Pu production, and the low thermal output which is a desired characteristic for clandestine programs. Conveniently, X-10 hosted several fuel loading schemes coinciding with different mission periods. The Manhattan Project mission period and post-Manhattan mission period configurations are highlighted to show differences in TNF markers and S/U. The TNF markers considered here are the ^{242}Pu/^{240}Pu and ^{240}Pu/^{239}Pu ratios. These markers demonstrate operating neutron spectrum and efficiency of Pu production, respectively (Mayer et al., 2005). Scale’s Sampler module performed S/U analysis on all TNF markers. MCNP 6.1 and PENTRAN/PENBURN code packages were also employed for comparison (Williams et al., 2014; MCNP, 2003, Initial MCNP6 Release Overview - MCNP6 version 1.0, 2013; Sjoden and Haghighat, 2008; Manalo et al., 2009).

2. Sensitivity and uncertainty in nuclear forensics

Nuclear forensic scientists exploit and interpret subtle differences in material production and design that ultimately affect attribution conclusions. Refining the attribution process through advancement of nuclear forensic analysis bolsters in-direct