A Dedicated Detector for the Verification of Highly Enriched Uranium in Naval Reactors

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ABSTRACT. One of the requirements of a future Fissile Material Cutoff Treaty is that fissile material used in naval reactor fuel must not be diverted for weapons purposes. This could become relevant for both weapon and non-weapon states of the NPT because, in both cases, the geometry of the fuel and core may be considered sensitive information. Inspections and measurements would therefore have to rely on non-intrusive methods to determine the accuracy of the declared inventory in a reactor core. This talk will present MCNP-PoliMi simulations of a dedicated detector system to determine the amount of HEU present in various naval reactor core configurations. To test the viability of the method simulations have been done of interrogating a notional Russian icebreaker core. In this study we have found that many hypothetical diversion scenarios are detectable. We have also found that changing the reactor fuel configuration such as a smeared core, pin-type core or plate fuel all give similar results for the average enrichment.

Introduction

All five NPT nuclear weapon states operate submarines and, in some cases, surface ships propelled by nuclear reactors. By far the largest fleets are those of the United States and Russia. In addition, at least one non-NPT nuclear weapon state and one non-weapon state are pursuing naval nuclear propulsion today. Table 1 lists those countries that currently are operating or developing nuclear-powered naval ships and/or submarines. As the table indicates, at least four nuclear weapon states fuel their naval reactors with highly enriched uranium (HEU). Indeed, the United States and the United Kingdom fuel their naval reactors with weapon-grade uranium, i.e., enriched to over 90 percent in U-235. Russia and India are believed to use mostly HEU enriched to about 40 percent.

The use of HEU fuel by naval nuclear propulsion programs could make future nuclear disarmament agreements more difficult and also be a controversial aspect in the negotiations of a Fissile Material Cutoff Treaty (FMCT). As reductions in the nuclear-weapon arsenals proceed, the relative size of naval stockpiles of HEU could increase, and concerns could develop about their potential conversion to nuclear weapons. It would therefore be desirable that the weapons use of naval stocks of fissile material be subjected to international monitoring. Technically, this should not be a problem while the HEU is in unclassified form. It would become challenging, however, once the fuel is fabricated and also when it is loaded into a naval reactor, because the design of naval reactors and their fuel are considered militarily sensitive. Therefore, the intrusiveness of the verification regime would have to be limited so as to prevent the IAEA inspectors from acquiring classified information. This problem has been solved in the context of the Trilateral Initiative, where the participants devised a way in which the IAEA could monitor plutonium in classified weapons components without revealing classified information.

	USA	Russia	UK	France	China	India	Brazil
Nuclear Ships and Submarines	86	60	15	10	6-10	Under development	Under Development
Fuel Type	HEU	HEU	HEU	LEU	?	HEU	LEU
Annual HEU Demand	2000 kg	1000 kg	200 kg	-	-	Not yet Operational	-

Table 1. World Naval Nuclear Propulsion Programs. Annual HEU demands are estimates. Reportedly, China uses low-enriched uranium (LEU) or near-LEU fuel in its submarines, and France's new Barracuda-class attack submarine will use fuel with the same enrichment as France's pressurized-water reactors, which is less than five-percent enriched.

In this article, we consider a similar approach to determining the amount of HEU in nuclear fuel inside a container. The technology involved has to be somewhat different from that developed in the Trilateral Initiative, however, because the spontaneous neutron emissions from HEU are too low to allow useful measurements. It is therefore necessary to interrogate the material with neutrons from an external source to induce fissions and the emission of neutrons and gamma rays that make measurements feasible.

Design Classification Issues

Several performance characteristics of submarines and ships are considered militarily sensitive information. The peak power may not be so sensitive because the maximum speed of the submarine increases so slowly with peak shaft horsepower. A 50-percent increase in power only yields a 15-percent increase in speed. The fuel design may be more sensitive. It determines the "ruggedness" of the reactor core, i.e., its ability to withstand shocks from nearby explosions and how rapidly its power output can increase. Any verification procedure that could reveal such information would be unacceptable to countries with nuclear navies.

For a verification regime, however, only the initial uranium inventory in the core and its enrichment level are of interest. These are characteristics that determine the expected core-life of the reactor but are not directly related to its military performance. We therefore consider whether a verification system could be designed that would reveal *only the quantity of U-235 in naval fuel, while shielding sensitive design information*. The U.S. Navy apparently does not consider the enrichment of its fuel to be sensitive and has published this information.

Both rod-type and plate-type fuels have apparently been used in naval reactors. Beyond that, little is known publicly about the design of modern naval fuels—and we don't need to make particular assumptions about it for this analysis. Procedures for verifying the total quantity and enrichment of uranium in a core need not reveal features of the fuel design. If necessary, "information barriers," which have been successfully developed for other purposes, could be used to conceal such information.

General Approach to Verification

Our general approach to verification of HEU use in naval-reactor fuel cycles assumes that production of new HEU—if necessary at all—would be carried out under IAEA safeguards. Such material would remain under safeguards until needed. Countries also could place under IAEA safeguards pre-existing HEU that has been declared excess for weapons use and set aside for future naval use.

We assume that when HEU is needed for naval fuel, a country would inform the IAEA that it intends to withdraw a certain amount of HEU from the stockpile to fabricate a core for a specific new ship or submarine or to refuel an existing vessel. On the basis of public information about the shaft horsepower and refueling frequency of the ship (for example, from *Jane's Fighting Ships*), the IAEA could decide whether the request is plausible. The IAEA would not be able to refuse the release of the requested amount of HEU from safeguards, but it could alert the Parties to the FM(C)T if it believes that the request is implausible.

After the fuel is fabricated, it could be placed into an unshielded canister and, through radiation measurements as explored in this article, the IAEA could verify that the quantity of HEU in the fabricated fuel matches the amount and the enrichment level of the material that was released from the stockpile. Regular managed access inspections in the fuel fabrication plant could provide additional assurance that no fissile material is accumulating inside the plant.

It might also be possible for the IAEA to confirm that the fuel was installed in the reactor pressure vessel. Although it would be impossible to devise such a procedure without cooperation from the operators of the ships and submarines, we note that, under the START Treaty, Russia and the United States devised procedures by which each could check the number of warheads carried on the other's strategic missiles without compromising classified information. If such a procedure can be devised, it should also be possible for the IAEA later to verify the spent fuel being unloaded from the reactors and placed in canisters that would be subject to IAEA monitoring until the fuel was either reprocessed or placed in a deep underground repository. Even after spent fuel is discharged from naval vessels, sensitivities would remain about its design and access to the material for safeguards purposes could still be restricted. The United States and the United Kingdom, and possibly others, store their spent naval fuel rather than reprocessing it, so these restrictions could last indefinitely.

Detection Technique and Setup

This section presents the central element of a verification approach based on a Monte Carlo study for a dedicated detector system to determine the enrichment level and the quantity of the uranium fuel.

To detect and distinguish a high number of time-correlated particles/event in a several 100 ns time window a fast detector is needed., He-3 or BF_3 counters, were rejected because they require thermal neutrons to trigger them and relevant information such as the speed and time of emission used for selecting transmitted neutrons would be lost during the slowing down time. The approach taken in this investigation is to use large plastic scintillators (or perhaps liquid scintillators) arranged in five 2x2 m panels (labeled in Figure 1 as Inner Detector) surrounding the reactor core, which allows fast timing coincidence measurements and high coverage. Utilizing scintillators as detectors also allows particle discrimination based on pulse shape since neutron pulse-shapes have longer decay times than gammas. This is not discussed further in this document. In addition, as shown in Figure 1, the scintillator panel directly opposite to the DT generator neutron source is subdivided into 38 separate horizontal scintillators with a width of 6 cm and a length of 200 cm allowing 1-dimensional particle reconstruction. Each horizontal scintillator is itself subdivided into an additional 30 scintillators, which are optically isolated from neighboring scintillators. The full array of 30x38 scintillators allow the entire core to be imaged and diversions to be detected.

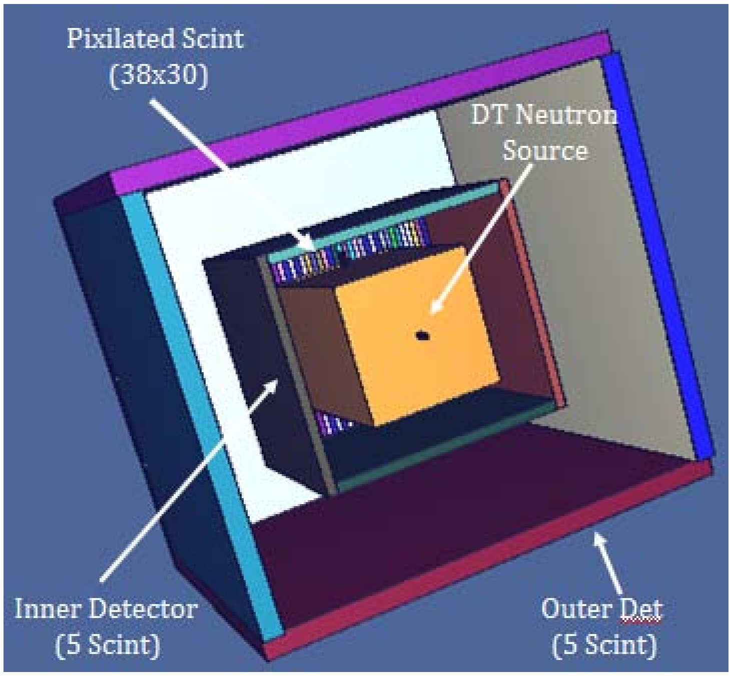

Figure 1: MCNP PoliMi model of detector system. The reactor to be interrogated by a DT generator is enclosed in a metal box surrounded by five 2x2 m scintillator panels. One of the panels is a highly pixelated (38X30) scintillator array with the vertical pixelation not shown in the diagram.

As mentioned, it is expected that these detector systems would be placed near a fuel fabrication facility so that they will not be expected to have a sizable overburden. Therefore, surrounding the Inner Detector are Outer Detector scintillator panels to reject cosmic ray events and stray neutrons that may trigger the inner detector and therefore may appear as an induced neutron event.

MCNP-PoliMi Simulations

As a first investigation of the potential of this dedicated detection system, MCNP PoliMi was used to simulate the detector geometry and the detection process. The advantage of employing MCNP PoliMi is that the physical transport of particles (electrons, neutrons and gammas) is tracked throughout the geometry. Cells tagged as detectors can be used to determine the time-correlated detections of particles. In addition to the MCNP PoliMi code itself, the package is bundled with a post-processing code to determine the time and the number of detected particles in the scintillator, the energy deposited in the detector, and the coincidences and correlations between detectors from the MCNP PoliMi data file (similar to the MCNP PTRAC file). As mentioned earlier, one of the panels is subdivided into 38 separate scintillators to allow for lateral position reconstruction. However, a further vertical pixelation is desired to allow for vertical position reconstruction as well.

The number of detector cells that can be modeled in MCNP PoliMi is effectively limited to 42, which is a problem for large pixelated detector arrays such as the one envisaged. To alleviate this problem, we modified the FORTRAN version of the post-processing code to track where particles are detected in the horizontally pixelated detector array (separated by 6 cm horizontally). Then, in the post-processing code, the horizontal pixel is subdivided to form 30 sub-detectors per detector, vertically separated by 7 cm. Therefore, each pixelated detector defines a 2-dimensional pixel of 6 cm by 7 cm. When a particle triggers the horizontal detector determined from the MCNP PoliMi data, the particle is assigned the vertical detector that corresponds to its position of impact. Based on the distance and the neutron velocity (14.1 MeV), directly transmitted particles can be easily selected by a timing cut.

In practice, each subdetector will need to be isolated from its neighbors by covering the scintillator with an opaque material and optically coupling them to photomultiplier tubes. Details describing the DAQ and specifics of the detector are not discussed further in this article.

The Analysis Observable M=5

In this analysis, a DT neutron source interrogates a cylindrical reactor core in a 30-degree forward cone completely illuminating the core with 14.1 MeV neutrons as well as illuminating the pixelated detector plane and part of the surrounding panel detectors. For our analysis, we seek an experimental variable that is correlated to the enrichment of the fuel in the core. There are many variables that meet this requirement. Here, we use as observable the number of particles detected in the scintillator panels surrounding the core during a specific time window, i.e., within 200 ns of the DT alpha trigger. For this analysis, no timing cut was applied after the trigger, all events where five particles were detected were accepted as M=5 events simplifying the data acquisition.

It is expected that the statistical fluctuations in the number of particles produced will follow a Poisson distribution, except for the particles emitted from fission or other neutron production reactions, which will produce prompt particles with a higher number of multiplets. As shown in Figure 2, the frequency of multiple particles (M=5 observable) observed in a run scaled with the enrichment level of the fuel in the core. The observable M=5 was chosen because this minimizes the intercept-to-slope ratio for the notional core while still having a high enough efficiency to be utilized. Clearly, if this ratio is small, then the sensitivity to the enrichment is high. For example, detecting M=6 will have a lower intercept-to-slope ratio compared to M=5, but will require much higher statistics.

M=5 Sensitivity for Reactor Types and Diversion Scenarios

1) Testing Enrichment Sensitivity to Reactor Configurations

We have modeled different reactor types for this analysis. All models are variants of a notional naval reactor core based on a Russian design similar to model 1 in [3]. The core contains 375 kg of uranium enriched to 40% (150 kg of ^{235}U) and uses metallic pin-type fuel metal (uranium dispersed in aluminum). The estimated volume ratios in the core are 30% fuel, 20% cladding, and 50% void (for water). In addition, we have also modeled plate-type fuel with a fuel region thickness of 0.12 mm, a cladding thickness of 0.04 mm, and a cooling channel of 2.00 mm, preserving the original ratios of the notional core. Finally, we have also modeled a smeared (homogeneous) core with a density equivalent to the average density of the notional core. The M=5 relationship is shown in Figure 2 as a function of enrichment for the three different reactor (pin-type, plate-type, homogeneous) configurations and we find that the M=5 value does not vary significantly among the different models.

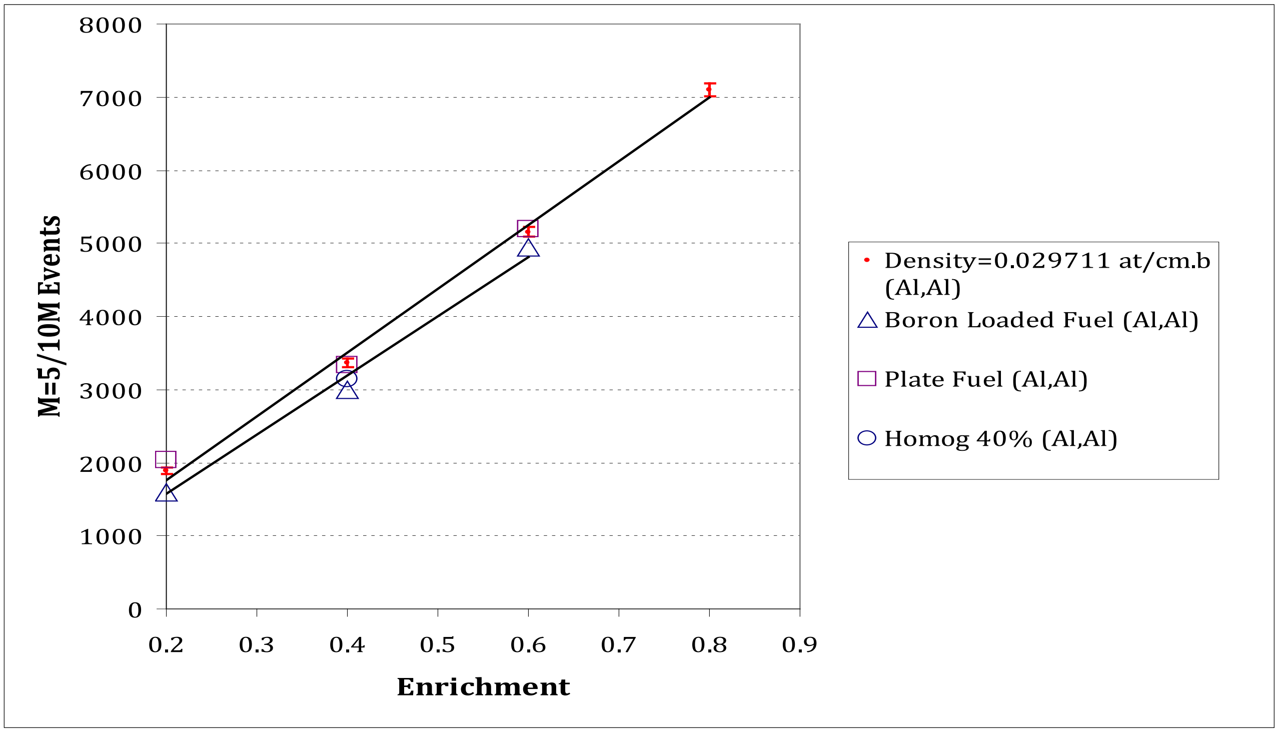

Figure 2: M=5 as a function of U-235 enrichment (expressed as a fraction) for three different reactor models where each data point corresponds to a 10M event run. All models contain the same amount of U-235 and have the same volume ratios of fuel to cladding as the notional core (denoted as (Al,Al)). Also, shown is a linear fit to the notional core (red) and to the Boron-loaded fuel data set to show the decreasing slope. Note that for all M=5 data the intercept associated with an empty detector has been subtracted off.

In other words, if the full composition of the core is known then the enrichment of the core can be determined without having detailed knowledge of the fuel configuration of the core. In addition if Boron is added to the notional core the enrichment would be underestimated by several percent so that it is in the interest of inspected parties to declare the Boron content in the core. Based on the assumption of a linear fit to the M=5 observable as a function of enrichment, and assuming only Poisson statistics, we conclude that for a ten-million-event run three standard deviation corresponds to 11 kg 90% HEU uncertainty for the notional naval reactor core (<1 min run with 1e7 n/sec). Obviously, if the statistics are improved the precision in this determination will also improve.

2) Testing Variation of Radii

A possible diversion scenario could be for the inspected party to claim the naval reactor to be of a specific radius slightly larger ($R_{Declared}$) than the true radius (R_{true}) forcing a miscalculation in mass of $\Delta M = \varepsilon M\left(1-\frac{R^2_{Declared}}{R^2_{True}}\right)$, where ε is the enrichment. This is significant considering that a onecentimeter uncertainty of the radius leads to an inventory uncertainty of 16ε kg for the notional core. We have tested the variation of different radii by measuring the flux of transmitted neutrons (defined as all events detected 2 ns from the direct transmission peak) as a function of the detected events in the pixelated plane detectors. For example, the number of transmitted events through the notional core for various reactor radii is shown for the horizontal pixelated detectors in Figure 3. The simulations indicate that, with adequate calibration of the experimental setup and statistics, the radii can be quantitatively estimated with high confidence. An argument could be made for using digital photography (with information barriers) or other optical means to determine the radius of the reactor. These results could be checked for consistency against the neutron measurements.

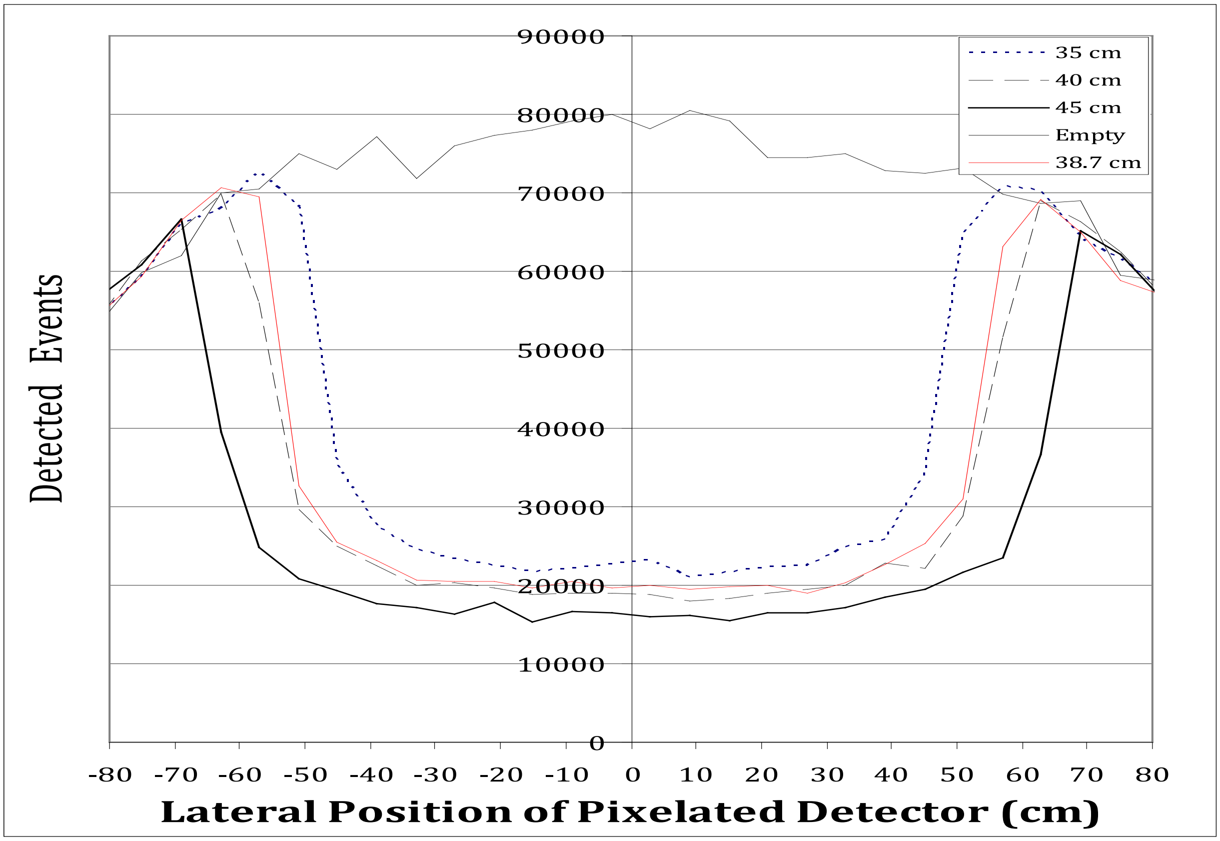

Figure 3: The lateral (horizontal) position of the pixelated detectors for different reactor radii of the notional core. The difference between reactor radii is clearly visible. Each data set corresponds to a 10M event run.

3) Testing Missing and Replaced Fuel Assemblies

Missing fuel in fuel assemblies, or fuel assemblies replaced with natural uranium, may also be a plausible diversion scenario. Several tests were done where fuel assemblies in the notional core were modified (materials were changed) and compared to the expected uranium mass. In these tests, 15 and 23 out of 252 fuel assemblies were removed at the center of the core. When we plot the lateral position of the pixelated detector for the diverted core, we find that the diversion for both the removal of a fuel assembly and the change to natural uranium are detectable (see Figure 4). In addition, if the core is rotated so that the base faces the source (see Figure 5), then the removal of the fuel assemblies is immediately recognizable allowing simple algorithms for detecting these diversion scenarios.

More challenging are scenarios, in which fuel assemblies are randomly removed or replaced rather than removed in groups. In this case, the coarse pixelation does not allow single missing fuel assemblies to be detected. In Figure 6 the M=5 magnitude is plotted for various diversion scenarios and compared to the notional reactor core with varying enrichment. The measured average enrichment appears to track the expected change in the enrichment (see fit to notional core) corresponding to an uncertainty of the mass of HEU in the notional core of less than 10 kg for the notional core.

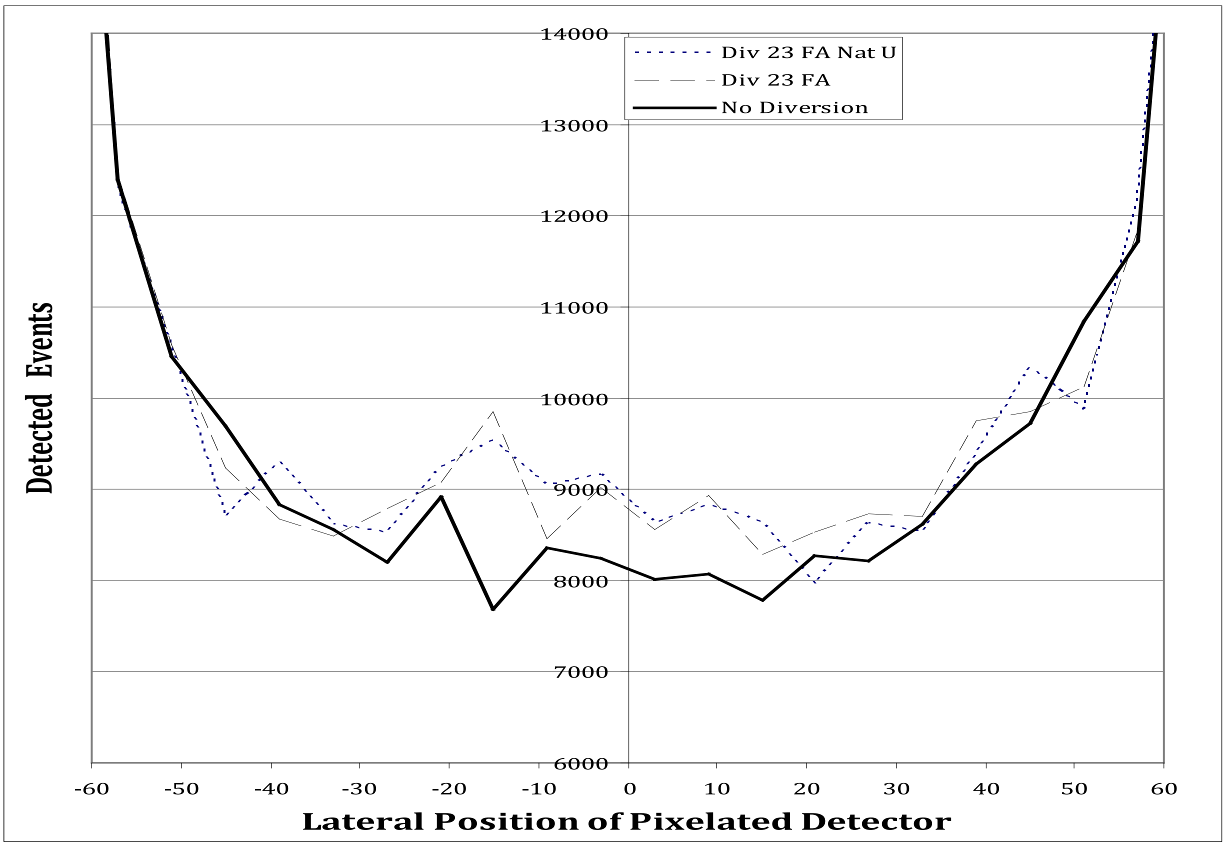

Figure 4: The lateral (horizontal) scan of the notional core for 10 M event run diversion scenarios where 23 fuel assemblies have had their fuel removed from the pins (dashed) and where the fuel has been switched to natural U (dotted).

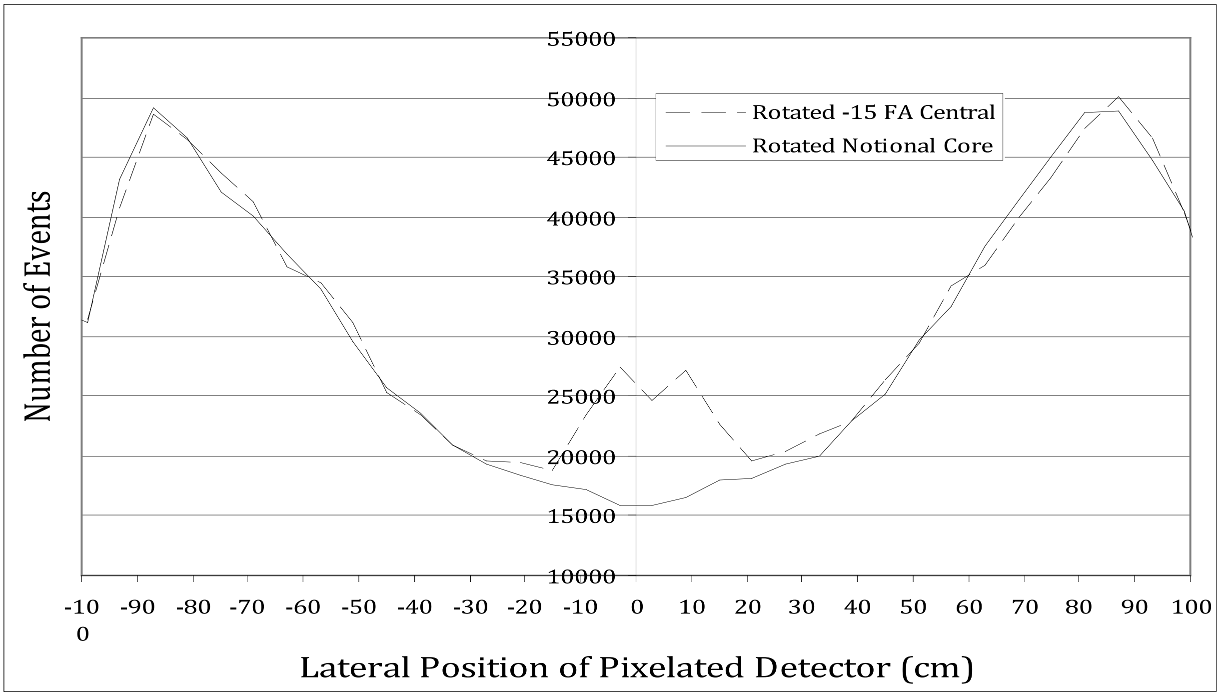

Figure 5: Lateral (horizontal) scan of a rotated reactor core where the base faces the neutron source for the diversion scenario where the fuel from 15 fuel assemblies have been removed near to the central axis (10 M event run).

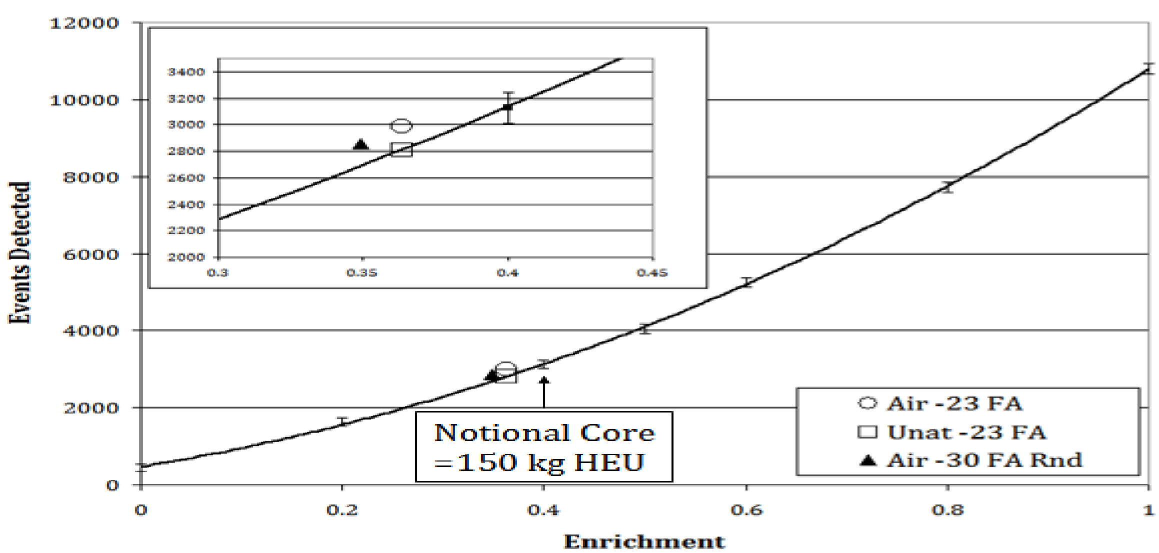

Figure 6: M=5 for 10 M event run diversion scenarios when the fuel of fuel assemblies are changed to air and to natural uranium. The M=5 values appear to track the expected average enrichment of the core when the fuel assemblies are removed. Note that the best fit curve through the notional core over the full range of enrichments is slightly non-linear.

Conclusions

We have reported on a preliminary study describing a possible dedicated detector system to non-intrusively verify the uranium enrichment and uranium inventory of naval reactor cores. We have used M=5 as the primary observable for determining the U-235 enrichment, although it does not appear to be linear with enrichment. Other potential variables should be investigated in a future study. The M=5 observable is largely insensitive to the particular configuration of the reactor core since the pin-type, plate-type, boron-loaded core, and homogeneous reactors which is important because it allows measurements without revealing sensitive information. Therefore, if the composition of the core (inventory of different elements) is declared by the inspected party the average enrichment can be determined without revealing sensitive details about the fuel design. In addition, we have determined that several types of diversions can be detected by determining the number of transmitted neutrons in the pixelated scintillators as well as by measuring the M=5 value.

Acknowledgements

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