EVALUATING SENSITIVITY TRENDS FOR MOBILE ANTINEUTRINO-BASED SAFEGUARDS

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ABSTRACT

Antineutrino detection systems show potential as a non-intrusive, tamper-proof monitoring tool for nuclear reactors. Mobile antineutrino detection systems are especially attractive as an emerging safeguard for their ease of implementation and flexibility to safeguard any type of reactor facility. In theory, these systems can confirm on/off status, monitor thermal power levels, and verify the isotopic inventory of any nuclear fission reactor. The extent of these capabilities depend on a wide variety of factors, such as reactor designs of interest, detector characteristics, and site-specific attributes. In this work, we explore these reactor, detector, and site parameters to gauge how they influence the predicted collection period requirement, or the onsite system measurement time required to verify the reactor condition. The collection period requirement was quantified through a profile construction statistical method, in which simulated antineutrino spectra were given likelihood values of belonging to different reactor operation modes. Our results indicate that a reasonably-sized, near-field, mobile antineutrino detection system can confirm On/Off status on the order of days to minutes. However, for scenarios in which a frequent background event rates are largely uncertain, the collection period requirements become unfeasible.

Mobile antineutrino detection systems, unlike previously deployed stationary near-field antineutrino detection systems, can leverage varying reactor-detector standoff distances to isolate events due to background. From a two-position measurement, the reactor status can be deduced without the need for any reactor-off period. This type of system also introduces a novel parameter of interest in which the system can be balanced between antineutrino measurements at the near and relatively far standoff distances. Our results indicate that a near equal amount of measurement time should be spent at both of these standoff distances to optimize the overall collection period requirement.

INTRODUCTION

The international atomic energy agency (IAEA) could utilize new detection technologies to safeguard next-generation small nuclear reactors [1]. One potential technology, antineutrino detection systems, shows potential to continuously monitor and safeguard these novel cores [2]. There maintains a challenge, however, connecting developing antineutrino detection systems to realistic applications for IAEA implementation [3]. In the NuTools report [4], subject matter experts for relevant topics, including neutrino physics and international safeguards, explored potential applications for neutrinos in nuclear security and safeguards. In their findings, they highlight the value of flexible, independent antineutrino detection systems to safeguard advanced reactors, including small modular reactors.

Mobile antineutrino detection systems could provide the flexibility to safeguard advanced nuclear reactors. A mobile detection unit could be implemented with custom facility-to-facility or core-to-core spacial and temporal considerations. With next generation nuclear facilities having unique facility designs, including multi-core reactor halls [5], and unprecedented fuel cycles, including cycles lasting 30 effective full power years (EFPYs) [6], there is value in developing a flexible safeguard that can be implemented in a wide-range of scenarios. While a mobile antineutrino detection system can be flexible to fit a variety of reactor safeguarding scenarios, there are system sensitivity trends that are consistent for general implementation. In this work, multiple case studies are modified and investigated to determine sensitivity commonalities for a mobile antineutrino-based safeguards system.

SPECTRA SIMULATION AND SYSTEM SENSITIVITY

The Reactor Evaluation Through Inspection of Near-field Antineutrinos (RETINA) System [2] was used to simulate high-fidelity antineutrino detection spectra and determine the system sensitivity for reactor misuse scenarios. The RETINA system computes the reactor antineutrino emission spectra from isotopic fission rates and antineutrino yield libraries. The isotopic fission rates are computed for each reactor design of interest using the Monte Carlo particle transport code SERPENT2 [7]. The antineutrino yield libraries are referred to as the Huber-Mueller libraries [8, 9] and provide the deterministic spread of antineutrino energies and quantities per fission. The reactor antineutrino emission spectra is then processed through detection parameters to simulate the detection spectra during an onsite measurement. These detection parameters vary by detector design and site-specific factors, such as the background radiation levels. For this study, we assumed detection parameters matching the PROSPECT detector design and the measurement performed at the High Flux Isotope Reactor at Oak Ridge National Laboratory [10]. While the PROSPECT experiment was originally designed to measure neutrino oscillation [11], the detection parameters are similar to those expected for a mobile antineutrino-based safeguards system. More details regarding the spectra simulation methodology can be found in Dunbrack [12].

The system sensitivity for each scenario was determined through a profile construction method. The method involves iterating over potential verification collection periods until the scenario spectra profile reaches our statistical boundaries. Verification collection periods, or the measurement duration required to verify the null hypothesis and not the alternative hypothesis, is used as the figure of merit for this study. Samples are generated for both the null hypothesis, x_0, and alternative hypothesis, x_1, for all energy bins, b. A profile is computed for each collection period iteration based on the likelihood, L, of the samples belonging to the null hypothesis distribution, X_0, and not the alternative hypothesis distribution, X_1. The final profile is classified in terms of the log-likelihood ratios, λ_0 and λ_1, as shown in Equations and . These profiles are iteratively developed until a classification boundary can be established over the profile boundaries while maintaining an acceptable false negative and false positive rate. Following limits established by the IAEA for highly-probable diversion scenarios, we allowed for a false negative rate of 10% and a false positive rate of 5% [13].

$$\lambda_0 = ln(\frac{\prod_{i=0}^{b} L(x_{i,0} \in X_{i,0})}{\prod_{i=0}^{b} L(x_{i,0} \in X_{i,1})}) \tag{1}$$

$$\lambda_1 = ln(\frac{\prod_{i=0}^{b} L(x_{i,1} \in X_{i,0})}{\prod_{i=0}^{b} L(x_{i,1} \in X_{i,1})}) \tag{2}$$

SINGLE CORE CASE STUDY

A single reactor core scenario, in which we assume a core is operating at full power (our null hypothesis) when the core is actually operating at 90% power (our alternative hypothesis), was initially chosen to study for evaluating sensitivity trends for a mobile antineutrino-based safeguard. The Advanced Fast Reactor (AFR)-100 [6] was used as the reactor design of interest. The AFR-100 is a fast, sodium-cooled reactor with a power rating of 250 MW_th and a fuel cycle of 30 EFPYs. For the scenario of interest, we assume the core is 1 EFPY into its fuel cycle. For the detector parameters, we assume the detector is placed 25 meters from the core for the safeguards measurement and that the detector shielding is comprised of either 50 cm, 80 cm, or 200 cm of borated-polyethylene shielding equivalent. The detector fiducialized mass is assumed to be 1 ton with a 2.5 ton option for the 200 cm shield.

As there is a temporal consideration to bringing a mobile antineutrino detection system to a facility after construction, we tested varying background collection periods for system sensitivity. The background collection period is used to establish a baseline understanding of the radiation background event rate. With an increasing background collection period, the verification collection period requirement for null hypothesis verification decreases. Our results indicate that this trend is more significant for antineutrino detection systems with less shielding as shown in Figure 1, since these systems have a higher background event rate.

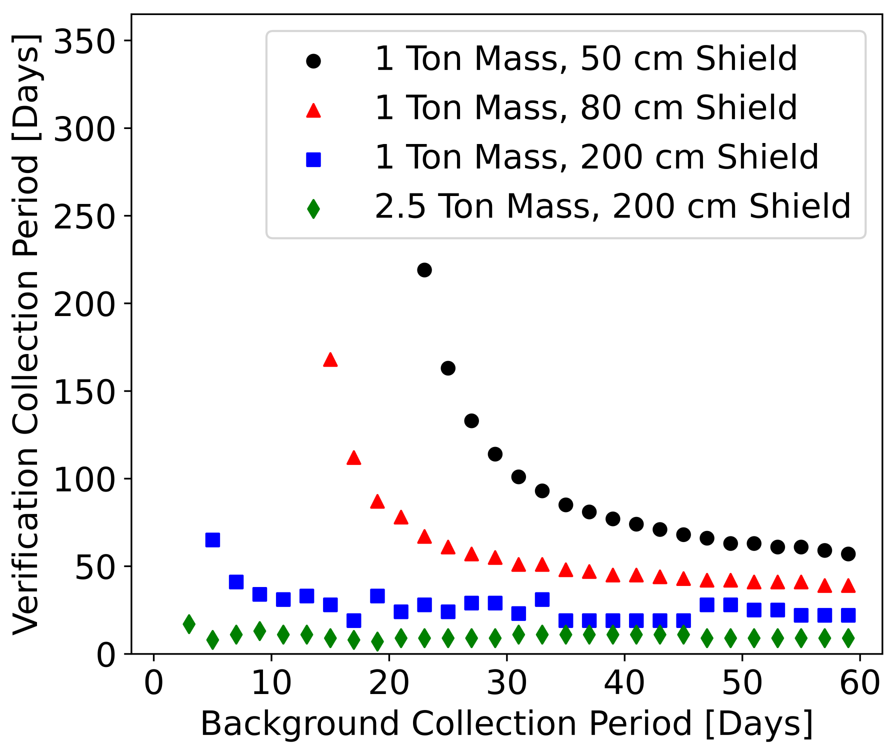

Figure 1: The collection period required for power verification with varying background collection periods and detector configurations

Alternatively, with a mobile detection unit, the background event rate can be deduced from a two-position measurement. Since the source term of the reactor core drops off as a function of the standoff distance squared, the background event rate can be further isolated at a greater distance from the core. This is an important implementation consideration as some next generation reactors have limited outages. The background-oriented further distance must be far enough away from the source-oriented closer distance to effectively deduce the background event rate. Considering our initial measuring position of 25 meters away from the core, the differing detector system compositions reach this reasonable distance between 60 meters are 100 meters, as shown in Figure 2.

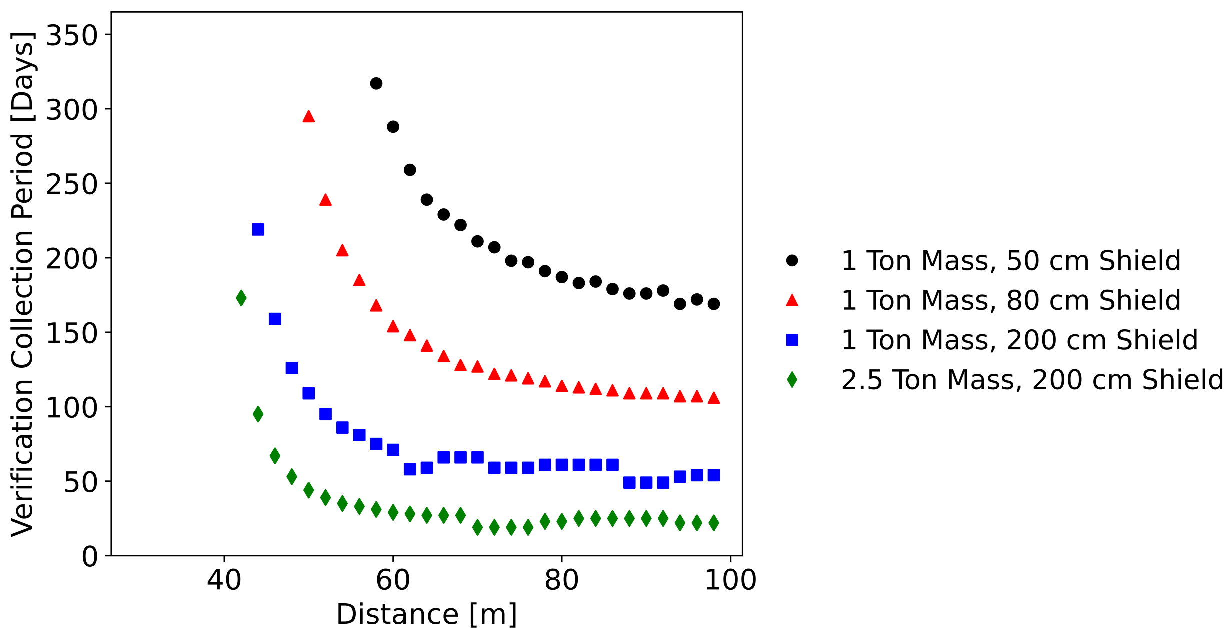

Figure 2: The collection period required for power verification with varying background collection standoff distances and detector configurations

Considering the figure of merit of verification collection period was chosen to find sensitivity trends that minimize the overall time spent at a facility, it is important to examine the optimal duration split in the two measurement positions. A new parameter, duration ratio, or the collection period at the far position divided by the collection period at the near position, is introduced. An approximately even split in collection periods is ideal for minimizing the collection period required for verification. The far position requires slightly less time given less background events, but this trend is slight and retains fairly consistent stability at the equal split position (i.e. duration ratio = 1), as shown in Figure 3.

REACTOR HALL CASE STUDY

The sensitivity trends become more complicated as more reactors are introduced to the problem. Similar trends are seen as with the single reactor case, but the influence of extra source terms cause an increase in the required verification collection period depending on the reactor pitch. As reactor pitch, or the distance between the reactor cores, increases, the influence of the nearby reactor cores diminish. The reactor hall case study follows the same reactor, detector, and sensitivity parameters as

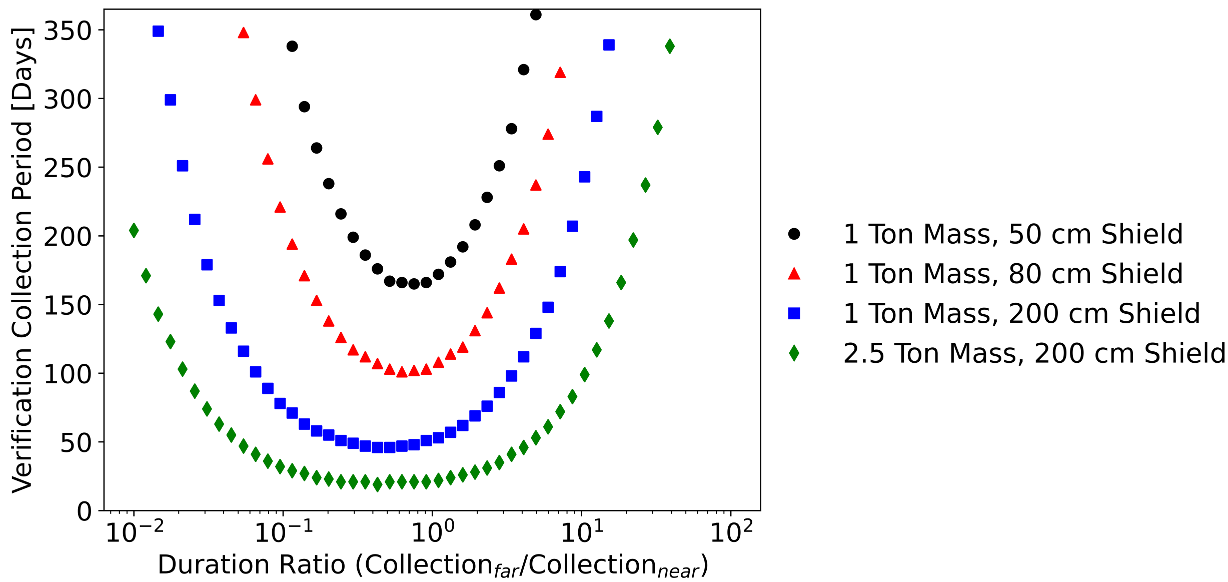

Figure 3: The collection period required for power verification with varying duration ratios and detector configurations

the single reactor core case. This new case, however, includes 6 AFR-100 reactor cores (with 5 cores operating at full power and 1 core operating at 90% power).

The detector position plays a large role in the antineutrino detector measurement. Without knowing which core is diverted, the optimal collection position to measure the antineutrino flux from all reactor cores remains as close to the center of the reactor hall as possible. In this configuration, we simulated the detector placed 25 meters across from the center of the reactor hall. In general, a larger reactor pitch led to a longer collection period being required for power verification, as seen in Figure 4. This is due to the weaker diverted source term since increasing the reactor pitch in this scenario also increases the detector standoff from the misused core. There is also a faint increase in verification collection period for small reactor pitches. This trend is noted from the other reactor source terms masking the misused core's flux.

If a specific core is to be targeted for the measurement, the reactor pitch would not longer alter the detector's standoff distance from the reactor core of interest. With the primary standoff distance stationary, the increase in reactor pitch correlates to a decrease in the verification collection period, as shown in Figure 5. This decrease in verification collection period is associated with the nearby reactor cores contributing a less significant source strength to the detector as the reactor pitch increases.

CONCLUSIONS

There are many parameters that alter the safeguards sensitivity of mobile antineutrino detection systems for various scenarios. There are, however, trends that are consistent for many of the scenarios. For these scenario measurements, obtaining reasonable background knowledge is vital to

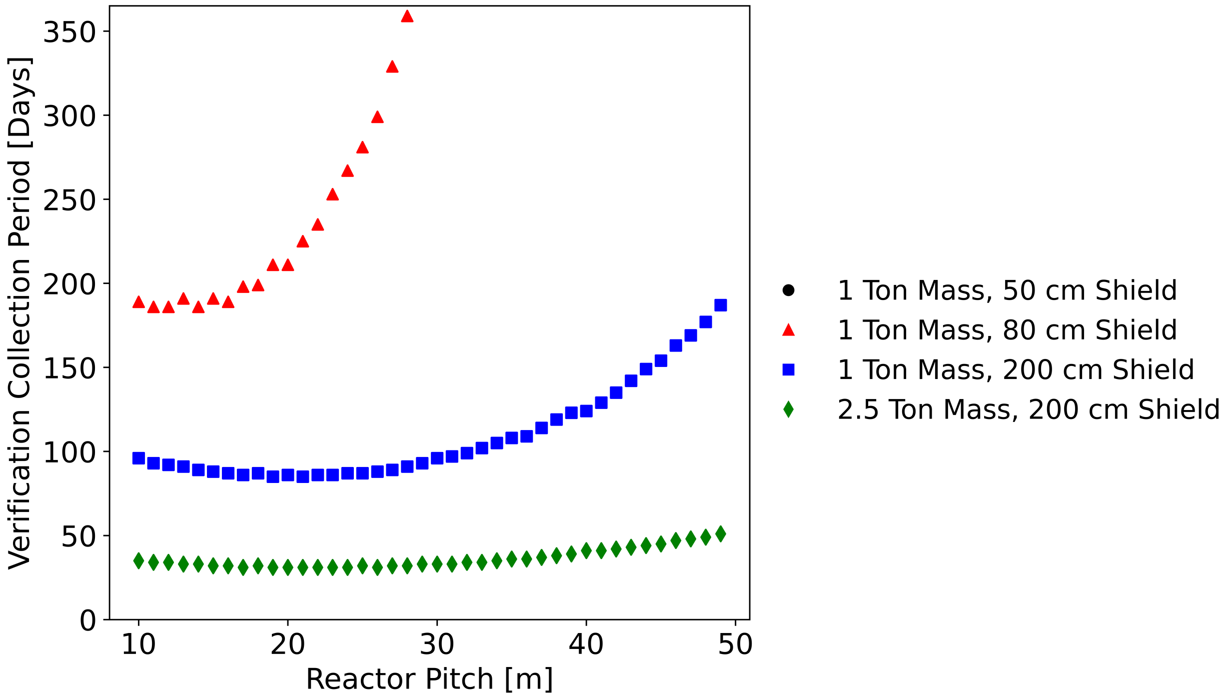

Figure 4: The collection period required for power verification with varying reactor pitches and detector configurations. The antineutrino detector is assumed to be placed directly in the middle of the reactor hall and the misused reactor core is assumed to be an innermost core

verifying the core integrity. This can be done through a direct background measurement, assuming a long enough background measurement, or a two-position measurement scheme, assuming the far position is far enough from the near position and a near-equal duration is used for both positions. It is also important that all source terms are considered effectively. In the case of a reactor hall, a large reactor pitch could either hinder timely reactor misuse verification, as is the case with a mid-position detection system, or can aid in the verification of the reactor, as is the case with a core-specific detection system.

While these trends are fairly consistent for the varying scenarios, there are assumptions and parameters that should be further explored. One significant assumption, for example, is that the radiation background is similar at both the near and far position when utilizing a two-position background measurement. This assumption breaks down as the far position increases. Further research should go into verifying the consistency of background event rates over distances on the order of meters. Future work should also go into exploring multiple misused reactors and multiple detectors. The case studies presented in this work only evaluate a narrow reactor core misuse case when there can be multiple reactor cores misused in a reactor hall. Multiple detectors can be used to try and mitigate the complexity of the problem, but then more customization is required to determine the optimal positioning of composition of the detection systems. More research is needed to narrow the safeguards problem and simplify the detection space for future safeguards studies.

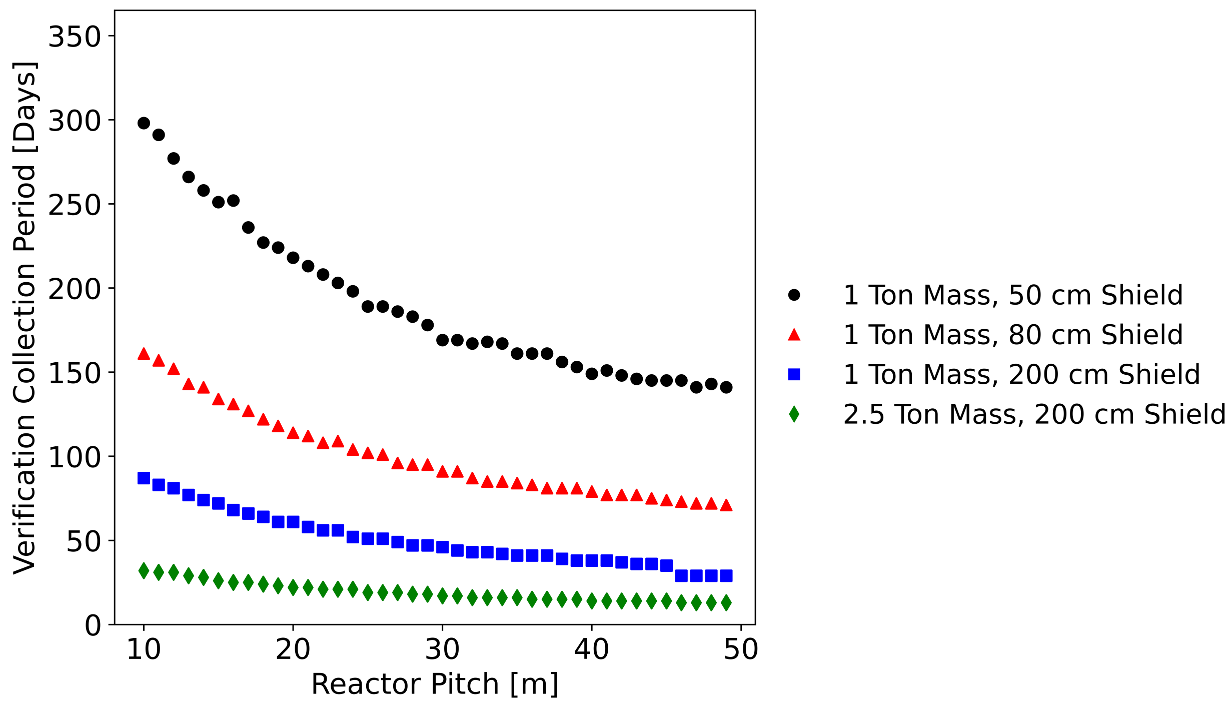

Figure 5: The collection period required for power verification with varying reactor pitches and detector configurations. The antineutrino detector is assumed to be placed directly across from the misused reactor and the misused reactor core is assumed to be an innermost core

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