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Monitoring of nuclear reactors with antineutrinos: comparison of advanced reactor systems

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Abstract. Single-assembly diversion scenarios are analyzed for two advanced fast reactors, UCFR-1000 and AFR-100. The two reactors represent large and small core geometries, resulting in a larger reactor core providing good counting statistics, but relatively small fraction of material contained in a single assembly, while the small core showing poor counting statistics, but a larger fraction of the core must be altered to yield one significant quantity (SQ) of material. We consider detection probabilities of inner and peripheral assemblies. We show that while diversion inner assemblies are more feasible to detect with a PROSPECT-type antineutrino detector, they also require significantly less time to accumulate one SQ of material.

1. Introduction

Data regarding the state of an operating nuclear reactor core are vital to its safe and secure operation and the optimal utilization of its fuel. Instruments which provide these data must either be radiation-hardened or suffer a loss of precision due to operation outside containment. This leads to a situation in which high-fidelity measurements on reactor fuel isotopics are unavailable until well after the fuel has been discharged. Additional instrumentation based on neutrino physics offer the ability to track long-term phenomena such as burnup and core isotopic evolution from outside containment in near-real time as well as providing redundancy to the current instrumentation portfolio. In addition, material safeguards can greatly benefit from nearly real-time tracking of material while in the reactor core and potentially yield information whether material diversion has happened.

In this paper, we perform material diversion analysis using advanced reactors as a case study. In particular, we focus on large-size core UCFR-1000 [1] and smaller reactor AFR-100 [2], both long-lived reactor cores (30-60 year life time) which are envisioned to be deployable at remote places as well as non-nuclear power countries (countries without front- and back-ends of the fuel cycle, but with a desire to benefit from nuclear energy). The UCFR-1000, a larger reactor core, acts as a 3D source of antineutrinos providing good counting statistics. However, acquisition of one significant quantity of material (SQ, IAEA definition) constitutes changing only $\sim$0.1% of the core loading. On the other hand, the AFR-100 is a smaller core which can be approximated as a point source. The consequence is poor counting statistics, but a larger fraction of the core ($\sim$1%) must be altered to yield one SQ.

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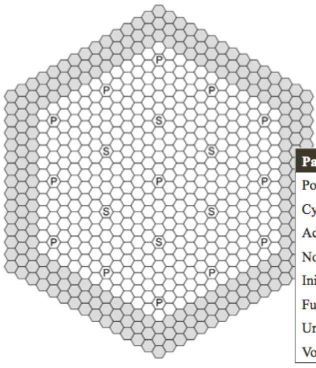
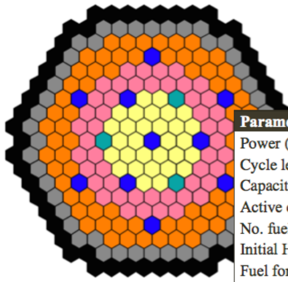
High-power core: UCFR-1000



Parameter	Value (293 K)
Power (MW_t/MW_e)	2600/1000
Cycle length	60 EFPY
Active core height	360 cm
No. fuel assemblies	378
Initial HM inventory	201 t
Fuel form	U-10Zr
Uranium enrichment	12.3% / natural
Volumetric power density	81.0 kW/L

Low-power core: AFR-100



Parameter	Value (293 K)
Power (MW_t/MW_e)	250/100
Cycle length	30 EFPY
Capacity factor	90%
Active core height	110 cm
No. fuel assemblies	150
Initial HM inventory	24.64 t
Fuel form	U-10Zr
Core average enrichment	13.47%
Volumetric power density	58.2 kW/L

High-power core: UCFR-1000	Low-power core: AFR-100
3D source	Point source
Good counting statistics	Poor counting statistics
SQ ~ 0.1%	SQ ~ 1%

Figure 1. Layout of the assemblies in the UCFR-1000. Reflector assemblies are in grey. Letters indicate control assembly positions: "P" for primary control and "S" for secondary control.

2. UCFR-1000 and AFR-100

The UCFR-1000, the design for which was developed by the Ulsan Institute of Science and Technology (UNIST) in conjunction with Argonne National Laboratory (ANL), has been selected as the large, high-power-rating core. The UCFR-1000 is a U-10Zr-fueled core with a low-enriched uranium (LEU) starter zone on top of which sits a 300 cm fertile region containing natural uranium. During operation, the burn zone propagates upward at about 5 cm/year as plutonium is bred into the fertile zone and depleted fuel is left behind, consistent with the CANDLE[3] burnup scheme. It is intended to operate on a once-through cycle which lasts 60 years at full power. The major core parameters are taken from the design paper [1] and shown in Figure 1.

An additional motivation for choosing the UCFR-1000 is that the axial progression of the burn zone causes the geometric attenuation of the antineutrino flux to slowly change—opening the door for the use of relative signal strength among multiple detectors to track progression once the core has completely transitioned to burning ^{239}Pu.

The AFR-100, developed at ANL, has been chosen for the small, low-power-rating fast reactor design; it is a 250 MW_{th} sodium cooled fast core designed for a 30-year, once-through cycle. The major parameters of the AFR-100 and the core layout are shown in Figure 1.

The AFR-100 shares the assembly and pin design cross section with the UCFR-1000, but instead of a tall core with distinct starter and fertile regions at the beginning of cycle, the AFR-100 has the more traditional pancaked geometry of fast reactors. To achieve a balanced coolant exit temperature and power distribution, it has an onion-type enrichment scheme which propagates the burn zone from the periphery of the reactor toward the center. The propagation is symmetric, much slower, and the effect much less pronounced than in the UCFR-1000, primarily due to the small core volume, but also the more gradual enrichment differences. The change in geometric attenuation of the antineutrino flux is negligible.

3. Detector

The choice of detector was motivated by the desire to keep to near-field antineutrino detector experience so as to not extrapolate too egregiously upon the capabilities of detectors which would be installed at the earliest a few years from now. This excluded the physics experiments

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geared toward solar and stellar neutrino characterization, guiding the choice instead toward oscillation experiments, many of which use commercial-scale nuclear reactors as their source of pure electron antineutrinos. A detector based heavily on the Phase-I (AD-I) and Phase-II (AD-II) detectors for the PROSPECT project[4] has been adopted for antineutrino safeguards calculations.

The SONGS-1 antineutrino monitoring experiment[5, 6, 7] used otherwise unoccupied space in the tendon gallery for commercial PWR observations. In the spirit of remaining unobtrusive to normal reactor operation, the detectors are placed as close to the core as possible without requiring special consideration during plant construction, resulting in locations within the containment building but outside the chamber containing the reactor pressure vessel, guard vessel, etc. For commercial-scale PWR's, this approach usually results in a standoff of 20-25 m from the center of the core. Sodium-cooled fast cores are much more compact per unit power than PWR's, but prevailing designs use a large pool-type reactor vessel to provide additional thermal inertia during transient events.

Given UCFR-1000 preluminary design, we assumed that the core compactness and pool-type vessel sizing should roughly offset, resulting in a standoff of 25 m (based on the SONGS-1 standoff from a reactor with similar power rating). Three PROSPECT-like segmented antineutrino detectors will be symmetrically arranged around a circle with a radius of the minimum unobtrusive standoff to estimate the performance of an antineutrino detector suite. If necessary to distinguish such a particular arrangement in the discussion of named detectors from another established detector or project, the suite will be referred to as RETINA (**R**eactor **E**valuation **T**hrough **I**nspection of **N**ear-field **A**ntineutrinos), although it should be noted that RETINA is not a set-in-stone arrangement or detector design in the general sense.

4. Reactor modeling

Reactor cores were modeled using the MC^2-3 and REBUS codes developed by ANL. The fission rates of each isotope as a function of burnup were extracted with their full 3D geometry preserved and used to calculate the emitted antineutrino source distribution of the reactor. Due to the substantial change in the neutron flux distribution with the progression of fuel burnup in the UCFR-1000, mid-cycle updates to the effective broad group (ANL33 structure) cross sections were necessary to preserve computational accuracy. These were performed every 1 EFPY of burnup by recalculating the fine group (ANL2082) flux distribution in TWODANT with updated fuel compositions. The AFR-100 was found to need no such updates to the neutron cross sections.

5. Results of Diversions

Preliminary analysis using a coarse-grained model of the UCFR-1000 indicated that the diversion of one SQ of LEU (75 kg of ^{235}U in LEU) from a freshly loaded core, with replacement of natural uranium, would be unable to be detected within the weapon conversion window (< 12 months) via near-field antineutrino safeguards. The exceedingly small change in the isotopes undergoing fission resulted in a nearly-identical antineutrino flux. Furthermore, the uranium acquired would be 12.3% enriched, requiring significant further enrichment in order to yield HEU that is weapons-usable ($> 90\%$ ^{235}U). A nation possessing the enrichment capacity to bring the stolen uranium to the required enrichment would likely have other more easily executed methods of obtaining the required material—whether through procuring uranium under the guise of overt peaceful use or through black market channels. The limited utility of antineutrino safeguards against LEU diversions from LEU-fueled fast reactors in addition to the availability of other acquisition methods for the material motivates a focus on diversions of plutonium.

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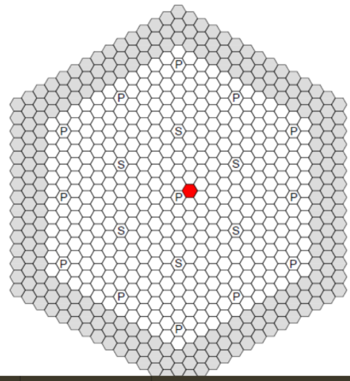
Burnup	2.17 EFPY	
Replacement fuel	(a) LEU (b) ^{Nat}U	
Plutonium removed	**Mass (kg)**	**%**
^{238}Pu	3.08×10^{-2}	0.38
^{239}Pu	7.53	93.04
^{240}Pu	5.07×10^{-1}	6.26
^{241}Pu	2.47×10^{-2}	0.31
^{242}Pu	1.08×10^{-3}	0.01
Total	8.10	



ID	Power Adjustment	1 month	2 months	3 months	3 months, no adjustment
1a	-1.031×10^{-3}	1.149×10^{-10}	4.276×10^{-6}	1.541×10^{-4}	0.255
1b	-1.469×10^{-3}	2.943×10^{-5}	3.257×10^{-3}	1.676×10^{-2}	0.523

Figure 2. Location (red) of the diverted & replaced assembly for diversion scenarios UCFR-1a and UCFR-1b.

5.1. UCFR-1000 diversion cases

Diversions UCFR-1a and UCFR-1b represent the earliest point at which 1 SQ of plutonium is available via removal of a single assembly from the UCFR-1000. This occurs in any of the center-adjacent assemblies (the core has $\pi/3$ rotational symmetry), as these are the locations of highest flux. The plutonium vector and the assembly location are shown in Figure 2. The plutonium obtained via these diversions is not far from the 7% threshold of ^{240}Pu contamination.

Diversions UCFR-2a and UCFR-2b represent a patient actor who only needs one SQ and can reasonably wait until enough plutonium is available via diversion of a single corner assembly in order to select one with a low probability of being caught. The plutonium is somewhat purer than that obtained from the UCFR-1a and UCFR-1b diversions due to the lower flux, and since the irradiation rate is about 15% as high, the concentration of surviving fission products is lower, potentially easing shielding requirements. While the probability of detection of diversion of a peripheral assembly is practically null, it takes 12.42 EFPY to obtain one SQ of material.

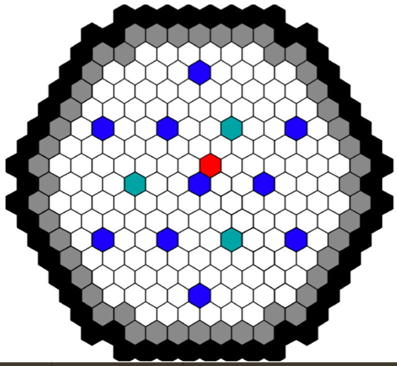
5.2. AFR-100 diversion cases

The AFR-100 does not breed one SQ of plutonium into every assembly by the end of its burnup cycle; the chosen diversion scenarios instead focus on obtaining one SQ of plutonium via removal of one, two, and three assemblies that are either available as early as possible (scenarios 1a/b) or at the core periphery (scenarios 2a/b).

The flatter flux distribution, lower local power density, and lack of true blanket assemblies keeps one SQ of plutonium from being obtainable via a single-assembly diversion in the AFR-100 until 15.75 EFPY into the burnup cycle. At this burnup, three of the center-adjacent assemblies (the core has $2\pi/3$ rotational symmetry) host one SQ of weapons-grade plutonium. The plutonium obtained at this point and the location of the withdrawn assembly are shown in Figure 3. The ^{235}U enrichment of the AFR-1a replacement assembly is 15% in the lower and upper fuel macrozones and 9% in the middle.

If a proliferator has access to an AFR-100 core late in its burnup cycle and is able to simultaneously divert two assemblies, 1 SQ can be obtained from the assemblies at the edge of the core, where they will disturb the neutron flux distribution the least and provide the greatest chance of remaining undetected. The plutonium obtained has superior purity to that from the center-adjacent assemblies obtained in scenarios AFR-1a/b, although the burnup (21.25 EFPY) is several years later in the cycle, so deploying an AFR-100 would not grant a proliferator a short

Burnup	15.75 EFPY	
Replacement fuel	(a) LEU (b) ^{Nat}U	
Plutonium removed	**Mass (kg)**	**%**
^{238}Pu	2.50×10^{-2}	0.31
^{239}Pu	7.56	93.93
^{240}Pu	4.47×10^{-1}	5.55
^{241}Pu	1.62×10^{-2}	0.20
^{242}Pu	6.12×10^{-4}	0.01
Total	8.05	



ID	Power Adjustment	1 month	2 months	3 months	3 months, no adjustment
1a	-1.469×10^{-3}	0	0	2.516×10^{-13}	2.213×10^{-2}
1b	-9.531×10^{-4}	0	0	6.344×10^{-12}	8.562×10^{-4}

Figure 3. Location (red) of the diverted & replaced assembly for AFR-1a and AFR-1b.

breakout period in which they remain undetected for over two decades. The ^{235}U enrichment of the AFR-2a replacement assemblies is 14% in the upper and lower fuel macrozones and 13% in the middle.

6. Conclusions

Long-lived reactor cores are designed to provide turn-key electricity without frequent refueling outages. Antineutrino-based monitoring of these reactors can provide an additional layer of security against material diversion including scenarios with assembly replacement using LEU and NatU fuel. We show that in order to achieve a removal of one SQ of material within a reasonable amount of time, an assembly must be removed from the center of the core, facing a potential alarm of the monitor. Peripheral assemblies can eventually yield one SQ of material (12 or more EFPY), but detection of this type of diversion is practically impossible.

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