Lawrence Livermore National Laboratory

Fuel Anomaly Detection Using Antineutrino Data: A Second Look at SONGS

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IAEA standards

- IAEA's safeguards objective: "…timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons .."

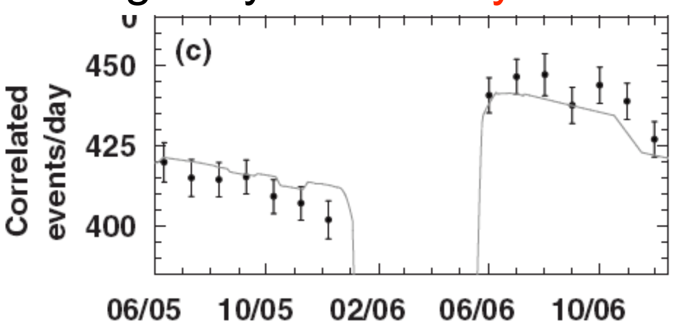
IAEA Timeliness goal	Material form
Three months	irradiated direct use material, (e.g., plutonium (Pu) in spent or core fuel)
One year	indirect use material (e.g., Low Enriched Uranium (LEU) (< 20% uranium, enriched in ^{235}U) or natural uranium)

IAEA Significant Quantity	Isotopic content
25 kg of ^{235}U in HEU	HEU is defined as uranium with ≥ 20% ^{235}U content
75 kg of ^{235}U in LEU	LEU is defined as uranium with < 20% ^{235}U content
8 kg of elemental Pu	Any isotopic mix of Pu except Pu with >20% ^{238}Pu

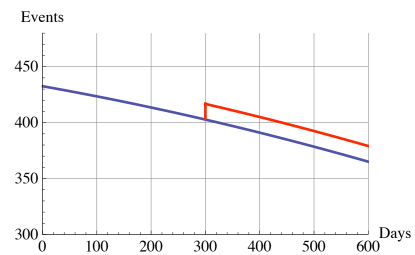
- The objective of this study: estimate sensitivity to anomalous changes in fissile content - such as diversion - using antineutrino rate data

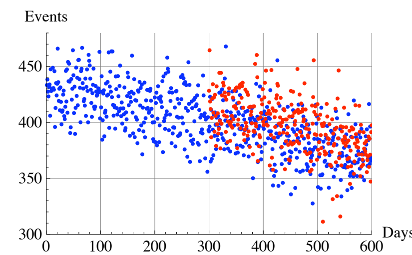
Prior work - a rough sensitivity estimate using the SONGS configuration

- **Data**: SONGS antineutrino data before and after refueling calibrates the effect of a step change in PU and U content
- 250 kg of ^{239}Pu are replaced with 1.5 tons of ^{235}U.
- The detected antineutrino rate changes by 35 evt./day ~ 10%



- **MC:** 100,000 Monte Carlo trials
- 14 evt./day step change at day 300
- chisq formed for shift v. no shift for 100,000 expts.





- includes errors from flux (3%) power (1%) and statistics (~5%)
- false positives: $p=10^{-5}$ for observing a shift *not* due to isotopic change

  false negatives: p= 0.1 that fluctuations *mask* the isotopic shift

The main limitation of this analysis: poorly quantified relation between antineutrino rate changes and changes in fissile mass inventories

Recent work: Quantify the effect of changes in plutonium content on the antineutrino rate using reactor simulations and a hypothesis test

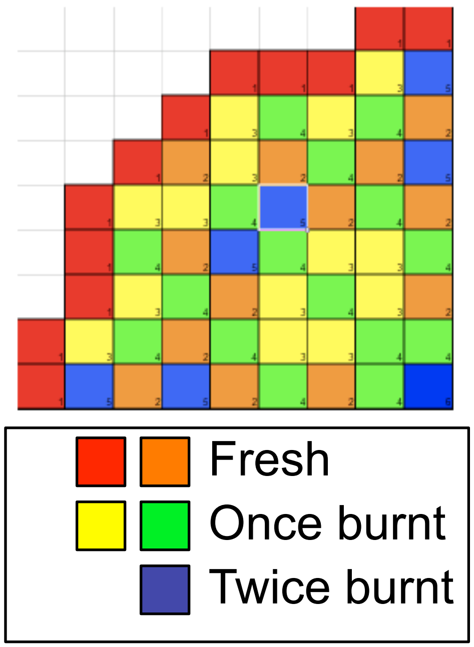
We compare two different fuel cycles using benchmarked simulations of our reactor and detector

- **Baseline Cycle** –SONGS PWR, standard fueling

- **Diversion Cycle** –

  Replace 10 once burnt — 70 kg Pu239 in removed assemblies

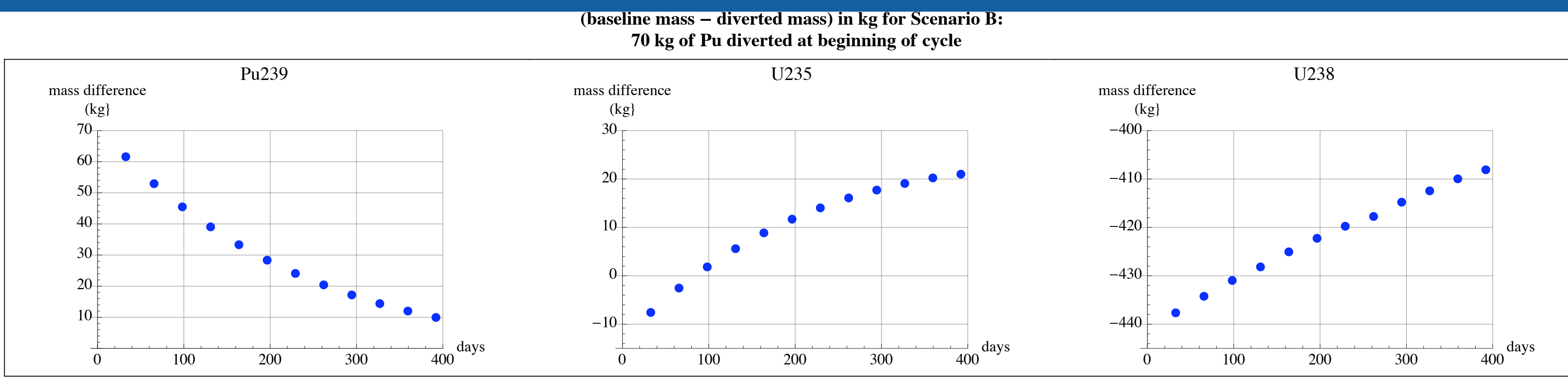
  With 10 fresh assemblies — Replacement keeps thermal power constant



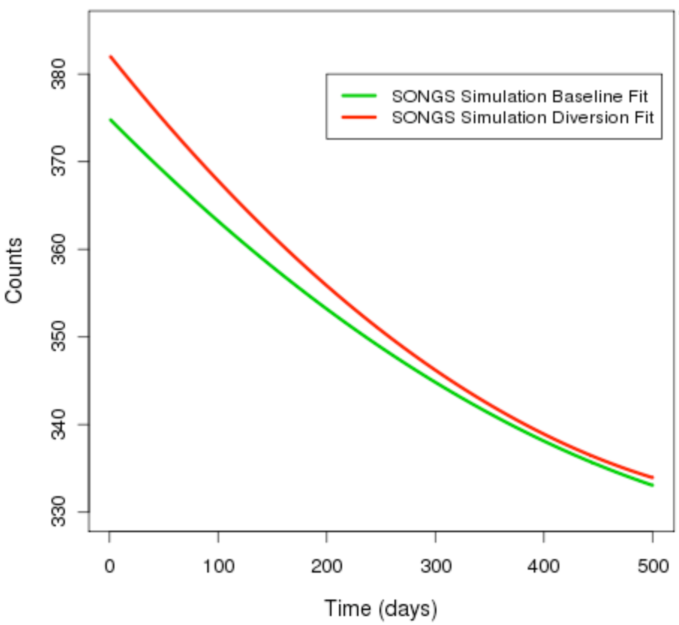
Disclaimer: This analysis shows a specific diversion scenario using a rate-based measurement/simulation– **this is not our ultimate sensitivity**

Simulation input: ORIGEN 0-d simulation relates mass and antineutrino rate for baseline and diversion evolutions

Out[78]=



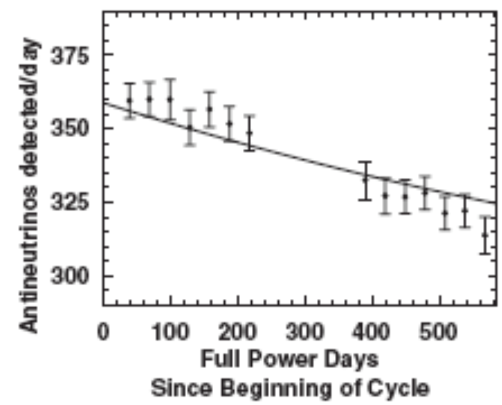
The simulation predicts mass inventory differences throughout the cycle



The simulation also predicts antineutrino count rates throughout the cycle

1) Count rate evolution with 73 kg Pu removed

2) Count rate evolution for a standard fuel cycle (no diversion) (presumably)



The simulation was checked against SONGS data

Hypothesis test: compare fit coefficients for the two cycles

We compare the 'observed' antineutrino count evolution $\{N^T_\nu(t)\}$ to the simulated theoretical baseline count evolution $\{N^B_\nu(t)\}$, modeled as

$N^B_\nu(t) = \gamma^B_0 + \gamma^B_1 \cdot (t - t^*) + \gamma^B_2 \cdot (t - t^*)^2$ *(baseline counts, no diversion, only sim. errors)*

$N^T_\nu(t) = \gamma^T_0 + \gamma^T_1 \cdot (t - t^*) + \gamma^T_2 \cdot (t - t^*)^2$ *(diversion counts being tested, includes* all errors)

(t^* is the mean of t values - this improves the test performance)

The statistical test compares coefficients γ^B_k *to* γ^T_k, $k = 0, 1, 2.$ *and sets a threshold of significance*

$$s_i = \frac{\hat{\gamma}_i^{(M)} - \hat{\gamma}_i^{(B)}}{\sqrt{se^2(\hat{\gamma}_i^{(M)}) + se^2(\hat{\gamma}_i^{(B)})}}$$

n.b: In this exercise, both the 'observed' and predicted counts are taken from the ORIGEN simulation

Hypothesis test outputs

- **probability of a false positive** at a given threshold

= the proportion of 100,000 **baseline** scenario evolutions found to be different from the baseline by the test

- **probability of a true positive** at a the same threshold

= the proportion of 100,000 **diversion** scenario evolutions found to be different from the **baseline** by the test

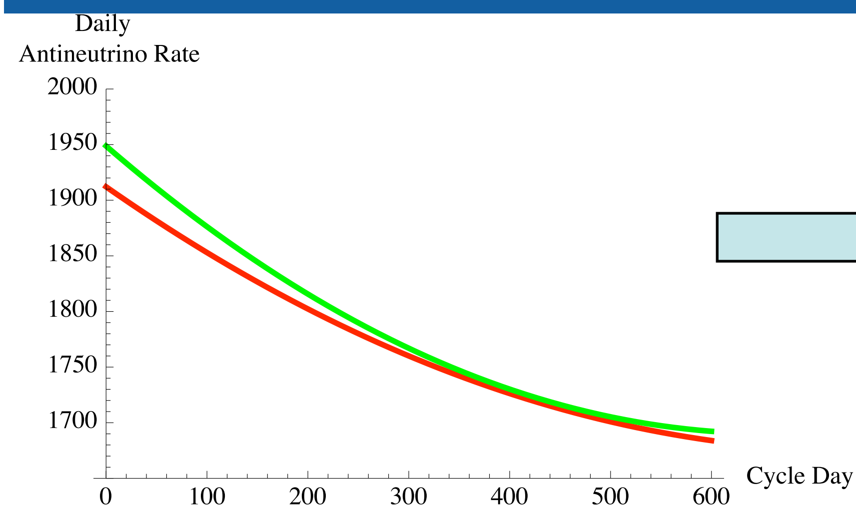
- Repeat the above for a series of thresholds to obtain a receiver-operator characteristic or ROC curve
  - Shows the **probability of true positive** as a function of the **probability of false positive**

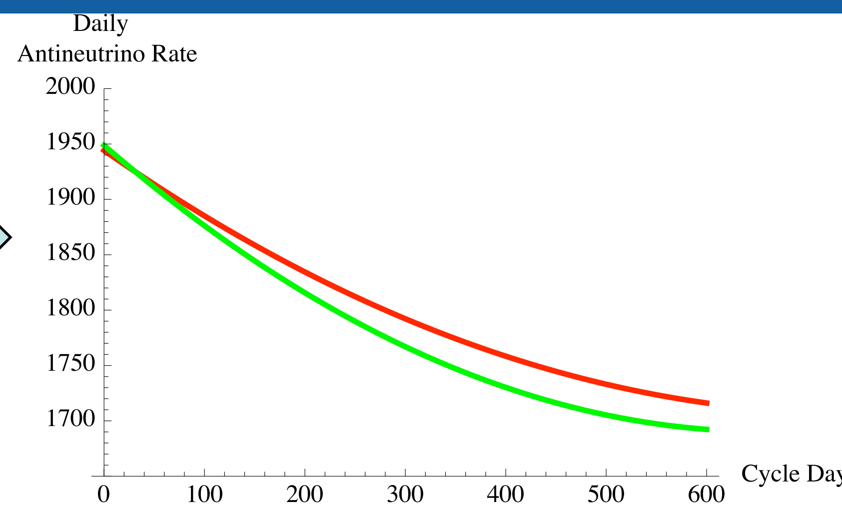
The effect of various factors on the test performance

We considered the impact of:

- **Measurement bias:** Adding a 1% systematic error to the measured count rate not due to diversion
- **Statistics:** High counts vs. low counts (about 400 per day - measured rate at SONGS)
- **'Malfeasance':** Adding a 1% systematic shift in the predicted baseline count evolution to deliberately obscure the difference between the baseline and diversion evolutions
- **Duration of acquisition:** The number of data points in the cycle used to obtain the estimates of the coefficients (30, 90, 250, 500 days)
- **The starting point of the acquisition:** The part of the cycle used to obtain the estimates of the coefficients
- **Simulation error:** 1% noise in the baseline count evolution

The effect of systematic uncertainties in detector response





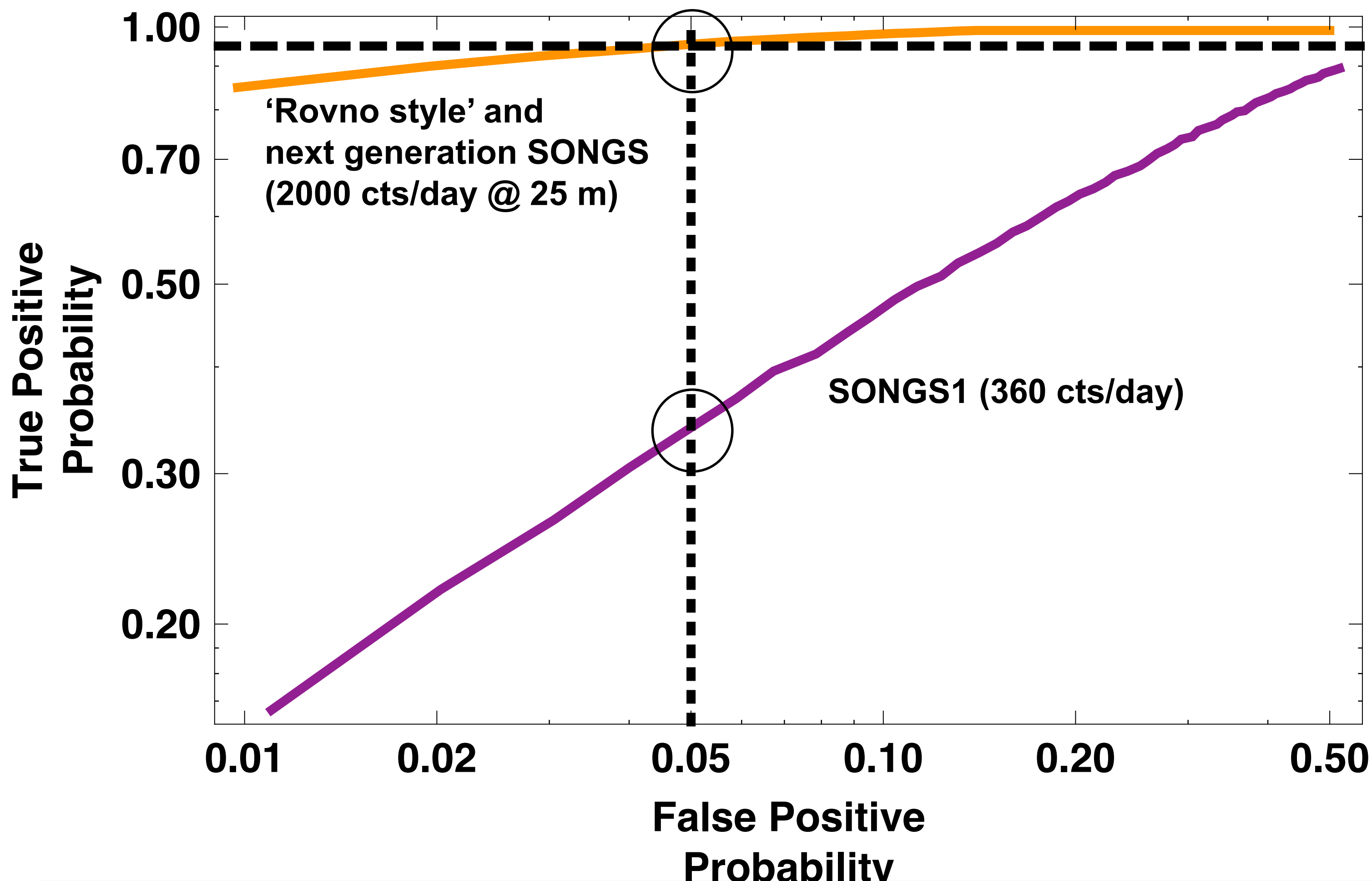
What if a ~2% shift between prediction and measurement at beginning of cycle arises from a overall systematic shift in detector response, rather than diversion

Result: the test performs poorly if the shift is attributed to detector bias (high false positive rate)

First solution: add a fixed constant to all data to remove the initial shift.
Result: *The test still sees diversion, but only for longer time integrations*

Second solution: create a single measured template antineutrino rate evolution based on a known baseline cycle. Use in future cycles
Result: *The test performs well and independently of simulations*

The effect of counting statistics



2000 counts per day is necessary and sufficient for 95% True Positive Detection of 73 kg of Pu in 90 days

Summary of results: sensitivity to removal of 10 assemblies and 73 kg of ^{239}Pu

- Systematic error in detector response,
- Counting statistics
- Misreporting of thermal power

are the dominant effects on test sensitivity

True positive rates given a 5% false positive rate

Number of days of acquired data	Error considered	SONGS1 (360 cts/day)	2000 cts/day
90	1% absolute systematic error		0.02
250	Systematic shift removed by comparison with initial measurement		0.96
90	Systematic shift removed by template matching (assumes identical cycles)	0.34	0.95
90	1% misreported thermal power		0.23
500	1% misreported thermal power		0.99

Summary and Results

A) **Illustrate how antineutrino detectors might be used for safeguards**
- Used a hypothesis test to compare predicted and measured rates
- Gives an additional level of independence from declarations compared to current practice

B) **More rigorously connect changes in Pu content with antineutrino rate evolutions**
- Simulations are indispensable for this task

C) **Study various effects on sensitivity**
- Sensitivity to ~75 kg Pu changes with 90 days of data seems possible
- Improvements may come from better reactor simulations, better detectors, and integration with other safeguards methods

D) **Gain insight into detector requirements for a given level of performance**
- 2000 counts per day are necessary, sufficient and achievable for sensitivity to the present diversion scenario

Proposed future work

- Use improved simulations and redo rate analyses

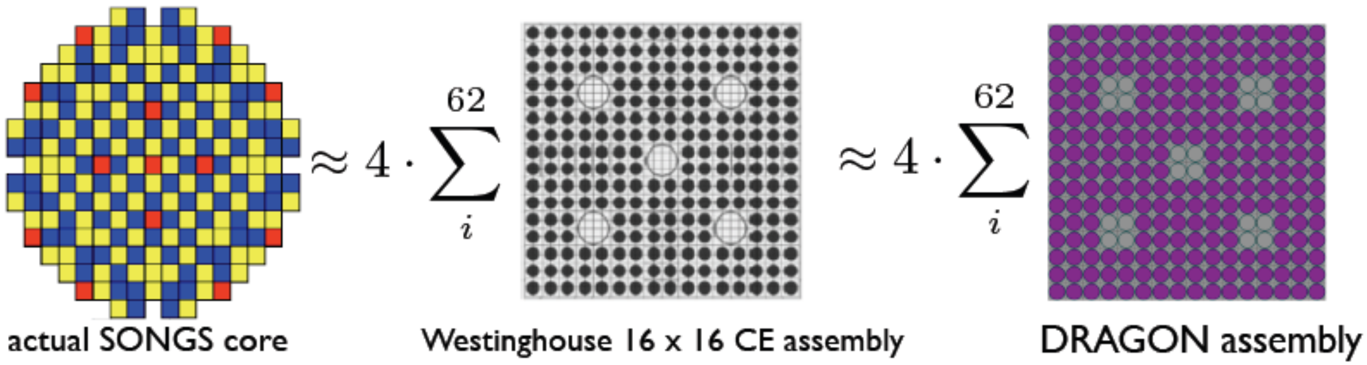
- Examine other diversion scenarios and reactor types

Work with IAEA to study the most relevant diversion scenarios

- Study an improved spectral analysis to directly extract fission rates estimates without requiring simulation or operator inputs such as power

  - This requires well understood systematic errors
  - Huber and Schwetz paper: http://arxiv.org/abs/hep-ph/0407026
  - a courageous first attempt – equates fission rate uncertainties with mass uncertainties
  - Must use MC to relate mass uncertainties to fission rate uncertainties
  - Must include effect of burnup in the analysis

Best benchmark of SONGS data so far – a 2-D deterministic simulation using the 'DRAGON' code



Chisq/d.o.f = 1.5 -2

We expect further improvements in data-MC agreement

The simulated data is sufficiently accurate for the present analysis