Big Picture: Case Study of Diversion and Limits of Antineutrino Safeguards Technology

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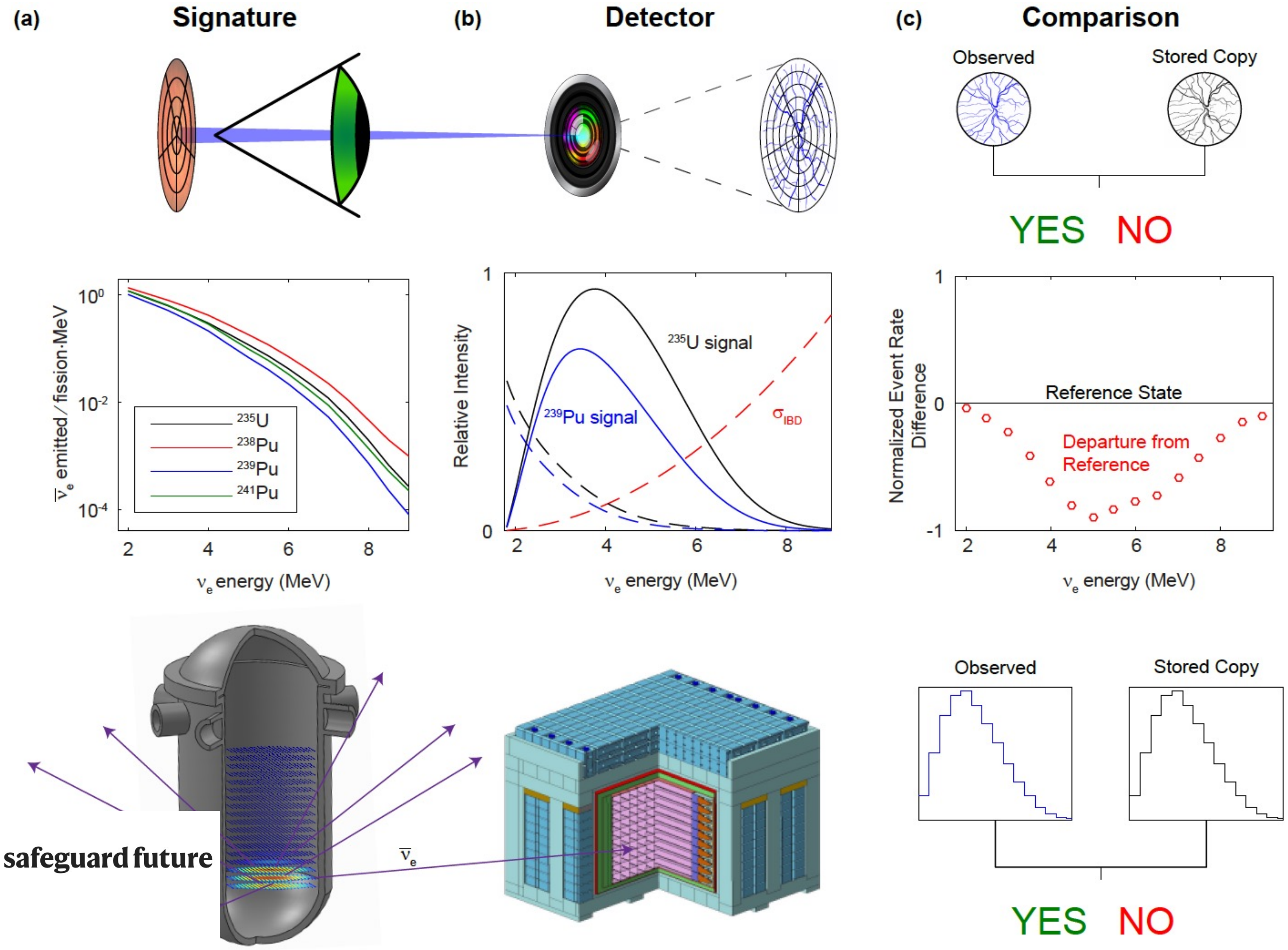
RETINA

Reactor Evaluation Through Inspection of Near-field Antineutrinos



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

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Employing antineutrino detectors to safeguard future nuclear reactors from diversions

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Comparison of reactor antineutrino sources

<table>
<tr><th>High-power core: UCFR-1000</th><th>Low-power core: AFR-100</th></tr>
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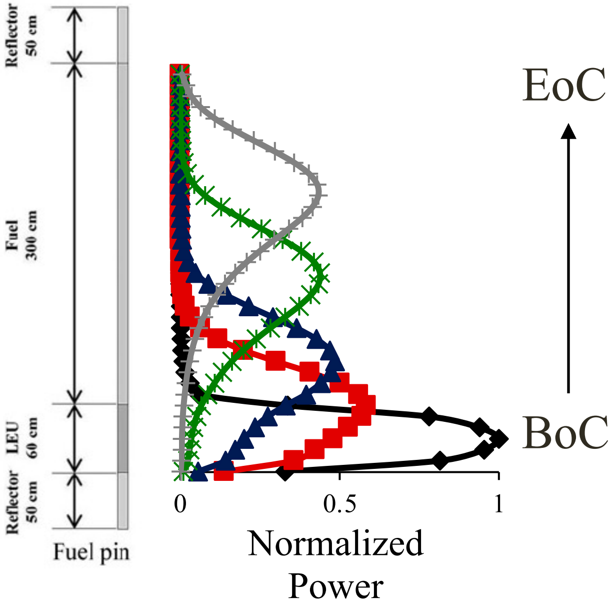

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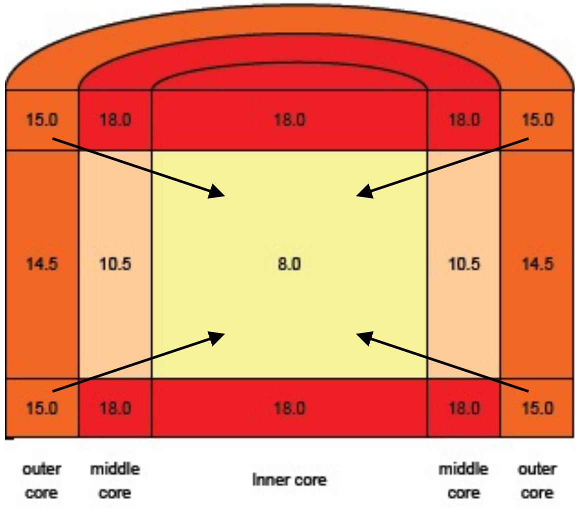

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<tr><td>3D source</td><td>Point source</td></tr>
<tr><td>Good counting statistics</td><td>Poor counting statistics</td></tr>
<tr><td>SQ ~ 0.1%</td><td>SQ ~ 1%</td></tr>
</table>

Diversions case studies were chosen to represent well-supplied, technologically adept actors

Goal	Criteria
Focus on removal of plutonium	• Higher weapon yield per unit mass • Antineutrino monitoring poorly suited to detecting LEU removal • Diverted uranium still requires enrichment
Plutonium amount and purity	• $\geq$ 1 SQ (8 kg) • $< 7\%$ ^{240}Pu • Few fission products
Remain covert	• Replacement assembly installed • Low change in fissile mass • Remove assemblies near core periphery
Early availability	• Central assembly
Test the limits of antineutrino safeguards technology	• No change in steel composition or volume • U-10Zr replacement fuel (natural or LEU) • Uranium enriched to nearest % of removed assembly fissile content (U + fissile Pu) • Remove as little total material as possible

A goodness of fit test is used to compare the reference and perturbed antineutrino signals

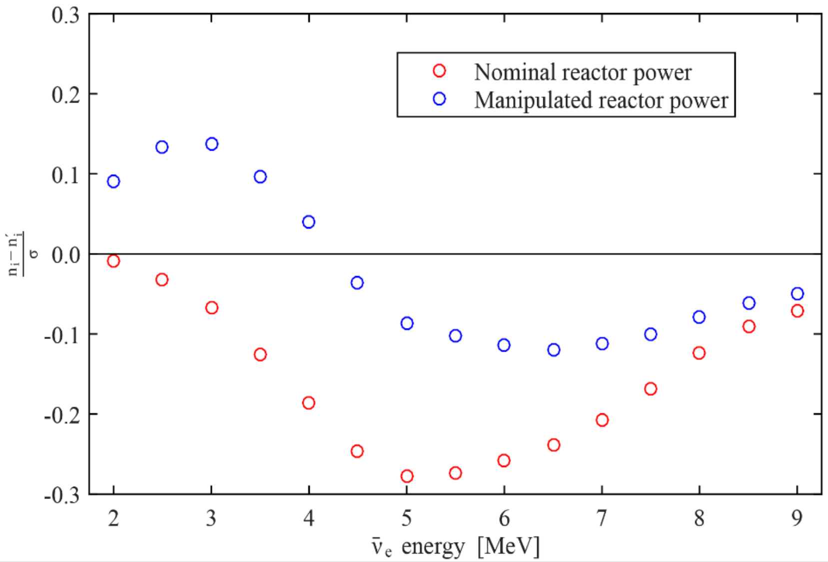
- Minimize a χ^2 statistic as a function of one free parameter, x:

$$\chi^2 = \left(\sum_i \frac{(n_i - (1+x)n_i')^2}{n_i}\right) + \left(\frac{x}{\sigma_{norm}}\right)^2$$

- x allows the operator to vary the reactor power to conceal a diversion as best as possible

- The “real” diverted case will vary about the expected value of $T_0 = \chi^2$ in a Gaussian:

$$T \sim N\left(T_0, 2\sqrt{T_0}\right)$$



The safeguards null hypothesis: no material has been lost or diverted

Type-I Error: False Positives

The IAEA concludes that a diversion has taken place when no material is missing, but depending on deployment logistics, reactor downtime, etc., can be quite costly

Type-II Error: False Negatives

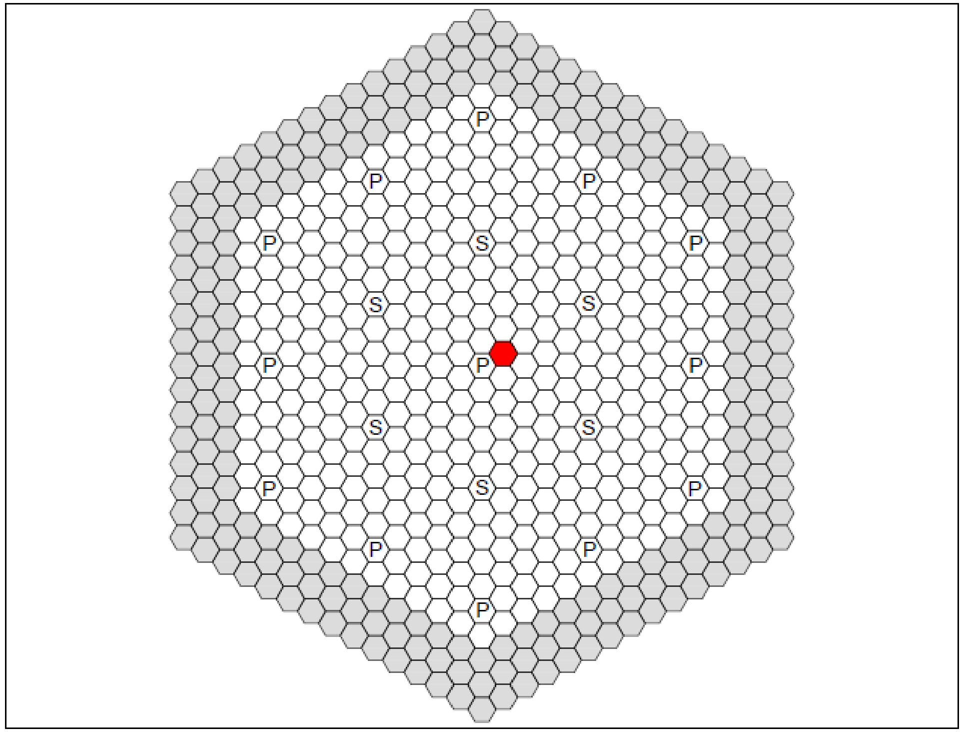
The IAEA concludes that all material is accounted for when some material has been diverted (non-detection probability)

Low Type-II error implies a strong safeguards method

UCFR Diversions 1a and 1b

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	

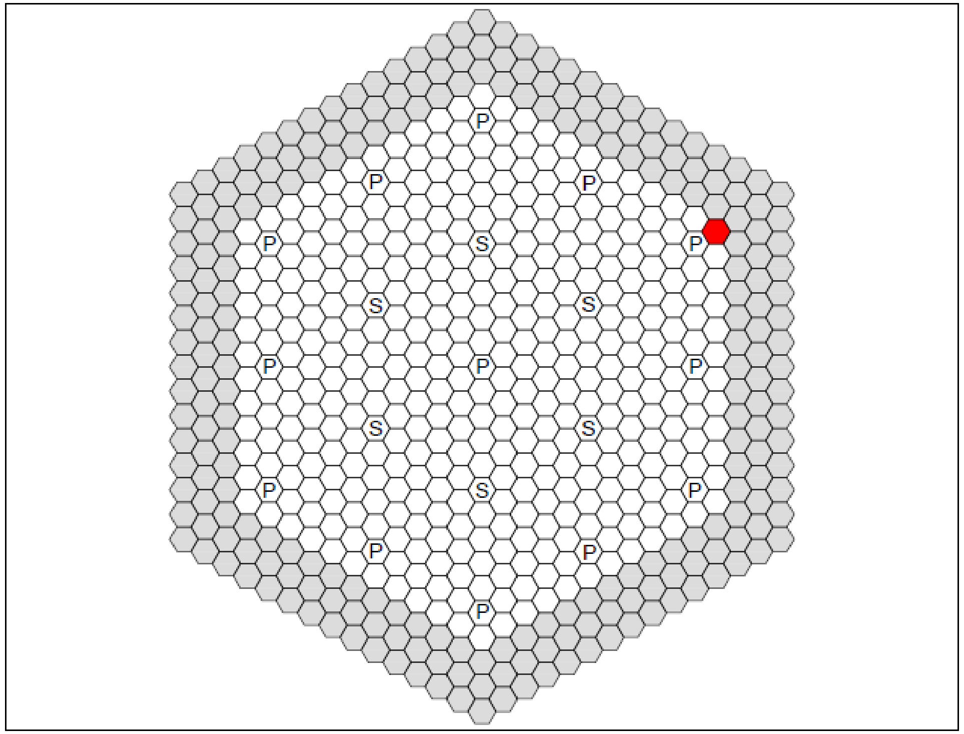


ID	Power Adjustment	1 month	2 months	3 months	3 months, no adjustment
1a	-1.031×10^{-3}	1.149×10^{-10}	4.276×10^{-6}	1.541×10^{-4}	0.255
1b	-1.469×10^{-3}	2.943×10^{-5}	3.257×10^{-3}	1.676×10^{-2}	0.523

UCFR Diversions 2a and 2b

Burnup	12.42 EFPY
Replacement fuel	(a) LEU (b) ^{Nat}U

Plutonium removed	**Mass (kg)**	**%**
^{238}Pu	1.82×10^{-2}	0.23
^{239}Pu	7.55	93.95
^{240}Pu	4.49×10^{-1}	5.59
^{241}Pu	1.77×10^{-2}	0.22
^{242}Pu	6.49×10^{-4}	0.01
Total	8.04	

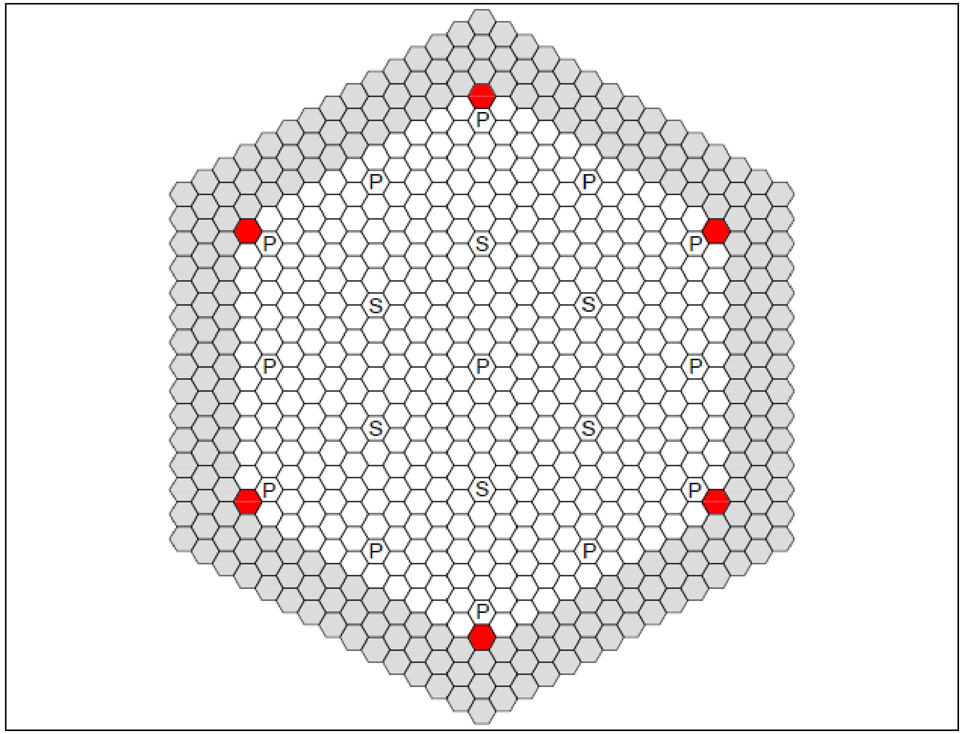


ID	Power Adjustment	1 month	2 months	3 months	3 months, no adjustment
2a	-7.031×10^{-5}	0	0	0	0
2b	7.813×10^{-5}	0	0	0	0

UCFR Diversions 3a and 3b

Burnup	12.42 EFPY
Replacement fuel	(a) LEU (b) ^{Nat}U

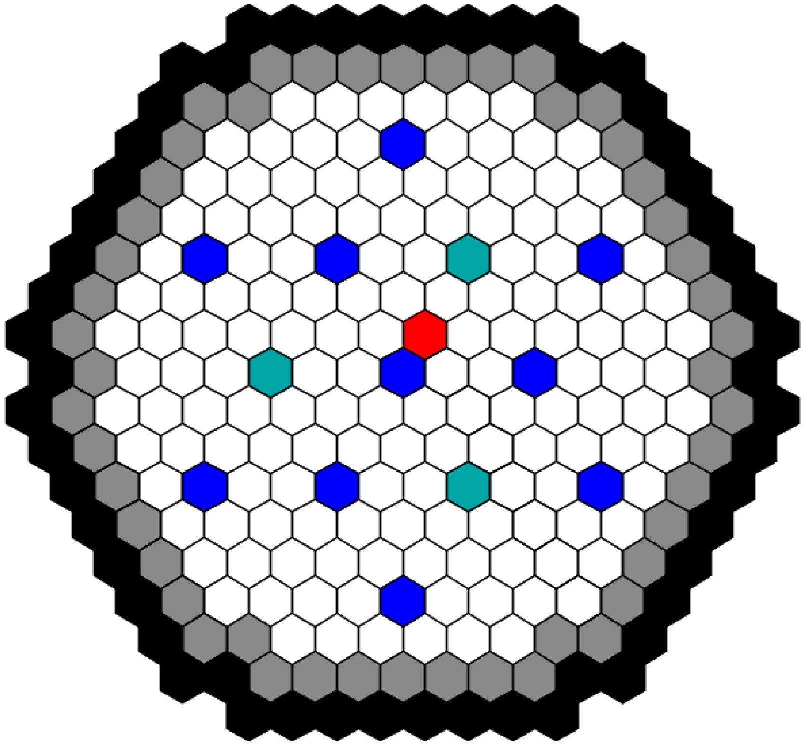
Plutonium removed	**Mass (kg)**	**%**
^{238}Pu	0.11	0.23
^{239}Pu	45.3	93.95
^{240}Pu	2.70	5.59
^{241}Pu	0.11	0.22
^{242}Pu	3.90×10^{-3}	0.01
Total	48.21	



ID	Power Adjustment	1 month	2 months	3 months	3 months, no adjustment
3a	-4.063×10^{-4}	0	0	0	2.154×10^{-4}
3b	4.531×10^{-4}	0	0	0	7.685×10^{-4}

AFR Diversions 1a and 1b

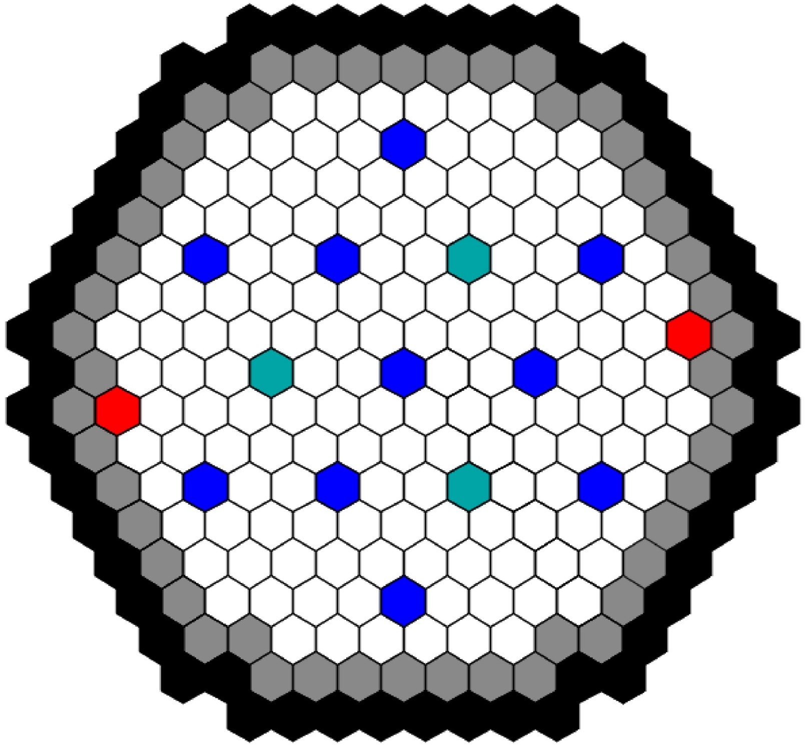
Burnup	15.75 EFPY	
Replacement fuel	(a) LEU (b) ^{Nat}U	
Plutonium removed	**Mass (kg)**	**%**
^{238}Pu	2.50×10^{-2}	0.31
^{239}Pu	7.56	93.93
^{240}Pu	4.47×10^{-1}	5.55
^{241}Pu	1.62×10^{-2}	0.20
^{242}Pu	6.12×10^{-4}	0.01
Total	8.05	



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}

AFR Diversions 2a and 2b

Burnup	21.25 EFPY	
Replacement fuel	(a) LEU (b) ^{Nat}U	
Plutonium removed	**Mass (kg)**	**%**
^{238}Pu	6.05×10^{-3}	0.15
^{239}Pu	3.91	97.00
^{240}Pu	1.13×10^{-1}	2.80
^{241}Pu	2.02×10^{-3}	0.05
^{242}Pu	3.78×10^{-5}	< 0.01
Total	4.03	

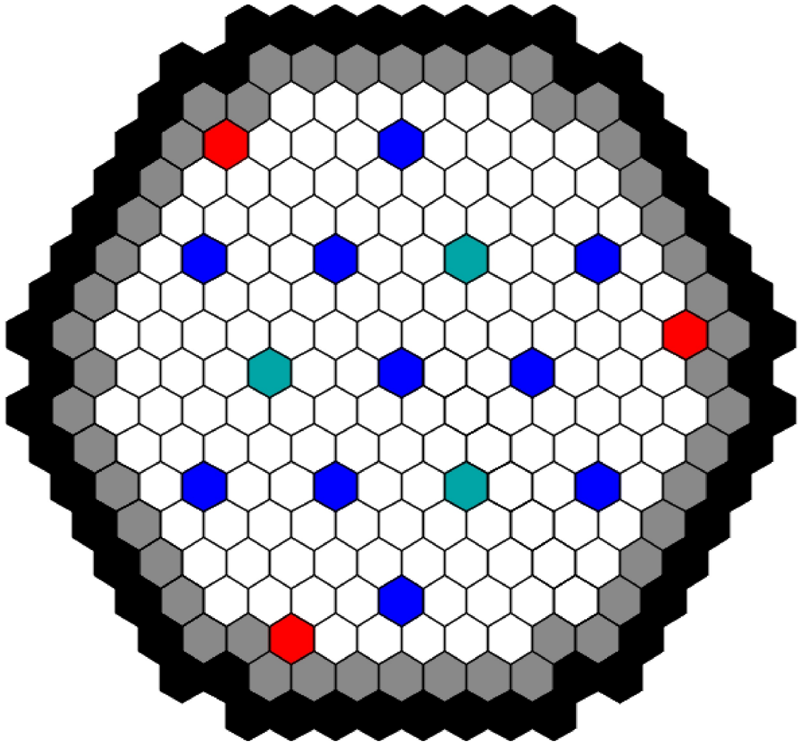


ID	Power Adjustment	1 month	2 months	3 months	3 months, no adjustment
2a	-5.313×10^{-4}	0	0	0	5.626×10^{-12}
2b	4.063×10^{-4}	0	0	0	0

AFR Diversions 3a and 3b

Burnup	13.25 EFPY
Replacement fuel	(a) LEU (b) ^{Nat}U

Plutonium removed	**Mass (kg)**	**%**
^{238}Pu	2.19×10^{-3}	0.08
^{239}Pu	2.62	98.15
^{240}Pu	4.68×10^{-2}	1.75
^{241}Pu	5.79×10^{-4}	0.02
^{242}Pu	6.84×10^{-6}	< 0.01
Total	2.67	



ID	Power Adjustment	1 month	2 months	3 months	3 months, no adjustment
3a	-5.000×10^{-4}	0	0	0	4.687×10^{-12}
3b	3.750×10^{-4}	0	0	0	0

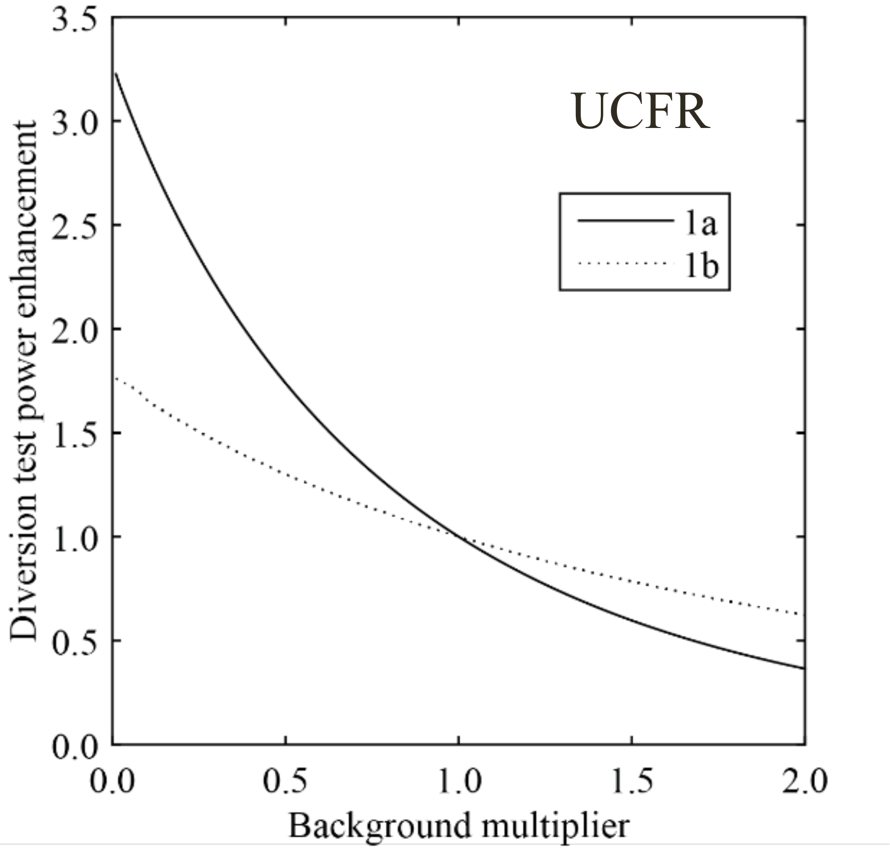
Test parameter variation directs antineutrino safeguards implementation and improvement

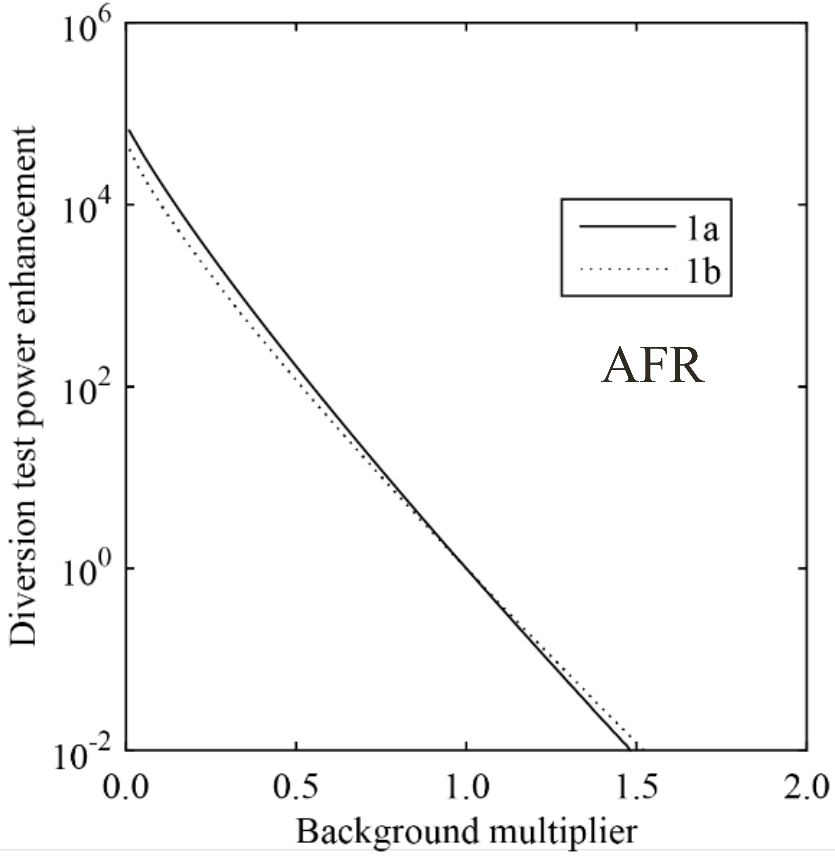
$$\chi^2 = \left(\sum_i \frac{(n_i - (1+x)n_i')^2}{n_i}\right) + \left(\frac{x}{\sigma_{norm}}\right)^2$$

Test parameter	Parameter's influence on safeguards test
IBD-like background	Increases/decreases n_i and n_i', but not their difference
Detector suite fiducial mass	Number of target protons for IBD reaction
Detector intrinsic efficiency	Number of IBD and IBD-like events which are tallied
Reactor-detector standoff	Geometric attenuation of the reactor antineutrino source
Manipulation of reactor power	Minimization of the difference between each n_i and n_i'
Required true negative rate	Lower integration limit of Gaussian centered at χ^2
σ_{norm}	Uncertainty on the detector event rates which allows for count difference minimization

Background reduction is vital for monitoring small reactors, helpful for large reactors

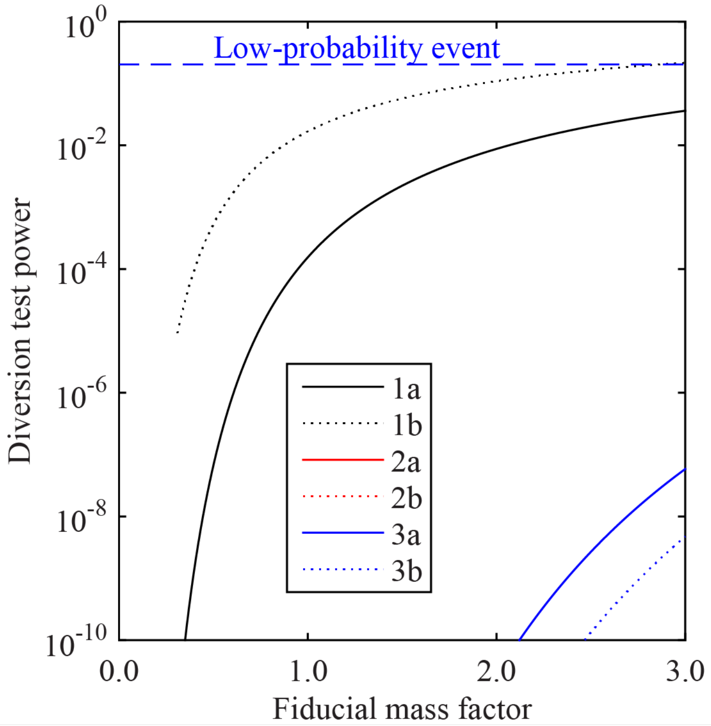
Metric	UCFR-1a/b	AFR-1a/b
Signal:Background	~ 8:1	~ 1.5:1
	$\boldsymbol{O}(10^{-3})$	$\boldsymbol{O}(10^{-3})$
	$0.9 \times \boldsymbol{O}(10^{-3})$	$0.6 \times \boldsymbol{O}(10^{-3})$
	$\boldsymbol{O}(10^{-1})$	$\boldsymbol{O}(10^{-2})$





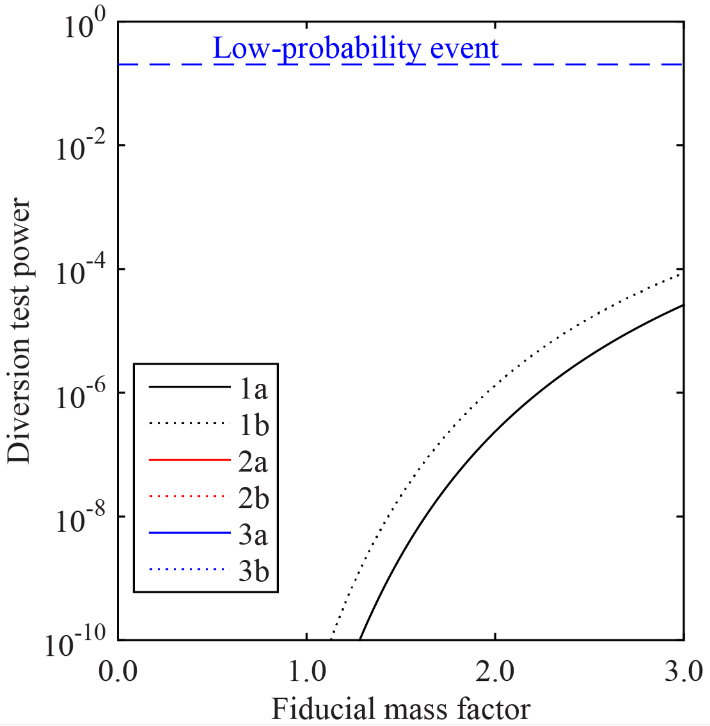
Increasing total fiducial mass is useful for tipping on-the-bubble detection probabilities

UCFR



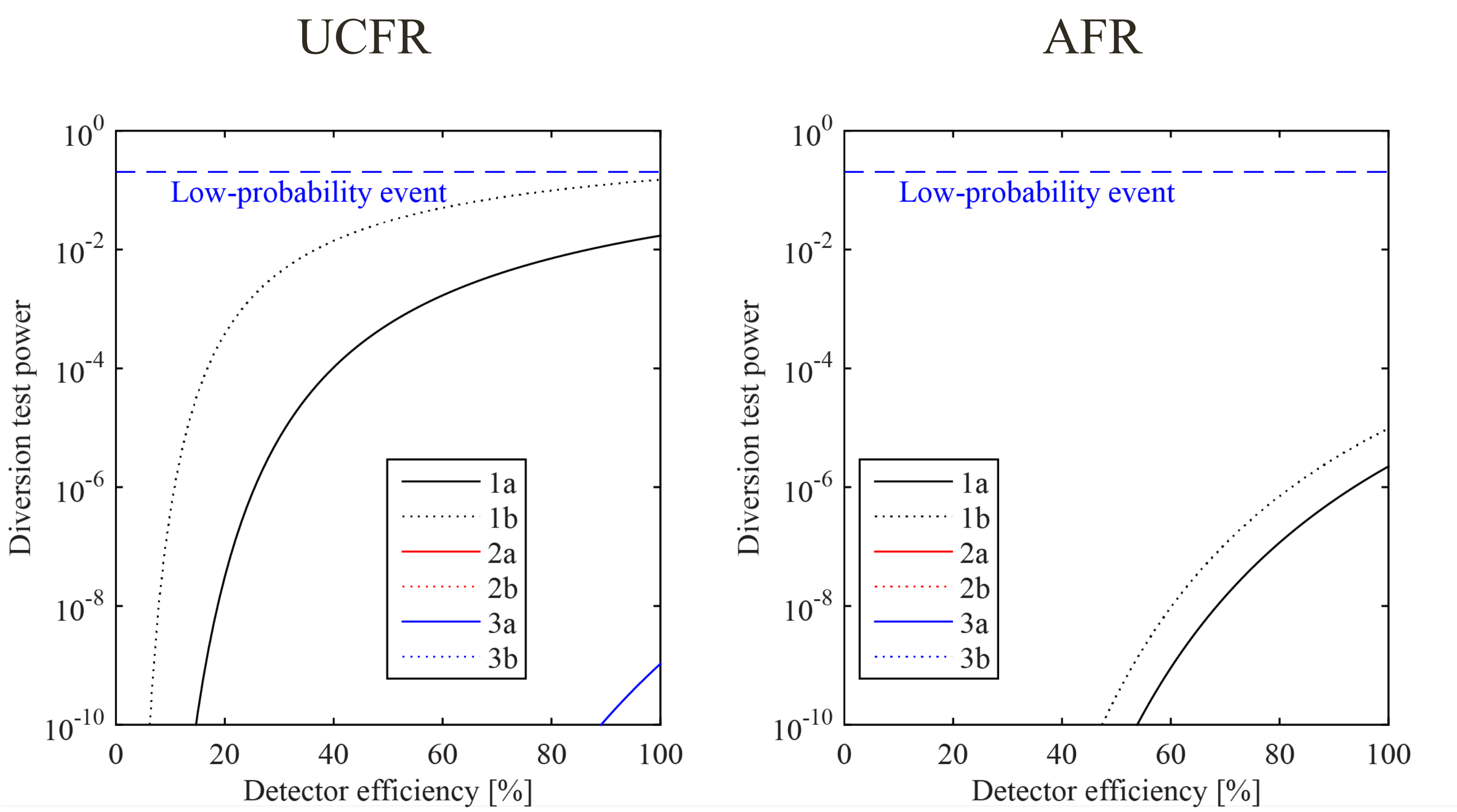
- Unless a particular diversion mode is near minimum detection thresholds, increasing fiducial mass does not matter.
- If a diversion mode has < 99% non-detection probability, add more detectors!
- Throwing $ at problem

AFR

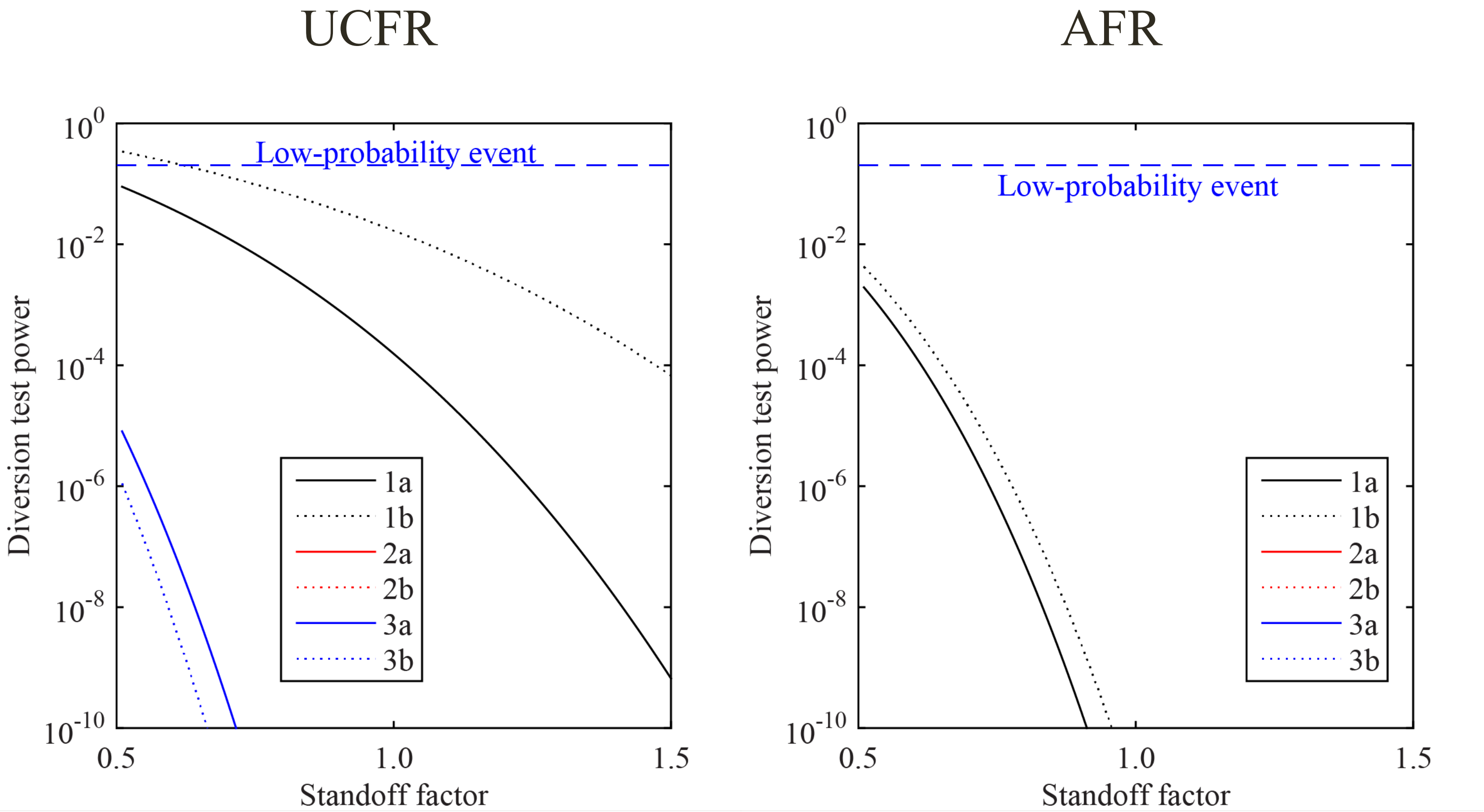


Detector efficiency increases have a low ceiling for safeguards improvement

- Linearly increase counting statistics
- Efficiency affects both signal and IBD-like background
- Ton-scale detectors are about as efficient for IBD as they ever will be.



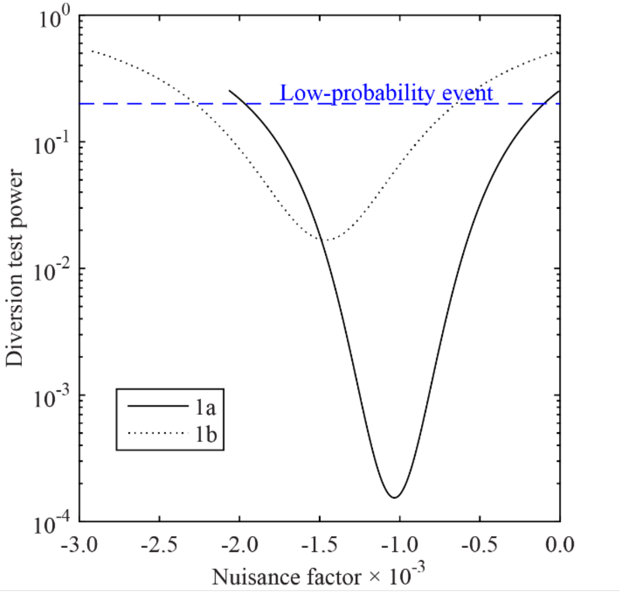
Reactor-detector standoff strongly affects count rate statistics and alters Signal:Background



- $^1/_{r^2}$ geometric attenuation of S
- Standoff changes signal but does not alter background
- Reassess containment building design if antineutrino safeguards are adopted

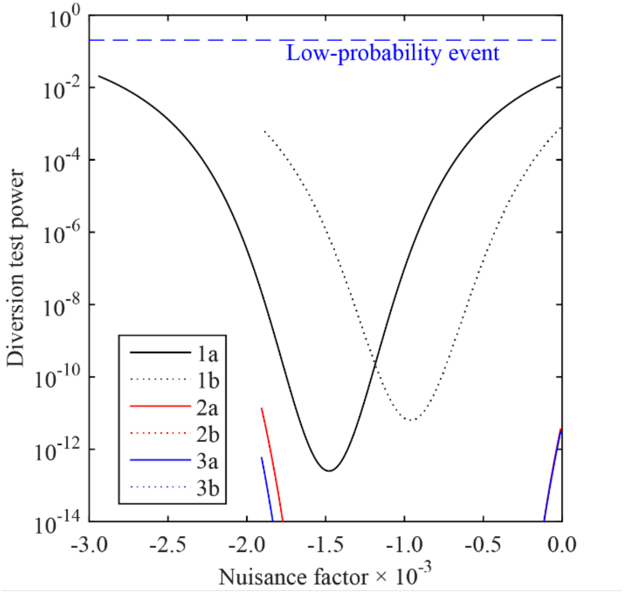
Improper signal manipulation greatly increases detection probability

UCFR

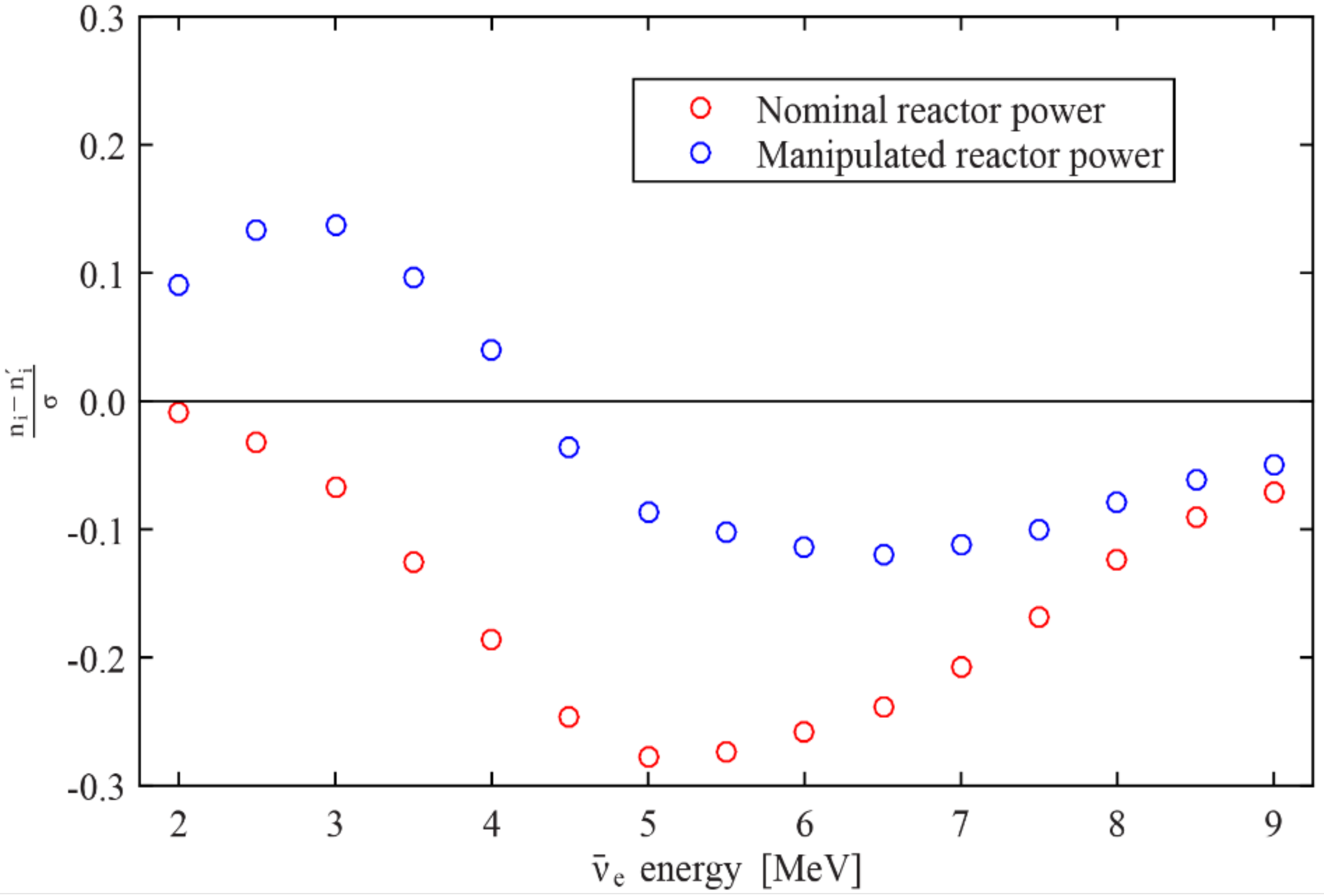


- Operator non-involvement causes UCFR core-center diversions of one SQ to be visible to present-day devices with no other changes.
- Operator non-involvement causes AFR core-center diversions of one SQ to enter “realm of possibility”
- Inflection points where reference and perturbed spectra separate
- Overcompensation is worse than inaction

AFR

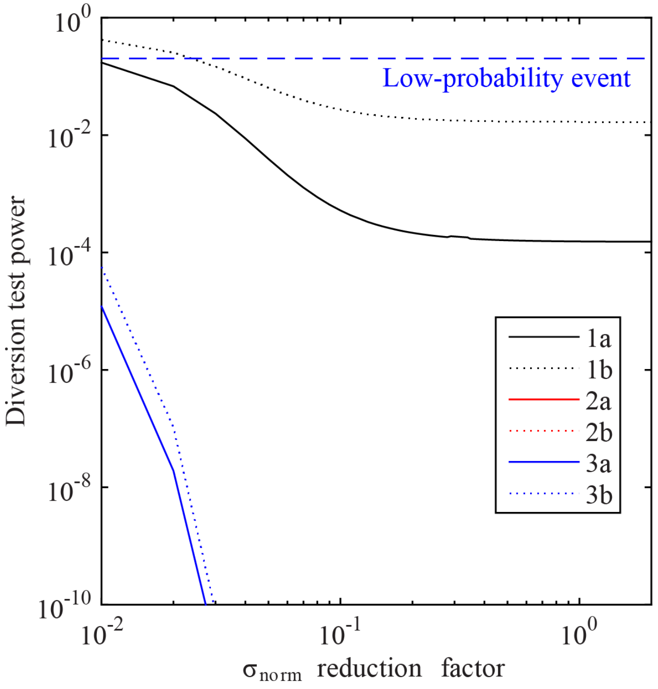


Signal manipulation illustration

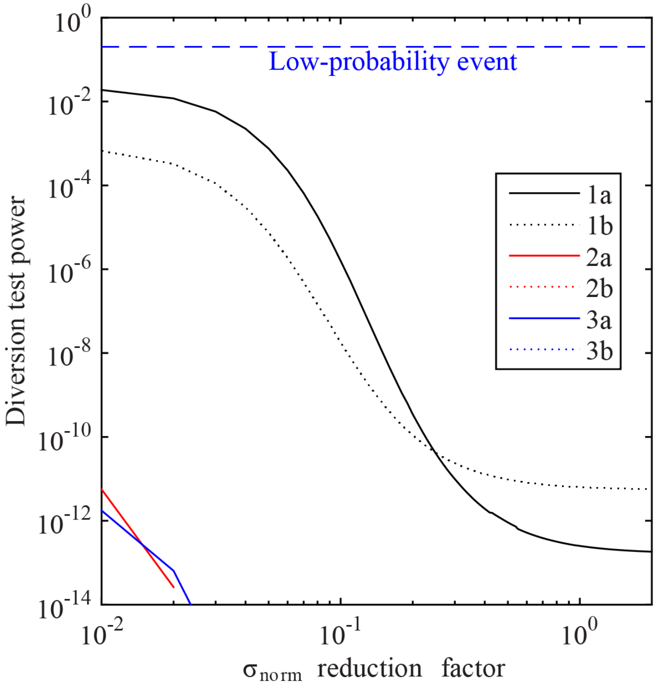


Uncertainty reduction increases penalty for ideal signal manipulation and increases its difficulty

UCFR



AFR



- Elastic region of large improvement
- At low σ_{norm} , the ideal operator manipulation changes
- Antineutrino yield uncertainty is ~ of σ_{norm}
- Improvements in ^{235}U spectrum and IBD cross section expected with PROSPECT and SOLI∂

Conclusions

1. Continuous safeguards employing current-generation antineutrino detectors cannot protect against all ideally concealed diversions from high-burnup fast reactors at the 1-SQ level within IAEA-defined weapon conversion times.

2. Antineutrino-based safeguards tend to work best against diversions from high-importance regions in the core.

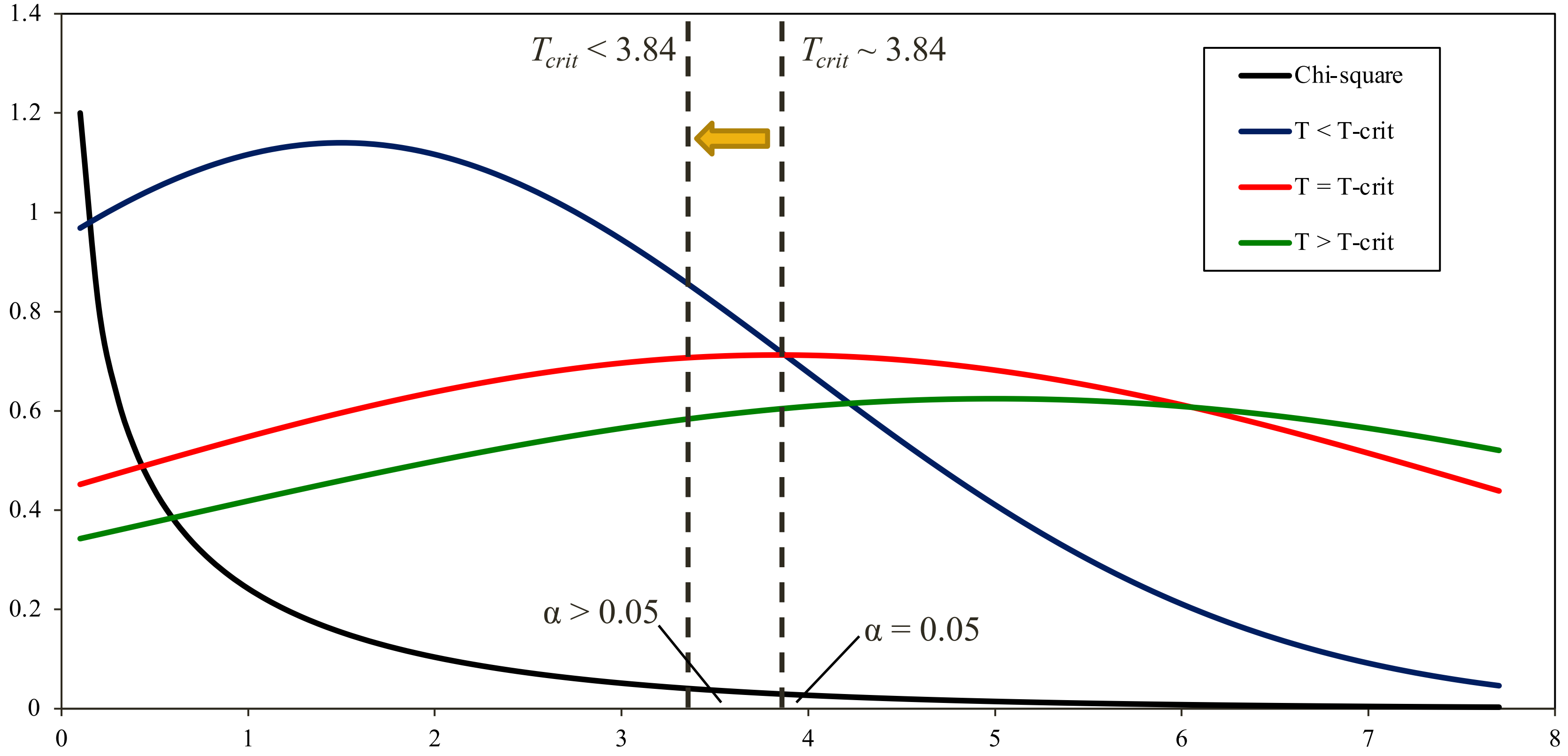
3. One of the most impactful factors influencing detection probability for 1-SQ diversions is the manipulation of the reactor state by the operator to minimize the change in signal.

4. Improvements in signal-to-background ratio are required for safeguarding low-power fast reactors.

5. If a useful reactor monitoring niche is carved out for which a higher than 5% rate of false alarms is acceptable, antineutrino detectors can fill it, particularly for high-power reactors.

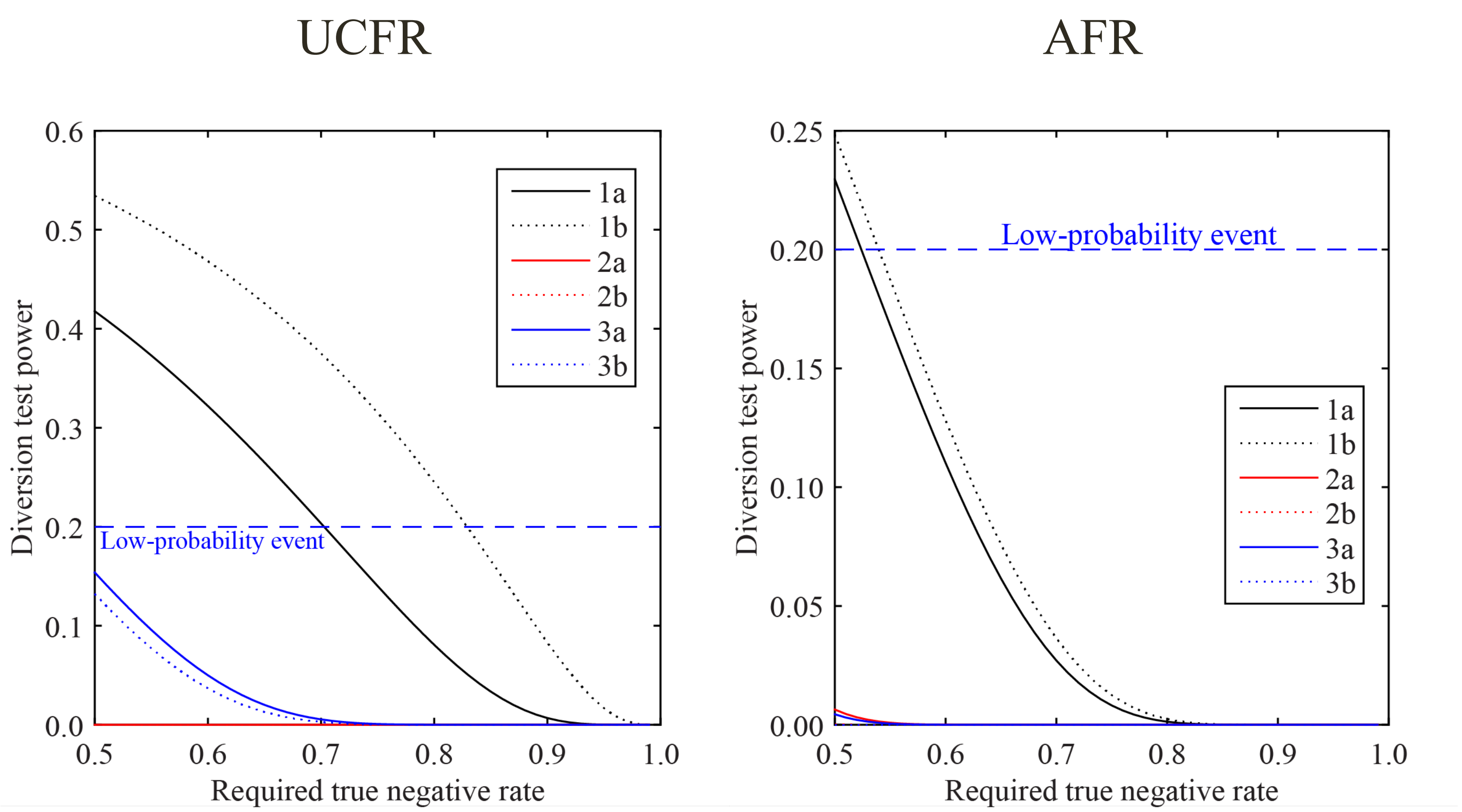
Thank you!

Relaxing the 95% true negative rate requirement

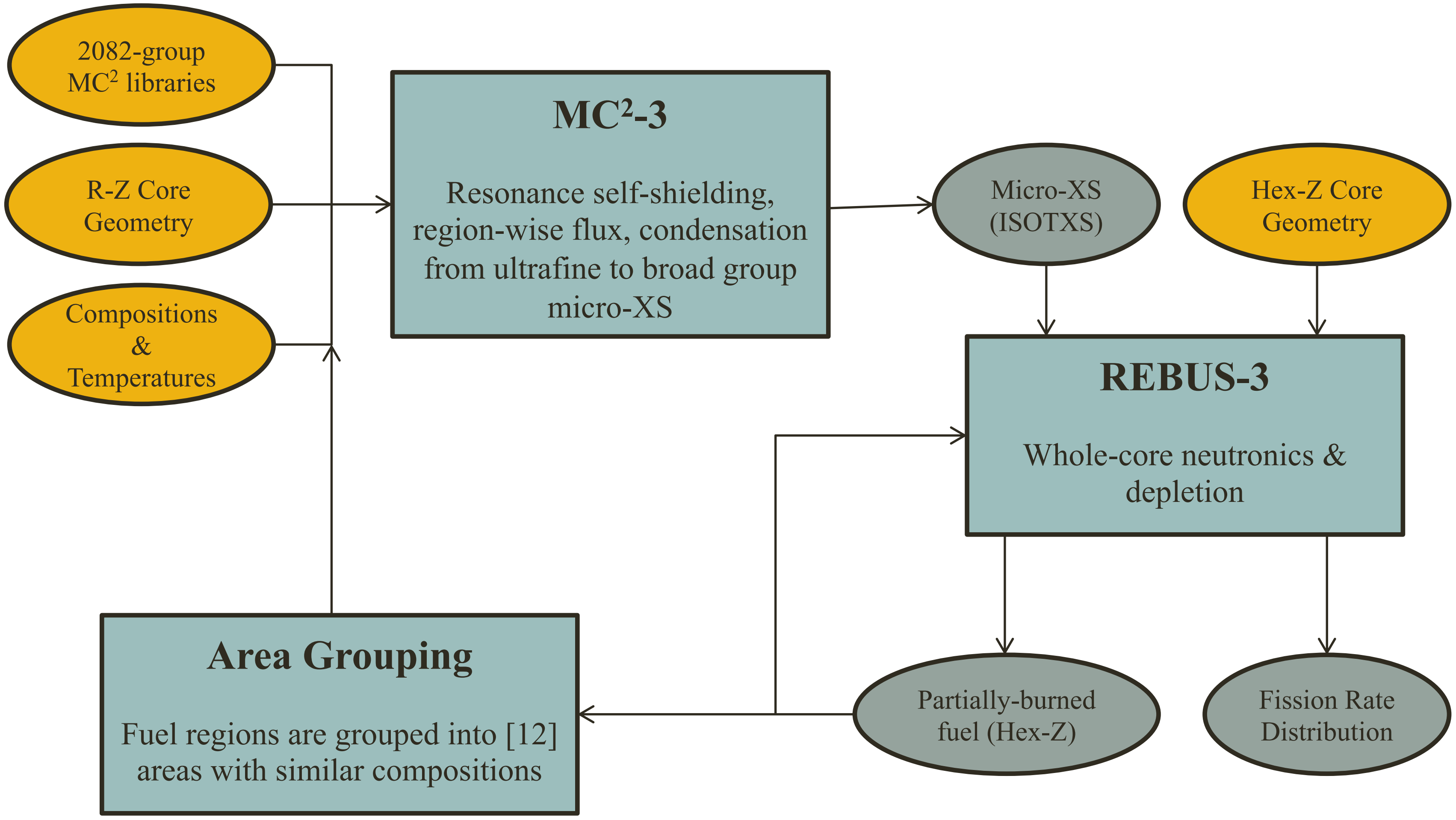


Relaxing the required true negative rate sacrifices specificity for large sensitivity improvements

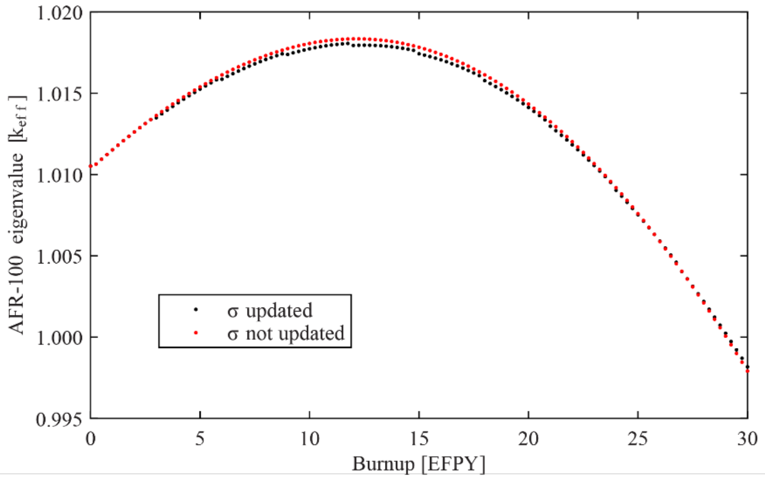
- Shifts location of T_{crit}
- If T_0 is near T_{crit}, shifting T_{crit} to the left integrates the meat of the distribution.
- If continuous-data safeguards have different false positive criteria, detection probability is dramatically improved

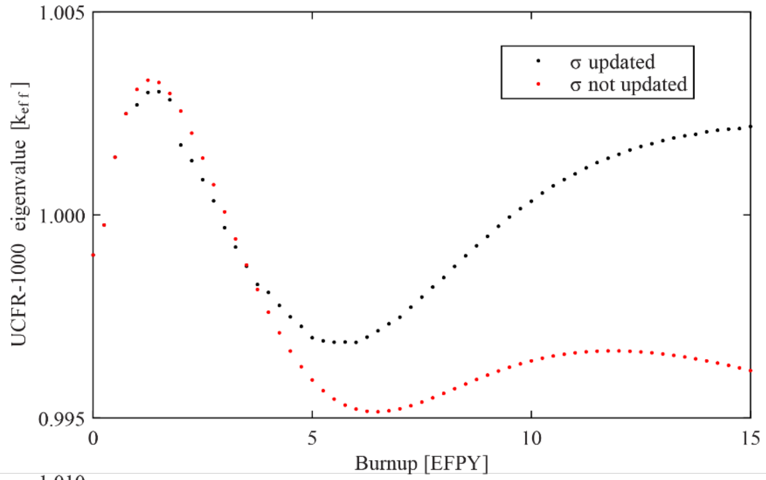


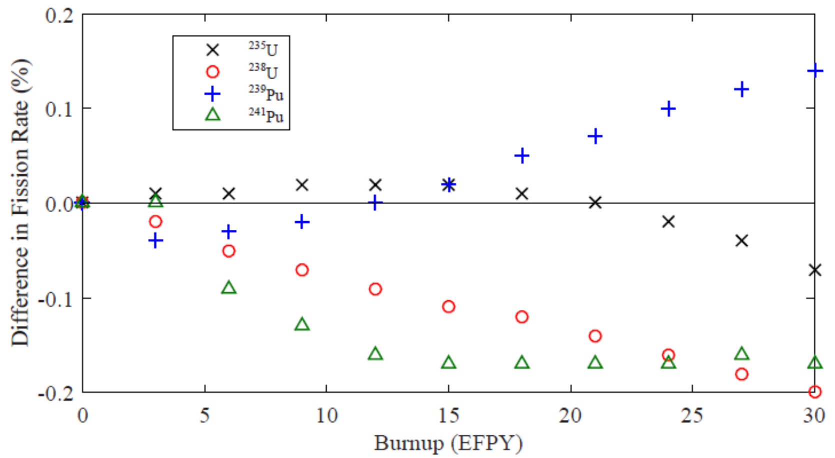
Fuel Cross Section Update Scheme

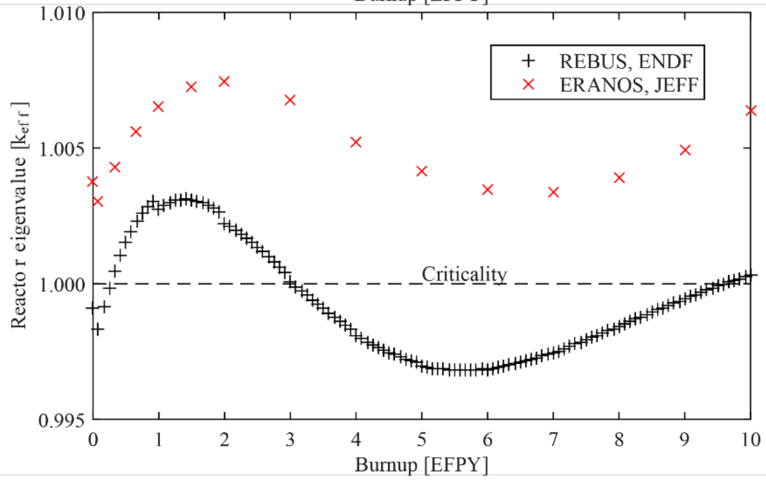


Effects of XS updates









Convergence of Monte Carlo fuel cycle histories