Modeling of High-Burnup Reactors for Antineutrino Safeguards

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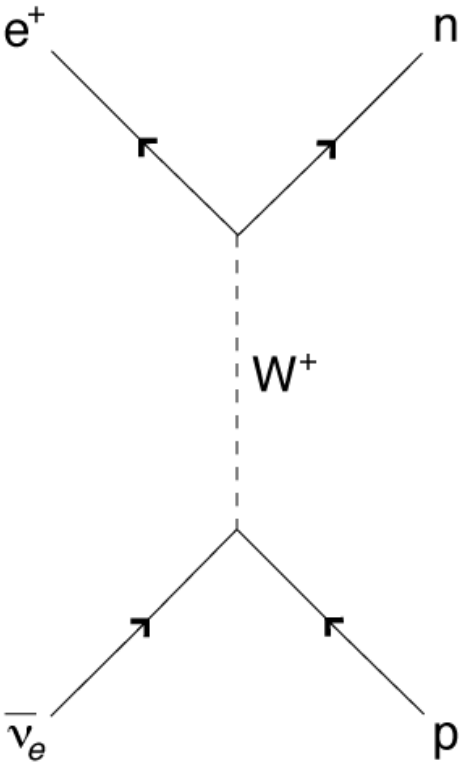


NNSA SSGF Annual Meeting
Washington D.C.
July 1 2015

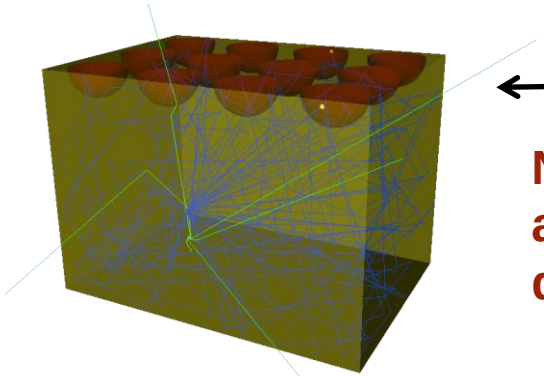
LANNS:
Nuclear Non-proliferation and Safety

Non-proliferation and nuclear defense in the post-Cold War era were presented with new problems

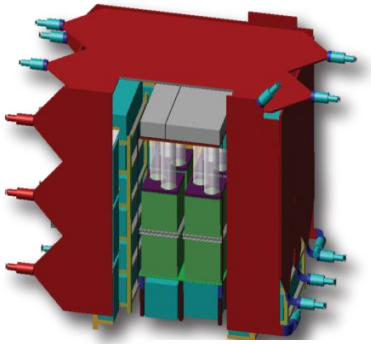
- Terrorist groups and sub-national actors are seeking nuclear materials and weapons instead of national weaponization
- Building nuclear weapons is no longer a daunting problem because of widespread of nuclear technologies and expertise

Small but widespread groups

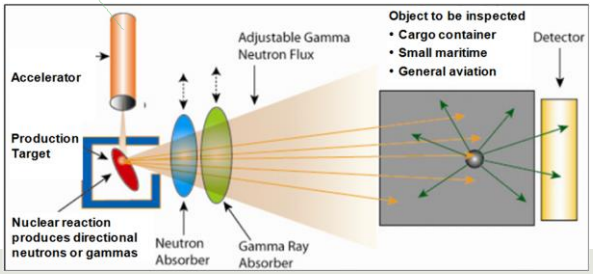
Unique challenge: interdisciplinary science of detection methods, reactor physics, fuel cycle and policy.



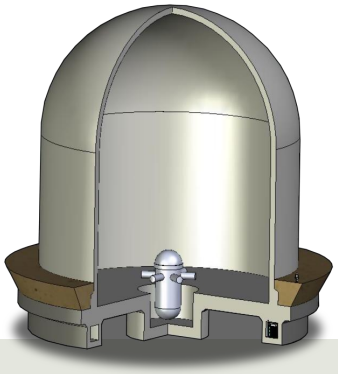
New detector and materials development



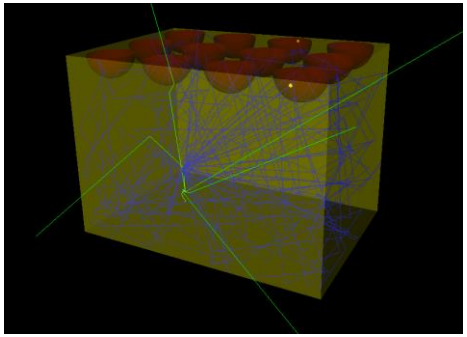
Reactor and fuel cycle challenge: monitor and verify



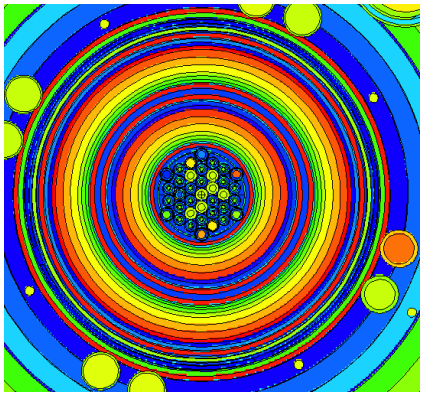
En route material interception and identification



LANNS Research and Capabilities: Computational Work



- Nuclear nonproliferation: radiation detection (modeling and simulation) and advanced reactor analysis (fuel design, fuel cycle, neutrino monitoring)
- Modeling and simulations of source-detector interactions and detector optimization using Geant4/ROOT and MCNP6
- Current work: Cherenkov detectors, neutron detectors, aerogel detectors, active interrogation, spent fuel signatures, proton computed tomography for medical applications



- Reactor analysis using MCNP6/REBUS3/SERPENT/ERANOS/COMSOLE/BISON

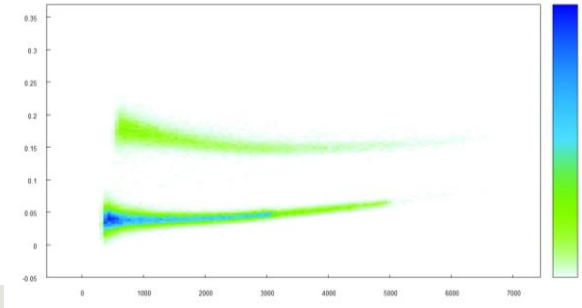
Current work: Fuel selection framework (composite fuels for high-burnup reactors), antineutrino monitoring of long-lived cores (UCFR-1000), HFIR reactor modeling for neutrino studies

LANNS Research and Capabilities: Experimental Work

- Digital laboratory (CAEN hardware/software)

  Current work: coincidence algorithms, DPP-CI/DPP-PSD

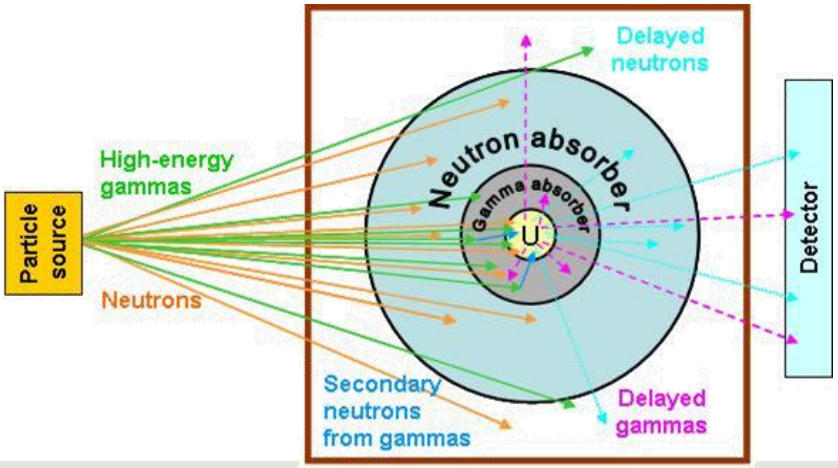
- Perchloric hood
- Detectors for a variety of applications: PIPS, scintillators, CZT
- High intensity sources: 50 Ci AmBe, Cf-252, 5 Ci PuBe, 6 MeV/18 MeV Varian Bremsstrahlung Clinac
- High intensity x-ray source for imaging applications
- Novel detector development and characterization: stilbene (fast neutrons), aerogel, large-scale Cherenkov



NSF-DNDO Center: Low-Dose Inspection for Nuclear Threats Using Monochromatic Gamma-Rays

- Collaborative research:
- The grand challenge of detection of shielded special nuclear material:
  - Active interrogation is required
  - BUT these approaches often require large accelerators and also produce very high doses
- A new approach to the detection of SNM based on a low dose method for rapidly imaging of shielded material

Production of monoenergetic gammas through nuclear reactions such as 3 MeV d on B-11.



Outline

- Nuclear energy expansion and the necessity of monitoring
- Antineutrino reactor monitoring and safeguards
- Antineutrino spectrum
- Uncertainty calculations
- Conclusions

Nuclear Energy Expansion

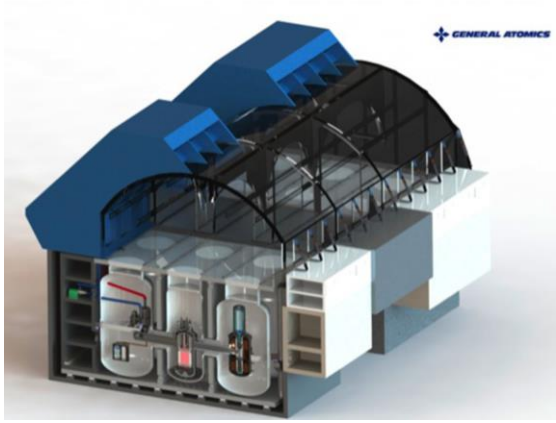
- Over 45 countries, both developing and sophisticated economies, are considering (or actively pursuing) nuclear capabilities
  - Industrialization of developing countries demands increases in energy production
  - Recognition that global greenhouse gas output should not increase proportionally
- 60 new reactors are under construction in 13 countries, with 160 total planned constructions

Country	# of Reactors	Design	Est. Completion
UAE	4	APR1400	2020
Vietnam	2	VVER-1000	2021-2024
Jordan	1	N/A	2020

New Constructions: Gen. III+ and IV Designs

- Current constructions are Gen. III+ designs (AP1000, ABWR, etc.)
  - Safe
  - Reliable
  - High capacity factor
- Gen. IV designs have features which are attractive for foreign installations
  - Emphasis on modular construction
  - Fast neutron spectrum allows for deep burnup of fuel
  - Long-life designs advertise no need to open reactor vessel
- Current DOE strategy emphasizes the importance of Gen. IV reactors in the future developments

http://www.atomicheritage.org



General Atomics EM2 reactor concept

Treaty on the Non-Proliferation of Nuclear Weapons

Non-Proliferation

- Recognizes Nuclear Weapons States
- Bans transfer of weapons and production capability
- Non-NWS subject to IAEA safeguards

Disarmament

- NWS should seek to reduce their weapons stockpiles and ultimately disarm

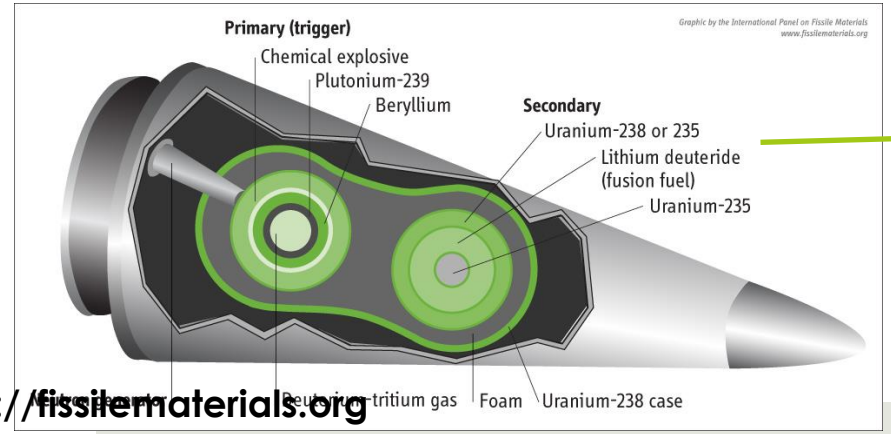
Peaceful Use

- Nations have the right to pursue nuclear power for peaceful purposes

- Non-signatories: India, Pakistan, Israel, South Sudan
- DPRK has withdrawn
- **Monitoring is an important element in each part**

Disarmament: PMDA Between US & Russia

- Plutonium Management and Disposition Agreement:
  - Dispose of 34 tons of weapons-grade plutonium
  - Blend as MOX fuel and irradiate in reactors
  - US – Thermal (planned)
  - Russia – Fast (BN-600, BN-800)
- Verification is necessary, but access to the plant or to operations data may be unavailable



http://fissilematerials.org

The Success of the NPT Relies on Safeguards and Monitoring

- Every signatory declares their nuclear facilities' capacity and operations as well as material flows, stockpiles, etc. to the IAEA
  - Verification of the correctness of each country's declared materials & facilities
  - Verification of the completeness of the scope of declaration
- Properties of ideal safeguards data:
  - Real-time
  - 100% reliable – tamper and spoof proof

Why Fast Reactors? And How to Monitor Them…

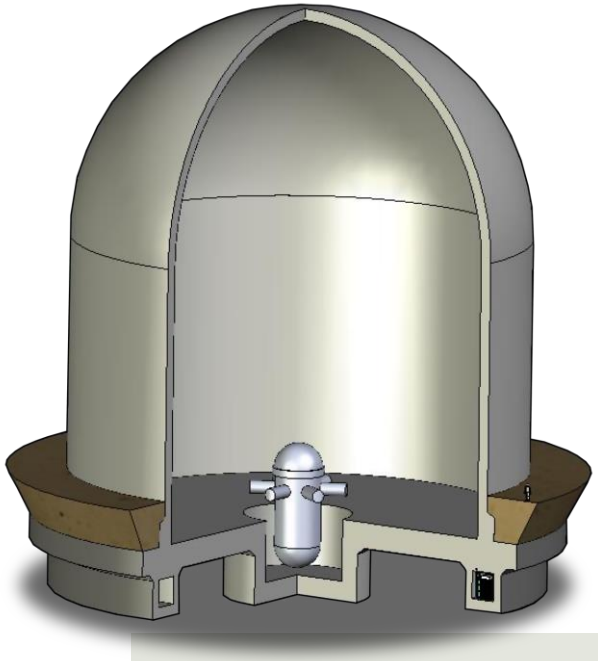
- Fast reactors with long cycle are gaining popularity
  - Relatively benign initial fuel
  - very long interval between refueling
  - small plant footprint and power rating
- Long-life cores are possible with fast reactor physics
  - Attractive to utilities for economic/financing reasons
  - Offer attractive refueling logistics for installation abroad
- Reactors unavoidably generate TRU, making them targets for diversion of nuclear material
  - ^{239}Pu – nuclear device deliverable by missile
  - TRU isotopes have high radiotoxicity – radiological threat
- Real-time monitoring with transparent, spoof-resistant technology is essential to safeguarding the nuclear material in foreign installations
- Nonproliferation-by-design is an essential consideration

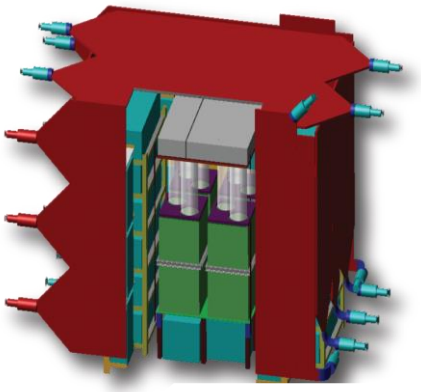
Metrics

- We are interested in three things:
- Uncertainty from reactor core (source) and antineutrino yields (this talk)
- Diversion scenarios and associated errors
- Error reduction through observation approach

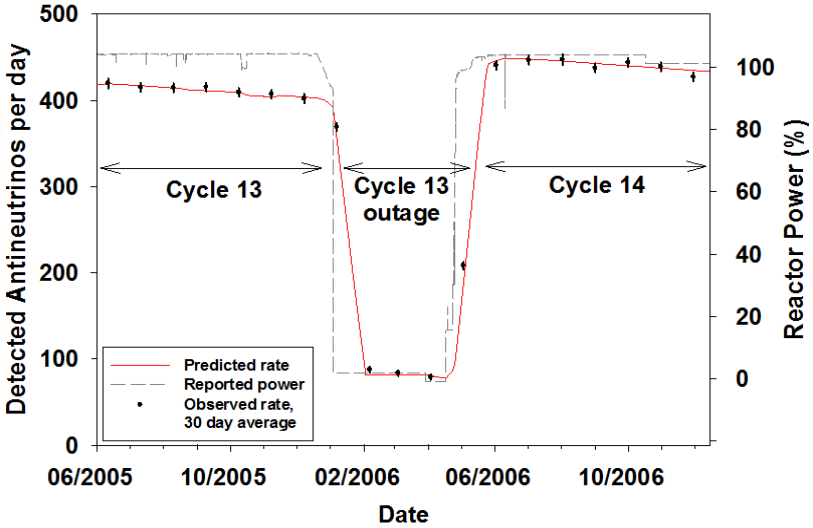
Remote Reactor Monitoring with Antineutrinos - Demonstration

- Antineutrino Reactor Monitoring (ARM, A. Bernstein, LLNL) has shown to provide independent measurement of reactor power and fissile inventory (SONGS1 detector)
- The detector had NO connections to any of the plant systems (tamper-resistant and outside of containment)





From A. Bernstein

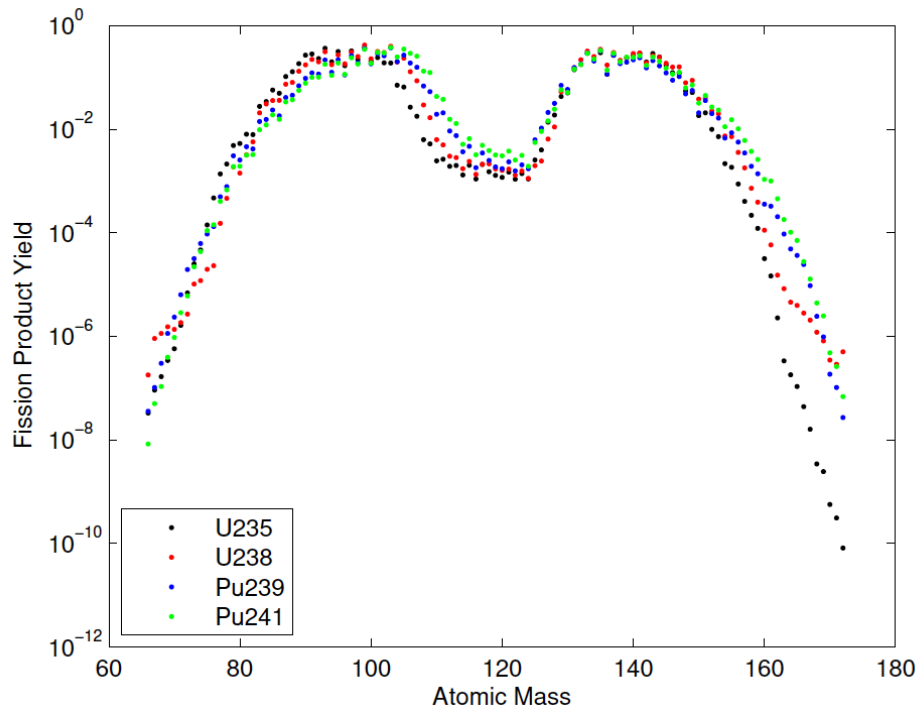


Relating Antineutrino Rate to Reactor Parameters

- Rate = Power*(1+k(t))
- To measure power, assume k(t) is constant (true for ~1 month periods)
- To measure k(t), integrate the known power into the analysis

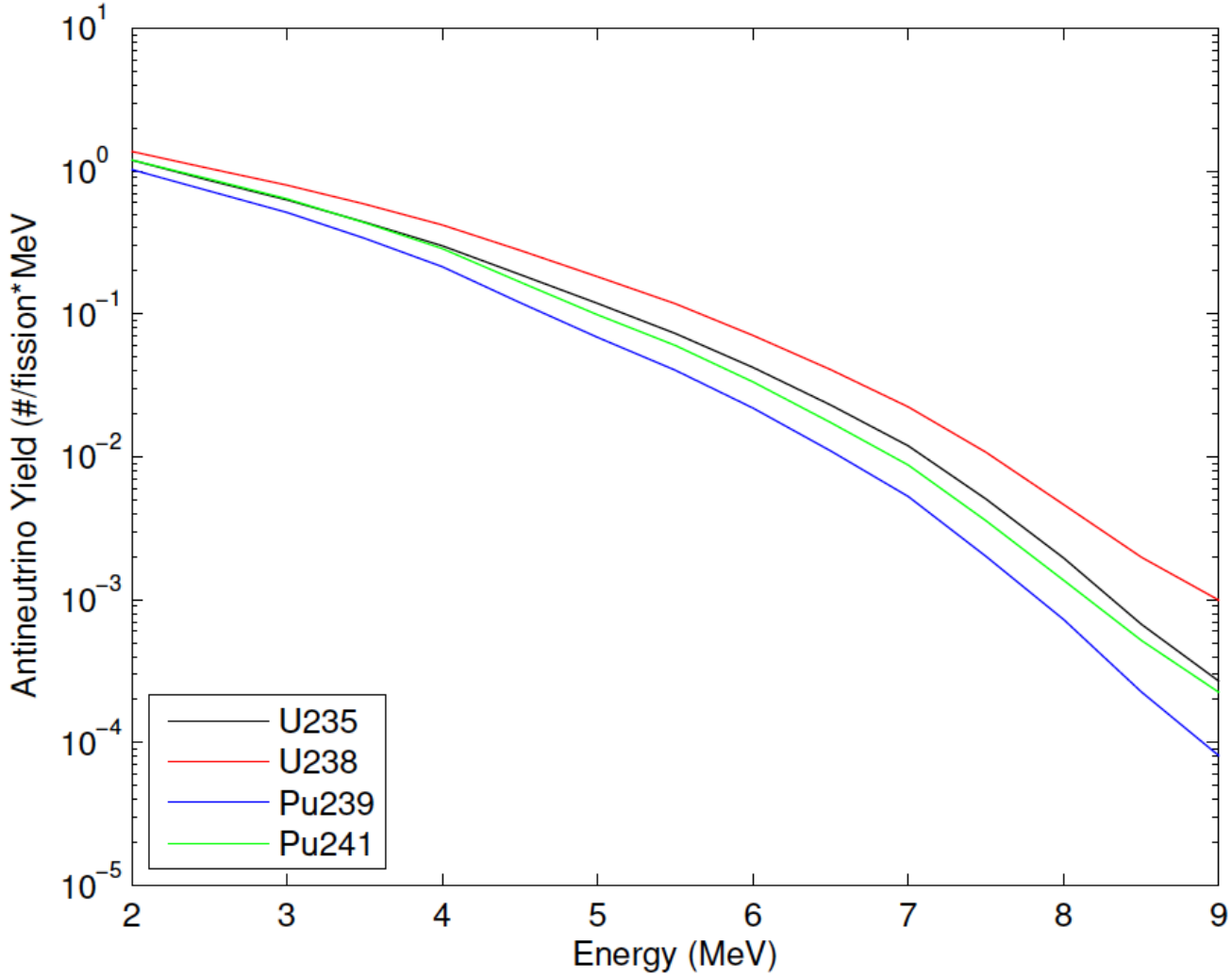
Reactor Antineutrinos

- Reactors are a great source of antineutrinos
- $\bar{n}_e$ are not stopped by the reactor structures unlike other forms of radiation
- $\bar{n}_e$ are unique fission signatures (~6 per fission)
  - Which nuclides undergo fission?
  - Reactor spectrum (neutron energy)?
  - Reactor power?



$$\frac{2800 MW_{th}}{200 MeV} \times 6 \frac{\bar{n}_e}{fission} \approx 5 \times 10^{20} \frac{\bar{n}_e}{\sec}$$

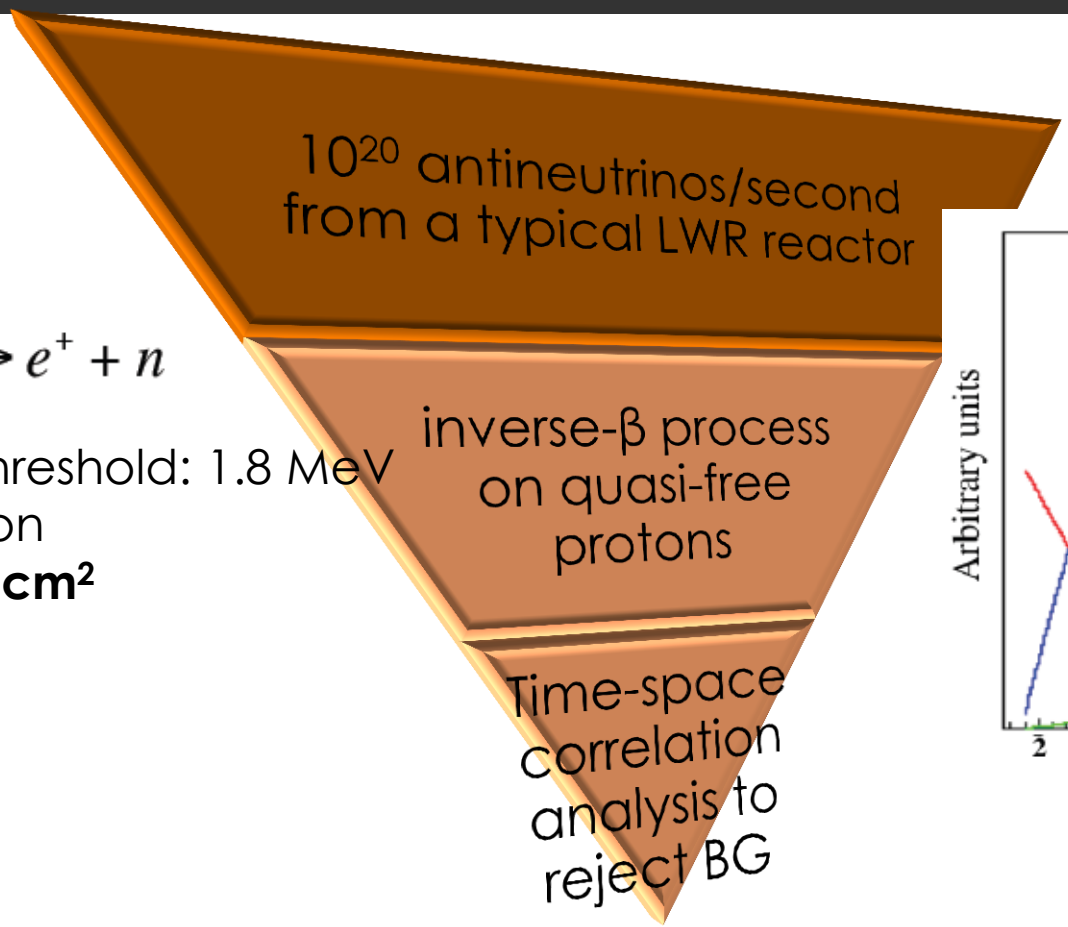
Antineutrino Spectrum

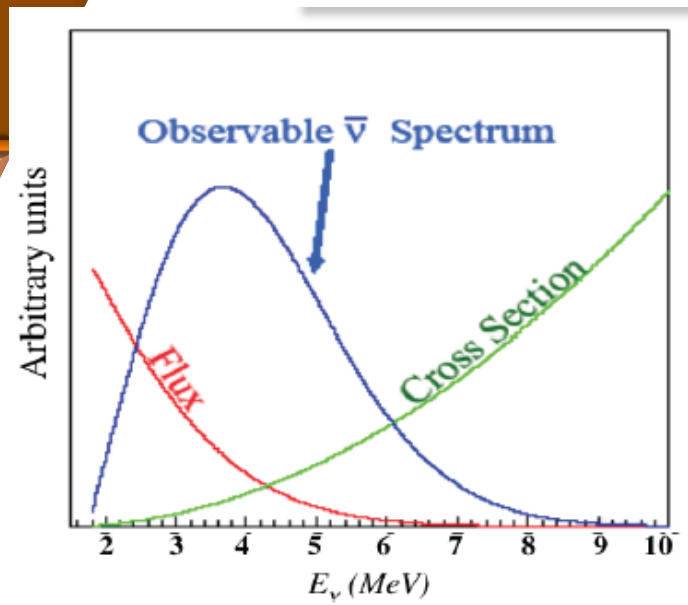


Detecting the Signal

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

Reaction threshold: 1.8 MeV
Cross section
<σ> ~ 10^{-43} cm^2

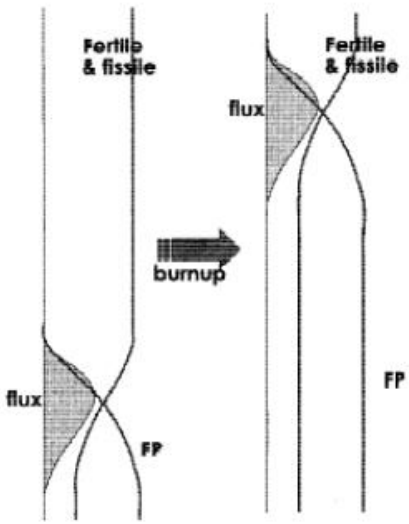




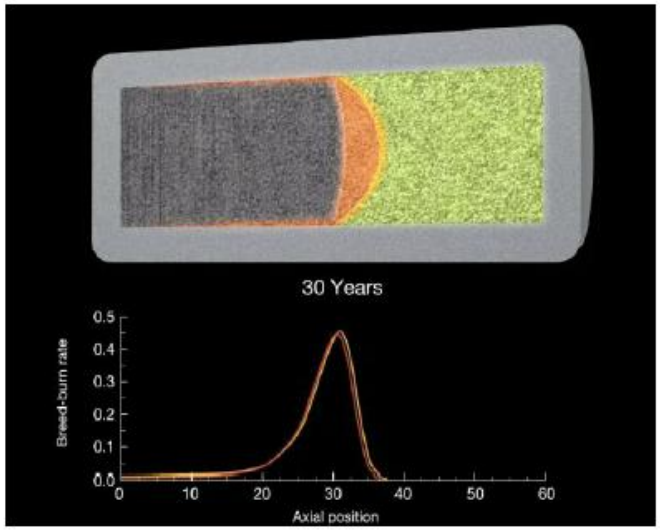
At ~25 away from the reactor core, 600-6000 events per days can be detected, depending on the detector size

Fast and Exotic (but Very Promising) Reactors

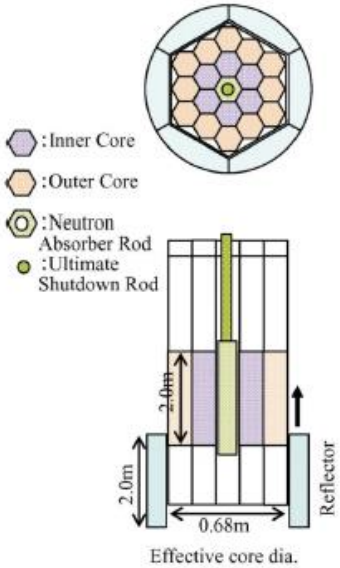
- "Candle" type and "onion" type
- Need to understand fast spectrum and exotic fuel cycle, that are very different from conventional thermal reactors



*CANDLE



**TWR

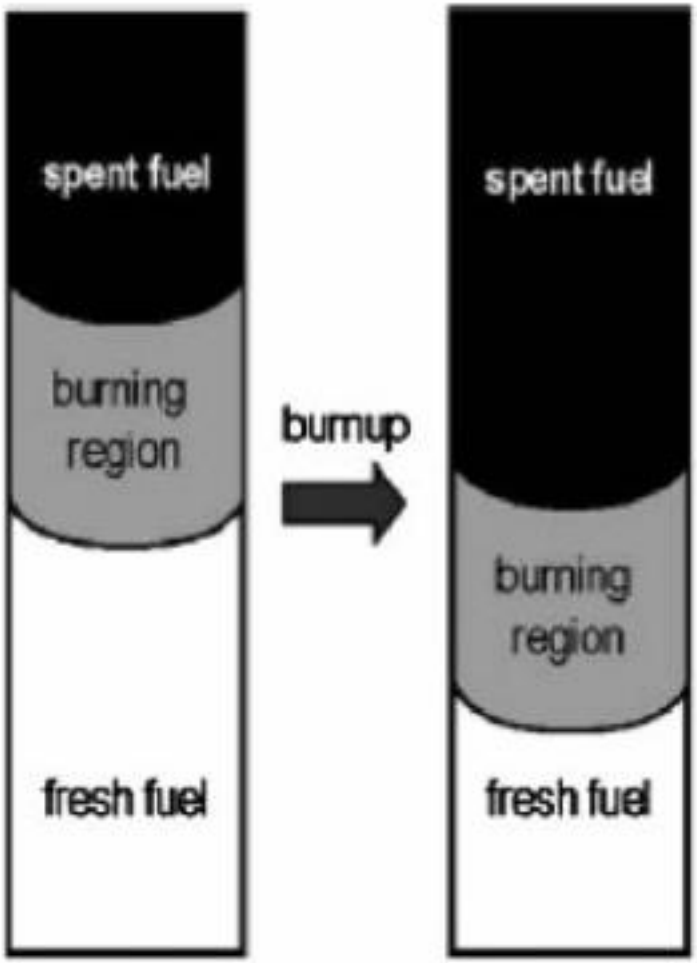


***4S

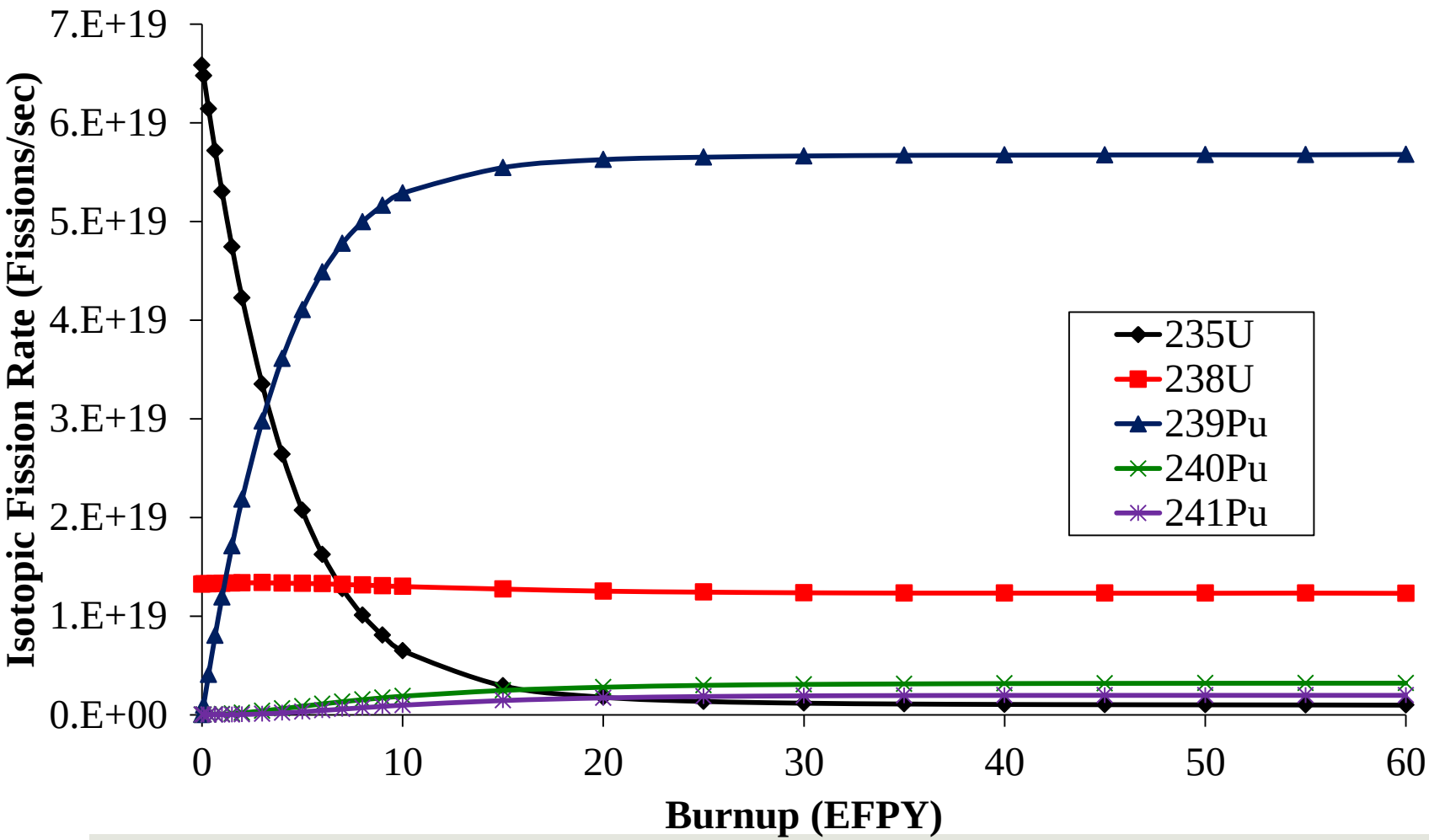
*CANDLE: The New Burnup Strategy", Hiroshi Sekimoto, 2001
**Nuclear initiative, Terrapower LLC, 2009
***Sodium Cooled Small Fast Long-Life Reactor "4S", Nobuyuki Ueda, 2005

"Candle" SFR: UCFR-1000

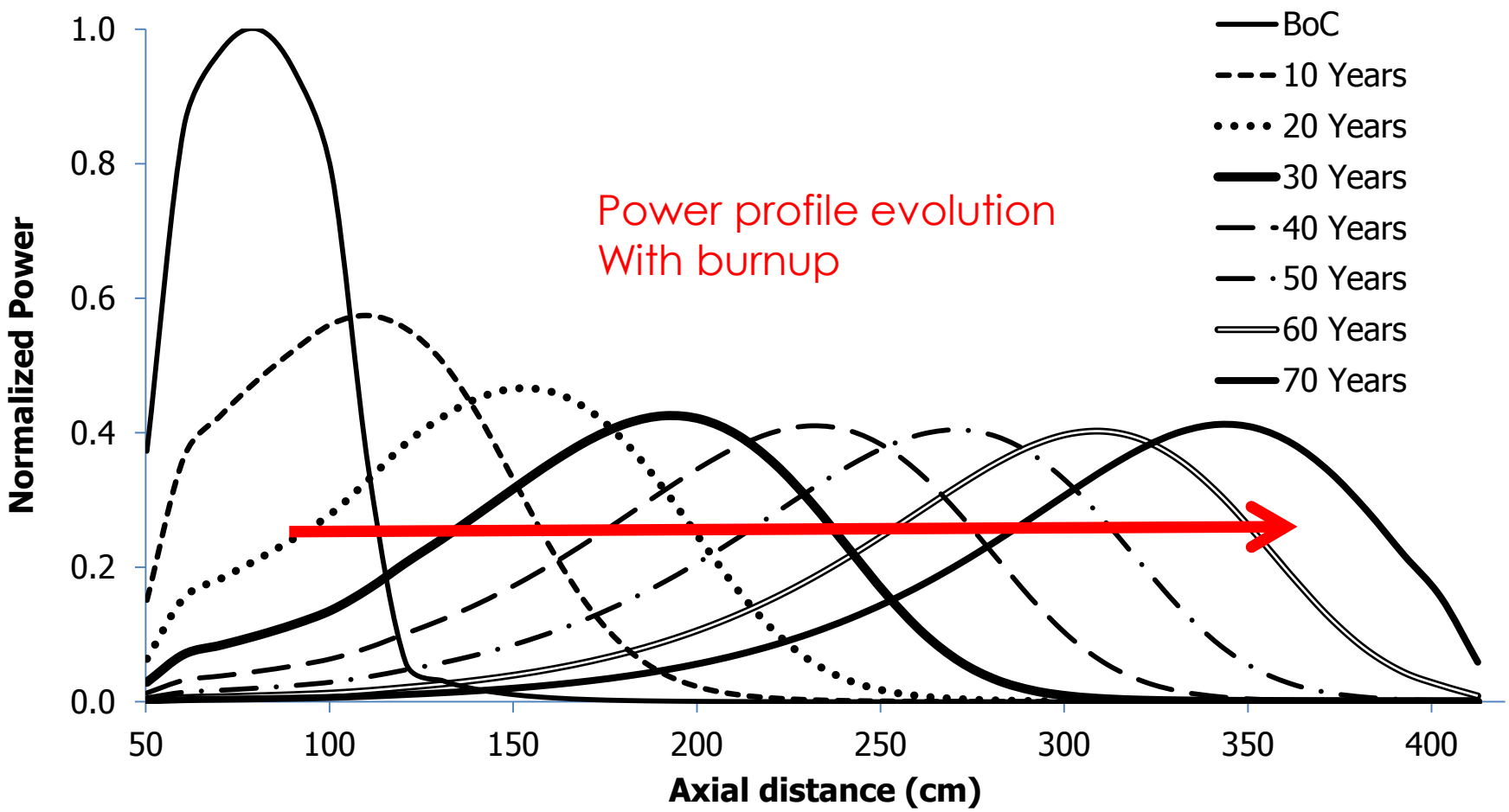
- Design under development (ANL)
- 30-60 year refueling interval
- 2600 MWth/1000 Mwe
- Burn zone moves axially upward @ 5 cm/year
- Vented fission gas plenum



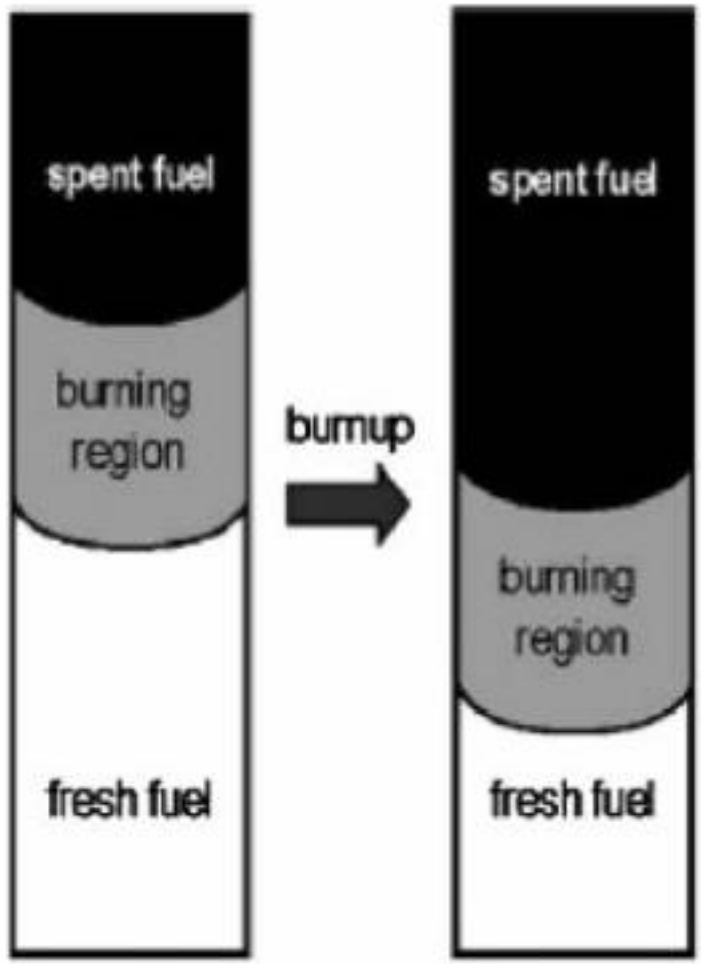
UCFR Fission Rates



Normalized Axial Power Distributions (ARO, 16.02g/cc U-10Zr)



Monitoring of Core Evolution with Antineutrinos

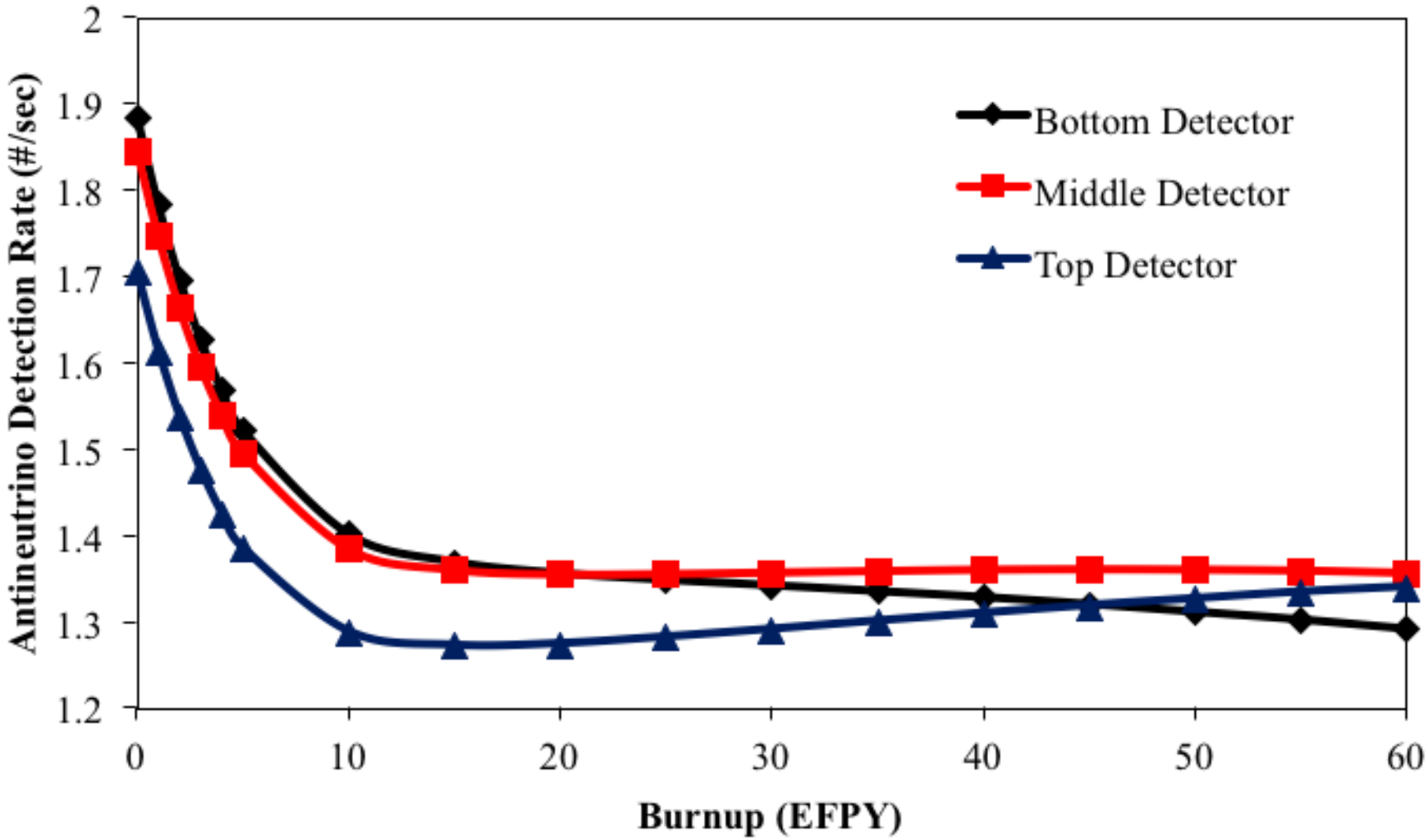


Top Detector

Middle Detector

Bottom Detector

Neutrino Rate Evolution (5t detectors)



What about Uncertainties?

- Work in progress – new for fast reactors, no measurement have been done
- Recall the dependence of rate on power and fuel evolution
- Reactor power output
  - Linear change in antineutrino signal
  - Measured via flowmeters in coolant loops (accurate to 2%)
  - New devices promise order of magnitude improvement
- Antineutrino yield data: an order of magnitude higher uncertainty for minor actinides yield than for measured isotopes
  - ~1% uncertainty for 235U, 239Pu, 241Pu
  - 10-20% for 238U, 240Pu, and minor actinides, especially by fast fission
- Detection reaction (IBD) cross section value (1.4%)

Uncertainties, Continued

- Accuracy and precision of the neutronics code
  - Cross section library data uncertainty
  - Solution method for flux distribution
- Approximations made in reactor models
  - Minimum size of reactor volume element = O(10 cm)
  - Discretization of time (burnup)
  - Energy discretization
- Error in reactor isotope inventory
  - Positive function of burnup
- Error in isotopic fission rates

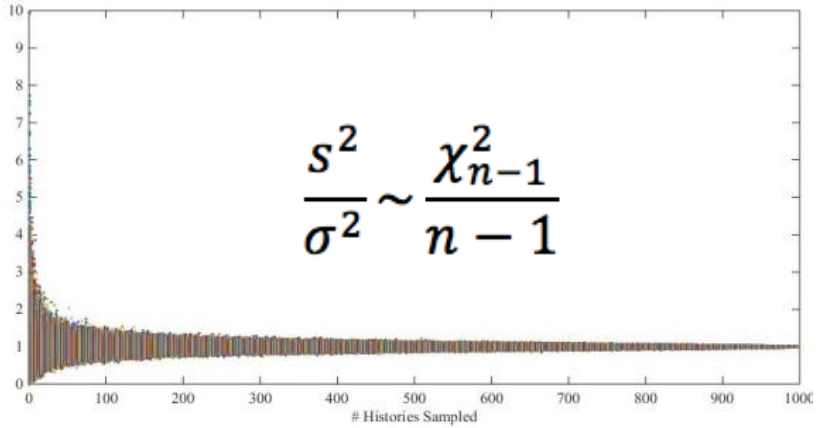
Reactor Uncertainties

- a Monte Carlo approach was taken to evaluating output sensitivity to uncertainty on reactor model inputs (the fuel loading and cross sections)
- Model inputs are sampled to produce a covariance matrix **V** of the outputs (fission rates):

$$V_{ij} = \langle (f_{ik} - f_{i0})(f_{ik} - f_{i0}) \rangle_k$$

$$R_{ij} = V_{ij} / (f_{i0} \times f_{j0})$$

- 1000 histories to converge
- Statistical modeling error<3%



Combination of the Reactor and Antineutrino Uncertainties

- Antineutrino yield remained the largest source of uncertainty due to lack of measurements

$$\Delta N_{\bar{\nu}}^{b} = \sum_{i} \Delta y_i^b f_i$$

$\bar{\nu}_e$ Energy (MeV)	0 EFPY	1 EFPY	15 EFPY	30 EFPY
2.0	1.526	1.551	1.908	2.313
2.5	1.611	1.633	1.964	2.348
3.0	2.330	2.358	2.751	3.167
3.5	2.353	2.387	2.856	3.328
4.0	2.423	2.461	2.980	3.488
4.5	2.707	2.762	3.485	4.140
5.0	2.969	3.025	3.774	4.444
5.5	3.276	3.343	4.221	4.981
6.0	3.982	4.089	5.458	6.566
6.5	4.848	4.992	6.806	8.224
7.0	5.600	5.802	8.341	10.274
7.5	8.626	9.002	13.729	17.432
8.0	5.423	5.896	11.937	16.670
8.5	6.102	6.570	12.551	17.237
9.0	0.247	0.250	0.555	1.208

Conclusions

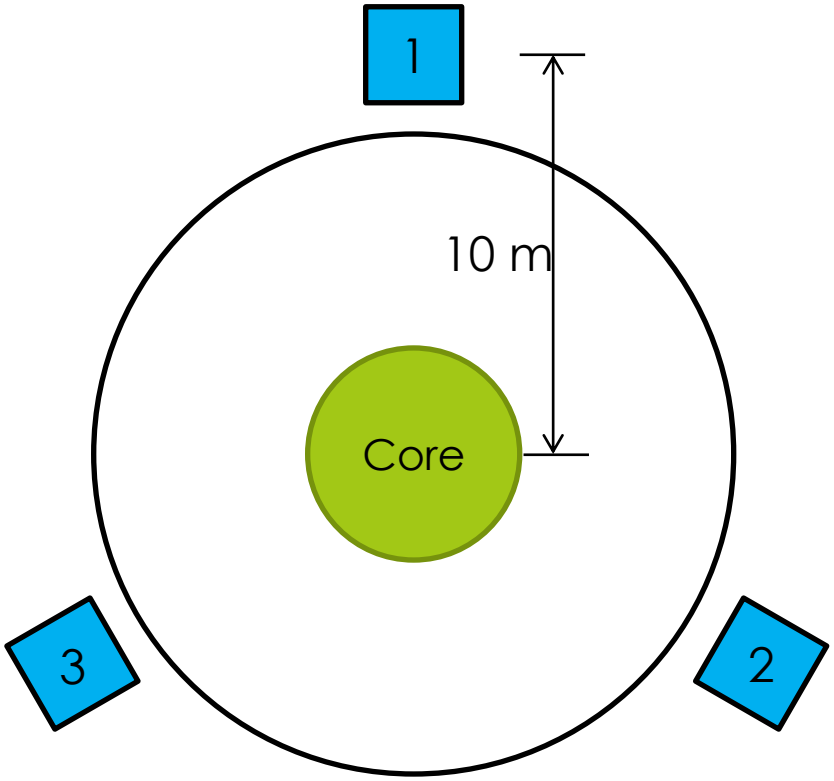
- Antineutrino monitoring of fast reactors could provide with the necessary tool for fuel cycle and operation verification.
- Safeguards requirements may result in interesting design features (long cycle requires "candle" design).
- Understanding of source evolution and associated uncertainties is part of the nonproliferation-by-design.
- A method of reactor-related uncertainty calculation was developed using Monte Carlo approach coupled with a stochastic code.

Assumed Detector Characteristics

- Based on SONGS detector developed by LLNL
  - 10.7% efficiency with 0.64 m^3 scintillator volume and low overburden
- 1 m^3 scintillator volume
  - H_2O doped with 0.1 % Gd
  - ~50 m overburden (water equivalent)
- 30 % assumed detector efficiency
  - Slightly increased size relative to SONGS
  - Increased overburden
- Treated as point

Diversion: Core-Detector Geometry

- Installation adjacent to primary containment
- 10 m standoff
- 3 detectors spaced 120° around core
- One detector each at bottom, middle, and top core planes



Construction of the Detector Signal

$$n_i = N_D \sum_k \sum_\alpha \left(\frac{1}{4\pi D_\alpha^2}\right) f_\alpha^k \sigma_i \nu_i^k \, \varepsilon_i$$

- Indices:
  - i = Energy bin
  - a = Reactor volume element
  - k = Heavy metal isotope
- 0.5 MeV energy bins
- Uncertainty on each bin:

Comparison of Detector Signals

- χ^2 statistic is calculated based on the difference between the detector counts of the reference (n_i) and perturbed (n_i') states in each energy bin
- allows for the reactor operator to attempt to reduce the difference between the reference state and its post-diversion state by operating at a different power level

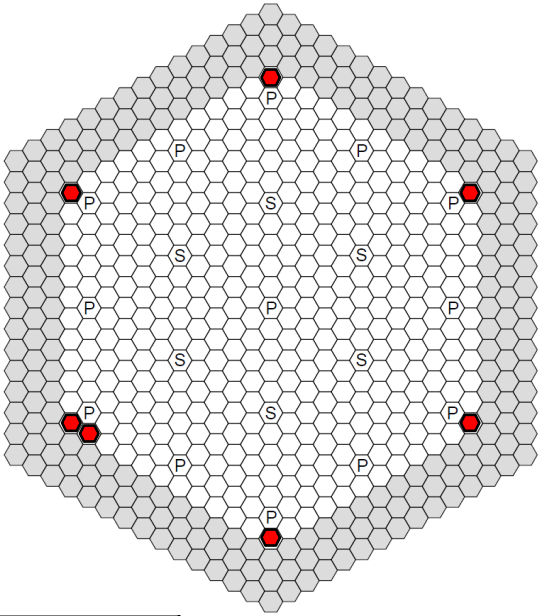
$$\chi^2 = \left(\sum_i \frac{\left(n_i - (1+x)n_i'\right)^2}{n_i}\right) + \left(\frac{x}{\sigma}\right)^2$$

Interpretation in a Safeguards Context

- 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
  - 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

BoL Diversion of LEU

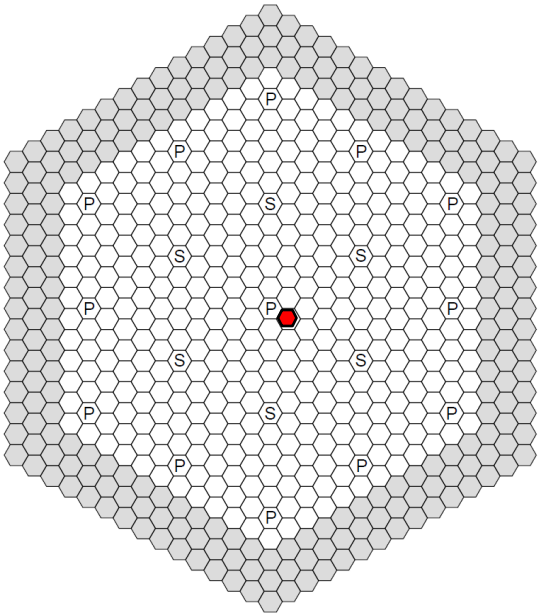
- LEU diversion must occur at periphery of core to maintain criticality
- Nearly impossible to detect via antineutrinos
- Small difference due to different plutonium breeding rate and location and small change in axial burn zone progression



Value	3 Months	12 Months
Minimization Parameter	~0	5.47×10^{-5}
	0.006854	0.01721
p-value	0.93402	0.89563
β (α = 0.05)	1	1
Power (α = 0.05)	0	0

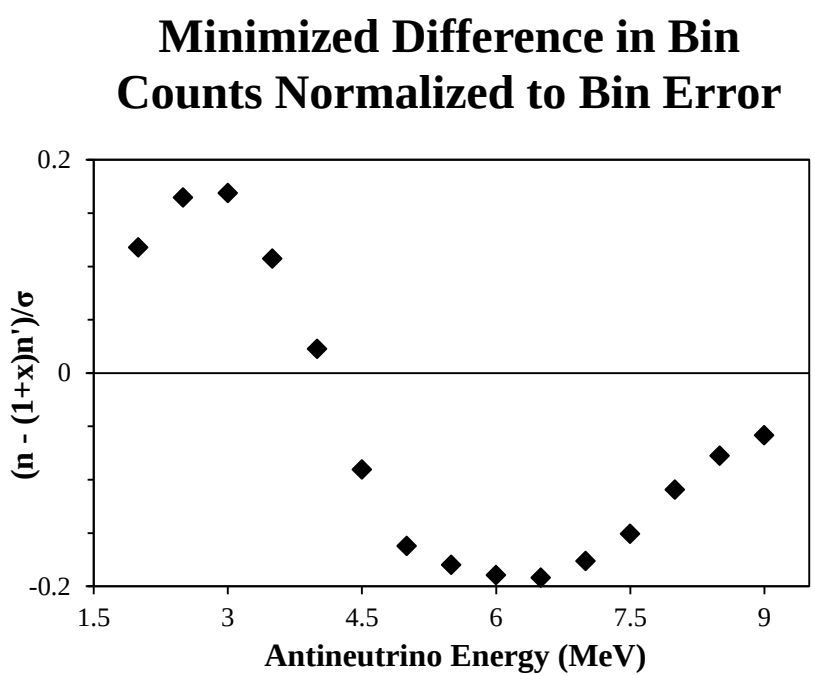
Plutonium Diversion at 2.34 EFPY, NatU Replacement

- Plutonium diversion changes the isotopic fission rates; more amenable to detection
- Local flux depression near replaced assembly amplifies the change in fission rates
- Minimization parameter has a significant effect on the detection probability



Parameter	1 Month	2 Months	3 Months	3 Months (No Minimization)
Minimization Parameter	-1.44×10^{-3}	-1.56×10^{-3}	-1.59×10^{-3}	0
	0.61083	0.91068	1.16536	5.94736
p-value	0.43448	0.33993	0.28036	0.01474
β (α = 0.05)	0.9806	0.9377	0.8924	0.33296
Power (α = 0.05)	0.0194	0.0623	0.1076	0.66704

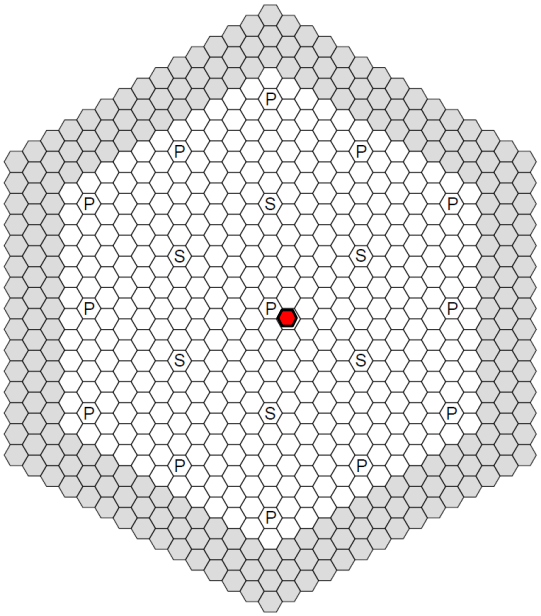
Spectral Effect of Diversion



- Increased ^{235}U fission rate relative to reference case
  - Harder spectrum
- Distribution uniformly shifts downward when magnitude of *x* is reduced

Plutonium Diversion at 2.34 EFPY, LEU Replacement

- It was expected that this would be the most visible of the 3 cases due to replacement of the fissile isotope
- Factor of 2-3 less visible than for the same diversion with natural uranium replacement
- No local flux depression near replaced assembly



Parameter	1 Month	2 Months	3 Months	3 Months (No Minimization)
Minimization Parameter	-9.53×10^{-4}	-1.04×10^{-3}	-1.05×10^{-3}	0
	0.2368	0.3424	0.42757	2.5000
p-value	0.6265	0.55846	0.51318	0.11385
β (α = 0.05)	0.9999	0.9986	0.9955	0.6643
Power (α = 0.05)	0.0001	0.0014	0.0045	0.3357