Modeling of High-Burnup Reactors for Antineutrino Safeguards

Anna Erickson
Nuclear and Radiological Engineering Program
Georgia Tech

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.

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

New detector and materials development

Small but widespread groups

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
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

<table>
<thead>
<tr>
<th>Country</th>
<th># of Reactors</th>
<th>Design</th>
<th>Est. Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>UAE</td>
<td>4</td>
<td>APR1400</td>
<td>2020</td>
</tr>
<tr>
<td>Vietnam</td>
<td>2</td>
<td>VVER-1000</td>
<td>2021-2024</td>
</tr>
<tr>
<td>Jordan</td>
<td>1</td>
<td>N/A</td>
<td>2020</td>
</tr>
</tbody>
</table>
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**

<table>
<thead>
<tr>
<th>Non-Proliferation</th>
<th>Disarmament</th>
<th>Peaceful Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Recognizes Nuclear Weapons States</td>
<td>• NWS should seek to reduce their weapons stockpiles and ultimately disarm</td>
<td>• Nations have the right to pursue nuclear power for peaceful purposes</td>
</tr>
<tr>
<td>• Bans transfer of weapons and production capability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Non-NWS subject to IAEA safeguards</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- 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
  - $^{239}\text{Pu}$ – 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
- Antineutrinos are not stopped by the reactor structures unlike other forms of radiation
- Antineutrinos are unique fission signatures (~6 per fission)
  - Which nuclides undergo fission?
  - Reactor spectrum (neutron energy)?
  - Reactor power?

\[
\frac{2800\, MW_{th}}{200\, MeV} \quad 6 \frac{\nu}{\text{fission}} \quad 5 \times 10^{20} \frac{\nu}{\text{sec}}
\]
Antineutrino Spectrum

Antineutrino Spectrum

Antineutrino Yield (#/fission*MeV)

Energy (MeV)

- U235
- U238
- Pu239
- Pu241
Detecting the Signal

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

Reaction threshold: 1.8 MeV
Cross section \(<\sigma> \sim 10^{-43} \text{ cm}^2\)

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

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

Power profile evolution With burnup
Monitoring of Core Evolution with Antineutrinos
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 $\leq 3\%$
Combination of the Reactor and Antineutrino Uncertainties

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

\[ \Delta N_{\nu}^b = \sum_i \Delta y_i^b f_i \]
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$_2$O 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

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

- Indices:
  - \( i \) = Energy bin
  - \( \alpha \) = Reactor volume element
  - \( k \) = Heavy metal isotope

- 0.5 MeV energy bins

- Uncertainty on each bin:
Comparison of Detector Signals

- $\chi^2$ 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.

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

<table>
<thead>
<tr>
<th>Value</th>
<th>3 Months</th>
<th>12 Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimization Parameter</td>
<td>~0</td>
<td>5.47 x 10^{-5}</td>
</tr>
<tr>
<td></td>
<td>0.006854</td>
<td>0.01721</td>
</tr>
<tr>
<td>p-value</td>
<td>0.93402</td>
<td>0.89563</td>
</tr>
<tr>
<td>β (α = 0.05)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Power (α = 0.05)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1 Month</th>
<th>2 Months</th>
<th>3 Months</th>
<th>3 Months (No Minimization)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimization Parameter</td>
<td>-1.44 x 10⁻³</td>
<td>-1.56 x 10⁻³</td>
<td>-1.59 x 10⁻³</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0.61083</td>
<td>0.91068</td>
<td>1.16536</td>
<td>5.94736</td>
</tr>
<tr>
<td>p-value</td>
<td>0.43448</td>
<td>0.33993</td>
<td>0.28036</td>
<td>0.01474</td>
</tr>
<tr>
<td>β (α = 0.05)</td>
<td>0.9806</td>
<td>0.9377</td>
<td>0.8924</td>
<td>0.33296</td>
</tr>
<tr>
<td>Power (α = 0.05)</td>
<td>0.0194</td>
<td>0.0623</td>
<td>0.1076</td>
<td>0.66704</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1 Month</th>
<th>2 Months</th>
<th>3 Months</th>
<th>3 Months (No Minimization)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimization Parameter</td>
<td>-9.53 x 10^{-4}</td>
<td>-1.04 x 10^{-3}</td>
<td>-1.05 x 10^{-3}</td>
<td>0</td>
</tr>
<tr>
<td>p-value</td>
<td>0.2368</td>
<td>0.3424</td>
<td>0.42757</td>
<td>2.5000</td>
</tr>
<tr>
<td>( \beta ) (\alpha = 0.05)</td>
<td>0.9999</td>
<td>0.9986</td>
<td>0.9955</td>
<td>0.6643</td>
</tr>
<tr>
<td>Power (\alpha = 0.05)</td>
<td>0.0001</td>
<td>0.0014</td>
<td>0.0045</td>
<td>0.3357</td>
</tr>
</tbody>
</table>