Antineutrino Monitoring of Reactors
Theoretical Feasibility Studies

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Can antineutrinos be used to monitor Pu content of reactor?

Are undeclared fuel removals/diversions detectible with neutrinos?

Are other fuels distinguishable from Lightly enriched Uranium (LEU), e.g., $^{232}$Th-$^{233}$U

Can neutrinos verify the burnup of MOX-Pu fuel?

Can neutrinos determine the isotopic content of spent fuel?

Can neutrinos detect the movement/diversion of spent fuel?
Antineutrino Spectra for Different Fissionable material distinguishable

\[ N(E_\nu) = \sum Y_i(A_i, Z_i) \sum b(E_{i0}) \cdot N(E_\nu, A_i, Z_i, E_{i0}) \cdot F(E, Z) \]

Fission fragment yields
\(~ 300\)

Branching ratios
\(~ 10\) per fragment

Approximately 10% of the beta decays have unknown end-point energies \( E_0 \)
Use continuous theory of beta-decay or energy-independent scaling
Reactor Burn Calculations using LANL code Monteburns

Monte Carlo burnup code that links MCNP transport with isotope production/depletion code CINDER’90 (or ORIGEN2.1)

Monteburns Flow Chart

- Accurate reactor modeling for a broad class of fuels.
  - Spatial and temporal power, fuel composition, radiation and decay heating

- Detailed characterization of removed fuel content and emissions.
  - Fuel proliferation index, weapons usability, decay signatures for safeguards

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Antineutrino Spectrum for Different Fuel Diversion Scenarios

Start of cycle:
1/3 fresh 2.7% enriched
1/3 irradiated 1 year
1/3 irradiated 2 years

End of cycle:
1/3 irradiated 1 yr, 2 yr, 3 yr

Diversion of 10% (> Critical Mass):
37% fresh 2.7% enriched
33% 1 yr, 30% 2 yr

Gross Violation (diversion of 1/3):
2/3 fresh 2.7% enriched
1/3 irradiated 1 yr
Antineutrino Monitoring of Th-U-233 reactors - Advanced Fuel cycle concept

\[
\begin{align*}
^{238}\text{U} + n & \rightarrow ^{239}\text{U} \quad \sigma = 1.73 \text{ b} \\
^{239}\text{Np} + \beta^- + \nu & \rightarrow ^{239}\text{Pu} + \beta^- + \nu \\
^{232}\text{Th} + n & \rightarrow ^{233}\text{Th} \quad \sigma = 4.62 \text{ b} \\
^{233}\text{Pa} + \beta^- + \nu & \rightarrow ^{233}\text{U} + \beta^- + \nu
\end{align*}
\]

Advantages of Th-U fuel cycle:
• Abundance of Th 3 times than U
• Reduced proliferation hazard
• Reduced radiological hazard

Main Disadvantage:
• Requires fissile seed \(^{235}\text{U}\) to initiate cycle

Seed: LEU \(^{238}\text{U} + 2.7\%^{235}\text{U}\)
Blanket: \(\text{ThO}_2\) or \(\text{ThO}_2 + 20\%\) LEU
Proliferation Implications for Th-U Cycle

Weapons usability of $^{233}\text{U}$ determined by the proliferation index

Proliferation Index:

$$PI = \frac{^{233}\text{U} + 0.6^{235}\text{U}}{U_{\text{total}}} < 12\% \text{ if non-weapons usable}$$

PI typically requires about 20% of Th$\text{O}_2$ rods to contain LEU ($^{238}\text{U} + 2.6\%^{235}\text{U}$)

Examine antineutrino spectra differences for Th-U fuels comply/violate PI
Derived $\beta/\gamma$ spectra for $^{232}\text{Th}$ and $^{233}\text{U}$ from ENDF/B-VI data

$^{232}\text{Th}$ spectrum very similar to $^{238}\text{U}$ - enhanced
$^{233}\text{U}$ spectrum very similar to $^{239}\text{Pu}$ - suppressed
Reactor Burn calculation for Th-U cycle

a. Th0\textsubscript{2}+LEU PI compliant
b. ThO\textsubscript{2} to max weapons usability

- Fast in-growth of 233U in both cases, but especially for pure Th0\textsubscript{2}
- Burn for the purposes of producing weapons usable 233U very distinctive
Antineutrino Spectra for Th-$^{233}$U cycles

Number of $\nu$/fission drops steadily as $^{233}$U grows
Considerably faster drop than seen from in-growth of Pu in PWR LEU case
Situation Complicated by Change in Power Density for Th-U Burn

- For PWR LEU reactors power density remains approximately constant.

- For Th-U reactors the power would be shared between LEU seed assemblies and Th-U blanket assemblies.

- Power in Th-U-233 assemblies can change significantly over several cycles and be compensated for by a change in the LEU power.

Need detailed model of change in power density in order to determine expected change in antineutrino spectrum.
Burning of Weapons-grade and Reactor-grade MOX Pu

Schemes to burn MOX fuel to burn Pu

$$U_0^2 + 5.3\% \text{ PuO}_2$$

Starting Isotopics for Weapons- and Reactor-grade fuels

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<th>w%</th>
<th>Weapons-Grade</th>
<th>Reactor-Grade</th>
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<tr>
<td>U-235</td>
<td>0.67897%</td>
<td>0.67897%</td>
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<tr>
<td>U-238</td>
<td>93.622%</td>
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<tr>
<td>Pu-238</td>
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<td>0.2026%</td>
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<tr>
<td>Pu-239</td>
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<td>Pu-240</td>
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<td>Pu-241</td>
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<tr>
<td>Pu-242</td>
<td>-</td>
<td>0.5372%</td>
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</tbody>
</table>
Antineutrino Spectra Emitted for Pu MOX Fuels Clearly Distinguishable

Number Antineutrinos/fission *increase* with burn for MOX PU
May be able to distinguish grade of fuel from power density
Monitoring Spent Fuel

The antineutrino source describes total activity well - essentially all decays are $\beta$-decay.

Calculated activity of discharged fuel drops to:
- 7.5% in the 4 weeks
- 1.5% in a year
- 0.2% in 10 years

Fuel assembly would have to be moved far from reactor
Radioactivity at WIPP
Carlsbad, NM

WIPP designed to store ~ 9000 Mtonnes of radioactive waste

Presently 25% full

Radioactivity includes:
Antineutrinos
Betas
Delayed photons
Alphas
Delayed neutrons

WIPP antineutrino and beta spectra
Dominated by 241Pu 18 keV β-decay
Summary

- For LEU PWR gross changes in fuel content likely to be observable
- Diversions of a critical mass of Pu from GW LEU PWR difficult to detect
- Th-U233 fuels distinguishable from LEU
- Violations of the proliferation index for Th-U233 quite distinguishable.
  important for monitoring the proposed Indian breeder reactor program.
- Burning of MOX Pu fuels also distinguishable
- Antineutrino spectrum from spent fuel peaks at very low energies