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Reactor Monitoring and Safeguards Using Compact Antineutrineutrino Detectors

ABSTRACT

Fission reactors emit large numbers of antineutrinos and this flux may be useful for the measurement of two quantities of interest for reactor safeguards: the reactor power and plutonium inventory throughout its cycle. The high antineutrino flux and relatively low background rates mean that simple cubic meter scale detectors at tens of meters standoff can record hundreds or thousands of antineutrino events per day. Such antineutrino detectors could add online, quasi-real-time bulk material accountancy to the set of reactor monitoring tools available to the IAEA and other safeguards agencies with minimal footprint and impact on reactor operations. We have deployed a prototype safeguards antineutrino detector at a reactor in order to test both the method and the practicality of its implementation in the field.

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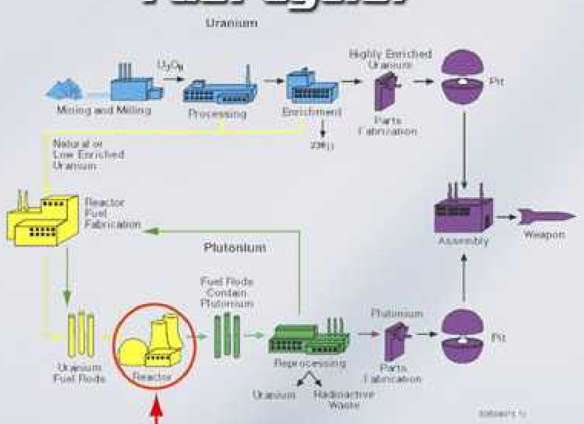
Safeguards Agencies Ensure Fissile Material is Used for Peaceful Purposes

- Agencies such as the I.A.E.A. track the flow of fissile material through the civil nuclear fuel cycle
- Current reactor safeguards involve:
  - Checking declarations
  - Containment and Surveillance
  - Item Accountancy
- These are effective, but:
  - require regular and detailed inspections of the reactor site and records
  - do not directly measure the amount of plutonium produced by a reactor

IAEA has requested member states to develop quantitative, automated, monitoring techniques

Antineutrino Detectors Address One Part Of The Fuel Cycle:



Monitoring of the Nuclear Reactor

Reactors Produce Antineutrinos in Large Quantities

~ 6 Antineutrinos are produced by each fission: $\Rightarrow N_{\bar{\nu}} \propto P_{th}$

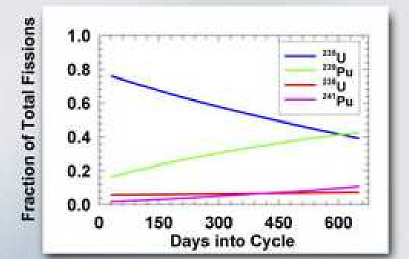
- Antineutrinos interact so weakly that they cannot be shielded, but small detectors have useful interaction rates
  - **0.64 ton** detector, **24.5 m** from **3.46 GW** reactor core
  - 3800 events/day for a 100% efficient detector
- Rate is sensitive to the isotopic composition of the core
  - Detailed reactor simulations show antineutrino rate change of about 5-10% through a 300-500 day PWR fuel cycle, caused by Pu ingrowth

$$N_{\bar{\nu}} = \gamma(1+k)P_{th}$$

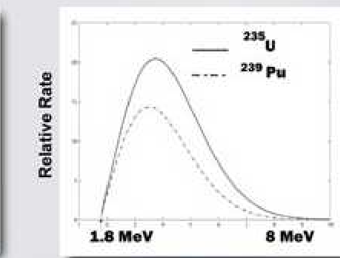
Constant (Geometry, Detector mass)

Fuel composition dependent: Sum overfissioning isotopes, Integral over energy dependent cross section, energy spectrum, detector efficiency

The Antineutrino Production Rate varies with Fissioning Isotope



The fuel of a reactor evolves under irradiation: ^{235}U is consumed and ^{239}Pu is produced

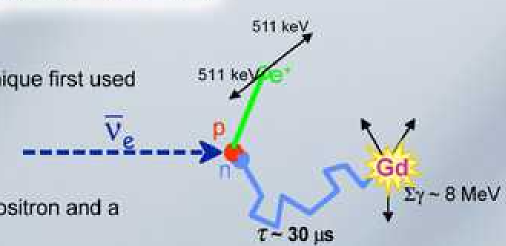


The energy spectrum and integral rate produced by each fissioning isotope is different

Prototype Deployment

We use the same detection technique first used to detect antineutrinos:

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



Inverse beta decay produces a positron and a neutron.

Gd-loaded liquid scintillator captures the neutron after a short time. This produces a pair of correlated events (effective for background suppression)

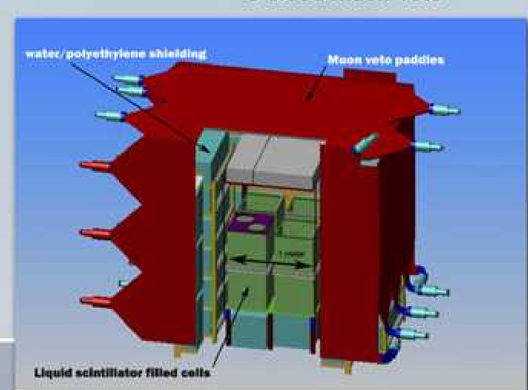
Prototype Detector:

- ~ 1 m^3 Gd doped liquid scintillator
- readout by 8 x 8`` PMT
- 6-sided water shield
- 5-sided muon veto

Prototype detector is deployed in tendon gallery of Unit 2.

- rarely accessed for plant operation
- as close as can be without being inside containment
- provides ~ 20 mwe overburden

Reactor Power: 3.4 GW$_{th}$? 10^{21} n/s
In tendon gallery: ~ 10^{17} n/s per m^2
Rate: ~3800 interactions expected per day (~10^{-2} s^{-1})

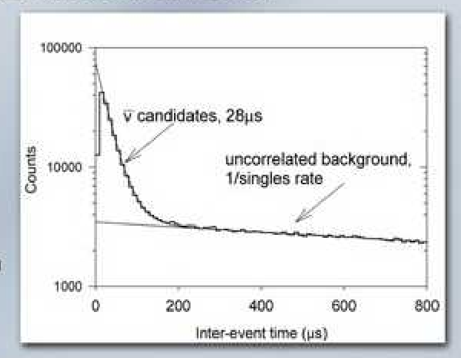


Results and Analyssis

We record ~30 million events per day.
Only a handful of these are antineutrino events.
Cuts are applied to the data to extract antineutrino evets.

energy cuts:
- > 2.5 MeV (prompt)
- > 3.5 MeV (delayed)

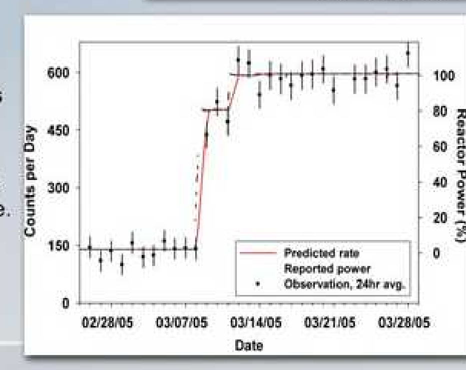
timing cut:
- must occur 100 ms after detected muon



In this example, the reactor was restarted after unscheduled maintenance.

The reactor off period allows us to measure the background rate.

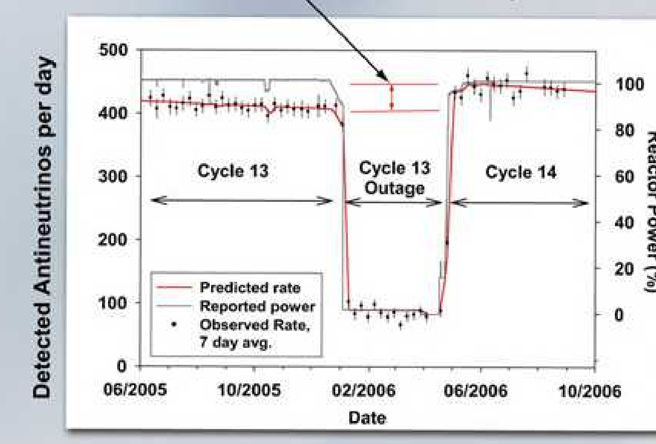
Large power changes are readily oserved with no connection to the plant except anitneutrinos.



Change in antineutrino count rate indicates:

Removal of 250 kg ^{239}Pu in spent fuel.

Replaced with 1.5 tons ^{235}U.



CONCLUSION

Antineutrino detectors can be used to monitor nuclear reactors remotely and non-invasively.

The technology may fill an important niche by provideing quantitative measurements early in the fuel cycle.

Ongoing effort:
- Shrink footprint and improve efficiency
- Quantify benefits relative to existing safeguards methods

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