# Fissile content from spectra and the DPRK's plutonium program

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# Limitations of rate-only

A result of 100 IBD events translates to power

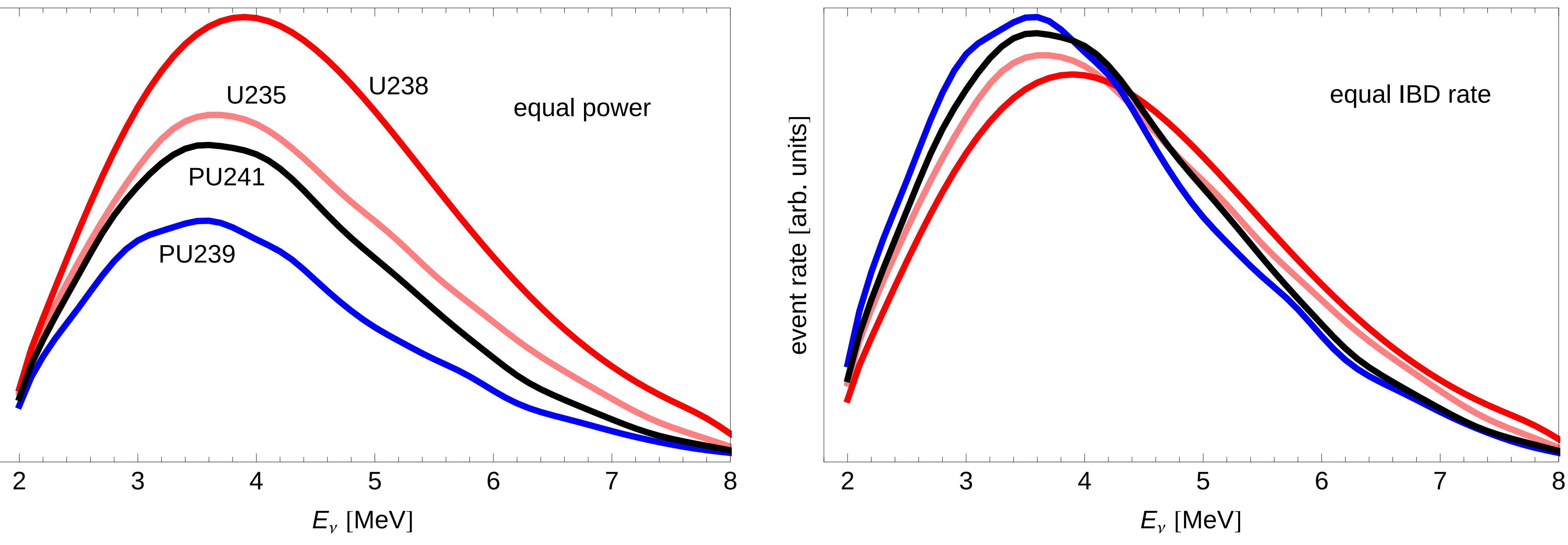
| isotope | $^{235}$U | $^{238}$U | $^{239}$Pu | $^{241}$Pu |
|---|---|---|---|---|
| power [au] | 100 | 74 | 159 | 116 |

Therefore, one needs to know, either

- the reactor power to infer the fission fractions
- the fission fraction to infer the reactor power

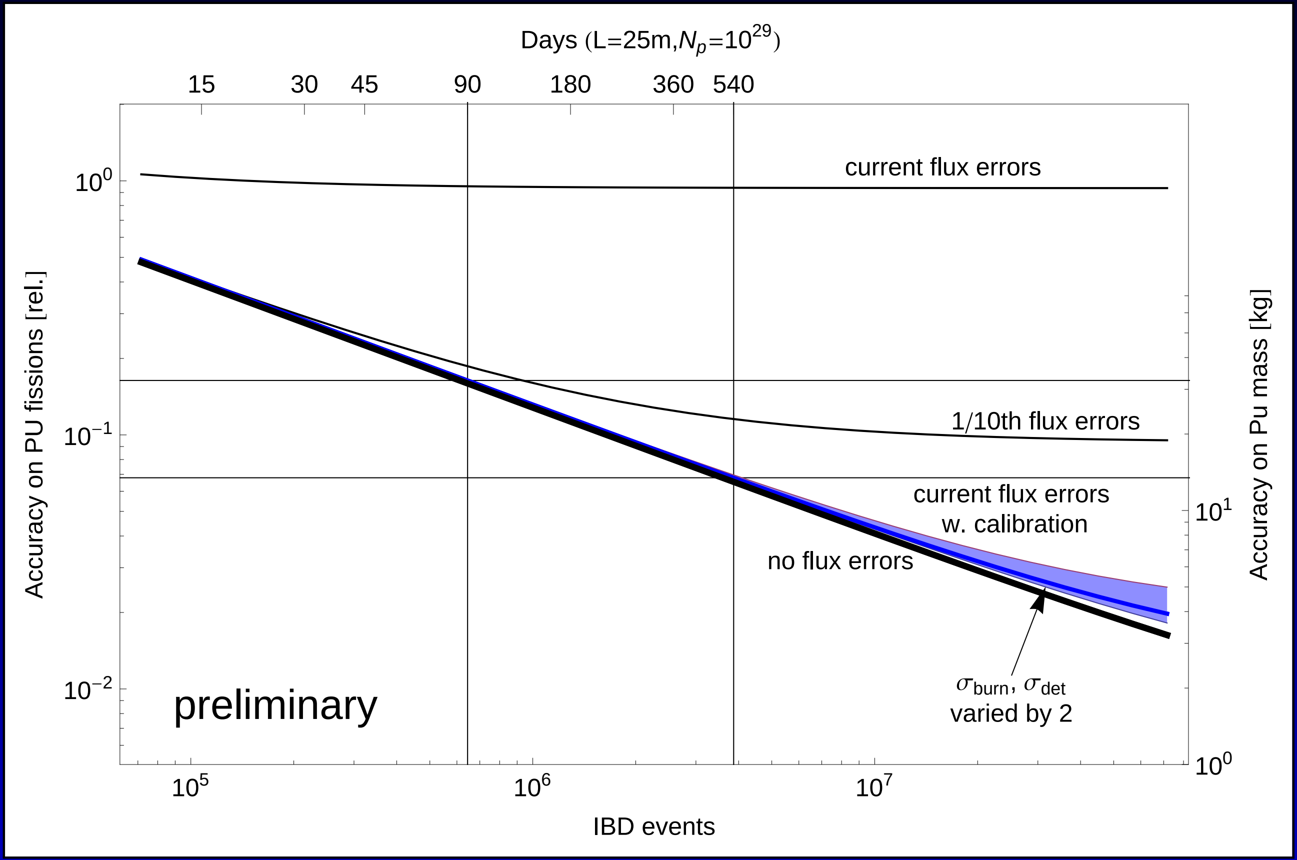
But why trust the operator's declared power and not the fission fractions and *vice versa*?

# IBD event spectrum




This is the basis for the use of spectral information.

# Pu mass inventory




PH, AAP 2011

This figure is for a PWR of 3.4 $GW_{th}$ and assumes a 1-2 ton detector.

At 90 days we reach a 1 $\sigma$ accuracy of 12 kg.

# IAEA safeguards

The IAEA goal for in-core Pu is detection of the diversion of 1 significant quantity (SQ) within 90 days.

Neutrinos, basically can deliver that (just take a 5 ton detector) – but . . .

- A PWR fuel assembly is 5 m long, weighs 500 kg and glows in the dark – easy to keep track of by item accountancy
- Not a single nuclear weapons program started from a light water reactor

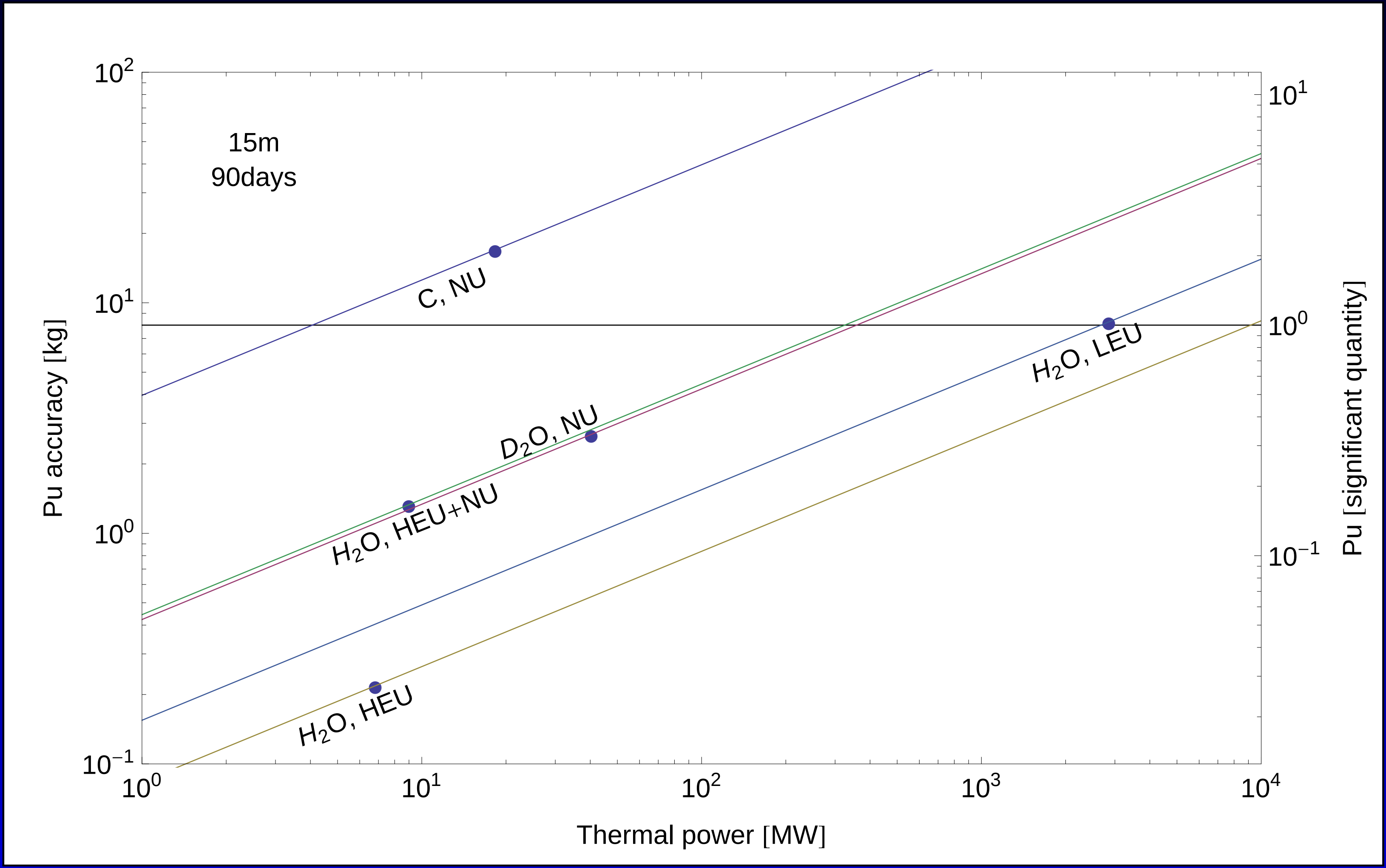
Therefore, some conclude that IAEA's current safeguards are fully adequate for large LWR Zykov, INMM 2012

# Path to nuclear weapons

U.S. – Hanford, graphite
Russia – Mayak, graphite
U.K. – Windscale, graphite
France – Marcoule, heavy water
China – uranium enrichment
Israel – Dimona, heavy water
South Africa – uranium enrichment
India – CIRUS, heavy water
Pakistan – uranium enrichment
DPRK – Yongbyon, graphite

Out of 10 countries: 4 graphite, 3 heavy water, 3 uranium enrichment

# Different reactor types




5 ton detector – based on detailed SCALE calculations.

# Scaling laws

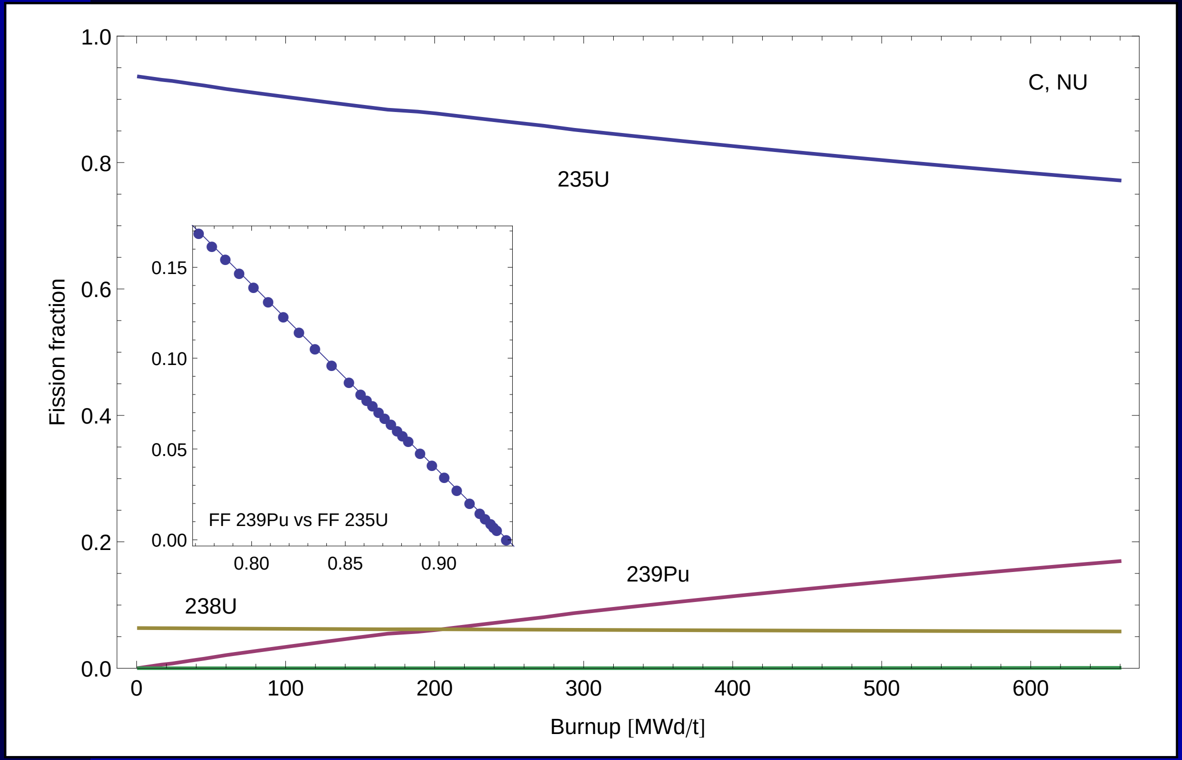
$$\delta m_{\mathrm{Pu}} = 1.9\,\mathrm{kg}\left(\frac{\gamma}{10^{-16}\mathrm{kg\,s}}\right)\left(\frac{L}{\mathrm{m}}\right)\left(\frac{P_{th}}{\mathrm{MW}}\right)^{1/2}\left(\frac{\mathrm{ton}}{M}\right)^{1/2}\left(\frac{\mathrm{days}}{t}\right)^{1/2},$$

with $\gamma = \frac{m_{\mathrm{Pu}}}{\phi_{\mathrm{Pu}}}$.
Note that the absolute error scales with $\sqrt{P_{\mathrm{th}}}$.

| reactor type | C, NU | $H_2O$, HEU | $H_2O$, HEU+NU | $D_2O$, NU | $H_2O$, LEU |
|---|---|---|---|---|---|
| $\gamma$ [$10^{16}$ kg s] | 2.9 | 0.064 | 0.34 | 0.3 | 0.1 |

These values of $\gamma$ are characteristic for the reactor type and change only by a few per cent with burnup.

# Burnup




Reactor physics correlates fission fractions (FF)

FF function of burnup only (to very good accuracy)

$\Rightarrow$ use burnup in the fit

Burnup can be measured in two ways

Method 1: fit to FF – no prior history necessary
Method 2: neutrino power measurement – complete history required

# DPRK nuclear program

1977 IRT – 6 $\mathrm{MW_{th}}$ light water moderated, HEU fueled reactor, supplied by the Soviet Union. Due to soviet insistence under IAEA safeguards since then

1989 5$\mathrm{MW}_e$ – 20 $\mathrm{MW_{th}}$ graphite moderated, natural uranium fueled reactor designed and built by the DPRK. Uses magnox fuel cladding, which makes it impossible to keep SNF in wet storage for long periods of time.

1989 Radiochemical Laboratory – a reprocessing facility for the SNF from the 5$\mathrm{MW}_e$ with a capacity of 100-200 ton per year

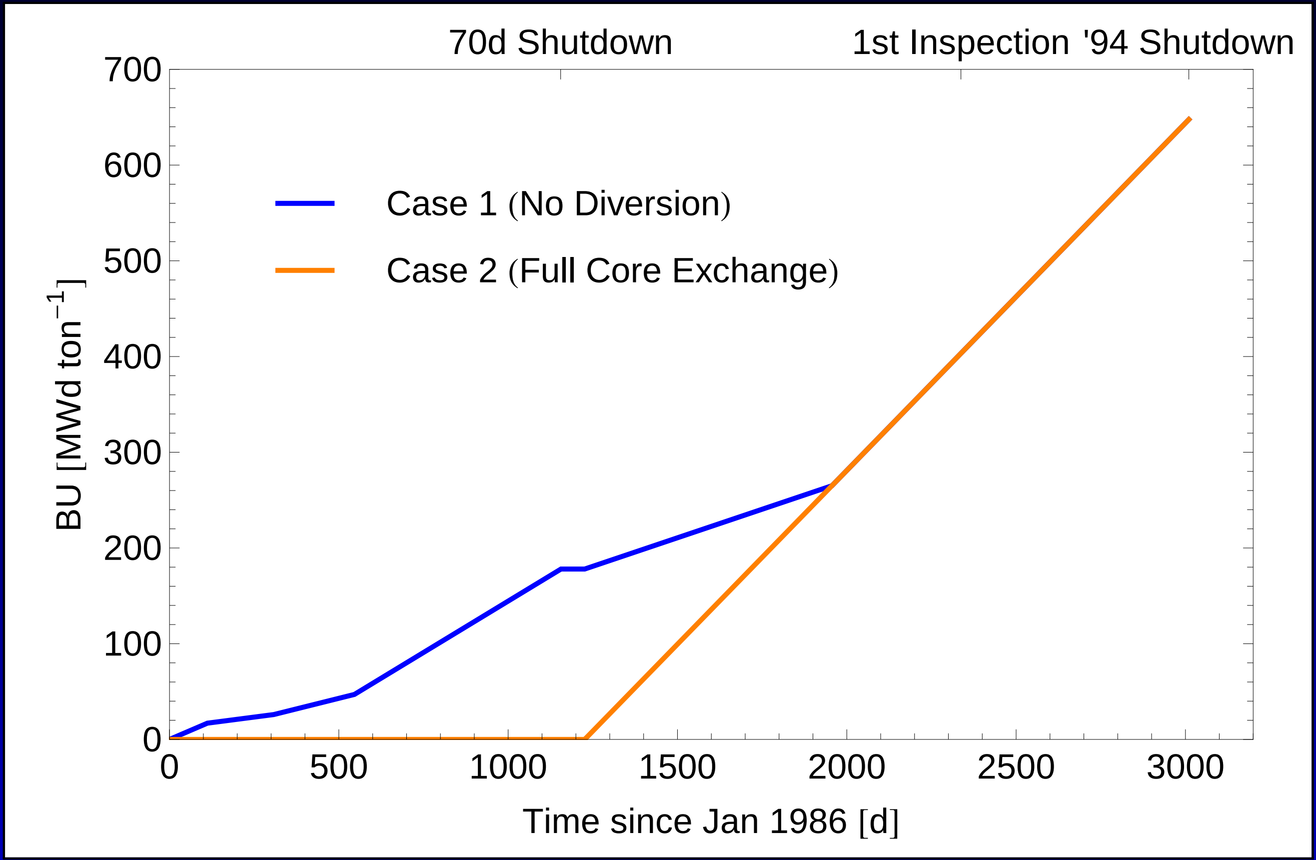
# The 1994 crisis

In its initial declaration to IAEA, the DPRK declared

- In 1989 during the shutdown of their 5MWe reactor a few hundred (out of 8 000 total) fuel elements were discharged.
- A part of the discharged fuel was reprocessed in a hot test of their reprocessing facility resulting in about 60 g of separated Pu.

However, the IAEA found by careful isotope analysis of samples taking during its first inspections in 1992 that there must have been at least 3 reprocessing campaigns. This raises the possibility that in 1989 the DPRK may have discharged the full core, containing about 8 kg of Pu.

# The fate of the first core

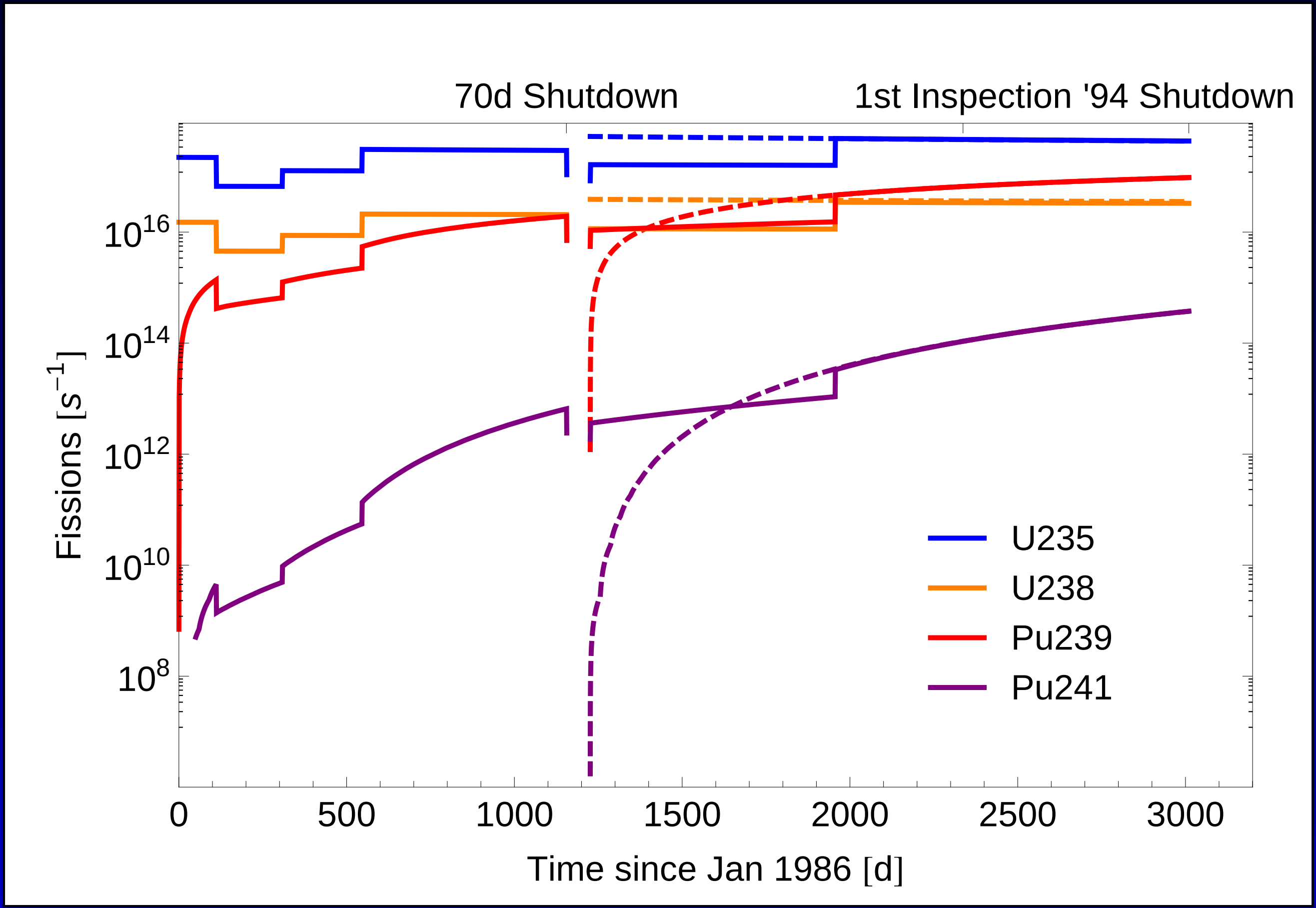



Albright, Solving the North Korean Nuclear Puzzle, 2000

All subsequent IAEA efforts centered around finding out whether the blue or orange curve was true.

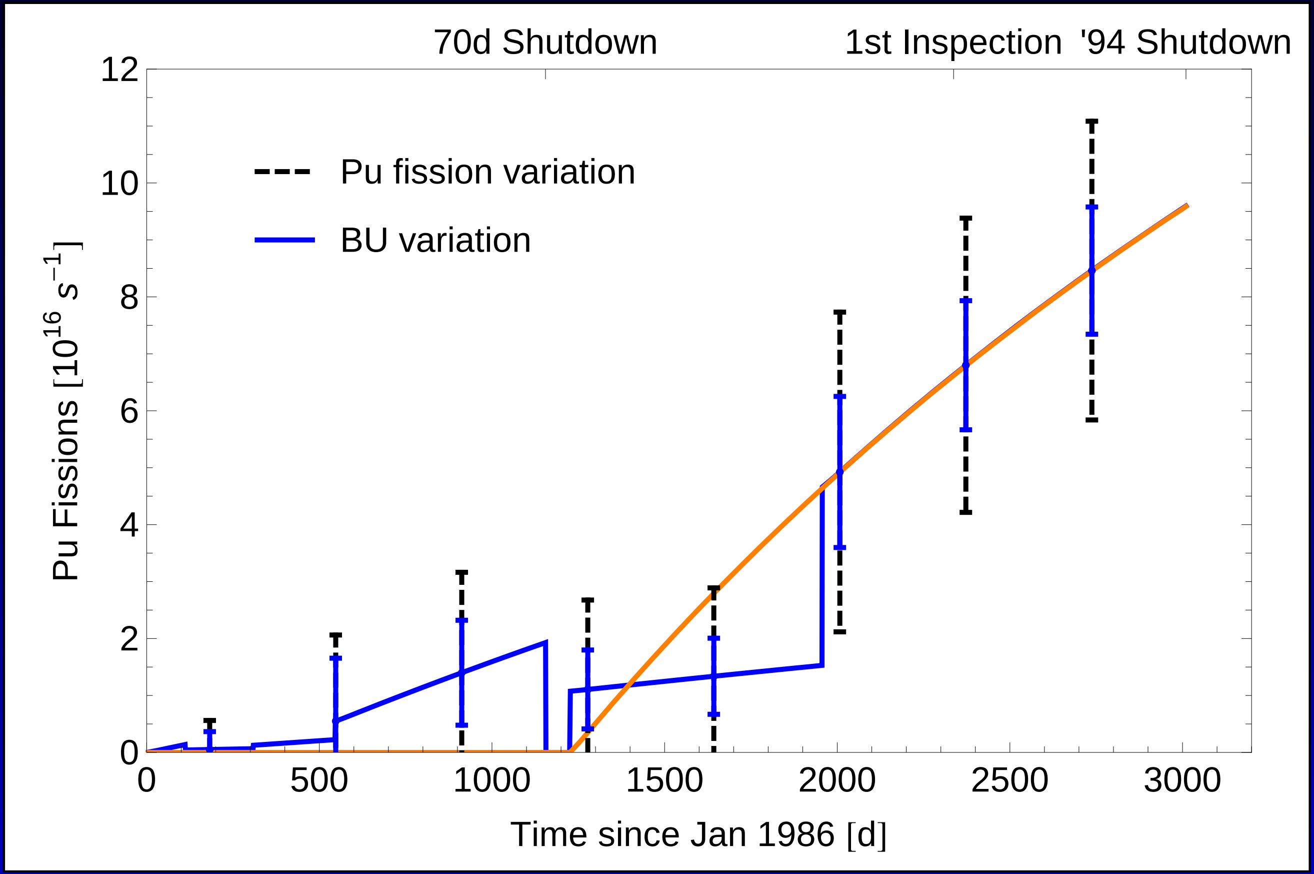
In particular, in the diversion case, there has to be reprocessing waste somewhere.

# Reactor simulation




Based on a full SCALE calculation using a detailed power history and the magnox cross section libraries.

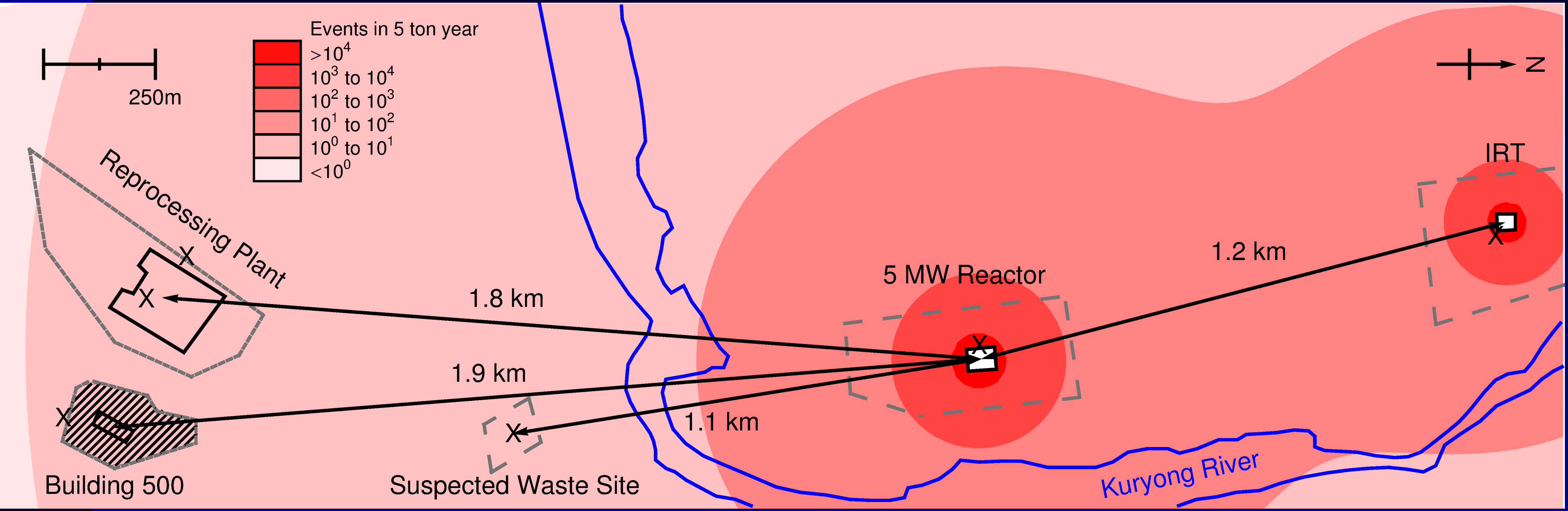
# Neutrino measurement




This demonstrates the gain in accuracy from using reactor physics to constrain the variation of FF.

This observation would constitute a $2\,\sigma$ detection of the diversion of the first core without assuming a full power history (data points are independent)

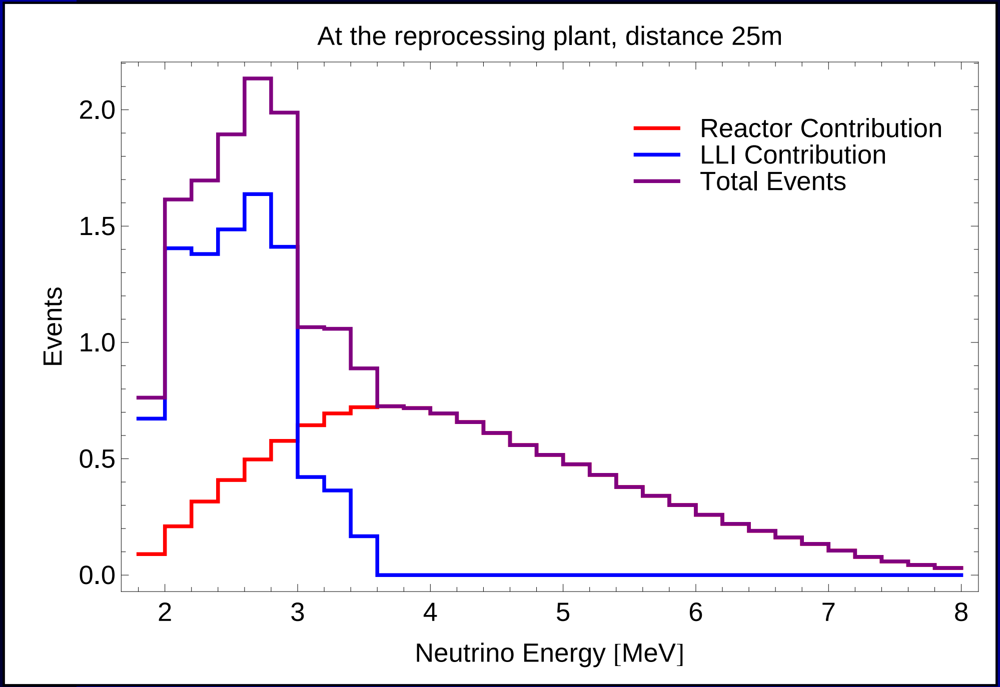
# Indirect means

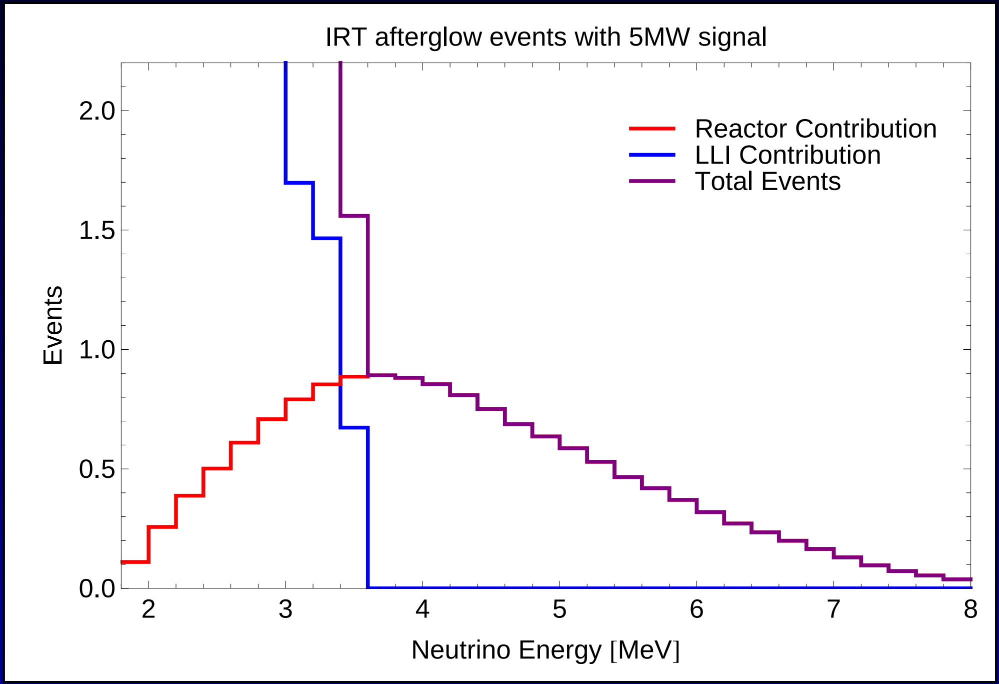



The IRT is a small (6MWth) HEU reactor which has been under safeguards since 1977, neutrinos from the 5MWe will be visible at its site

We can look for reprocessing wastes since the long-lived isotopes (LLI), $^{90}$Sr, $^{106}$Ru and $^{144}$Ce will still emit detectable neutrinos

# Indirect results




Waste neutrinos from LLI

Abundances based on detailed reactor simulation and decayed till start of data taking in Nov 1992

$4\,\sigma$ detection with only reactor backgrounds

The IRT is running 200 days a year

Use the remaining 165 days to remotely measure 5MWe power, which is either 6MWth or 18MWth

$3.2\,\sigma$ detection with only reactor background

# Backgrounds

Muon induced backgrounds have been scaled from Daya Bay numbers for surface (0 mwe) deployment using

$$R \propto \phi_\mu \langle E_\mu \rangle^\alpha \,,$$

where $\phi_\mu$ is the muon flux and $\langle E_\mu \rangle$ is the average muon energy Double Chooz, 1210.3748.

Assuming that the hadronic component is controlled, we get the following noise-to-signal ratios

| Source | Fast neutron suppression | $\beta$-n suppression |
|---|---|---|
| 5MW$_e$ | 0.04 | 0.12 |
| IRT | 0.08 | 0.24 |
| IRT parasitic | 260 | 1050 |
| Waste | 740 | 3080 |

# Conventional methods

Measuring the $\gamma$-activity (esp $^{137}$Cs) allows to determine the burnup of a given SNF assembly. Mapping the burnup distribution in the core by sampling a few hundred assemblies from known, carefully chosen sites in the reactor would have allowed to infer the presence of a second core. This is what IAEA tried to do in June 1994.

Certain trace elements present in the graphite change their isotope ratios due to neutron capture, thus these ratios record to the total local neutron fluence. Destructively sampling the graphite throughout the core allows to make a three dimensional fluence map, which then can be translated into the total produced Pu. Fetter, 1993

Both methods have an accuracy for burnup around 5%, but can be applied only after the fact.

# Quantitative results

Using indirect methods, we could have, based on actual safeguard access, determined the presence of a second core at somewhere between 3-4 $\sigma$ by two independent and redundant methods.

Continuous access would have allowed to obtain a constraint on the total amount of Pu produced to within 2-5 kg even for extended running (till 2007) of the 5MWe resulting in 65 kg Pu total.

Thus the accuracy is at 5-10% level and this information would be available in real time.

# Summary

- Large LWR reactors are considered proliferation resistant and "easy" to safeguard by conventional means
- Neutrino safeguards works well for small to medium sized reactors
- We apply spectral analysis to a wide range of plutonium production reactors
- The DPRK 1994 crisis provides a historic, real world case study
- Some application scenarios require very good background rejection
- Neutrino sensitivities similar (within a factor two) to alternative, conventional methods – information available in real time
- Timeliness of information is key advantage when dealing with potential break-out scenarios

# Outlook


Iran

Arak – 40MW$_{th}$ heavy water moderated, NU or LEU fueled reactor

5 ton detector at 15 m provides 2.5 kg plutonium accuracy in each 90 day interval

S/B>1 even with Daya Bay design at the surface