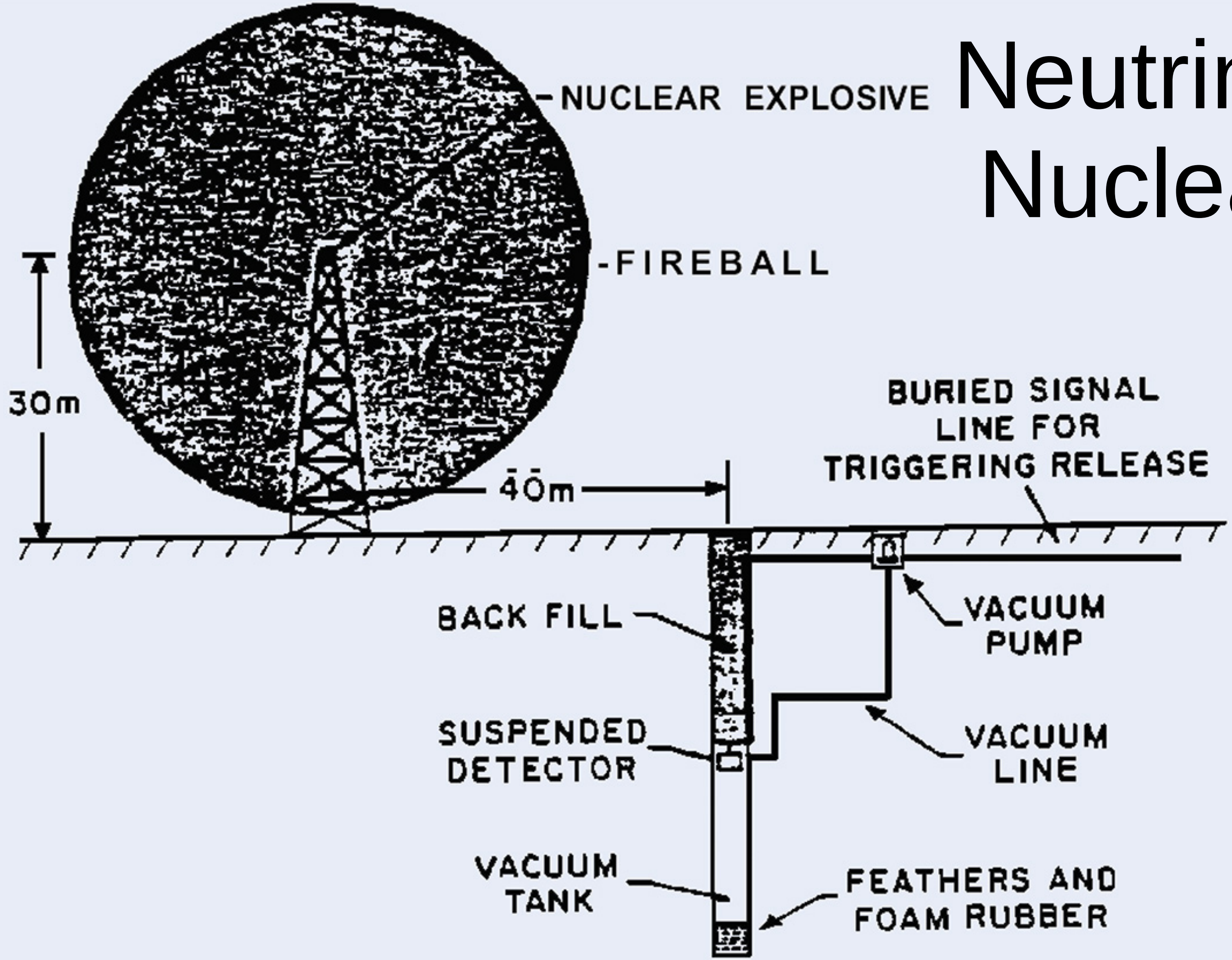
# Neutrino Science
# Nuclear Security





Patrick Huber
Center for Neutrino Physics
Virginia Tech



XXX International Conference on Neutrino Physics and Astrophysics
May 30 – June 2, 2022, Virtual Seoul

# Special nuclear materials

For a nuclear explosion a chain reaction of fast neutrons is required – only very few materials have this property of being fissile

| Isotope | 235U | 233U | 239Pu | 241Pu |
|---|---|---|---|---|
| Half-life | 700 Million years | 160,000 years | 24,000 years | 14 years |
| Natural abundance | 0.72% | 0% | 0% | 0% |

This is **the major barrier** to obtaining nuclear weapons

# Treaties

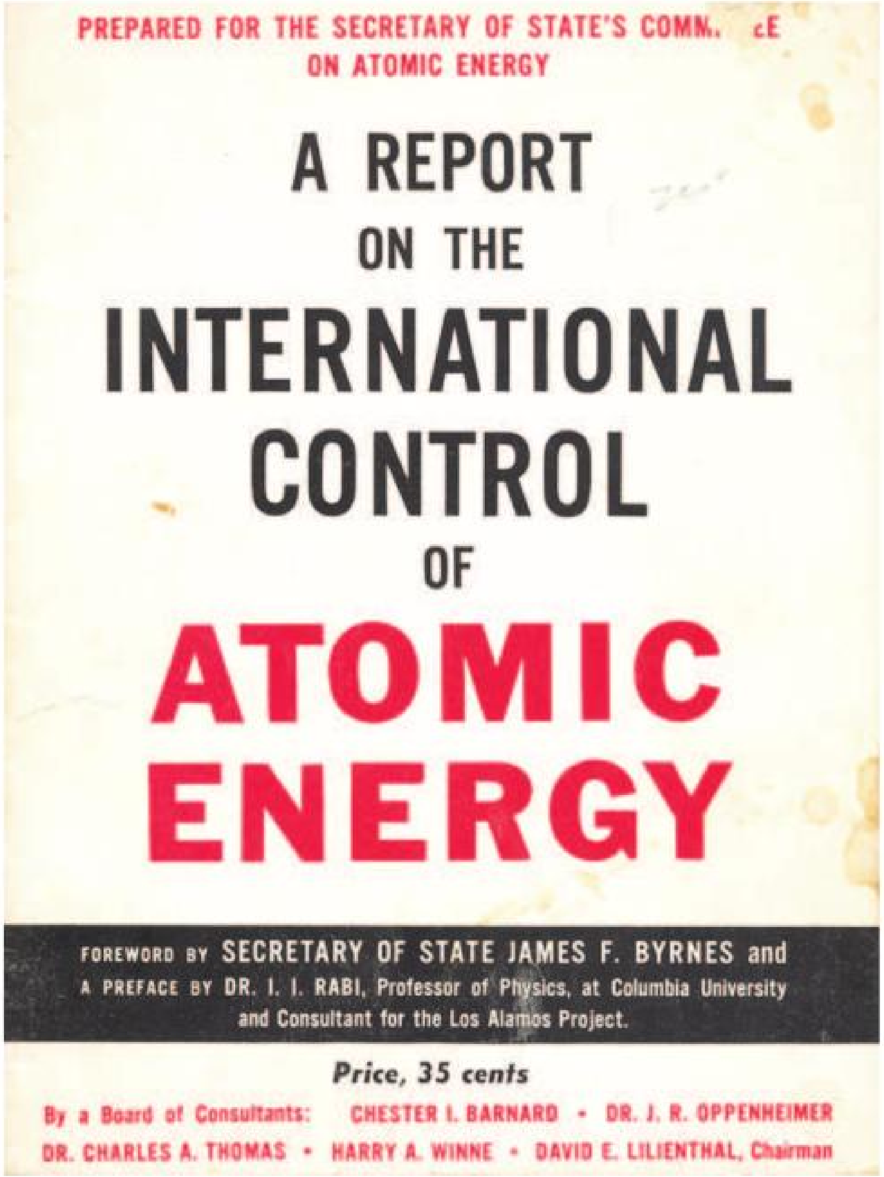
1946 Acheson-Lilienthal report recognizes that control of fissile material is at the center of nuclear non-proliferation

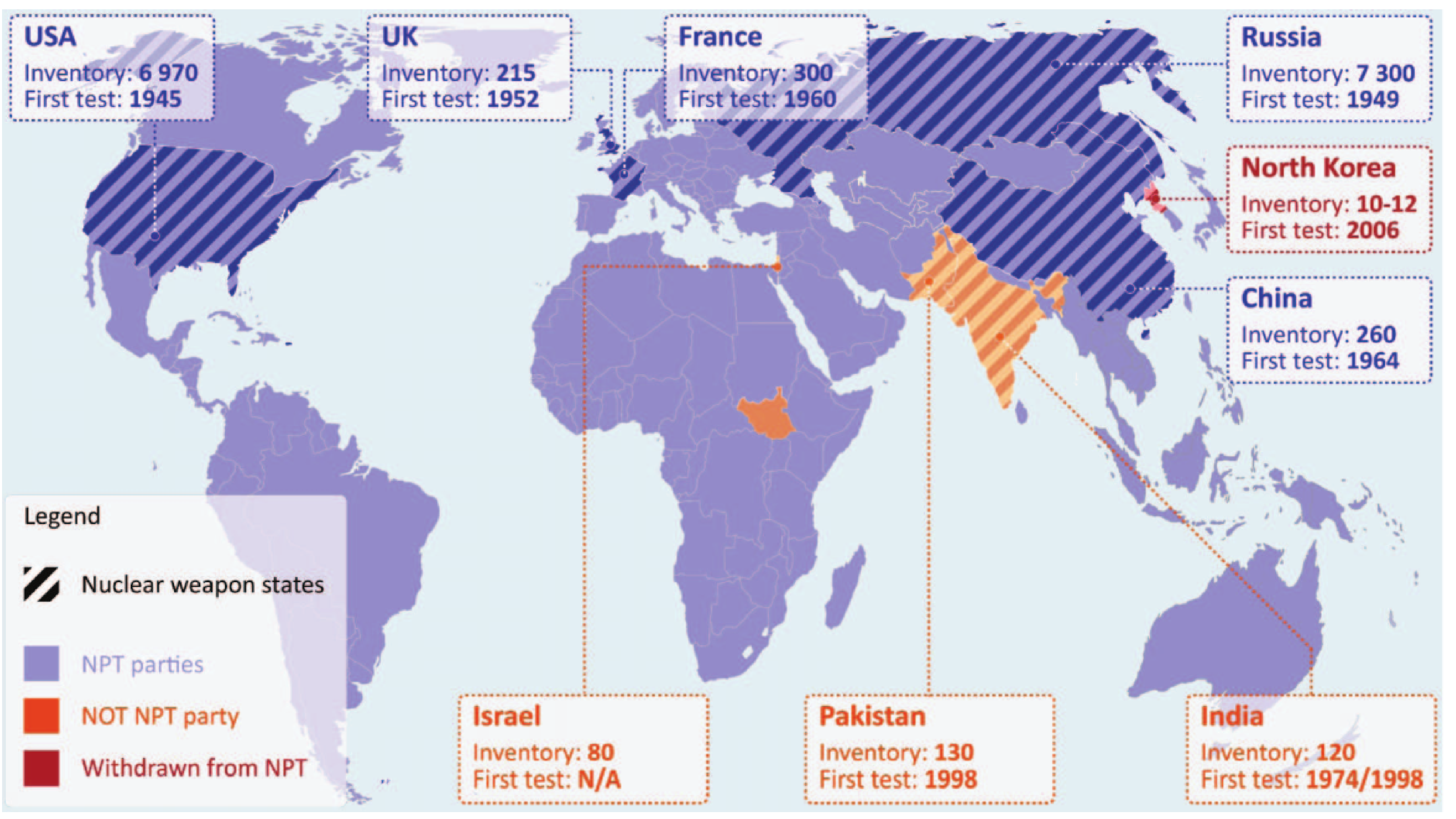
**1970 The Treaty for the Non-Proliferation of Nuclear Weapons (NPT) enters into force**

1995 NPT extended indefinitely

1996 Comprehensive Test Ban Treaty
(still not ratified)

2021 Treaty on the Prohibition of Nuclear Weapons (TPNW)




USA
Inventory: 6 970
First test: 1945
UK
Inventory: 215
First test: 1952
France
Inventory: 300
First test: 1960
Russia
Inventory: 7 300
First test: 1949
North Korea
Inventory: 10-12
First test: 2006
China
Inventory: 260
First test: 1964
Israel
Inventory: 80
First test: N/A
Pakistan
Inventory: 130
First test: 1998
India
Inventory: 120
First test: 1974/1998
Legend
Nuclear weapon states
NPT parties
NOT NPT party
Withdrawn from NPT

# IAEA

International Atomic Energy Agency

*Atoms for Peace and Development*

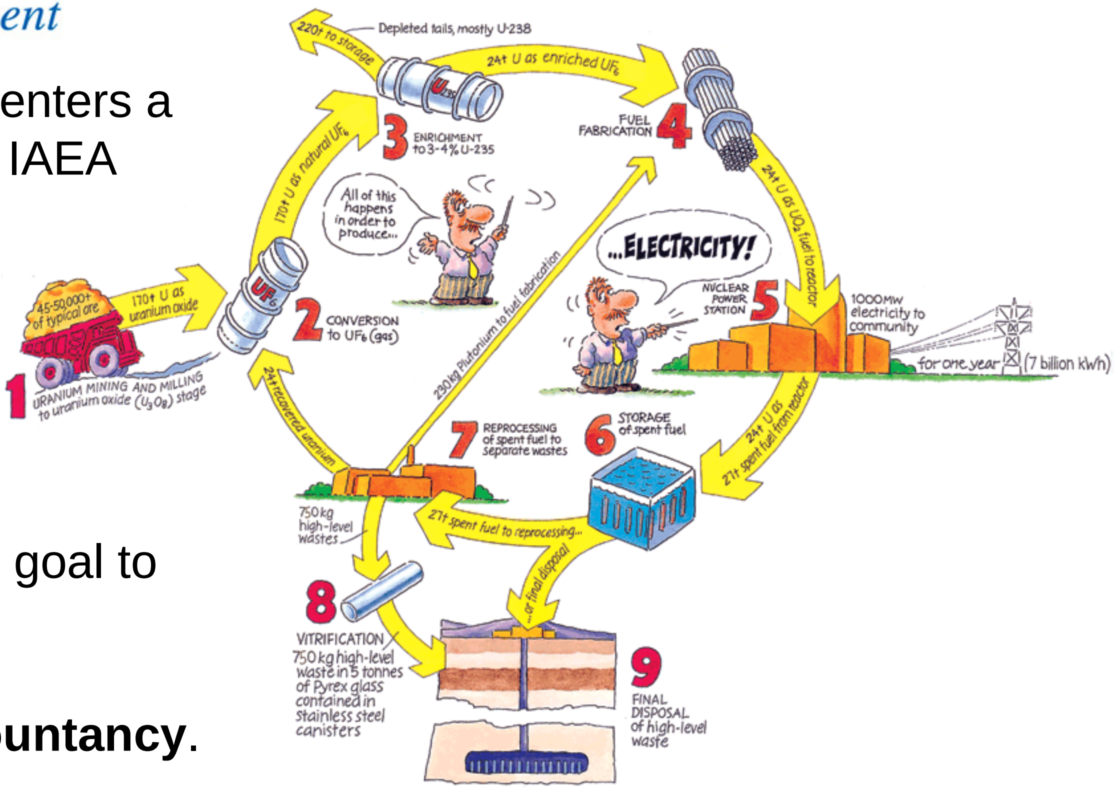
The IAEA is in charge of implementing the verification regime of the NPT

Under the NPT each non-weapon state enters a bilateral safeguards agreement with the IAEA providing for

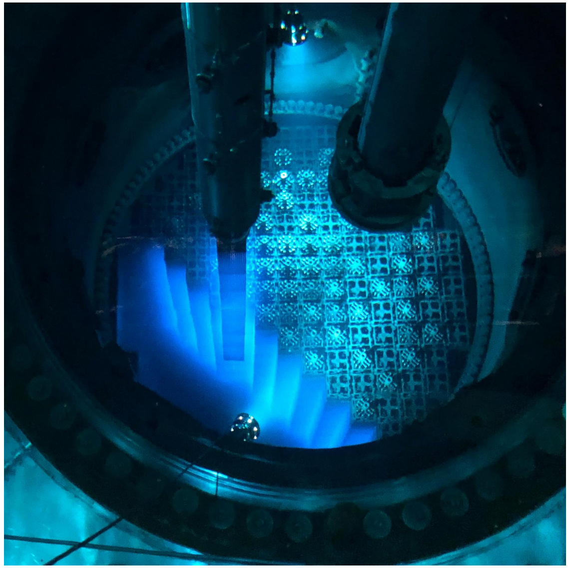
- accounting
- containment
- surveillance

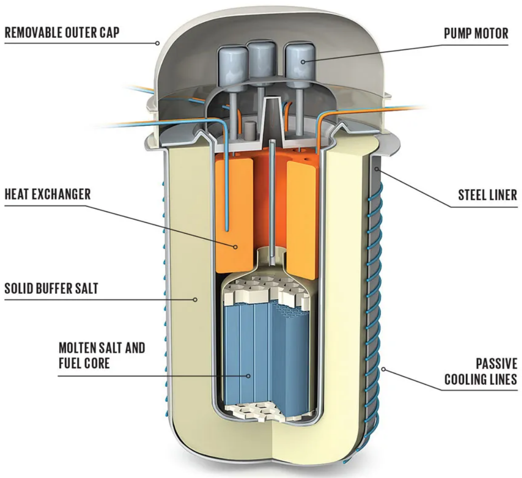
for the entire nuclear fuel cycle, with the goal to achieve continuity of knowledge (CoK).

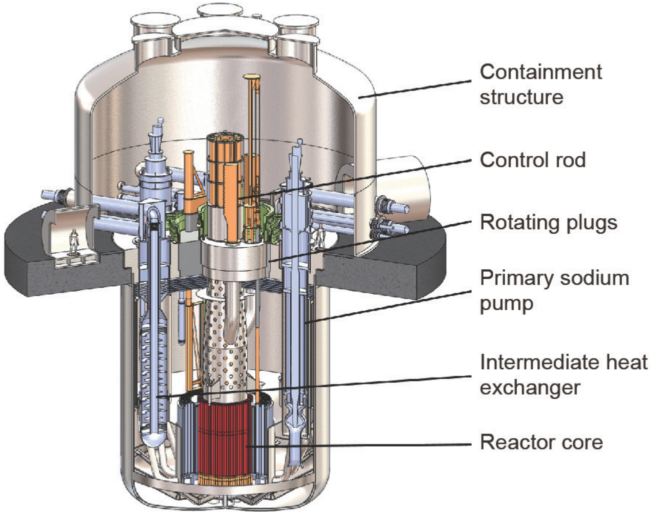
Reactor safeguards relies on **item accountancy**.



# Challenges of advanced reactors






Item accountancy relies on:
- itemizable fuel assemblies
- transparent coolant
- frequent refuelings

Non-itemizable fuel
- molten salt reactor
- pebble bed reactor

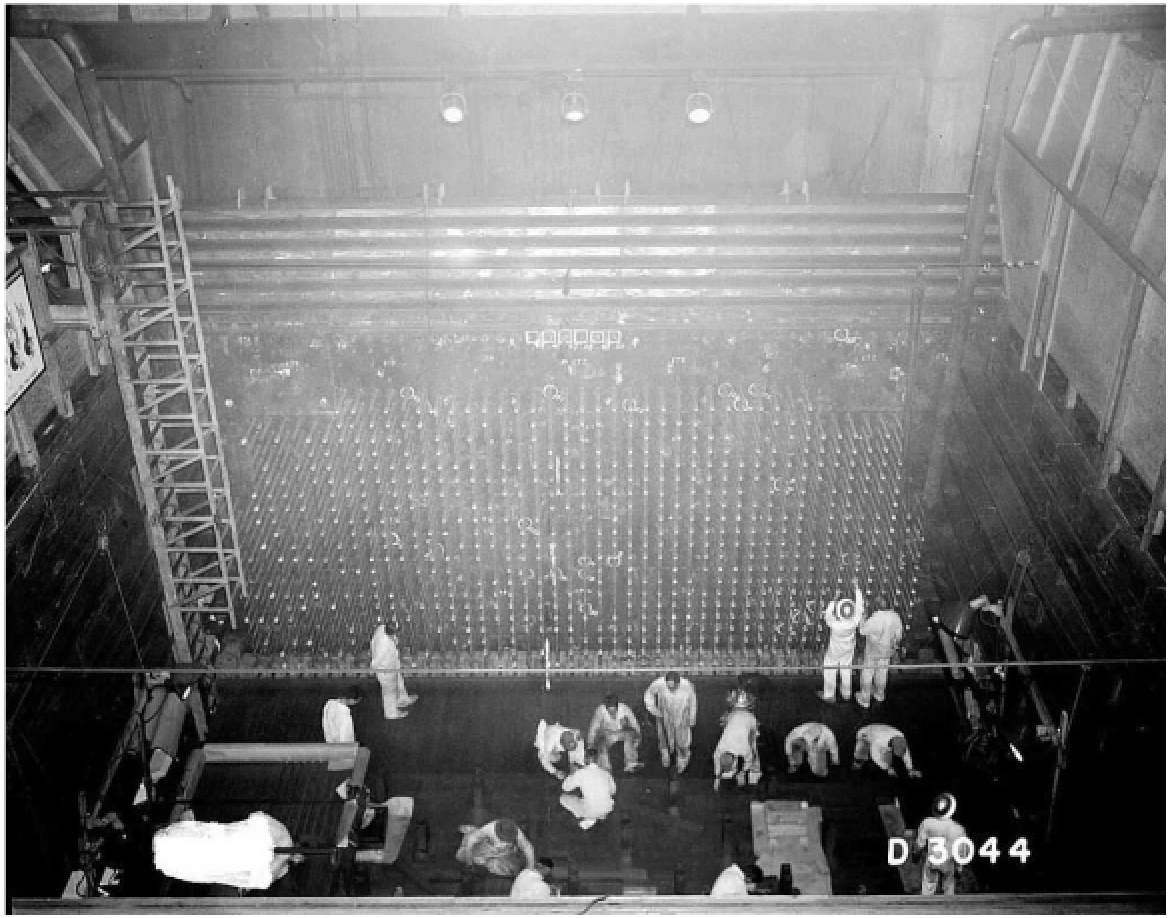
Sodium coolant (intransparent)
Lifetime cores
Reprocessing

**Each of these characteristics invalidates some of the current safeguards practices.**

# Historical weapons pathways

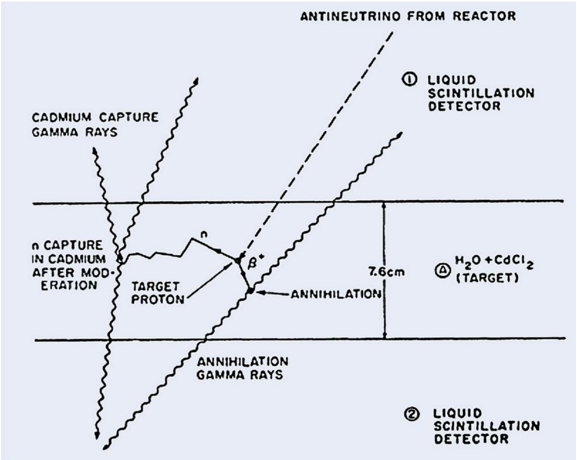
| | |
|---|---|
| U.S. | Hanford, graphite |
| Russia | Mayak, graphite |
| U.K. | Windscale, graphite |
| France | Marcoule, heavy water |
| China | uranium enrichment |
| Israel | Dimona, heavy water |
| South Africa | uranium enrichment |
| India | CIRUS, heavy water |
| Pakistan | uranium enrichment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

For smaller weapons programs typical reactor power is around **100MW – not your typical PWR**



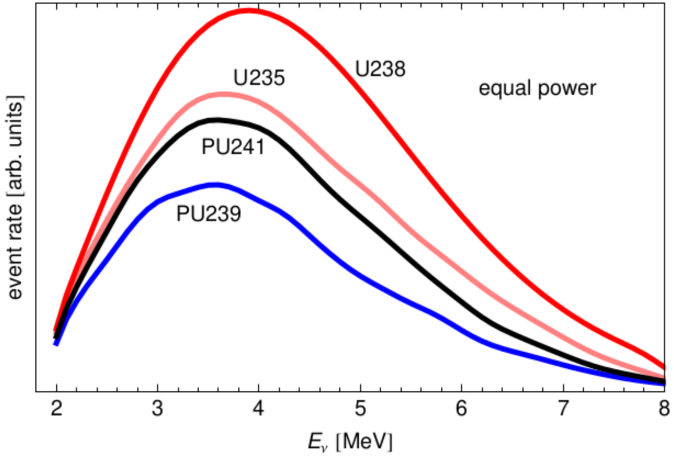

Hanford B reactor making plutonium for the Trinity test

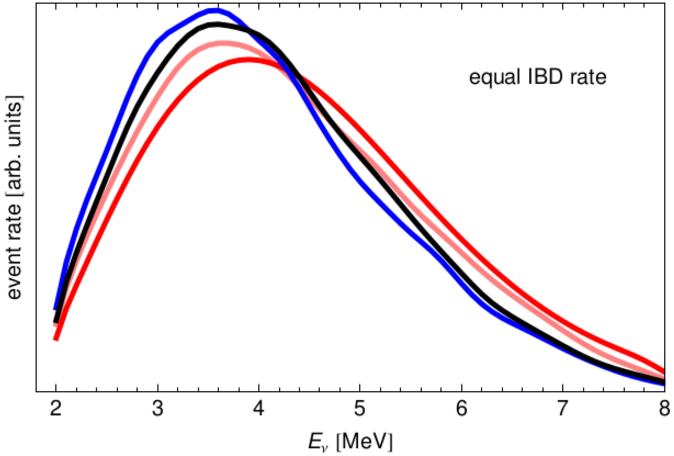
# Neutrinos for reactor safeguards




Neutrinos offer unique safeguards opportunities:

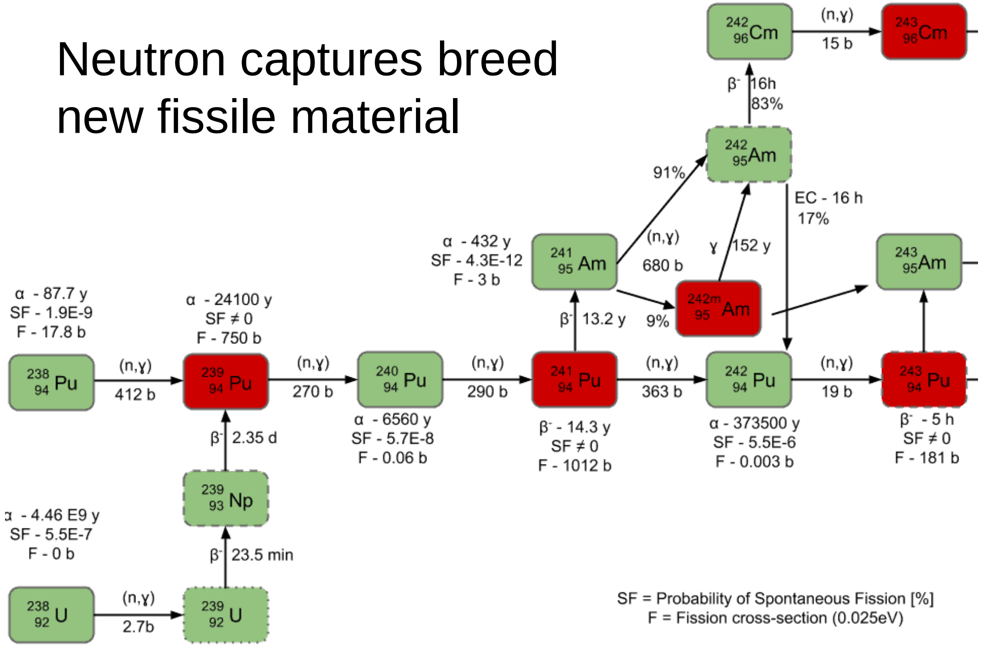
- measure reactor power
- detect undeclared production of fissile material
- independent verification of fuel burn-up

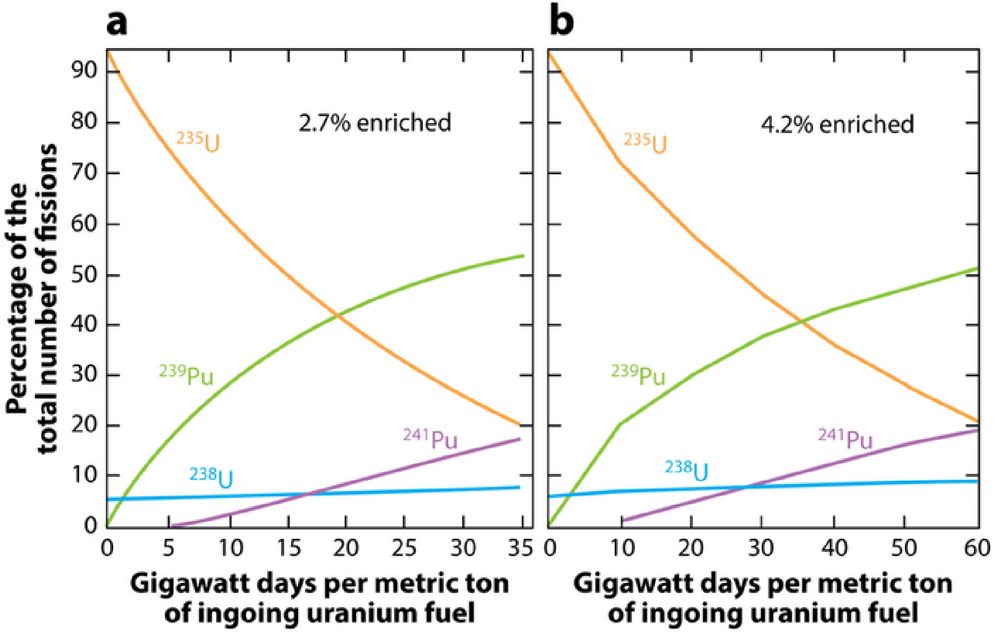


# Fuel evolution

Neutron captures breed new fissile material

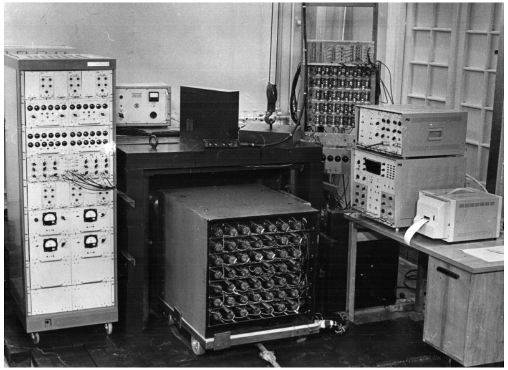


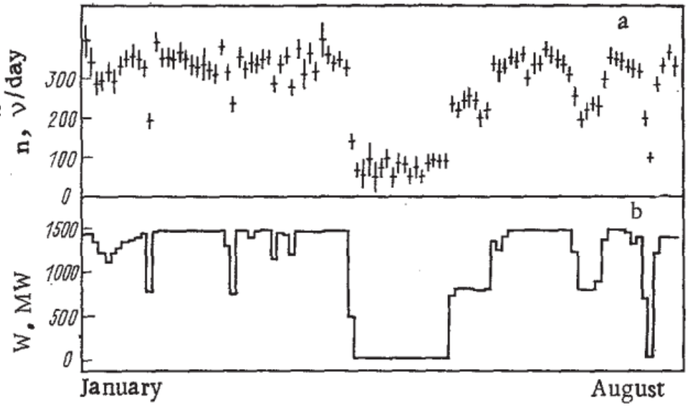

Hayes, Vogel, 2016

# Pioneering work

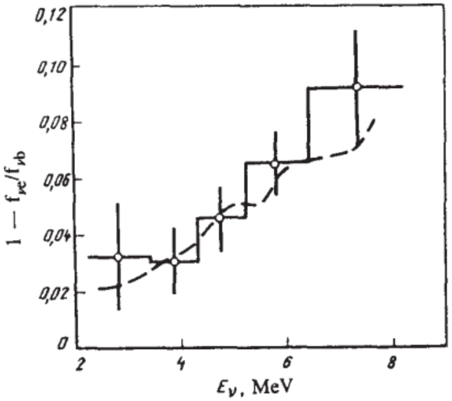
Lev Mikaelyan started work in the late 70’s on applied questions.



Rovno detector

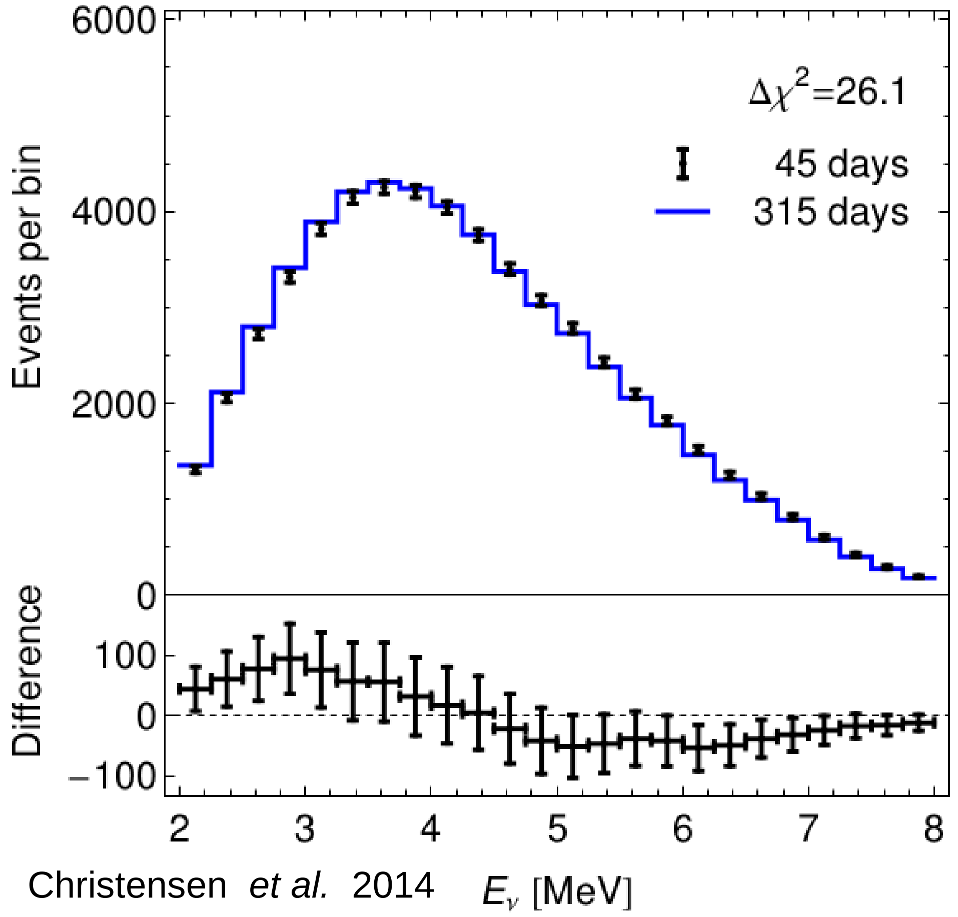



Korovkin *et al.* 1988




Klimov *et al.* 1994

# Using the energy spectrum



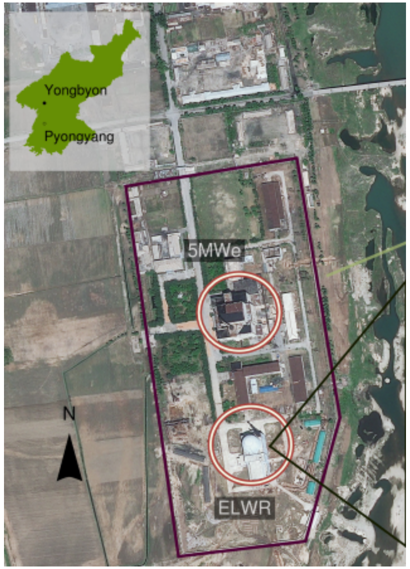

Christensen *et al.* 2014

Comparing a reactor core at 45 days in the cycle to the same core at 315 days in the cycle

Corresponding to a difference in plutonium content of about 7kg

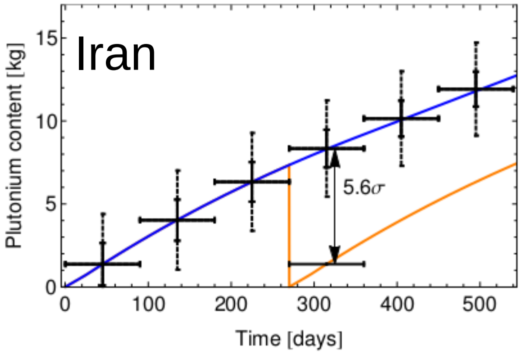
# Case studies

DPRK 2018

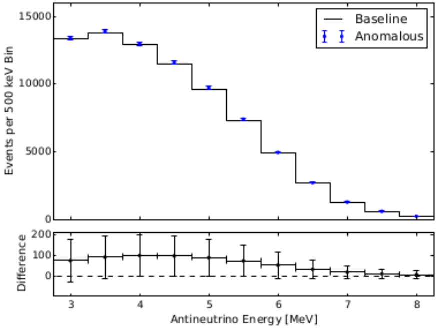



Carr *et al.* 2018

Christensen *et al.* 2014



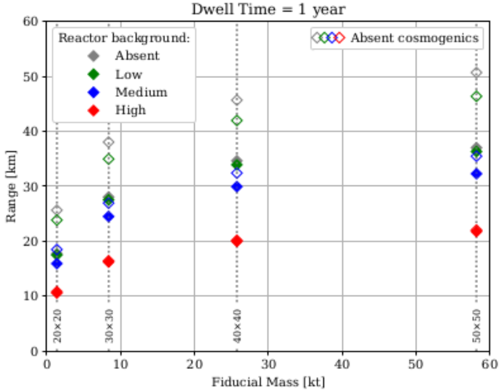

Thorium

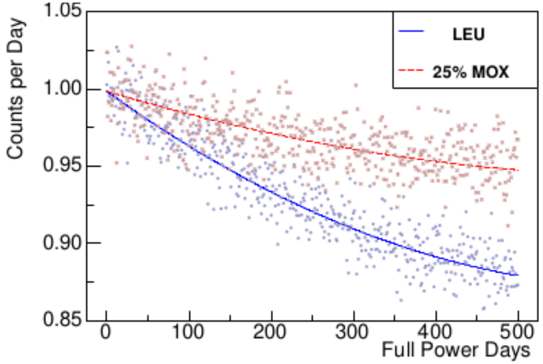



Akindele *et al.* 2016

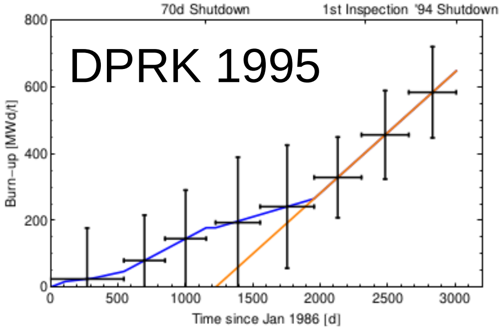
Li *et al.* 2022

Large water Cerenkov

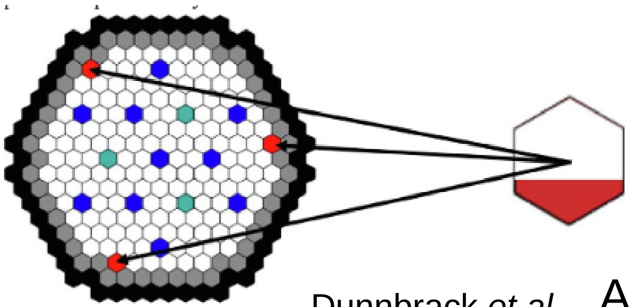



Bernstein *et al.* 2016




Christensen *et al.* 2013

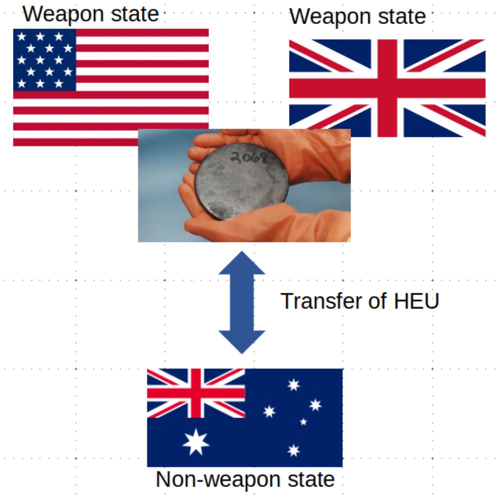


Dunnbrack *et al.* 2022

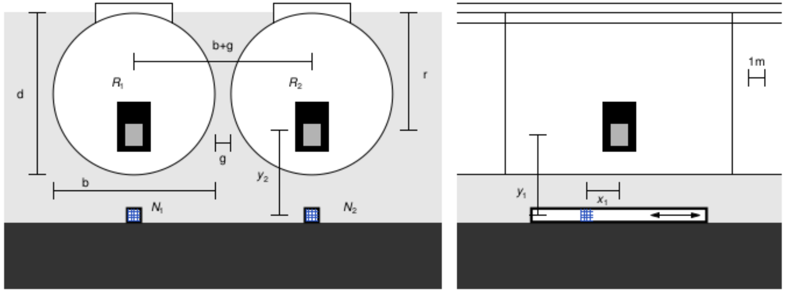
Advanced reactors

# Naval reactor safeguards

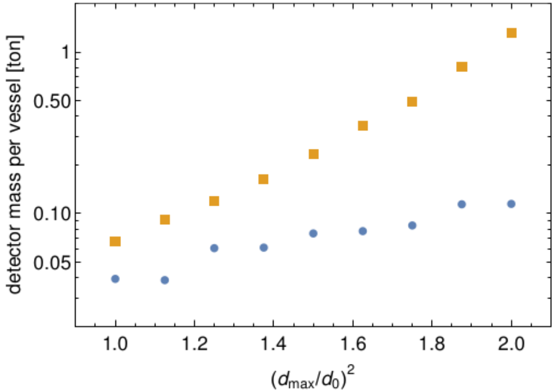
## AUKUS agreement

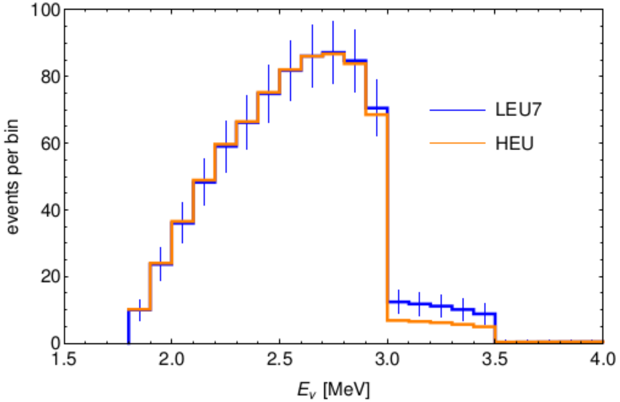



Can not observe reactor while at sea – reactor in port shut down




| Parent | $^{90}$Sr | $^{144}$Ce | $^{106}$Ru | $^{88}$Kr |
|---|---|---|---|---|
| Lifetime $\tau$ [d] | 15218 | 411 | 536 | 0.2 |
| Daughter | $^{90}$Y | $^{144}$Pr | $^{106}$Rh | $^{88}$Rb |
| $Q_\beta$ [MeV] | 2.28 | 3.00 | 3.54 | 5.31 |
| $\sigma_{\rm IBD}$ [$10^{-43}$ cm$^2$] | 0.08 | 0.45 | 0.75 | 2.84 |
| CFY $^{235}$U | 0.057 | 0.055 | 0.004 | 0.035 |
| CFY $^{239}$Pu | 0.02 | 0.037 | 0.042 | 0.012 |



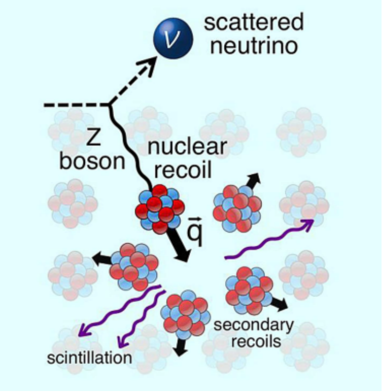




Post-shutdown IBD rate

Ton-scale segmented detectors & water overburden can **effectively safeguard** fuel in a naval reactor

B. Cogswell, PH 2022

VIRGINIA TECH. The Center for Neutrino Physics




# CEvNS studies

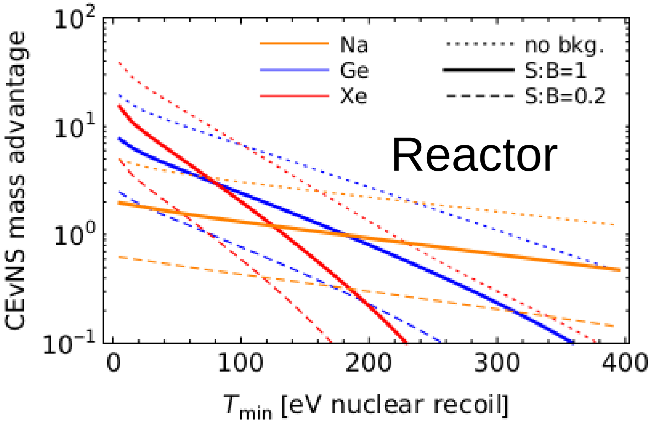
Large cross section
→ small detectors
→ lots of ideas
**Need observation!**

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} N^2 M_N \left(1 - \frac{M_N T}{2E_\nu^2}\right)$$

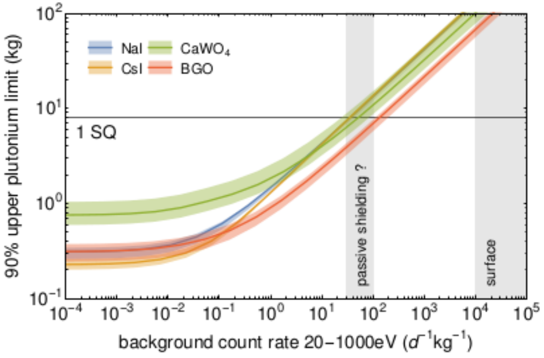
$T$ recoil energy, $N$ neutron number

P0056 Zepeng Li
P0158 Beatrice Maurice
P0166 Chloé Goupy
P0179 Janine Hempfling
P0206 Janina Hakenmüller
P0231 Olga Razuvaeva
P0399 Dario Rodrigues
P0566 Youssef Sarkis
P0619 Dimitrii Rudik
P0632 Ran Chen
P0653 Diana Manus
P0738 Nicole Scherrer
P0762 Sofia Andringa
P0789 Byungju Park

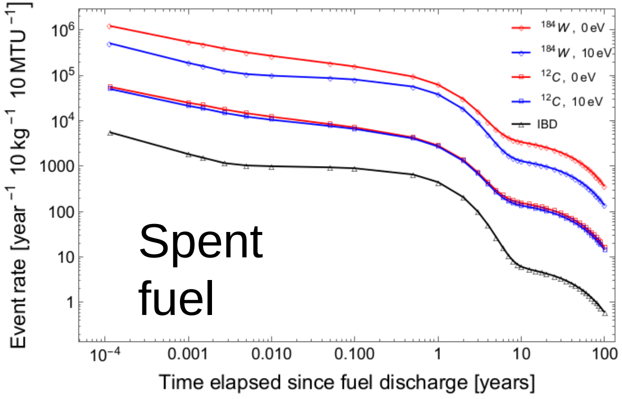
Bowen, PH, 2021




Cogswell *et al.* 2021

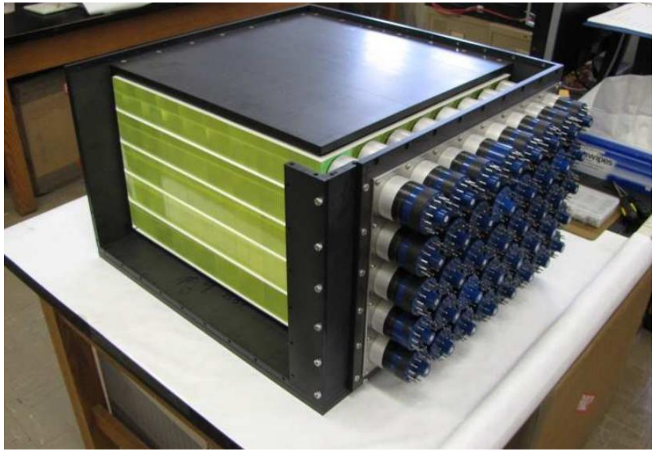



PALEOCCENE
Passive color center-based detectors
P0226 Bernadette Cogswell

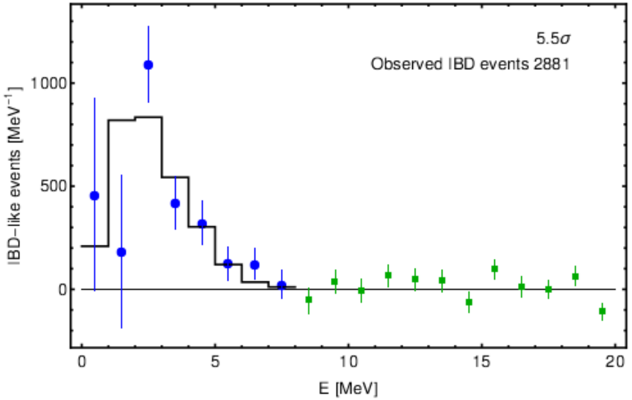



v. Raesfeld, PH 2022

# Surface detection

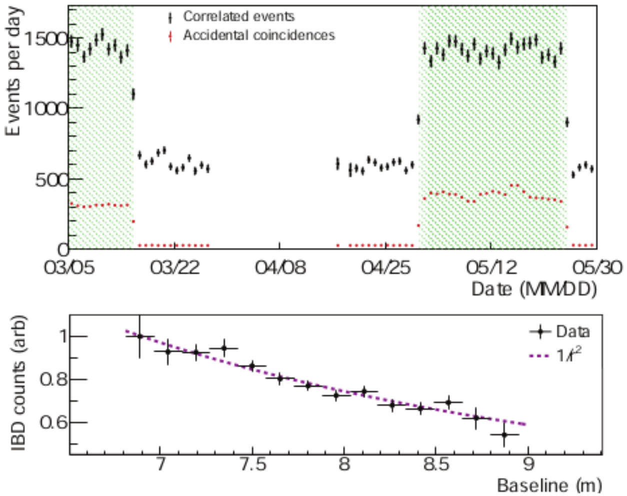


CHANDLER 2018
3D segmentation
solid plastic scintillator
topology
P0090 Keegan Walkup




**Essential step towards applications!**

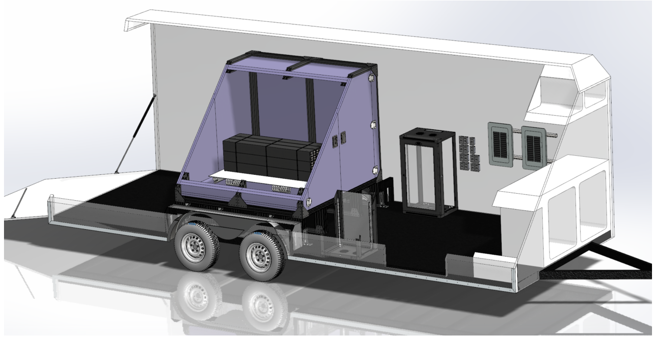
PROSPECT 2018
2D segmentation
liquid scintillator
pulse-shape discrimination



# U.S. surface detector R&D

P0422 Steven Dazeley

ROADSTR – 100kg

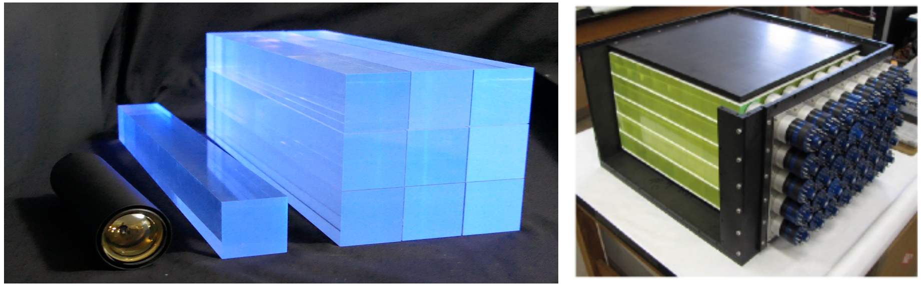


Lawrence Livermore National Laboratory

Technology testbed, test of concepts and neutron background characterization

Mobile Antineutrino Demonstrator – ton scale

*Detector Technology Options*



*2D segmentation with $^{6}$Li-doped PSD plastic scintillator*

*3D segmentation with $^{6}$LiZnS & WLS plastic scintillator*

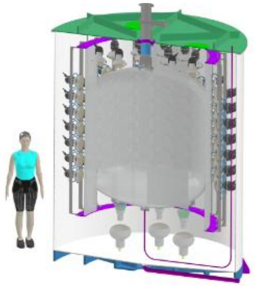
Lawrence Livermore National Laboratory · Oak Ridge National Laboratory · NIST · Georgia Tech · Illinois Institute of Technology · Virginia Tech · Yale · U.S. Naval Academy

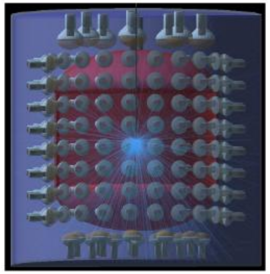
Goal is to advance the technical readiness of reactor neutrino detection

# Water Cerenkov R&D

## WATCHMAN – 1kton

EOS 4 ton prototype





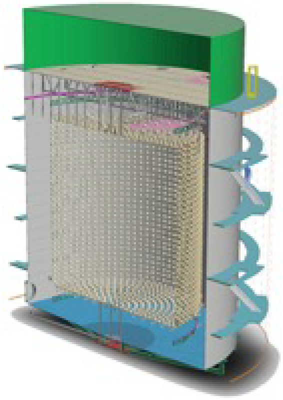
Closely coupled to BNL effort to construct 30-ton tank for demonstration of WbLS production, transparency and stability

Together these prototypes will demonstrate the feasibility and capabilities of hybrid detectors for nonproliferation and fundamental physics applications

Multi-kton detectors can provide reactor monitoring and exclusion over 10’s of km distance.

Potential role in future agreements.

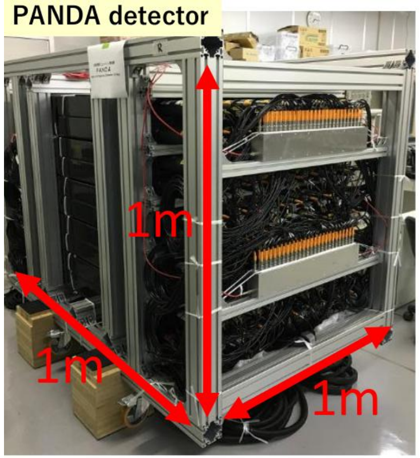
P0093 Tanner Kaptanoglu
P0268 Ayşe Bat
P0671 Viacheslav Li
P0690 Edward Callaghan

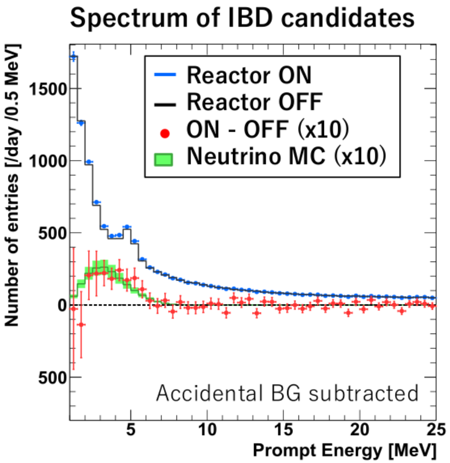


A candidate conceptual design for a kiloton-scale aqueous detector demonstrating remote sensitivity to reactor operations. Shown is a 12 m diameter cylindrical tank.

Possible early shutdown of original UK reactors motivates reconsideration of sites in the US.

# Global detector R&D efforts



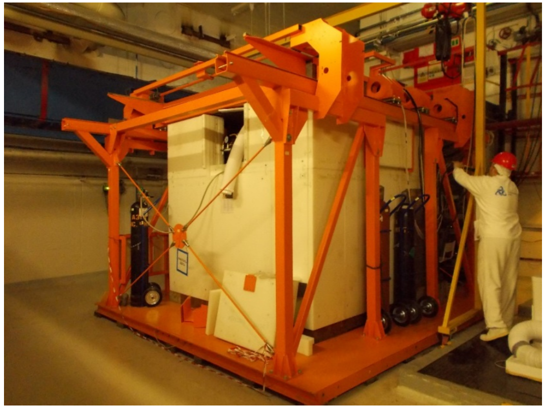




PANDA at Ohi NPP (Japan) 2018/2019
2D segmented, plastic scintillator


ISMRAN installed at 100MW Dhruva reactor (India), 2D segmented, plastic scintillator


VIDARR Detector developed at the University of Liverpool, re-visit of supplementary Wylfa data underway (UK), 2D segmented, plastic scintillator

iDREAM has been installed and commissioned in 2021 at Kalinin NPP (Russia), 20m from 3GW reactor core, single volume, liquid scintillator



P0625 Rudik Nugamanov

P0426 Saurav Saha
P0357 Felicia Sutanto
P0636 Rijeesh Keloth

NuTools

Exploring Practical Roles for **Neutrinos** in **Nuclear Energy and Security**

P0706 Michael Foxe

Department of Energy
National Nuclear Security Administration
Washington, DC 20585

NNSA
National Nuclear Security Administration

June 1, 2020

**Charge to the Executive Group for the Antineutrino Reactor Monitoring Scoping Study**

NNSA's Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D) detection portfolio seeks strategic input to guide future R&D investments. The charge to the **Antineutrino Reactor Monitoring Scoping Study** Executive Group is to facilitate broad engagement with interested communities on the topic of antineutrino-based monitoring of nuclear reactors and associated post-irradiation fuel cycle activities. The particular focus of such engagement should be on the **potential utility** of antineutrino detection technologies and required detection capabilities in the following contexts:

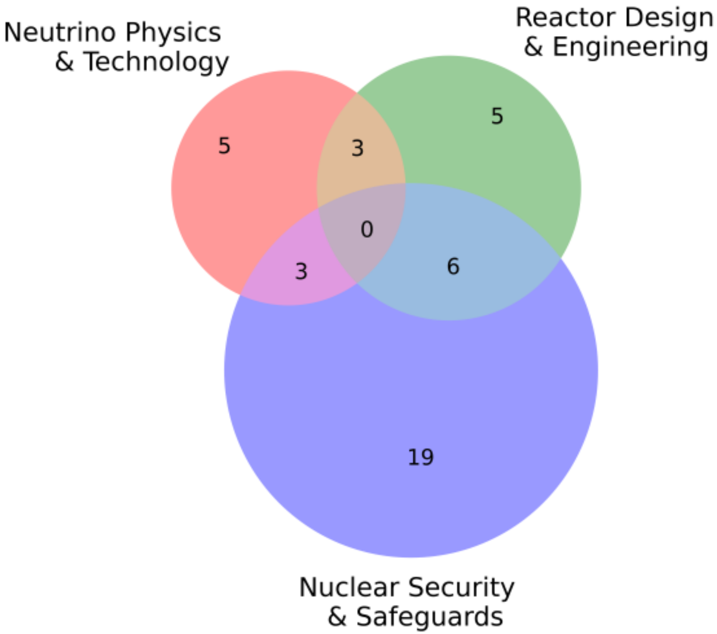
Focus on **utility**

Method is end-user engagement **not** technical analysis

# NuTools executive group

| | |
|---|---|
| Oluwatomi Akindele | Lawrence Livermore National Laboratory |
| Nathaniel Bowden | Lawrence Livermore National Laboratory |
| Rachel Carr | Massachusetts Institute of Technology |
| Andrew Conant | Oak Ridge National Laboratory |
| Milind Diwan | Brookhaven National Laboratory |
| Anna Erickson | Georgia Institute of Technology |
| Michael Foxe | Pacific Northwest National Laboratory |
| Bethany L. Goldblum | Lawrence Berkeley National Laboratory & University of California, Berkeley |
| Patrick Huber | Virginia Tech |
| Igor Jovanovic | University of Michigan |
| Jonathan Link | Virginia Tech |
| Bryce Littlejohn | Illinois Institute of Technology |
| Pieter Mumm | National Institute of Standards and Technology |
| Jason Newby | Oak Ridge National Laboratory |

# End-user engagement during the pandemic




41 interviews between May – September 2020

2 or more interviewers in each case

Notes from each interview approved by each interviewee

Input from technical community via a virtual workshop with 131 participants from 14 nations with presentations from:

PANDA, Ocean Bottom Detector, LiquidO, JUNO TAO, Efforts in Turkey, VIDARR, CHANDLER, PROSPECT, SANDD, Watchman, ISMRAN, CONUS, NUCLEUS, Efforts at U. Chicago, MINER, RICOCHET, Nucifer, Angra/CONNIE, vIOLETA, NuLAT and NUDAR.

# Cross cutting findings

Three findings of this study apply across all potential applications of neutrino technology:

**End-User Engagement** The neutrino technology R&D community is only beginning to engage attentively with end-users, and further coordinated exchange is necessary to explore and develop potential use cases.

**Technical Readiness** The incorporation of new technologies into the nuclear energy or security toolbox is a methodical process, requiring a novel system such as a neutrino detector to demonstrate sufficient technical readiness.

**Neutrino System Siting** Siting of a neutrino-based system requires a balance between intrusiveness concerns and technical considerations, where the latter favor a siting as close as possible.

# Utility framework

- 1) Need for a new or improved capability
  - → Determined by end-user communities.
- 2) Existence of a neutrino signal
  - → Determined by technology development community.
- 3) Availability of a neutrino detection technology
  - → Determined by technology development community.
- 4) Compatibility with implementation constraints
  - → Determined by end-user communities.

**Need to meet/likely meet all four criteria**

# Use case findings

**Current International Atomic Energy Agency (IAEA) Safeguards** For the vast majority of reactors under current IAEA safeguards, the safeguards community is satisfied with the existing toolset and does not see a specific role for neutrinos.

**Advanced Reactors** Advanced reactors present novel safeguards challenges which represent possible use cases for neutrino monitoring.

**Future Nuclear Deals** There is interest in the policy community in neutrino detection as a possible element of future nuclear deals involving cooperative reactor monitoring or verifying the absence of reactor operations.

# Use case findings

**Reactor Operations** Utility of neutrino detectors as a component of instrumentation and control systems at existing reactors would be limited.

**Non-Cooperative Reactor Monitoring or Discovery** Implementation constraints related to required detector size, dwell time, distance, and backgrounds preclude consideration of neutrino detectors for non-cooperative reactor monitoring or discovery.

**Spent Nuclear Fuel** Non-destructive assay of dry casks is a capability need which could potentially be met by neutrino technology, whereas long-term geological repositories are unlikely to present a use case.

**Post-Accident Response** Determining the status of core assemblies and spent fuel is a capability need for post-accident response, but the applicability of neutrino detectors to these applications requires further study.

# Summary

**Antineutrinos likely have some utility in a nuclear security and nuclear energy context.**

**Utility often lies in areas orthogonal to what physicists tend to expect.**

**Room for technology R&D, but needs to be informed by end-user needs, not just a better mousetrap.**

Potential application space is large, did not say much about passive detectors, naval reactors, spent fuel, breeder reactors, explosion monitoring etc.

Maitland Bowen

Apurva Goel

Caroline v. Raesfeld

NSF REU students

Dr. Bernadette Cogswell

Dr. Eric Christensen

Dr. Patrick Jaffke

Dr. Tom Shea

Group members current & former

COLLEGE OF SCIENCE VIRGINIA TECH

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NSF

U.S. DEPARTMENT OF ENERGY | Office of Science

National Nuclear Security Administration

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