Sensitivity Tool for Antineutrino Monitoring of Small Modular Reactors

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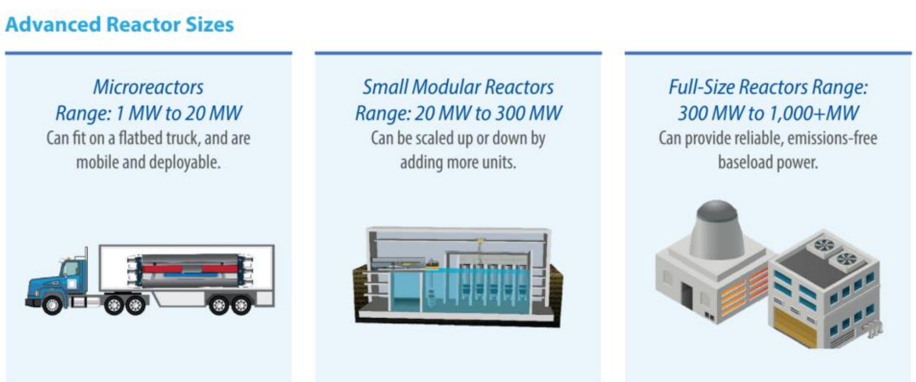
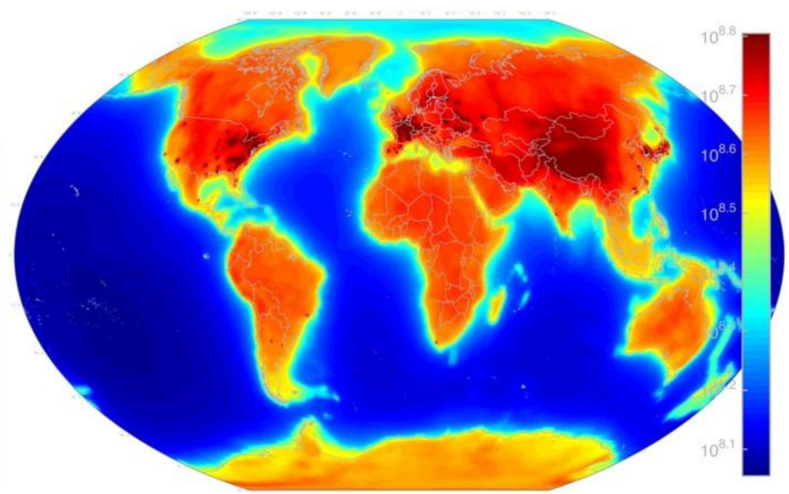
Applied Antineutrino Physics (AAP) – York, England

Overview

- Small modular reactors (SMRs) are a promising technology to meet global energy demands while offering flexible power loads
- SMRs are the most likely Generation IV reactor to first reach commercial operation
- Capability for neutrino detectors for SMR applications has been underexplored



U.S. DOE Advanced Reactor Fact Sheet



Antineutrino Global Map

SMR Design Differences vs. LWRs

- Smaller power by an order of magnitude
- Potential for multiple modules on a singular site
- Infrequent or non-existent refuelings
- Can be of any design (Gen IV+, not just LWR)
  - Molten salt
  - Pebble bed
  - Liquid metal

NuScale Power Overview Future Vision of Nuclear R&D

IAEA Safeguards of Current Reactors

- Comprehensive Safeguards Agreements (CSA)
  - Verification that a state's declaration of nuclear material is complete
- Additional Protocol (AP)
  - Supplement agreement for declared and undeclared use at reactors
- Material accountancy & containment/surveillance
  - Continuity of knowledge (CoK) is key

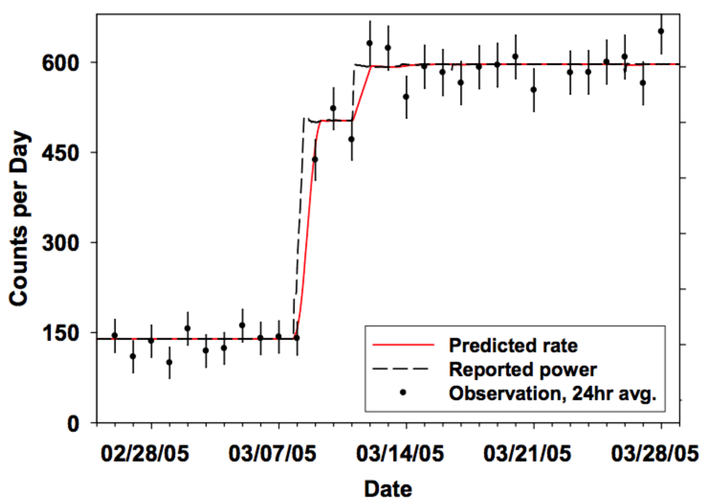
Safeguards Challenges of SMRs

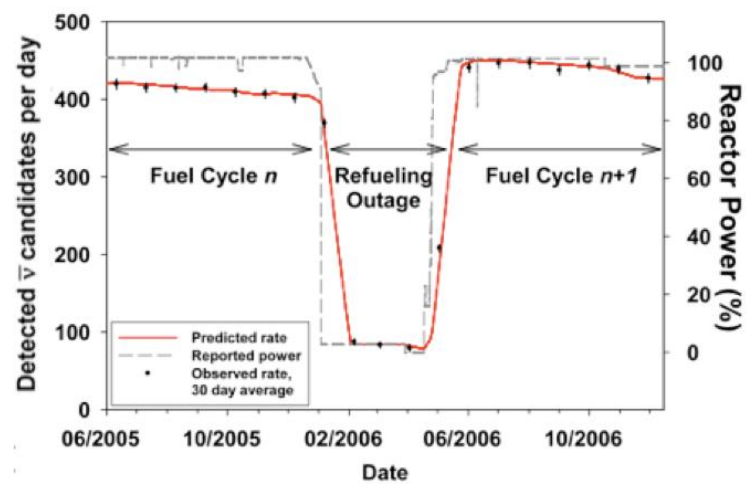
Feature	LWR	SMR
Fueling (FF) (Storage of FF and loading)	On-site – refuel every 12-24 months – 40 year life	On-site or off-site (Factory Site or Service Facility) – refuel few times if ever over lifetime – 40-60 year life
Spent Fuel (SF) (Removal from core and storage)	SF stored in pool to cool – shipped after years to dry storage or reprocessing (May have 40 year old fuel on site)	1) SF may be stored on-site by reactor or in pools or casks 2) Shipped to supplier State 3) Fuel remains in reactor for life
Reactor core (CF) (Fuel in vessel in operation)	Reactor core access during refueling	Reactor core may only be accessible during initial loading – tight spacing may make reactor cores refueled on site difficult to access
Operations – Power levels, continuity of knowledge of CF, SF	Refueling allows for access and analysis of core 12-24 months	With infrequent or no refueling – no information on core fuel status could occur for decades
Decommissioning – Removal of all fuels and essential equipment	D&D activities on-site including defueling and removal of Essential Equipment with IAEA inspection and visitation rights	SMR can be dismantled and shipped complete to supplier

B. Boyer "Understanding the Specific Small Modular Reactor Safeguards Challenges." 2016

How could neutrinos play a role?

- Verification of plant operation
  - Plant on vs. off status
- Single unit status verification
  - (N) vs. (N-1) reactors operating
- Single unit power uprate/downrate
  - Unit X operations at +/- power

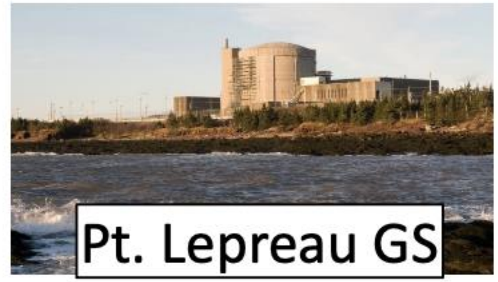




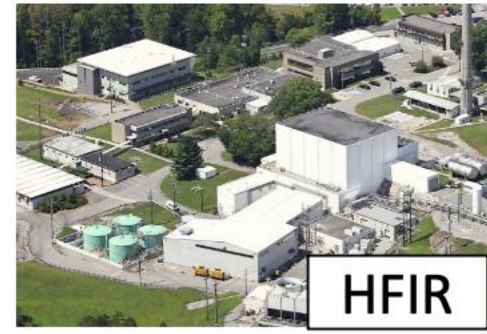
Bowden et al (2008)

Sensitivity tool for Mobile Antineutrino Demonstrator (MAD)

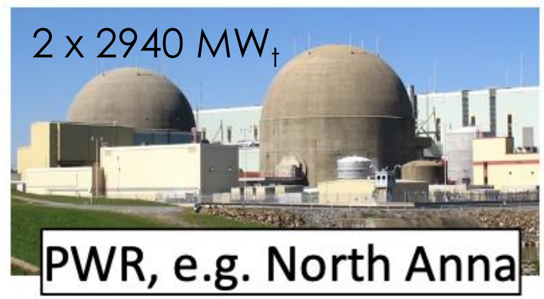
- Current U.S. project to construct & deploy mobile ton-scale antineutrino detector
  - Several reactor site deployment options
- Develop easy tool to understand sensitivities of above-ground detectors for applications
  - Python-based
  - Communicate various use cases

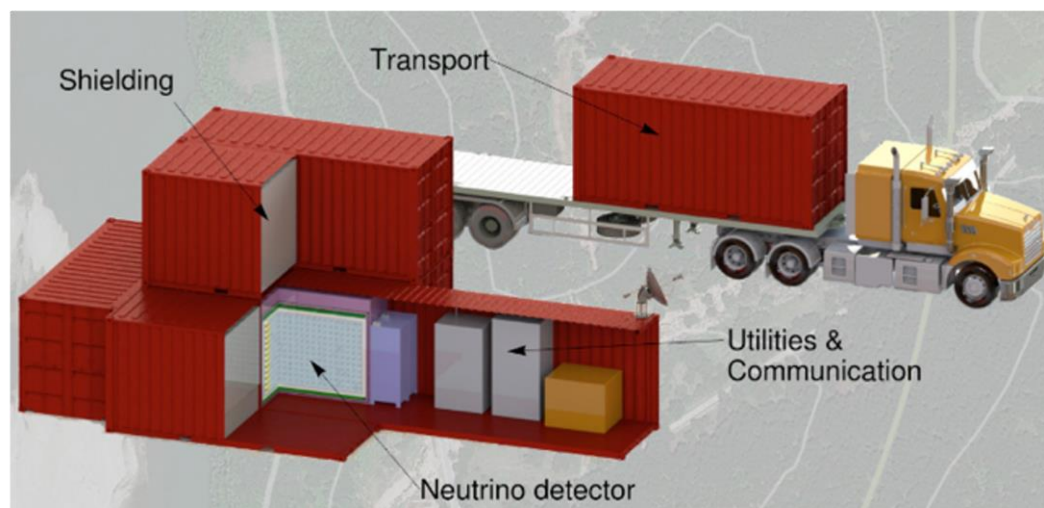


PHWR, 2064 MW_t

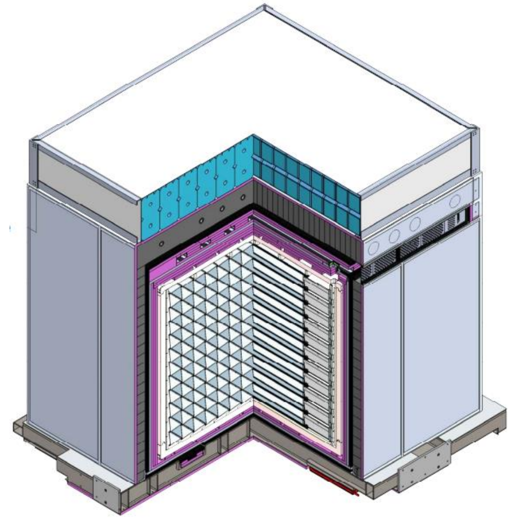


Research reactor, 85 MW_t

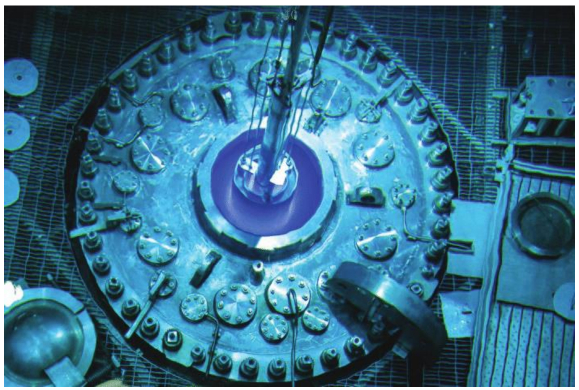




Tool Structure



Detector Response
- Response matrix
- Selection efficiency
- Mass

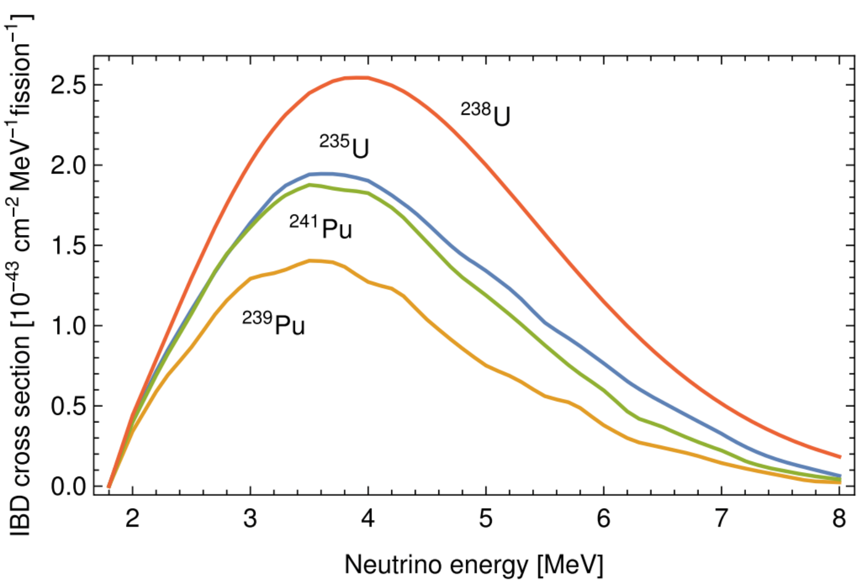


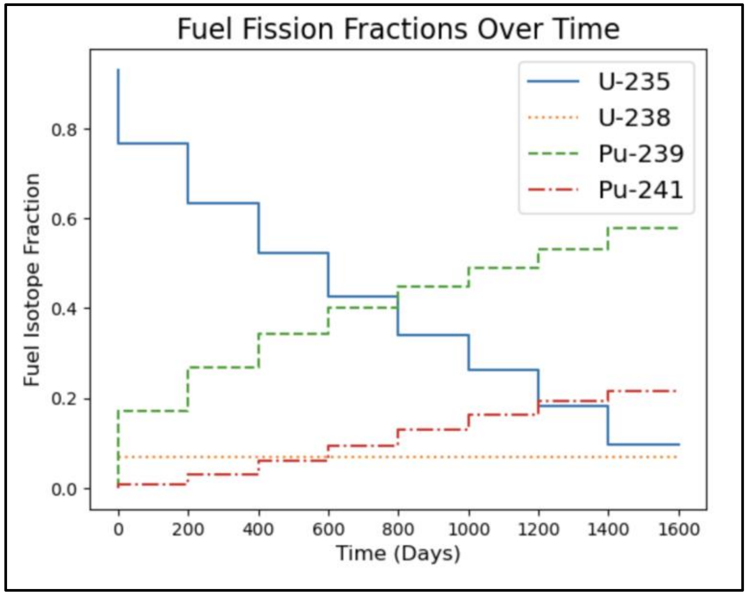
Source Spectrum **[MW/m²/MeV]**
- 4 isotopes
- Conversion/summation
- Global data
- IBD cross-section
- Oscillation

Background Spectrum **[Hz/MeV]**
- Reference surface spectra
- Elevation/humidity

Reactor input calculation

- Multiple detectors and reactors
- Fission fractions for U and Pu isotopes
- Time-dependent capability
- Neutrino spectrum from Huber-Mueller

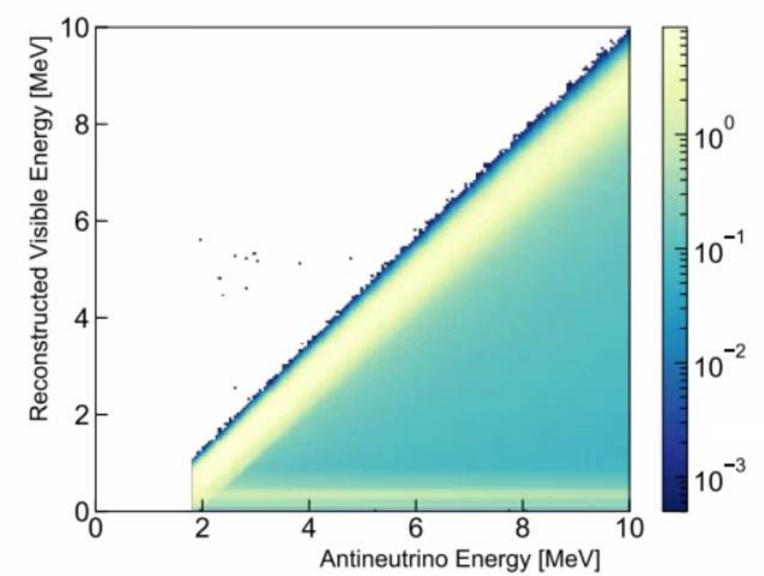




Example fission fractions

Detector and background

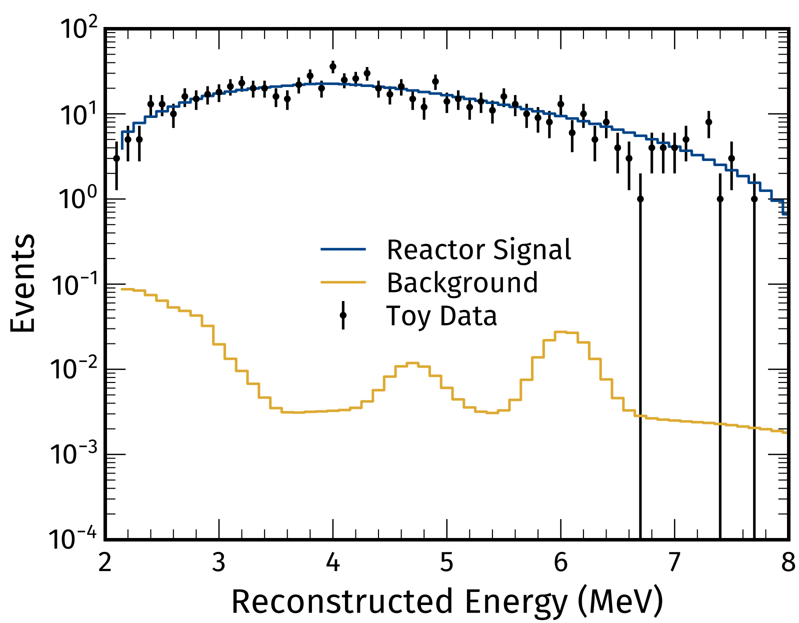
- Near-field detector
  - Based on PROSPECT systematics
    - Response matrix
    - Selection efficiency
  - Option for custom mass and efficiencies
- Background model
  - Based on PROSPECT backgrounds
  - Fixed percentage backgrounds

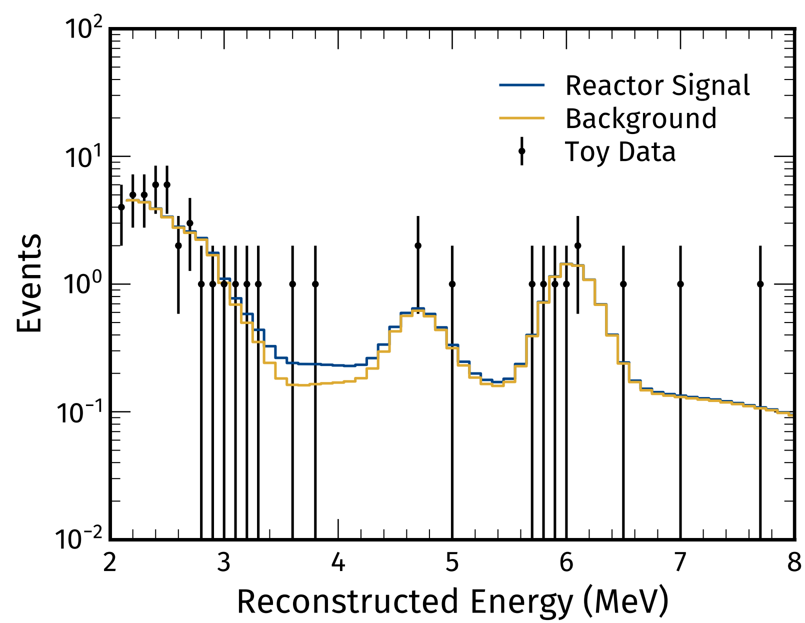


[Prospect, *Phys. Rev. D.* (2021)]

Statistical analysis tool

- Use **phyf** fitting code to form confidence intervals
- Feed in output of neutrino event rates from signal/BG
- Form signal and background PDFs
- Sample from PDFs to form fake datasets
- 5% false positive and false negative rates

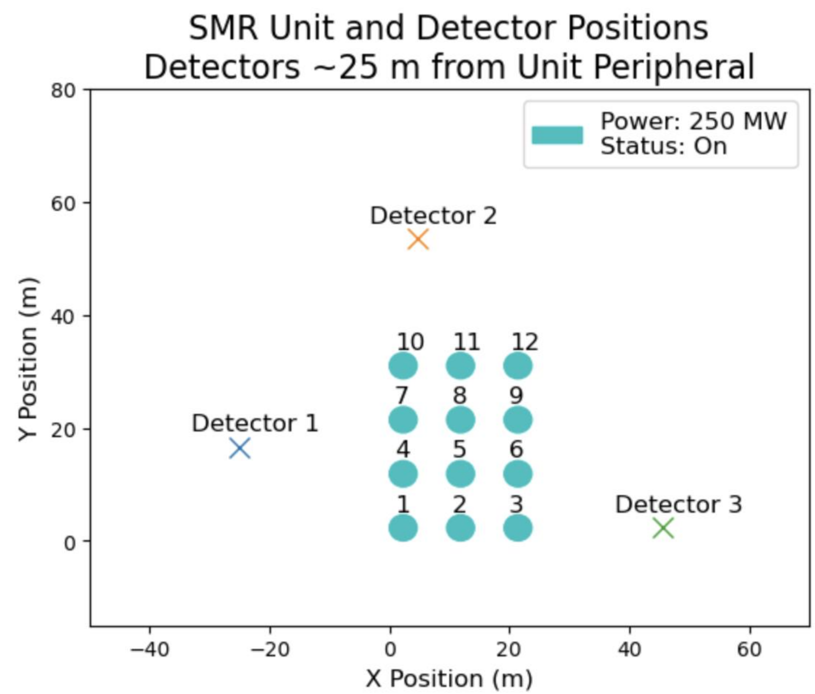




Example case spectra

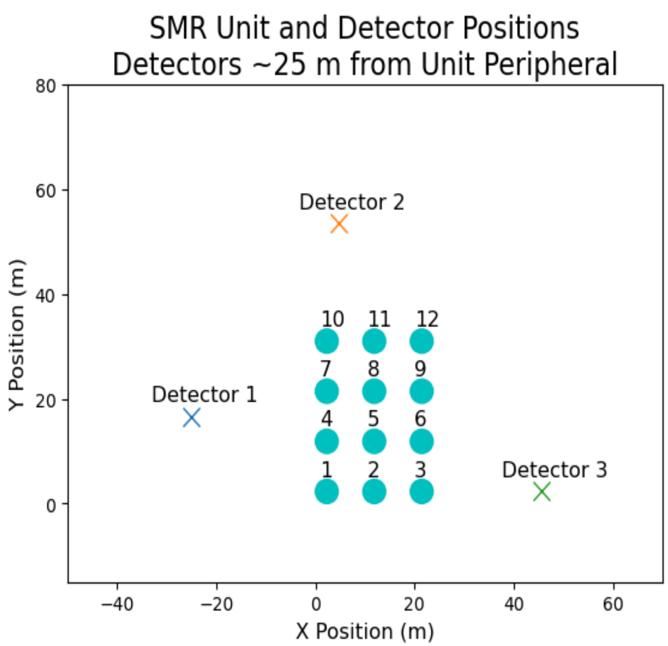
Example SMR facility layout

- N reactors, M detectors
- 12 power modules
  - Each 250 MWt, ~ 100 MWe
- 3 detector locations
  - Approximately same distance from reactor array boundary
  - Considered as three individual detectors for this study



Example analysis for 12 unit SMR plant

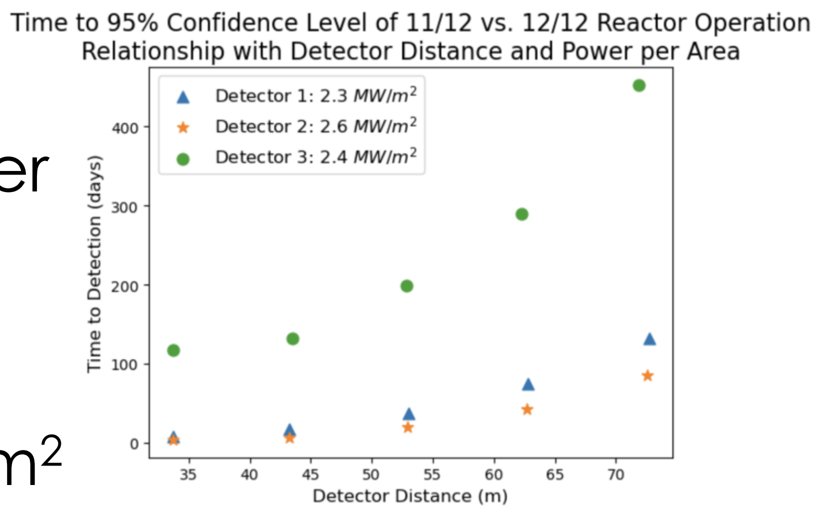
- H_0: All units in off status
- H_A: All units in on status
- Relationship with distance nearly identical

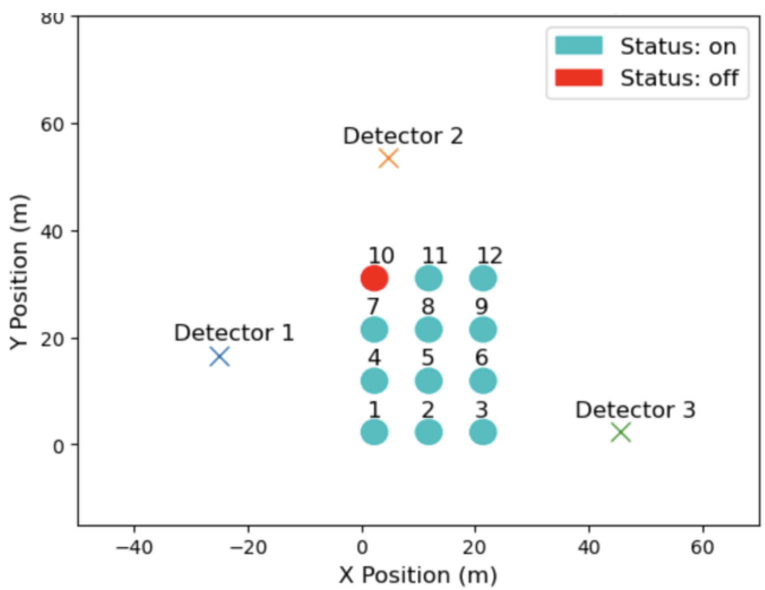


Detector Position	Distance (m)	Time (d)
1	34	1.8
2	34	1.3
3	34	1.6
1	43	4.3
2	43	3.8
3	43	4.5
1	53	9.4
2	53	7.8
3	53	8.7
1	63	16.9
2	63	45.9
3	63	16.2
1	73	31.9
2	73	28.1
3	73	28.1

Example analysis for single unit operation at increased power

- H_0: All reactors at nominal power
- H_A: Single reactor at increased power
- Super-positional measure MW/m^2 measure not sufficient





Unit 10 increased power	Detector Position	Time (d)
10%	1	1352
10%	2	363
10%	3	> 1600
20%	1	301
20%	2	90
20%	3	> 1600
50%	1	44
50%	2	14
50%	3	368

To the future

- **Understand the relevant questions to answer in the operations and international safeguards context**
  - E.g., Power measurement from a reactor operator perspective is likely not desired
- Calculate reactor power measurement and quantification of fissile isotope vector
- Explore MAD-relevant possibilities for reactor deployment
- Streamline tool for simple user input and manipulation

Thanks to MAD Collaboration

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