Oak Ridge National Laboratory

Neutrinos for Nonproliferation: Safeguards and Advanced Reactors

Andrew Conant

Oak Ridge National Laboratory

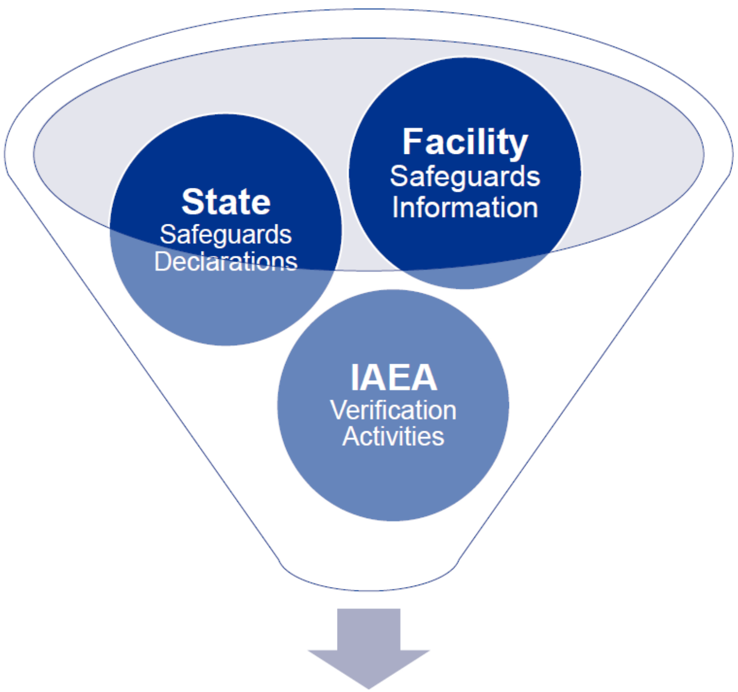
Applied Antineutrino Physics (AAP) – September 18th, 2023

York, England

U.S. DEPARTMENT OF ENERGY

What is international safeguards?

- Credible conclusions on a State's fulfilment of their safeguards obligations



Drawing Credible Conclusions on State's safeguards obligations

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International Atomic Energy Agency (IAEA)

- "The Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health, and prosperity throughout the world [and that assistance] is not used in such a way as to further any military purpose."

IAEA

IAEA Quick Facts

Year Founded	1957	**Headquarters**	Vienna, Austria
Member States	173	**Liaison Offices**	Geneva, Switzerland New York, USA
Number of Employees	ca. 2,500	**Regional Offices**	Toronto, Canada Tokyo, Japan
Laboratories	19	**Regular Budget**	approx. €380 million

IAEA at a Glance 2021

Role of IAEA Safeguards

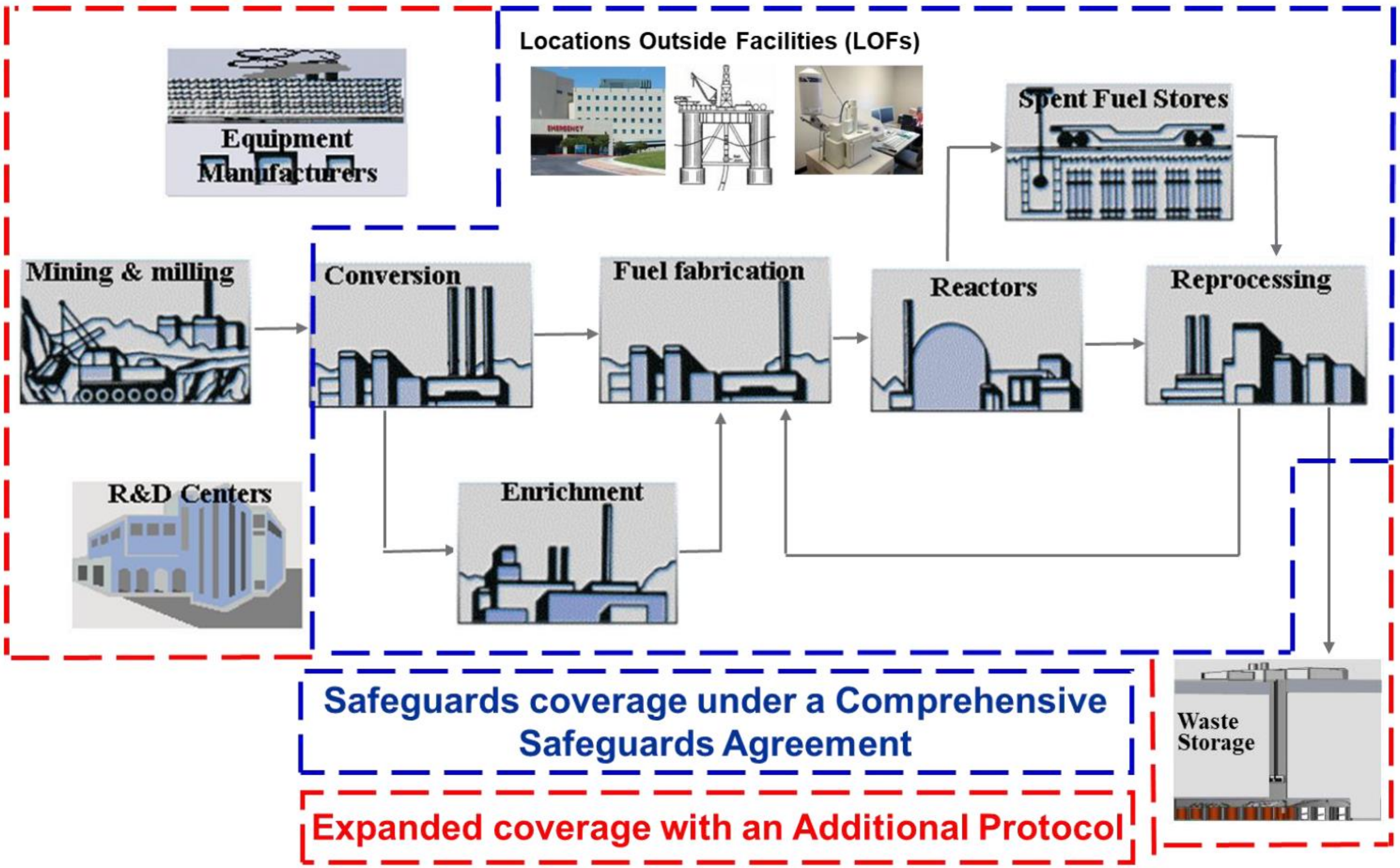
- Three main goals
  - Non-diversion of nuclear material at declared facility (detection of diversion)
  - Absence of undeclared production or processing of nuclear material at declared facilities (detection of misuse)
  - Absence of undeclared nuclear material or activities

- Safeguards is **not**
  - Physical security
  - Discovery of insider threat or non-state actors

Safeguards Agreements

- Comprehensive Safeguards Agreements (CSAs)
  - Applied to all Non-Nuclear Weapons States (NNWS) in the NPT
  - Verify that state's declarations are correct and complete
  - But main limitation is the only on declared material
- Additional Protocol (AP) to safeguards agreements
  - In 1997, gives IAEA access to (in some states):
    - Information on whole nuclear fuel cycle within state
    - Complementary Access to facilities and locations within state
    - Use of environmental sampling for undeclared activities

Nuclear Fuel Cycle



Significant quantities (SQ) and Timeliness of Detection

- SQ: approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded
- Inspection frequency based on timeliness goals

TABLE 1. SIGNIFICANT QUANTITY (SQ) VALUES CURRENTLY IN USE

Material	*SQ*
Direct use nuclear material	
Plutonium[a]	8 kg *plutonium*
^{233}U	8 kg *^{233}U*
High enriched uranium (HEU) (^{235}U $\geq$ 20%)	25 kg ^{235}U
Indirect use nuclear material	
Uranium (^{235}U < 20%)[b]	75 kg ^{235}U (or 10 t *natural uranium* or 20 t *depleted uranium*)
Thorium	20 t *thorium*

[a] For *plutonium* containing less than 80% ^{238}Pu.
[b] Including *low enriched uranium (LEU)*, *natural uranium* and *depleted uranium*.

TABLE 2. ESTIMATED MATERIAL CONVERSION TIMES FOR FINISHED PLUTONIUM OR URANIUM METAL COMPONENTS

Beginning *material form*	*Conversion time*
Plutonium, *high enriched uranium (HEU)* or *^{233}U* metal	Order of days (7–10)
PuO_2, $Pu(NO_3)_4$ or other pure *plutonium* compounds; *HEU* or *^{233}U* oxide or other pure *uranium* compounds; *mixed oxide (MOX)* or other unirradiated pure mixtures containing *plutonium*, *uranium* (*^{233}U* + ^{235}U $\geq$ 20%); *plutonium*, *HEU* and/or *^{233}U* in *scrap* or other miscellaneous impure compounds	Order of weeks (1–3)[a]
Plutonium, *HEU* or *^{233}U* in irradiated fuel	Order of months (1–3)
Uranium containing <20% ^{235}U and *^{233}U*; *thorium*	Order of months (3–12)

[a] This range is not determined by any single factor, but the pure *plutonium* and *uranium* compounds will tend to be at the lower end of the range and the mixtures and *scrap* at the higher end.

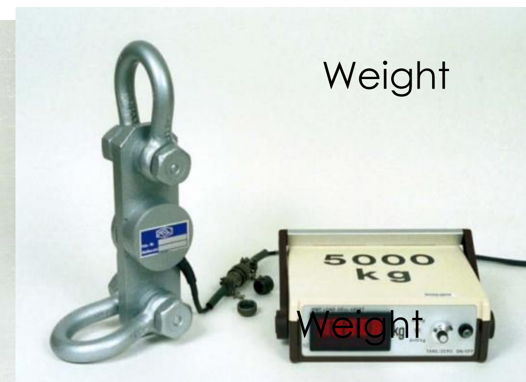
IAEA Safeguards Glossary 2022

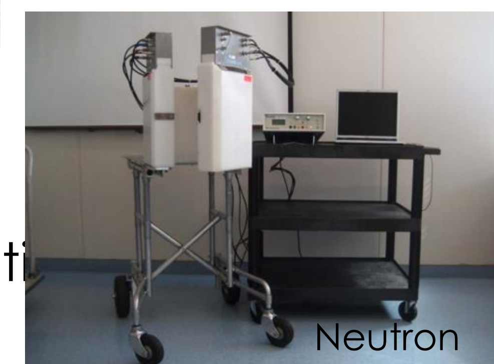
Safeguards Activities

- Nuclear Material Control and Accounting (NMC&A)
  - Verification of inventory and any inventory changes
  - Statistically based random sampling, material balance areas
  - Includes NDA and DA, radiation and otherwise
- Containment & Surveillance
  - Includes seals, video surveillance, and related systems
  - Helps maintain continuity of knowledge of safeguarded material
- Design Information Examination and Verification
  - Design information of facilities is submitted to IAEA
  - Inspectors verify with drawings, visual observation, etc.

Safeguards Activities

- Nuclear Material Control and Accounting (NMC&A)
  - Verification of inventory and any inventory changes
  - Statistically based random sampling, material balance areas
  - Based upon material balance areas (MBAs)





[IAEA Techniques and Equipment]

drawings, visual observati

Safeguards Activities

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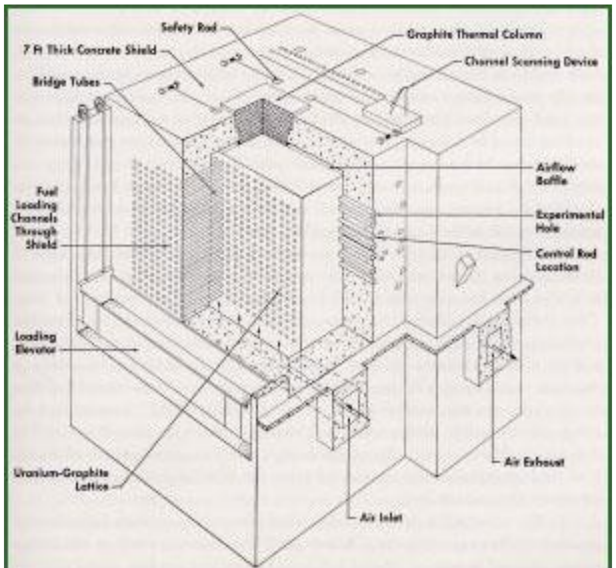
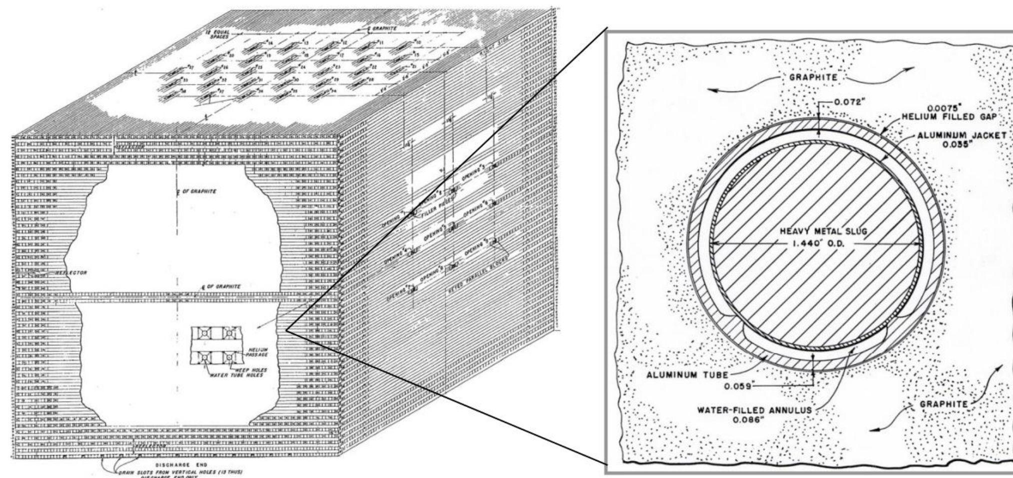
Safeguards Activities



Schematic of the X-10 Graphite Reactor, Oak Ridge



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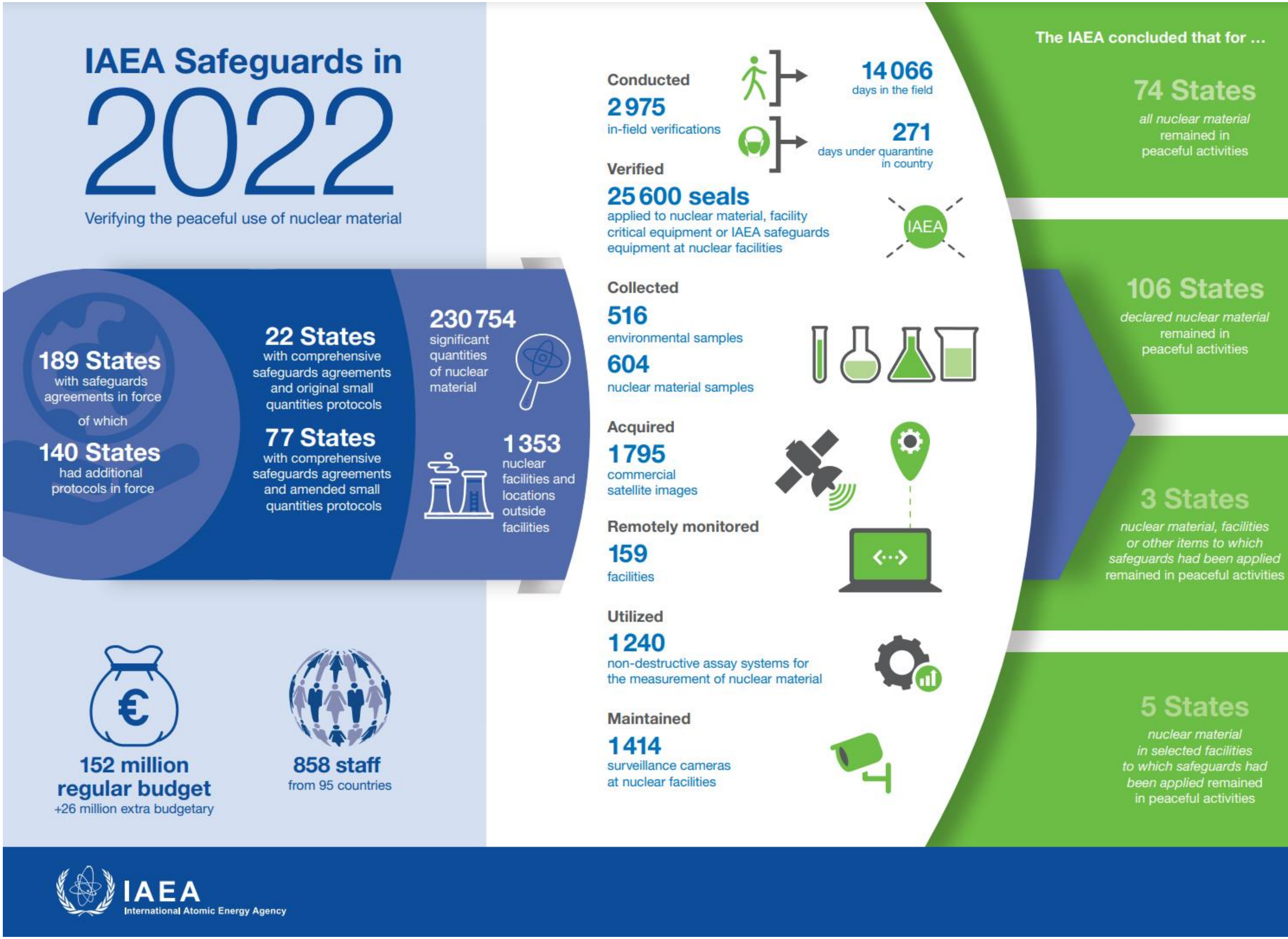

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[IAEA Safeguards Implementation, 2022]

Neutrinos not a good fit for current safeguards

- Safeguards approaches have been well-established
- Neutrino detection technology limited in
- Neutrinos will likely not replace traditional technologies
  - Only relevant in reactor facilities
  - Alternative methods exist, i.e. item accountancy
  - Enrichment and reprocessing facilities are of large concern
- Limited utility in undeclared situations to verify completeness (e.g., AP)

NuTools Study – Potential for Neutrinos

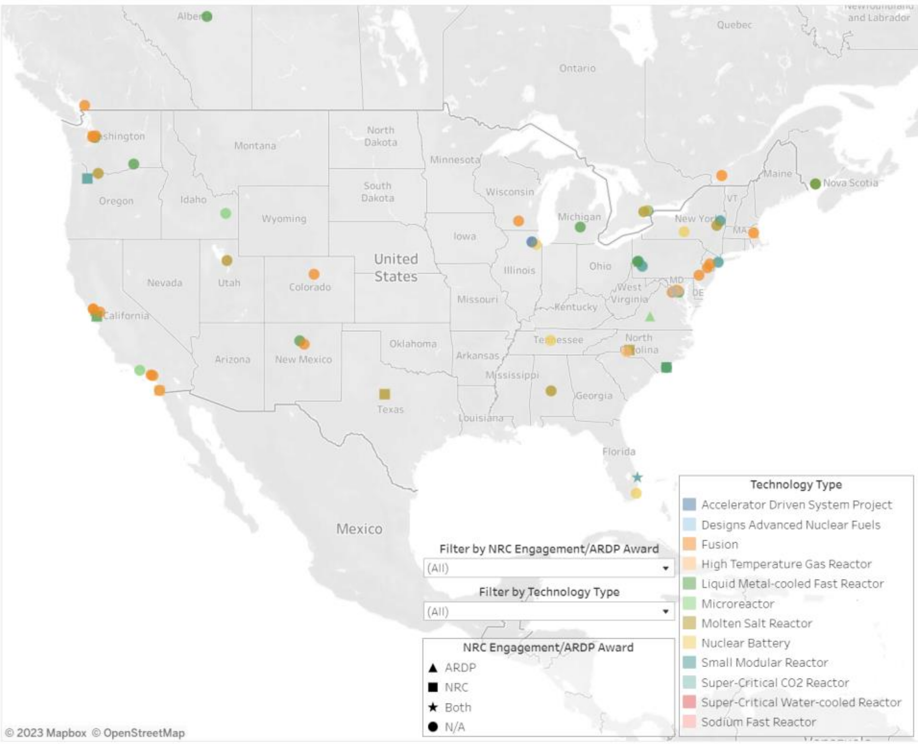
U.S. study to evaluate practical uses of neutrinos in nuclear energy and security

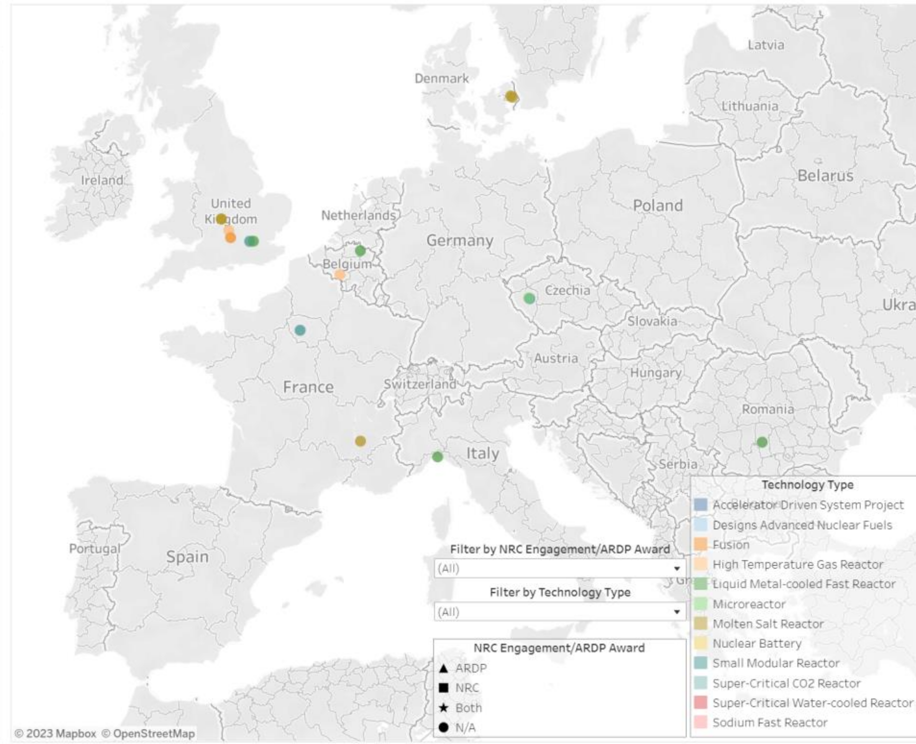
Relevant Findings:

- **End User Engagement:** *“.. neutrino technology R&D community is only beginning to engage attentively with end users … further coordinated exchange is necessary”*
- **Technical Readiness:** *“... novel system such as a neutrino detector requires a dedicated qualification exercise.”*
- **Neutrino System Siting:** *“... requires a balance between intrusiveness concerns and technical considerations, where the latter favor a siting as close as possible”*
- **Advanced Reactors:** *“… present novel safeguards challenges which represent possible use cases for neutrino monitoring”*
- **Future Nuclear Deals:** *“… interest within the policy community in neutrino detection as a possible element of future nuclear deals”*

Advanced Nuclear Reactors

Advanced Reactor Landscape





[Advanced Nuclear Map 2022](#)

Third Way

Advanced Reactor Classes
From Advanced Nuclear Map 2022

Molten salt

High temperature gas

Super-Critical Water/CO2

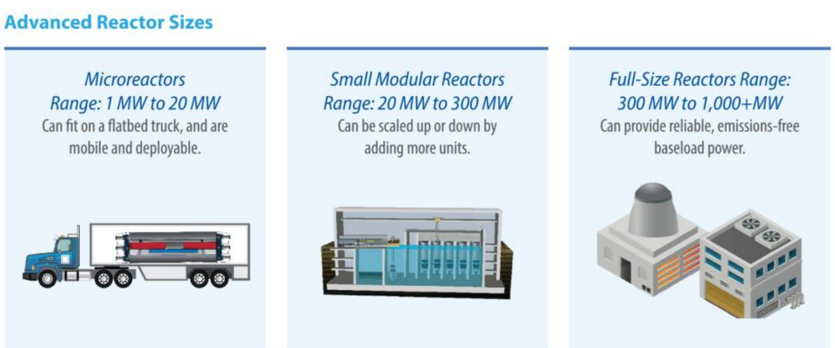
Cross-cutting: Small modular, micro-reactors, and nuclear batteries

Sodium Fast

Lead-cooled fast

Fusion

Accelerator-Driven



U.S. DOE Advanced Reactor Fact Sheet

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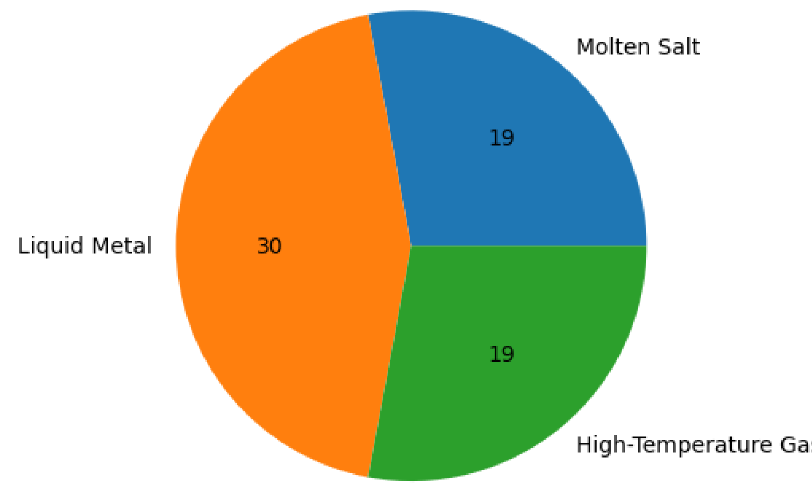
Filtering down classes

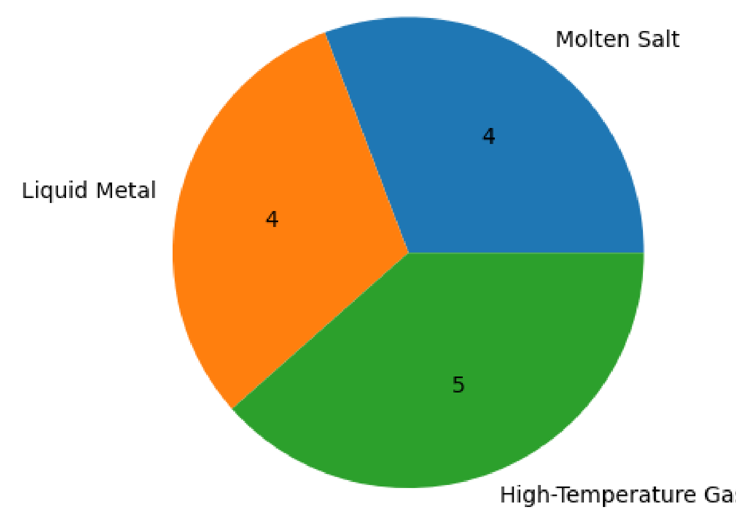
Filter	Number
Total	142
Exclude Fusion or Accelerator	119
Exclude SMR and Micro	71
Exclude Super-Critical CO2/H2O	68

- Molten salt
- High temperature gas
- Super-Critical Water/CO2
- Sodium Fast
- Lead-cooled fast
- Fusion
- Accelerator-Driven

Global non-LWR Advanced Reactor Technologies



Filtered for US-only, funded by ARDP and/or NRC



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Filtering down to relevant types

Filter	Number
Total	142
Exclude Fusion or Accelerator	119
Exclude SMR and Micro	71
Exclude Super-Critical CO2/H20	68

Molten salt

High temperature gas

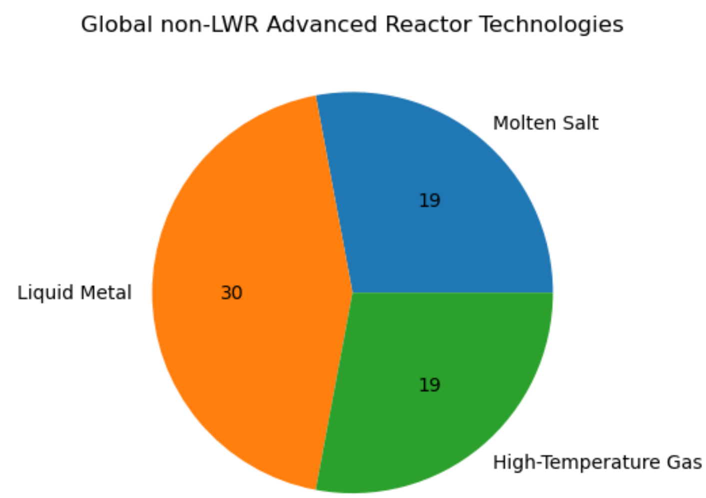
Super-Critical Water/CO2

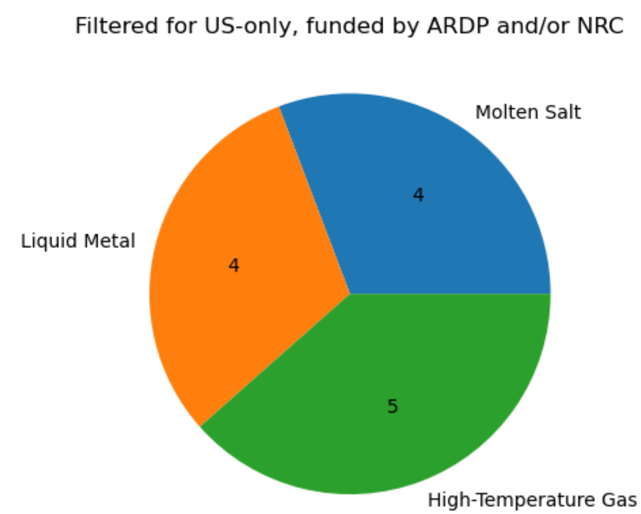
Sodium Fast

Lead-cooled fast

Fusion

Accelerator-Driven



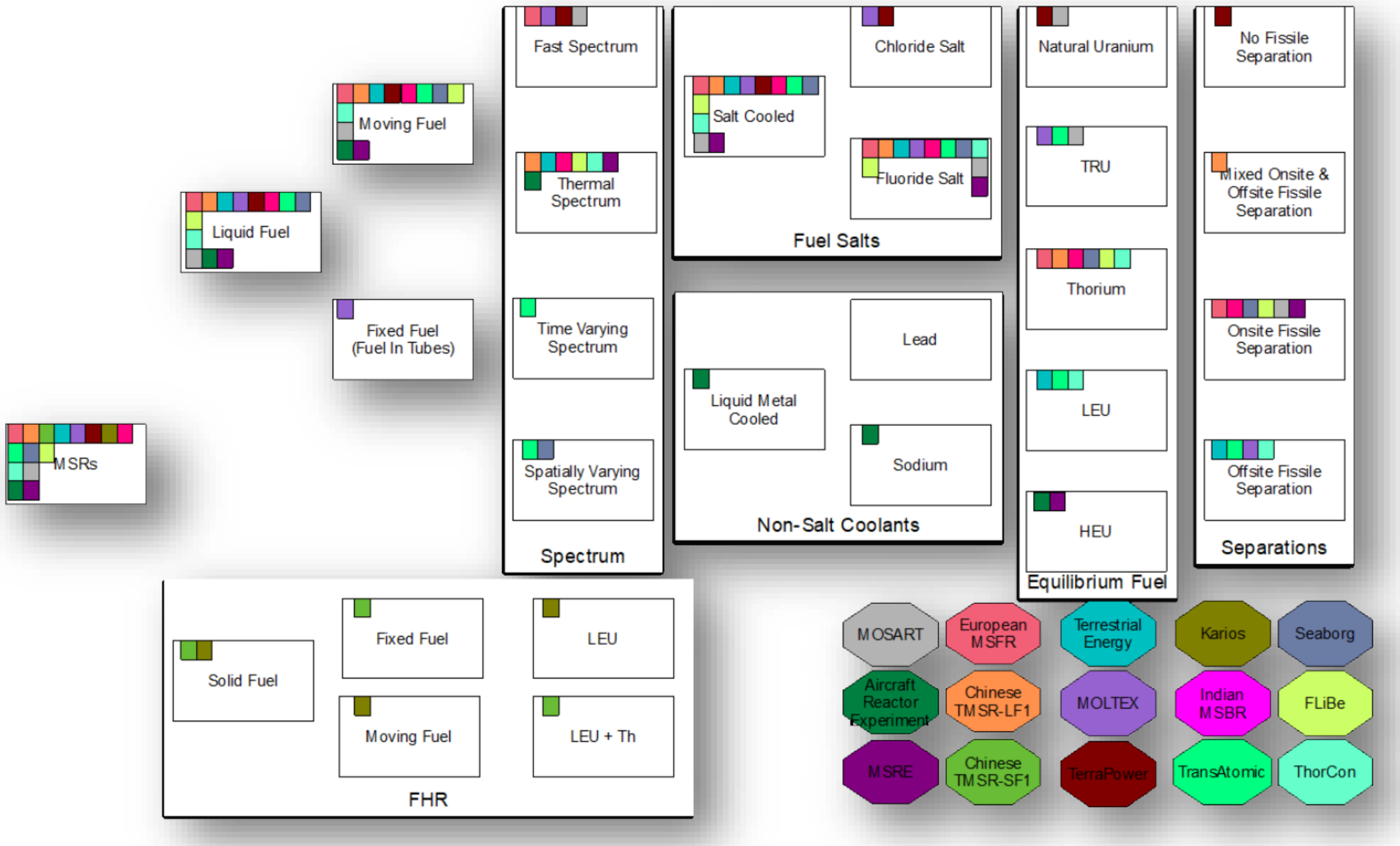


Molten salt reactors

Molten salt	High temperature gas	Super-Critical Water/CO2
Sodium- and Lead-cooled Fast	Lead-cooled fast	Fusion
	Accelerator-Driven	

These are the main types funded by the U.S. DOE
Advanced Reactor Demonstration Projects (ARDP)

Molten Salt Reactors (MSRs)



Holcomb. "Overview of MSR Technology." (2017)

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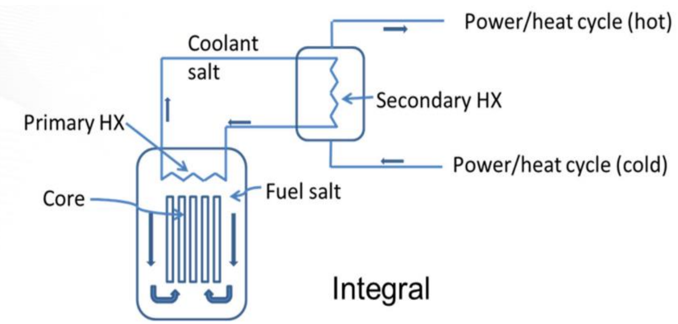
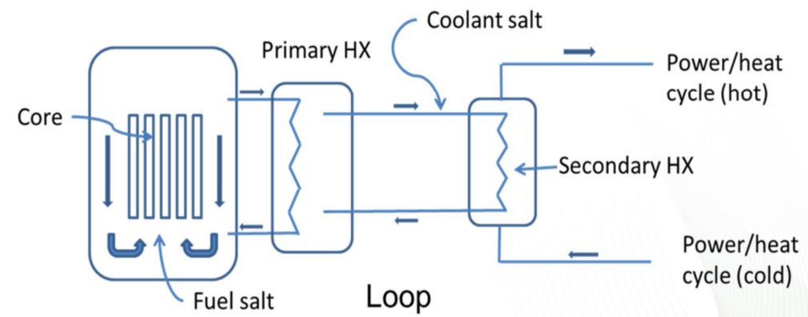
Molten Salt Reactor Design Features

- Reactor with fuel dissolved in fluoride or chloride salt
- Advantages
  - Thermodynamically stable
  - Good heat transfer
  - Chemically inert
- Variety of types
  - Molten salt cooled vs. fueled
  - U vs. Th fuel cycle
  - Fast vs. thermal
- Designed and operated at ORNL in 1960s

Molten Salt Reactor Experiment (MSRE)





Holcomb. "Overview of MSR Technology." (2017)

MSR Safeguards Challenges

- Homogeneous mixture of fuel, salt, fission products, etc.
- Passive or active removal of fuel salt
- Potential online reprocessing while reactor is operational
- Thorium fuel cycle (^{233}U production)
- Chemical compatibility of instrumentation
- Some MSRs are designed as breeder reactors
- Bulk accountancy measures not used at current reactors

Kovacic et al. (2018)

High-Temperature Gas Reactors

Molten salt

High temperature gas

Super-Critical Water/CO2

Sodium- and Lead-cooled Fast

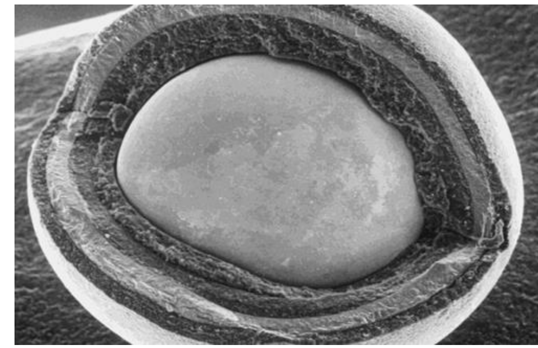
Lead-cooled fast

Fusion

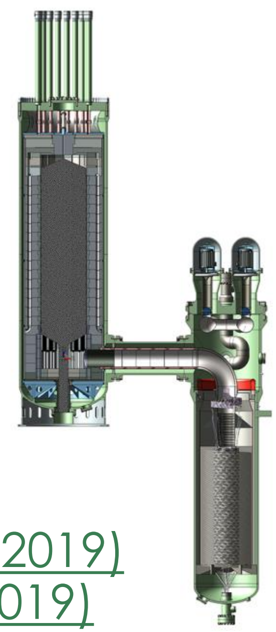
Accelerator-Driven

High-Temperature Gas Reactors (HTGRs)

- Often helium cooled, graphite moderated
- Greater thermal efficiency
- Many are pebble bed reactors (PBR)
  - TRISO particle fuel*
    - Extremely robust, cannot melt, passive cooling
    - Retention of fission products
    - Typically UO2 or UCO
    - Online refueling
    - O(10^5) per reactor
  - First TRISO particles were tested in UK DRAGON reactor



*Note that some MSR designs have TRISO fuel



Schematic of pebble bed operation
DOE-NE and X-energy

Seibert et al. *J. Nucl. Mat.* (2019)
Demkowicz. INL report. (2019)

HTGR/PBR Safeguards Challenges

- Large numbers of pebbles, likely not IDed
  - Infeasible for item verification
- Continuous loading of pebbles
- Variation in pebble irradiation histories
- Bulk accountancy measures not used at current reactors

Kovacic et al. (2020)

Sodium- and Lead-Cooled Fast Reactors

Molten salt	High temperature gas	Super-Critical Water/CO2
Sodium- and Lead-cooled Fast	Lead-cooled fast	Fusion
	Accelerator-Driven	

Sodium/Metal-cooled fast reactors (SFR)

- Better fuel utilization
  - Can use U/Pu mixed fuel (e.g., from spent fuel)
  - Breeding of fuel from ^{238}U
- Typically metal fuel
- Limited transuranic waste
- Improved safety
  - Lower operating pressure
  - Higher operating temperature
  - Negative reactivity feedback

EBR-II at Idaho National Laboratory

SFR Safeguards Challenges

- Potential for breeding high quality plutonium
- Visual inspection of fuel not possible
- Inaccessibility of fuel
- Need to maintain continuity of knowledge during fuel handling

A. Garrett et al.
PNNL. 2021.

Sodium- and Lead-Cooled Fast Reactors

Molten salt

High temperature gas

Super-Critical Water/CO2

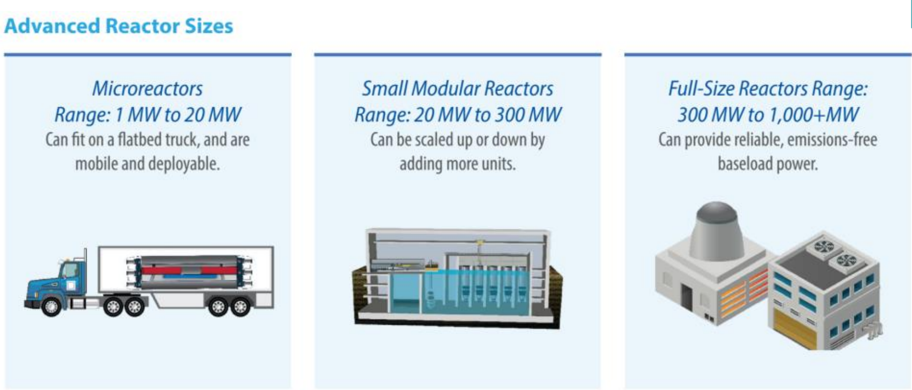
Sodium- and Lead-cooled Fast

Lead-cooled fast

Fusion

Cross-cutting: Small modular, micro-reactors, and nuclear batteries

Accelerator-Driven



U.S. DOE Advanced Reactor Fact Sheet

Cross-Cutting: Small Modular Reactors (SMR) and Microreactors

- Varied deployment (SMR, micro)
  - Difficult to access via inspections
- Mass produced (SMR, micro)
  - Design validation, country of production vs. operation
- Multiple modules (SMR)
  - Individual unit verification

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

Other Considerations: High-Assay Low-Enriched Uranium

- Most commercial reactors have ^{235}U < 5%
- Advanced reactor designs are aiming to be < 20%
  - Designated as HALEU
- Potential safeguards impacts
  - New material category (e.g., HEU, LEU)
  - Inspection frequency
  - Fuel cycle facilities

Vendor	Design Type/Model	Enrichment
Advanced Reactor Concepts	**ARC-100: Pool-type modular sodium-cooled fast-neutron-spectrum reactor**	**10.1-17.2%**
Elysium Industries	Molten Chloride Salt Fast Reactor (MCSFR)	15%
Framatome	Steam Cycle High Temperature Gas-cooled Reactor (SC-HTGR)	14.5-18.5%
General Atomics	Energy Multiplier Module (EM^2): Fast-neutron version of the Gas Turbine Modular Helium Reactor (GT-MHR)	12%
GE Hitachi	Power Reactor Innovative Small Module (PRISM): Pool-type modular sodium-cooled fast reactor	11-17% Pu
Kairos Power	**KP-FHR: Modular fluoride-salt-cooled high-temperature reactor**	**15-19.75%**
Oklo	Aurora: Compact Fast Microreactor cooled by liquid metal	15-19.75%
TerraPower	Traveling Wave Reactor-Prototype (TWR-P): Pool-type sodium-cooled fast reactor	15.75%
TerraPower & GE Hitachi	**Natrium: pool-type sodium fast reactor**	**20%**
ThorCon US	Thorium cycle modular molten salt reactor	19.70%
Ultra Safe Nuclear Corporation	MMR™ (Micro Modular Reactor) Micro-reactor HTGR	19.75%
Westinghouse	Lead Fast Reactor (W-LFR): Pool-type lead-cooled fast reactor	≤19.75%
Westinghouse	**e-Vinci Micro reactor**	**5-19.75%**
X-Energy	**Xe-100: Modular High-Temperature Gas-cooled Reactors (HTGR)**	**15.50%**

Brookhaven National Lab

Summary of Safeguards Challenges for Advanced Reactors, Relevant for Neutrinos

Technology Feature	Types	Safeguards Challenge
Fuel form (non-countable or easily transportable fuel)	MSR, PBR	Item accountancy not sufficient, burnup validation, etc.
Online refueling	MSR, PBR	Increased resource demand (e.g., inspections, remote monitoring)
Long-lived cores	SMR, SFR, HTGR, Micro	No core information for extended periods of time
Higher enrichment	Various	Physical protection, higher BU,
Multi-unit	SMR	Individual unit verification
Remote area operation	SMR, Micro	Challenging inspections

How could neutrinos play a role?

Technology Feature	Safeguards Challenge	Potential opportunities
Fuel form (non-countable or easily transportable fuel)	Item accountancy not sufficient, burnup validation, etc.	Neutrinos agnostic to fuel form, but measurements difficult when outside reactor
Online refueling	Increased resource demand (e.g., inspections, remote monitoring)	N/A, likely difficult
Long-lived cores	No core information for extended periods of time	Neutrinos do not need access to the core
Higher enrichment	Physical protection, higher BU	Neutrinos could provide inventory measurements
Multi-unit	Individual unit verification	Single unit verification possible
Remote area operation	Challenging inspections	Provide continuity of knowledge

Summary

- ARs have complicated and varied designs
- IAEA safeguards is an established landscape that is changing with new advanced reactor technologies
- Neutrino detection will likely not be a **primary** solution, but perhaps a **complementary** one
- Future application studies need to be developed in conjunction with AR technology developers
- For advanced reactor safeguards:

Advantages	Disadvantages
Non-intrusive measurement	High reliability / long operation times
No need for core access (e.g., nontransparent coolant, long lived cores)	Interpretability of results / usability of data
Can give information on reactor status changes and contents	Reactors only small piece of safeguards

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Backup Slides