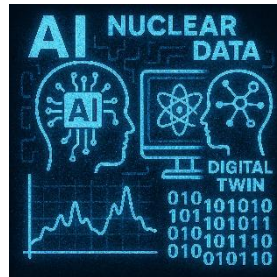


Data Science and Digital Technologies in Nuclear Security and Nonproliferation

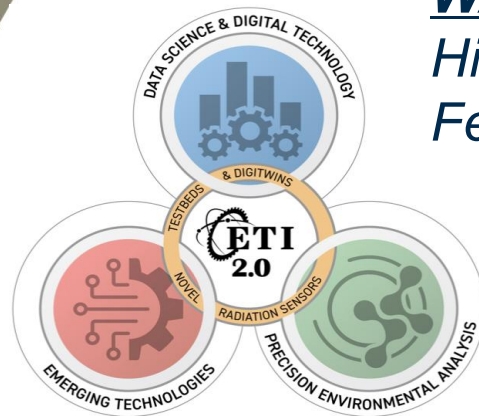


# Nuclear Data for Digital Twins

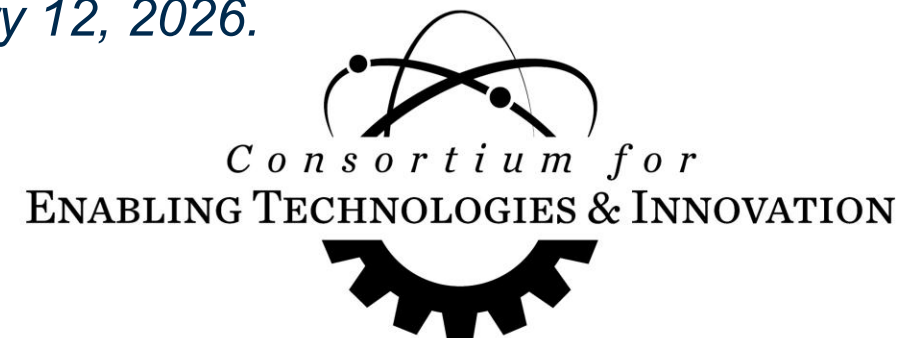
Pavel Tsvetkov

*Department of Nuclear Engineering  
Texas A&M University*

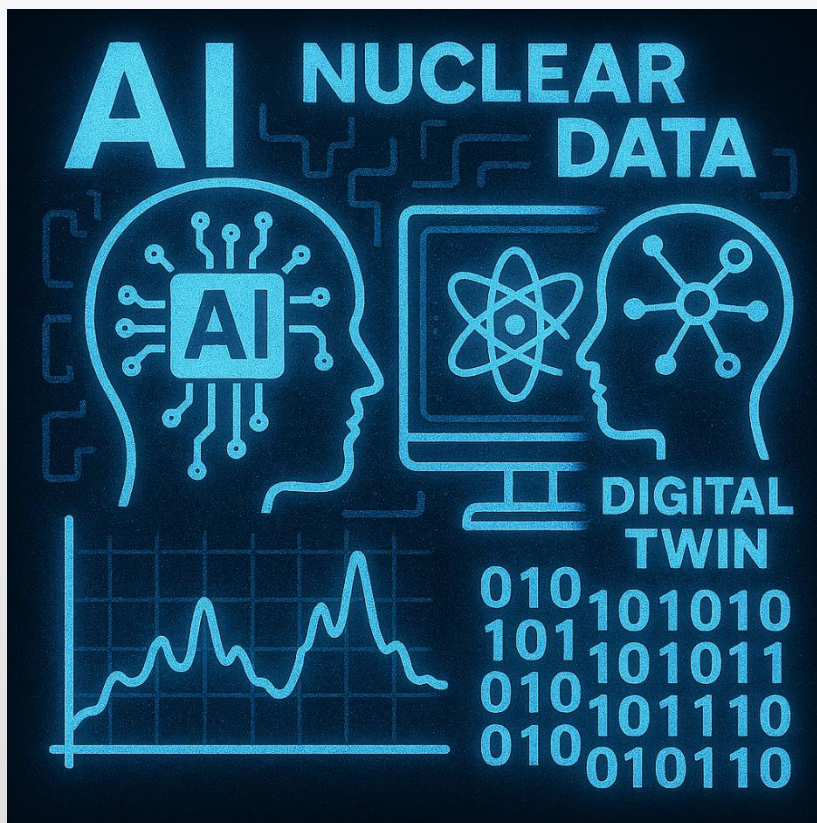
**WANDA 2026: Workshop for Applied Nuclear Data Activities**  
*Hilton Arlington National Landing in Crystal City, VA  
February 9 – February 12, 2026.*



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# Nuclear Data for Digital Twins



- Advanced reactors
- Why Digital Twins (DT) matter for safeguards of advanced reactors
- Digital Twin (DT) in the safeguard context
- How Digital Twins (DT) are being developed and used today
- Nuclear data needs for credible digital twins
- Gaps and challenges
- Priorities for collaboration

# Nuclear Data for Digital Twins

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## Advanced reactors

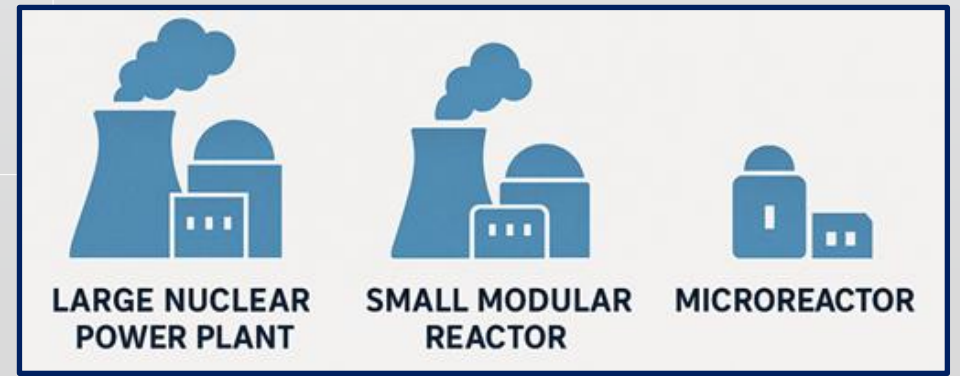
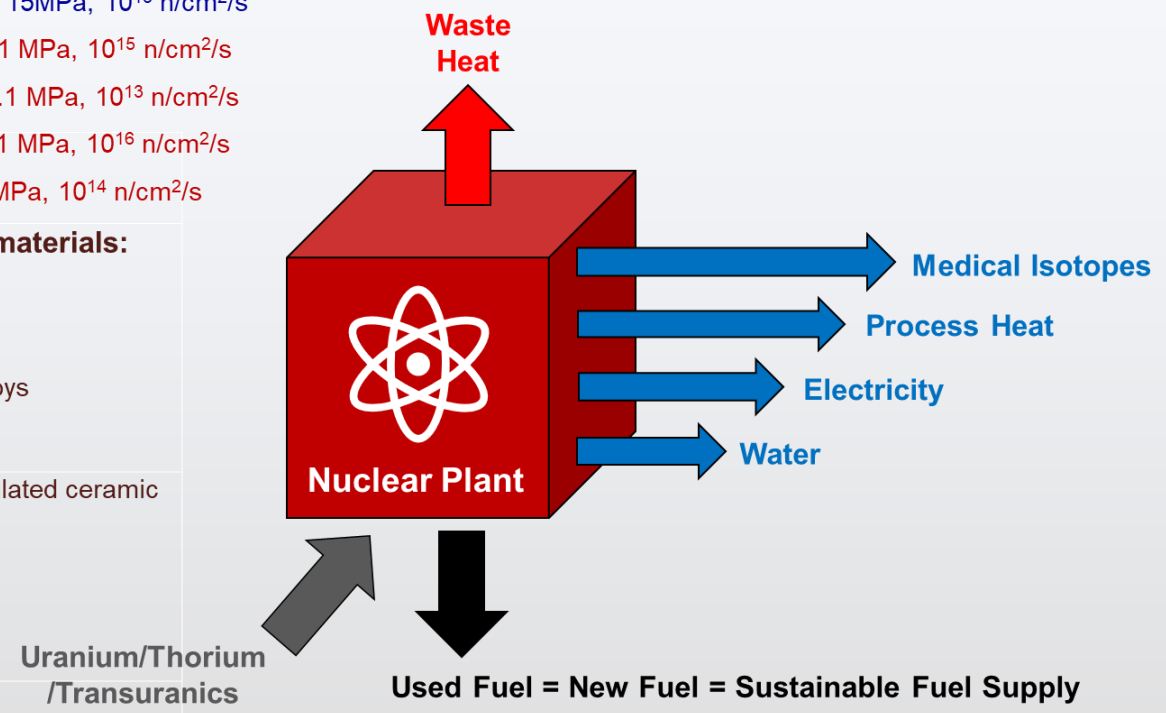
Reactor Type	Safeguards Focus Area	Nuclear Data Uncertainty Impact
Molten Salt (MSR)	Online Fuel Processing & Bulk Accounting	High: Uncertainties in FPY lead to "ghost" signatures in off-gas monitoring, masking potential material removal.
Sodium Fast (SFR)	Breeding Ratios & Blanket Monitoring	Moderate: Scattering data affects flux profile predictions; poor data can hide a "blanket" swap or diversion.
High-Temp Gas (HTGR)	Pebble/TRISO Burnup Verification	Moderate: TSL uncertainties affect reactivity and burnup estimates, essential for verifying "declared" fuel status.
Microreactors	Remote Autonomous Monitoring	High: Long-term autonomous DTs accumulate drift. Precise decay data is needed to "reset" the DT using NDA sensors.

**Coolant (single phase):**  
 H<sub>2</sub>O, ~325°C, 15MPa, 10<sup>13</sup> n/cm<sup>2</sup>/s  
 Na, 550°C, 0.1 MPa, 10<sup>15</sup> n/cm<sup>2</sup>/s  
 salt, 800°C, 0.1 MPa, 10<sup>13</sup> n/cm<sup>2</sup>/s  
 Pb, 800°C, 0.1 MPa, 10<sup>16</sup> n/cm<sup>2</sup>/s  
 He, 950°C, 7MPa, 10<sup>14</sup> n/cm<sup>2</sup>/s

**Structural materials:**  
 Graphite  
 Steels  
 Zirconium alloys

**Fuel:**  
 Microencapsulated ceramic  
 Metal  
 Ceramic

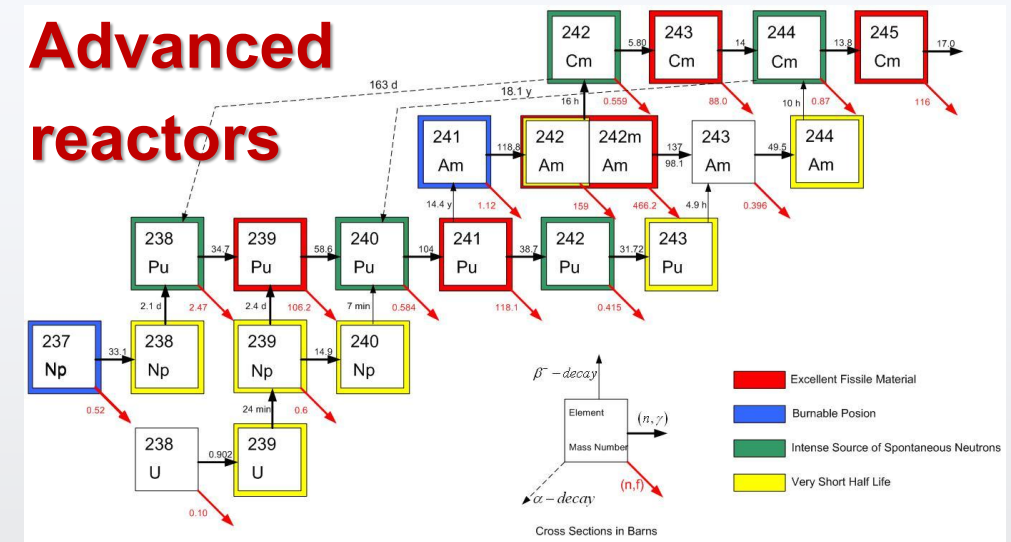
### Nuclear Plant



# Nuclear Data for Digital Twins

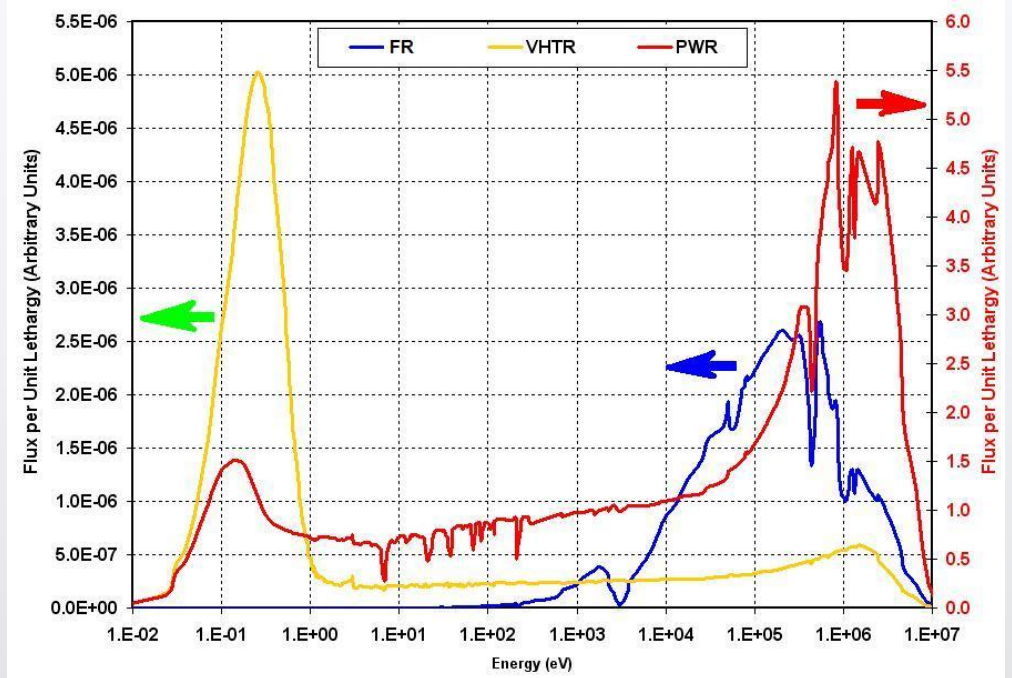
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## Advanced reactors

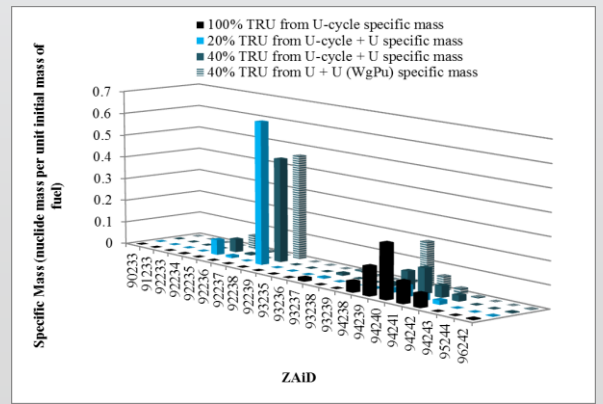
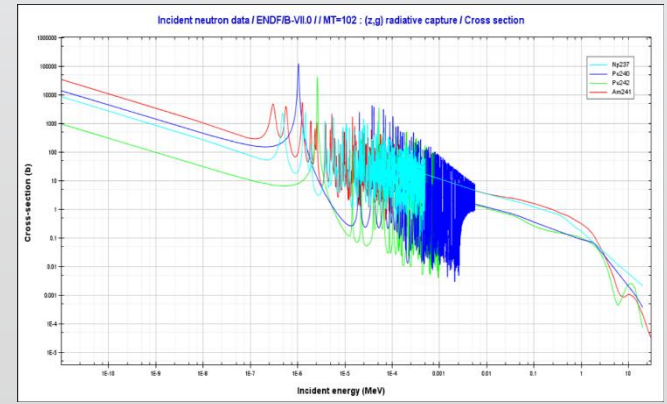
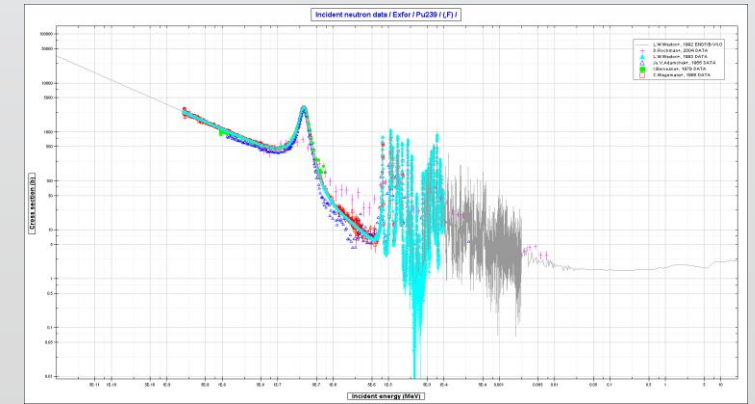


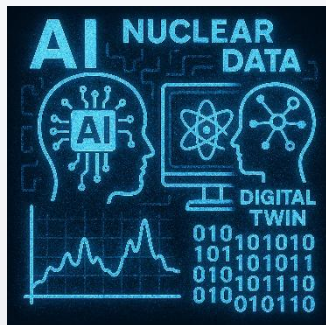
TRU vector (PWR 41,200 MWd/tHM, decay=23 years), at %:

237-Np - 6.121;  
 238-Pu - 1.986, 239-Pu - 51.718, 240-Pu - 21.899, 241-Pu - 4.104, 242-Pu - 4.451  
 241-Am - 8.250, 242m-Am - 0.020, 243-Am - 1.230  
 243-Cm - 0.003, 244-Cm - 0.194, 245-Cm - 0.021, 246-Cm - 0.003



- Reactors and facilities have distinct nuclide signatures characterizing their operational domain details
- Ability to reconstruct and interpret these signatures depends on the quality of nuclear data

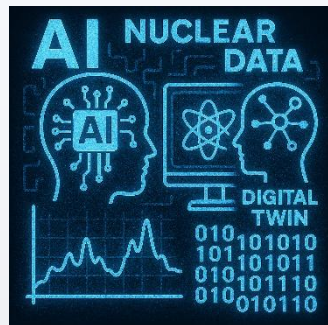




## Why Digital Twins (DT) matter for safeguards of advanced reactors

Digital twins are becoming the analytical backbone for advanced reactor monitoring, verification, and anomaly detection.

- Real-time synchronization of **sensor data, reactor physics models, and operational state**
- Ability to simulate **off-normal scenarios, material diversion pathways, and operator actions**
- Supports **risk-informed safeguards, predictive analytics, and AI-assisted decision support**
- Bridges **facility operators, regulators, safeguards inspectors, and national labs**



## Digital Twin (DT) in the safeguard context

A safeguards-relevant digital twin integrates:

- **High-fidelity multiphysics models** (neutronics, thermal-hydraulics, fuel behavior)
- **Process and instrumentation data streams** (neutron flux, gamma signatures, flow rates, temperatures)
- **Material accountancy models** (inventory, isotopics, decay chains)
- **AI/ML layers** for anomaly detection, predictive maintenance, and operator-action modeling
- **Human-machine interface (HMI)** for inspectors and analysts

Credibility depends on **nuclear data quality, model validation, and transparent uncertainty quantification.**

# Nuclear Data for Digital Twins

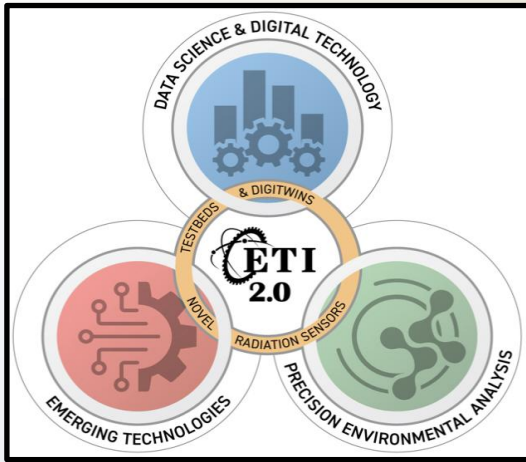
## How Digital Twins (DT) are being developed and used today

- **Development approaches:** Integration of physics-based models with ML for real-time synchronization.
- **Safeguards applications:** Remote monitoring for diversion/misuse detection
- **Benefits:** Enhances reactor efficiency, safety, and non-proliferation without physical intervention.

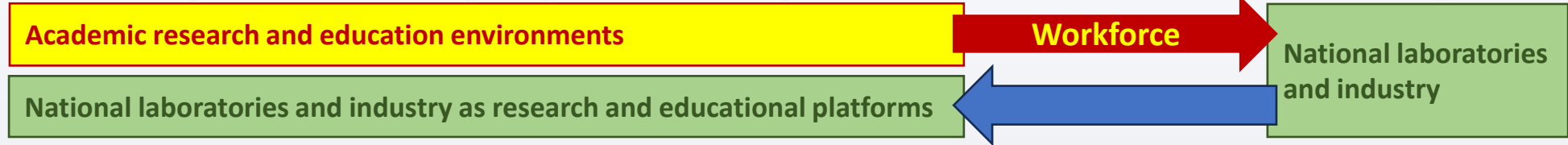


# Nuclear Data for Digital Twins

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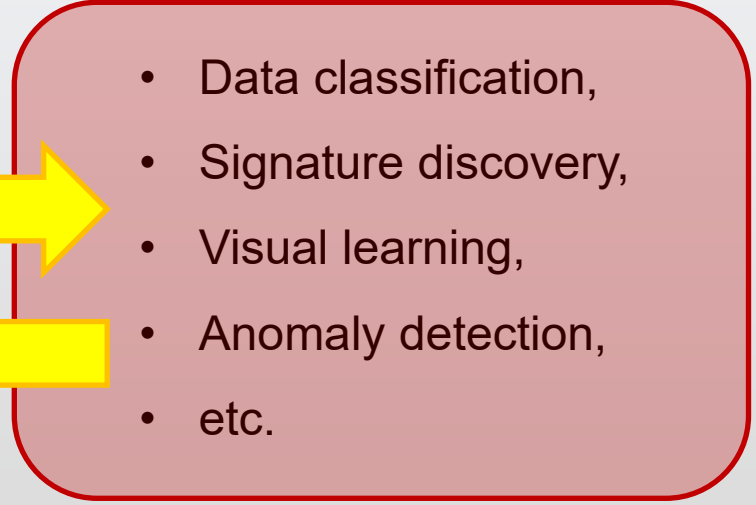
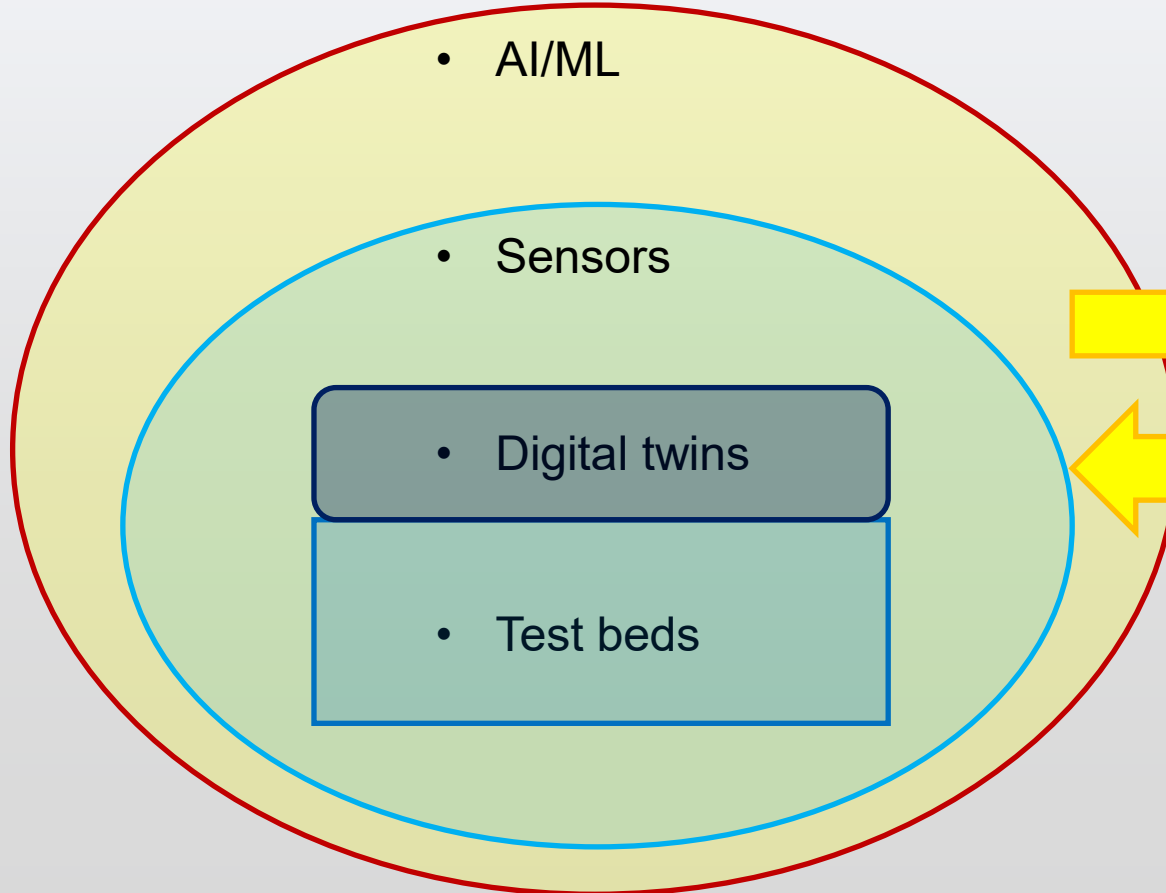


## How Digital Twins (DT) are being developed and used today



### Proliferation detection domain:

### Data Science for nuclear security and nonproliferation:



- Robust AI data collection and processing
- AI-assisted signature discovery for high-fidelity anomaly detection
- ML/AI-assisted automatic risk-based detection of cyber-physical threats
- Synthesis of augmented reality (AR) and AI with digital twin technologies

# Nuclear Data for Digital Twins

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## Nuclear data needs for credible digital twins

### 1. Reaction Data

- High-fidelity cross sections for **fast-spectrum** and **epithermal** systems
- Uncertainty-quantified data for **minor actinides, fission products, salt constituents, coolants**

### 2. Decay & Source Term Data

- Accurate decay heat, gamma yields, delayed neutron fractions
- Time-dependent isotopic evolution for safeguards signatures

### 3. NDA-Relevant Data

- Neutron/gamma emission spectra
- Self-shielding factors
- Detector response functions

### 4. Covariance Data

- Essential for uncertainty propagation through the digital twin
- Needed for AI-assisted anomaly detection thresholds

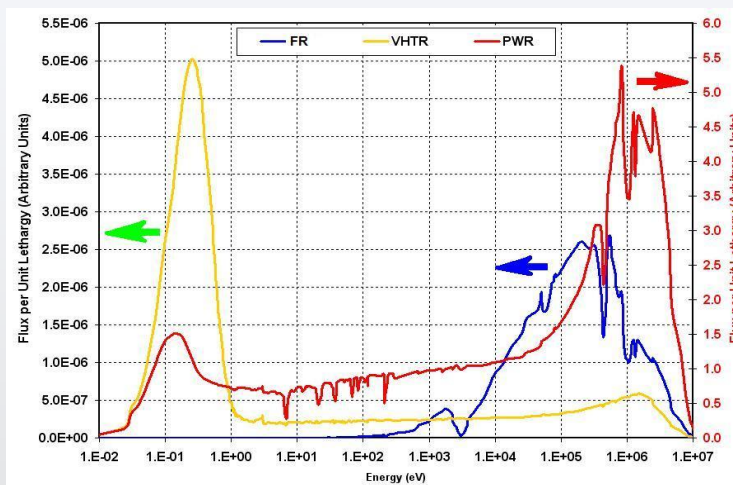
### 5. Benchmark Data

- Integral experiments for validation
- Transient data for operator-action modeling
- Process monitoring datasets for safeguards signatures

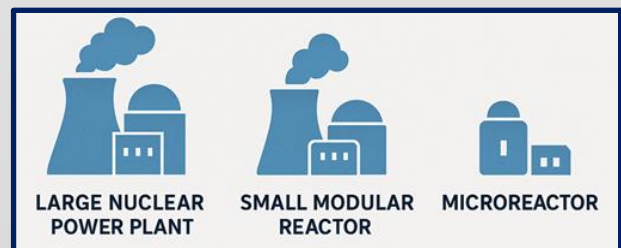
# Nuclear Data for Digital Twins

<b>FISSION PRODUCTS</b> Cesium-137 Strontium-90 Iodine-131 Krypton-85	<b>ACTINIDES</b> Plutonium-239 Americium-241 Neptunium-237
<b>UNSPENT FUEL</b> Uranium-235 Uranium-238	<b>STRUCTURAL MATERIALS</b> Zirconium Iron Chromium
<b>ISOTOPIC DIVERSITY</b> Hundreds of isotopes	<b>RADIOLOGICAL CHARACTERISTICS</b> Alpha particles Gamma rays
<b>SHORT-LIVED ISOTOPES</b>	<b>LONG-LIVED ISOTOPES</b>

## Gaps and challenges



- Nuclear data gaps for **non-traditional materials** (salts, liquid metals, advanced fuels)
- Sparse **transient and process monitoring** datasets
- Limited **safeguards-relevant benchmarks** for advanced reactors
- Need for **standardized digital twin architectures** across labs and vendors
- Regulatory acceptance requires **transparent uncertainty quantification**



# Nuclear Data for Digital Twins



## Priorities for collaboration

### 1. Nuclear Data Community

- Targeted measurements for safeguards-relevant isotopes
- Expanded covariance data
- NDA-specific data libraries

### 2. Safeguards Community

- Diversion scenario datasets
- Process monitoring signatures
- Inspector-in-the-loop validation

### 3. Advanced Reactor Community

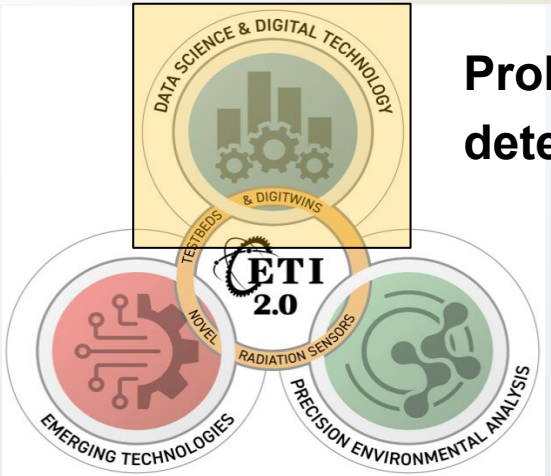
- Sharing operational data (even synthetic)
- Joint testbeds for digital twin validation
- Standardized interfaces for sensors and models

### 4. Cross-cutting

- Open digital twin benchmarks
- Shared uncertainty quantification frameworks
- AI/ML validation standards for safeguards

# Nuclear Data for Digital Twins

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## Proliferation detection domain:

- AI/ML
- Sensors
- Test beds
- Digital twins

## Priorities for collaboration

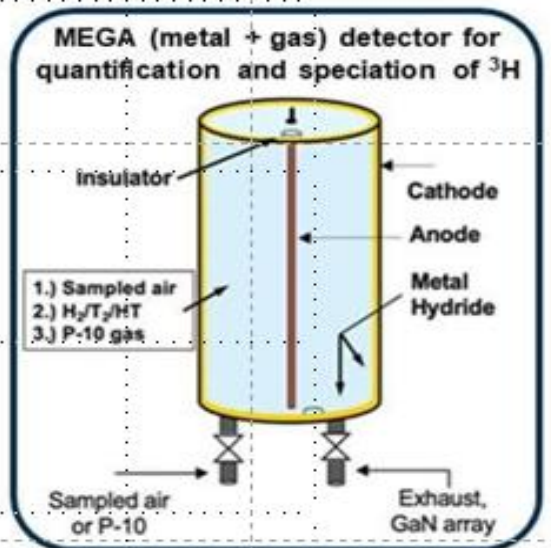
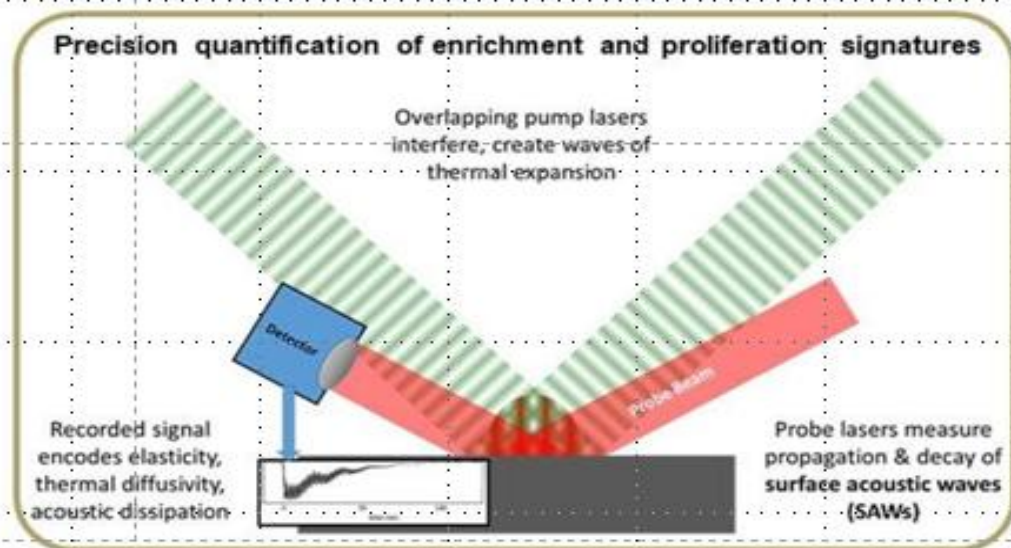
ROBUST AI FEATURE	PROBLEM	METHODS AND SOLUTIONS	ETI 2.0 CONTRIBUTION
Explainable and interpretable	Mission required features, blackbox appearance of the algorithms, lack of understanding how the algorithm made decision	Model description methods, interpretable metrics	Framework for model description through datasheets and decision trees
Metrics, validation and verification	Impact of component vs. system metrics, input and output data, accuracy vs. precision	Dimensionality reduction, robust training and regularization	Address the gap in end-to-end metrics through various sensors, testbeds and digital twins and feature inference
Security	Vulnerability to physics and cyber threats/actions	Model performance under adversarial attack, red team	Model assessment: access, agenda and pipeline assessment, cyber security counter-measures

## Data Science for nuclear security and nonproliferation:

- Data classification,
- Signature discovery,
- Visual learning,
- Anomaly detection,
- etc.

Subtopic Area	Consortium Members	National Lab Collaborators	Students
Robust AI data collection and processing for proliferation detection domains	Wilson (UW), Wu (VCU)	ORNL, LANL	2
AI-assisted signature discovery for anomaly detection	Manic (VCU), Tsvetkov (TAMU), Erickson (GT)	INL, PNNL, SNL	2
ML/AI-assisted automatic risk-based detection of cyber-physical threats	Davis (TAMU), Zhang (GT)	INL, ORNL	2
Synthesis of computer augmented reality and AI with digital twin technologies	Manic (VCU), Rogers (GT), Tsvetkov (TAMU), Erickson (GT)	INL, PNNL, ORNL	3

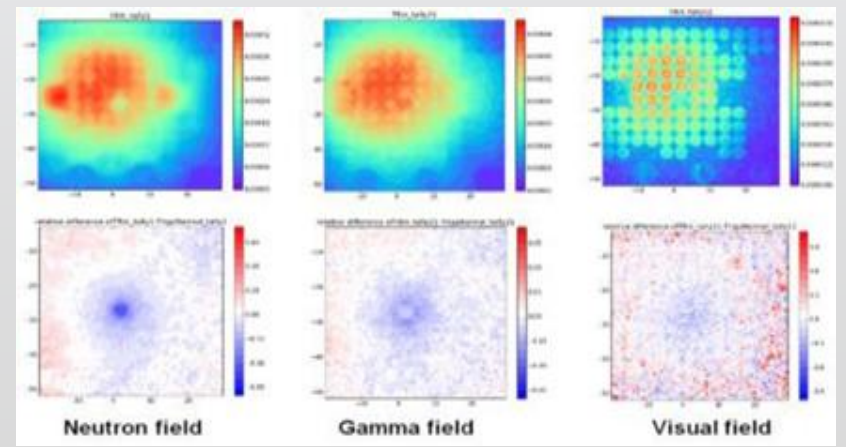
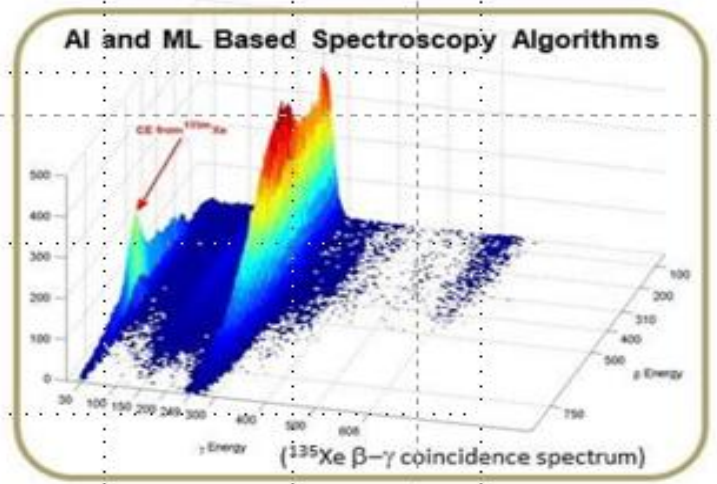
# Nuclear Data for Digital Twins



## Monitoring and characterization

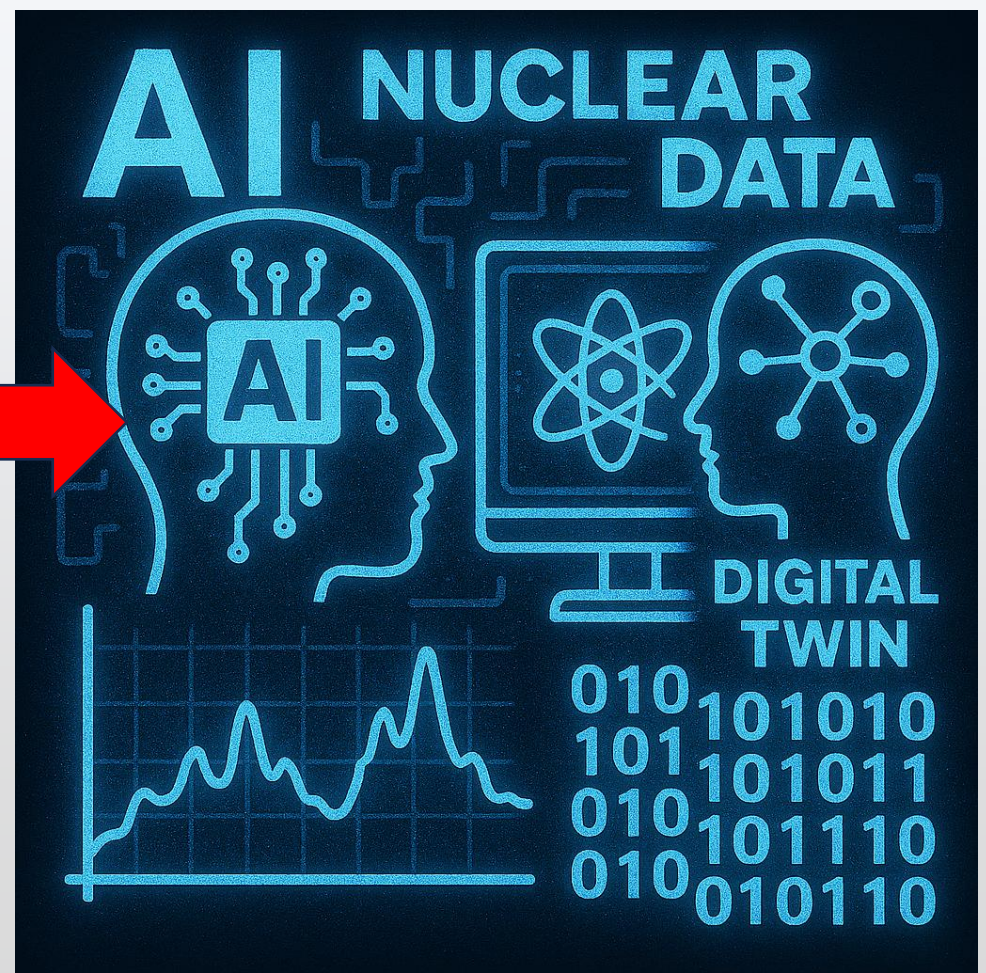
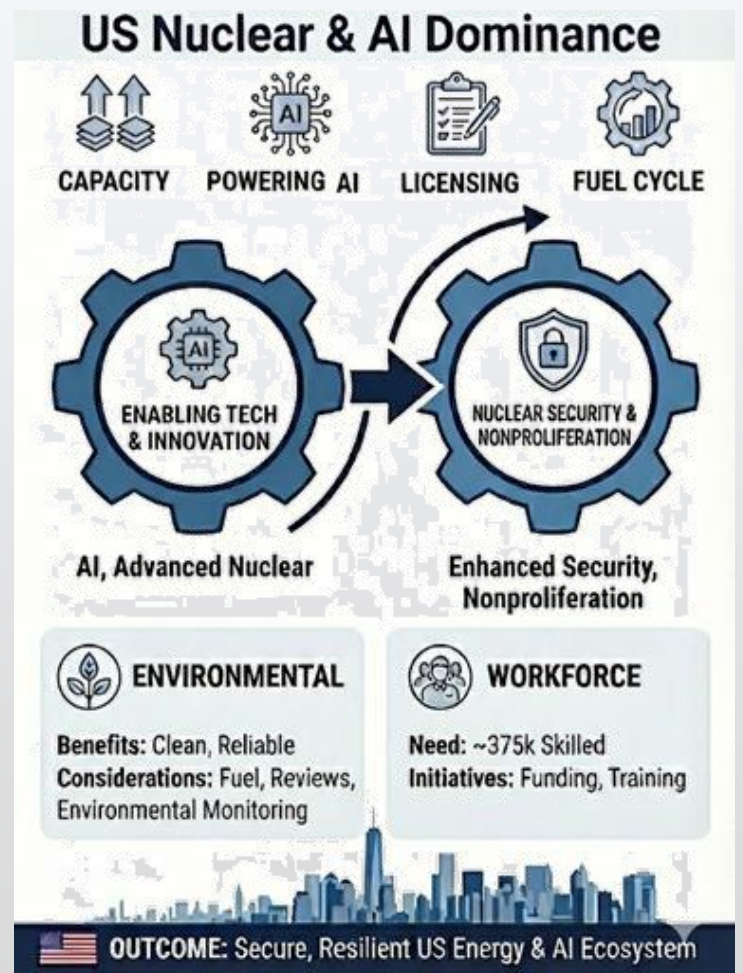


## Focused Ion Beam-Based Elemental Mapping and Composition Analysis of Radioactive Environmental Samples



# Nuclear Data for Digital Twins

## Priorities for collaboration



# ACKNOWLEDGEMENTS

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