LA-UR-25-24630
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Title: 1FRAME: 1F Fuel Retrieval and Monitoring Experiments

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Intended for: FACE, 2025-05-13/2025-05-16 (Daejeon, KOREA, SOUTH)

Issued: 2025-05-13

Los Alamos NATIONAL LABORATORY

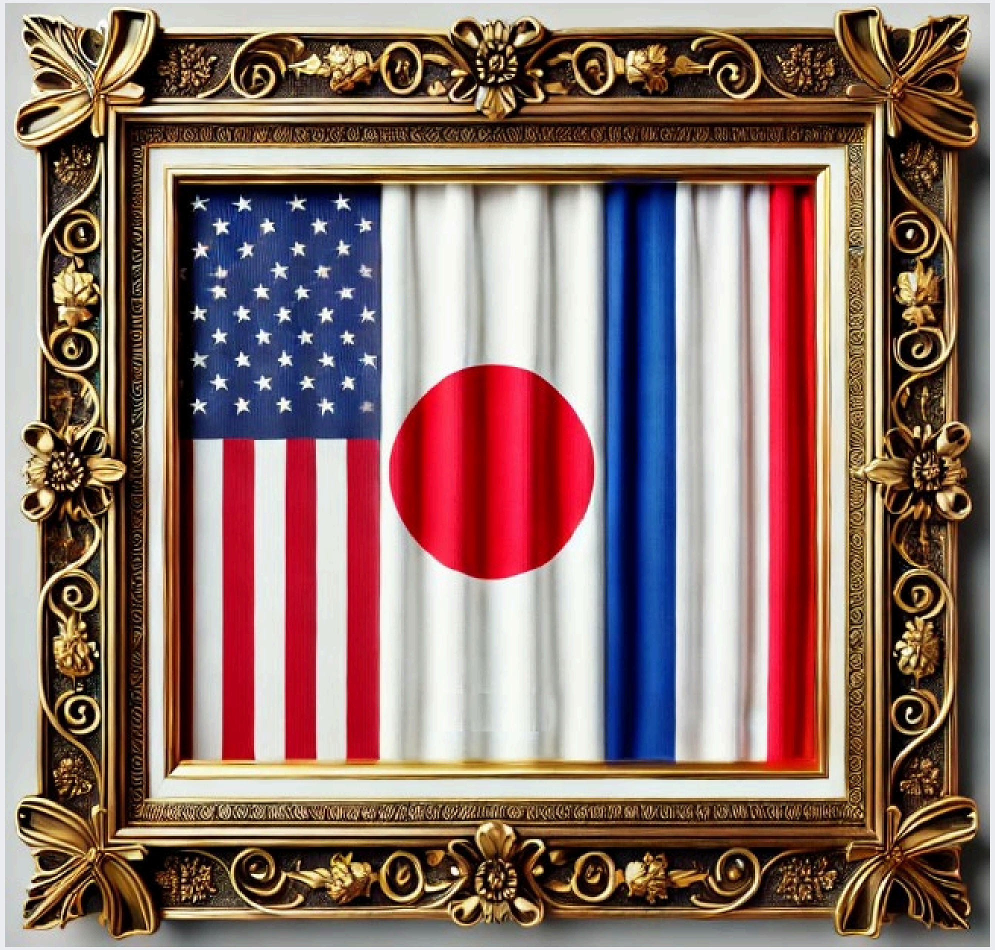
1FRAME:
1F Fuel Retrieval and Monitoring Experiments

FACE Meeting May 2025

G. McKenzie, J. Hutchinson, N. Cannon, J. Goda, D. Henzlova, C. Kostelac, J. Moussa, M. Nelson,
M. Rising, L. Rolison, R. Weldon, N. Whitman

1FRAME

- Focus on collaborative research in the area of criticality monitoring for fuel debris removal at Fukushima Daiichi nuclear power station (1F)
- 1FRAME: 1F Fuel Retrieval and Monitoring Experiments
  - Focus areas: neutron analysis, radiation detection, radiation transport simulations, collaboration
- Work will include blind tests (analysis of unknown data) using existing measured data, simulated data, and new experimental data
- Work started in Oct 2024



Objectives

- DOE-Nuclear Criticality Safety Program (NCSP) vision statement:
  - Continually improving, adaptable, and transparent program that communicates and **collaborates globally** to incorporate technology, practices, and programs to **be responsive to the essential technical needs of those responsible for developing, implementing, and maintaining nuclear criticality safety**.
- 1F fuel debris removal provides one of the most significant opportunities for international criticality safety technical collaboration today
  - New capabilities/technologies to help with fuel debris removal also align with needs of US applications
- Technology and methods developed in this project are directly applicable to:
  - Severe nuclear accident planning (DOE-NE)
  - Advanced reactor startup (DOE-NE)
  - Criticality safety (DOE-NCSP)
  - Nuclear emergency response (NA-80)
  - Nonproliferation/safeguards (NA-20)

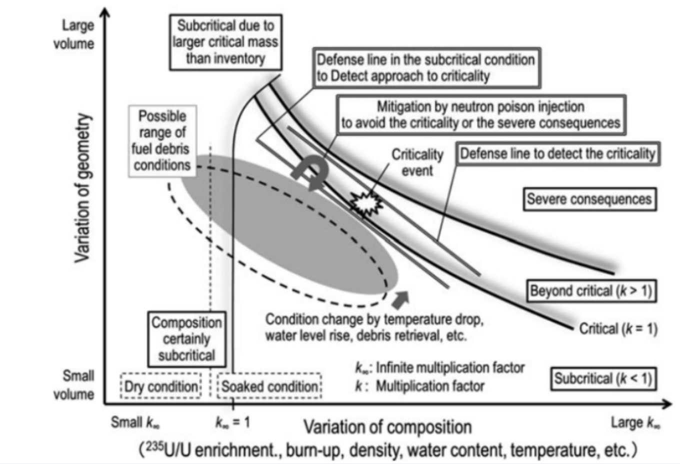
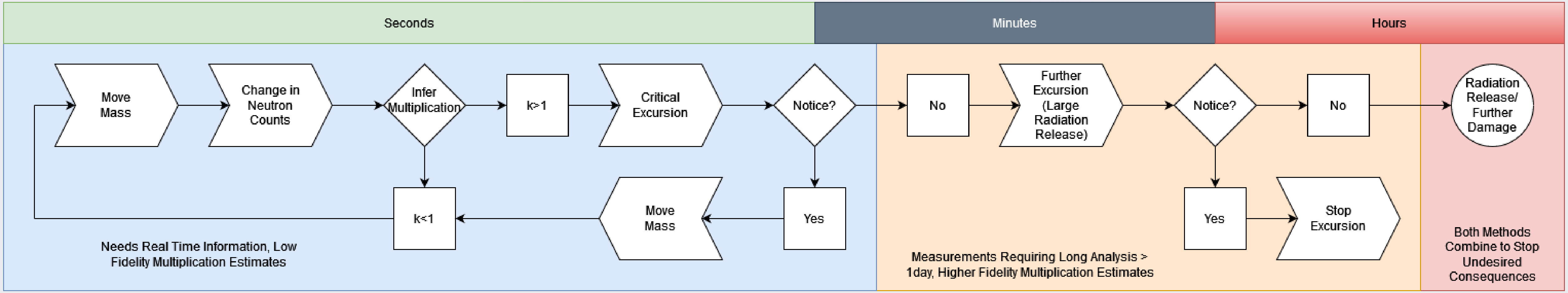
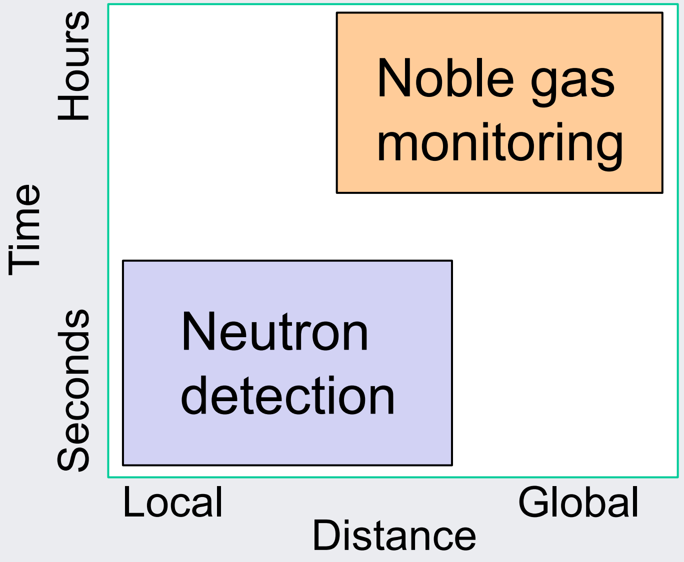


Figure from the book: Options of Principles of Fuel Debris Criticality Control in Fukushima Daiichi Reactors

Monitoring using both neutron detection and radio-xenon monitoring are complementary



- Research on both neutron detection and radio-xenon detection via noble has monitoring has been performed for application to fuel debris removal
- These are complementary technologies and both are needed to ensure that re-criticality is not achieved
- The 1FRAME project is focused on neutron detection and analysis, which is complementary to other R&D efforts on radio-xenon monitoring



Criticality monitoring will be very challenging

- Real-time measurements are needed for data-driven decisions.
- Fuel debris composition is not well known
- Fuel debris location is only partially known
- Very high gamma dose
- Some units are underwater
- Access is a large challenge
- Very different than laboratory measurement conditions

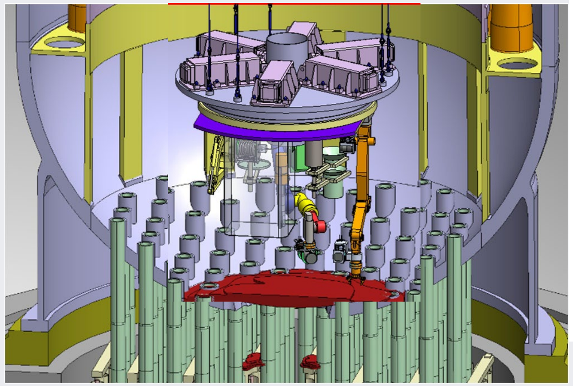
Figure 6. Bulky deposits (around point ① in Figure 5) [3]

Figure 7. Thread-like deposits (point ② to ④ in Figure 5) [3]

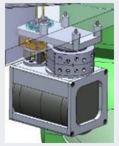
K. Owada, "Features of Fukushima Daiichi Nuclear Power Plant Accident and Information on Fuel Debris Obtained from PCV Internal Investigations," ICNC 2023.

Previous/current R&D efforts

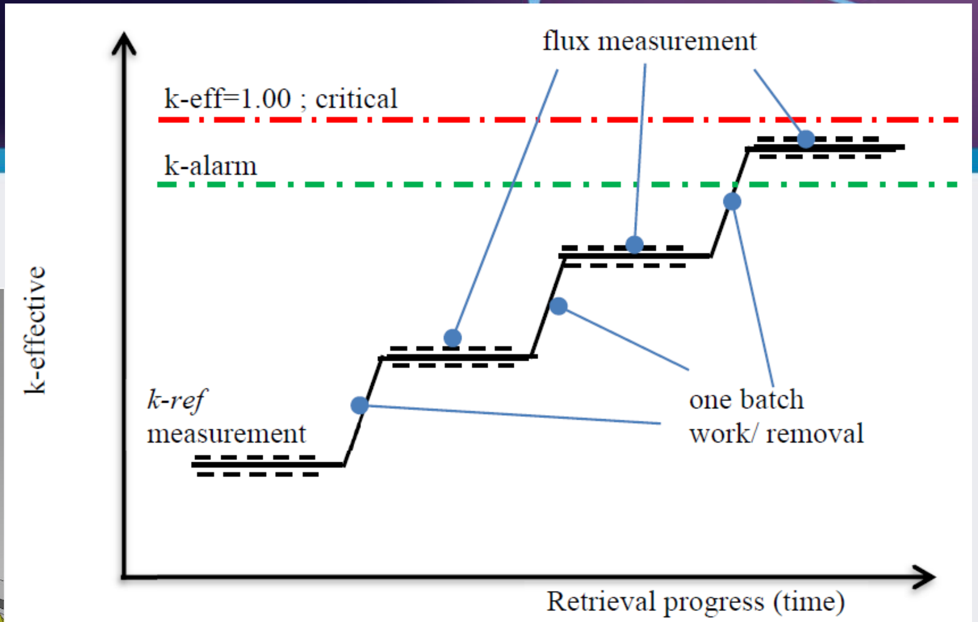
- Goal: detect when/if approaching criticality
- 2 kinds of technologies
  - Neutron detectors
  - Noble gas

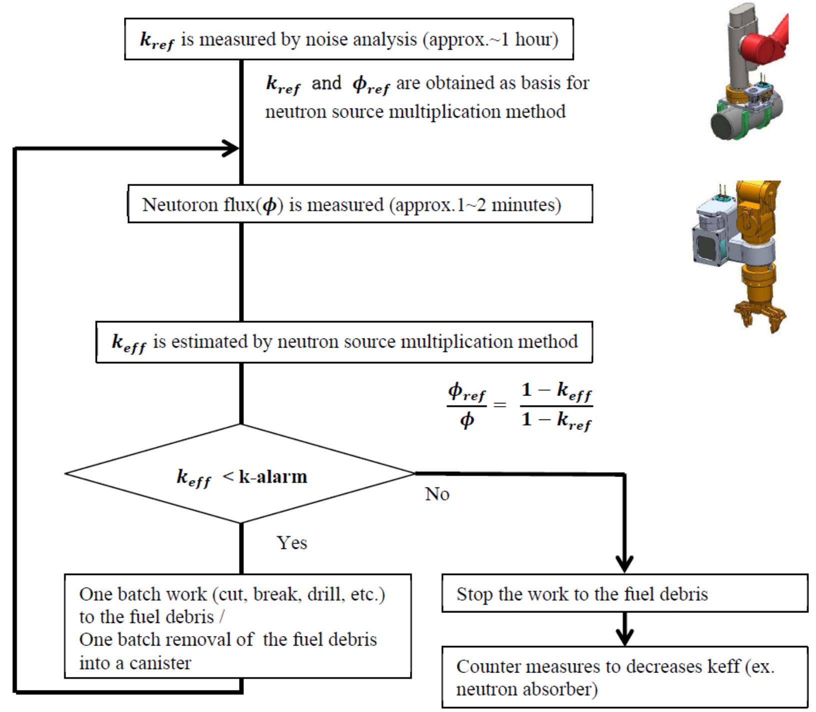


- 3 kinds of neutron measurements
  - **Sub-criticality measurement**
    Use neutron noise Feynman-α method to assess k-eff.
    Use at first to estimate k-eff
  - **Source Neutron Multiplication method**
    To decide to suspend of resume work
  - **Continuous neutron flux monitoring**
    To detect unexpected criticality change



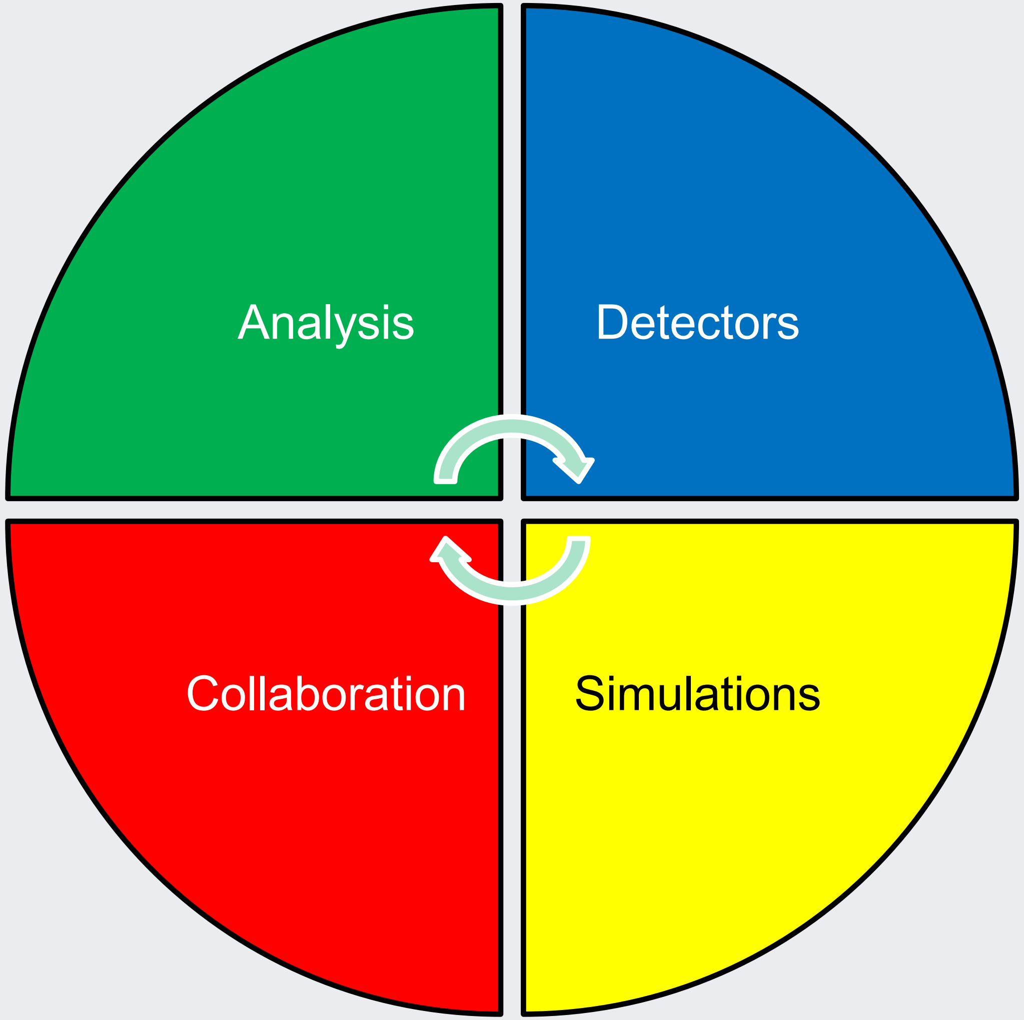
Y. Hayashi, “DEVELOPMENT OF CRITICALITY APPROACH MONITORING METHOD USING NEUTRON DETECTORS FOR FUEL DEBRIS RETRIEVAL IN FUKUSHIMA DAI-ICHI NPP,” ICNC 2023.





1FRAME focus areas

Details of FY25 progress in each focus area are given in the following slides



1FRAME focus area: detectors

Detectors

- We have experience in many types of radiation detectors
  - ^{3}He, boron-lined, BF_3, Organic Scintillators, Solid State, etc.
  - Measurements in laboratory and field conditions (zero-power reactors, spent fuel, emergency response, and others)
- 1FRAME focus: high gamma tolerant (10-100Gy/hr) neutron detection systems:
  - Detectors
    - Optimized and/or traditional detectors:
      - Optimized 3He tubes (quench gas, tube dimensions, boron lining)
      - Boron-lined detectors
      - Fission chambers
    - Next-generation detectors:
      - Diamond
      - Silicon carbide
  - Signal processing electronics
    - Conventional and next-generation amplifier modules
      - PDT, ORTEC, KM200
      - KM200 is a LANL developed, tunable next-generation amplifier module
    - FPGA pulse processing
    - Current mode optimization for extreme radiation environments

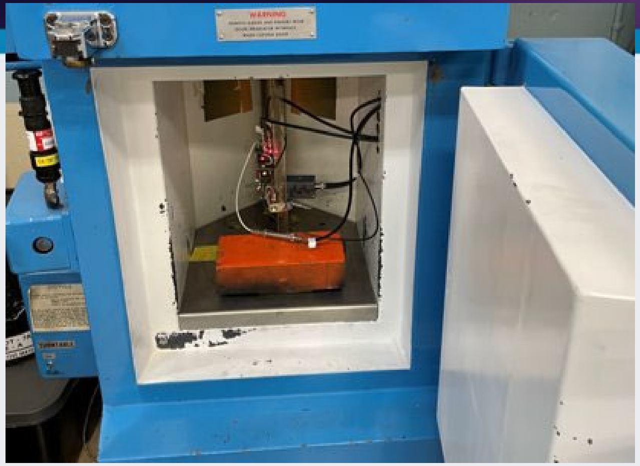
- 1FRAME goal: (a) evaluate radiation hardness of electronics components

  (b) evaluate neutron detection performance in high gamma background and mixed neutron/gamma environments representative of Fukushima conditions

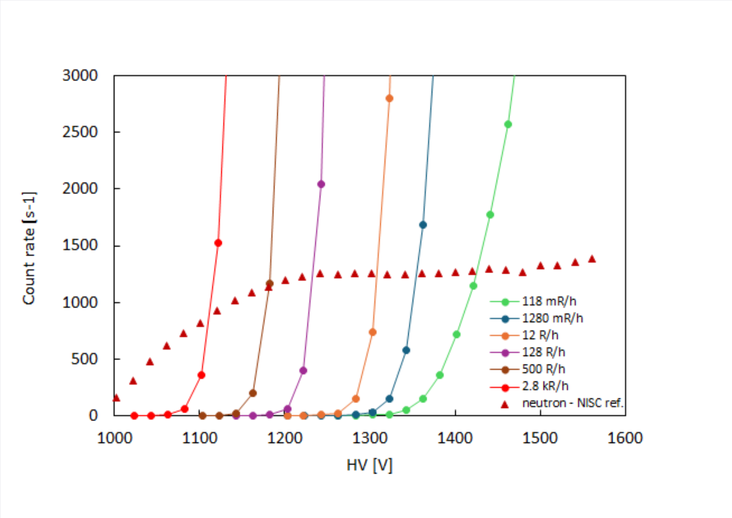
Focus area: detectors – gamma irradiation tests

Detectors

- Radiation hardness testing of LANL-developed KM200 amplifier
  - Amplifier installed inside Mark 1 irradiator (3kCi Cs-137)
  - Performance monitored using test input (no detector attached)



- Gamma characterization of standard ^{3}He detector with KM200
  - Goal: to establish capability for future testing of suite of neutron detectors
  - Initial gamma response characterization using calibrated Cs-137 sources shown below; neutron data are from earlier Cf-252 characterization



Focus area: analysis – source localization

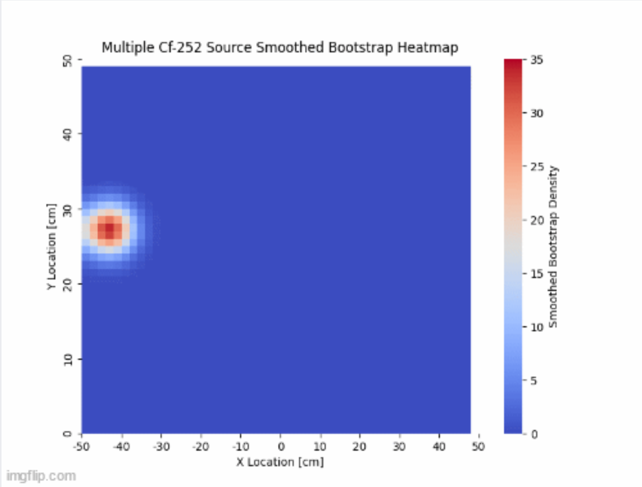
Goal: Enable real-time neutron source localization to support criticality monitoring during fuel debris removal

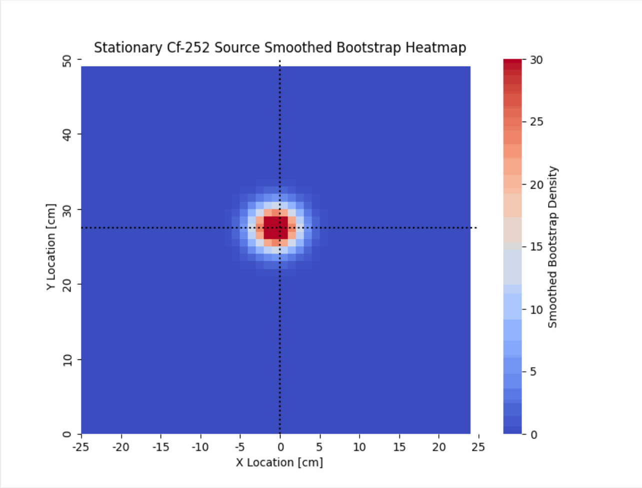
Method:

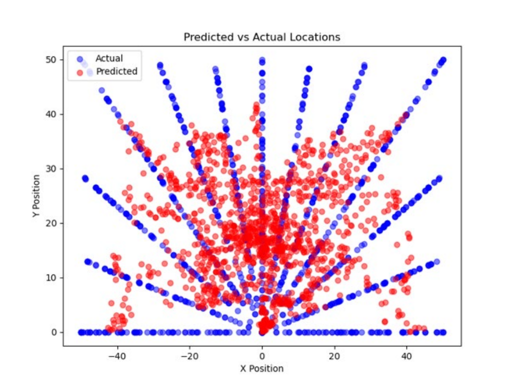
Use tube count data from NoMAD He-3 detector and Random Forest Regression (RFR) to predict neutron source positions from streamed data

Current & Expected Results

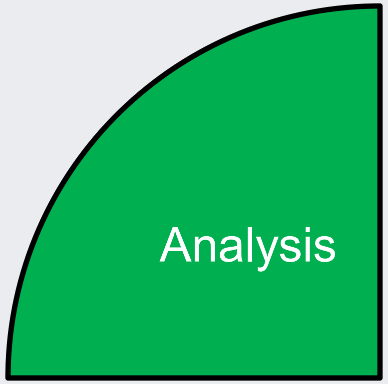
- Able to locate a stationary Cf-252 source in multiple positions
- Working towards being able to identify multiple sources of varying activities
- Lowering the needed dataset size to make accurate predictions
  - Currently ~5 min predictions, goal is <1 min



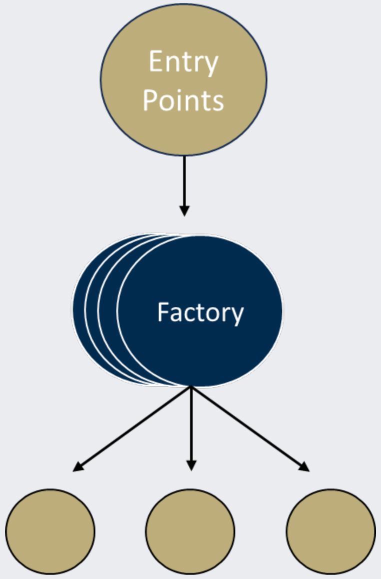


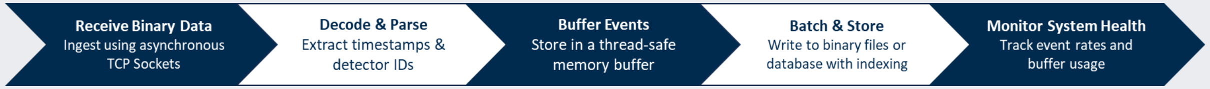


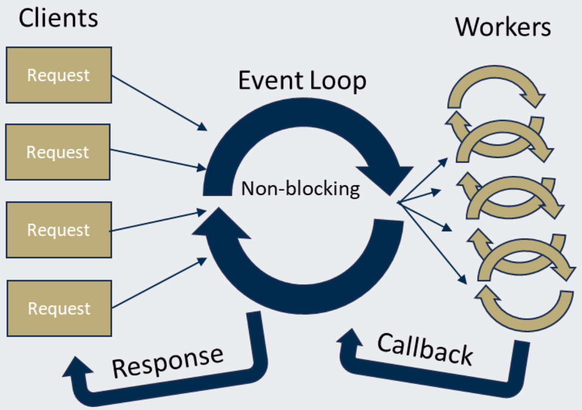
Focus area: analysis – real-time analysis



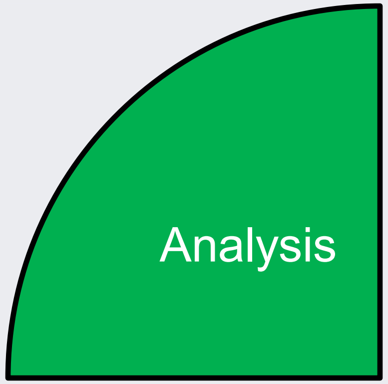
- Real-time neutron multiplicity analysis system for monitoring reactivity during fuel debris removal
  - Apply Hage-Cifarelli formalism on real-time neutron count data
- Detector-agnostic architecture to process time-correlated detection events
  - Critical step is ingesting and processing large amounts of data in real-time
- System performance will be validated under high gamma radiation to simulate core conditions
  - Will need to be adaptable to complex radiation environments



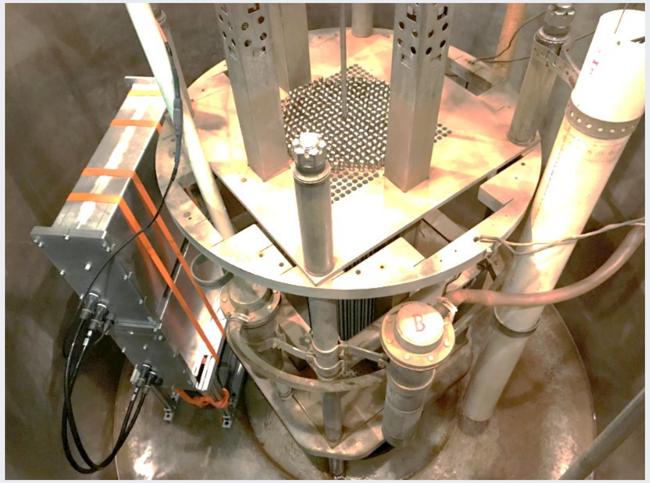


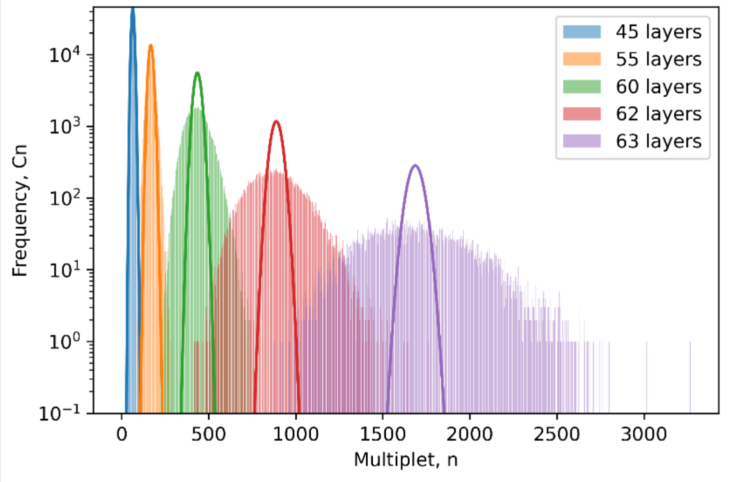


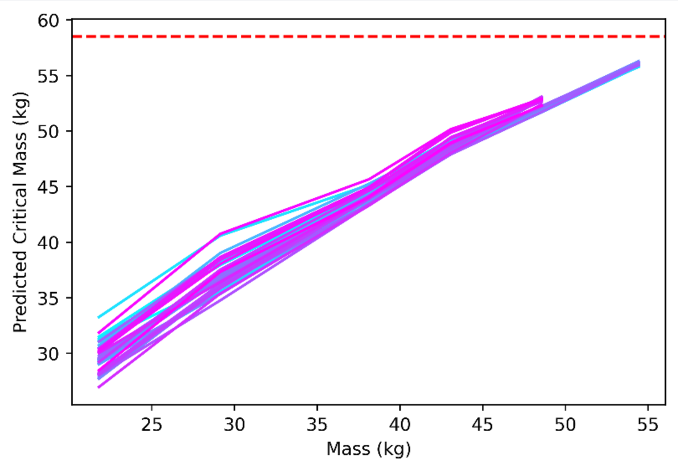
Focus area: analysis - regression with machine learning

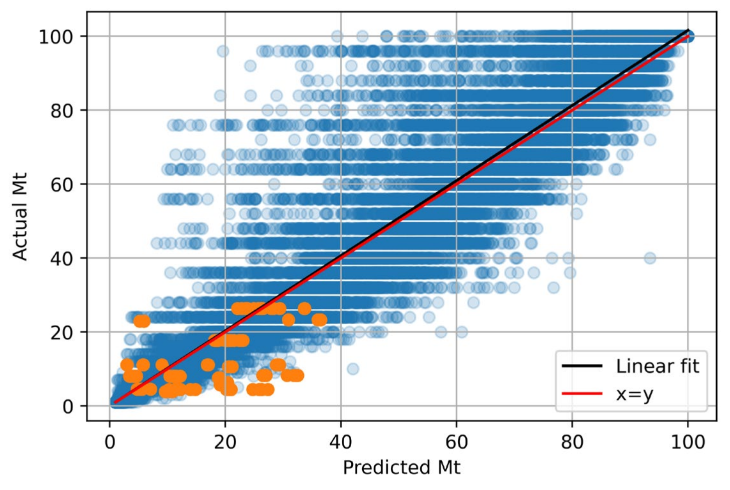


- Explored the use of neutron noise parameters for approach-to-critical analysis
  - The use of neutron noise parameters results in accurate estimates even if the starter neutron rates are changing
- Used machine learning to predict total multiplication
  - Generated large datasets (100,000+ files) to train ML models
  - Predicts total multiplication with no direct efficiency information





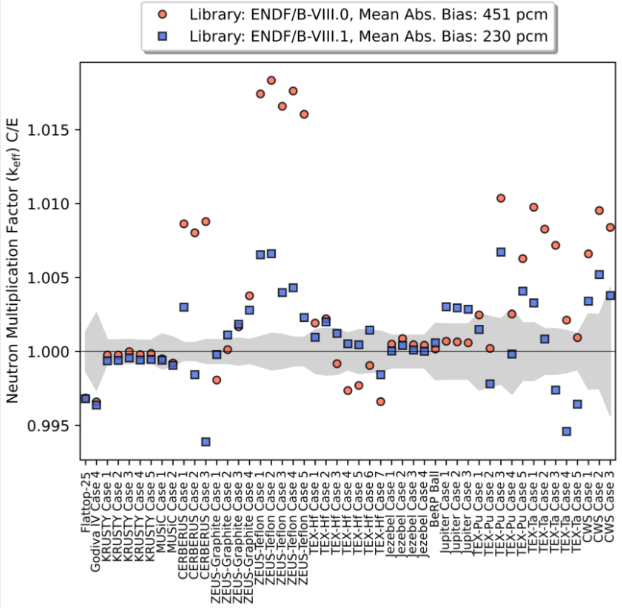


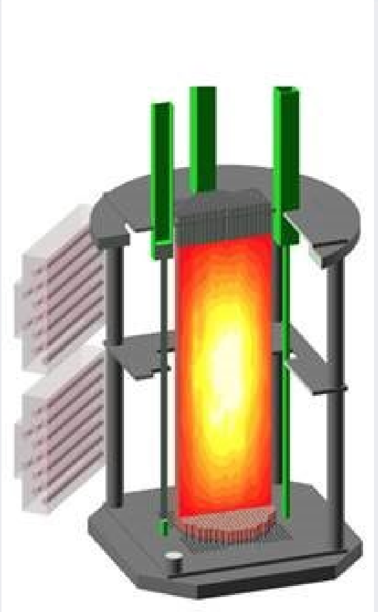


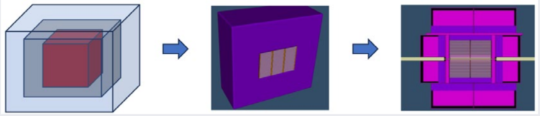
1FRAME focus area: simulations

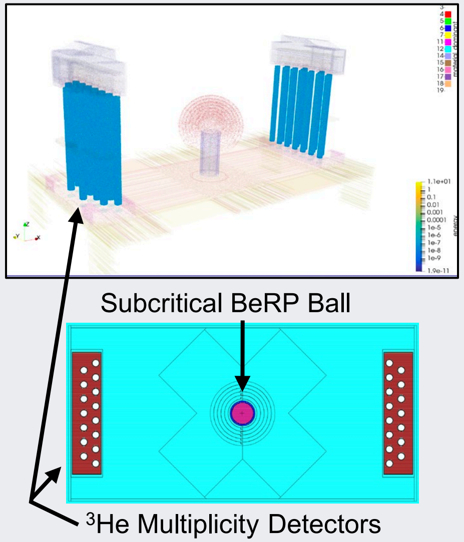
Simulations

- We have experience in Monte Carlo and deterministic modeling & simulation:
  - Criticality, fixed source, list-mode
  - Simple to highly complex models
  - Unstructured Mesh
  - Advanced Variance Reduction Techniques
- We are interested in a systematic assessment of how critically parameters could change during fuel debris removal operations
  - Build on lessons learned from modeling & simulation of previous incidents
  - Low- to high-fidelity models of 1F fuel debris
- We are also interested in extending research in the area of stochastic media (randomized geometry)





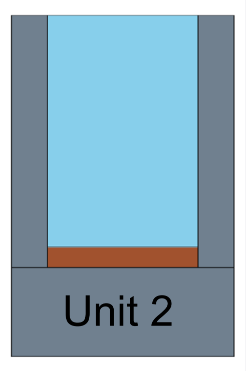


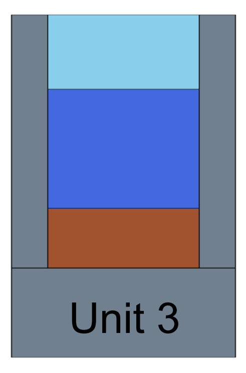


Focus Area: simulations – Unit 2 & 3 Pedestal Region Debris

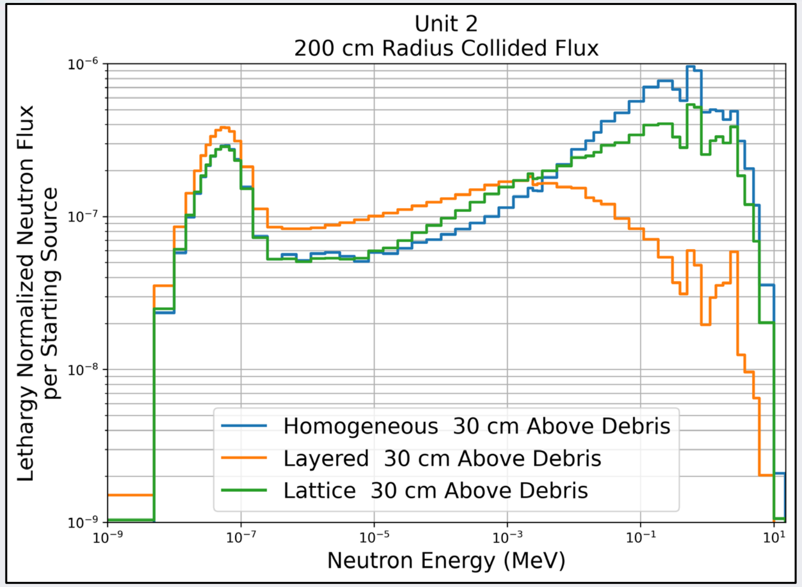
Simulations

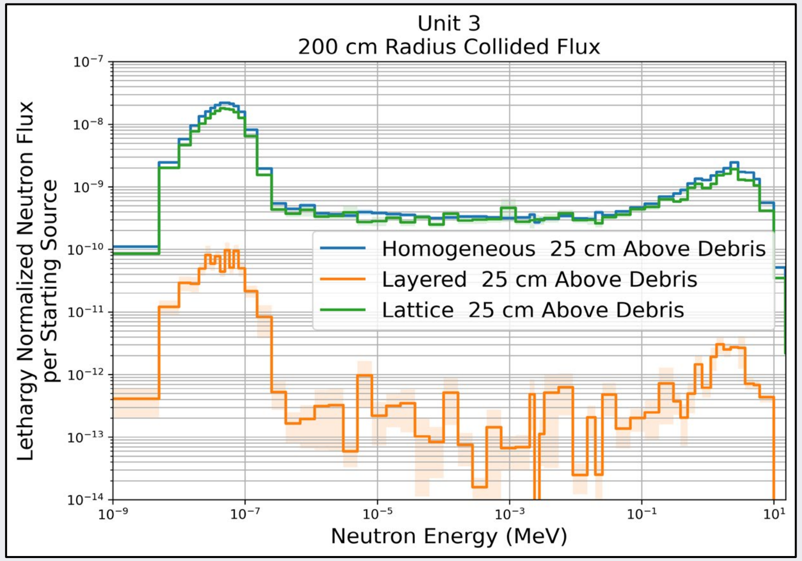
- Built simplified MCNP models of Unit 2 and 3 pedestal region debris based on PCV internal investigation reports from TEPCO
- Leveraging JAEA Dataset for debris material composition
- Assessing change in neutron spectral flux and source strength as a function of debris modeling choices:
  - Homogeneous (all materials mixed as one)
  - Layered (structural debris atop fuel debris)
  - Lattice (fuel spheres suspended in structural medium)
- Inform detector placement and spectral sensitivity to optimize counts





Debris Model Choice	Zr Mass (tons)	U Mass (tons)	Pu Mass (tons)	Cm-244 Mass (tons)	Cm-244 Activity (n/s)
Unit 2					
Homogeneous	13.36	63.90	0.413	5.134E-4	5.613E9
Layered	15.07	61.09	0.395	4.909E-4	5.336E9
Lattice (estimated)	31.22	34.49	0.223	2.771E-4	3.030E9
Unit 3					
Homogeneous	38.16	182.6	1.474	1.236E-3	1.352E10
Layered	37.73	183.3	1.420	1.241E-3	1.357E10
Lattice (estimated)	89.19	98.55	0.763	6.674E-4	7.295E9

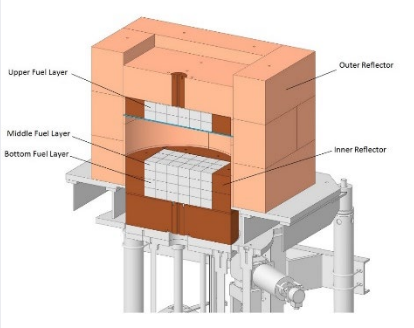


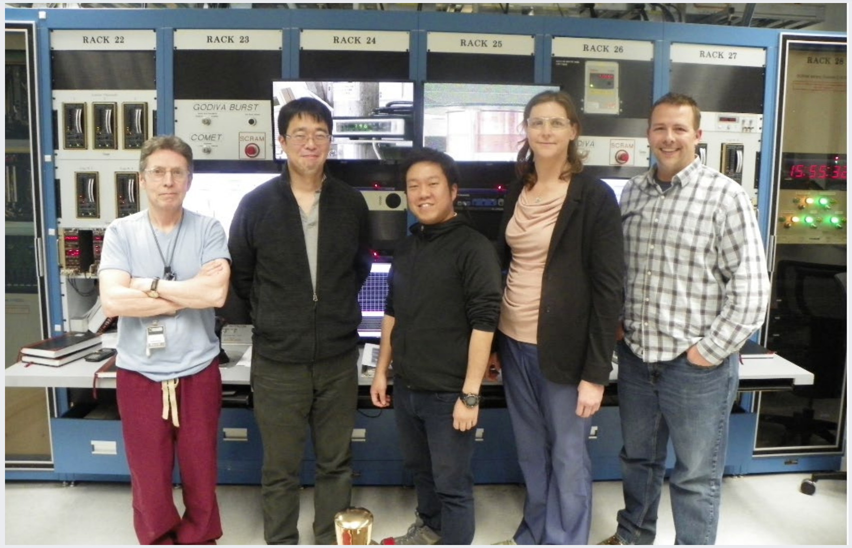


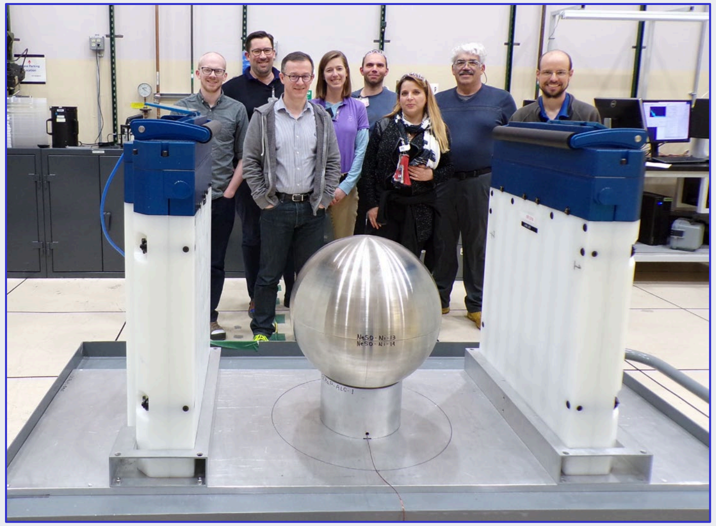
1FRAME focus area: collaboration

Collaboration

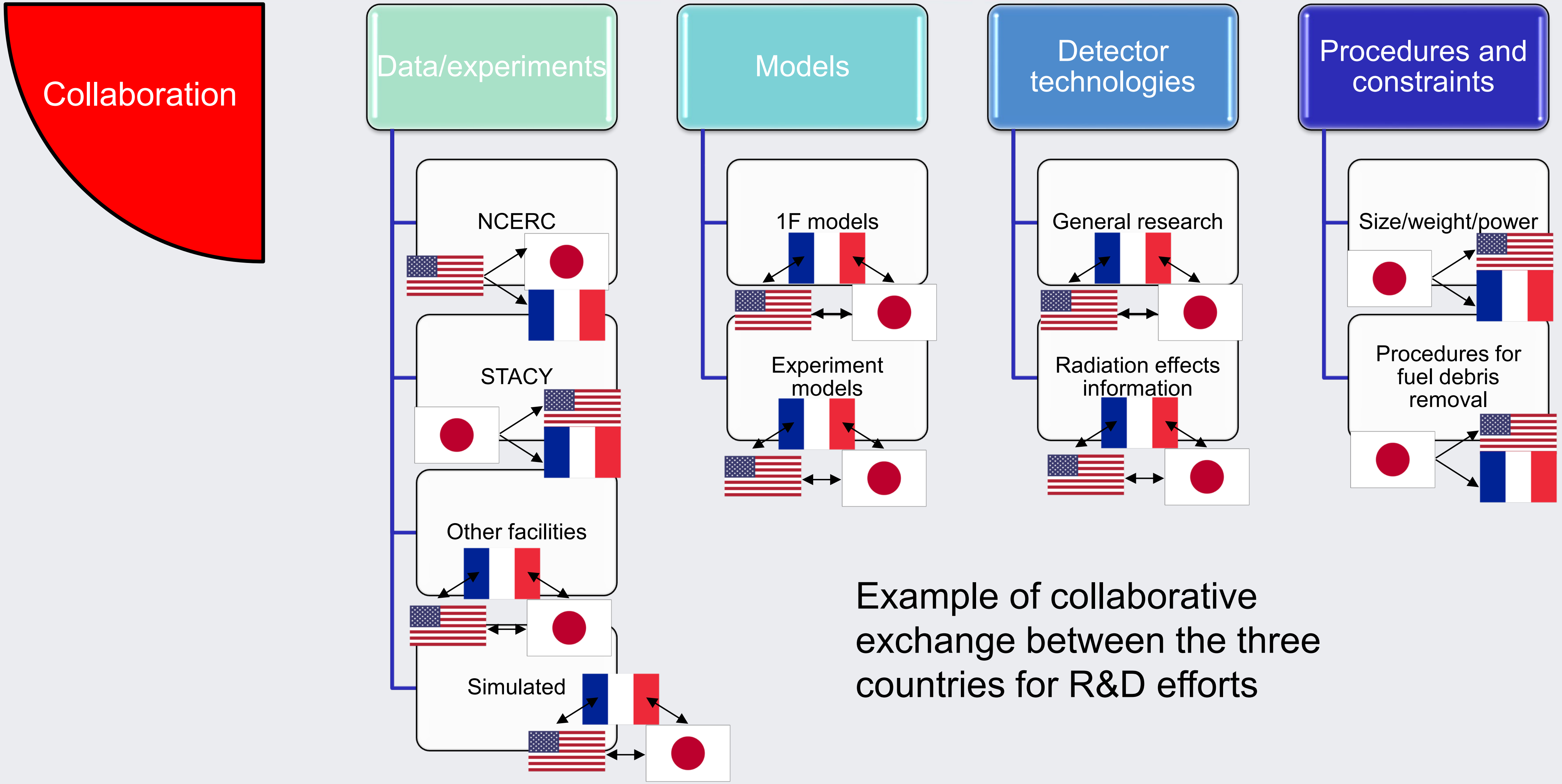
- JAEA: performed 5 joint criticality experiments in 2014-2019 focused on Lead validation for ADS systems
- A JAEA/METI employee is currently at Los Alamos for 1 year
- Collaborating with JAEA NUCEF on this project
- Discussions to collaborate with JAEA CLADS
- IRSN (now ASNR) France: collaborated on many critical and subcritical experiments in the last 10 years
- Interested in extending collaborations with JAEA, METI, Toshiba, GE-Hitachi, etc.
- Four team members are on the NEA Fukushima decommissioning working group FACE
- Participation in the Civil Nuclear Working Group (CNWG)







1FRAME focus area: collaboration



Example of collaborative exchange between the three countries for R&D efforts

1FRAME Intersection with FACE

Collaboration

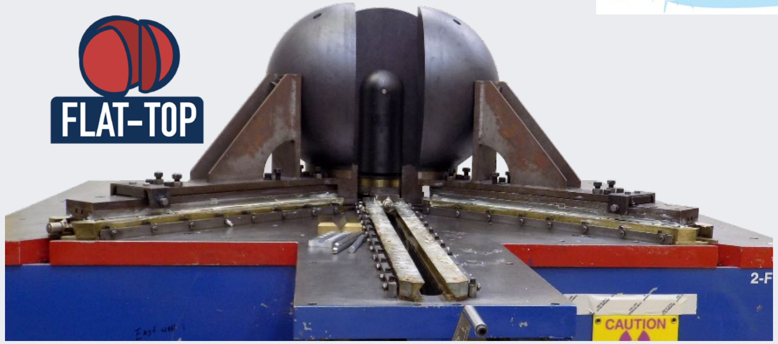
- 1FRAME and FACE objectives complement one another and enable the project to address several needs of the FACE project
  - Inform data/information needs from the viewpoint of reactor safety and decommissioning, the feasibility of collecting such information, and their priority
  - Confirm the feasibility and accuracy of analysis techniques for fuel debris retrieval operations
  - Aid in the interpretation of findings related to important observations relevant to accident scenarios
  - Aid in quantifying the uncertainty in parameters of interest to 1F fuel debris retrieval operations
  - Maintain communication channels with international partners to share data/information and expertise
- 1FRAME efforts align naturally with the scope outline for the FACE project:
  - Scope 2: the establishment of techniques for future fuel debris analysis for D&D
  - Scope 3: collecting and sharing data and information related to FDNPS investigations
- Future 1FRAME efforts can contribute to subsequent iterations of FACE

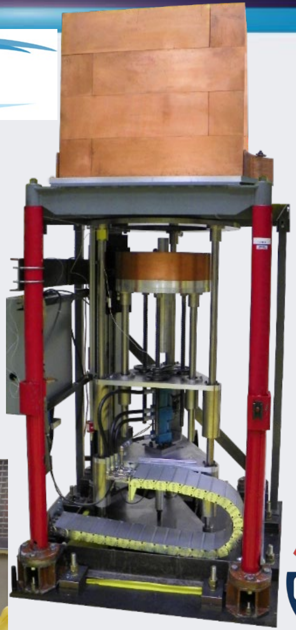
Current status

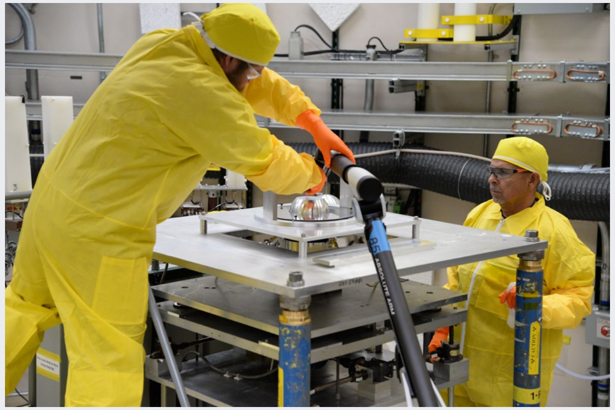
- Research started in Oct 2024
- Radiation detection: 2 successful measurement campaigns have been performed, analysis on-going
- Neutron analysis: working on first blind test set, presented source localization work, other analysis work ongoing
- Simulations: completed first large set of simulations
- Collaboration: regular meetings with ASNR and JAEA NUCEF, initial meeting with JAEA CLADS, Toshiba, GE-Hitachi, others.
- Publications: 1FD8 (Iwaki), Methods in Analytical RadioChemistry (MARC, Kona), ANS Student Conference (Albuquerque), Nuclear Data (ND2025, Madrid), Nuclear Criticality Safety Division topical meeting (NCSD, Austin) are all submitted.
  - Several publications will be submitted to IEEE NSS (Yokohama) soon

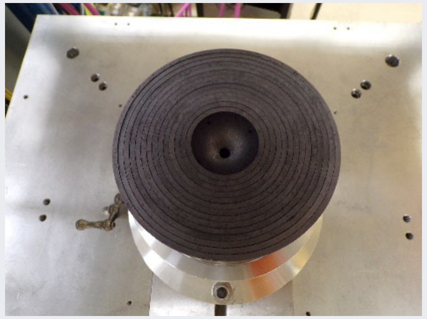
Backup

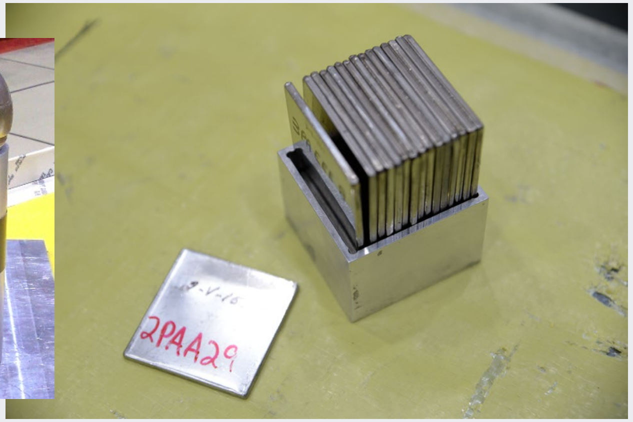
NCERC currently has four critical assembly machines, high bays, vaults, a count lab, and a large inventory of nuclear material





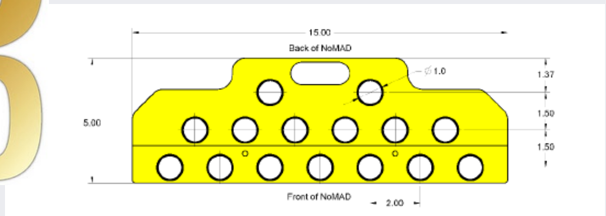


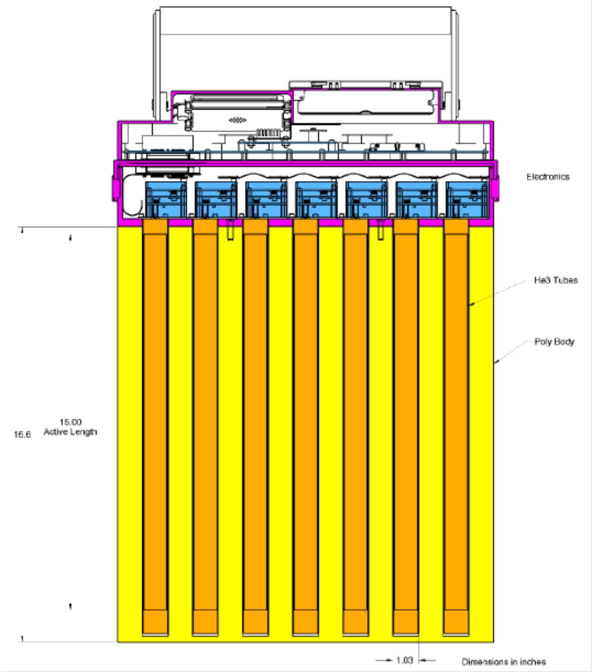




Experience with Measurement Systems and Noise Analysis

- We have experience in many types of radiation detectors.
- The MC-15 system (15 Helium 3 tubes in poly) has been used for many subcritical benchmarks (next slide) and was designed to measure unknown systems.
  - Nuclear nonproliferation and nuclear emergency response.
  - Benchmarks for the Nuclear Criticality Safety Program (NCSP)
- Used routinely for
  - Measurement campaigns at the National Criticality Experiments Research Center (NCERC).
  - Measurement campaigns at other nuclear facilities.
  - Field measurements.
- Very robust system built for field conditions.
- Acquired real-time measurements submerged underwater.



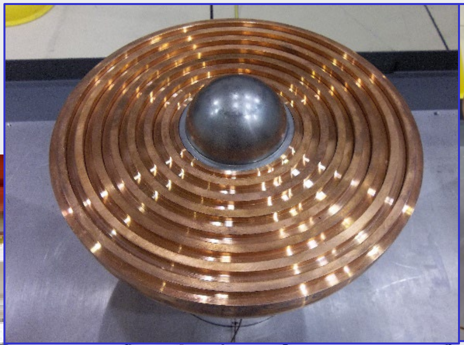


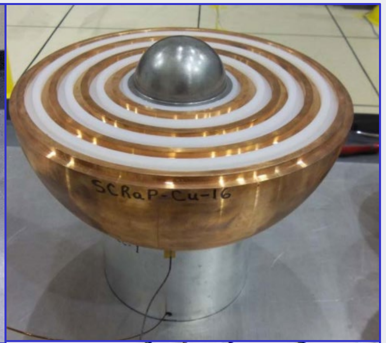
NCSP Subcritical Experiments

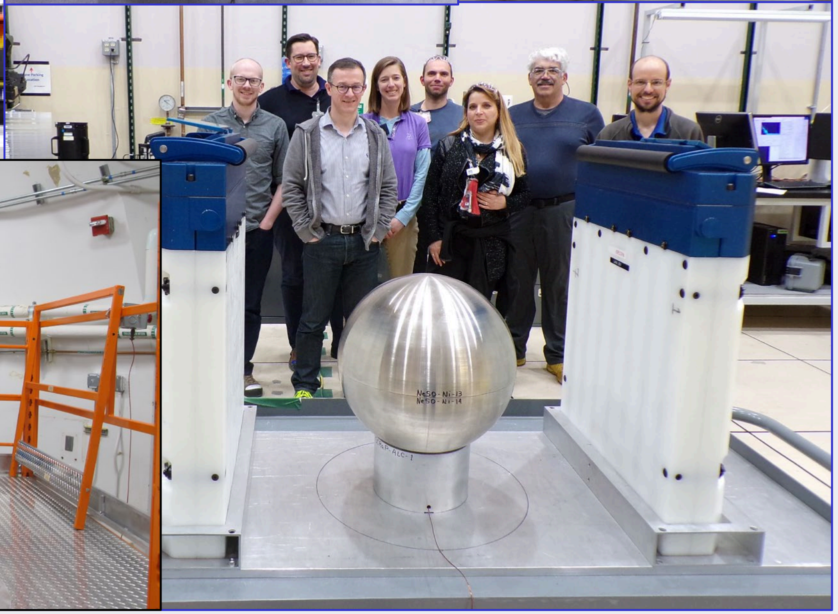
NCSP
NUCLEAR CRITICALITY SAFETY PROGRAM

IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

- Growing dataset of neutron multiplication benchmarks experiments/evaluations
  - Many years of sub-critical experiment research
  - Validate nuclear data and computational methods
- BeRP-Ni (2014)
- BeRP-W (2016)
- SCRαP (2019)
- NeSO (2019)
- MUSiC (2021)
- 7uPCX at Sandia (2022)
- Experiment design, simulations, data analysis, and uncertainty quantification

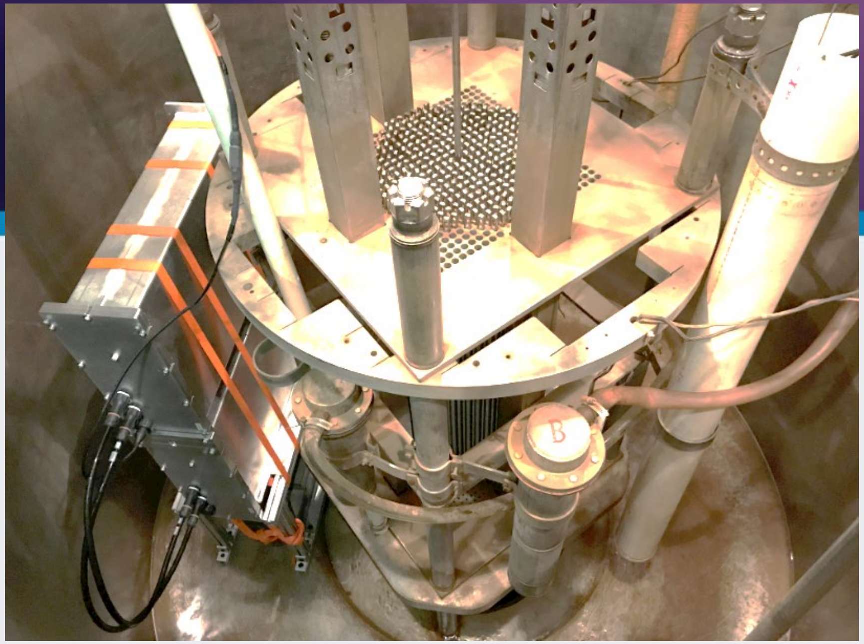


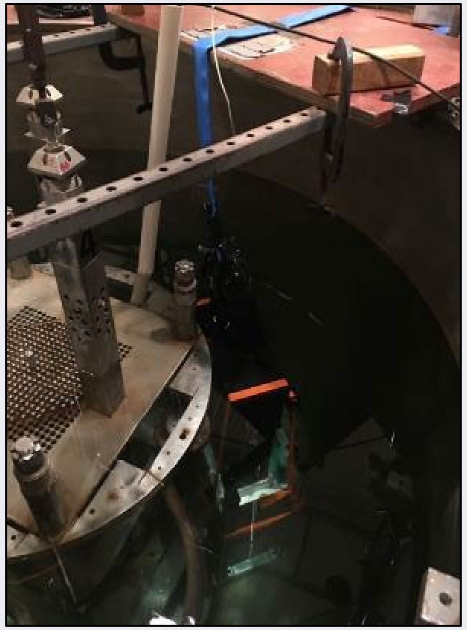


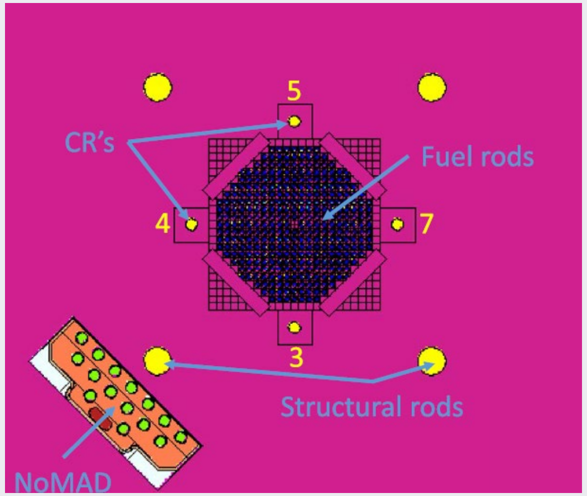


Research reactor measurements

- In 2016 and 2017, two measurement campaigns were performed at the RPI Reactor Critical Facility (RCF) in collaboration with IRSN.
- Configurations ranged from deeply subcritical to critical.
- A water-tight housing was designed to ensure the detection system could operate underwater.







communications physics

ARTICLE

Check for updates

https://doi.org/10.1038/s42005-021-00654-9

OPEN

Patchy nuclear chain reactions

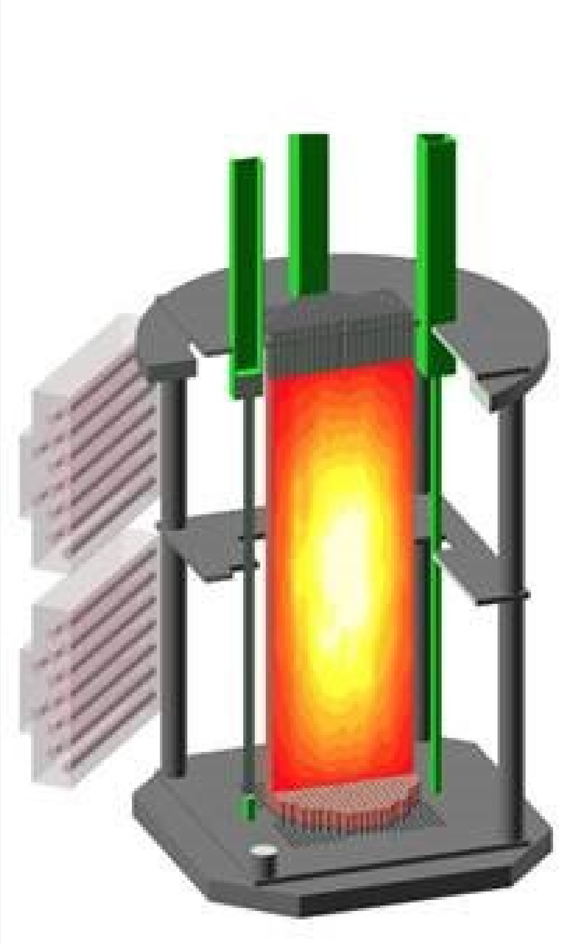
Eric Dumonteil[1,4✉], Rian Bahran[2], Theresa Cutler[2], Benjamin Dechenaux[1], Travis Grove[2], Jesson Hutchinson[2], George McKenzie[2], Alexander McSpaden[2], Wilfried Monange[1], Mark Nelson[2], Nicholas Thompson[2] & Andrea Zoia[3]

NCSP
NUCLEAR CRITICALITY SAFETY PROGRAM

IRSN simulation experience

- MORET6 : Analog calculation in fixed source mode (Neutron noise experiments interpretation)

  → *PHYSOR 2022 : New capabilities of the MORET 6 Monte-Carlo neutron transport code,*
  Wilfried Monange, Aurélie Bardelay (IRSN, FRANCE)



JAEA collaborations to support ADS

NCSP
NUCLEAR CRITICALITY SAFETY PROGRAM

- Experiments performed in collaboration with JAEA and supported by the NA-232 Office of Nuclear Material Removal.
  - DOE-NCSP provided support for benchmark evaluations
- Accelerated shipping schedule returned HEU and Pu fuel from FCA to US under Remove Program.
- Lead void measurements are important for regulatory approval of system with lead-bismuth coolant.
- HEU, LEU, and Pu experiments performed.
- 5 year program: 2015-2020.

JAEA