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Multi-Physics Code Prediction of Nuclear Material Quantities for Advanced Reactor Safeguards

Dr. Karen Koop Hogue

Oak Ridge National Laboratory

U.S. DEPARTMENT OF ENERGY

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Safeguards and Security by Design is Essential

"New reactor types, especially small modular reactors, or SMRs, and advanced reactors… will also require new safeguards and security approaches. With advanced reactors in the early stages of development, there is an opportunity for governments, regulators, and the nuclear industry to work together not only to strengthen safety features, but also security and safeguards features of nuclear reactors and their associated fuel cycle facilities."

-Jill Hruby
Former National Nuclear Security Administrator

U.S. advanced nuclear industry

The Molten Chloride Reactor Experiment was selected as a Risk Reduction Award winner under the Advanced Reactor Demonstration Program

The Zero Power Physics Reactor (ZPRR) facility at Idaho National Laboratory is the intended home of the Molten Chloride Reactor Experiment

https://www.ans.org/news/article-4873/get-to-know-mcre-the-fastspectrum-msr-from-southern-and-terrapower/

The Kairos Hermes Test Reactor was selected as a Risk Reduction Award winner under the Advanced Reactor Demonstration Program and issued a construction permit in Dec 2023

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Office of Public Affairs, Headquarters
Washington, DC. 20555-0001
www.nrc.gov ■ opa.resource@nrc.gov

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CONTACT: Scott Burnell, 301-415-8200
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NRC to Issue Construction Permit for Kairos Hermes Test Reactor in Tennessee

The Nuclear Regulatory Commission has directed the staff to issue a construction permit to Kairos Power for the company's proposed Hermes non-power test reactor in Oak Ridge, Tennessee. The permit authorizes Kairos to build a 35-megawatt thermal reactor that would use molten salt to cool the reactor core.

Following a mandatory hearing held on Oct. 19, the Commission authorized the agency's Office of Nuclear Reactor Regulation to issue the permit, having found the staff's review of the Kairos application adequate to make the necessary regulatory safety and environmental findings. The staff expects to issue the permit by the end of the month.

Kairos submitted its application to build the Hermes reactor in 2021. The test reactor, which will not generate electricity, is intended to provide operational data to support the development of a larger version for commercial power.

The NRC issued the final environmental impact statement for the site in August 2023 and the final safety evaluation for the permit in June 2023.

Kairos will have to submit a separate application for an operating license before it could operate the Hermes reactor.

The NRC announces a construction permit issued to Kairos Power

https://www.nrc.gov/cdn/doc-collection-news/2023/23-078.pdf

NRC issued a construction permit for the Natura Resources' MSR-1 at Abilene Christian University in Sept 2024

The NRC with Natura Resources, ACU, and NEXT Lab leadership

https://www.naturaresources.com/natura-resources-molten-salt-reactor-at-acu-receives-historic-nrc-construction-permit

Reporting requirements for nuclear materials

Material	Domestic Safeguards[1]	International Safeguards[2]
Total U	whole g (for enriched U) whole kg (for depleted U) ^{235}U isotope wt%	g (for U enriched in ^{235}U or ^{233}U) kg (for natural U, depleted U)
^{235}U	whole g	g
^{233}U	whole g	g
$^{233}U + ^{235}U$	-	g
Total Pu	whole g ^{240}Pu isotope wt%	g
^{238}Pu	g to tenth	g
^{239}Pu	-	g
^{240}Pu	-	g
^{241}Pu	-	g
^{242}Pu	whole g	g
$^{239}Pu + ^{241}Pu$	whole g	g
Thorium	whole kg	kg

[1]*Nuclear Materials Management and Safeguards System (NMMSS) Users Guide-Rev. 2.1*
[2]SG-FM-1172 *Model Subsidiary Arrangement Code 10*

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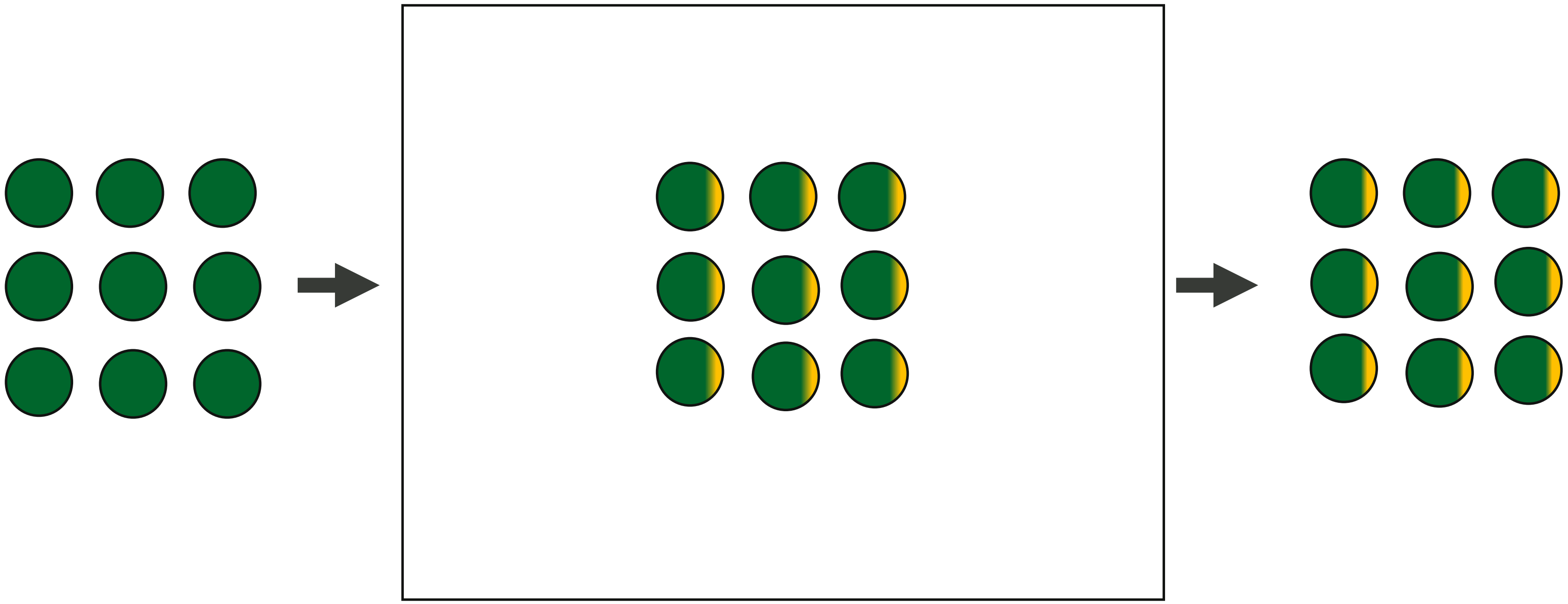
Simplified nuclear material reporting

Uranium
Plutonium



Fresh fuel receipt/storage

Reactor containment

Spent fuel pool

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Nuclear data uncertainties impact both predicted and measured nuclear material quantities

Predicted nuclear material quantities

Similar to LWRs, in advanced reactors, physics or multi-physics codes will likely be used to predict inventories for reporting purposes:

- SCALE
- Monte Carlo N-Particle Transport (MCNP)
- OpenMC
- Serpent
- Multiphysics Object Oriented Simulation Environment (MOOSE)
- System Analysis Module (SAM)

Measured nuclear material quantities

Some measurement systems may leverage radiation-based signatures

Nuclear data uncertainties will impact measurement uncertainties

- (α, *n*) cross sections in novel coolants (e.g., FLiBe)
- Neutron multiplicity

Similar findings related to nuclear safety applications: Bostelmann F, Ilas G and Wieselquist WA (2023), Key nuclear data for non-LWR reactivity analysis. Front. Energy Res. 11:1159478. doi: 10.3389/fenrg.2023.1159478

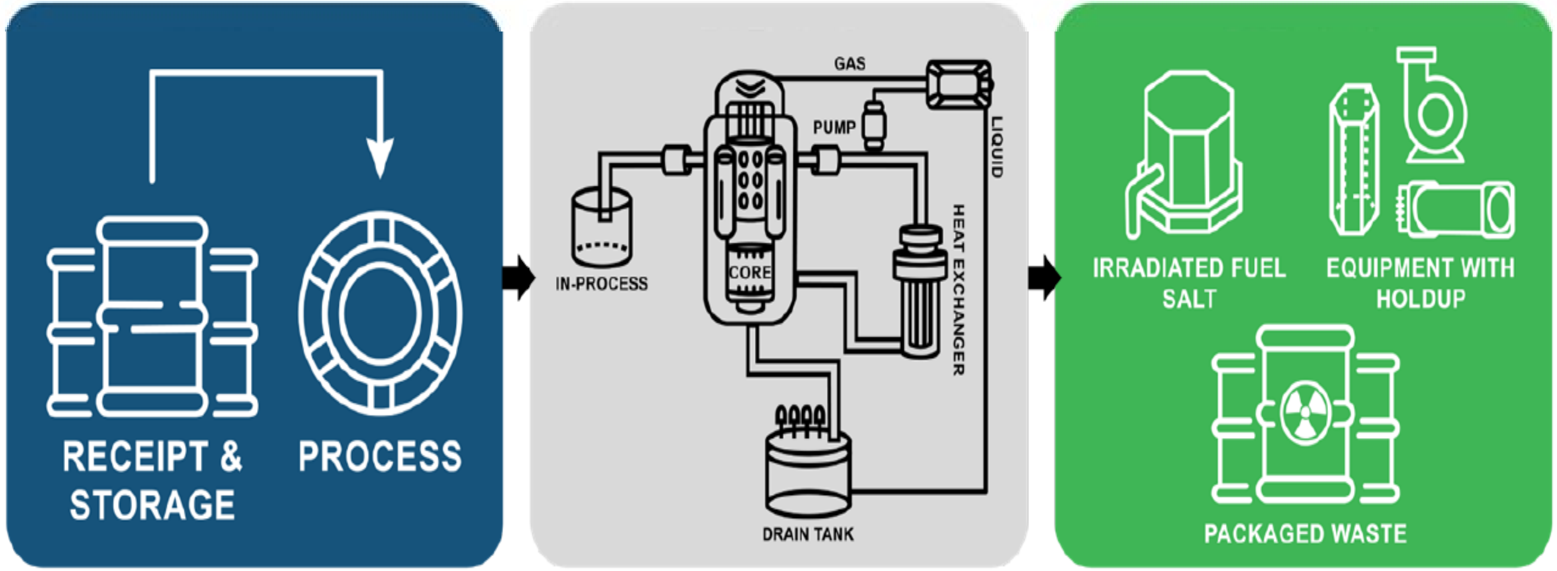
Predicted vs Measured Quantities

- Nuclear data uncertainties in advanced reactors may lead to discrepancies between *reported nuclear material quantities* and *measured inventories*
- Challenging to evaluate whether each discrepancy is
  - A valid discrepancy due to propagated uncertainties; or
  - An indicator of diversion or misuse (or concealment thereof)
- With many advanced reactor designs currently under development, it's challenging to prioritize nuclear data R&D. E.g.., for molten salt reactors:
  - U/Pu fuel cycles or Th/^{233}U?
  - Chloride-based salts or fluoride-based salts?
  - Thermal or fast neutron spectrum?

Advanced Reactor Application: Liquid-fueled Molten Salt Reactors

Additional challenges to quantifying nuclear material in reactor containment through measurements:

- Nuclear material is in bulk form
- Measurements may impact operations
- Salt is corrosive
- Nuclear material may be in several process streams at any given instant while operational
- In many cases, measurement systems to quantify nuclear material are at low technical readiness levels



Conclusions

We need an intentional R&D effort to quantify uncertainties on nuclear material inventories calculated using physics codes for each class of advanced reactor

There are opportunities for collaboration between nuclear data, reactor physics, and safeguards communities for the most efficient use of limited test beds for benchmarks, verification, and validation

- Pair irradiation experiments with post-irradiation examination for radio-chemical assay benchmarking of codes
- Partner with industry to leverage research, test, and demo reactors
- Consider impacts of operational parameters that impact reactivity for each class of reactors

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