MSR Integrated Off Gas Roadmap

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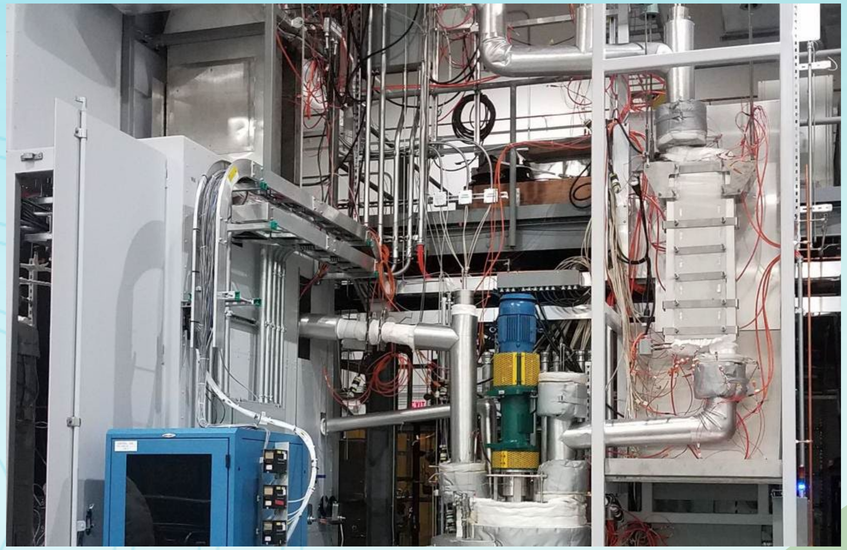
An integrated off-gas system will be developed and demonstrated by FY30



FY26

Develop roadmap

FY27

Construct integrated off-gas system

FY28

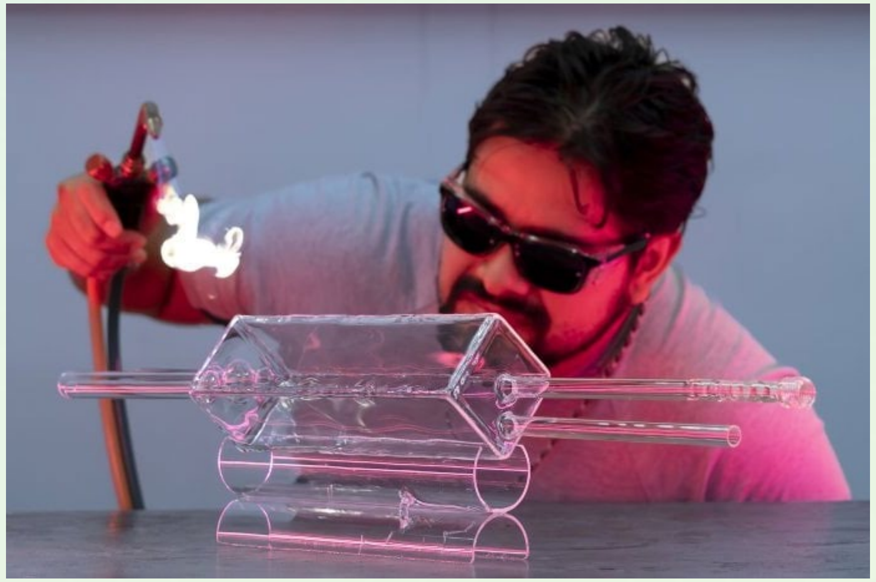
Perform cold testing on salt loop

FY29

Modify design based on cold tests

FY30

Start radiological tests



Key Takeaways from MSR Workshop 2025 Off-Gas Session

MOLTEN SALT REACTOR WORKSHOP 2025

A 3-hour session focused on current state of MSR off-gas systems and knowledge

Presentations:

Randy Ngelale, ORNL

Joanna Mcfarlane, ORNL

Praveen Thallapally, PNNL

R&D Panel: *Joanna McFarlane, ORNL – Chair*

Hunter Andrews, ORNL

Matt Christian, SNL

Katie Johnson, ORNL

Daniel Orea, ORNL

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Industry Panel: *Hunter Andrews, ORNL – Chair*

Rol Johnson, Muons, Inc.

Khalil Ghaleb, Orano

Aslak Stubsgaard, Copenhagen Atomics

Kim Pamplin, ACU

David Lambertin, NAAREA

Jonathan Scherr, Natura

Natura Resources

copenhagen atomics

naarea

orano

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U.S. DEPARTMENT of ENERGY
Office of Nuclear Energy

Big Picture

- Off-gas management is emerging as a central challenge in molten salt reactors (MSRs), with clear development timelines targeting integrated systems and radiological testing by ~2030.
- Off-gas is safety-critical and tied to licensing
- Integrated system testing is essential
- Early systems will prioritize data collection over optimization

System Architectures

Multiple competing approaches exist for off-gas handling:

- Continuous: low inventory but complex and prone to aerosols/plugging
- Batch: simpler, allows decay and sampling
- Sealed: avoids processing but creates heat and storage challenges
- Design choices are heavily influenced by regulatory constraints

Key Knowledge Gaps

Significant uncertainty remains in:

- Gas-phase chemistry and radionuclide speciation
- Aerosol formation, transport, and deposition
- Bubble transport dynamics in molten salts
- Liquid–gas interface behavior

Overall: strong understanding of liquid phase, weak understanding of transport into gas phase

Aerosols and Reliability

Aerosols are a dominant issue:

- Primary transport pathway for radionuclides
- Cause plugging and deposition in lines
- Operational reality: clogging is expected
- Requires redundancy and mitigation strategies

Thermal Considerations

Off-gas systems must handle decay heat:

- Potentially large fraction of total decay heat
- Gas-phase heat removal is challenging
- Passive cooling (e.g., water shielding) commonly used

Capture Technologies

Technologies for radionuclide capture include:

- Traditional: carbon beds, cryogenic systems
- Emerging: MOFs with higher efficiency and smaller footprint
- Challenges: long-term stability, aerosols, temperature effects

Diagnostics and Instrumentation

Strong need for real-time monitoring:

- LIBS and Raman are promising complementary tools
- Need spatially resolved measurements throughout system
- Sensors must be robust, low-cost, and replaceable
- Offline validation remains essential regardless of online sensors

Industry Perspective

Industry prioritizes:

- Reliability, simplicity, and cost
- Use of commercial off-the-shelf components
- Incremental innovation rather than complex systems
- Flexible and modular designs

Research Reactors Role

Early MSRs will act as data platforms:

- Heavy instrumentation
- Sampling at multiple points
- Used to inform future commercial designs

Data and Collaboration

Data sharing will be limited:

- Proprietary concerns exist
- National lab partnerships critical
- <u>Integrated testbeds needed for open data</u>

Future Research Opportunities

High-impact research areas include:

- Aerosol science: formation, transport, mitigation
- Sensor development: durability, radiation resistance, cost reduction
- Integrated system experiments with spatial diagnostics
- Off-gas thermal management strategies
- Coupled modeling (chemistry + transport + capture)
- Scalable, modular off-gas system design
- Validation datasets for regulatory and modeling needs

Vision for off-gas roadmap

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Vision, Mission, and Objectives

- Vision: Provide nationally accessible, validated capabilities to study, measure, and improve MSR off-gas transport, capture, and monitoring
  - INTEGRAL - Integrated Off-Gas Research and Analysis Laboratory (for MSRs)
- Mission: “Advancing MSR performance through integrated off-gas science”
  - Accelerate readiness of off-gas technologies for noble gases, tritium, iodine/halogens, volatiles, and aerosolized species
  - Deliver benchmark data and models under prototypic salt, temperature, radiation, and flow conditions
  - Support licensing-relevant performance metrics and standards

Fundamental Science Questions

- Salt–gas interfacial phenomena:
  - Bubble dynamics for He sparging in molten salts; effect of redox and impurities on gas desorption
- Tritium chemistry and transport:
  - Speciation among T_2/HT/HTO under MSR conditions; permeation through structural alloys and coatings; getters and barriers efficacy
- Sorption and separation science:
  - Competitive adsorption of Xe/Kr in humid/fluorinated streams; iodine chemisorption kinetics and capacity under halogenated conditions; regeneration thermodynamics
- Radiation chemistry and materials:
  - Radiolysis pathways generating and influencing off-gas species; materials compatibility and corrosion in the presence of halogens and tritium
- Multiscale modeling and validation:
  - Coupled CFD–mass transfer models; sorbent breakthrough and decontamination models; permeation models; uncertainty quantification and scale-up laws
- Effect of decay
  - How do capture systems cope with radiation-based heat loads; change in phase during decay – does this effect sorbent/filter lifetime

Facility Architecture and Capabilities

- Modular testbeds
- Salt systems:
  - Static cells and recirculating loops with controlled redox; aerosol generation/mitigation; materials test coupons
- Gas handling and generation:
  - He spargers, precise $Xe/Kr/I_2/H_2/HT/T_2$ dopers; humidity/halogen control; tritium confinement systems, blower for recirculation system
- Capture and separation modules:
  - Swappable capture media: noble gas beds, tritium permeators/oxidizers, iodine sorbents, cryo/PSA/membranes
- Sensing and analytics:
  - On-line MS/GC, FTIR, Raman, LIBS, gamma spectrometry, tritium analyzers, electrochemical probes; calibration infrastructure and standards
- Controls and DAQ:
  - High-integrity control system, synchronized time-stamped data, model-in-the-loop capability, linked to sensors
- Safety and utilities:
  - Confinement ventilation, gloveboxes/hot cells, secondary containment, inerting, waste handling
  - Standard effluent filtering (HEPA) must be in place after integrated off-gas system
- Procedure for integrating new test units
  - Define acceptance criteria, preliminary tests that must be done, safety review

Other considerations for roadmap

- Integration and Interfaces
  - Modular integration with salt loops or irradiation sources
  - Test articles, sample handling, decontamination, infrastructure requirements
- Research milestones
- Technoeconomic Analysis Plans
  - Isotope recovery value proposition
- Workforce Development Plan
- Data Management and Sharing Plan
- User Access Plan
  - Define integration criteria for off-site module development
  - Define strategy for proprietary research agreements when needed

Today's Discussion

To join, go to: ahaslides.com/83UAA

Thank you!

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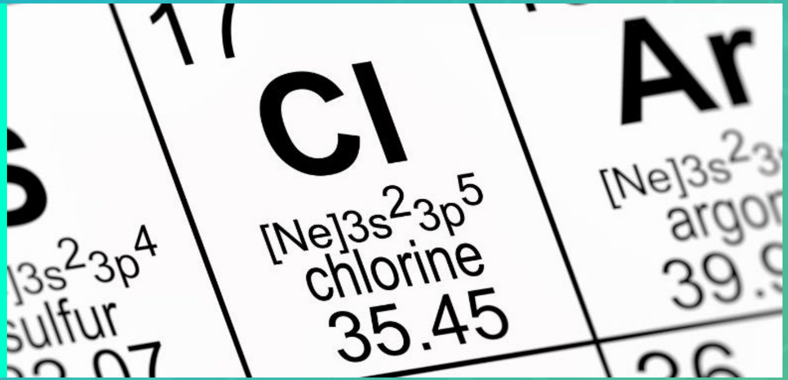
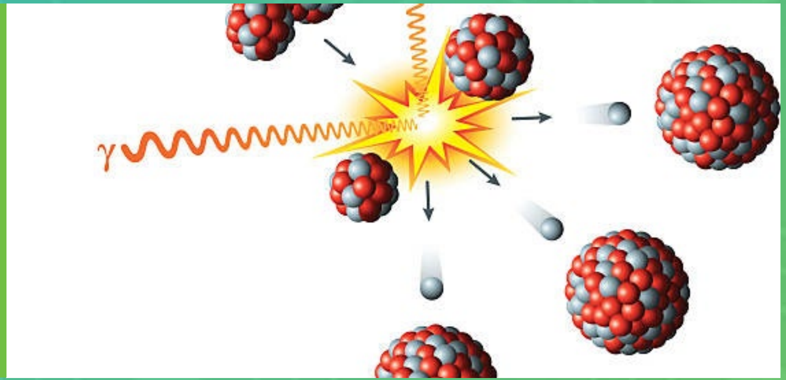
Extra Slides

The off-gas system represents one of the fundamental challenges brought about by liquid fueled MSRs

Reactor and Salt Type

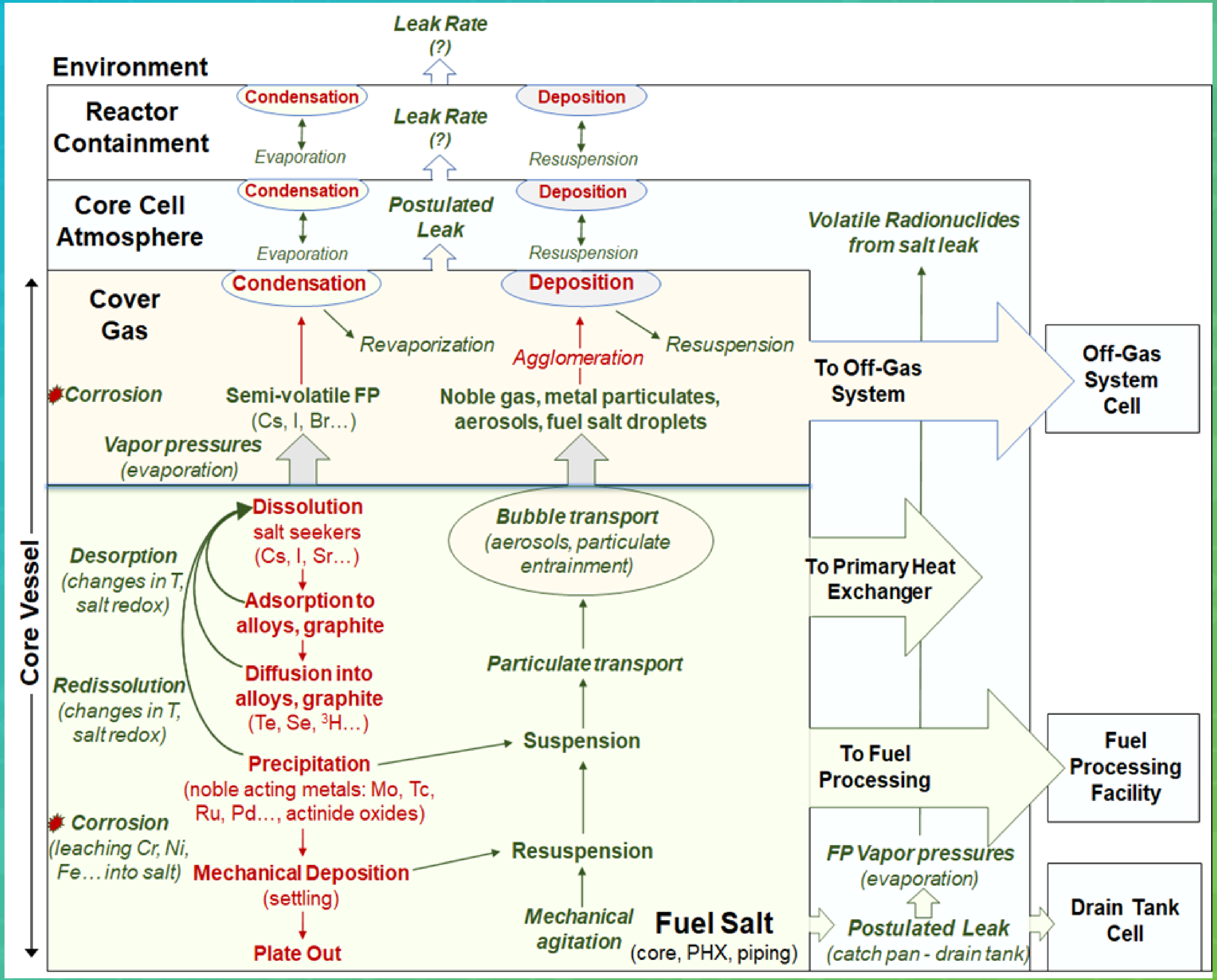


Fast or Thermal Spectrum



Real-Time Separation Technologies

MSR Radionuclide Transport



S. Thomas and J. Jerden. ANL/CFCT-20-16. 2020.

We can expect a large variety of chemical species in our off-gas streams

Type of cover gas constituent	Example species
Mists, aerosols, and particles	Salt residues, graphite debris for graphite-moderated fluoride systems, corrosion products, and noble metals (e.g., Ru, Pd, Rh)
Gases and volatile species	^{3}HF, HF, F_2, Cl_2, Br_2, I_2, Ar, interhalogens (e.g., ICl, IF_5, IF_7), volatile halides, and the decay products (e.g., Cs, Ba, Rb, Sr, La, Br, I, Se, Te)
Tritium	$^{3}H_{2(g)}$, $^{3}HH_{(g)}$, $^{3}HF_{(g)}$, $^{3}HF_{(l)}$, and possibly $^{3}HHO_{(g)}$ and/or $^{3}H_2O_{(g)}$
Short-lived fission gases and their daughters	^{139}Xe $t_{½}$ = 39.5 s, ^{137}Xe $t_{½}$ = 3.83 min, ^{135m}Xe $t_{½}$ = 15.3 min, ^{135}Xe $t_{½}$ = 9.1 h, ^{133m}Xe $t_{½}$ = 2.19 d, ^{133}Xe $t_{½}$ = 5.25 d, ^{90}Kr $t_{½}$ = 32.3 s, ^{89}Kr $t_{½}$ = 3.18 min, ^{88}Kr $t_{½}$ = 2.84 h
Longer-lived radionuclides	^{129}I $t_{½}$ = 1.57×10^{7} y, ^{79}Se $t_{½}$ = 6.5×10^{4}y, ^{85}Kr $t_{½}$ = 10.7 y, ^{36}Cl $t_{½}$ = 3×10^{5} y

Riley et al. Nuclear Engineering and Design, 2019, 345, 94-109.
Andrews et al. Nuclear Engineering and Design, 2021, 385, 111529.

Noble gas generation

Summary of solid sorbent options in the literature for noble gas capture.

Class	Type	Notes	Reference(s)
Zeolite	Mordenites for Xe/Kr	AgZ for Xe (25 °C); HZ for Kr (80 °C); regenerated at 200–250 °C	(Trevorrow et al., 1983b)
	ZSM-5	Ag-ZSM-5 showed Xe and Kr capacities of $35 \pm 3 \times 10^{-5}$ and $\sim 50 \times 10^{-8}$ mol g^{-1}, respectively; Xe/Kr selectivity of > 100	(Daniel et al., 2013; Deliere et al., 2016)
AC	SorboNorit B3	Comparable properties to zeolites tested	(Bazan et al., 2011)
	—	Delay beds can be used to allow short-lived radionuclides to decay	—
MOF	SBMOF-1 (Ca-SDB)	Very high Xe/Kr selectively	(Banerjee et al., 2016)
	Ni/DOBDC, FMOF-Cu	Two-bed approach with Ni/DOBDC for Xe removal and FMOF-Cu for Kr removal	(Liu et al., 2014)
CG	S-based	$(NH_4)_{0.03}MoS_4$, $Na_{0.3}Sb_2S_3$, $K_{0.15}Na_{0.3}Sb_2S_{2.5}$, and $Na_{0.1}Sb_2S_3$ showed 0.29–0.69 mmol g^{-1} Xe and 0.16–0.28 mmol g^{-1} Kr capacities	(Subrahmanyam et al., 2017)

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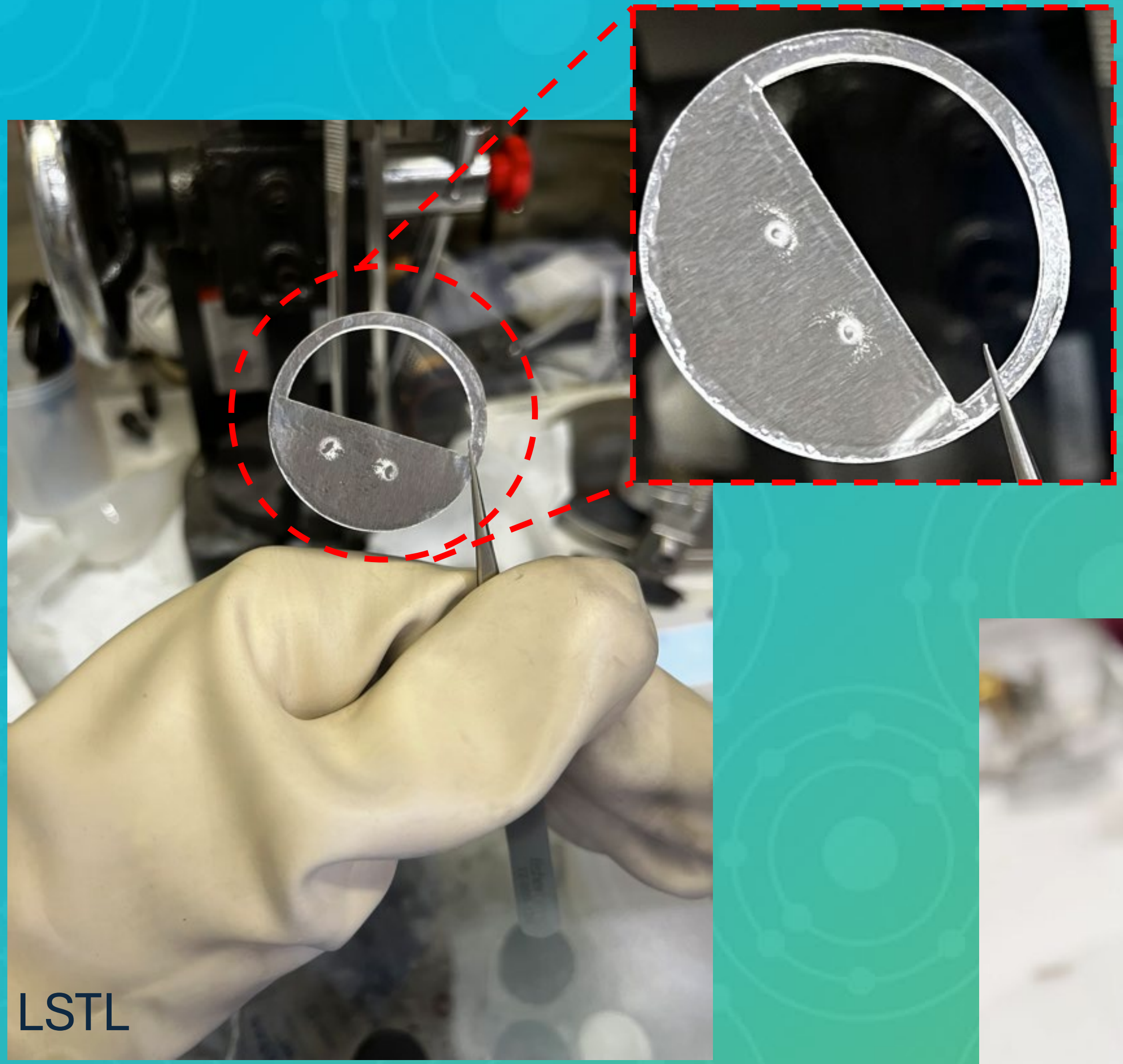
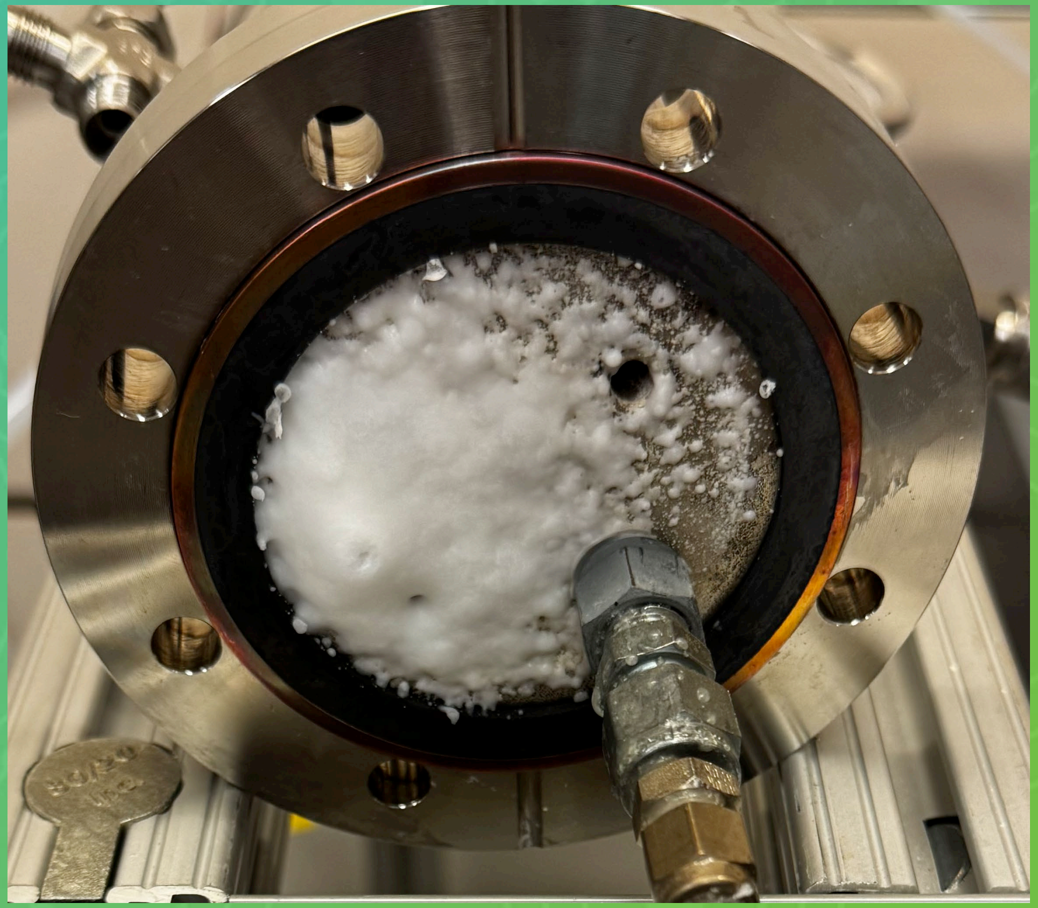
Particulates, mists, aerosols, and residual halides





Nonvolatile components in the reference MSBR off-gas design were divided into three groups

1. Fuel salt particles, generated in the pump bowl and the bubble separator, having potential sizes ranging from 1 to 10 μm.
   - This agrees with recent ORNL salt tests.
2. An estimated 1–50% of all the noble metal (Nb through Te) fission products were entrained in particles ranging in size from 0.01 to 10 μm. For a 2,250 MW_{th} reactor, the mass flow rate could be as high as 300 g day^{-1}.
3. Nonvolatile fission product daughters of Kr and Xe. The assumption is made that noble gas daughters, which are born in the salt, will be retained in the salt as fluorides.
   - For a 2,200 MW_{th} reactor, and assuming a 2-hour gas holdup volume, an estimated 140 g day^{-1} of noble gas daughters will accumulate in the holdup tank. Many of these will likely deposit on the walls of the tank, but their chemical form is not definitively known.

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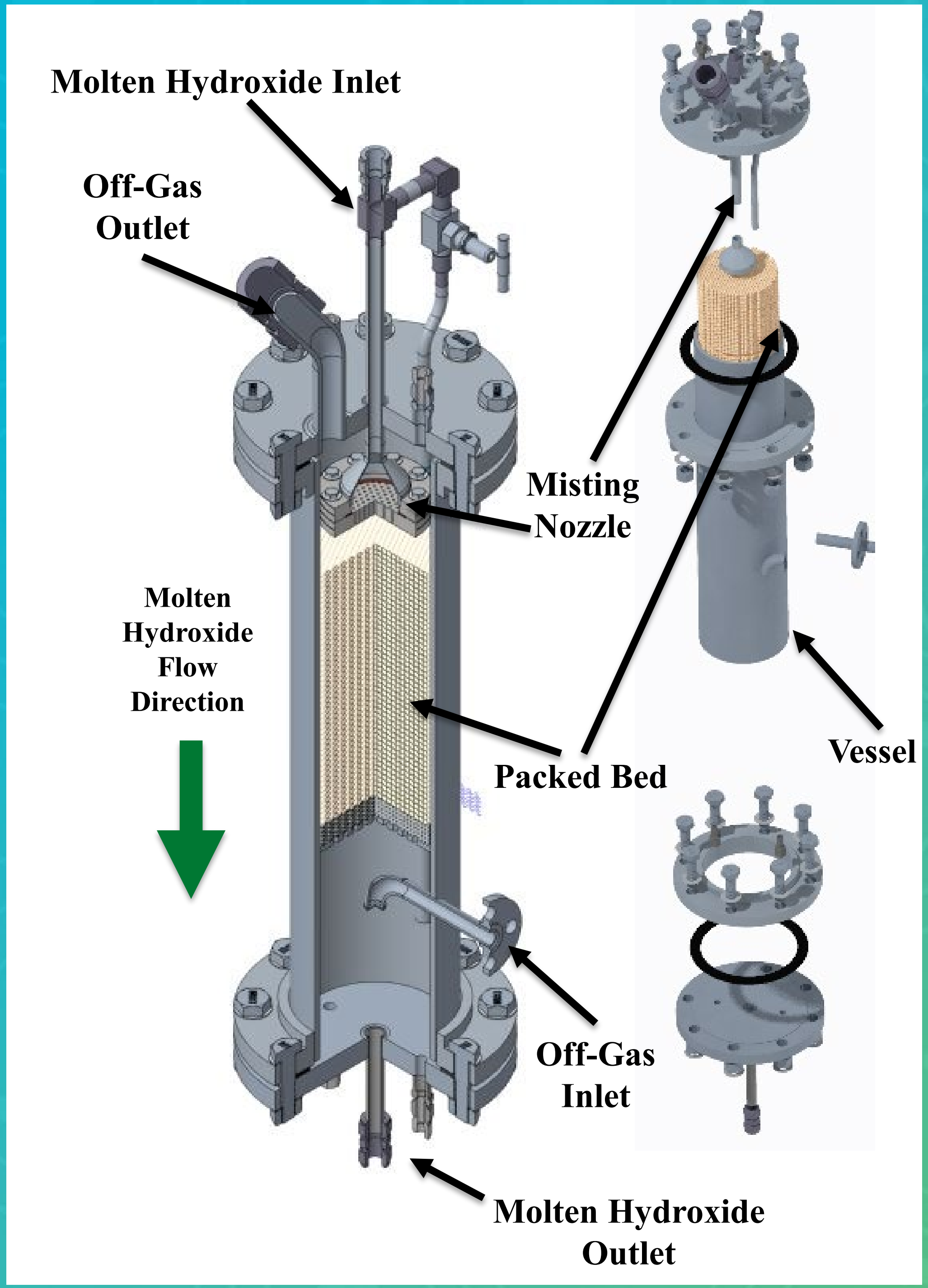
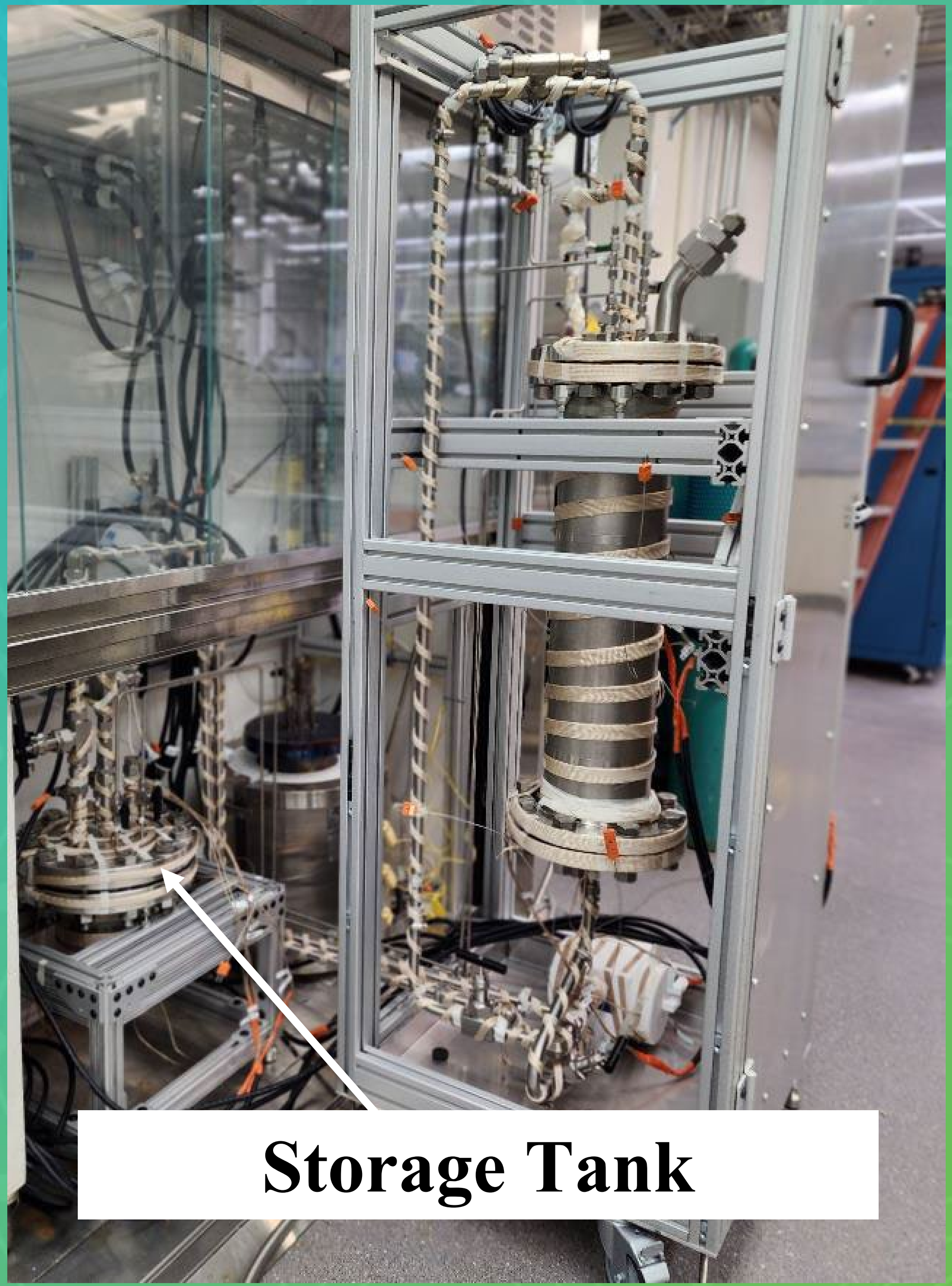
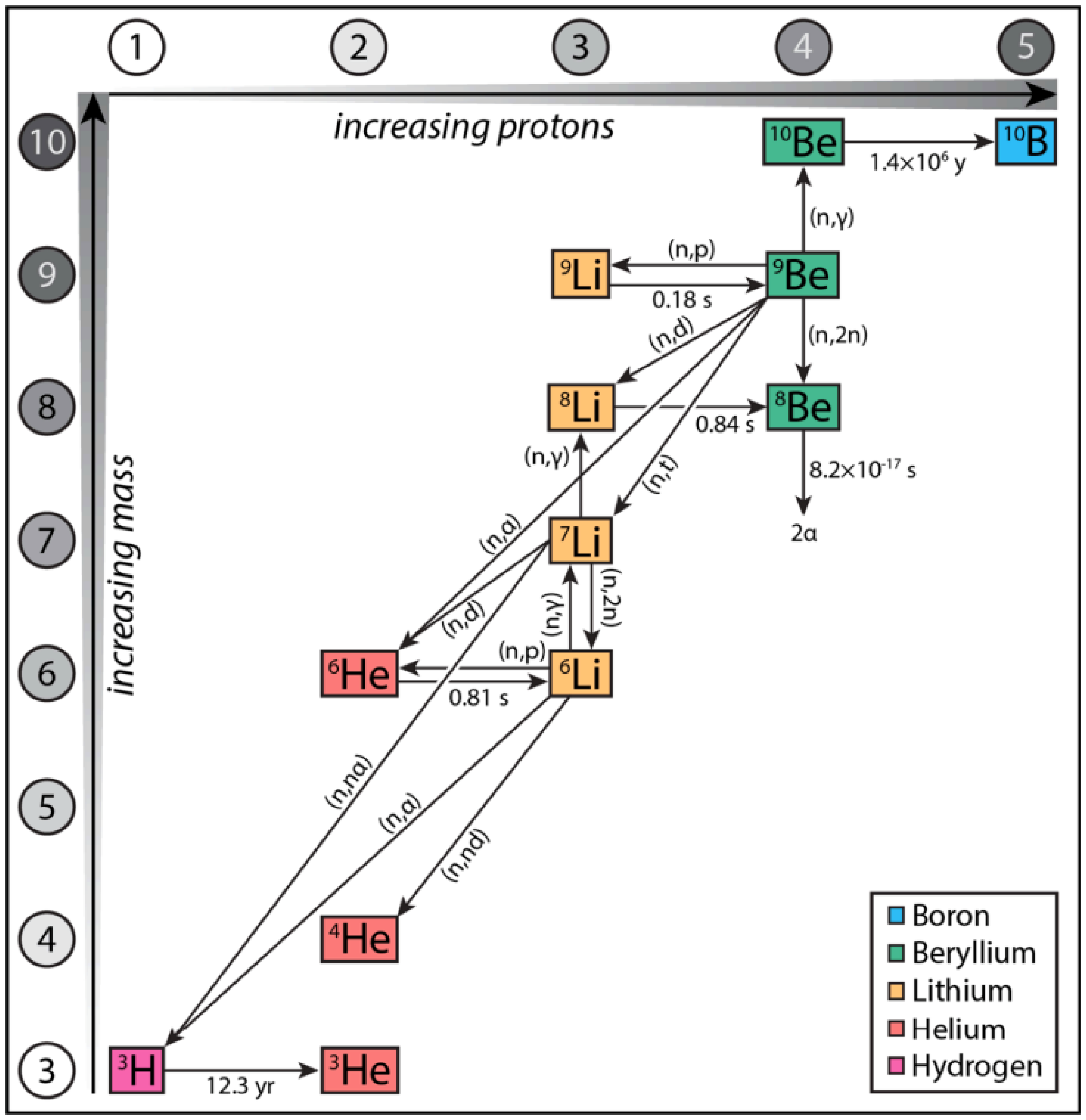
Molten hydroxide scrubber would capture particulates and treat acidic gases



SS-304 Prototype for Radioiodine Capture



Tritium and other non-noble gases



Source of ^{3}H production 2250 MW_{th} MSBR for an enrichment of 99.99% ^{7}Li (Briggs, 1972; Briggs et al., 1970).

Contribution	TBq d^{-1}
Ternary fission	1.15
$^6Li(n,\alpha)^3H$	44.77
$^7Li(n,\alpha n)^3H$	43.29
$^{19}F(n,^{17}O)^3H$	0.33
Total	89.54

Gases such as O_2(g) and N_2(g) could be present in the salts or helium purge gas as minor contaminants. Oxygen buildup in the fluoride or chloride salts may become a problem because, as an electronegative impurity, it shifts the redox state of the salt, promoting formation of CrF_3 or $CrCl_3$, respectively (*i.e.*, chromium corrosion loss from the stainless-steel container).

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Overall, there exists many off-gas treatment options for MSRs, but they are largely not considered as an entire system

Summary of volatile off-gas components and potential capture approaches.

Cover gas constituent	Separation and capture methods	Reference(s)
All	Decay tank to capture short-lived fission products and dissipate decay heat	(Robertson, 1971)
Noble gases(e.g., Xe on short time frame, later primarily Kr)	Cryogenic distillation	(Liu et al., 2014)
	Solid sorbents (AgZ, HZ, activated charcoal)	(Vienna et al., 2015)
	Metal-organic frameworks	(Liu et al., 2014)
	Sulfide aerogel (chalcogel)	(Subrahmanyam et al., 2017)
Aerosols (e.g., salt mists and splashes, particulates, condensed daughters of noble gases)	Packed bed liquid scrubber	(Smith, 1956)
	Particle traps, charcoal beds	(Zagnit'ko and Chuvilin, 2009; Robertson, 1971; Greenwood et al., 2018)
	HEPA filters (≥300 nm diameter)	(International Atomic Energy Agency., 1987)
Tritium (i.e., $^{3}H_{(g)}$, $^{3}H_2O$)	Permeation cell and capture on solid sorbent (e.g., desiccant, molecular sieve, carbon)	(Vienna et al., 2015)
	Hydrogen saturation on secondary side	(Holcomb et al., 2020)
	Oxidize to water by contacting with heated copper oxide	(Robertson, 1971)
Residual gaseous halides (e.g., $F_{2(g)}$, $Cl_{2(g)}$, $I_{2(g)}$, $ICl_{(g)}$)	Gravitational liquid scrubber	(Kim et al., 2001)
	Silver mordenite (AgZ)	(Bruffey et al., 2016)
	Ag^{0}-functionalized silica aerogel	(Matyáš et al., 2011)
	$Ag^{+/0}$-loaded aluminosilicate aerogels	(Riley et al., 2017)
Other gases (e.g., N_2, O_2)[†]	Activated carbon, magnetic separation, cryogenic	(Baker et al., 2007)

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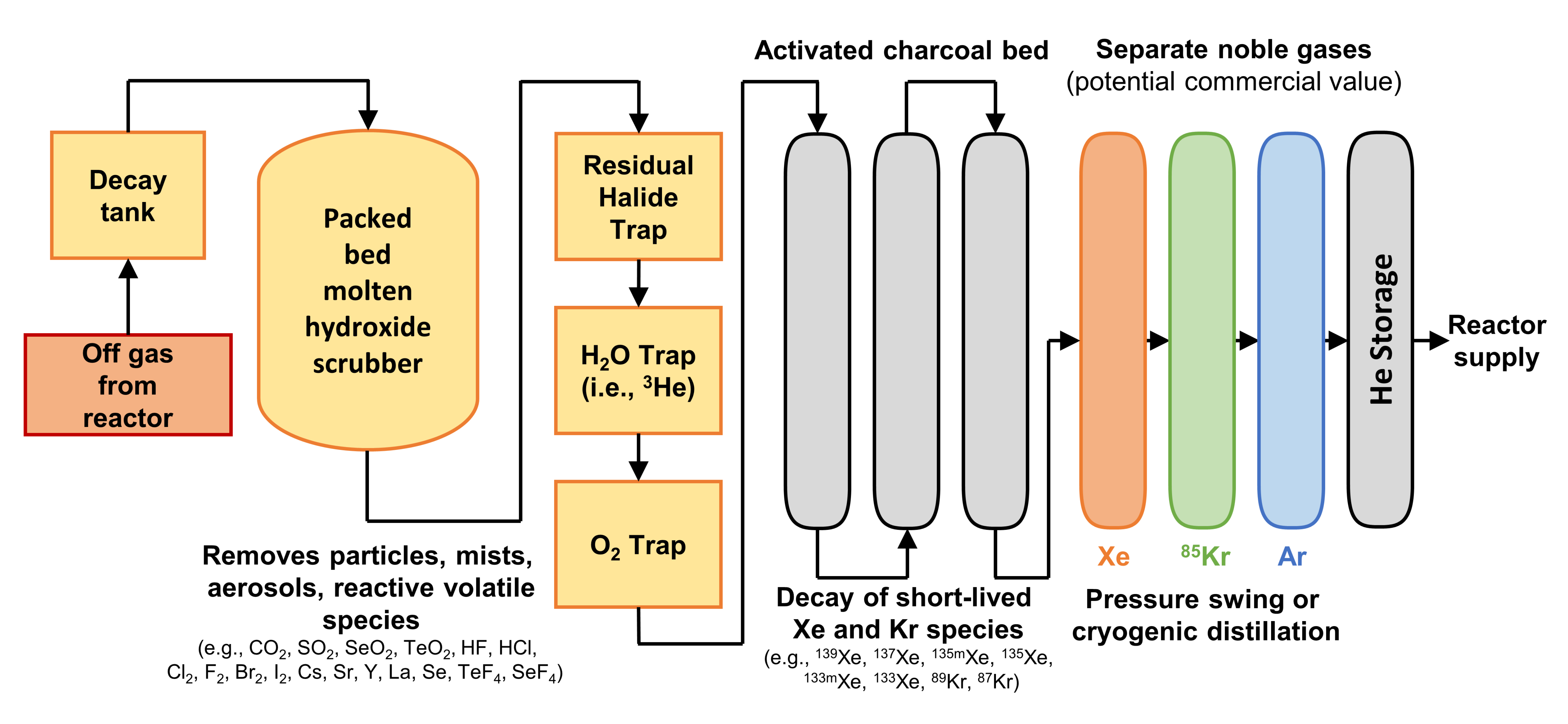
What does a prototypical off-gas system look like?



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Detection and monitoring the off-gas

Radiation Measurements

These species have characteristic gammas, but how much is too much?

Optical Sensors

These non-contact sensing capabilities offer great opportunity for process analytical technology (PAT)

Physiochemical Sensors

Many diverse sensors (e.g., ultrasonics, electrochemical, thermal) connected to off-gas components could provide signatures.