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MELCOR: The Evolution of Nuclear Safety Analysis Technology

Dr. David L. Luxat and Dr. Matthew S. Christian

12 November 2026

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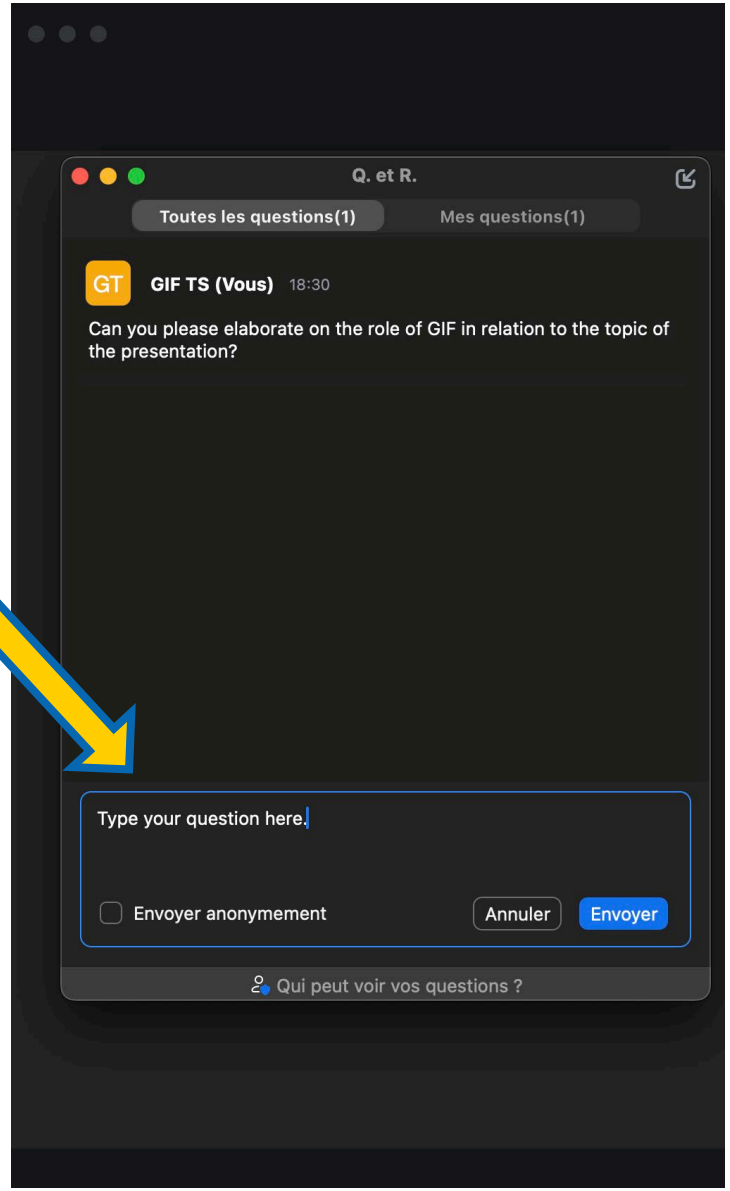
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Meet the Presenters



Dr. David L. Luxat leads the Nuclear Energy Safety Technologies department at Sandia National Laboratories. He directs the development of the MELCOR computer code—a technology-neutral analytical platform uniquely capable of simulating safety and risk across the full spectrum of nuclear technologies and facility types. Prior to joining Sandia in 2019, Dr. Luxat led a broad range of initiatives for the United States nuclear industry following Fukushima that enhanced plant safety while preserving economic operation. He directed industry efforts to forensically evaluate the March 2011 accidents at Fukushima Daiichi, work that proved central to developing new safety insights and informing remediation planning for the damaged reactors.



Dr. Matthew S. Christian is a research scientist in the Nuclear Energy Safety Technologies department at Sandia National Laboratories. He primarily develops chemical and physical models for the MELCOR computer code. His focus for the past few years has concentrated on improving MELCOR's capabilities to model molten salt reactors (MSRs) as part of the US-DOE's ART-MSR Program. Prior to joining the MELCOR team, Dr. Christian developed atomistic density-functional theory approaches for modeling nuclear materials, including molten salts and actinide structures. This work included extensive theoretical analysis to deconstruct if calculation results were based in physical reasoning or numerical inconsistences.

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Early Reactor Safety, 1947–1962

1947 Teller's AEC committee sets the first siting rules
A "maximum credible accident" set a 5-mile buffer for 250 MW

1951 EBR-I in Idaho lights four light bulbs (Dec 20)
The first electricity generated from atomic energy

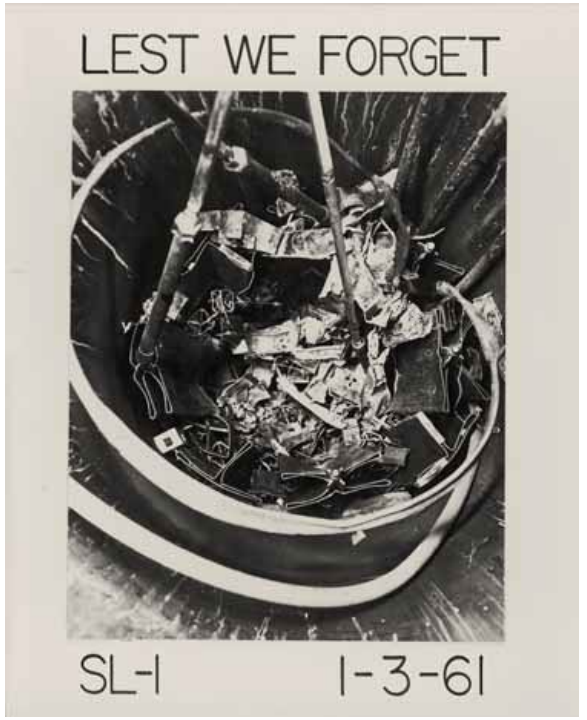
1953 The Advisory Committee on Reactor Safeguards forms
The ACRS reviews reactor sites and whether plants run safely

1954 BORAX-I is pushed past its limit on purpose
Boiling stopped over 200 surges until a forced one destroyed it

1955 EBR-I partly melts down (Nov 29)
In a test with coolant off, a 2-second delay melted about half the core

1961 Army reactor SL-1 runs away and three operators die
One rod was the likely cause. No single rod may now start the reaction

1962 10 CFR 100 and TID-14844 fix one assumed "source term"
100% of noble gases, 50% of halogens and 1% of solids escape



SL-1 vessel top, 1961

Early safety relied on siting distance and one assumed worst-case release.

NUREG/KM-0010 · DOE/ID-10799 · ANL-5731 · IDO-19311 · TID-14844

First Probabilistic Methods and WASH-1400, 1953–1975

1953 **A GE memo proposes the first probabilistic approach**
It multiplied the odds of a chain of failures. GE dropped it in 8 months

1957 **WASH-740 finds up to 3,400 deaths and 43,000 injuries**
Its own odds had “no demonstrable basis in fact”

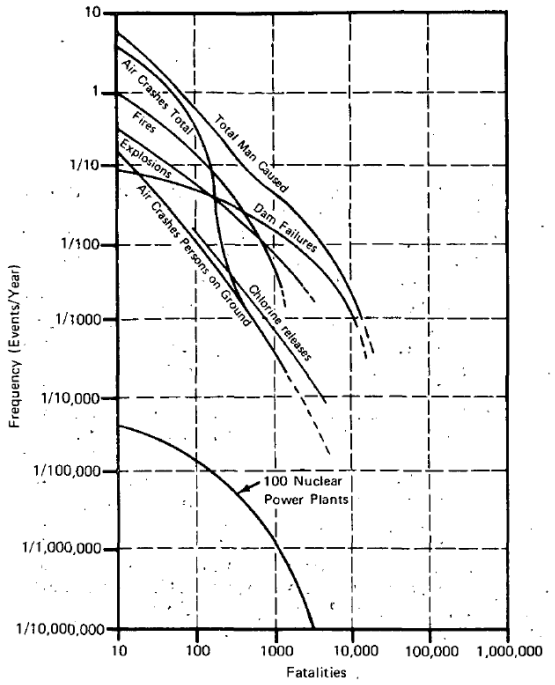
1960s **Fault trees arrive from the Minuteman missile program**
They trace a failure to its causes. Garrick drew one for a reactor

1964–65 **A WASH-740 update finds even worse consequences**
Larger reactors meant larger consequences. Unpublished until 1973

1966–67 **The Ergen task force reviews emergency core cooling**
Meltdown is improbable if it works. If it fails, so may containment

1972 **The Reactor Safety Study begins, led by Rasmussen**
About 80 people, $4 million and three years of work

1975 **WASH-1400 is the first full-scope risk assessment (PRA)**
Core melt frequency about 1 in 20,000 per reactor-year



From WASH-1400, 1975

Event and fault trees gave regulators accident probabilities as well as consequences.

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NUREG/KM-0010 · WASH-740 (1957) · WASH-1400 Executive Summary

WASH-1400, Its Critics and TMI-2, 1975–1979

MARCH
Core melt and containment response

Packaged the WASH-1400 meltdown models, released Oct 1980

→

CORRAL
Transport in containment

CORRAL-2 covered more plant designs, released 1977

→

CRAC
Offsite consequences

CRAC2 added better weather sampling and emergency response (1982)

After the study each code in the WASH-1400 chain was improved and run in sequence

1975–1978

Critics

- APS and UCS challenge the methods
- Lewis report finds uncertainties greatly understated

January 18, 1979

NRC policy statement

- Withdraws endorsement of the Executive Summary
- Absolute numbers not to be used uncritically

March 28, 1979

TMI-2

- The small-LOCA kind of accident WASH-1400 flagged
- TID-14844's release assumptions proved wrong

By 1979 the NRC had withdrawn its endorsement of the WASH-1400 numbers, and TMI-2 showed the codes needed rebuilding.

NUREG/CR-2825 · NUREG-0773 · NUREG/CR-0400 · NUREG/KM-0010 · SAND2018-13524

Code Deficiencies and the 1982 Research Plan

Between 1980 and 1982 MARCH and CORRAL fell short, NUREG-0772 gave new fission-product data, and the NRC research plan named MELCOR

Deficiency in the old chain	Status in the STCP (1986)
Inconsistent phenomena	**Partly fixed**, single core–concrete model
No uncertainty estimate	**Still open**, qualitative only (ACRS)
Rigid code structures	**Partly fixed**, in-vessel circulation missing
Poorly matched interfaces	**Partly fixed**, codes still pass output files
Poor documentation	**Still flagged** by the ACRS
New in 1986	**New concern**, user choices drive core melt

The 1982 plan upgraded the old chain into the STCP for near-term use and started MELCOR to replace it.

NUREG/CR-2825 · NUREG-0773 · NUREG/CR-4481 · NUREG/CR-4624 Vol. 5

The Source Term Code Package, 1986–1990

Battelle linked its BMI-2104 codes into the STCP for the NRC. Mod 1 was released in 1986.

MARCH3
Core melt and thermal-hydraulics
MARCH2 + CORSOR-M + CORCON-Mod2

→

TRAP-MELT2 + MERGE
Transport in the coolant system

VANESA
Release from core–concrete attack

→

NAUA, SPARC, ICEDF
Aerosols in containment, pools and ice condensers

→

Release to the environment

Use and retirement

1986 NUREG-0956
Methods match the source-term reassessment

1986–90 Plant calculations
Zion, Surry and other plants for the NUREG-1150 risk update

Nov 1990 ACRS review
Staff had “discarded” the STCP, and MELCOR was “not yet fully developed”

Dec 1990 NUREG-1150
Uncertainty work used fast parametric models, checked with STCP runs

MELCOR replaced the STCP with one code that couples all phenomena at every step.

NUREG/CR-4624 Vol. 5 · NUREG/CR-4624 Vol. 6 · NUREG-1150 · NUREG/CR-6119 Vol. 1

Building MELCOR, Versions 1.0 to 1.8.0 (1982–1989)

1982	NRC research plan names MELCOR and Sandia starts the project
1986	The 1986 V&V papers run versions 1.0 to 1.6 against analytic solutions and tests such as HDR and ABCOVE
Jan 1987	Version 1.6.0 released and nine standard test problems defined
Mar 1989	**MELCOR 1.8.0**, the first full release, for BWRs and PWRs

MELGEN Builds the initial state → **MELCOR** Advances the plant in time

CVH, FL Volumes and flow paths	**HS** Heat structures	**COR** Core heatup and degradation	**DCH** Decay heat
SPR Containment sprays	**CAV** Core–concrete (CORCON)	**RN** VANESA and MAEROS	**BUR** Burns (HECTR)

Tiles with a blue rule carry models from earlier stand-alone codes

Built for uncertainty
A “fully integrated, relatively fast running” code for uncertainty studies

Parametric first
Simple models where physics was uncertain, refined over time

One of two tiers
MELCOR for integrated risk, SCDAP/RELAP5 and MELPROG/TRAC for detail

MELCOR was built package by package on shared control volumes and released in 1989.

NUREG/CR-4830 · SAND1990-0364 · NUREG/CR-6119 Vol. 1 · SAND2017-0876

MELCOR 1.8 and the MELCOR 2 Rewrite, 1989–2010

MELCOR 1.8.x (Fortran 77) | **MELCOR 2.x (Fortran 95)**

Mar 1989	1994	Oct 2000	Fall 2005	Sept 2006	2008
1.8.0	**1.8.3**	**1.8.5**	**1.8.6**	**2.0 beta**	**2.1**
Peer review 1990–92, QA program by 1992	CORCON-Mod3 and advanced reactor models	DOE “toolbox” code (2004)	Molten pool upgrades, widely used	IBRAE port, bit-for-bit with 1.8.6	All new development, 1.8.6 in maintenance

One NRC code (1999–2000)

Code consolidation weighed MELCOR, SCDAP/RELAP5, VICTORIA and CONTAIN. MELCOR became the integrated code and was assessed against PHEBUS-FP

Why MELCOR 2.0 (2006–08)

- Dynamic memory with no fixed object limits
- Objects named by the user (1.8.x used numbers)
- Double precision, and one platform for all new models

MELCOR became the NRC’s integrated code, and MELCOR 2 the platform for all new work.

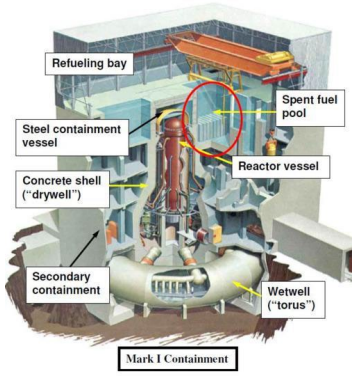
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SAND1995-0561C · SECY-99-078 · SAND2017-0455

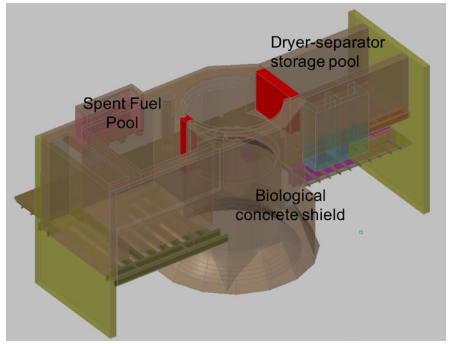
Fukushima Daiichi and Spent Fuel Pools, 2011–2014

Reconstructing Fukushima Daiichi (2011–12)

- The earthquake and tsunami cut power and three cores melted
- MELCOR 2.1 models of Units 1–3 and the Unit 4 pool
- Unit 1 was the most damaged, with lower head failure
- Results agree well with plant data



Mark I building with the pool high beside the reactor



The NUREG-2161 pool model

Spent fuel pools (2014)

NUREG-2161 found the pool survives a beyond-design-basis earthquake, so earlier transfer to dry casks was not warranted

MELCOR was used to reconstruct Fukushima and to show that spent fuel pools survive a major earthquake.

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NUREG/KM-0010 · SAND2012-6173 · NUREG-2161 · NRC IN 2014-14

Source Terms for Next-Generation LWR Fuel, 2023–2024

Four plants

Peach Bottom	Grand Gulf
BWR, Mark I	BWR, Mark III
Sequoyah	**Surry**
PWR, ice condenser	PWR, large dry

60–80 GWd/MTU and 5–8% enrichment, MELCOR 2.2 with SCALE

Findings against NUREG-1465

- Burnup and enrichment barely change the source term
- Low-pressure sequences release the most
- Early in-vessel halogen release is higher
- Peer review supports RG 1.183 use as representative, non-bounding values
- Cr-coated accident-tolerant cladding reduced hydrogen and release in a 2024 DOE study

MELCOR is updating the NUREG-1465 source term for the fuel the fleet will use.

SAND2023-01313 · INL/RPT-24-77203

Non-LWR Challenges and Existing MELCOR Capability

Salt reactors

FHRs use TRISO fuel in salt and MSRs dissolve the fuel in salt. Needs include salt properties, chemistry and retention, and liquid-fuel kinetics.

HTGR

TRISO particle failure and diffusion, graphite oxidation, and air and moisture ingress.

Sodium fast reactor

Sodium pool and spray fires, sodium–concrete interaction, metallic fuel, and retention in sodium.

Heat pipe reactor

A failed heat pipe can overload its neighbors. There was no heat pipe model in 2019.

What MELCOR already had

2008 HTGR models for TRISO release, graphite and point kinetics

2013 Sodium properties, chemistry, pool and spray fires

Recent FLiBe salt model and new fluids through library files

MELCOR's modular design let it extend existing models to each new reactor type.

NRC Non-LWR Volume 3 (2019) · SAND2023-10830

NRC Non-LWR Plan and Demonstrations, 2019–2025

- Volume 3 selects MELCOR, SCALE and MACCS
- Chosen for staff familiarity and for one integrated code without data hand-offs
- Generic public designs serve as proof-of-concept models
- From 2023, Volume 5 adds the fuel cycle

Nine public demonstrations

Design	Accident	Fuel cycle
Heat pipe	2021	2025
HTGR	2021	2023
FHR	2021	—
MSR	2022	2024
SFR	2022	2023

The NRC extended MELCOR and tested it on five reactor designs.

NRC Non-LWR Volume 3 (2019)

Demonstration Calculations for Three Designs, 2021–2023

HTGR pebble bed

PBMR-400, 2021–22

1634 °C

peak fuel temperature, depressurized loss of forced cooling (35 h)

- TRISO failure fraction about 1.6×10^{-4}, with silver the largest release
- In the ATWS, power falls to decay heat in about 290 s

Heat pipe reactor

INL Design A, 2021

- A new heat pipe model follows failures as they cascade
- 20% of the elements failed and about 0.0008% of the core inventory reached the environment in overpower case

Sodium fast reactor

ABTR, 2022–23

- Radionuclides move with the sodium and noble gases collect in the argon cover gas
- Overpower and loss-of-flow cases released nothing

The same code handled all three designs, and HTGR releases depend on TRISO fuel.

SAND2022-2750 · SAND2022-2745 · SAND2023-10830

Radionuclide Locations in MSRs and LWRs

Topic	LWR	Liquid-fueled MSR
Fuel form	Pellets in cladding	Dissolved in salt and mobile
Pressure	High, boiling important	Low, far from salt boiling
Feedback	Fuel and moderator	Strongly negative as fuel expands out
Other hazards	Zr–steam hydrogen	Tritium, graphite, corrosion, freezing

Radionuclide locations in an MSR

Fuel salt, cover gas, offgas system, graphite pores and metal surfaces

Retention

- Salt is the first barrier. Volatiles vaporize and insolubles deposit
- Salt and cover gas share one boundary
- Functional containment and release limits replace LWR rules

MSRs avoid high pressure and hydrogen, but every radionuclide location needs its own barrier.

ORNL/TM-2022/2555 · SECY-18-0096 · Gelbard et al., Nucl. Sci. Eng. (2023)

MSR Safety Goals and Event Categories

The safety functions are to **retain radionuclides**, control reactivity and reject decay heat.

AOO	DBE	BDBE	DBA
Anticipated	**Design basis**	**Beyond design basis**	**Design-basis accident**
> 10^{-2} /plant-yr	10^{-4} to 10^{-2} /plant-yr	5×10^{-7} to 10^{-4} /plant-yr	Deterministic

- Allowed offsite dose falls as event frequency rises
- In 2018 ORNL re-ran the MSRE licensing basis this way
  - One of eight sequences gives a measurable dose, about 5 rem at the site boundary
  - All eight fall below the frequency–consequence curve
- ANS 20.2 applies the RG 1.233 approach to MSRs, and Part 53 may change it

MSRs meet the same safety goals as any reactor, judged by frequency and consequence.

ORNL/TM-2018/788 · SECY-18-0096

MSR Event Families

Event family	Examples
Reactivity insertion	Rod withdrawal, fuel or poison errors
Loss of flow	Pump trip or seal failure
Loss of heat sink	Decay heat removal failure, blackout
Boundary breach	Fuel-salt leaks and spills
Offgas, cover gas	Plugged lines, holdup piping leak
Heat exchanger	Tube or steam generator rupture
Freezing and draining	Unplanned freeze-valve opening
Overcooling	Excess cooling raises reactivity

MSRE maximum credible accident

Salt spill with water making steam. Used in the MELCOR MSRE demonstration

What drives the source term

Spills, offgas failures and the behavior of the spilled salt

ORNL/TM-2019/1246 · ORNL/TM-2018/788

MELCOR MSR Capabilities

Capability	What MELCOR does	Status
Salt properties	Equations of state for FLiBe (with frozen salt) and FLiNaK	MELEOS makes working salt fluids
Flowing-fuel kinetics	Precursors carried around the loop with SCALE feedbacks	Benchmarked on the MSRE pump coast-down
Isotope tracking	ORIGEN inside MELCOR tracks about 2,000 isotopes per region	Used in the 2024 MSBR demonstration
Salt chemistry	Solubility and vapor pressure from Thermochimica and MSTDB-TC	2024 study supports “frozen chemistry”

MELCOR now has the salt, kinetics, isotope and chemistry models an MSR analysis needs.

SAND2023-01803 · SAND2022-5442C · SAND2024-13136

Fluoride Salt-Cooled Reactors

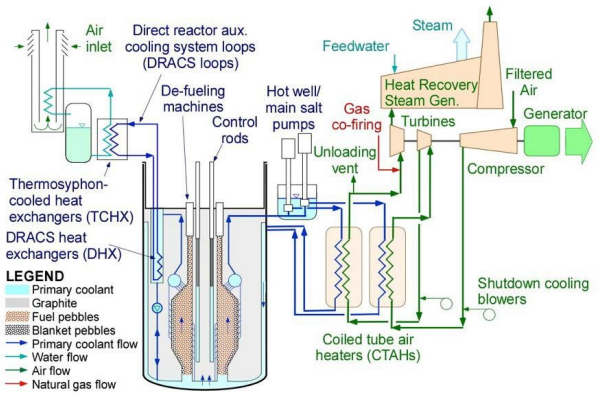
FHR demonstration, 2021

UC Berkeley Mark 1, 236 MWth, TRISO pebbles in FLiBe, three passive DRACS loops

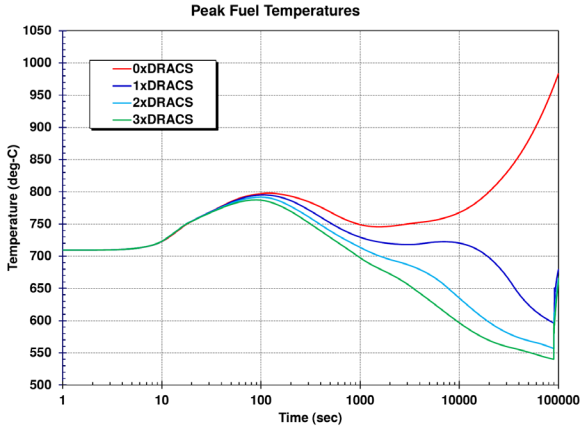
Cases for reactivity control, decay heat removal and a drain-line leak

Kairos Hermes 2, 2024

NRC scoping calculations for the construction permit review



UC Berkeley Mark 1 layout. The DRACS loops are at upper left.



Peak fuel temperature after a loss of power without scram. With no DRACS loop the fuel reaches 990 °C after about 28 h.

The FHR was the first NRC review supported by MELCOR's salt modeling.

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SAND2022-2751

MSRE Demonstration Plant Model (2023)

What was new in MELCOR

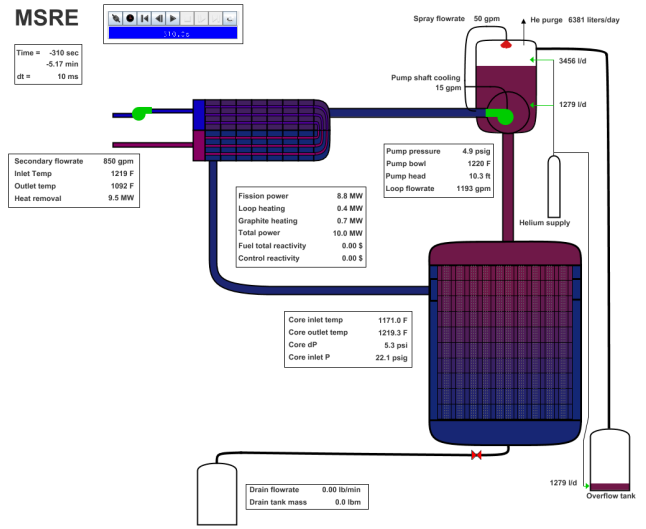
- Fluid-fuel fission power with precursors carried around the loop
- FLiBe equation of state extended below freezing
- First use of the generalized radionuclide framework
- 15 radionuclide classes regrouped for salt

From SCALE

Inventories, decay heat, power, feedbacks

Steady state at 10 MW

Core outlet 663 °C, matching the reference



MSRE primary loop at steady state

This was MELCOR's first full-plant model of a liquid-fueled reactor, from the core to the stack

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SAND2023-01803

MSRE Salt Spill Results

An earthquake causes a loss of offsite power and breaks a drain pipe.

Dry spill (base case)

3,860 kg	salt on the floor in about 10 min
635 °C	peak salt temperature at 4 min
≈ 21 psia	cell pressure, below the burst disks
0.2%	of the xenon reaches the environment

Sensitivity cases

Ventilation	Most xenon release with HVAC and filter running
Aerosol size	Cerium release is lowest for 10 μm particles
Water	Cell reaches 46 psia and the disks open. The tank holds about 65% of the cerium.

Ventilation and filtration set the release. With water, the condensing tank traps the aerosol.

SAND2023-01803 · SAND2021-12956

MSBR Fuel Cycle Demonstration (2024)

- Pump trip with failure to insert rods, emergency drain, and partial loss of drain-tank cooling
- 2,250 MWth with LiF–BeF_2–UF_4 salt, four loops, a drain tank and offgas holdup

Vapor pressure at 1,000 °C

Species	Pa	Role
BeF_2	1,101	Own class
UF_4	39.2	Own class
$CsBeF_3$	0.09	Negligible
LiI	0.02	Negligible

ORIGEN inside MELCOR

About 2,000 isotopes are decayed in each region and moved by MELCOR

Dynamic chemistry in development

Evaporation, decay chains, bubble bursting and splashing

Salt chemistry now sets the release, and decay chains can change what is volatile.

ORNL/TM-2024/3659 · SAND2024-13135

MSBR Demonstration Results

Emergency drain with 50% drain-tank cooling

- Core drains in about 7 min, decay heat 97 to 30 MW
- Salt peaks near 980 °C at about 5 h
- Peak airborne fractions 10^{-5} (BeF_2) and 10^{-8} (UF_4)

Sensitivities

Case	Result
Leak to the cell	Some BeF_2 condenses
Offgas 100, 50, 1%	No change
Tank-bottom leak	1,180 °C, 1,000× more BeF_2

Effect of ORIGEN coupling

With ORIGEN, I-135 decays to Xe-135, which leaves the salt and becomes Cs-135

Salt temperature sets the airborne release, so drain-tank cooling is the key safety function.

Why MELCOR Is Being Modernized

Goals are faster runs, better numerics, fewer limits and new reactor designs

Legacy MELCOR

Fortran packages
Physics, data, and numerics in each package

New models meant changing the code

Modernized MELCOR architecture

Physics manager Runs the models and accepts new ones

Validated physics
Retained

New models
Chosen by input

Field manager
Data kept separate

Solution engine
Robust numerics

General physics
Supports new designs

2023
Five-year plan

2024
Cavity package first

2025–26
Cavity validated

Next
Core and point kinetics

Modernization keeps the validated physics and lets new models plug in beside it.

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Modernized MELCOR Architecture

Application	Executive driver: input file to systems, couplings, steps and output
Coupling	Thermal hydraulics to walls, species, decay heat and kinetics
Physics	Two-fluid flow, wall heat transfer, species transport, kinetics, chemistry
Materials	Fluid properties: water, gases, molten salts, liquid metals; solids
Framework	Systems, registry, coupled time stepping, coupling slots
Numerics	PETSc Newton solvers, Krylov methods, sparse direct solvers
Foundation	Named data channels, HDF5 output, logging, plugin interface

- Each layer depends only on the layers below it
  - C++23 modules with CMake presets and vcpkg
- Physics systems never call each other
  - They exchange named channels through coupling slots
- Plugins load at run time through a stable C interface
  - Native physics or external codes

Outside groups can add physics the same way.

PSI is building a machine-learning condensation closure as a plug-in.

New physics plugs in without touching the solver or the other systems.

SAND2026-27273

From Input File to Results



- A misspelled key stops the run before the first step, never silently ignored
- A rejected step restores every system and retries with a smaller step
- The full list of keys the code read is written on request

The run is refused if any input key goes unread.

One Implicit Newton Solve

- All unknowns of the flow network in one nonlinear system
  - Pressure, phase fractions, temperatures, velocities, crystal fractions
- Newton's method with the exact Jacobian
  - Derivatives from automatic differentiation rather than finite differences
  - PETSc nonlinear and linear solvers
- Physical bounds enforced inside the solve
  - Gas fraction, liquid mass and salt constituent masses kept at zero or above (variational inequality)
- Smooth blends where the physics switches
  - Flow reversal, phase appearance and freezing onset blend smoothly, so Newton does not stall
- No Courant limit, so the time step follows the physics instead of the cell size

Stiff, slow salt transients take large steps without losing the coupling.

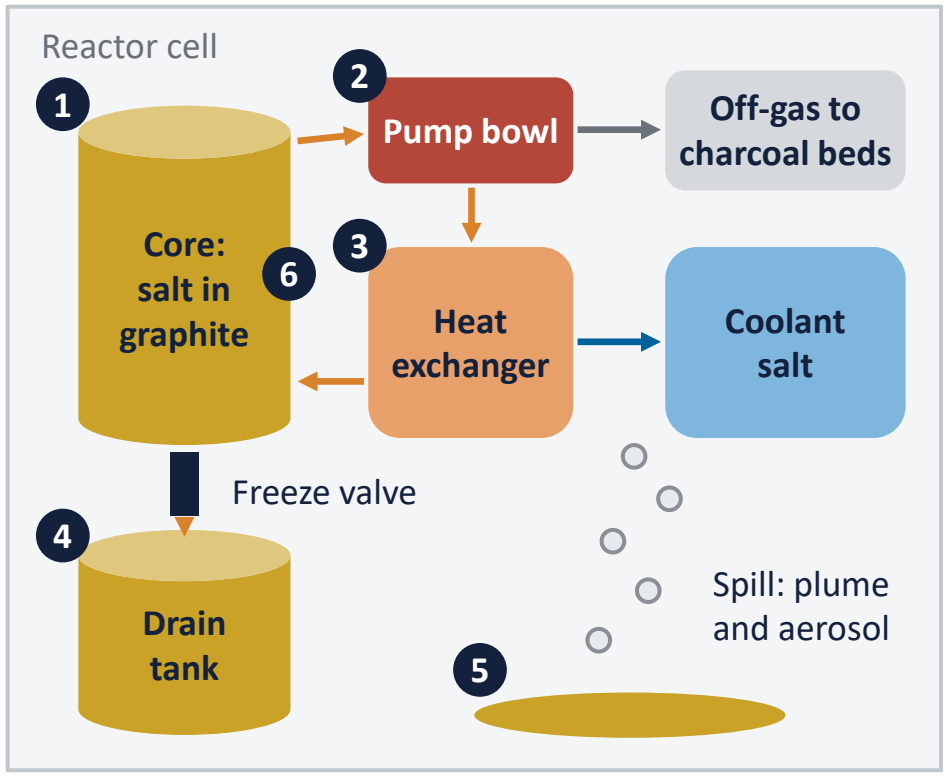
Run Times for Long Transients

Case	Simulated	Wall time	Faster than real time
Fuel salt freezing in heat exchanger tubes	120 s	1.4 s	86 times
Crust on cooled walls	120 s	3.0 s	40 times
Freezing and remelting	320 s	4.3 s	75 times
Plume in a 6 m room	600 s	8.4 s	71 times
MSRE xenon buildup at 5 MW	25 h	80 s	1,100 times
Noble metals in the MSRE loop	30 days	40 min	1,100 times

Wall times from each run's own log

Hours to a month of plant time run in seconds to minutes.

Modernized MELCOR Models the Whole Salt System



1 Circulating fuel kinetics
Delayed neutron precursors carried around the loop

2 Two-fluid flow
Salt, helium sparge and cover gas, each with its own velocity and temperature

3 Freezing and melting
Phase-diagram crystal phases, latent heat and contraction

4 Salt vapor
Every constituent from the melt, with deposition on cold walls

5 Plumes, trace species and aerosol
Fission products carried as vapor or as particles

6 Salt chemistry
Deposition and corrosion set by the fluorine potential

One code for the salt, the gas and what they carry, from core to reactor cell.

Two-Fluid Flow Extended for Salt

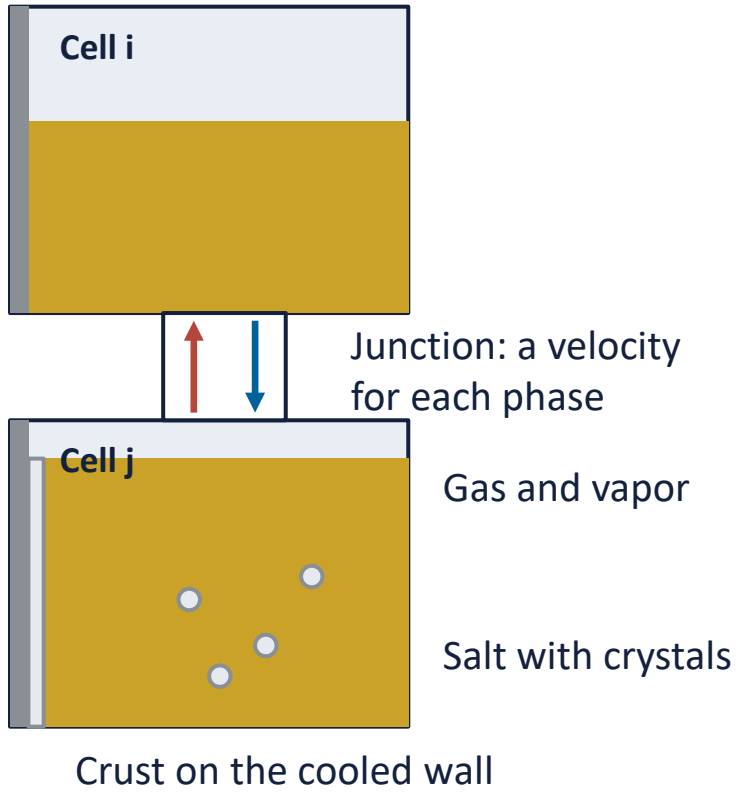
- Fields in every cell
  - Liquid salt, and gas made of cover gas and salt vapor
  - Crystal phases as wall crust or particles in the bulk
- Mass for each field, energy for the mixture and the gas

$$\frac{\partial(\alpha_k \rho_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k \mathbf{u}_k) = \Gamma_k$$

- Momentum for each phase on every junction

$$\frac{\partial v_k}{\partial t} = -\frac{\Delta P}{L\rho_k} - g\frac{\Delta z}{L} - F_{wall,k} - F_{int,k}$$

- Staggered grid, donor cell transport, smoothed upwind split



Salt, gas and crystals are solved together and carry the trace species.

Generalized Radionuclide and Chemistry Framework

The radionuclide package now characterizes “transport of any trace species.”

Each species is tracked by

Nuclear state
Isotope

Chemical state
Speciation

Phase and location
Vapor or particle (with size), mobile or trapped

“Degrees of freedom designed to be expanded”

How a species changes state

- Decay and transmutation
- Transport as mass flux across interfaces
- Chemical reactions
- Aerosol dynamics

User-defined materials and gases, oxidation and fluid equations of state are also generalized

One representation covers LWR aerosols, sodium and salt. New phenomena are added as degrees of freedom or transfers instead of new packages.

Circulating Fuel Kinetics

- Point kinetics with six delayed neutron groups

$$\frac{dn}{dt} = \frac{\rho - \beta}{\Lambda} n + \sum_i \lambda_i \overline{C}_i^f$$

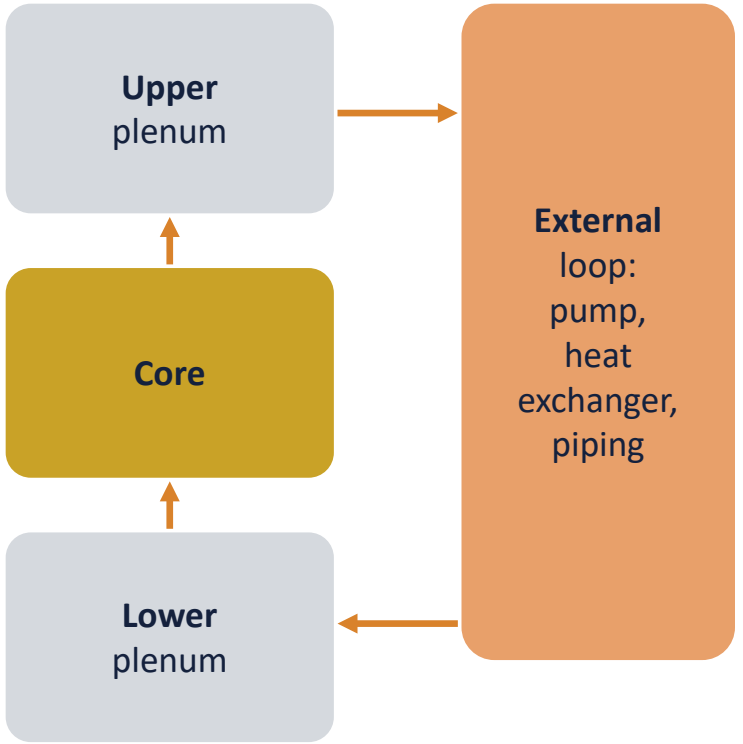
  – MSRE cases are held at zero power by a computed reactivity

- Each precursor group is carried with the fuel through every loop cell

$$\frac{\partial C_i}{\partial t} + u \frac{\partial C_i}{\partial z} = \frac{\beta_i}{\Lambda} n q(z) - \lambda_i C_i$$

  – Produced with the fission shape and decaying everywhere

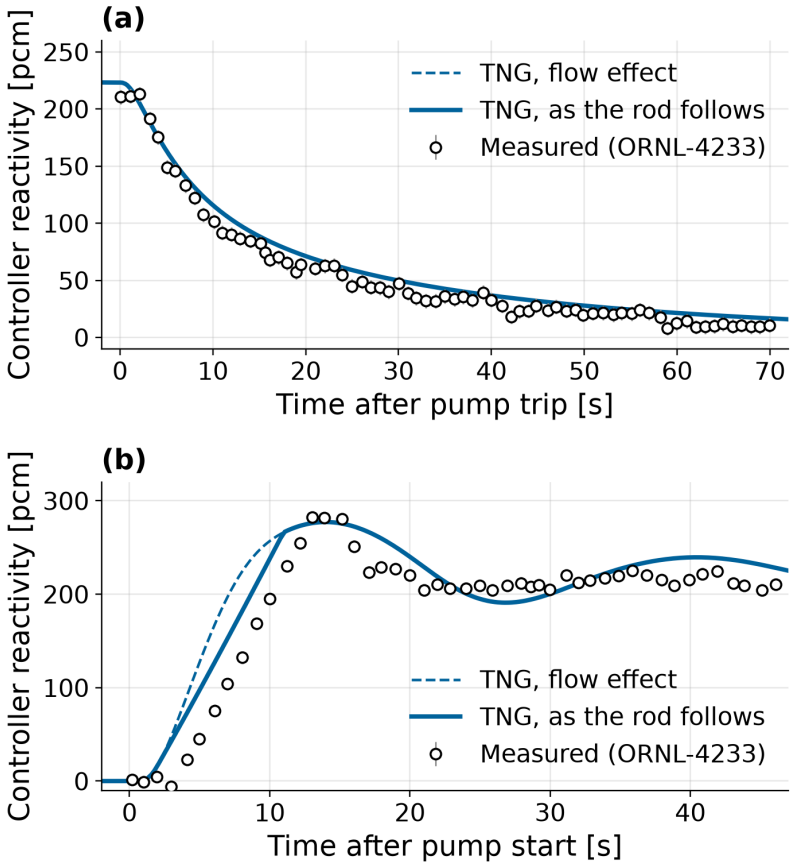
- Second order (van Leer) transport keeps the precursor front sharp
- Only decays in the fission volumes return neutrons, weighted by importance



Precursors decay wherever the fuel is

Pump transients change where precursors decay, and the kinetics feels it within seconds.

MSRE Fuel Pump Coastdown and Startup



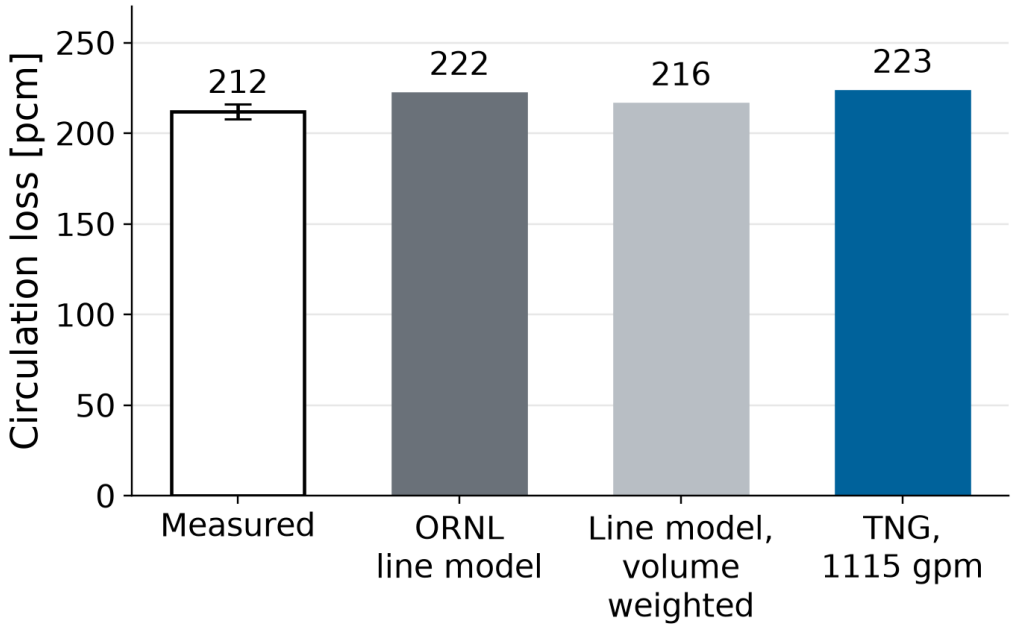
- Precursors drift out of the core with the fuel

$$\frac{\partial C_i}{\partial t} + u\frac{\partial C_i}{\partial z} = \beta_i q(z) - \lambda_i C_i$$

  – Second order upwind, well mixed lower plenum
  – Transit time 27.1 s (ORNL 25.2 s at 1200 gpm)
- After a pump trip the circulation loss is given back
  – Half the loss returns in 11.2 s (measured 9.6 s)
- On pump start the loss overshoots until precursors return
  – Peak 277 pcm at 14 s (measured 282 pcm at 13 s)

Modernized MELCOR follows the precursors through both MSRE pump transients.

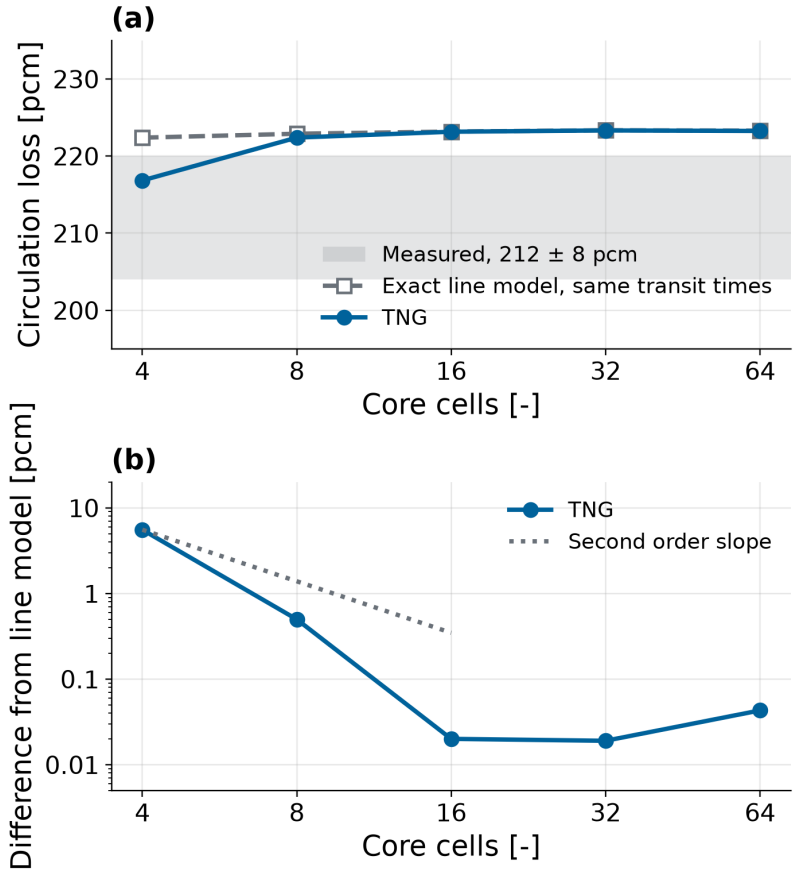
MSRE Reactivity Loss from Circulation



- Steady loss with the fuel circulating
  - Measured 212 ± 4 pcm at 1200 gpm (ORNL-4233)
  - ORNL line model 222 pcm (ORNL-TM-1626)
  - Modernized MELCOR gives 223 pcm at 1115 gpm with ORNL's published loop losses
- Modernized MELCOR solves the line model's transport exactly
  - Matches the exact solution to 0.02 pcm
- The plenum weighting and the loop flow set the spread
  - At 1200 gpm: 230 pcm by transit time, 216 pcm by volume

Modernized MELCOR gives 223 pcm against the measured 212 pcm using ORNL's published loop losses.

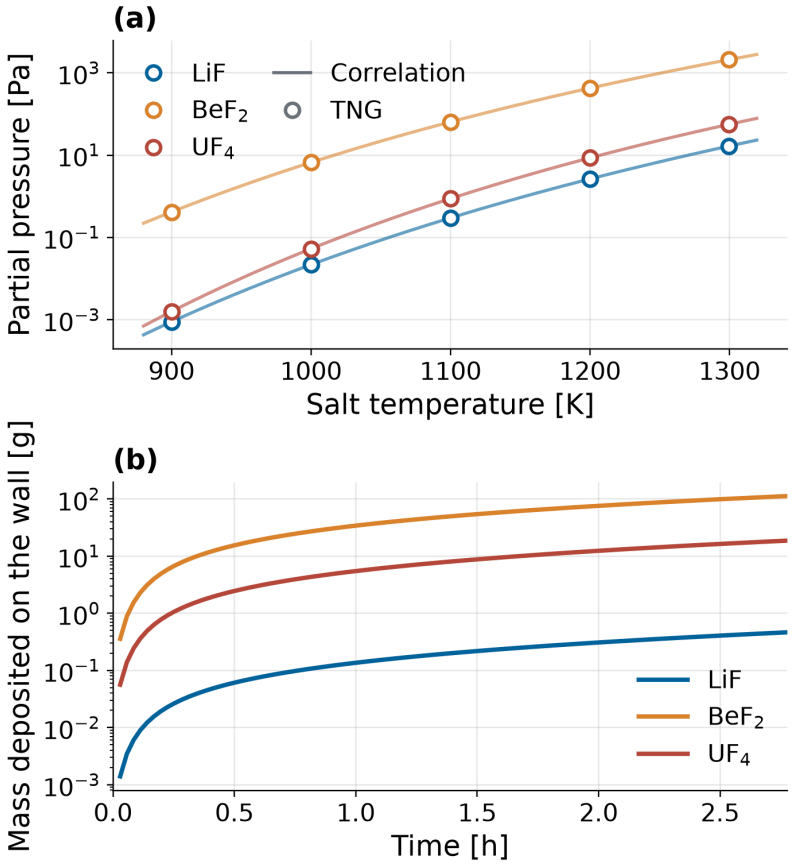
Core Cell Study of the MSRE Circulation Loss



- Steady circulation at 4, 8, 16, 32 and 64 core cells
  - Same loop and ORNL losses, with flow settling at 1106 to 1117 gpm
- Compared with the exact line model at each run's own transit times
  - 5.5 pcm apart at 4 cells, 0.5 pcm at 8, 0.02 pcm at 16
  - From 16 cells on, within 0.04 pcm
- The 8 pcm measurement uncertainty is 200 times larger
- The MSRE results in this talk use 16 core cells

Sixteen core cells resolve the circulation loss to within a few hundredths of a pcm.

Fuel Salt Vapor and Wall Deposition



- Vapor over LiF-BeF_2-UF_4 (60-30-10 mol %)

$$p_i = \gamma_i(x,T)x_i p_i^\circ(T)$$

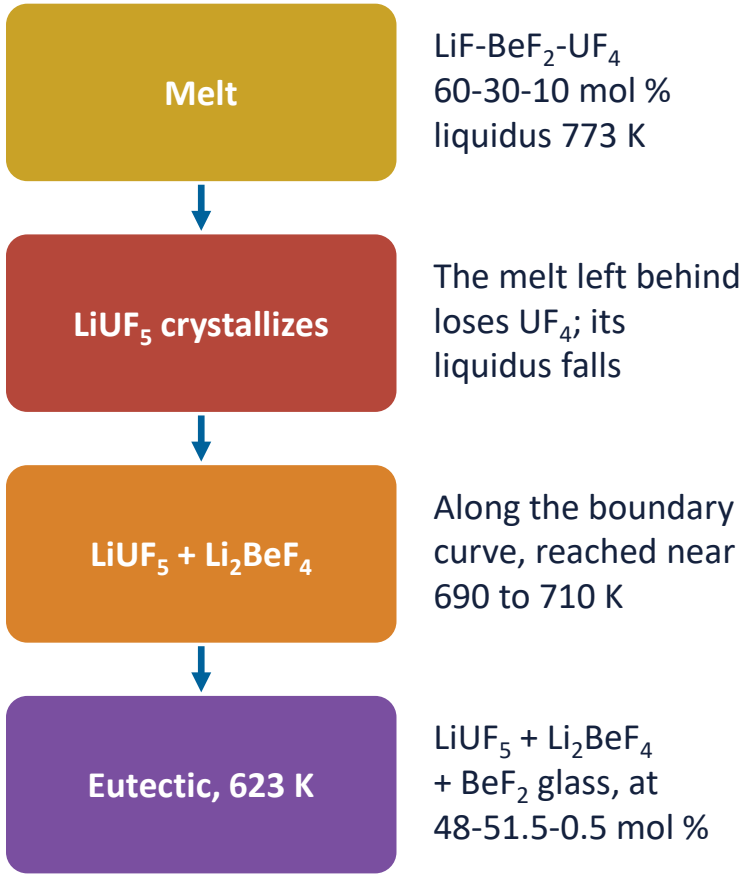
  - Hitch and Baes activity coefficients with pure constituent vapor pressures
  - BeF_2 is 99 % of the vapor at 900 K
- A 1250 K pool beside a 700 K wall for 2.8 h
  - 110 g of BeF_2, 19 g of UF_4 and 0.5 g of LiF freeze onto the wall

BeF_2 dominates the vapor and carries salt from hot pools to cold walls.

How Fuel Salt Freezes

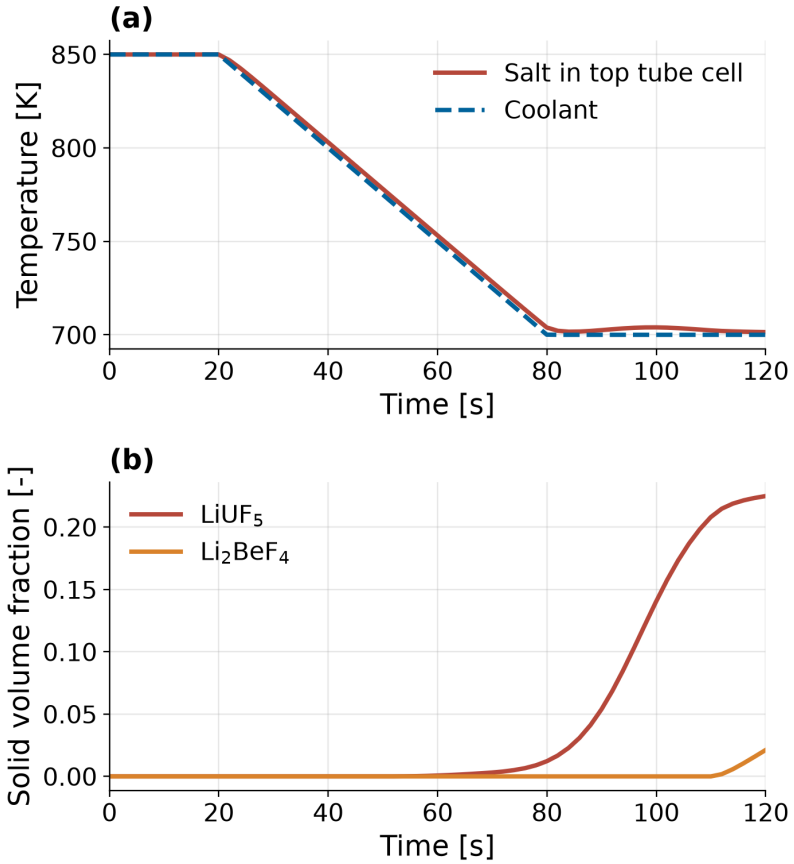
- The melt follows its measured freezing path
  - ORNL phase diagram reports (ORNL-2548, ORNL-2896)
  - Each stretch deposits one solid of fixed composition
  - A composition off the measured path is rejected
- Where the solid goes
  - Crust on a wall that cools the salt; particles in the bulk
- What the solid does
  - Densities from measured crystal cells, so the salt contracts as it freezes
  - Latent heat from the constituents' heats of melting
  - Melting scales with the solid present, so solid stays nonnegative

The phase diagram sets what freezes and when.



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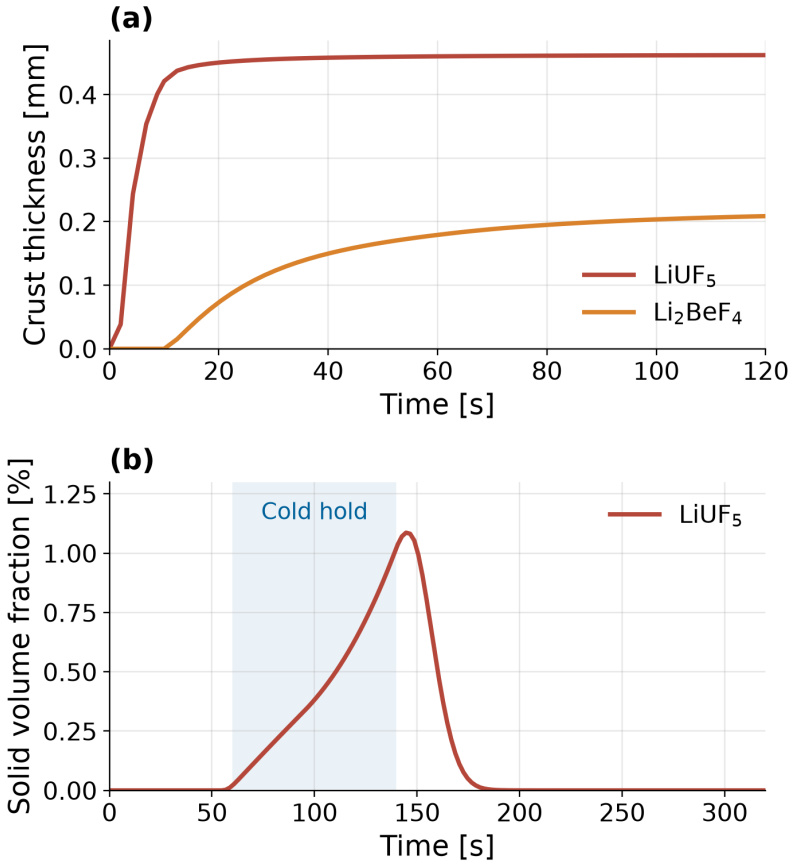
Fuel Salt Freezing in Heat Exchanger Tubes



- Four cooled tube cells under a pump bowl, coolant going from 850 K to 700 K over 60 s
  - $LiUF_5$ crystallizes first, Li_2BeF_4 from 112 s, as the phase diagram sets
  - Latent heat holds the salt above the coolant while it freezes
- The solid is denser than the liquid, so salt drains down from the bowl
  - Top tube pressure falls from 1.24 MPa to 0.88 MPa

Freezing follows the phase diagram, with $LiUF_5$ first and then Li_2BeF_4.

Crust on Cooled Walls and Remelting



- Tube walls cooled from a 700 K far side, 73 K below the liquidus
  - – $LiUF_5$ crust 0.46 mm within 15 s, then Li_2BeF_4 to 0.21 mm
  - – Crust forms only on cooled walls and not in the pump bowl
- Reheating a partly frozen column
  - – 1.1 % of the salt freezes during the cold hold
  - – All of it melts within 60 s of reheating and the melt returns to 60-30-10 mol %
- Both cases run 30 to 65 times faster than real time

Crust grows only where a wall cools the salt, and remelting restores the starting composition.

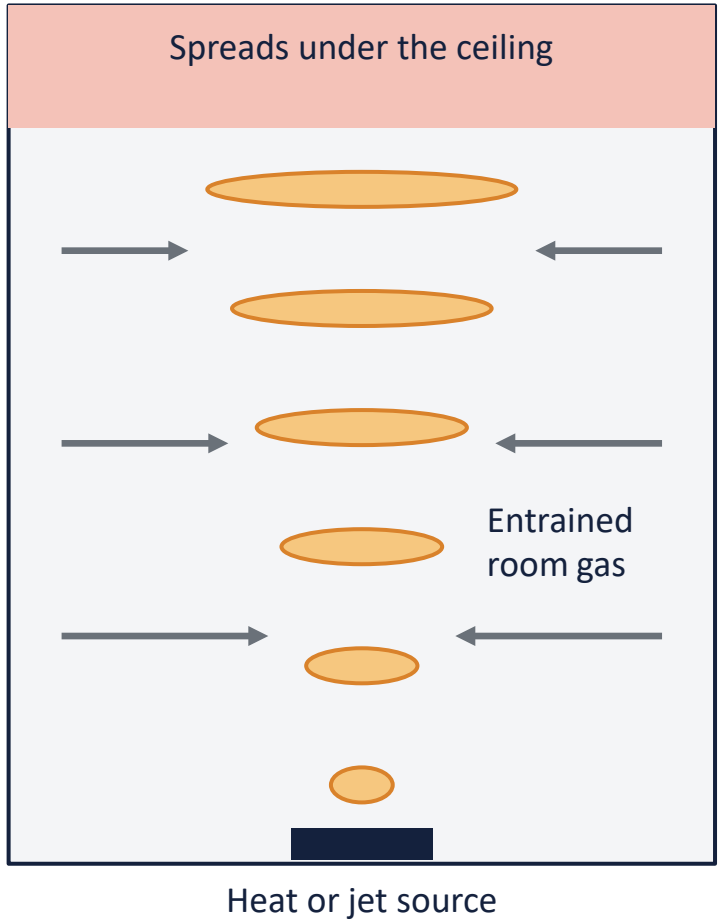
Lagrangian Plume Element in the Network

- A lumped network mixes hot gas into the first cell it reaches
  - Real plumes fill a room from the top down
- The element follows the plume from the source upward
  - Carries mass, enthalpy, momentum, gases, trace species and aerosol

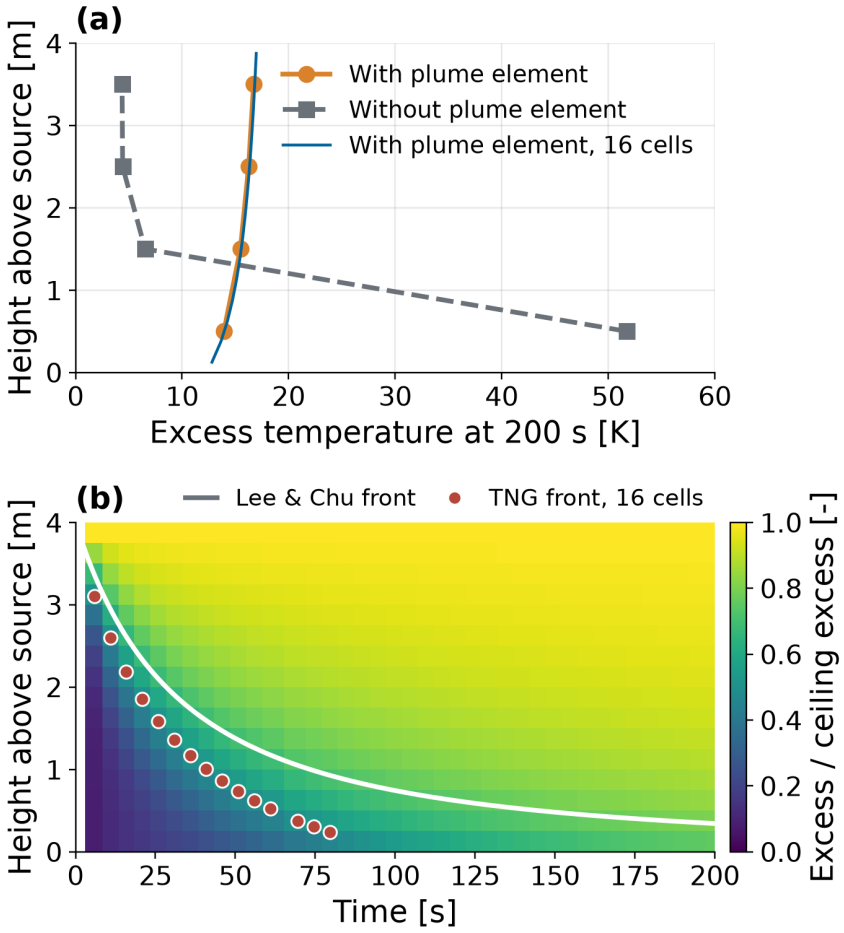
$$\Delta M = 2\pi\alpha b h \rho_a \Delta U \Delta t$$

  - b is the plume radius and α ranges from 0.081 (jet) to 0.124 (plume)
- At its maximum rise it releases its contents over 0.38 of the rise
- Equal and opposite streams on each junction give zero net flow
- Solved implicitly with the network, its Jacobian included

The network keeps its coarse cells while the element carries the plume between them.



Verification Against Turner's Filling Box

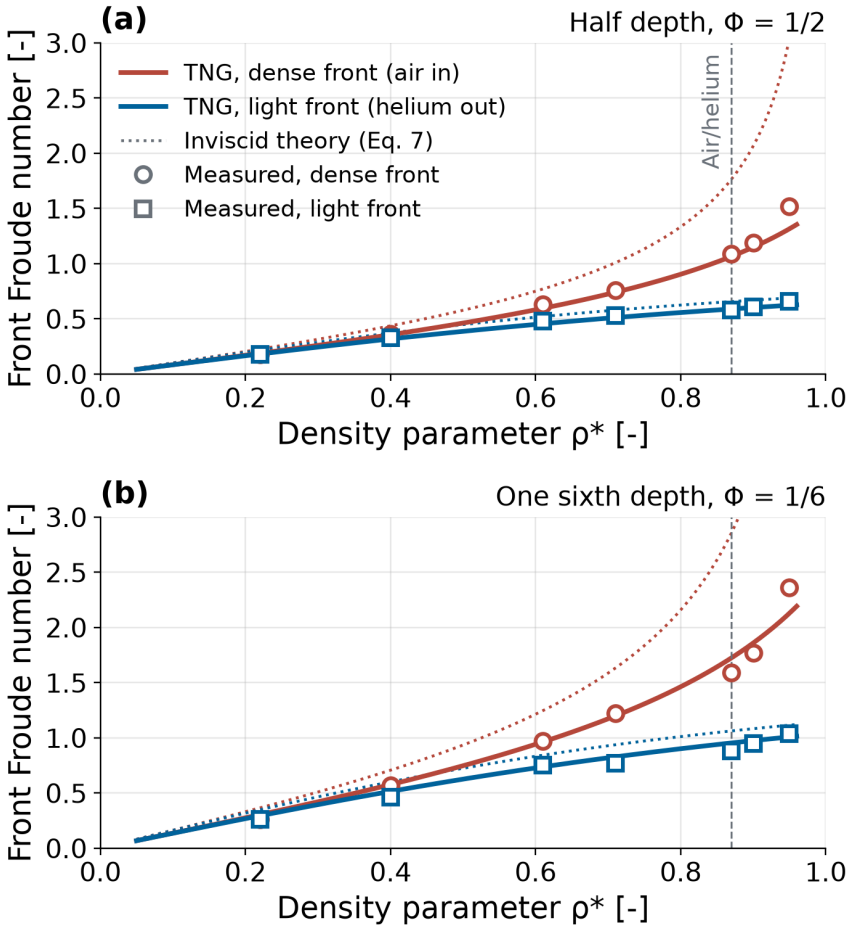


- Closed air column 4 m tall with a 4 m² floor, 1 kW heater, 200 s
- With the element the ceiling is warmest
  - 13.9 K at the source to 16.7 K at the ceiling, above the start
  - Without it, heat stays in the source cell at 51.7 K
- The stored heat sits at 2.08 m against 2.17 m from theory
  - The same at 4, 8 and 16 cells
- The warm layer's front descends ahead of the Lee and Chu solution

With the element, a heat source fills a room from the ceiling down.

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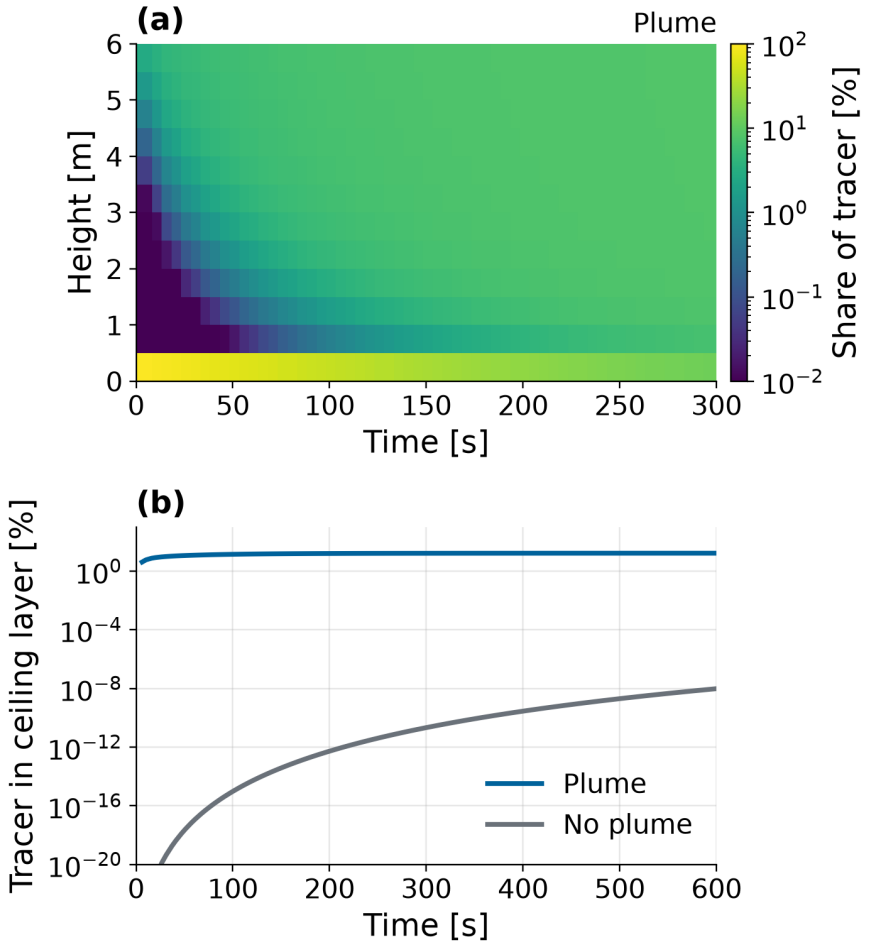
Validation Against Two-Layer Exchange in a Duct



- Lock exchange (Gröbelbauer, Fanneløp and Britter, 1993)
  - 7 gas pairs, two current depths, 28 measured front speeds
- Modernized MELCOR's exchange formula, with one dissipation constant
  - Worst 16.7 %, root mean square 6.7 %
  - Air and helium: dense to light speed 1.81, measured 1.88
- Inviscid theory overpredicts the dense front by up to 62 %
- Used where gas exchanges through a break or opening

Counterflowing layers through openings move at the measured speeds.

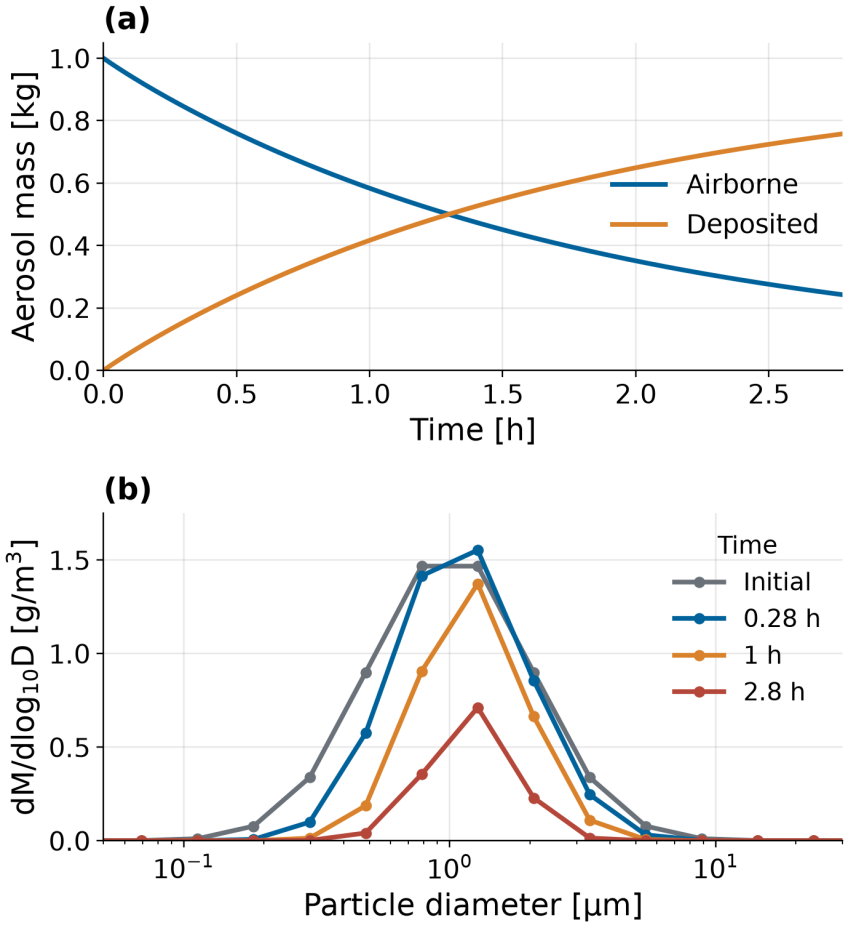
Plume Transport of Released Material



- Closed room 6 m tall, 4 m by 4 m, twelve 0.5 m cells
  - 5 kW heat source on the floor, 0.1 m across
  - 1 mg each of a vapor and a 1 μm aerosol released at the floor
- The plume entrains air and the material it carries
  - At 60 s the ceiling layer holds 12 % and the cell above the source 0.05 %
  - The layer then deepens downward from the ceiling
- By 600 s the room is mixed
  - Without the plume, 10^{-8} % reaches the ceiling layer in 600 s

The plume moves released material to the ceiling within a minute, then fills the room top down.

Aerosol Size Distribution by Population Balance



- Aerosol mass tracked in size sections
  - Particles collide and stick, settle, deposit and grow by condensation
- Demonstration with 1 kg of NaI aerosol in 850 m³ of air
  - 1 µm mass median, 20 sections from 0.01 to 100 µm, 500 m² floor
- Airborne mass falls to 0.58 kg at 1 h and 0.24 kg at 2.8 h
  - Mass conserved to 1 part in a million
- Small particles join larger ones and the largest settle first

Agglomeration and settling change both the airborne mass and its size.

Particle Dynamics in Salt, FY25–FY26

FY25 (complete)
Deposition models

➡

FY26 (complete)
Predict particle size

➡

FY26 (complete)
Deposits to salt

➡

Next
Full plant and bubbles

FY25 with size as an input

- Turbulent, thermophoretic, and settling models, checked against Kedl's data
- Deposition hinges on salt viscosity, flow, and particle size

FY26 sectional population balance in liquid

- Tracks particles by size and component, precursors, and deposits
- For noble metals, sticking sets size while turbulence and temperature gradients set deposition
- For CrF_2, chemistry sets how much becomes particles, and aggregates can carry radionuclides
- Same trends as FY25 at MSRE flow

FY25 showed that deposition depends on particle size, and FY26 lets MELCOR predict that size.

SAND2025-12380 · SAND2026-27273

One Model for Deposition and Corrosion

- One law for every element as fluoride or metal

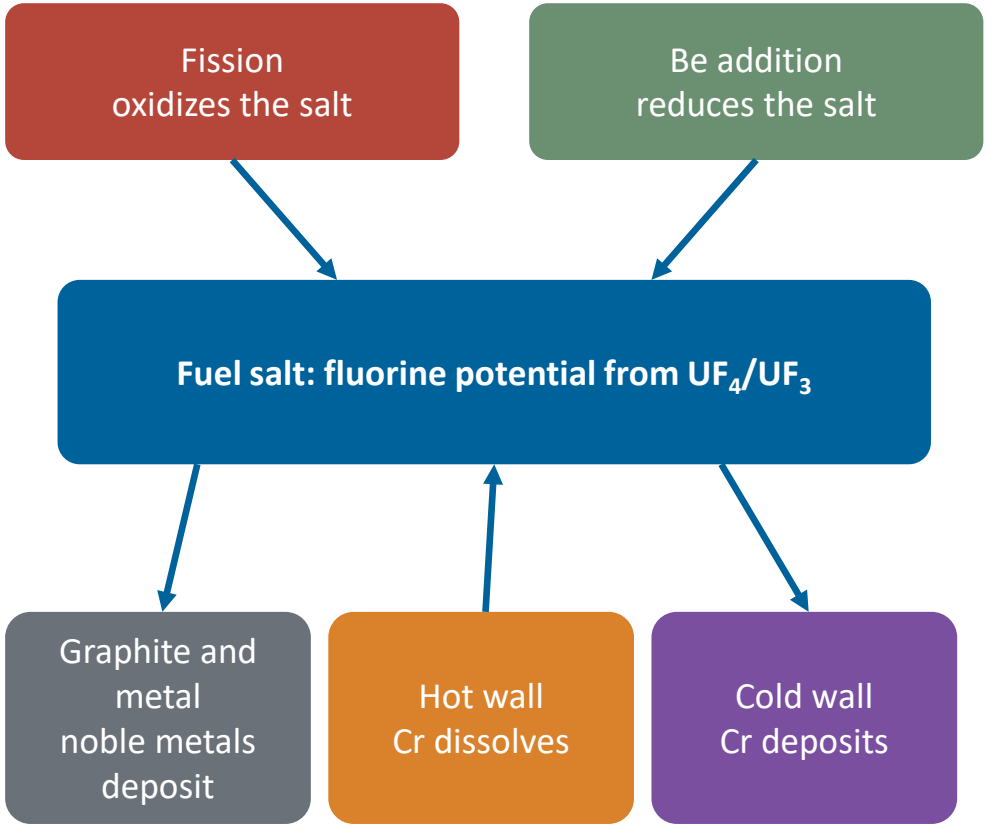
$$x_{eq} = a_M \exp\left(-\frac{\Delta G_{f,MF_n} - \frac{n}{2}\Delta G_{F_2}}{RT}\right)$$

$$\Delta G_{F_2} = 2\Delta G_{f,UF_4} - 2\Delta G_{f,UF_3} + 2RT\ln\frac{x_{UF_4}}{x_{UF_3}}$$

  - Salt seekers stay dissolved, Cr moves from hot to cold walls, noble metals plate
- Every surface exchanges at its mass transfer rate

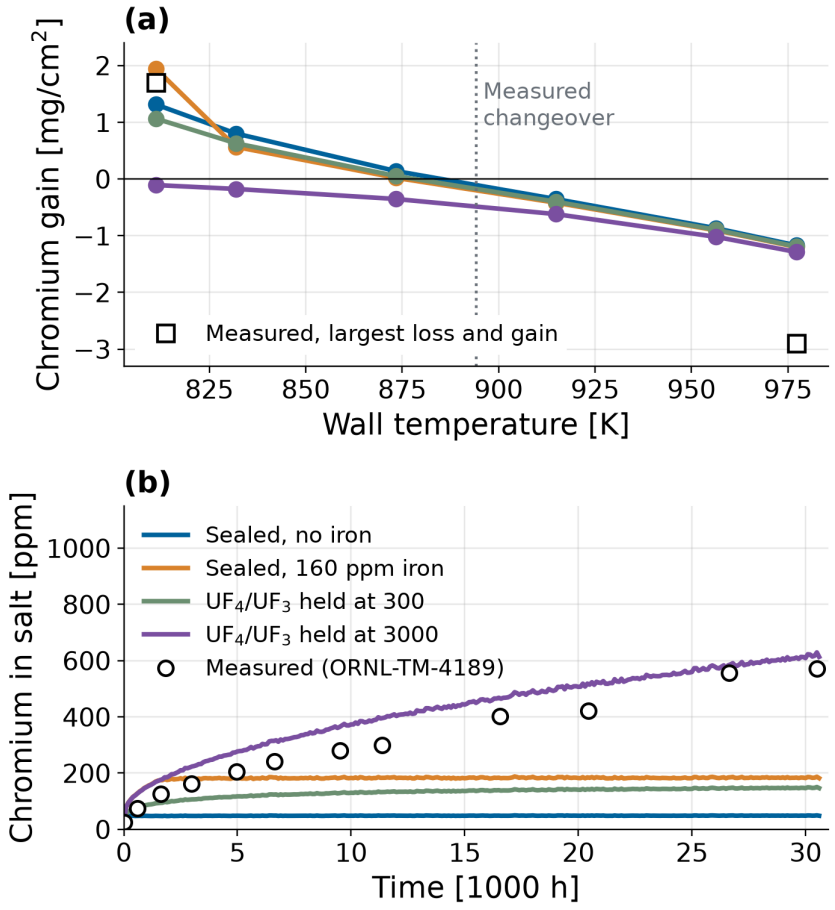
$$J = sh_m(c - c_{eq}), h_m = \frac{ShD}{D_h}$$

The fluorine potential couples fission, deposition, corrosion and chemistry control.



Each element carries its own free energy and diffusivity data

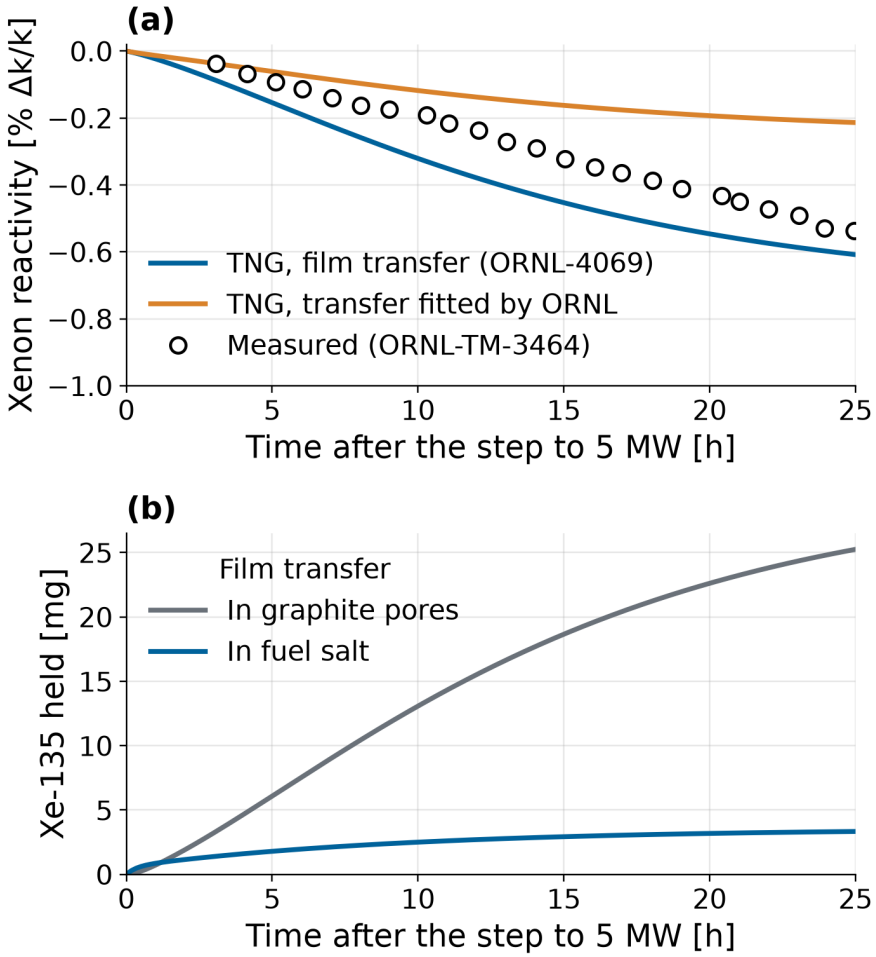
Corrosion Chemistry in ORNL Loop NCL-16



- Hastelloy N loop, 29,500 h (ORNL-TM-4188)
  - LiF-BeF_2-UF_4 65.5-34.0-0.5 mol %, walls 811 to 977 K
- Four redox conditions explored
  - Sealed, UF_3 builds up as Cr dissolves (with and without 160 ppm Fe)
  - UF_4/UF_3 held at 300 or 3000
- Hot walls always lose 1.2 to 1.3 mg/cm² of chromium
  - Cold walls gain it in three cases, changeover at 875 to 885 K (894 K measured)
- A sealed loop levels off and a held redox state keeps corroding, limited by wall diffusion
- The measurement sits within the range explored

One model covers sealed and controlled salt chemistry around the whole loop.

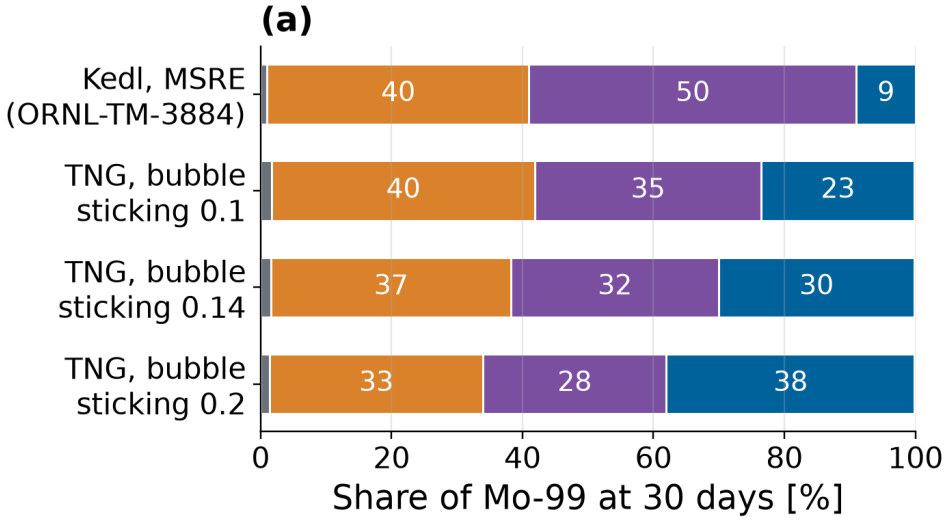
Xenon Poisoning in the MSRE at 5 MW

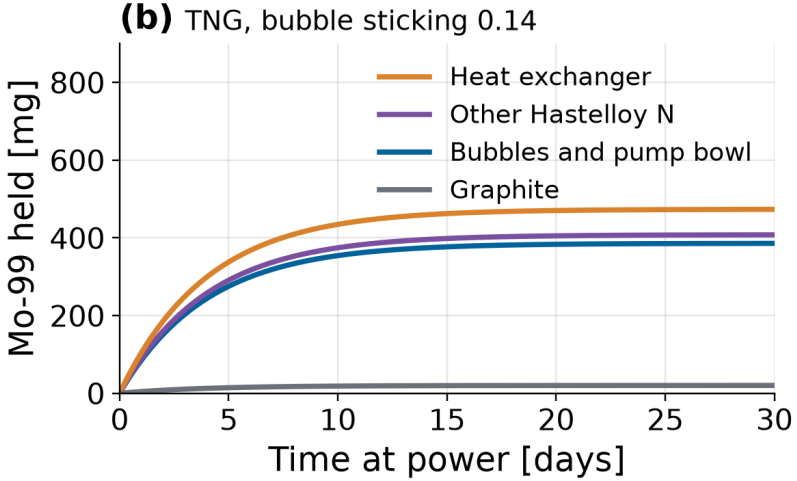


- I-135 and Xe-135 circulate with the fuel salt
  - Xenon leaves by decay, burnup, the pump bowl stripper and the graphite pores
  - The kinetics feels the xenon in the core salt and graphite
- MSRE inputs from ORNL-4069 and ORNL-TM-3464
  - The film transfer case has no input adjusted to this transient
- The salt to graphite transfer brackets the measurement
  - At 20 h the film case gives −0.55 %, the ORNL fit −0.19 %, and the measurement −0.43 %
- At 25 h the graphite holds 7.6 times the xenon in the salt

Xenon transport through salt, gas and graphite sets the reactor's poison reactivity.

Noble Metal Distribution in the MSRE

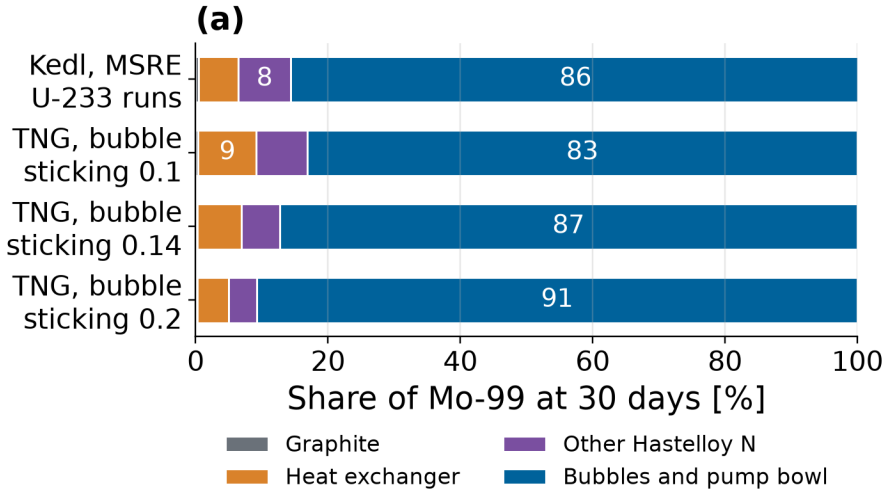


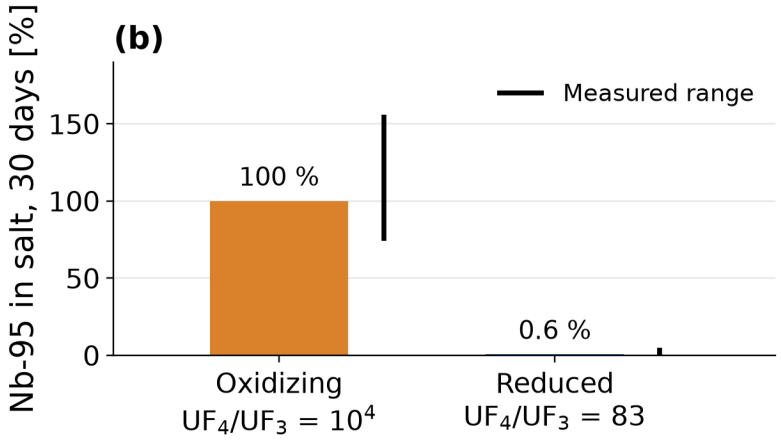


- Mo, Ru and Te leave the salt within hours
  - Mass transfer from each region's computed flow
  - Graphite sticking from MSRE specimens (ORNL-4865), metal 1
  - Bubble sticking 0.1 to 0.2, Kedl's fitted range (ORNL-TM-3884)
- Whole loop transfer within 7 % of Kedl's
- 30 days at power for Mo-99, Ru-103, Ru-106 and Te-132
- Metal walls hold 61 to 75 % (Kedl 90 %)
- Graphite holds 1.1 to 4.1 % by element (Kedl 1 %)
- Bubbles 23 to 38 %, Kedl 9 % (remainder after metal)
  - Set by bubble sticking, the one unmeasured input

About two thirds of the noble metals plate on metal, and bubble sticking sets how much leaves on bubbles.

MSRE with U-233 Fuel, Bubbles and Niobium



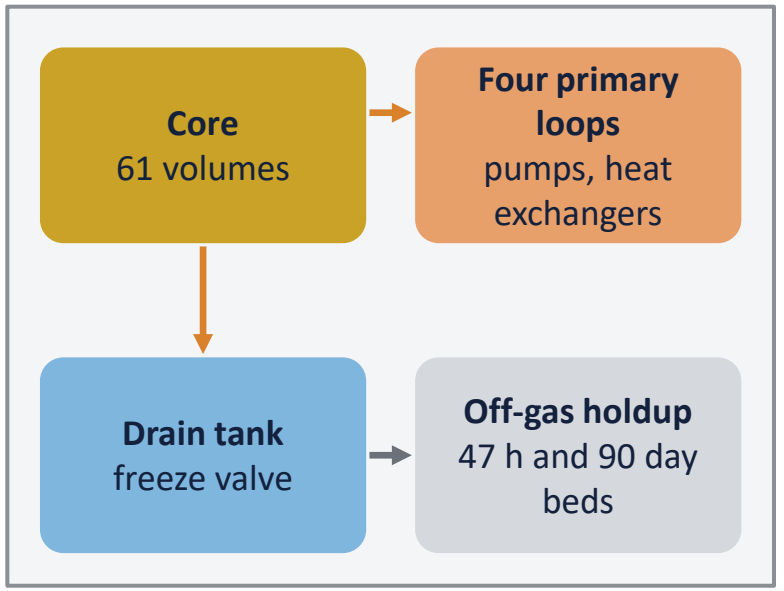


- The U-235 model with three U-233 inputs changed
  - Bubbles 0.55 % of the salt, U-233 yields, 7.4 MW (ORNL-TM-3884)
- Bubbles carry 83 to 91 % of the noble metals (Kedl 86 %)
  - Heat exchanger share falls to about a fifth of the U-235 value
  - Kedl's foam carried into the overflow tank is not modeled
- Niobium follows the salt's redox state
  - Oxidizing conditions keep all of it dissolved (run 15 measured 74 to 156 %)
  - Reducing conditions leave 0.6 % dissolved (about 0 after beryllium)

With the same input for both fuels, the bubble fraction and redox state set where the metals go.

Full-Plant MSBR Model in Modernized MELCOR

- The 2250 MWt Molten Salt Breeder Reactor (ORNL-4541)
  - 123 volumes, 151 junctions, 116 heat structures
- Circulating fuel kinetics over all 61 core volumes
- Salt, helium cover gas and cell nitrogen in one solve
  - A pump trip opens the freeze valve; salt drains and helium replaces it
- Source term carried with the flow
  - Decay heat in six radionuclide classes
  - Salt mist, I-135 to Xe-135, deposition in the drain tank, off-gas and cells



Reactor and drain tank cells, nitrogen

The models shown today assemble into one input for a full salt plant.

Conclusions

LWR safety, 1982–2014

One integrated code

- Succeeded the linked WASH-1400 codes and the STCP
- Couples all phenomena at every step
- Applied to Fukushima, spent fuel pools, new LWR fuel

Non-LWR designs, 2019–2025

Demonstrated for MSRs

- Nine NRC demonstrations on five designs
- MSR models for salt, kinetics, isotopes and chemistry
- MSRE and MSBR show chemistry sets the release

Modernized MELCOR, 2023–2026

A new architecture

- Validated physics kept and new models plug in
- Salt, gas, crystals and trace species in one solve
- Checked against MSRE kinetics, xenon, noble metals

Next steps are full-plant demonstration models for xenon removal failure and online redox control

MELCOR's integrated approach now reaches molten salt reactors, from core to reactor cell.

NUREG/CR-4830 · SAND2017-0876 · SAND2023-01803

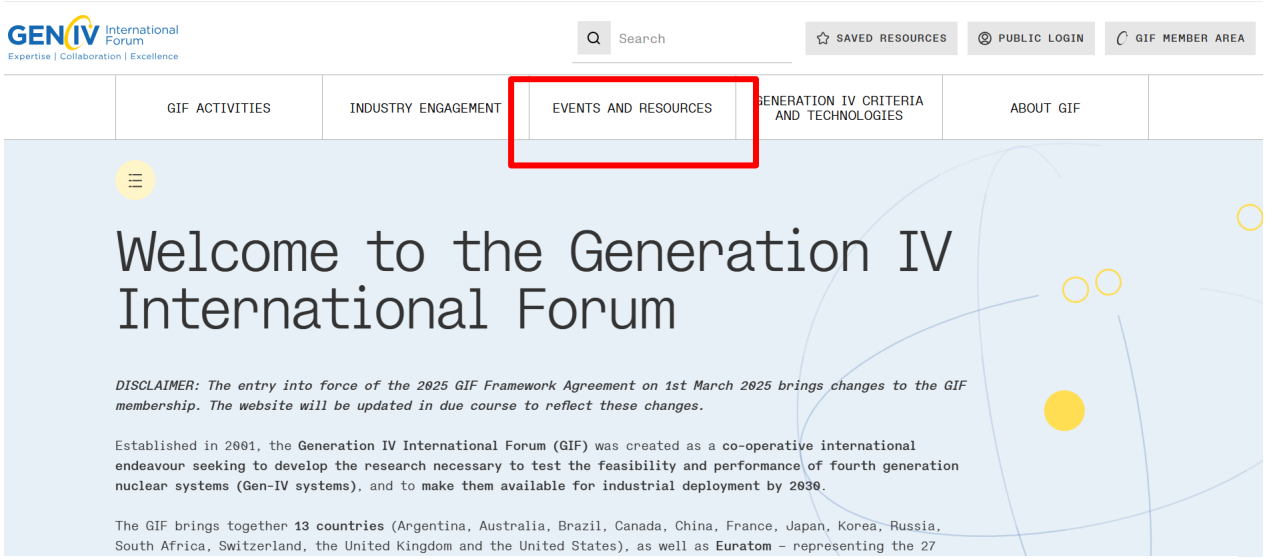
Upcoming Webinars

Date	Title	Presenters/Moderators
16 December 2026	Pyrochemistry for Advanced Nuclear Fuel Cycles: From Spent Fuel Recycling to Molten Salt Reactor Fuels	Pavel Soucek, Joint Research Center, Karlsruhe
21 January 2026	Joint GIF IAEA Webinar on Challenges and Opportunities for 21st-century SFRs	**Panelists:** Paul Gauthe, Hexana, France Justin Salerse, Terrapower, USA Fabienne Delage, CEA, France Christopher Grandy, ANL, USA **Moderators:** Bo Feng, ANL, USA Patricia Paviet, PNNL, USA
03 February 2027	Progress and Thoughts on Materials Research on Thorium-based Molten Salt Reactors	Heifei Huang, Shanghai Institute of Applied Physics, China

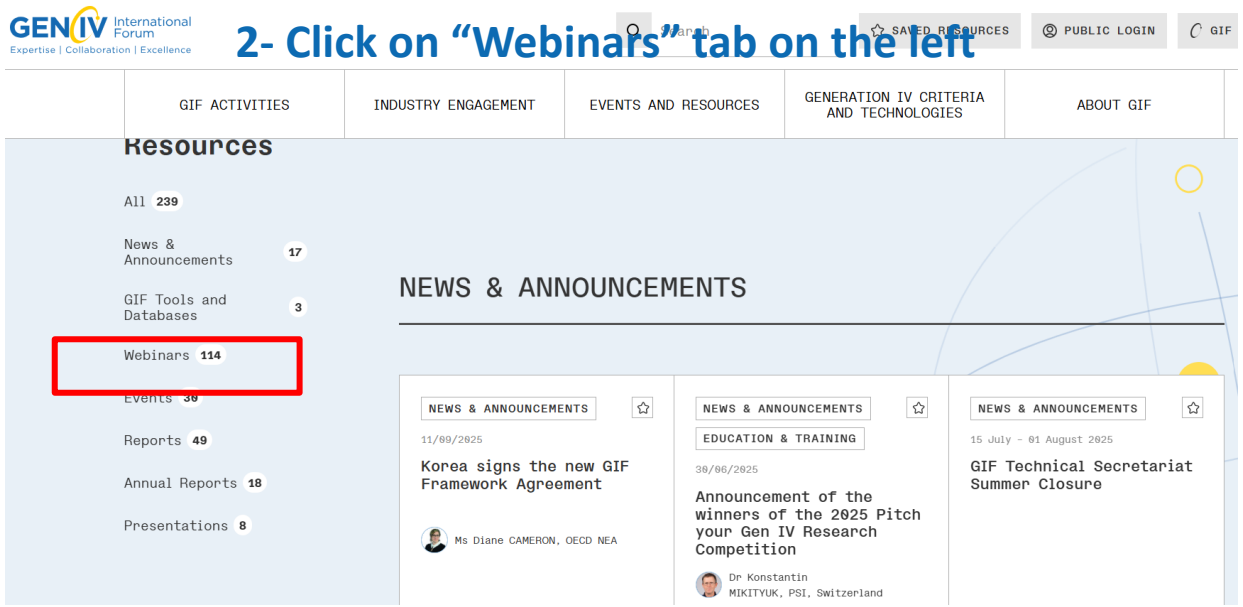
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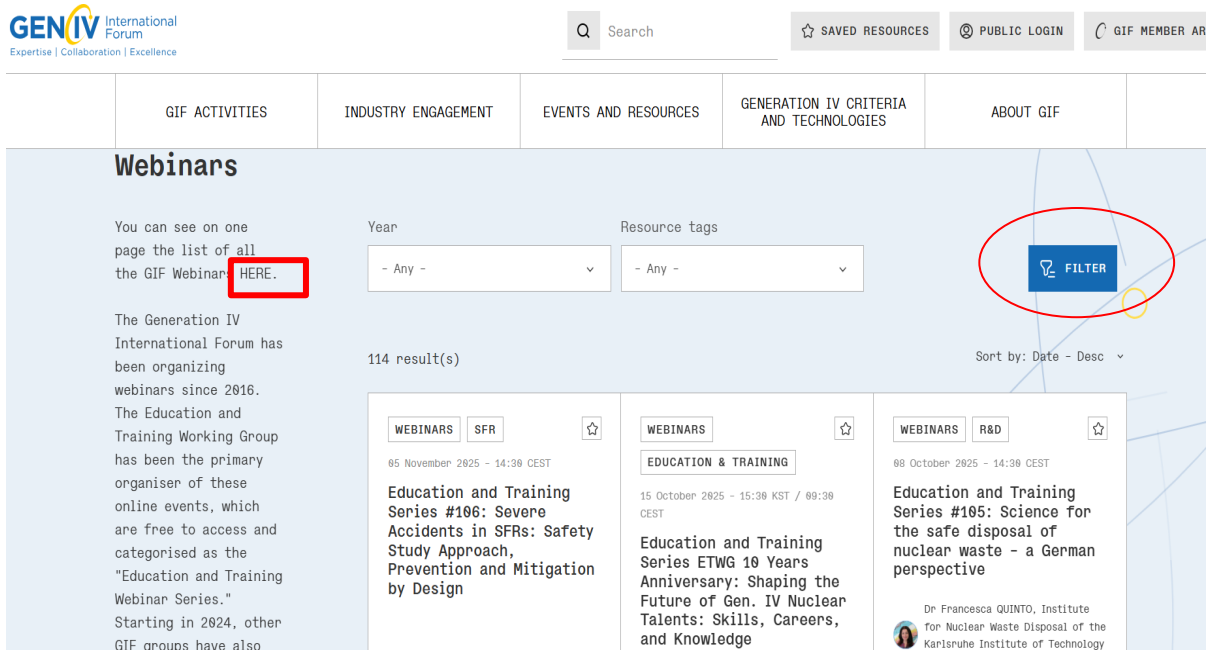
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