SAND2022-7733C

# Non-LWR Fuel Cycle Analysis with SCALE/MELCOR

JUNE 9, 2022

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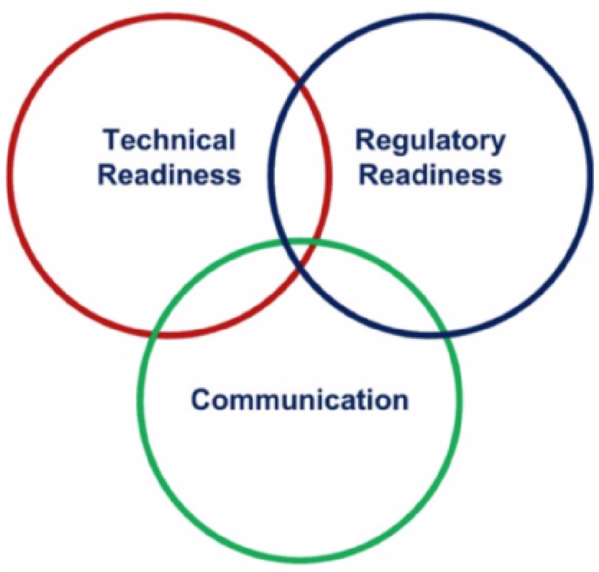
# Non-LWR Fuel Cycle Analysis

- **Project goal:** demonstrate NRC's capability to perform independent analyses in non-LWR fuel cycle:
  - Criticality safety
  - Radionuclide characterization
  - Decay heat development
  - Radiation shielding
  - Radiological and non-radiological hazardous material and energy release and transport

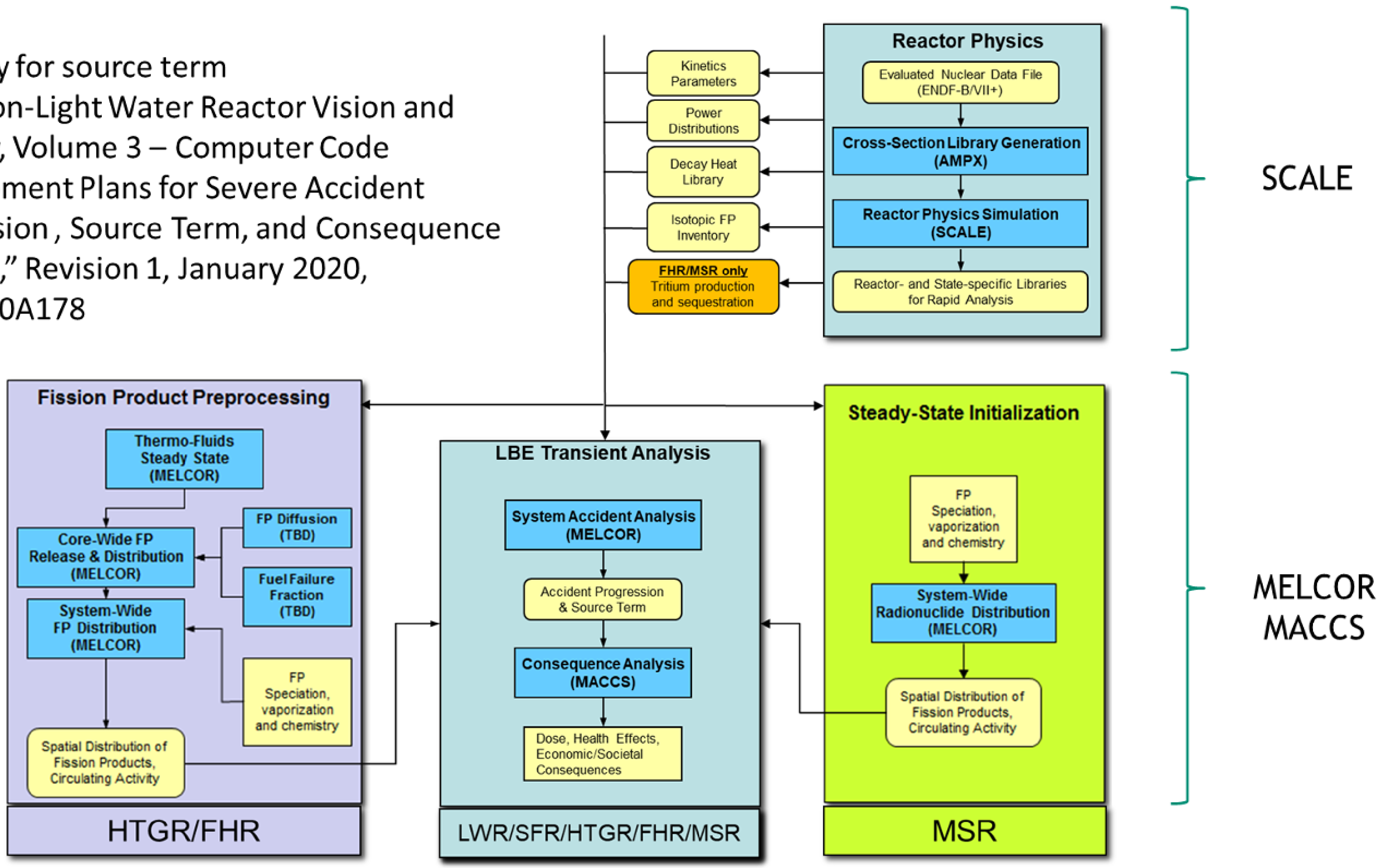
NRC Non-Light Water Reactor (Non-LWR) Vision and Strategy, Volume 5 – *Radionuclide Characterization, Criticality, Shielding, and Transport in the Nuclear Fuel Cycle*



# Evaluation Model and Suite of Codes

Code strategy for source term

"NRC Non-Light Water Reactor Vision and Strategy, Volume 3 – Computer Code Development Plans for Severe Accident Progression , Source Term, and Consequence Analysis," Revision 1, January 2020, ML20030A178



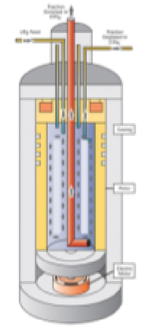
# Non-LWR Fuel Cycle Analysis

- Use SCALE and MELCOR to evaluate hazard scenarios during the following stages of a nuclear fuel cycle
  - Enrichment
  - Transportation of enriched material to fuel fabrication facility
  - Fuel fabrication
  - Transportation of fuel assemblies/pebbles to reactor facility
  - Fresh fuel staging and fuel loading/unloading (online refueling)
  - Power operation associated with chemical processes that might affect decay heat removal etc.
  - Spent fuel pool/shuffle operations and on-site dry cask storage

# Non-LWR Systems Under Consideration

- There are 5 reactors under consideration:
  - High Temperature Gas Reactors
  - Thermal/Fast Molten Salt Chloride/Fluoride Reactors
  - Sodium-cooled Fast Reactors (metal fuel)
  - Heat Pipe Reactors
  - Fluoride-salt-cooled High-temperature Reactor
- Current effort: development of representative fuel cycles for the non-LWRs based on publicly available information
  - Determine boundary conditions for each stage of the fuel cycle
  - Identify potential hazards and accident scenarios for each stage of the fuel cycle
  - From these, select accident scenarios for SCALE/MELCOR to simulate

# HTGR Fuel Cycle

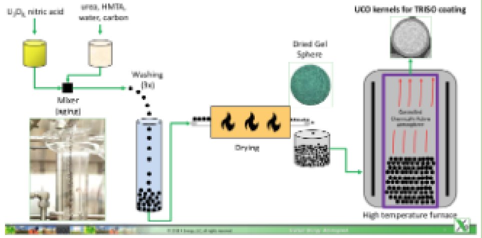


- Enrichment
- Gas centrifuges

**E1**

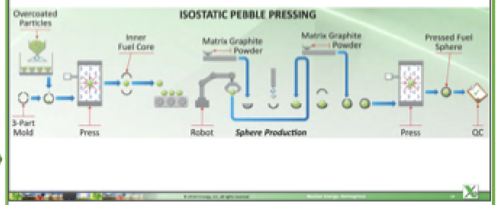
- Transportation of $UF_6$ - Package: DX-30

**T1**



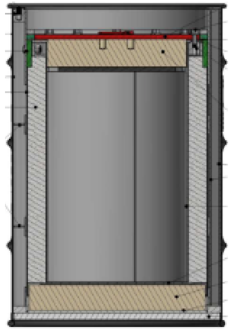

- TRISO fabrication
- Sol-gel process

**F1**



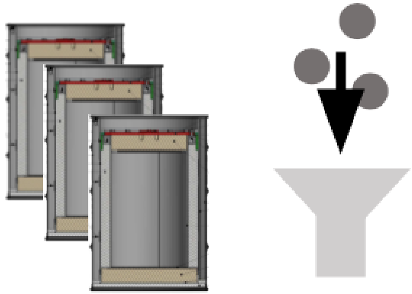

- Pebble fabrication
- Process: X-energy

**F2**



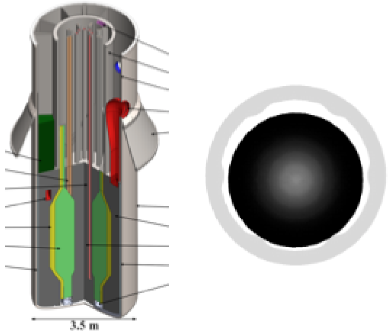
- Transportation of fuel pebbles
- Package: Versa-Pac

**T2**



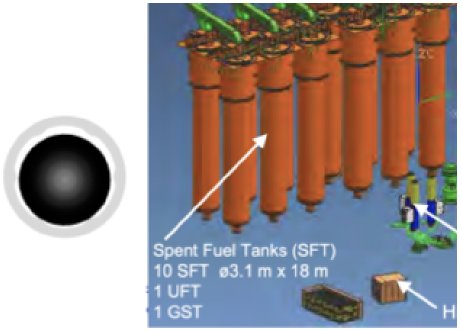
- Fresh fuel staging
- Pebble loading

**U1**




- Power production
- Online refueling

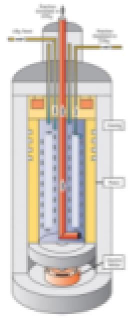
**U2**




- Discharged pebble storage onsite
- Spent fuel/used fuel/graphite tanks

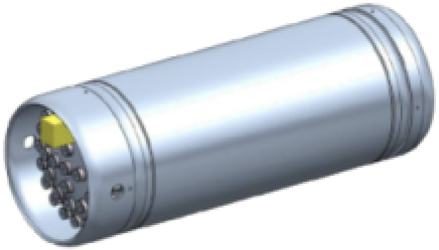
**U4**

# MSR Fuel Cycle



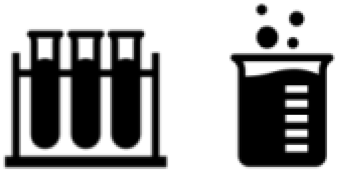
- Enrichment
- Gas centrifuges

**E1**



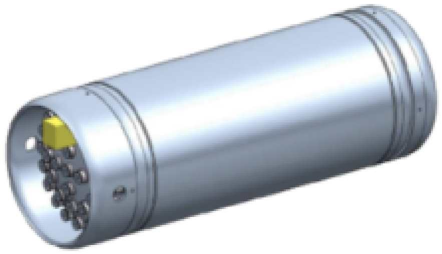
- Transportation of $UF_6$
- Package: DX-30

**T1**



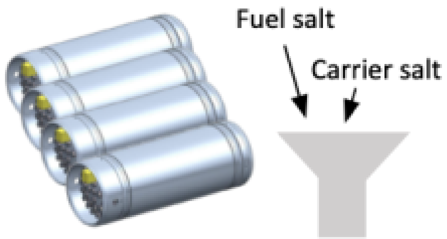
- Fuel salt synthesis

**F1**



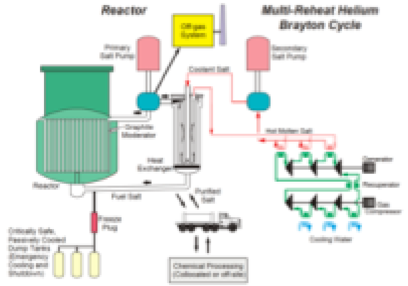
- Transportation of fuel salt
- Package: DX-30

**T2**




Fuel salt mixing and loading

**U1**




- Power production: continuous refueling and chemistry management

**U2**

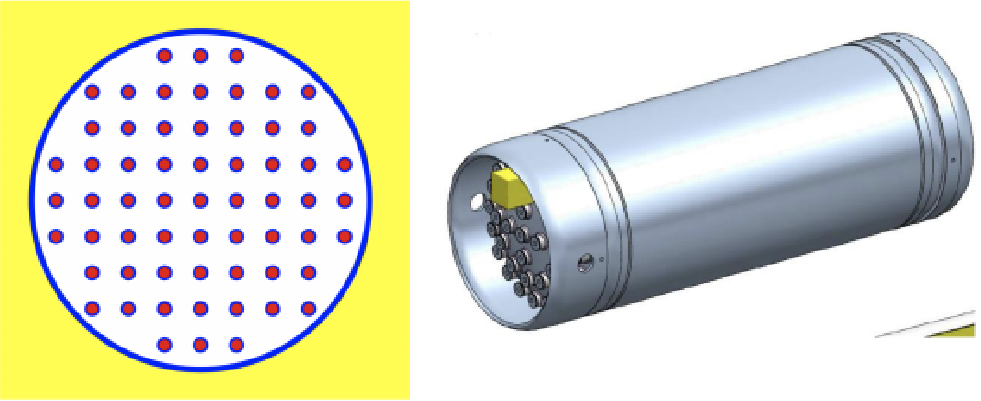

Onsite storage of waste products

**U4**

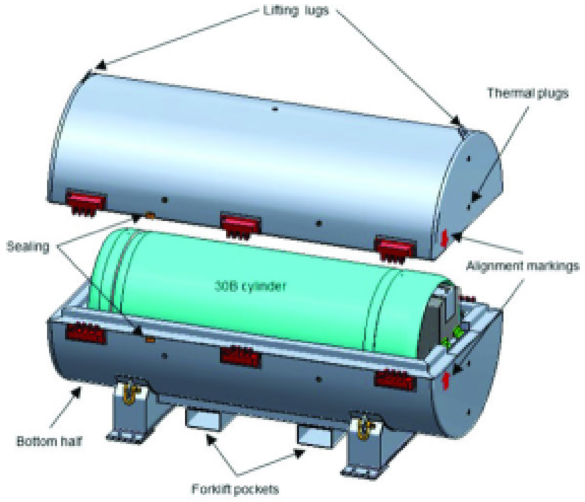
# EXAMPLE: T1 – Transportation of $UF_6$ Boundary Condition

**DAHER DN30-X package for up to 20% enrichment:**

- License under review by NRC
- 30B cylinder:
  - specified in ANSI N14.1-2019
  - 30 inches diameter, capacity of 2277 kg UF6
  - Licensed up to 5% U-235 enrichment
- DN30-X protective structural packaging (PSP) acts as a shock absorber during drop tests and as thermal protection in fire tests



**Daher 30B cylinder with B4C rods**



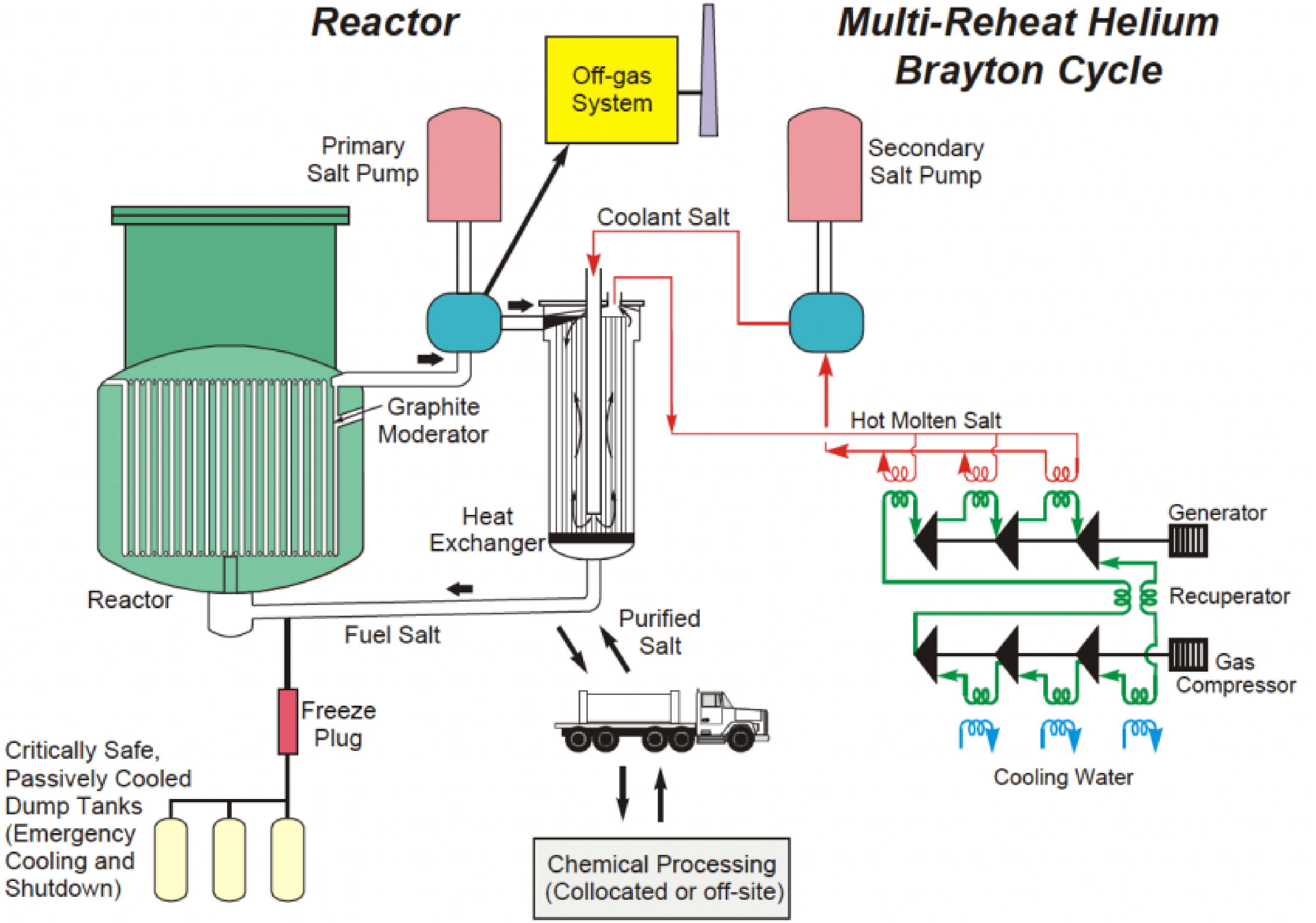

**DAHER DN30: 30B cylinder with PSP**

# Example: Transportation of $UF_6$ - Scenarios

- Water surrounding array of canisters at optimal moderator-to-fuel ratio and optimal canister→ criticality
- Water ingress into array of canisters at optimal moderator-to-fuel ratio (consider homogeneous sphere of UF6 and water, surrounded by water; potentially multiply layers) → criticality
- Water surrounding into array of canisters with simultaneous water ingress at optimal moderator-to-fuel ratio → criticality
- Low ambient temperatures → criticality at low temperatures
- Damage to container due to drop → reduced container array spacing → criticality
- Loss of overpack due to vehicle accident → reduced container array spacing → criticality
- Fire due to vehicle accident → melt/burn/combustion of overpack (foam insulation)
- Fire due to vehicle accident → combustion of melting of plugs → venting of gases

# Example: U1/U2/U4: Overview – Thermal Spectrum MSR

- Electric heaters used to heat up salt-wetted systems
- Fuel density change is major reactivity feedback mechanism (reactivity increase with decreasing fuel temperature)
- Fuel transferred out of core during emergency events or shutdown
  - Salt allowed to freeze here only for many MSR concepts



# Examples: U2 – hazard scenarios for power production with online chemical processes

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**Reactivity:**
- Too much fissile salt entering core → reactivity insertion
- Injection of fuel salt of incorrect concentration → reactivity impact (and potential impact on salt chemistry)
- Injection of fuel salt of incorrect temperature → reactivity impact
- Overcooling leading to precipitation and accumulation → reactivity [*concern of possibly precipitating out fissile salt, which would form a higher fissile concentration than the bulk liquid that flows back into the core, thus creating a transient power spike*]

**Release:**
- Flooding → Water–salt interactions, including hydrolysis in salt → steam generation
- Vessel/loop leak → hot liquid fuel salt - concrete reaction → release of bound water and production of hydrogen (in concrete with fine pores, already from 200°C on, water locked up in the concrete moves away from the source of heat and vaporizes, causing explosion)
- Breach in the off-gas system → release of FPs
- Breach in the cover-gas system → release of salt vapors, mists, and aerosols

**Heat removal:**
- Reduced salt pump speed or pump trip → higher build-up of FPs, insufficient heat removal
- Failure in the decay heat removal in the off-gas system → plating out of FPs, increased temperature, higher pressure
- Failure in heat removal of drain tank
- Plating out in heat exchanger → reduced heat removal

# MELCOR Accident Progression and Source Term Modeling for Facilities

## MELCOR Leak Path Factor Guidance

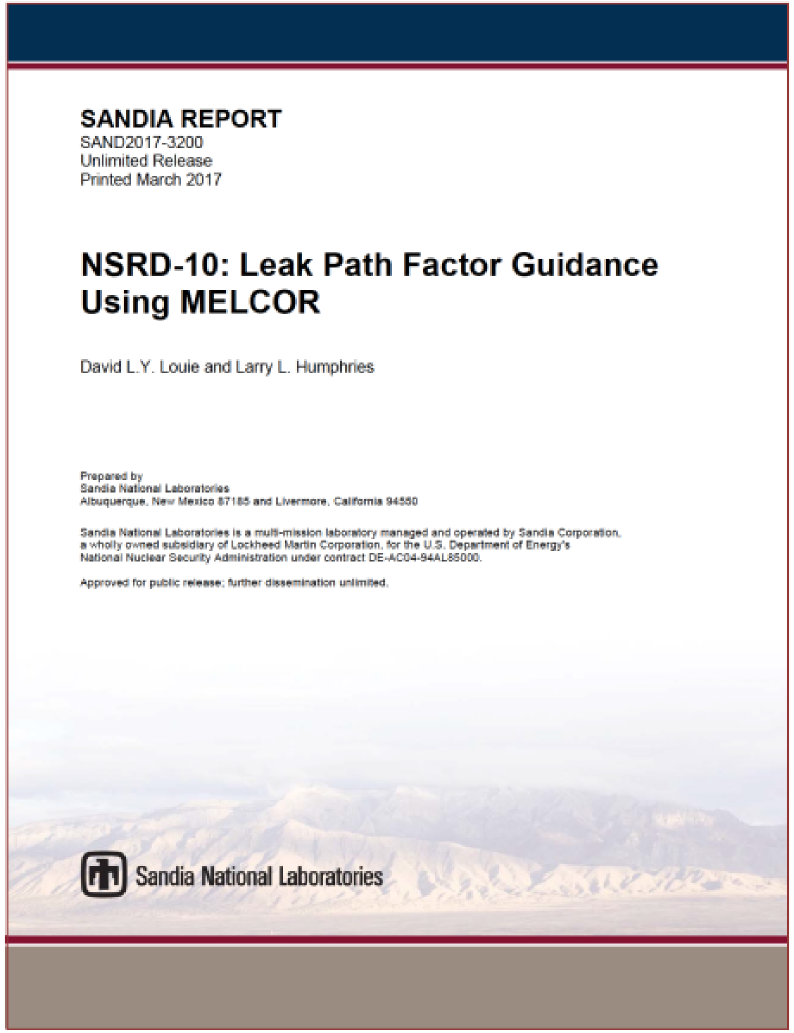
Establish technical basis for application of MELCOR 2 to facility safety assessment

Validation tests

- Fire test (LLNL Enclosure Fire – from CFAST validation)
- Aerosol resuspension test – STORM SR-11 Test
- Additional experiments from DOE-HDBK-3010-94
  - Wind Tunnel Gasoline pool fire tests conducted at the RART facility
  - Spill and Pressurized Release tests conducted in RART

Verification tests

- Version to version comparison - MELCOR 1.8.5, 1.8.6 and 2.1
- Additional verifications other than those in MELCOR 1.8.5 guidance report
- Best practices for common accident scenarios encountered at DOE facilities


SANDIA REPORT
SAND2017-3200
Unlimited Release
Printed March 2017

NSRD-10: Leak Path Factor Guidance Using MELCOR

David L.Y. Louie and Larry L. Humphries

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# Evolving from Barnwell Analysis

## SCALE/MELCOR – Best-Estimate Analysis

Basis for MELCOR non-reactor facility safety capability demonstration

- Available technical drawings, accident descriptions and safety analysis
- Facility de-commissioned prior to operation

MELCOR utilized as part of best-estimate analysis methodology

- Spent fuel inventories developed using ORIGEN-S from SCALE 6.1.3 package
- Aerosol transport modeling utilized best-estimate MELCOR models

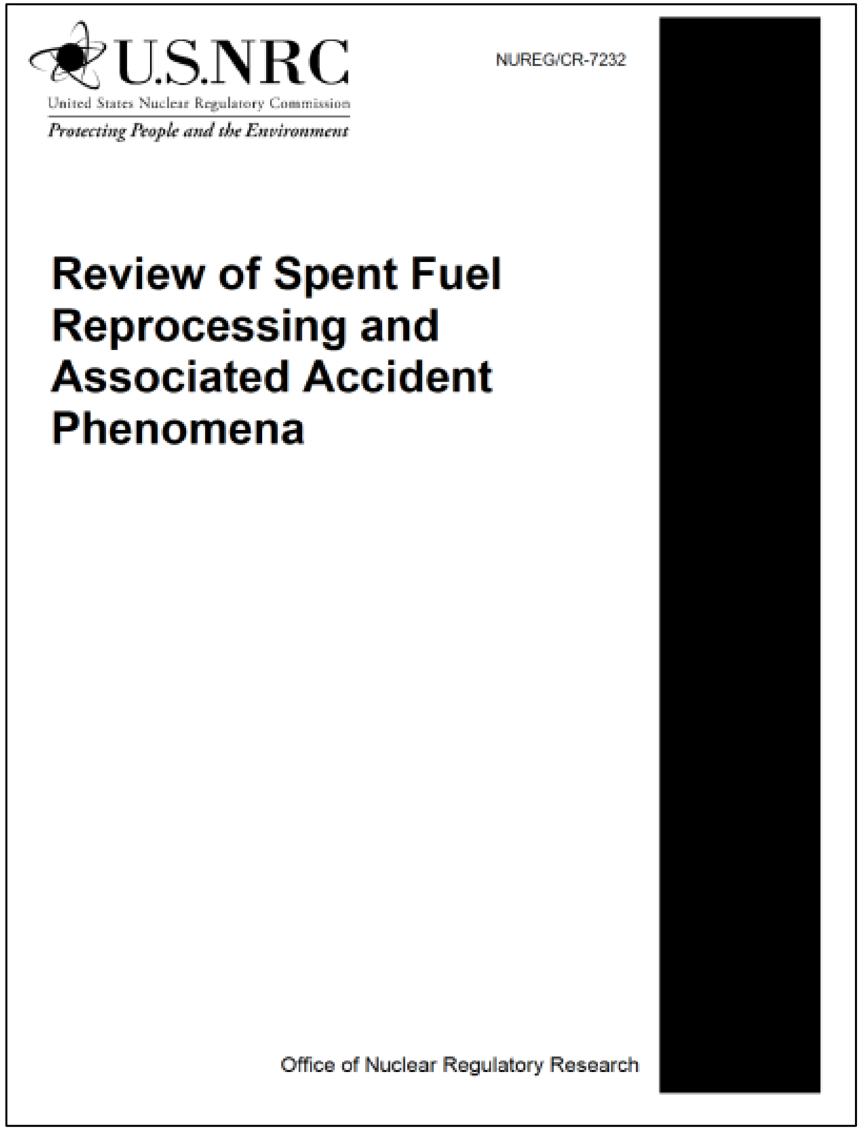
Integral MELCOR analyses estimate radiological transport and release

- Within the facility to assess hazards to personnel
- To the environment and ultimately public

MELCOR aerosol modeling enables estimation of transport of non-radiological, hazardous material within facility and to environment

Accident scenarios considered relevant to broad range of facility accidents

- Explosion scenario
- Fire scenario
- Combined explosion and fire scenario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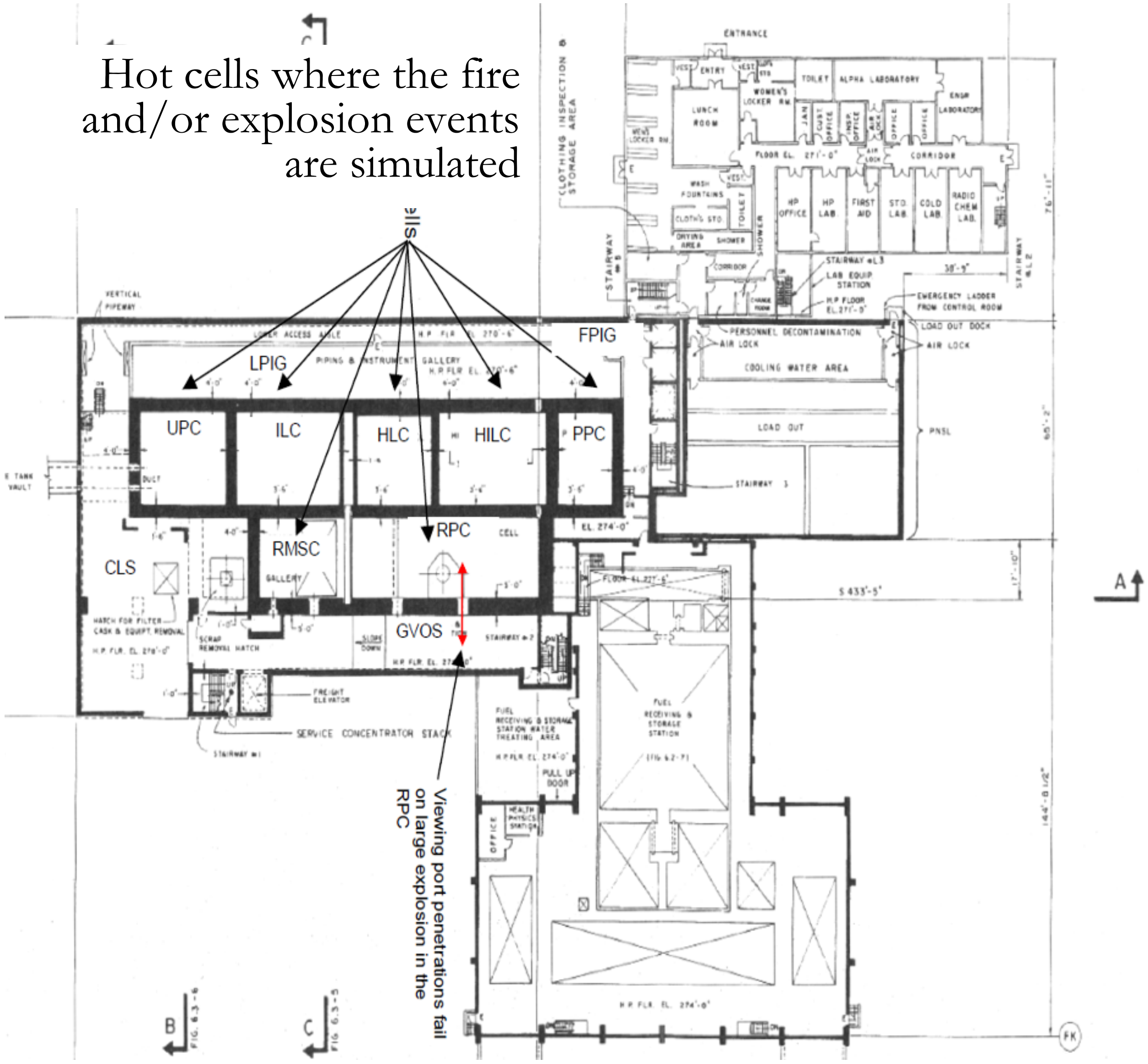
United States Nuclear Regulatory Commission
*Protecting People and the Environment*

NUREG/CR-7232

**Review of Spent Fuel Reprocessing and Associated Accident Phenomena**

Office of Nuclear Regulatory Research

# Barnwell Facility




## MELCOR Facility Model

Detailed control volume model of facility

- Incorporates major rooms along with supply/exhaust for ventilation and filtration system

Model comprises

- 208 control volumes
- 354 flow paths
- 294 heat structures

Processing cells nodalized to represent

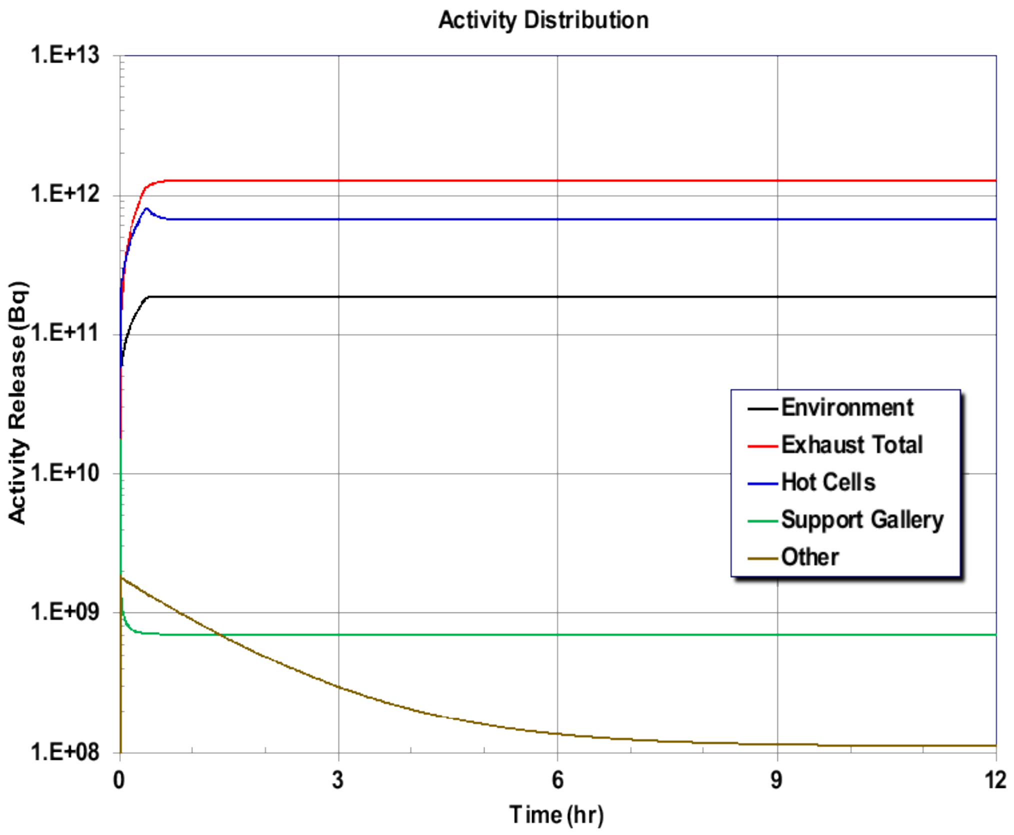
- Natural circulation flow patterns
- Formation of hot gas layer
- Propagation of pressure pulse from explosion

Ventilation and filtration system

- Prior to accident balances nominal room pressures
- Determines radioactive distribution from accident
- Room pressures ranged from -0.49kPa(g) to +0.12kPa(g)

# Fire and Explosion Scenario – MELCOR Simulation Results

## Fire Scenario Releases

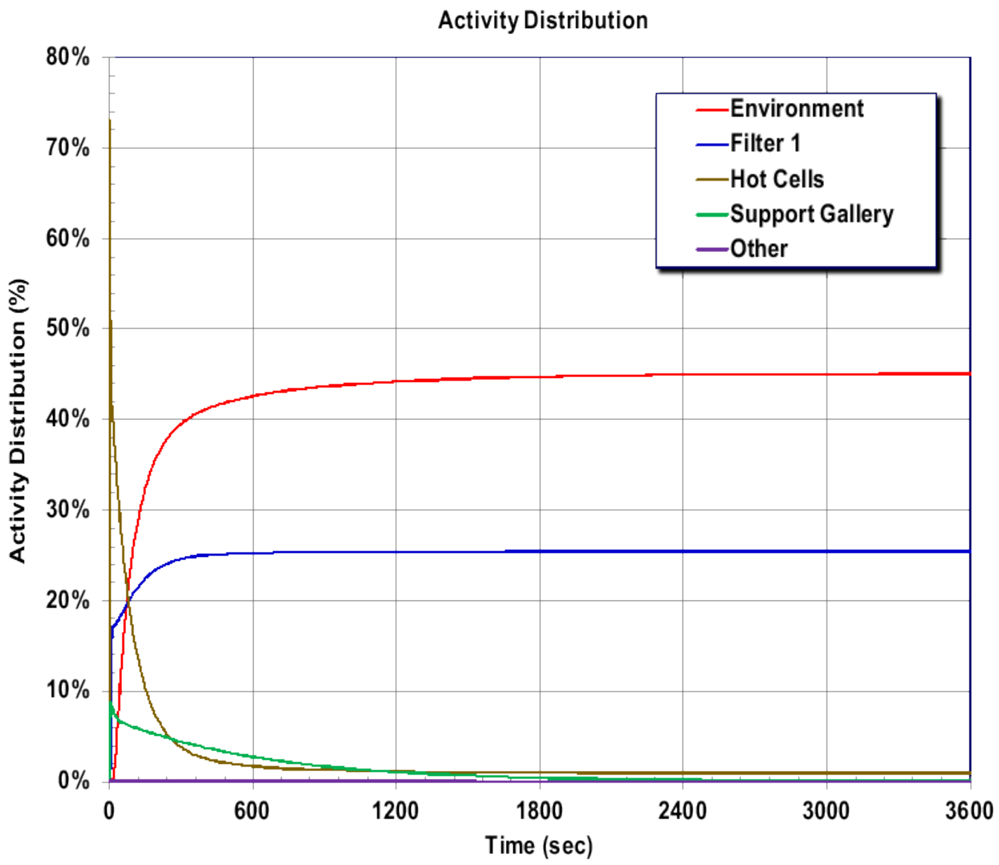



Fans draw releases to filters

Release mitigated by filters

- Released aerosols below capture size of HEPA filters and radionuclide gases

## Red Oil Explosion Releases




Large release to environment due to filter failures between Pu production cells and plant stack

# Next steps in modeling severe accidents in non -LWR fuel cycles

- Complete development of representative fuel cycles for all non-LWR systems and identify hazards that are most relevant and prioritize for analysis
- Set up SCALE models to evaluate the fuel inventory and decay heat as a result of the hazard conditions
  - Reactor physics calculations
- Pass the fuel inventory and decay heat data from SCALE to MELCOR for further analysis of severe accident progression and analyses
  - Determine transport of atmospheric radioactive material releases into the environment
  - Identify consequences associated with environmental releases
- **Example:**
  - SCALE calculation for inventory in spent fuel pebbles (to evaluate potential release considering manufacturing defects in a pebble)
    - Perform criticality calculation under different assumptions of discharge burnup, temperatures, etc
    - Pass inventory and decay heat data to MELCOR
  - MELCOR calculation for associated severe accident progression
    - Determine associated environment release

# Questions?