SAND2019-13346C

Code status and future challenges in severe accident analysis

PRESENTED BY

Larry Humphries

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Requirements of an Integrated Severe Accident Code

Fully Integrated, multi-physics engineering-level code
- Thermal-hydraulic response in the reactor coolant system, reactor cavity, containment, and confinement buildings;
- Core heat-up, degradation, and relocation;
- Core-concrete attack;
- Hydrogen production, transport, and combustion;
- Fission product release and transport behavior

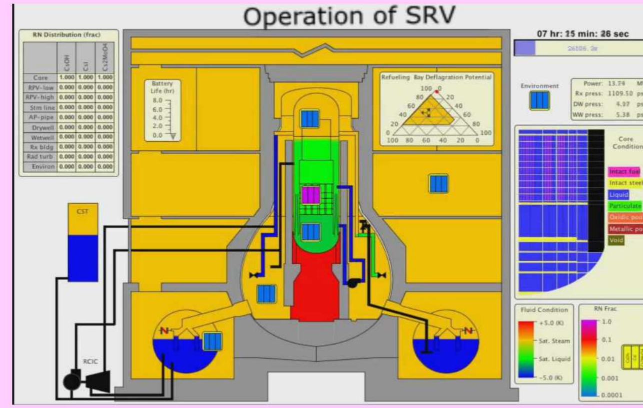
Diverse Application
- Multiple 'CORE' designs
- User constructs models from basic constructs
- Adaptability to new or non-traditional reactor designs
  - ACR700, ATR, VVER, HTGR, …

Validated physical models
- ISPs, benchmarks, experiments, accidents

Uncertainty Analysis & Dynamic PRA
- Relatively fast-running
- Reliable code
- Access to modeling parameters

User Convenience
- Windows/Linux versions
- Utilities for constructing input decks (GUI)
- Capabilities for post-processing, visualization
- Extensive documentation

Multi- Physics

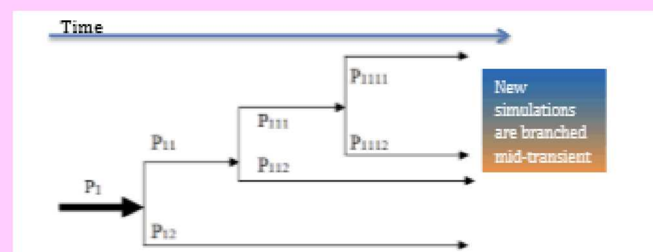


SOARCA LTSBO

Diverse Application

Advanced Test Reactor

Uncertainty & Dynamic PRA



Dynamic Event Tree

Significance of a fully-integrated source term tool

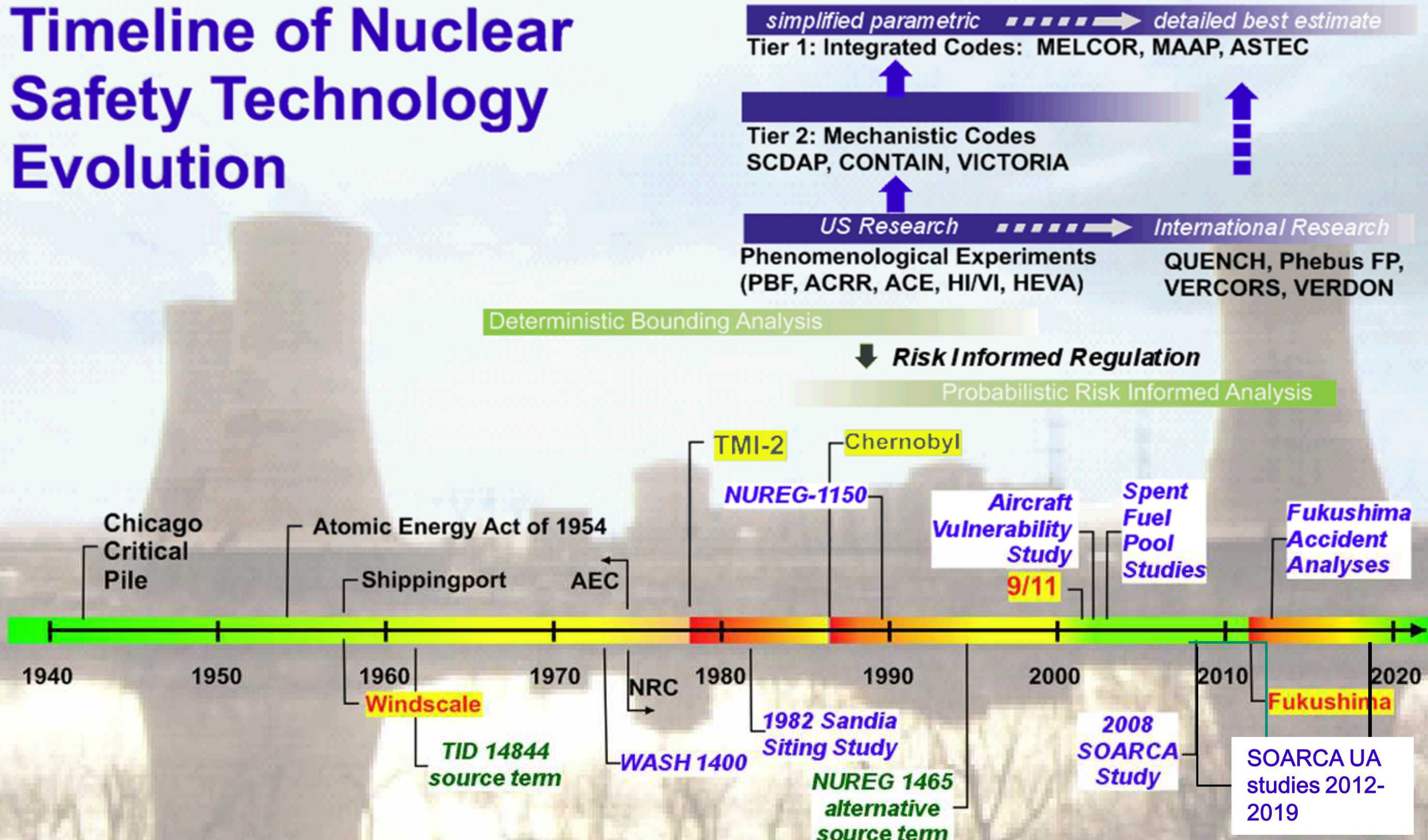
MELCOR is a fully-integrated, system-level computer code

- Prior to the development of MELCOR, separate effects codes within the Source Term Code Package (STCP) were run independently
  - Results were manually transferred between codes leading to a number of challenges
    - transferring data
    - ensuring consistency in data and properties
    - capturing the coupling of physics

Advantages of using a fully-integrated tool for source term analysis

- Integrated accident analysis is necessary to capture the complex coupling between a myriad of interactive phenomenon involving movement of fission products, core materials, and safety systems.
- A calculation performed with a single, integrated code as opposed to a distributed system of codes reduces errors associated with transferring data downstream from one calculational tool to the next.
- Performing an analysis with a single integrated code assures that the results are repeatable.
- Methods for performing uncertainty analysis with an integrated tool such as MELCOR are well established.
- Time step issues are internally resolved within the integral code

Timeline of Nuclear Safety Technology Evolution



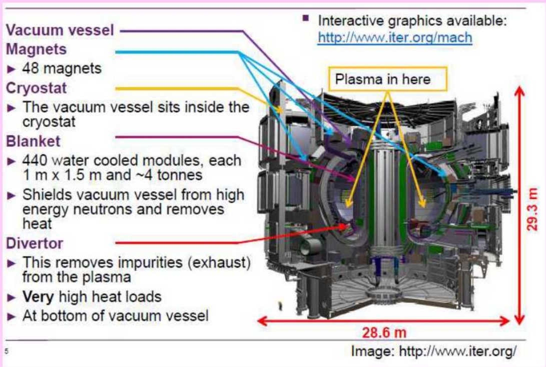
Nuclear Power Outlook

- Optimistic
- Guarded
- Pessimistic

Emerging Issues.....

- *Accident Tolerant Fuels*
- *Advanced non-LWR Reactors*
- *Accident Management*

Application Driven Development
Non-Reactor Applications

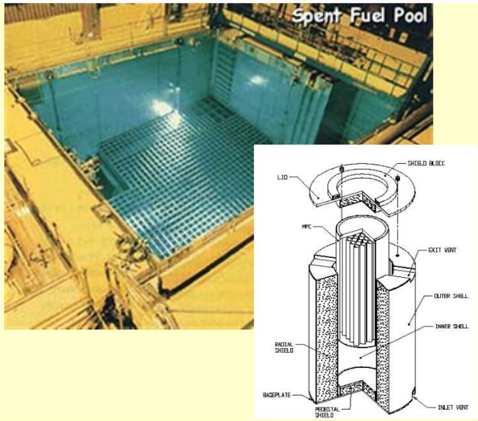


Spent Fuel

Spent fuel pool risk studies

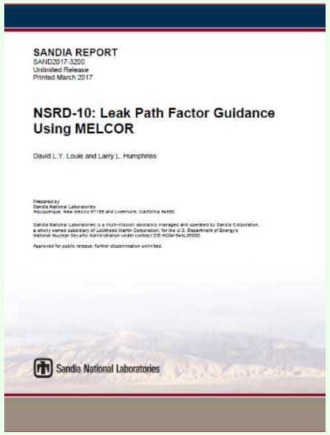
Multi-unit accidents (large area destruction)

Dry Storage



Fusion

- Neutron Beam Injectors (LOVA)
- Li Loop LOFA transient analysis
- ITER Cryostat modeling
- Helium Lithium
- Helium Cooled Pebble Bed Test Blanket (Tritium Breeding)



SANDIA REPORT
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NSRD-10: Leak Path Factor Guidance Using MELCOR

David L.Y. Louie and Larry L. Humphries

Sandia National Laboratories

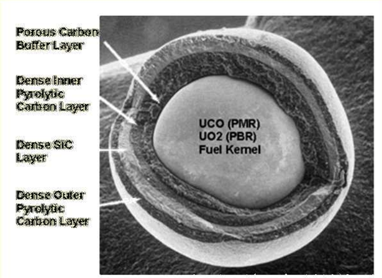
Non-Nuclear Facilities

- Leak Path Factor Calculations (LPF)
  - Release of hazardous materials from facilities, buildings, confined spaces
- DOE Safety Toolbox code
- DOE nuclear facility users
  - Pantex
  - Hanford
  - Los Alamos
  - Savannah River Site

MELCOR 2.2 Emerging Applications

HTGR Reactors

- Helium Properties
- Accelerated steady-state initialization
- Two-sided reflector (RF) component
- Modified Fuel components (PMR/PBR)
- Point kinetics
- Fission product diffusion, transport, and release
- TRISO fuel failure



Sodium Reactors

Sodium Properties

- Sodium Equation of State
- Sodium Thermo-mechanical properties

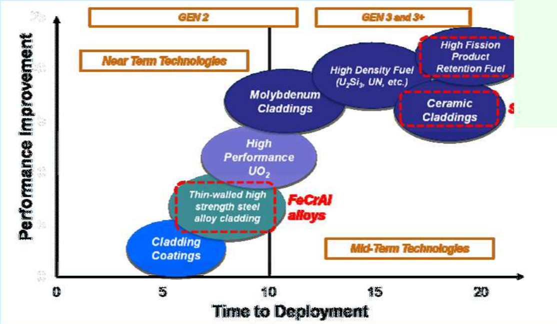
Containment Modeling

- Sodium pool fire model
- Sodium spray fire model
- Atmospheric chemistry model
- Sodium-concrete interaction

Molten Salt Reactors

- Properties for LiF-BeF2 have been added
  - Equation of State
  - Thermal-mechanical properties

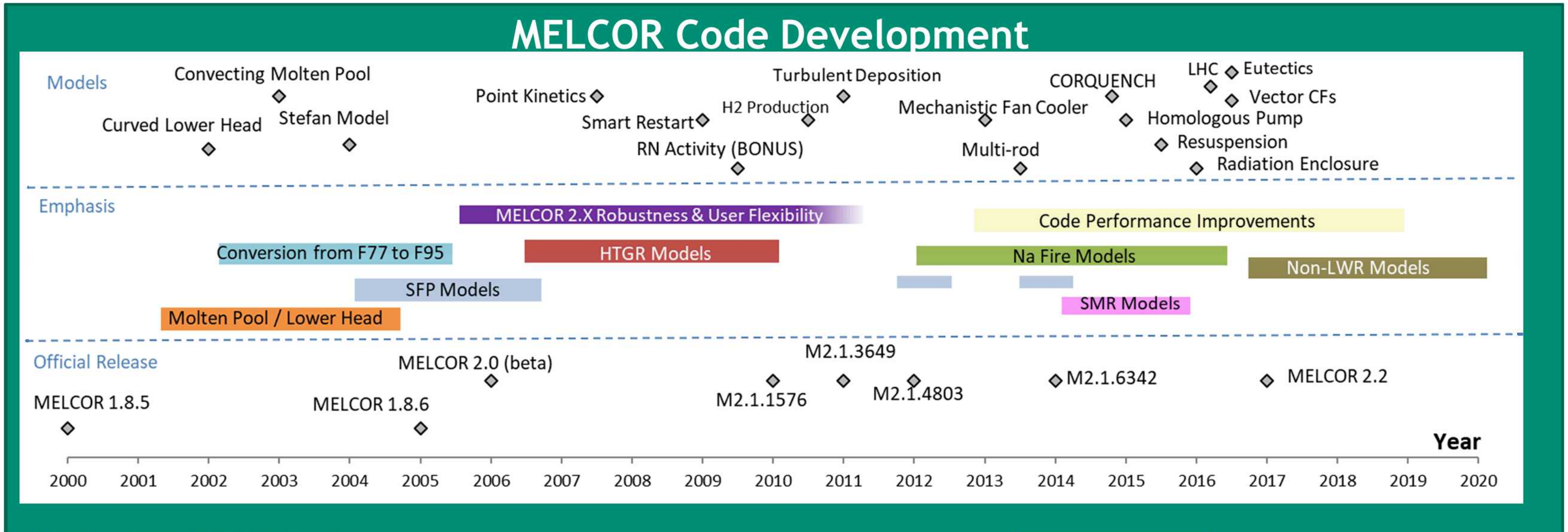
Accident Tolerant Fuels

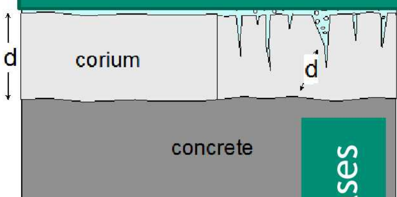


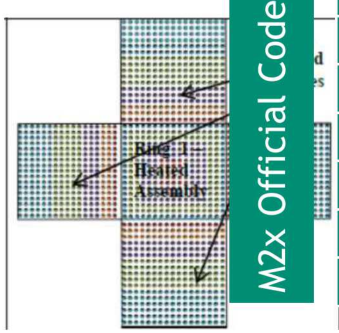
Model for FeCrAl implemented 2019

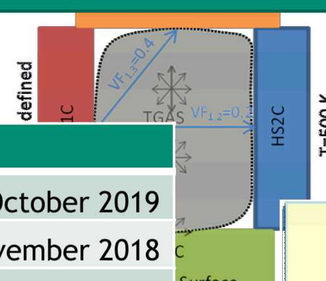
Application Driven Development

MELCOR Model Development



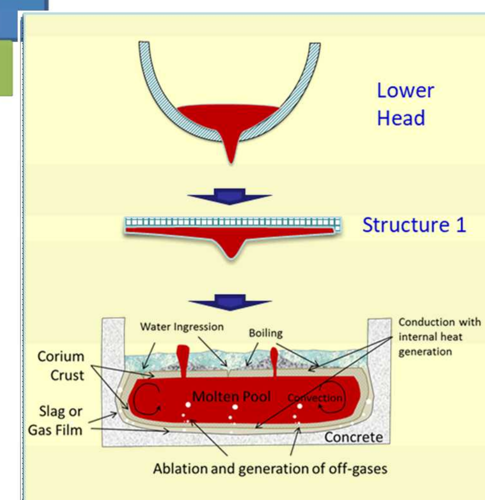






M2x Official Code Releases

Version	Date
2.2.14959	October 2019
2.2.11932	November 2018
2.2.9541	February 2017
2.1.6342	October 2014
2.1.4803	September 2012
2.1.3649	November 2011
2.1.3096	August 2011
2.1.YT	August 2008
2.0 (beta)	Sept 2006



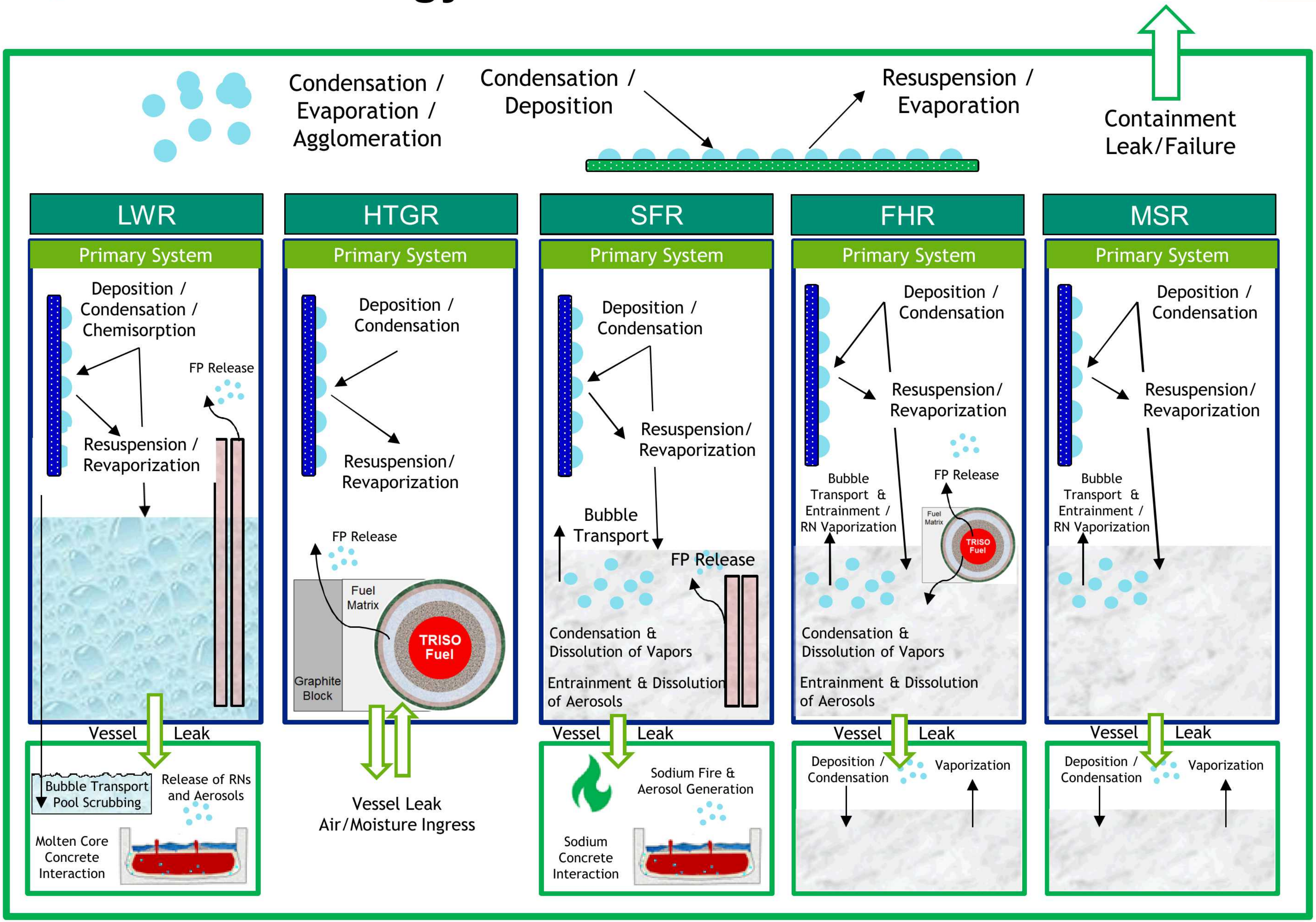
Phenomena Identification and Knowledge Gaps

HTGR
Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs), NUREG/CR-6944 , Volume 3: Fission-Product Transport and Dose PIRTs, 2008
Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs), NUREG/CR-6944, Volume 2: Accident and Thermal Fluids Analysis PIRTs, 2008
Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs), NUREG/CR-6944, Volume 5: Graphite PIRTs, 2008
TRISO-Coated Particle Fuel Phenomena Identification and Ranking Tables (PIRTs) for Fission-Product Transport Due to Manufacturing, Operations, and Accidents, NUREG/CR-6844, 2004

SFR
Advanced Sodium Fast Reactor Accident Source Terms: Research Needs, SAND2010-5506, Sandia National Laboratories, 2010.
Sodium Fast Reactor Gaps Analysis of Computer Codes and Models for Accident Analysis and Reactor Safety, SAND2011-4145, Sandia National Laboratories, 2011
Regulatory Technology Plan: Sodium Fast Reactor: Mechanistic Source Term Development," Argonne National Laboratories, ANL-ART-3, 2015
Regulatory Technology Development Plan: Sodium Fast Reactor : Mechanistic Source Term - Metal Fuel Radionuclide Release, Argonne National Laboratories, ANL-ART-38, 2016

MSR
Planned: Canadian Nuclear Laboratories, Chalk River
1st PIRT Meeting (3 Days): May 7-9, 2019 2nd PIRT Meeting (2 Days): Aug 21-22, 2019

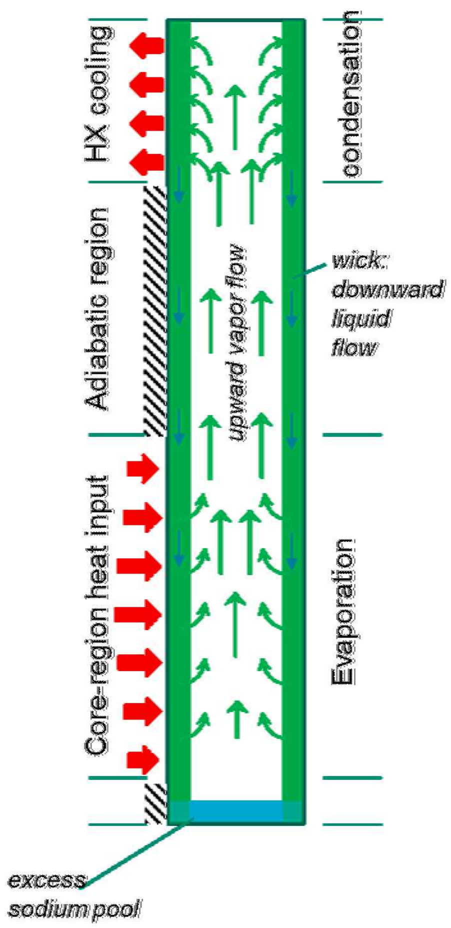
Phenomenology & Release Paths

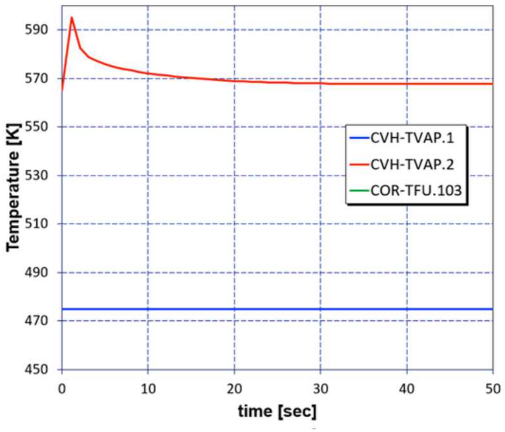


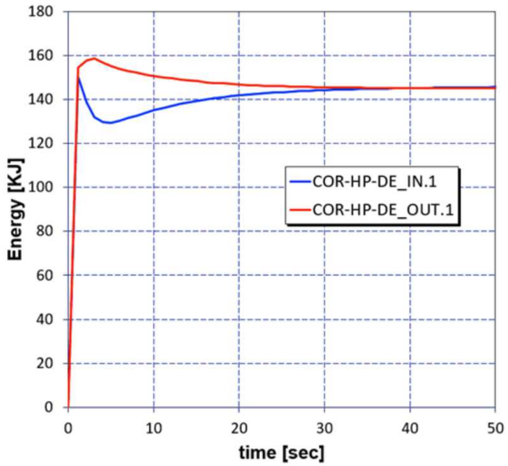
Heat Pipe Model

- MELCOR 2 model for simulation of Heat Pipes (HP) to transfer heat from the fuel to the secondary coolant flow.
- As implemented, the HP model is grouped with the COR package with interfaces to RN and CVH package.
  - COR provides a heat flux boundary condition to the evaporator region.
  - The HP model provides an energy source (from the condenser region) to CVH
  - Models of different fidelity and applicability (steady state, transient, 0D to 3D,. . .) can be written and be available for use. They would all used the same interfaces to COR and CVH.
- Use of multi-rod model to simulate propagation of local failure.

A Generic Heat Pipe Illustration

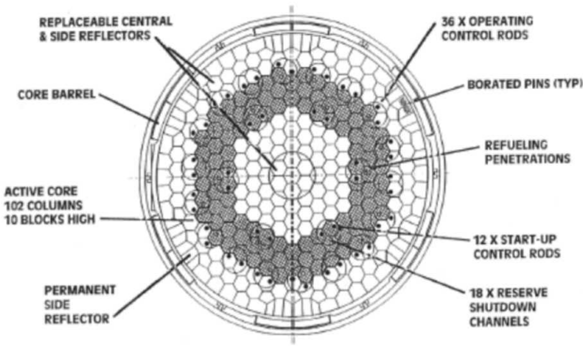




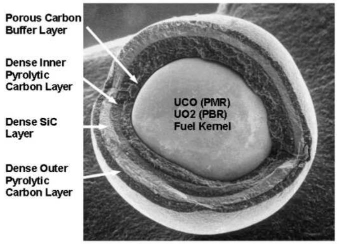


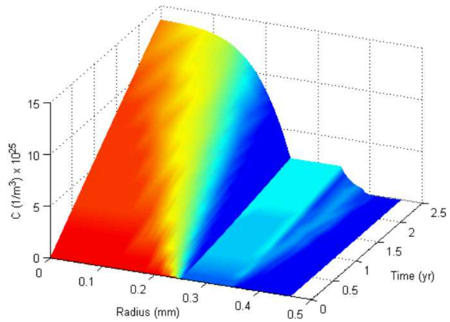
High Temperature Gas Reactor February 2012+

Reactor Components
- PBR Reactor components
- PMR Reactor Components

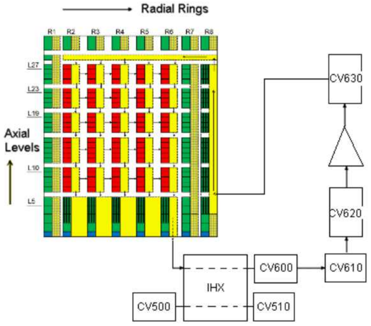


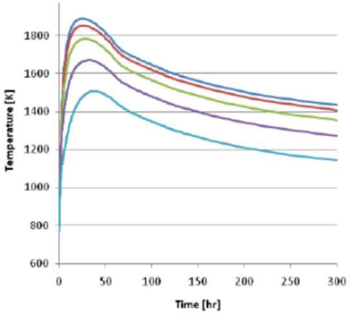
Materials
- TRISO Fuel Modeling
  - Fission product release modeling
- Helium Treatment
- Graphite modeling
  - Oxidation Models





Graphite Dust Modeling
- Aerosol physics models
  - Turbulent Deposition
  - Resuspension





Point Kinetics Model

Steady state initialization and transient solution strategy

MELCOR FP Modeling

Start of timestep

FP Sources: Fuel release (core/cavity, user-defined)

HTGR: Diffusional release as the function of temperature and burnup (includes matrix and graphite block)

Radioisotopes are grouped into classes with each class consisting of one or more chemically-similar elements
LWR: Core fractional release models (e.g., CORSOR-Booth)

Aerosol Dynamics: agglomeration and deposition

Agglomeration (Brownian, turbulent shear/inertial forces and differential gravitational settling , **HTGR: shape factor>1**)
Deposition (gravitational, Brownian, Thermophoresis, Diffusiophoresis)
HTGR: Turbulent deposition, lift-off , dust generation

Mass/composition of aerosols in RCS/containment impacted by agglomeration and deposition processes using MAEROS framework – a multi-sectional, multi-component aerosol dynamics code that evaluates the size distribution of each component as a function of time

Water and FP vapor condensation and evaporation

Condensation/evaporation of FP vapors to/from heat structures, pool surfaces, and aerosols based onTRAP-MELT2 code which is determined by rate equations based on the surface areas, mass transfer coefficients, atmosphere concentration, and the saturation concentrations.

FP and water vapor can condense onto or evaporate from aerosols, heat structure surfaces, and water pools. Water condensation and evaporation for heat structure and water pool surfaces are treated solely in the HS and CVH packages.

Auxiliary Models: Filters, Sprays, Iodine Pool

For HTGR application, no additional modeling is required. The efficiency of filter can be defined by decontamination factors, specified by user input . A maximum loading may be specified for each filter. The effect of filter loading on the flow resistance may be modeled through user input.

Models are currently available for the removal of radionuclides by pool scrubbing (SPARC-90), filter trapping (decontamination factor and maximum filter loading), and spray scrubbing (HECTR).

Aerosol and vapor transport by CVH

For HTGR application, no additional modeling is required. Dust and aerosols that become airborne during accident would leave the RCS and enter containment from break

Aerosols and vapors that are in the control volume atmosphere can be transported between different control volumes through flow paths using Control Volume Hydrodynamics (CVH) package

End of timestep

Sodium Coolant in MELCOR 2.2

Sodium Working fluid
- Implement Sodium Equations of State (EOS)
- Implement Sodium thermal-mechanical properties

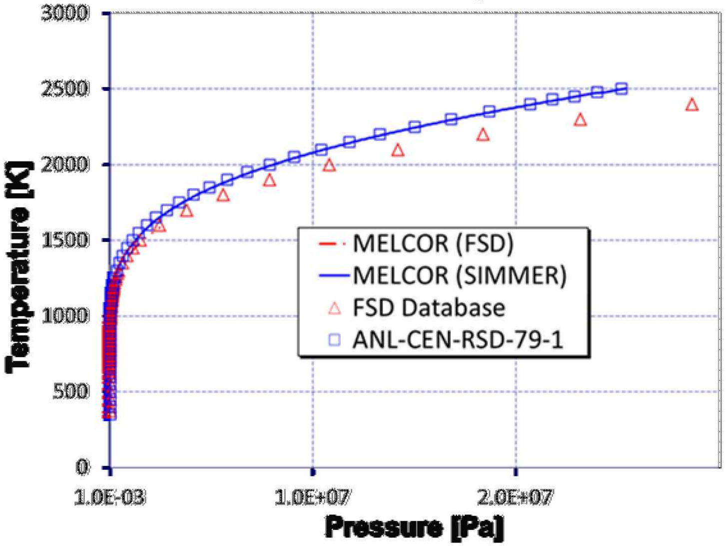
Two models implemented
- Fusion safety database (FSD) based on soft sphere EOS
  - Na (tpfna), FLiBe (tpffi), Pb-Li (tpflipb), He (tpfhe), N2(tpfn2)
- SIMMER database

Sodium properties for FSD are mainly read from an input file, so it is easy to adapt for other liquid metal fluids

Test problems have been created demonstrating model capability

Some improvement for FSD database were made last FY

Saturation Temperature



Spray Fire Chemistry

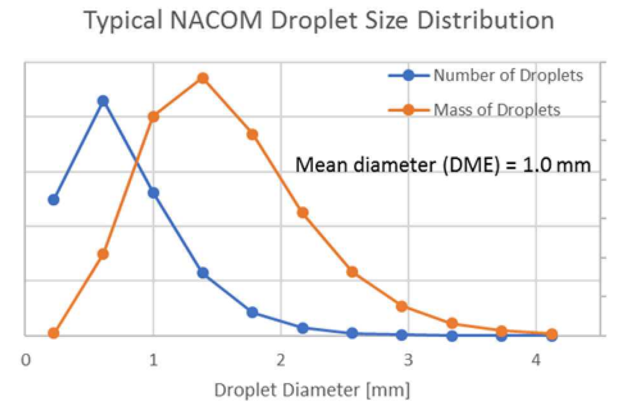
Based on NACOM spray model from BNL
- Input requirement: fall height, mean diameter and source
- Internal droplet size distribution (11 bins) from Nukiyama-Tanasama correlation
- Reactions considered:
  - (S1) $2\,Na + {}^{1}/_{2}\,O_2 \rightarrow Na_2O$,
  - (S2) $2\,Na + O_2 \rightarrow Na_2O_2$
- Fixed ratio of peroxide and monoxide

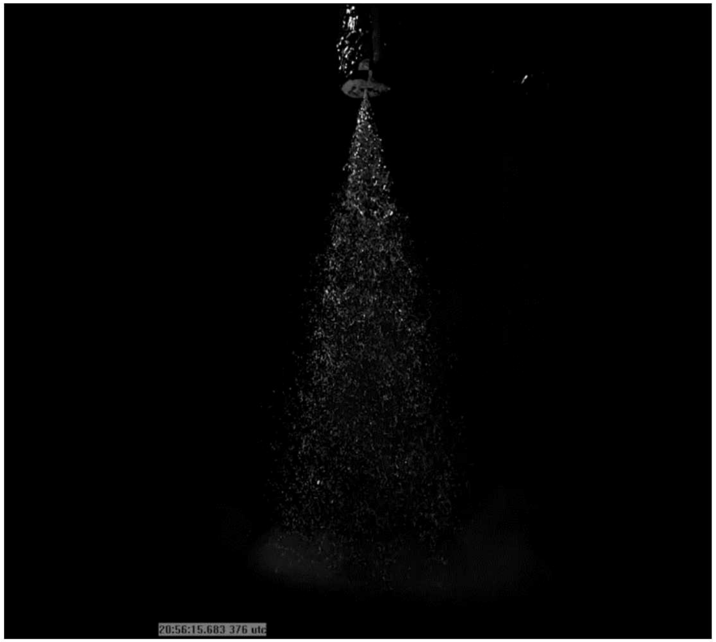
$$\frac{1.3478 \cdot F_{Na_2O_2}}{1.6957 - 0.3479 \cdot F_{Na_2O_2}}$$

- Predicted quantities include:
  - Mass of Na (spray, burned, pool), O_2(consumed), Na_2O_2+ Na_2O(produced)
  - Energy of reactions

Enhancements
- Droplet acceleration model
- Pre-ignition burn rate
- Adjustment to heat of combustion to include heat of vaporization
  - Na_2O from 9.18 to 13.71 MJ/kg of sodium
  - Na_2O_2 from 10.46 to 15.88 MJ/kg of sodium

Missing from model
- Maximum droplet size
- Radiant heat loss from droplets
- Swarm effects





Pool Fire Model

Based on SOFIRE II code from ANL

- Reactions considered:
  - $2\,Na + O_2 \rightarrow Na_2O_2$, 10.97 MJ/kg
  - $4\,Na + O_2 \rightarrow 2\,Na_2O$, 9.05 MJ/kg
  - Half of the heat produced by these reactions is assigned to the sodium pool, while the other half is assigned to atmospheric gases above the pool.
- Reactions depend on the oxygen diffusion as:

$$D = \frac{6.4315\times10^{-5}}{P}T^{1.823}$$

- Input requirement:
  - F1 – fraction of O_2 consumed for monoxide, F2 – fraction of reaction heat to pool, F3 – fraction of peroxide mass to pool, & F4 – fraction of monoxide mass to pool

Predicted quantities:

- Mass of Na(pool, burned), O_2(consumed), Na_2O_2+Na_2O(produced)
- Energy of reactions

Model Extensions

- Radiation Heat Transfer Between Heat Structures and Pool Surface
- Heat Transfer Between Pool and Atmosphere

  - CONTAIN/LMR uses film temperature for evaluating many thermodynamic properties.
- User controllable pool surface area
  - User-specified surface area (control function)

Atmospheric Chemistry
New in 2019 Code Release

A number of reactions have been considered:

- $Na(l) + H_2O\ (l) \rightarrow NaOH(a) + \frac{1}{2}H_2$
- $2\ Na(g, l) + H_2O\ (g, l) \rightarrow Na_2O(a) + H_2$
- $2\ Na(g, l, a) + \frac{1}{2}O_2$ or $O_2 \rightarrow Na_2O(a)$ or $Na_2O_2(a)$
- $Na_2O_2(a) + 2\ Na(g, l) \rightarrow 2\ Na_2O(a)$
- $Na_2O(a) + H_2O\ (g, l) \rightarrow 2NaOH(a)$
- $Na_2O_2(a) + H_2O\ (g, l) \rightarrow 2NaOH(a) + 0.5O_2$

Kinetics of atmosphere gases are not explicitly modeled.

All these reactions are assumed to occur in hierarchal order:

- In the order listed above
- By location of reactions
  - Atmosphere(g), aerosol, surfaces (i.e., HS)

Outputs

- Reaction number, reaction energy, byproducts (Na classes, H_2), gas and liquid consumed (Na, H_2O, O_2)

Sodium Fast Reactor Road Map

Phase I – Completed

- Extend EOS modeling to allow multiple working fluids
- Addition of new COR components
- Addition of heat pipe model to MELCOR
- Complete Sodium chemistry modeling

Phase II – Ongoing

- Fuel degradation modeling
- FP speciation, chemistry, and transport
- FP release modeling
- Hot gas layer modeling
- Critical assessments

MELCOR MSR and FHR Modeling Capabilities

Two reactor types envisioned

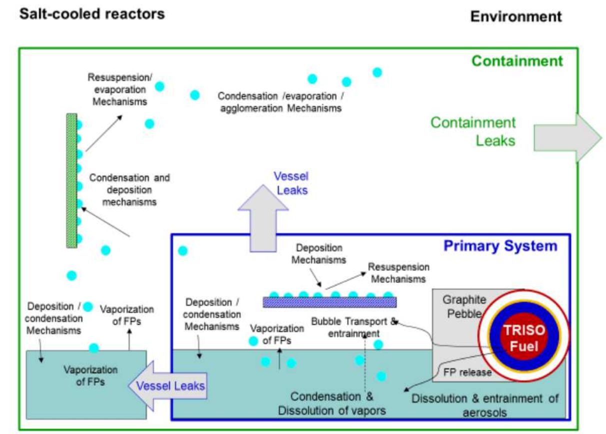
- Fixed fuel geometry
  - TRISO fuel models
    - Models already exist (developed for HTGR application) and have been tested with molten salt coolant
- Liquid fuel geometry
  - MELCOR CVH/RN package can model flow of coolant and advection of internal heat source with minimal changes.
    - Current capability
  - COR package representation no longer applicable but structures can be represented by HS package

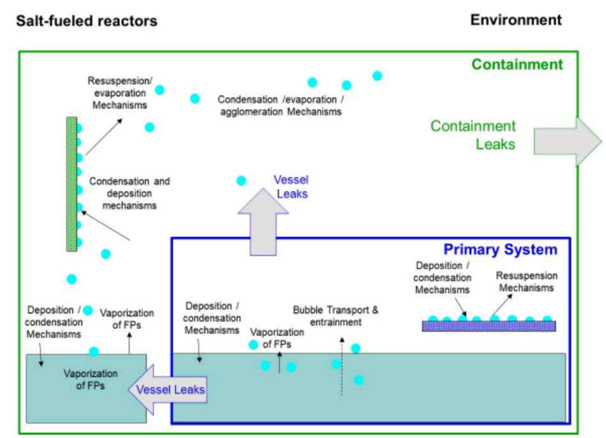
Expansion of capabilities under development

- Nuclide production/destruction (or transmutation/decay) model
  - More detailed inventory tracking and decay heat models
- Circulating fuel point kinetics
  - Treatment of delayed neutron precursor drift and effects of flowing fuel

New capabilities under development

- Different varieties of molten salt, their EOS models, effects of fission product build-up, reprocessing on EOS/properties
- Salt chemistry and chemical processing
  - Speciation as fission products build in, transmute, and decay away
  - Fission product vaporization and release
  - Salt and fission product interaction with structures
  - Chemical processing

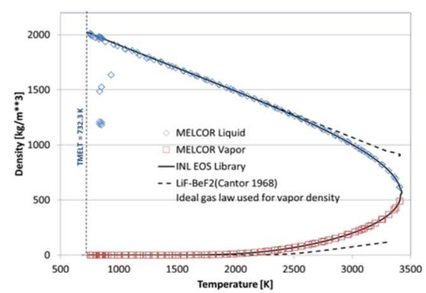


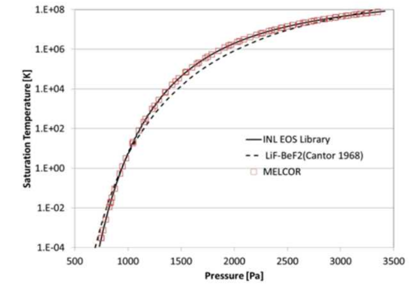


Molten Salt Reactors

Properties for LiF-BeF2 have been added

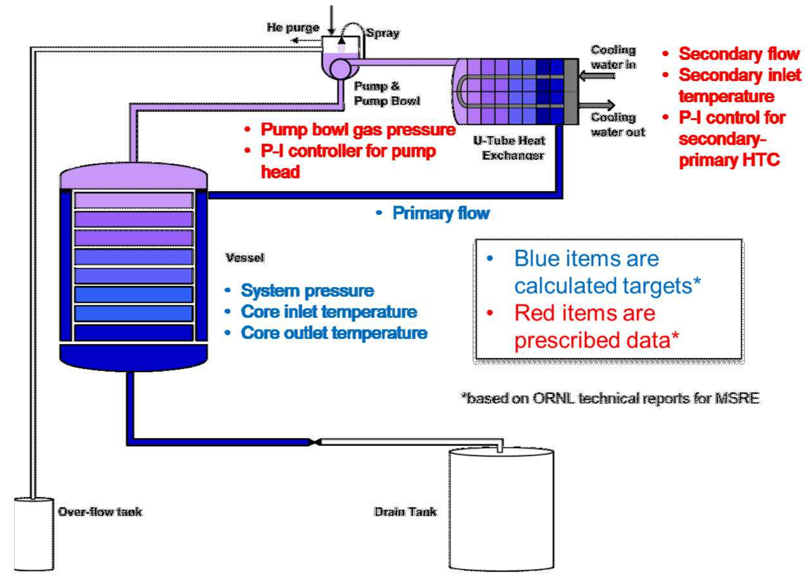
- Equation of State
  - Current capability, verification
- Thermal-mechanical properties
  - Current capability
- EOS for other molten salt fluids would need to be developed
  - Minor modeling gap

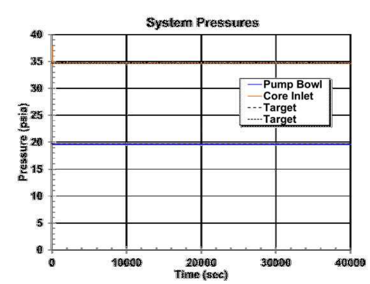


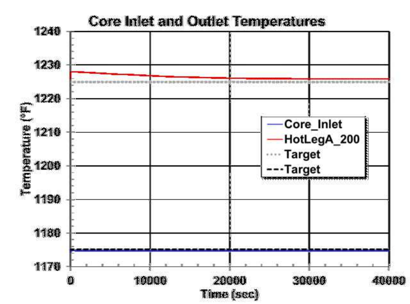


MSRE MELCOR V2.2 Model New Benchmark 2019

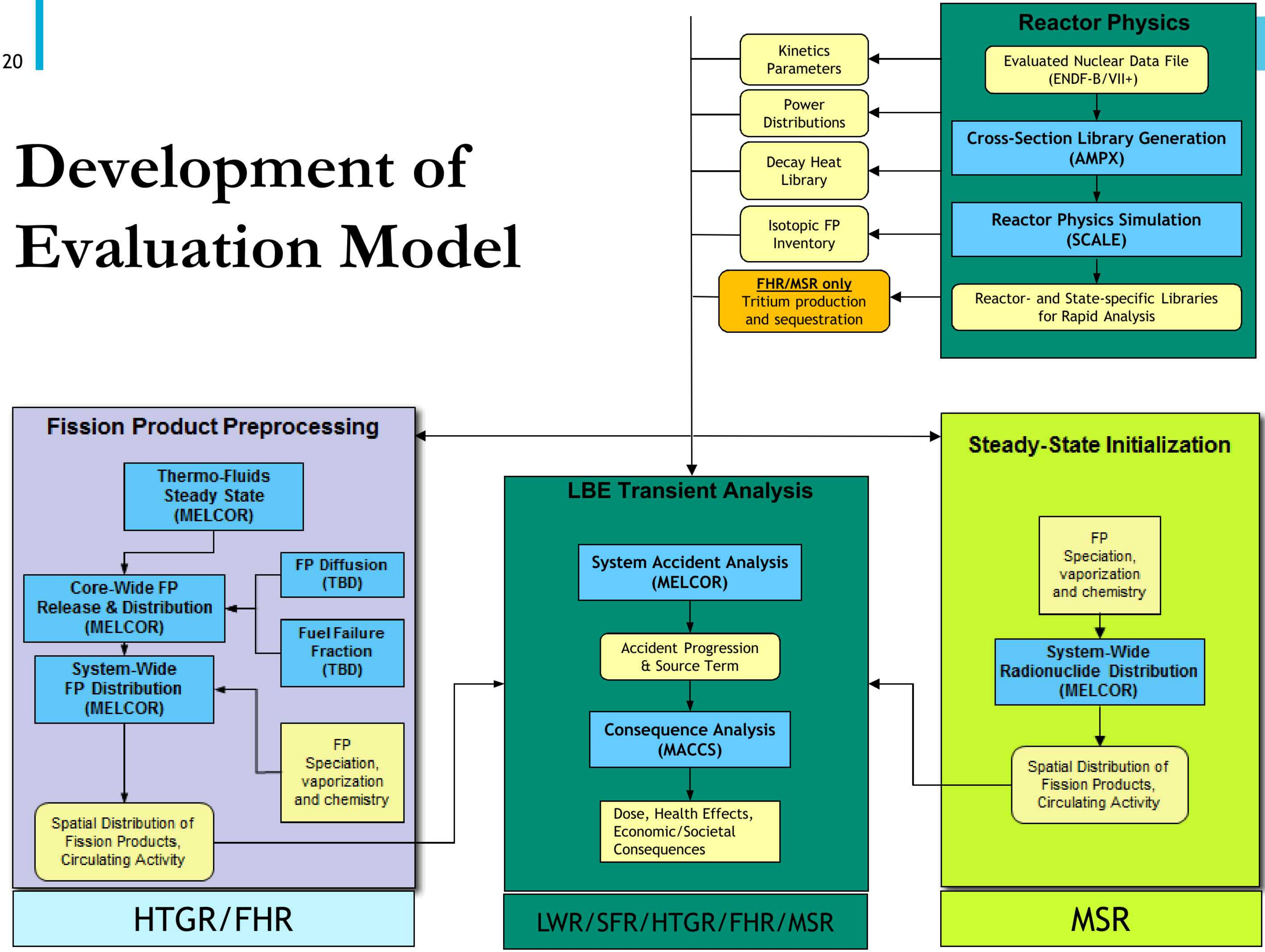
- **One-dimensional core**
  - 8 control volumes (2-dimensional enhancement straight-forward)
  - Graphite blocks
  - Connected diversion & drain tank
  - Core-bypass leakage flow
- **Primary system recirculation loop**
- **Fuel pump and pump bowl** (aka pressurizer)
- **Mechanistic horizontal U-tube heat exchanger**



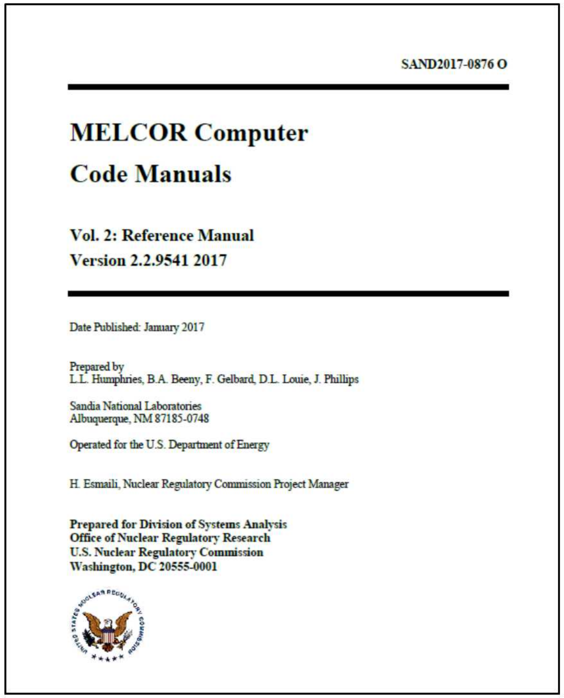




Development of Evaluation Model



Verification & Validation of Models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MELCOR Computer

Code Manuals

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Prepared by
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U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Volume II: Reference Manual

R&A Complete
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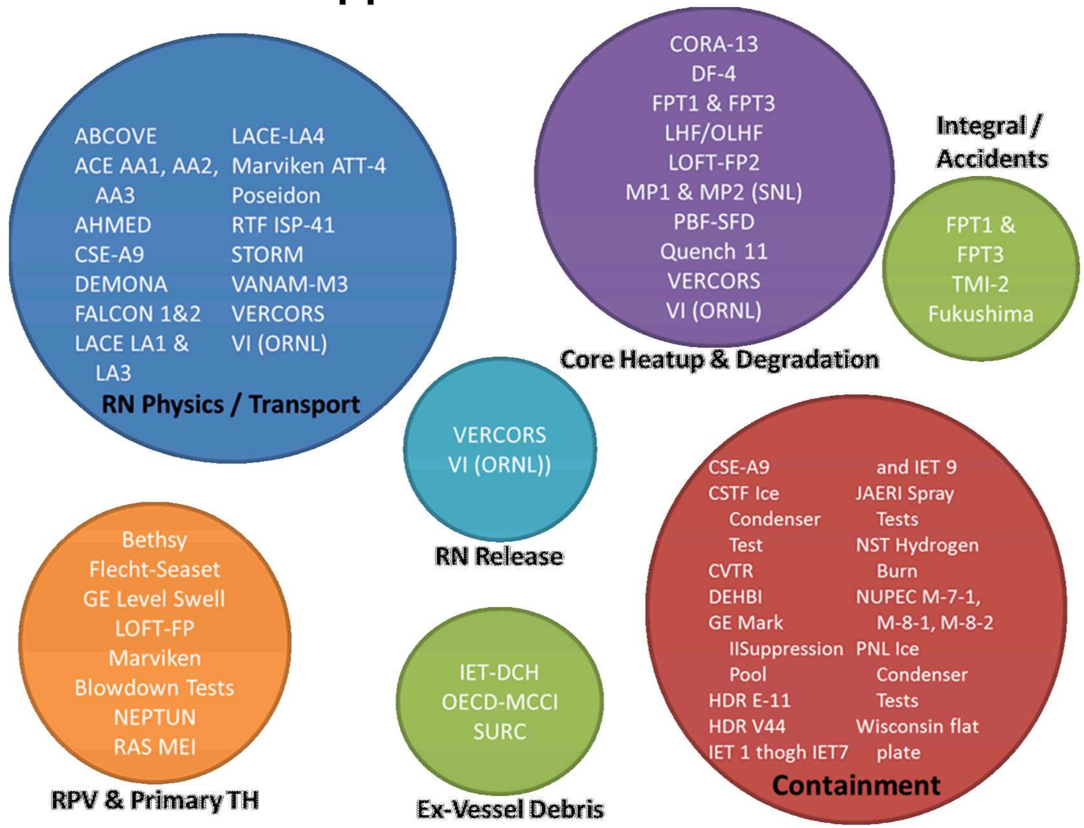
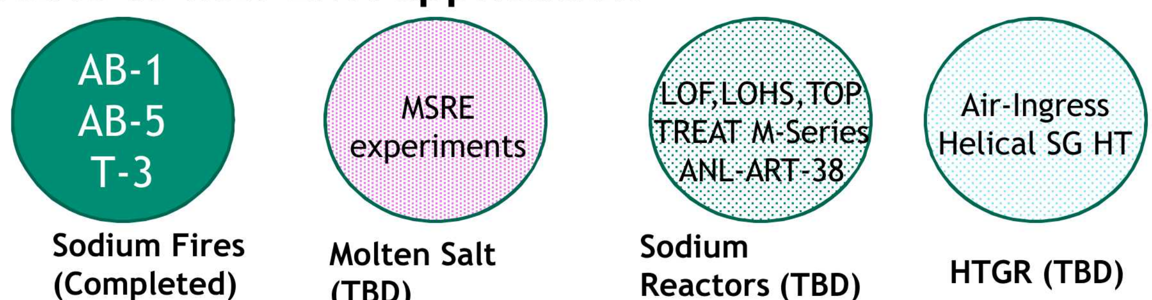
LWR & non-LWR applications



Specific to non-LWR application



Summary

HTGR Models

- Current application of HTGR models
  - ALLEGRO (see papers by Vacha & Gabor from 2018 European MELCOR User Group)
  - HTR-PM (see paper by Kalilainen from 2018 European MELCOR User Group)

Sodium Reactors

- Sodium pool fire and spray fire models implemented into MELCOR and validated against experiment.
- Roadmap for future development of sodium reactor models.

Molten Salt Reactors

- Equation of state for molten salt reactors
- Roadmap for future code development.