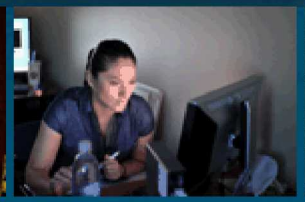
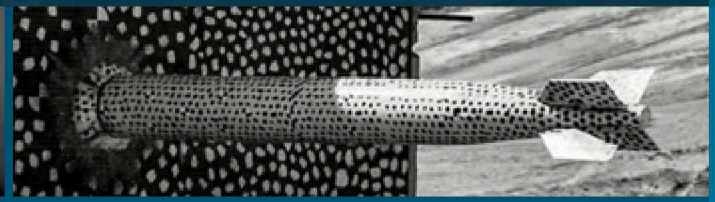
SAND2019-11734PE

MELCOR Modeling Capabilities for Molten Salt Reactors





Molten Salt Reactor Workshop 2019

October, 2019, Oak Ridge National Laboratory

PRESENTED BY

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DEVELOPED BY

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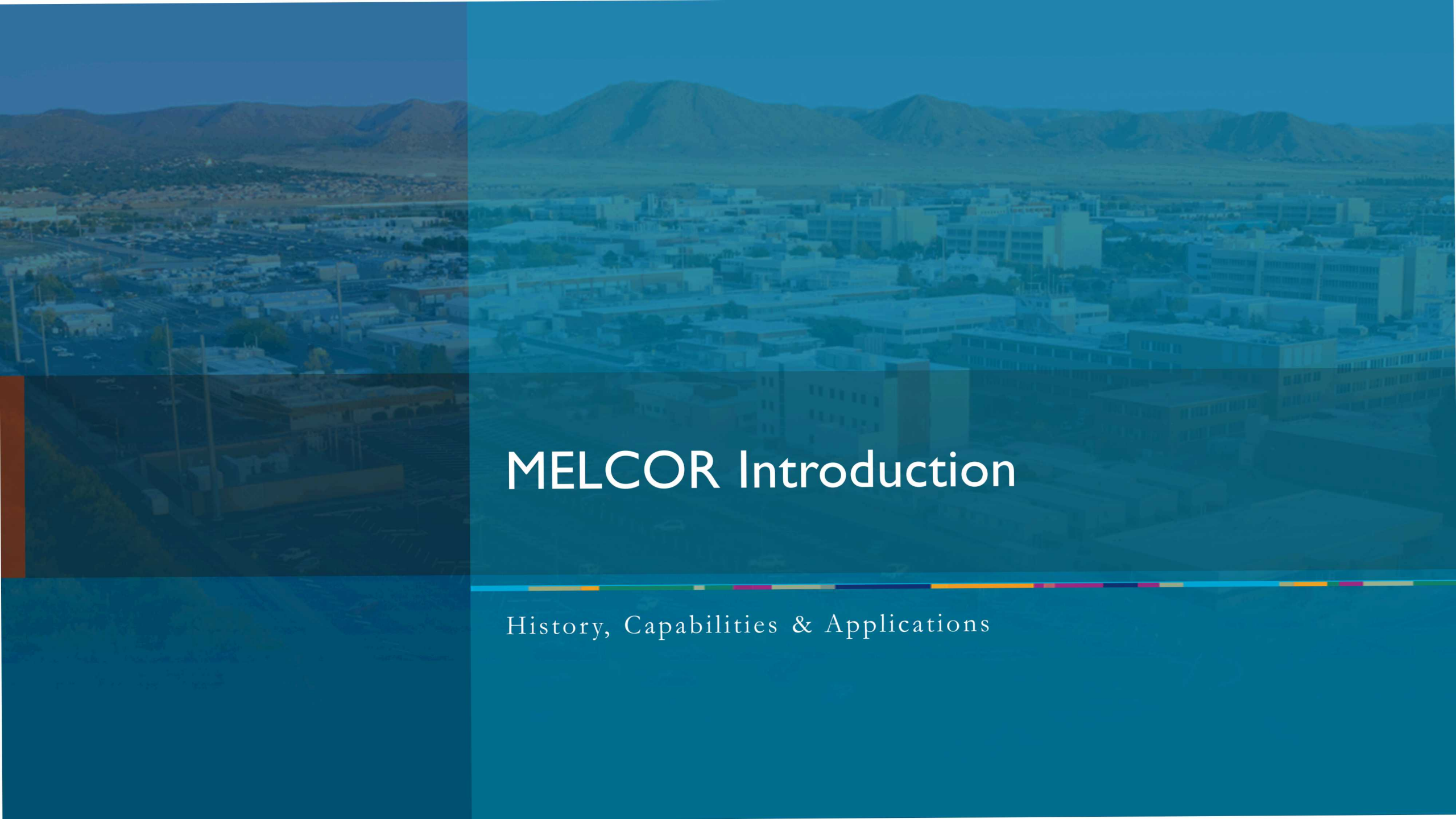
Overview

- MELCOR introduction
  - Historical context
  - Broad capabilities and characteristics
  - Non-LWR/MSR capabilities
  - Validation base
  - Applications and uses

- Overview of MELCOR code development activities for MSR modeling
  - Laboratory Directed Research & Development project and new/expanded physics models
  - Preliminary in-house salt-fueled and salt-cooled MSR modeling

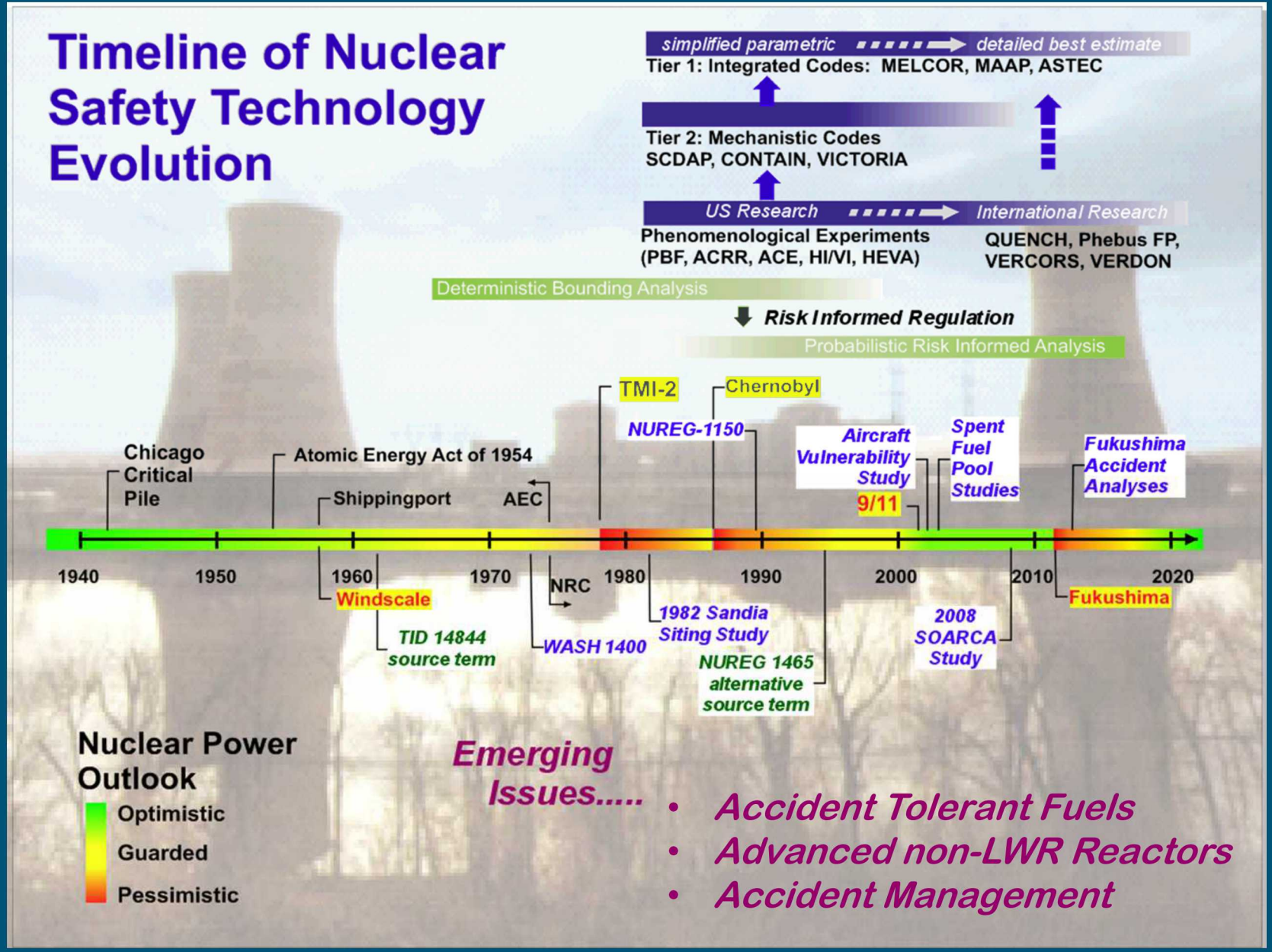
- Outline of current MELCOR/SNL engagements pursuant to MSRs
  - ONRL SCALE/MELCOR
  - Industry
  - Nuclear Regulatory Commission



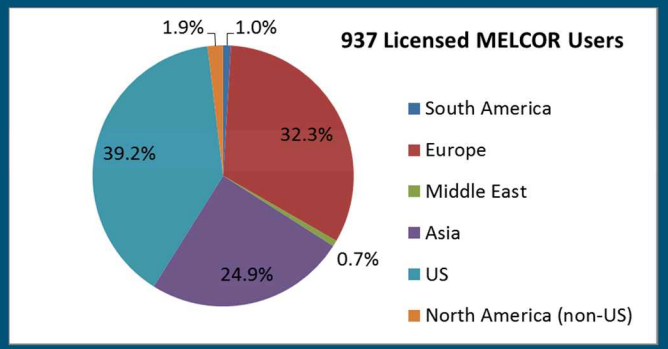
MELCOR Introduction

History, Capabilities & Applications

MELCOR Introduction - Historical Context

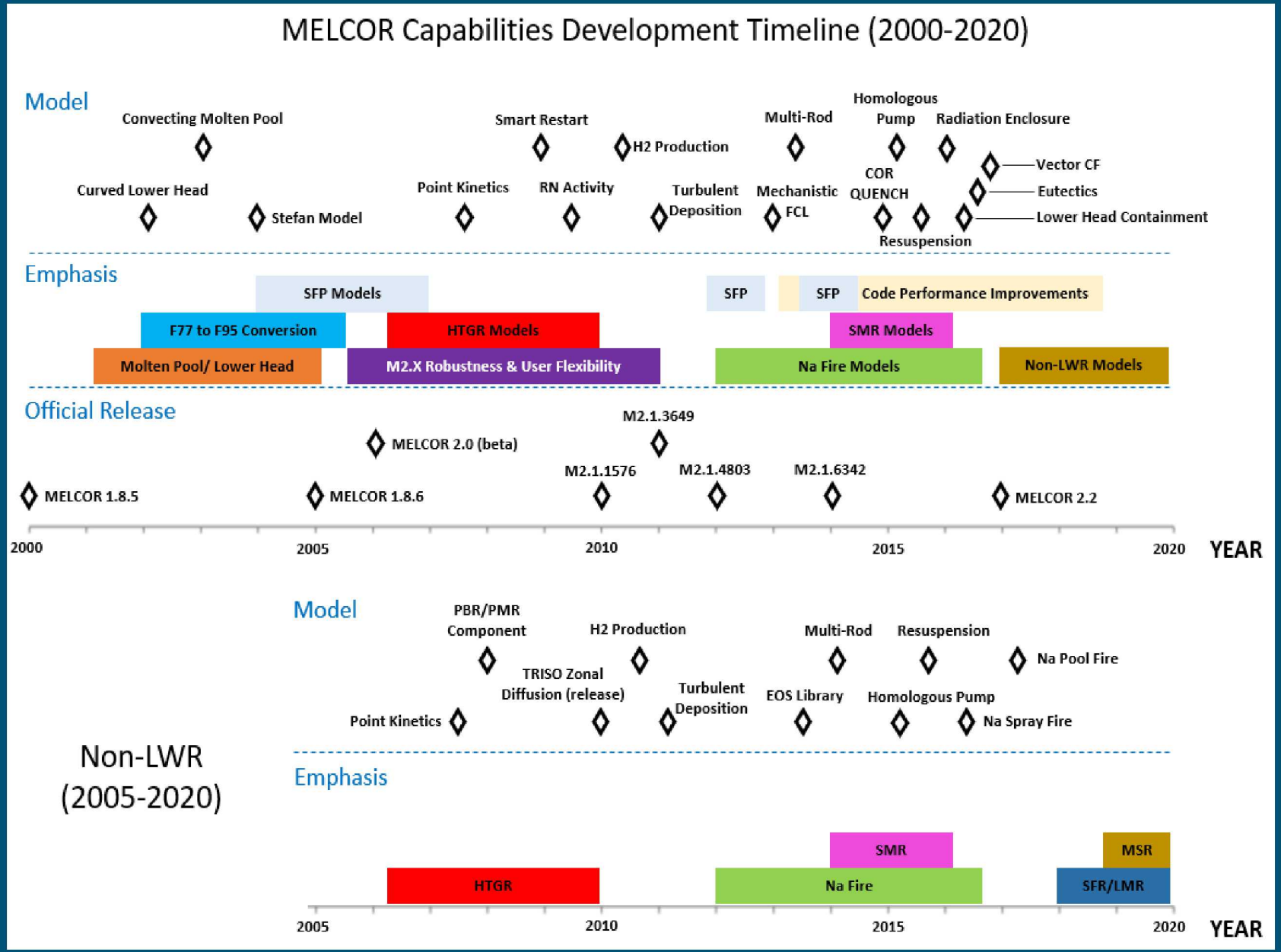


- Began in 1982 shortly after TMI-2
- Replaced Source Term Code Package
- Systems-level approach to modeling
- Emphasis on "best-estimate"
- Repository of knowledge
- Global standard (used by 31+ nations)
  - Users' groups (AMUG & EMUG)
  - Annual CSARP/MCAP meetings



- Used by USNRC, USDOE & US industry
- Used for naval reactors (US/UK)
- Evolves to meet regulatory needs

MELCOR Introduction – Broad Capabilities and Characteristics



- Severe accident analysis code
- Integrated, multi-physics, engineering-level
  - Thermal-hydraulic response
  - Core heat-up, degradation, and relocation
  - Core-concrete interactions
  - Hydrogen production, transport, combustion
  - Fission product release and transport
  - Validated physics models
    - International Standard Problems
    - Benchmarks and experiments
    - Accidents
  - Facilitates UA & dynamic PRA
    - Fast-running
    - Reliable and robust
    - User access to modeling parameters
  - User convenience
    - Windows & Linux versions
    - Utilities for input generation, post-processing
    - Extensive documentation
- Development for non-LWRs since 2005

MELCOR Introduction – Non-LWR/MSR Capabilities

HTGRs

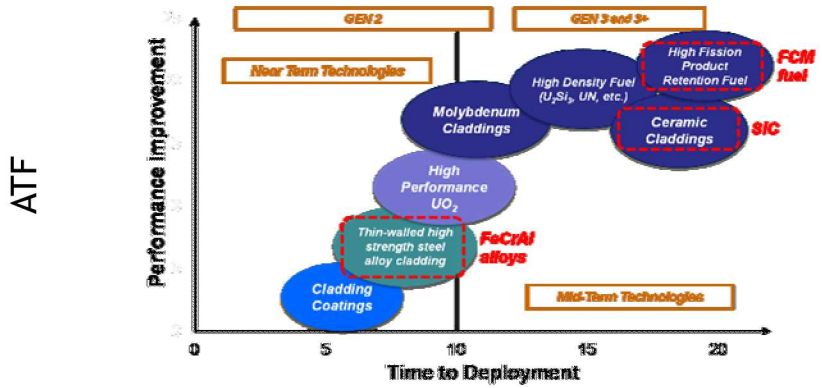
- Helium Properties
- Accelerated steady-state initialization
- Two-sided reflector (RF) component
- Modified Fuel components (PMR/PBR)
- Point kinetics
- Fission product diffusion, transport, and release
- TRISO fuel failure

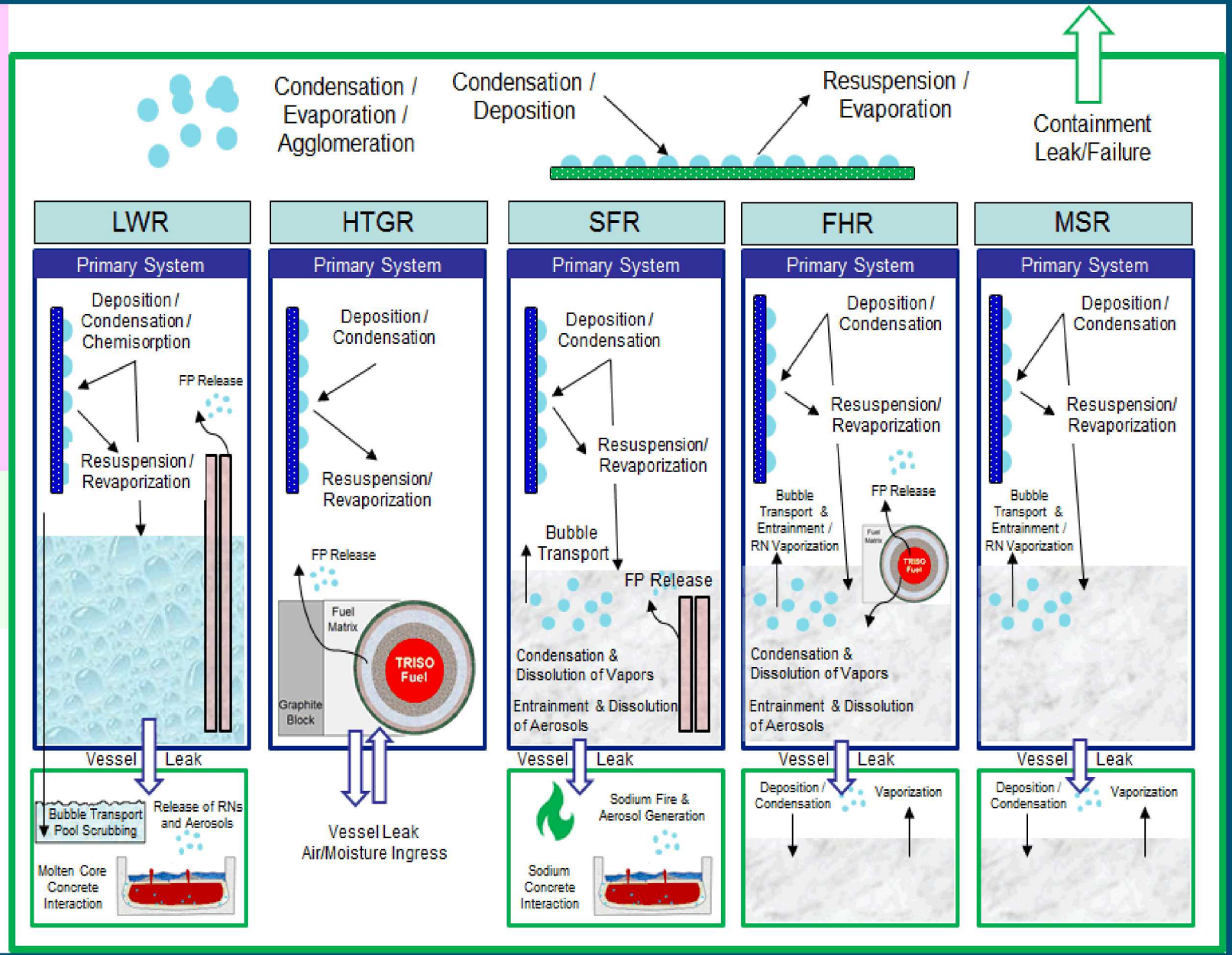
SFRs

- Sodium Properties
  - Sodium Equation of State
  - Sodium Thermo-mechanical properties
- Containment Modeling
  - Sodium pool fire model
  - Sodium spray fire model
  - Atmospheric chemistry
  - Sodium-concrete interaction

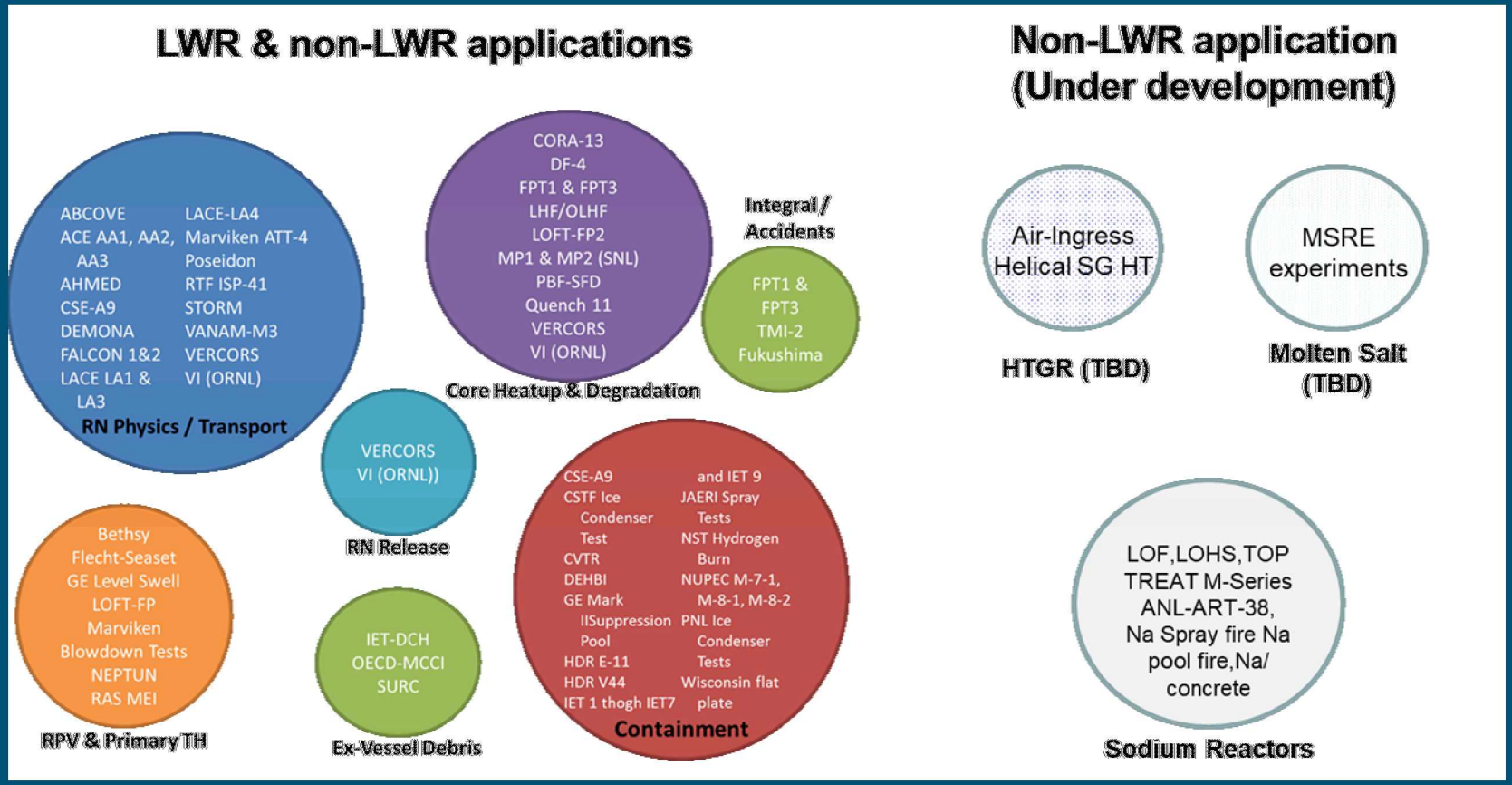
MSRs

- Properties for LiF-BeF2 (FLiBe)
  - Equation of State
  - Thermal-mechanical properties





MELCOR Introduction – Validation Base



- Current validation base consists of:
  - Separate effects tests
  - Integral tests
  - ISP's
  - Actual accidents
- Further validation required for certain aspects of non-LWR physics
- LWR validation overlaps non-LWR space:
  - Heat transfer
  - Energy/mass conservation
  - Fluid flow
  - Aerosol transport

MELCOR Introduction – Applications & Uses

- Nuclear reactor system applications:
  - LWR transient/accident analyses
  - LWR sustainability (accidents, ATF)
  - Accident forensics (Fukushima, TMI)
  - Probabilistic risk assessment
  - Experimental, naval, SMR, advanced
- Regulatory:
  - License amendments
  - Risk-informed regulation
  - Design certification
  - Vulnerability studies
- Commercial:
  - Analysis and design scoping calculations
  - Training simulators
- Non-reactor applications:
  - Fusion
    - Neutron beam injectors
    - Li loop LOFA transient analysis
    - ITER cryostat modeling
    - He-cooled pebble test blanket (H^3)
- Spent Fuel:
  - Risk studies
  - Multi-unit accidents
  - Dry storage
- Non-nuclear Facilities:
  - Leak path factor calculations
  - DOE safety toolbox code
  - DOE nuclear facilities (Pantex, Hanford, Los Alamos, Savannah River Site)

MELCOR Introduction – Applications & Uses

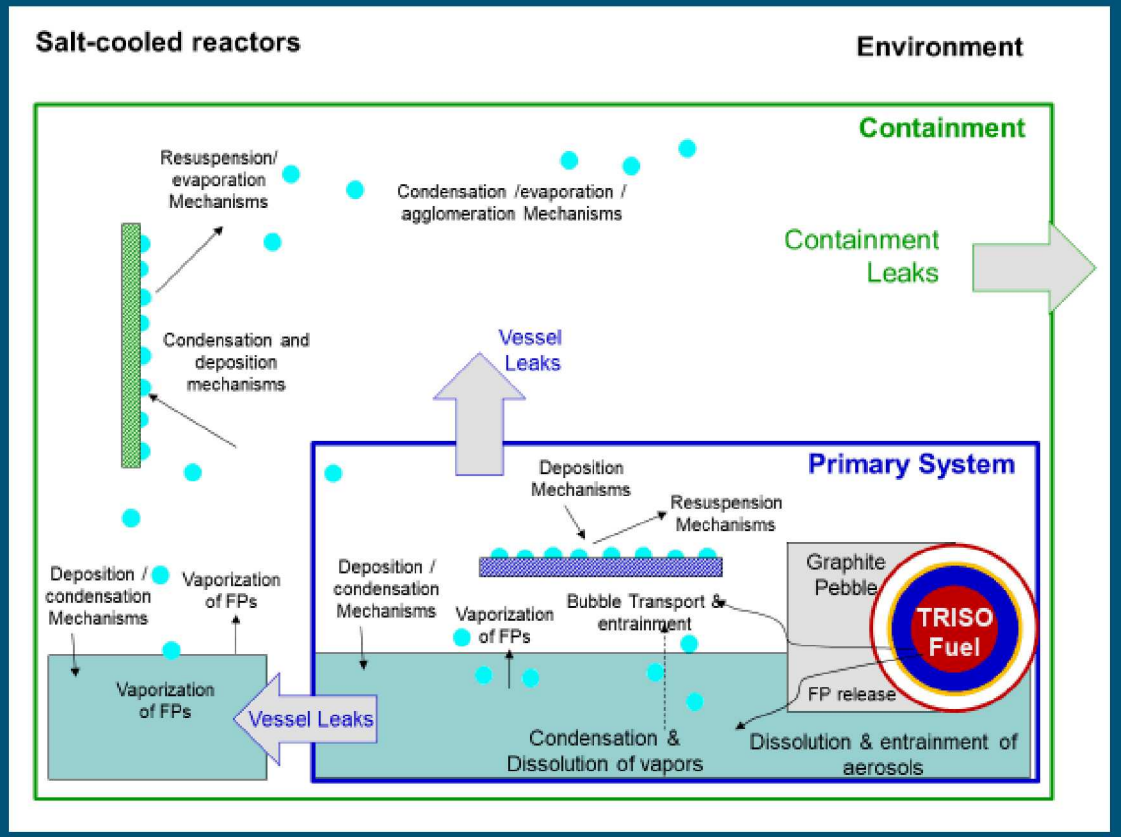
- For non-LWRs and MSRs, envision MELCOR could be of use to industry, reactor designers, and regulators:
  - An analysis tool for:
    - Operational conditions and broad classes of transients/accidents related to reactivity, power, and flow
    - The whole reactor system (to include containment/confinement)
    - Generation of mechanistic source terms (various types of regulatory source terms) for consequence analysis
    - Designer scoping calculations (similar to NuScale, Oklo)
    - Integral plant response and generation of quantitative risk profiles to support:
      - Safety case for functional containment
      - Risk-informed selection of design basis events and safety/non-safety SSC's to support licensing (licensing modernization project)
      - Risk-informed assessment of defense-in-depth adequacy to support licensing (licensing modernization project)
    - Miscellaneous items of interest:
      - Safeguards and non-proliferation
      - Tritium production and tracking
      - External hazards
  - A confirmatory tool for:
    - Reactor designers comparing results from in-house codes
    - Regulators judging credibility of a safety case

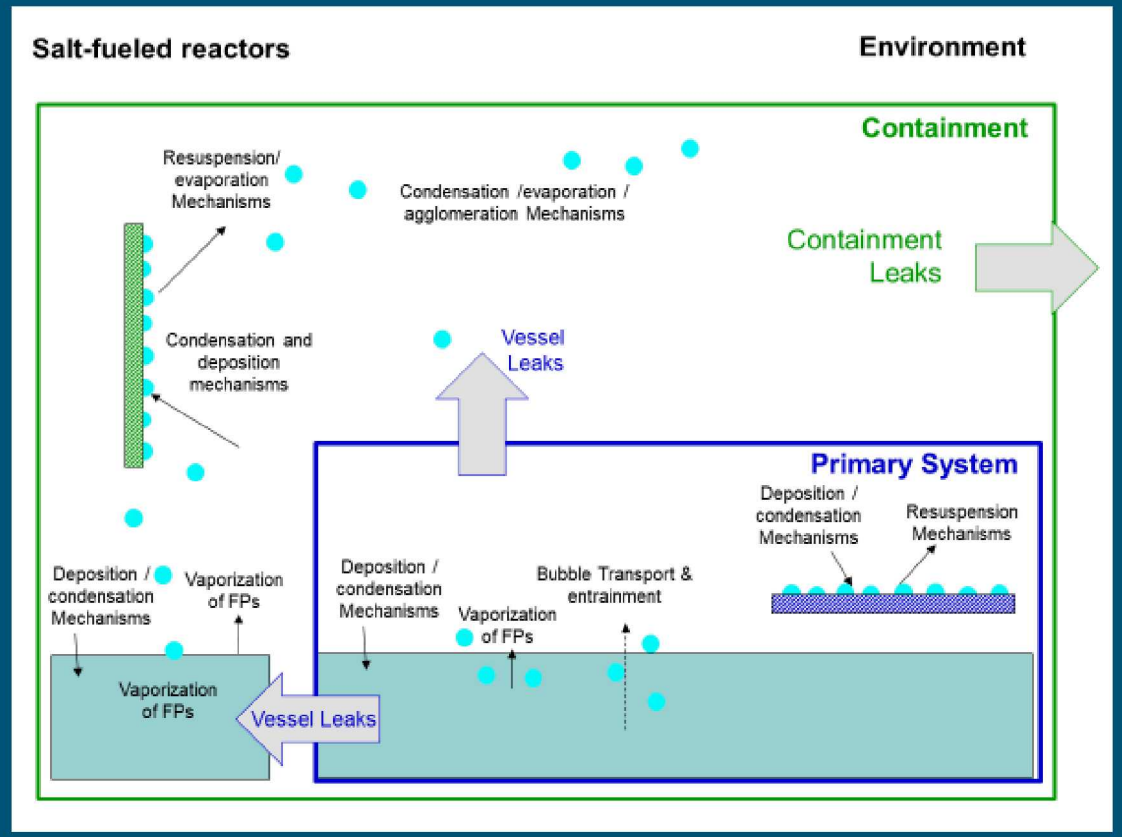
MELCOR MSR Development & Modeling

New/Expanded physics, MSRE & FHR-type models

MELCOR Development & Modeling – New/Expanded MSR Physics Models

- Leverage previous work and existing capabilities for salt-fueled and salt-cooled MSRs:
  - General EOS library read-in utility - developed for sodium/SFRs - enabled FLiBe (among others) as working fluid
  - TRISO fuel and pebble bed models – developed for HTGRs
  - Miscellaneous physics (see below) and flexible code architecture





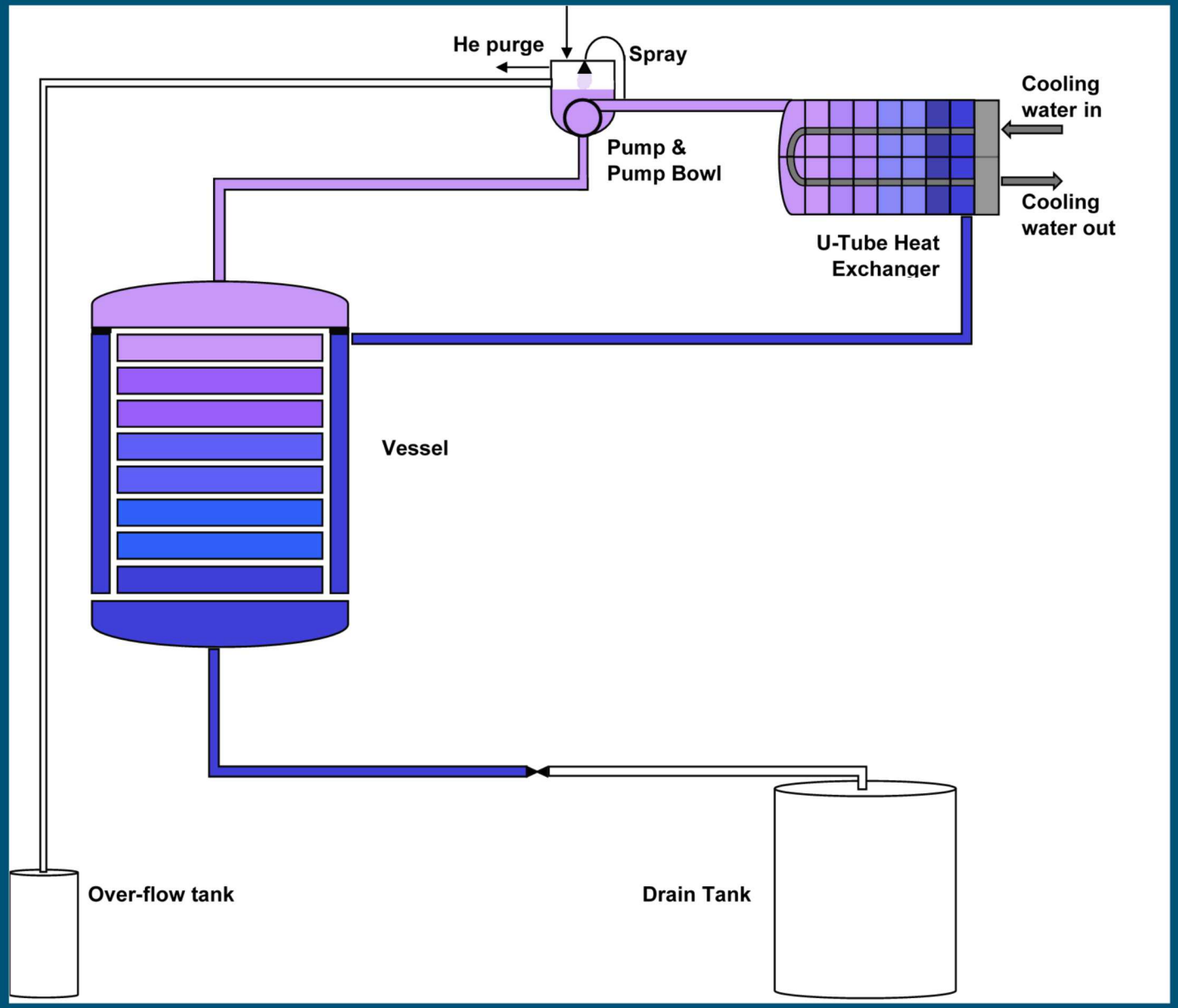
MELCOR Development & Modeling – New/Expanded MSR Physics Models

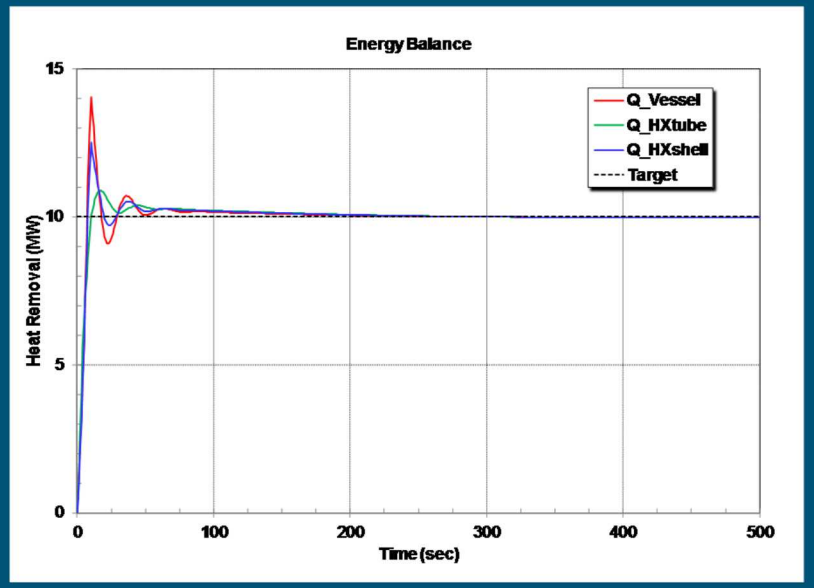
- SNL LDRD aimed at safeguard/non-proliferation in MSRs prompted new and expanded physics models
- Expanded capabilities for:
  - Nuclide production/destruction (or transmutation/decay) model – more detailed inventory tracking and decay heat models
  - Circulating fuel point kinetics – treatment of delayed neutron precursor drift and effects of flowing fuel
- New capabilities for:
  - 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
- Not all of the above are necessarily required for MSR scoping, safety, source term, or licensing calculations

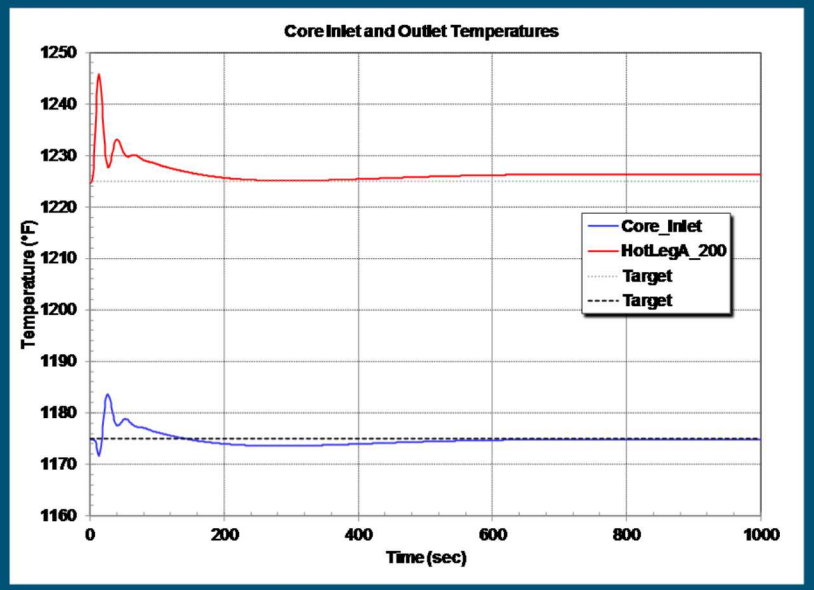
MELCOR Development & Modeling – Preliminary MSRE & FHR

- SNL LDRD effort includes MSRE modeling based on available information (ORNL-TM-0728)
  - Begin with currently available MELCOR physics models and architecture
  - Eventually, exercise new physics models to demonstrate/assess new capabilities and their adequacy
- Model features
  - One-dimensional core for now (8 control volumes, no traditional solid core structures), 2-D extension straightforward
  - Graphite blocks (heat structures)
  - Diversion and drain tanks connected to primary loop
  - Core bypass (leakage flow)
  - Primary loop (with heat structures for pipe walls – Schedule 40 INOR-8)
  - Fuel pump and pump bowl (connected overflow tank, pump spray with helium gas purge for salt clean-up)
  - Horizontal u-tube heat exchanger
- Model achieves a steady-state at nominal MSRE operating points (10 MW_{th}, T_{in}/T_{out} = 1175/1225 °F)
- In-house experimentation on FHR-type reactor - PBR-400 (HTGR) and FLiBe
  - Starts and runs error-free
  - Bodes well for future FHR modeling efforts

MELCOR Development & Modeling – Preliminary MSRE & FHR







MELCOR/SNL Engagement on MSRs

ORNL, Industry & NRC

MELCOR/SNL Engagement – ORNL & SCALE on HTGRs

- Historically, SCALE has been used (input or built-in defaults) to provide certain data to MELCOR:
  - Fission product and radionuclide inventories (e.g. initially in fuel an fuel/clad gap)
  - Decay heat (as a function of time since shutdown)
  - Reactor kinetics parameters and core power distribution

- Presently, SNL & ORNL are collaborating on HTGR calculations with MELCOR and SCALE
  - SCALE developers have calculated core isotopics and time-dependent decay heat for MELCOR
  - The isotope information may be collapsed to a MELCOR class structure and initialized in input
  - The decay heat information may be tabularized in MELCOR input for interpolation as problem time advances
  - In the near future, SCALE could furnish delayed neutron kinetics parameters and reactivity coefficients for use by the MELCOR (solid-fuel) point kinetics model

- This suggests a possible strategy and path forward for MSR modeling
  - Established MELCOR/SCALE methodology as practiced for HTGR analyses
  - New SCALE capabilities pursuant to MSRs (multi-compartment material tracking, precursor drift, chemical speciation)

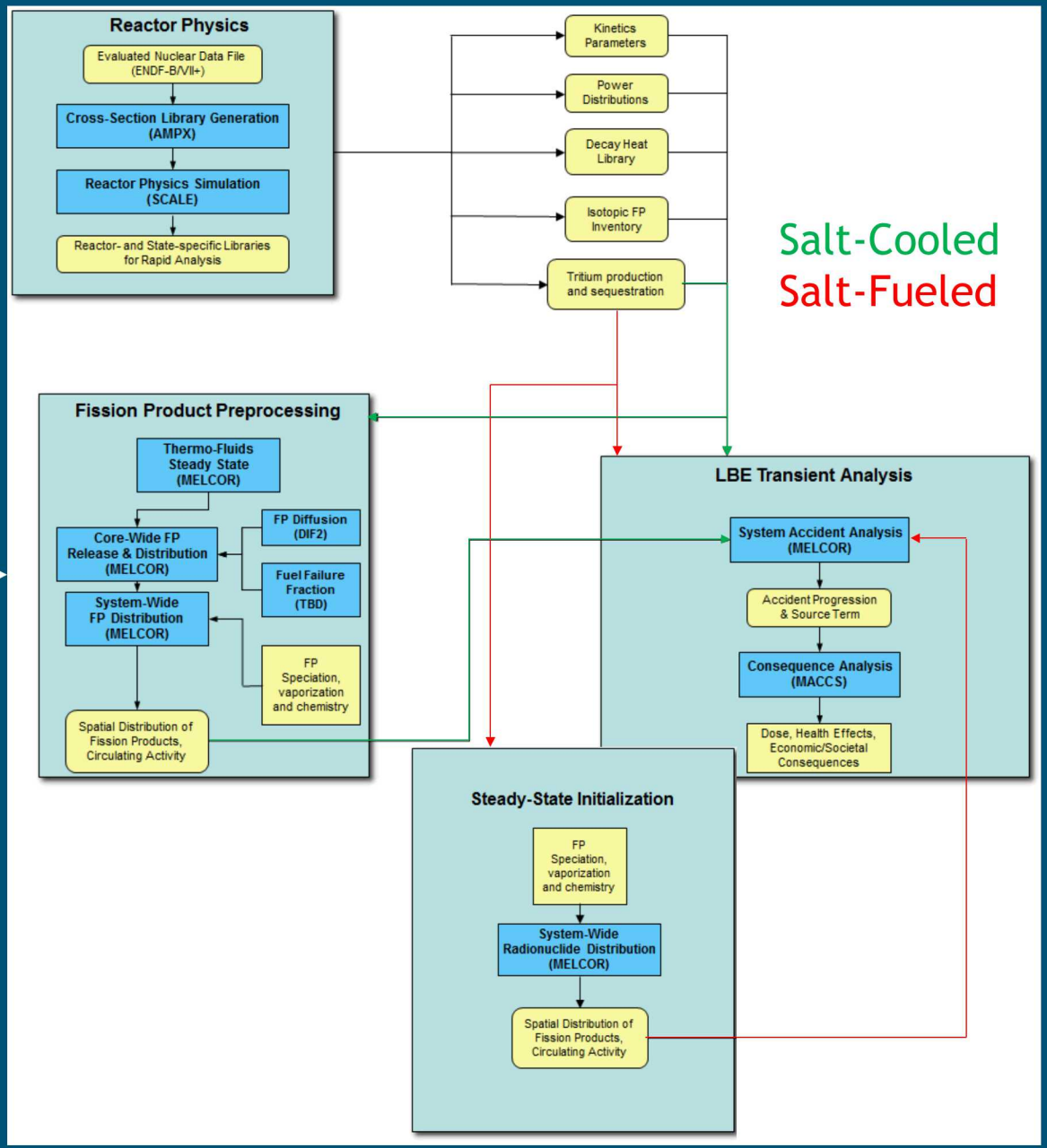
MELCOR/SNL Engagement – Interaction with Industry Members

- SNL has met with several reactor designers and other industry stakeholders in the advanced reactor space
  - Informational and introductory
    - Discuss MELCOR capabilities and development status/plans in some level of detail
    - Discuss experimental programs and data needs
    - Share R&D experience/expertise
    - Discuss aspects of licensing strategy including:
      - Merits of the systems-level philosophy
      - Virtues of a risk-informed approach to evaluating robustness of design safety in light of uncertainties
      - Vendor/designer time-tables
      - Obstacles to progress
      - Scoping calculations
    - Discuss SNL's conflict-of-interest concerns and clarify our allowable role given involvement with both industry and regulators
    - Plan future work and collaborations
  - Technical guidance and consulting
    - Developing new models and guiding users in their function
    - Counseling users on MELCOR modeling approach
    - Discussing other technical work and/or deliverables for existing projects

MELCOR/SNL Engagement – NRC

- On the technical side:
  - MELCOR project
    - Code development – NRC's anticipated licensing needs
    - Code maintenance – Debugging, documentation & testing
    - User support – Bug reports, workshops, guidance,…
    - Technical assistance to NRC, strategizing with NRC
  - Non-LWRs/MSRs get increasing levels of attention
  - NRC proposed licensing evaluation models for MSRs

- On the policy side, an example would include the application of the licensing modernization project framework to micro-reactors (generally non-LWR)
  - What does a regulatory source term look like?
  - What DBE's?
  - What does DID look like in passively-safe systems?
  - To what extent does PRA play a role?



Conclusions

- MELCOR is a fully-integrated, systems-level modeling and analysis tool with a flexible architecture
  - Conventionally used for LWRs, severe accidents, source-term generation, other non-reactor applications
  - At the "take-off" stage for non-LWR/MSR modeling with considerable capability already
  - Can facilitate a risk-informed approach to safety analysis in view of uncertainties
- MELCOR is under development to increase its capabilities in non-LWR/MSR space
- Simple MSR models (salt-cooled FHR and salt-fueled MSRE) have been built and exercised with success
- SNL actively engages with national labs (e.g. ORNL), industry stakeholders, and regulators (NRC) on MSRs