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# MELCOR for HTGR Applications

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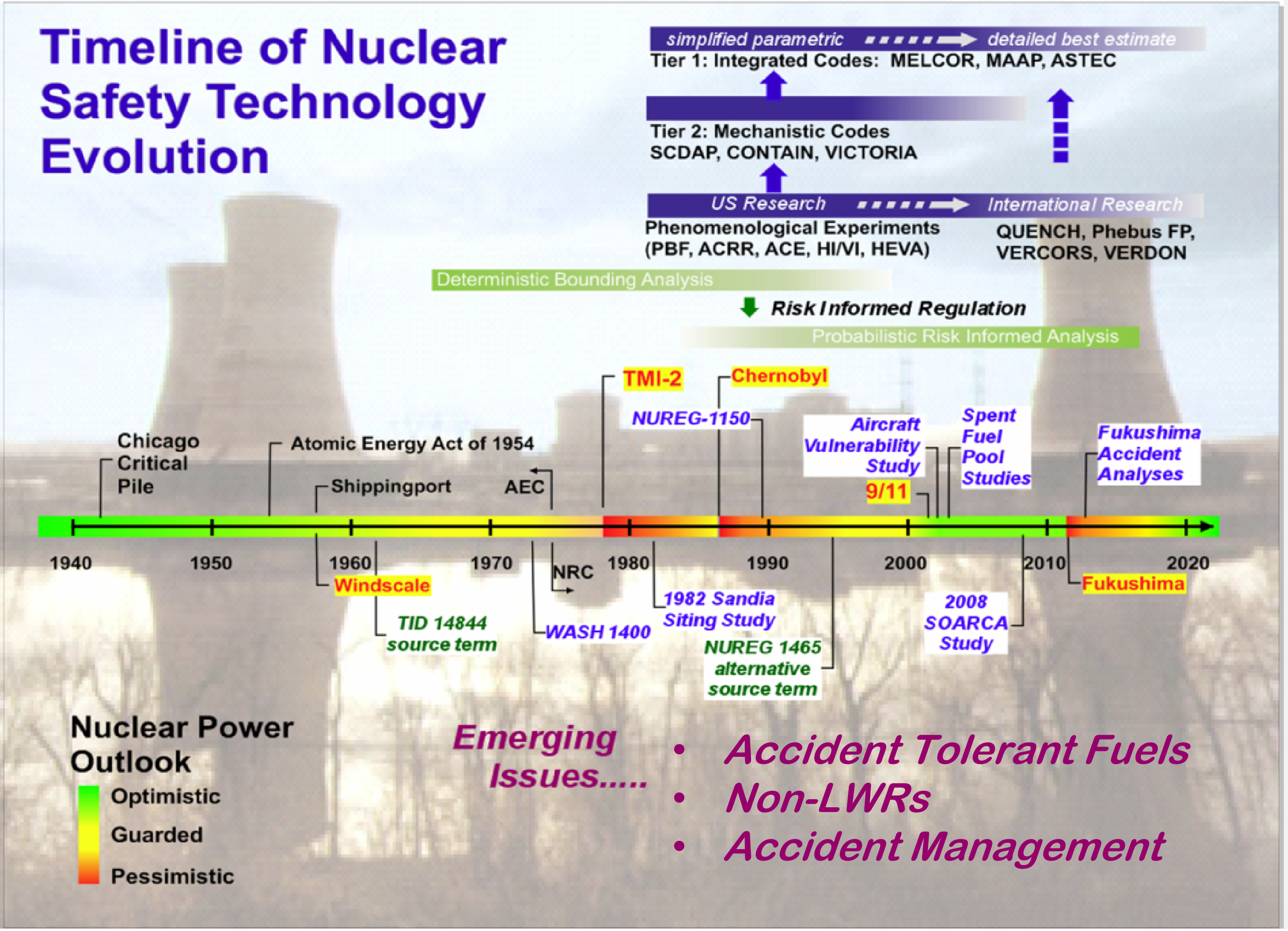
# Outline

- MELCOR code introduction

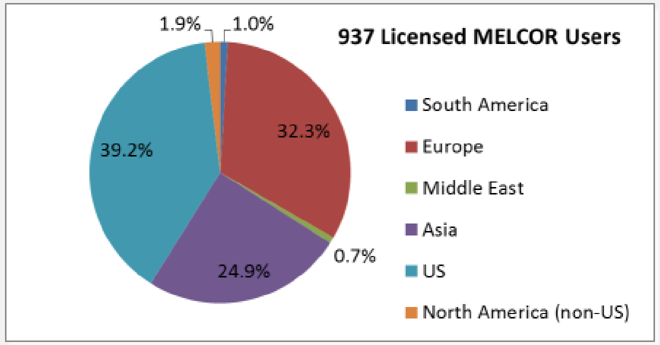
- Describe MELCOR physics models and capabilities for HTGRs in limited detail
  - Diffusional fission product release model
  - Core component conduction (intracell, intercell, core boundary)
  - Core control volume convection/flow
  - Graphite oxidation
  - Point reactor kinetics equations

- Conclusions

# MELCOR – History and Introduction




- 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

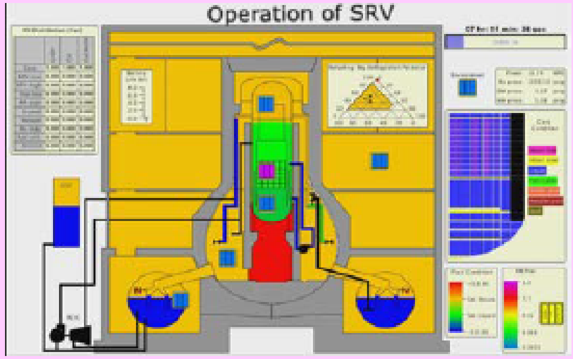



- Used by USNRC, USDOE & US industry
- Used for naval reactors (US/UK)
- Evolves to meet regulatory needs

# MELCOR – History and Introduction

- 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
  - Models built from basic code constructs
  - Adaptability to new or non-traditional reactor designs (ATR, Naval, VVER)
- Validated physics models (ISP’s, benchmarks, experiments, accidents)
- Uncertainty analysis & dynamic PRA (fast-running, reliable, access to parameters)
- User convenience
  - Windows/Linux versions
  - User utilities and post-processing/visualization capabilities
  - Extensive code documentation

Multi- Physics

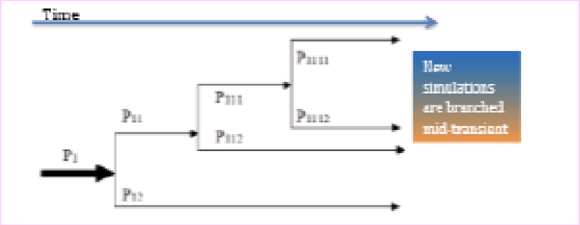



SOARCA LTSBO

Diverse Application

Advanced Test Reactor

Uncertainty & Dynamic PRA



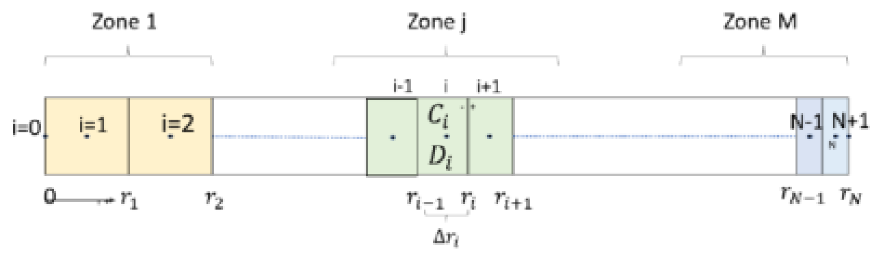

Dynamic Event Tree

# Diffusional Fission Product Release

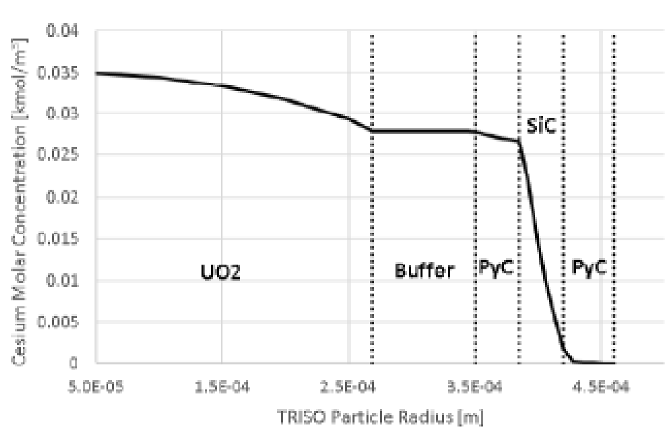
- Overall goals of the HTGR diffusional release model:
    - Predict radionuclide distributions within fuel elements in the core, and
    - Predict radionuclide release from fuel to coolant
- Entails a finite volume diffusion solver and a specially-tailored analytic release model for failed TRISO fuel

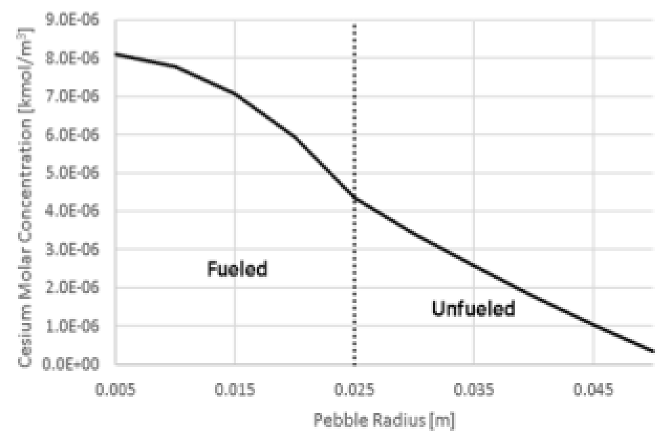
$$\chi \frac{\partial C}{\partial t} = \frac{1}{r^n} \frac{\partial}{\partial r}\left(r^n D \frac{\partial C}{\partial r}\right) - \lambda C + \beta$$

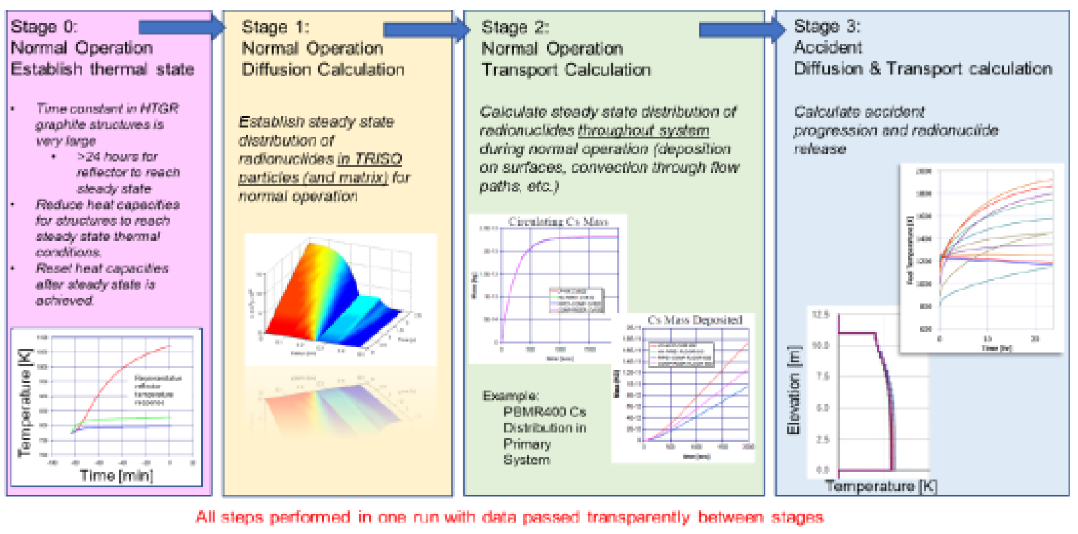
$$D(T) = D_0 e^{-Q/RT}$$




- Solution algorithm and run-time strategy
- Get molar concentration profiles and diffusional release



# Conduction

- Intercell
  - Between like or unlike components in axially or radially adjacent core cells, pending conduction logic
  - Formulated as a conductance times a temperature difference with the conductance equaling a parallel combination of:
    - FU term (geometry, solid material conductivity)
    - MX term (geometry and effective conductivity consisting of radiation, fluid conduction, and solid conduction terms)
      - Tanaka and Chisaka formulation for PMR
      - Zehner-Schlunder-Bauer formulation for PBR
- Intracell
  - Between components within the same core cell, more precisely fuel (FU) and matrix (MX) component in the context of HTGRs
  - Formulated as a conductance times a temperature difference with the conductance equaling a parallel combination of:
    - FU term (geometry, solid material conductivity)
    - MX term (geometry, solid material conductivity)
    - Another user-specified conductivity if necessary
- Boundary
  - Allow thermal energy to pass from core periphery (usually a reflector region) to bounding heat structures (usually the core barrel region)
  - Accounts for heat transfer across a user-specified gap
  - Key for modeling passive safety features of HTGRs

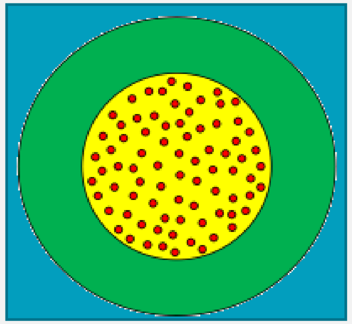
# Convection/Flow

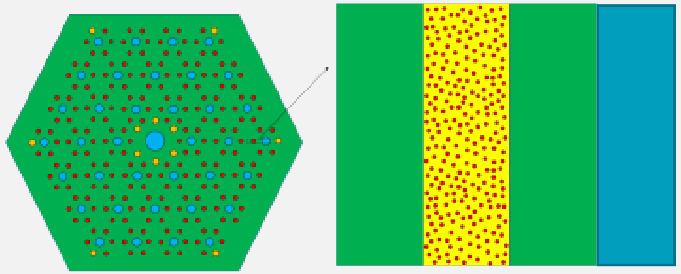
- Nusselt number correlations for heat transfer coefficients
  - Pebble fueled systems use correlations for isolated spherical particles:

$$NU_{forced} = 2.0 + 0.6Re_f^{1/2}Pr_f^{1/3}$$

$$NU_{natural} = 2.0 + 0.6Gr_f^{1/4}Pr_f^{1/3}$$

  - Prismatic fuel systems utilize conventional Dittus-Boelter correlation forms
  - Forced/natural laminar/turbulent Nusselt numbers computed and maximum used
  - Sensitivity coefficient access to all correlation multipliers, constants, exponents





- For either pebble bed or prismatic cores, the matrix component thickness contributes to heat transfer resistance

- For pebble bed cores, use packed bed correlations (Ergun, Achenbach)
  - Compute flow resistance and pressure loss
  - Frame as K-loss for convenience given phasic velocity equation forms

$$K_L(\varepsilon, Re) = \left[C_1 + C_2\frac{1-\varepsilon}{Re} + C_3\left(\frac{1-\varepsilon}{Re}\right)^{C_4}\right]\frac{(1-\varepsilon)}{\varepsilon D_p}L$$

| Correlation | $C_1$ | $C_2$ | $C_3$ | $C_4$ |
|---|---|---|---|---|
| Ergun (original) | 3.5 | 300. | 0.0 | - |
| Modified Ergun (smooth) | 3.6 | 360. | 0.0 | - |
| Modified Ergun (rough) | 8.0 | 360. | 0.0 | - |
| Achenbach | 1.75 | 320. | 20.0 | 0.4 |

# Graphite Oxidation

## Steam oxidation

$$R_{OX,steam} = \frac{k_4 P_{H_2O}}{1 + k_5 P_{H_2}^{0.5} + k_6 P_{H_2O}}$$

## Reaction

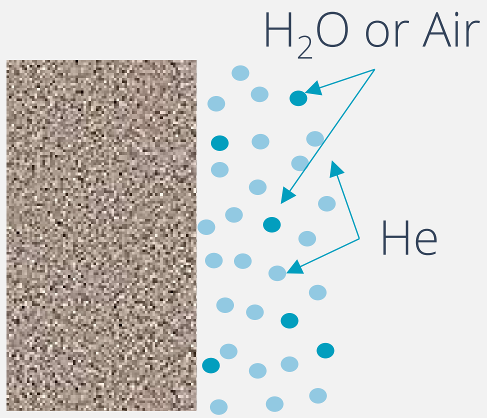
| |
|---|
| $C + H_2O(g) \rightarrow CO(g) + H_2(g)$ |
| $CO(g) + H_2O(g) \rightarrow CO_2(g) + H_2(g)$ |

## Air oxidation

$$R_{OX} = 1.7804x10^4 \exp\left(-\frac{20129}{T}\right)\left(\frac{P}{0.21228x10^5}\right)^{0.5}$$

## Reaction

| |
|---|
| 1. $C + O_2 \rightarrow CO_2(g)$ |
| 2. $C + \frac{1}{2}O_2 \rightarrow CO(g)$ |
| 3. $CO(g) + \frac{1}{2}O_2(g) \rightarrow CO_2(g)$ |
| 4. $C + CO_2(g) \rightarrow 2CO(g)$ |




*Both steam and air include rate limit due to steam/air diffusion towards active oxidation surface

- Graphite oxidation active in the context of a new generalized oxidation model
- For air oxidation, empirical correlation determines relative production of $CO/CO_2$

$$f = \chi_{CO}/\chi_{CO_2} = 7396 * \exp\left(-\frac{69604}{8.314 * T_{MX|RF|SS}}\right)$$

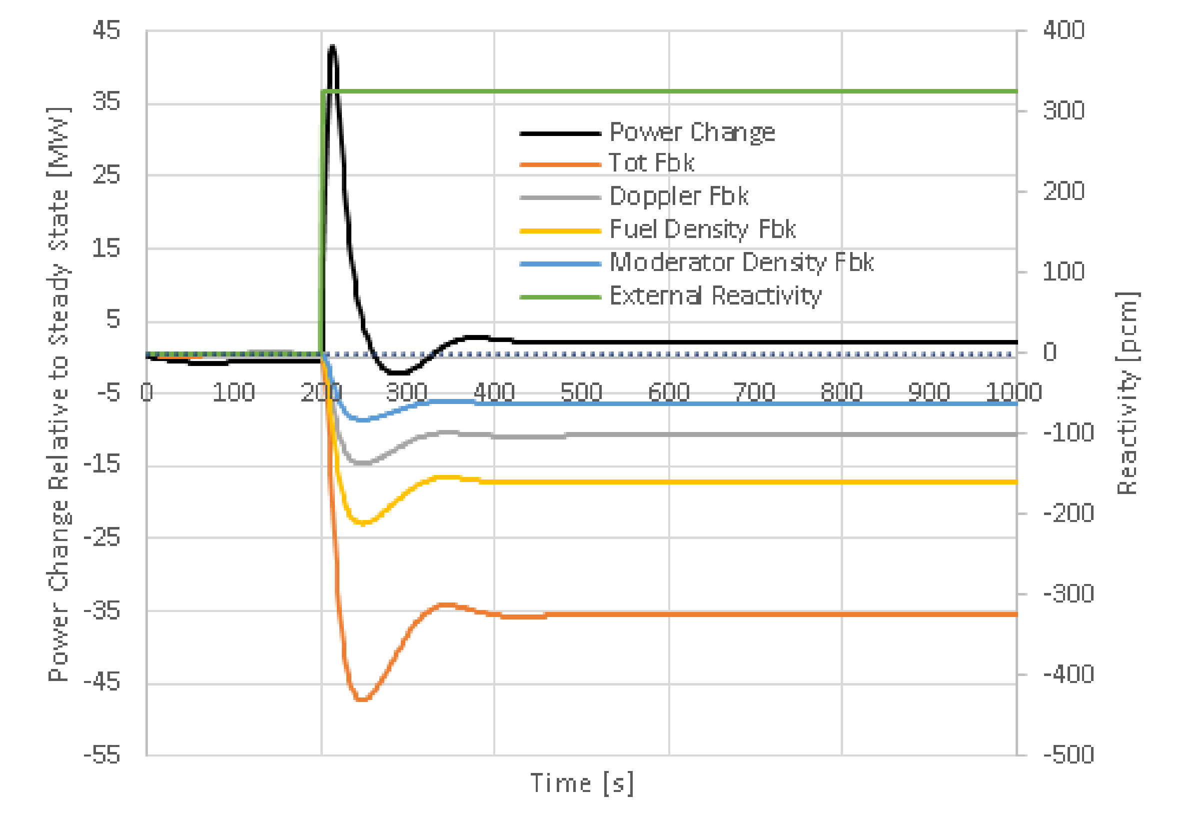
# Point Reactor Kinetics Equations

- Standard PRKE treatment

$$\frac{dP}{dt} = \left(\frac{\rho - \beta}{\Lambda}\right)P + \sum_{i=1}^{6} \lambda_i Y_i + S_0$$

$$\frac{dY_i}{dt} = \left(\frac{\beta_i}{\Lambda}\right)P - \lambda_i C_i, \qquad for\ i = 1 \ldots 6$$

- Kinetics data accessible by SC
- Feedback models
  - CF-specified external component
  - Doppler
  - Fuel and moderator density
- Define COR cell ranges as regions over which averages are taken to inform feedback models
- Useful capability for ATWS-type scenarios



# Conclusions

- To facilitate MELCOR modeling of HTGRs, several physics models and capabilities were developed and integrated

- An approach consistent with the systems-level modeling philosophy of MELCOR was taken

- Noteworthy aspects of HTGR physics models and/or modeling capabilities presented here
  - Further detail in NURETH-19 paper
  - Still further detail in MELCOR code documentation
  - Publicly-released demonstration calculation performed for USNRC