ARCADIA Rod Ejection Accident Methodology (AREA)

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Baden Feb. 28, 2023

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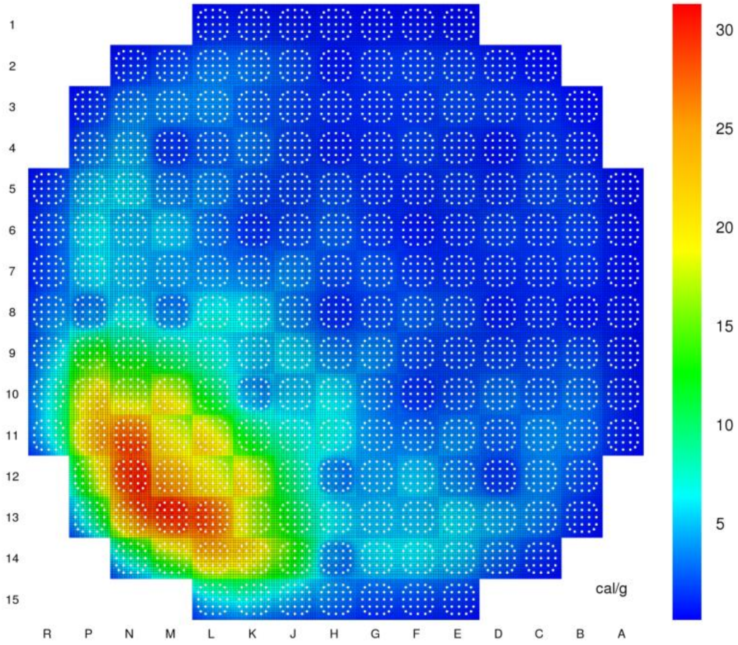
Rod Ejection Accident - REA

Description of Transient (Safety category 3)

- Mechanical failure of control rod drive mechanism
- Ejection of full length control rod in ~0.1s
- Localized fast reactivity insertion



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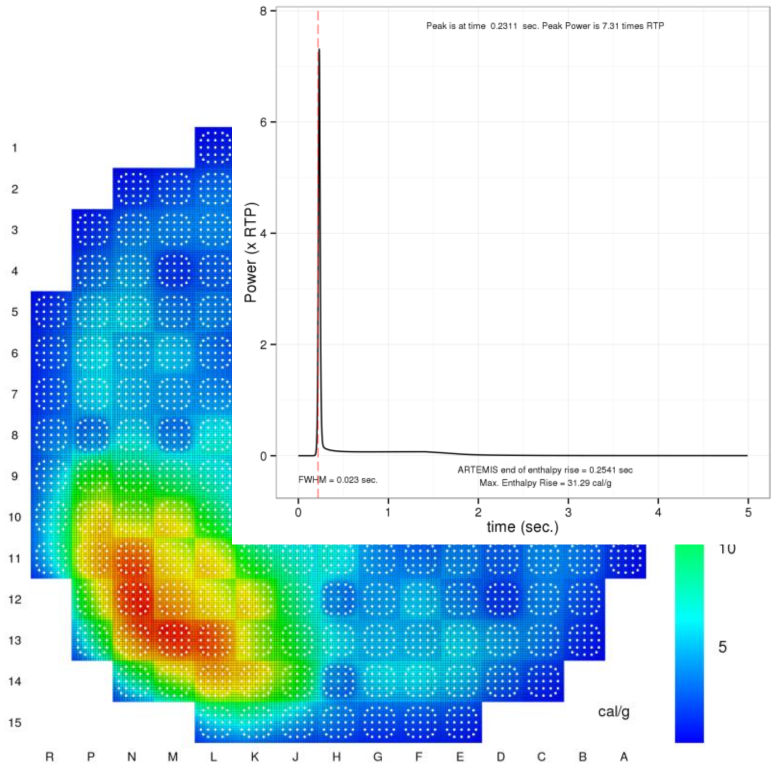
Rod Ejection Accident - REA

Description of Transient

- Mechanical failure of control rod drive mechanism
- Ejection of full length control rod in ~0.1s
- Localized fast reactivity insertion
- Fast and steep core power increase
(example: $\Delta\rho$ = 1.70 \$ = prompt critical)
- Doppler feedback mitigates power increase before reactor trip
- Safety criteria:
  - Minimum DNBR / Fraction of rods in DNB
  - Maximum fuel temperature
  - Maximum fuel enthalpy
  - Local fuel enthalpy rise
  - Reactor pressure



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ARCADIA Rod Ejection Accident - AREA

AREA - Deterministic 3D-Coupled Analysis of the Rod Ejection Accident

- 3D-coupled transient core simulation with ARTEMIS
  - Nodal N/TH/FRM transient coupled with subchannel-by-subchannel TH/FRM transient
  - Fuel property resolution at the pin level (materials, density, enrichment, gap conductance)
  - Fraction of rods in nucleate boiling (DNB) determined from pin-by-pin data
- Analysis of fuel thermal limits with fuel rod performance code (e.g. wppm ↔ B_{loc})
- Derivation of conservative biases based on case specific sensitivity calculations
- Analysis matrix of multiple power levels (HFP -> HZP) at multiple times in cycle (BOC, MOC, EOC)
- Option for maximum reactor pressure evaluation with a coupled system code

» **Approved by U.S. NRC - Powerful and Flexible Analysis Method Well Suited to Accommodate Revised NRC Analysis Guidance (NRC RG 1.236)**

» **Implementation has started in the US**

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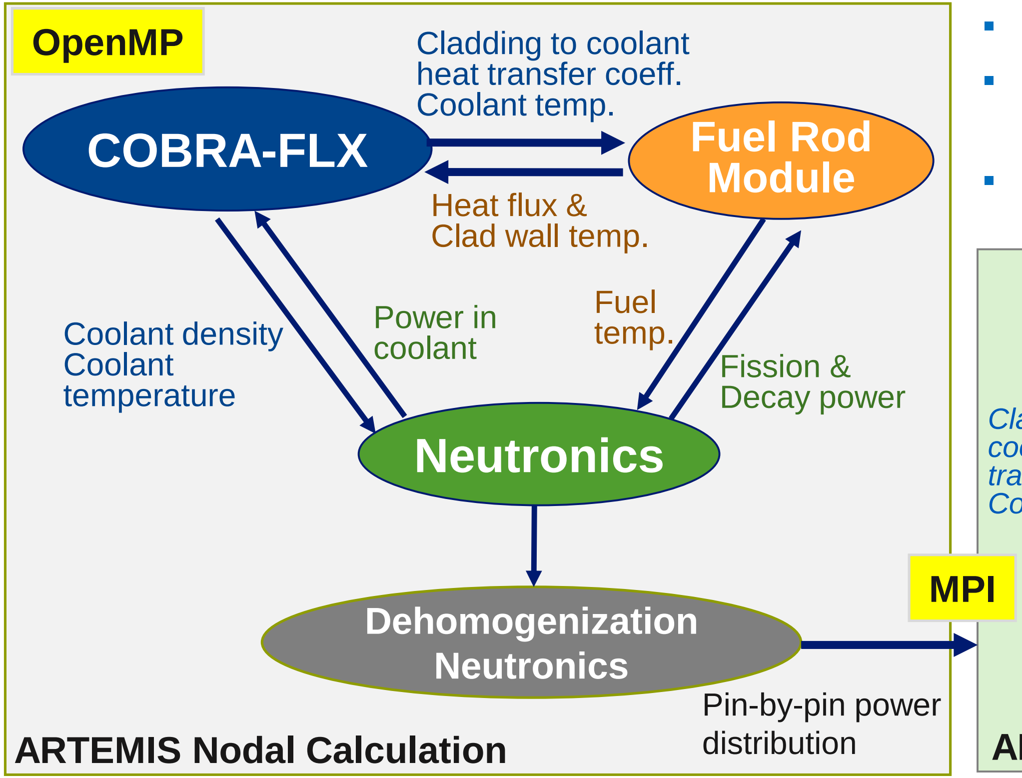
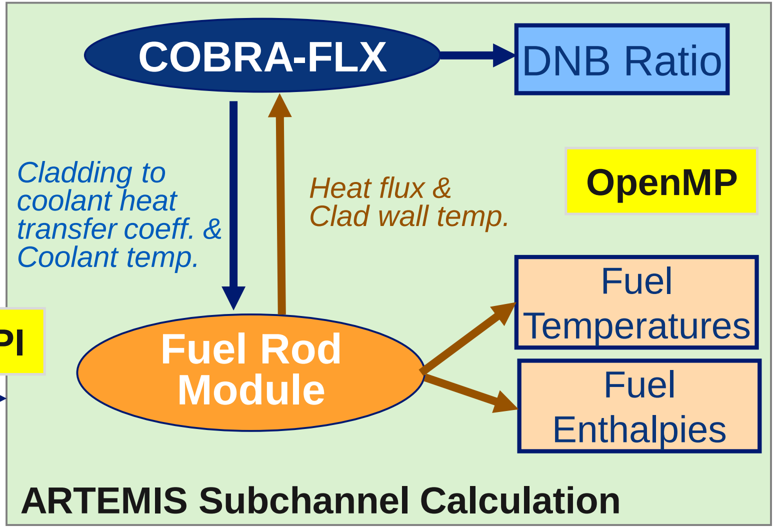
ARTEMIS Core-Coupled Calculation



- Transient power distribution
- TH feedback to Neutronics Solver
- Full core subchannel-by-subchannel (SBS) **local safety relevant parameters**



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Example: Coupled Nodal – Subchannel Calculations

"coarse mesh" Nodal Calculation

Neutronics – COBRA-FLX– FRM

4 box / FA radial nodalisation

- Number of fuel rods: ~ 700
- Number of subchannels: ~ 700
- Number of gaps: ~1500
- Number of axial nodes: ~30

"fine mesh" Subchannel Calculation

COBRA-FLX – FRM

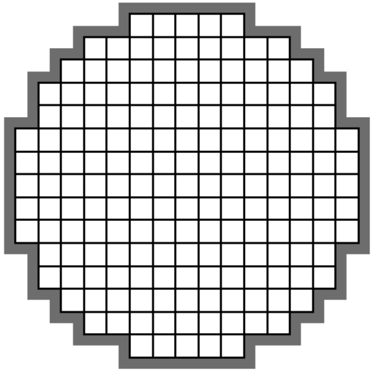
SBS / pin-by-pin radial nodalisation

Number of fuel rods: ~50000-60000

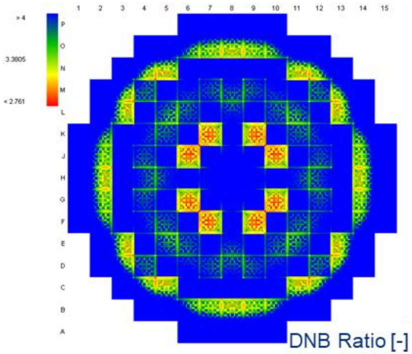
Number of subchannels: ~60000-70000

Number of gaps: ~125000

Number of axial nodes: ~40



- Internal mapping of boundary conditions from coarse mesh to fine mesh
  - Pin-by-pin axial power distribution mapped to "fine" mesh axial nodes
  - Operating conditions (inlet temperature, inlet mass flux, pressure)
- Steady state & transient calculations



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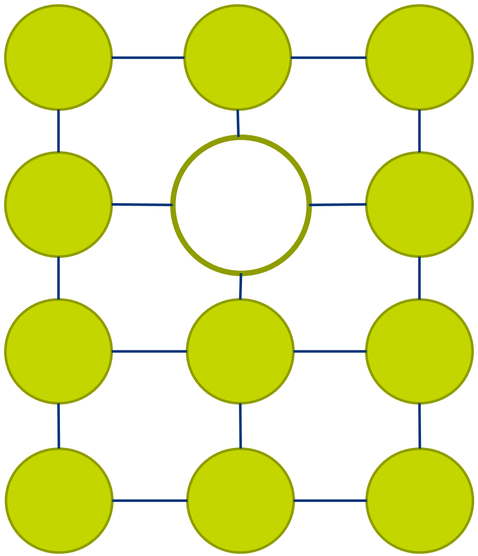
Subchannel-by-Subchannel Calculation



- All fuel rods and guide tubes with the associated subchannels are modeled in subchannel-by-subchannel resolution

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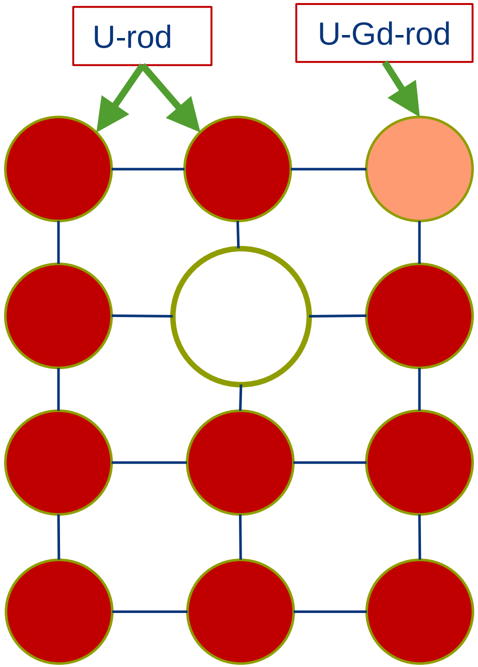
Subchannel-by-Subchannel Calculation



- All fuel rods and guide tubes with the associated subchannels are modeled in subchannel-by-subchannel resolution
- Dehomogenized Pin Powers and Pin Burnups are provided to FRM rods

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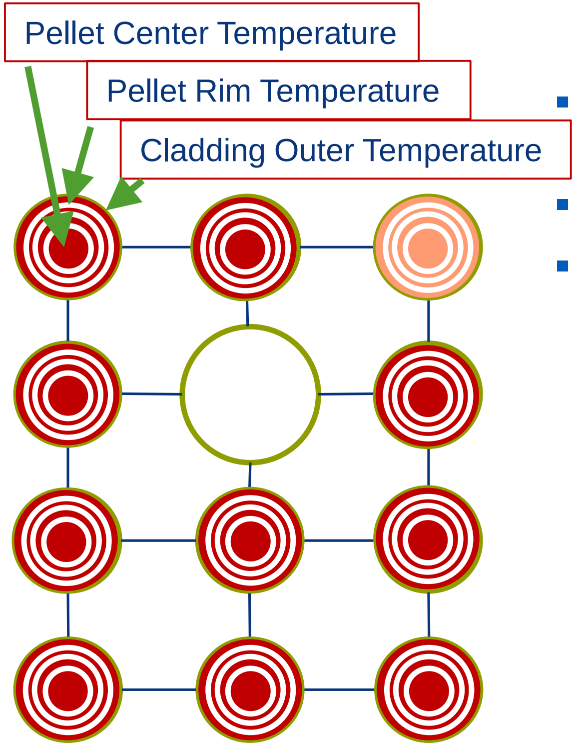
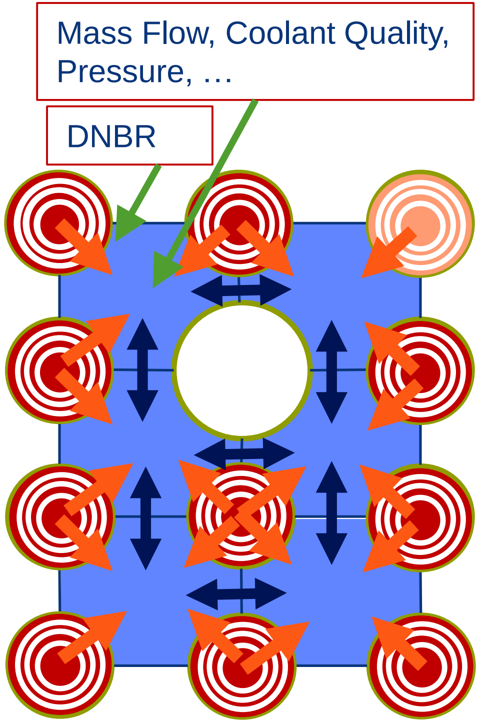
Subchannel-by-Subchannel Calculation



- All fuel rods and guide tubes with the associated subchannels are modeled in subchannel-by-subchannel resolution
- Dehomogenized Pin Powers and Pin Burnups are provided to FRM rods
- FRM calculates fuel properties in fuel rings on the rod
  - Iteration with COBRA-FLX (heat flux, wall temperature)
  - Based on local fuel properties (geometry, density, enrichment, burnup, gap conductance)
  - Fuel enthalpy, fuel enthalpy rise, fuel center and rim temperature
  - Cladding inner and outer temperature

Subchannel-by-Subchannel Calculation



- All fuel rods and guide tubes with the associated subchannels are modeled in subchannel-by-subchannel resolution
- Dehomogenized Pin Powers and Pin Burnups are provided to FRM rods
- FRM calculates fuel properties in fuel rings on the rod
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  - Based on local fuel properties (geometry, density, enrichment, burnup, gap conductance)
  - Fuel enthalpy, fuel enthalpy rise, fuel center and rim temperature
  - Cladding inner and outer temperature
- COBRA-FLX calculates coolant properties in each subchannel
  - Iteration with FRM (heat transfer coefficient, coolant temperature)
  - Based on local channel properties (geometry, pressure loss coefficients)
  - Mass flow, enthalpy/temperature, void/quality, density, pressure, DNBR for each surrounding rod

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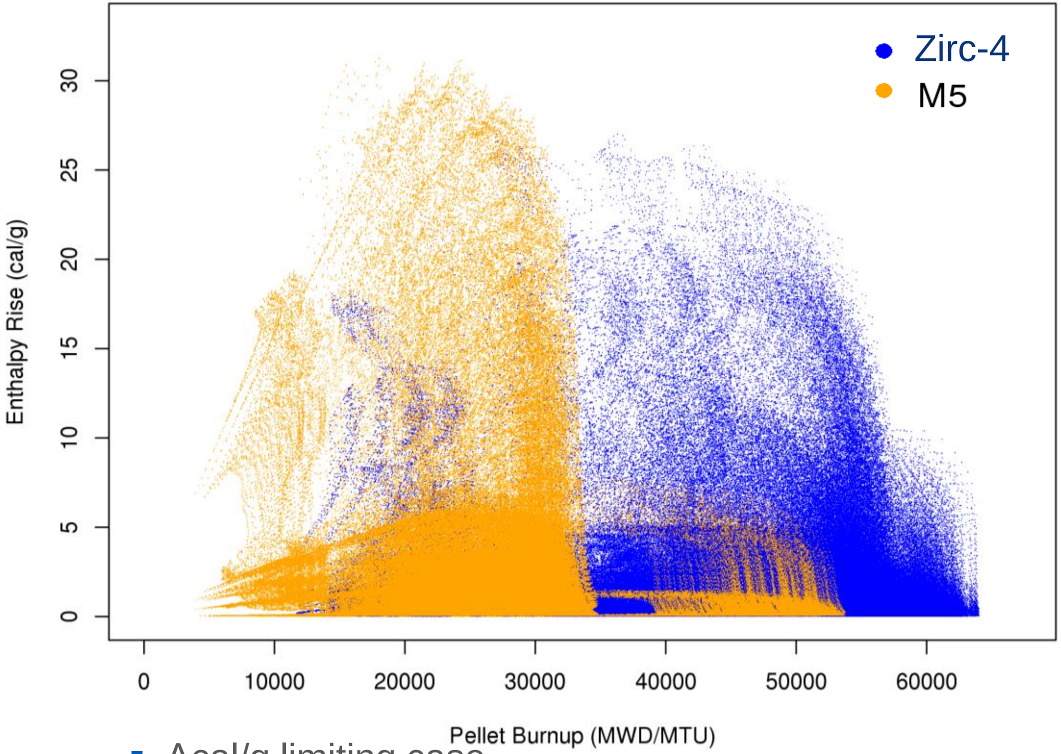
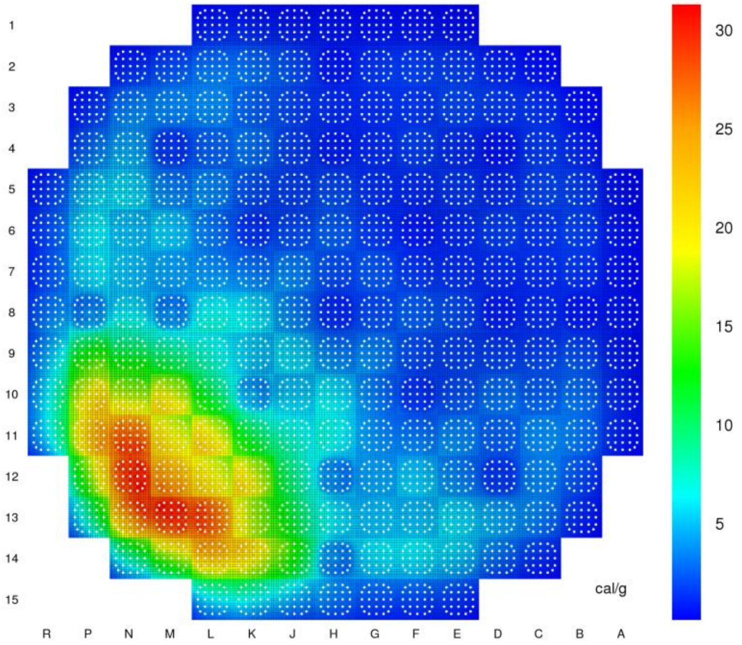
Local fuel properties

AREA Example (W4 plant) – transition cycle (Zirc-4 → M5) – HZP EOC





- Δcal/g limiting case

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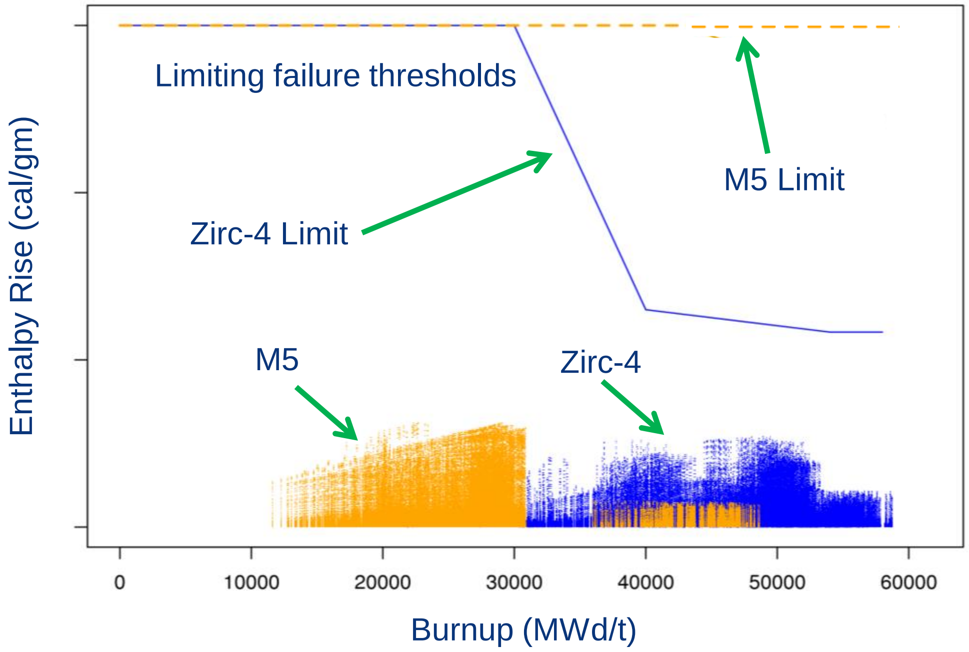
Fuel Properties and Fuel Limits

Sample case: REA, Hot Zero Power, EOC, Control Banks at PDIL – Evaluation Regarding Enthalpy Rise

Ejected rod worth 1.70 $ (= prompt critical), Maximum core power 730%

- **PCMI cladding failure threshold**
  - Function of clad excess hydrogen content converted to function of burnup using fuel rod performance code
  - Threshold may decrease with hydrogen pickup
- **AREA**
  - Models local feedback mechanisms
  - Provides Pin-By-Pin thermal results based on pin specific fuel rod properties
    - No assumptions regarding limiting locations



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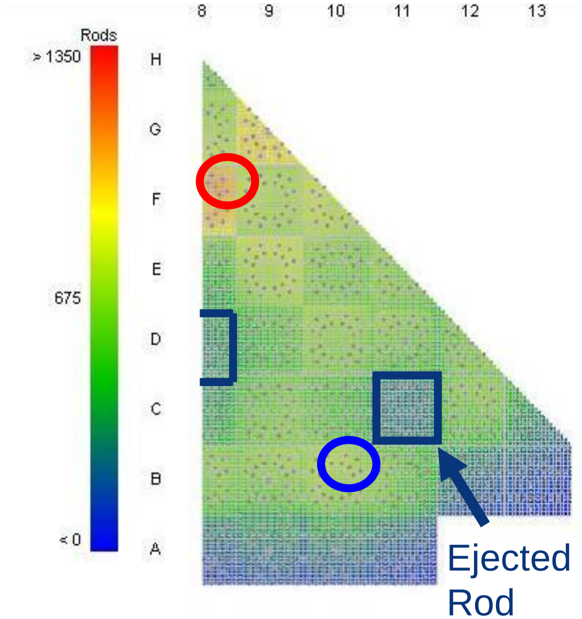
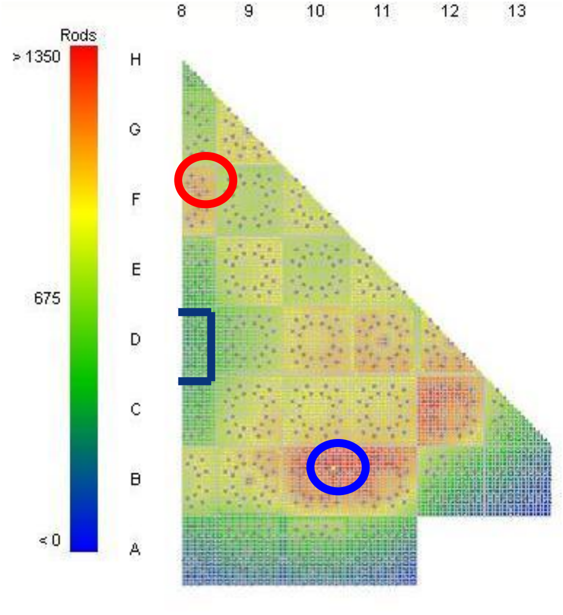
Full-Core 3D Subchannel-by-Subchannel analysis
Location of Maximum Fuel Temperature

Steady State Power (Heat Flux [kW/m²])

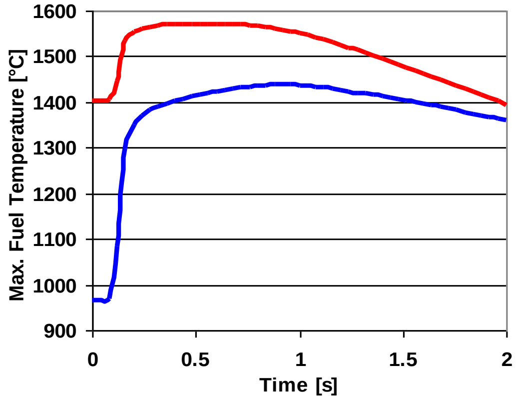


Initial State



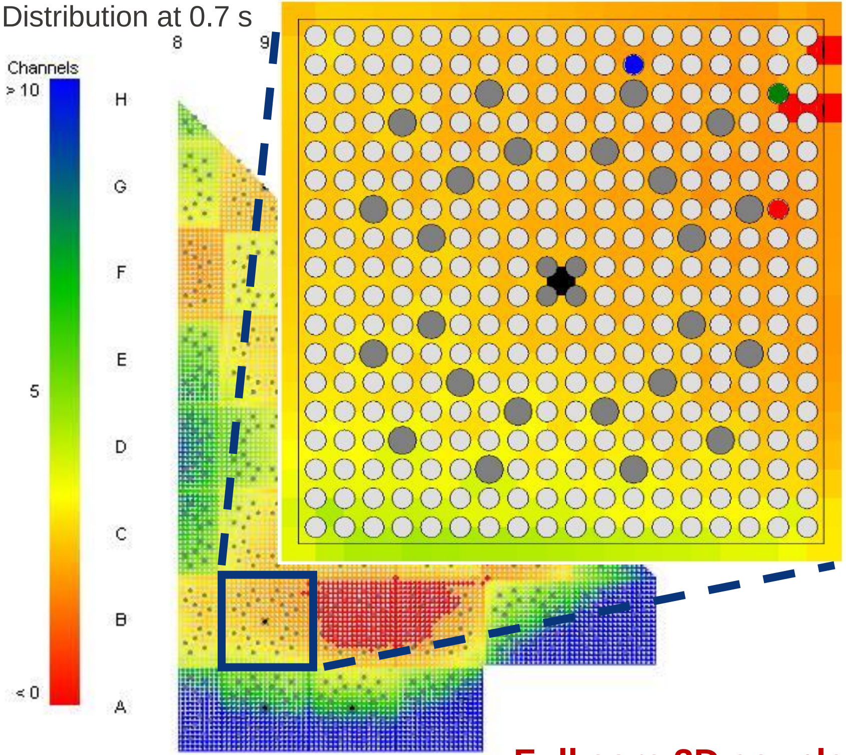
After REA

- Maximum power appears near ejected rod
- Max. fuel temperature could be expected at the **rod with maximum power** after REA



Full core 3D coupled calculation catches real limiting location

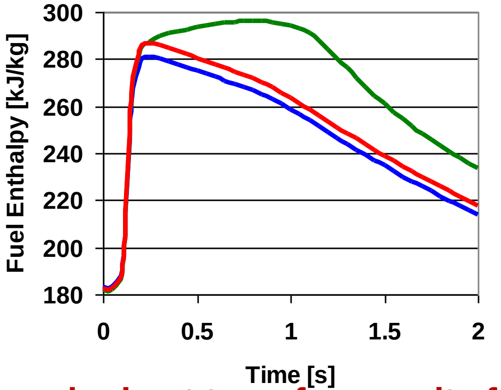
REA – Correlation of Fuel and TH Properties



- Does Film Boiling affect Enthalpy Rise?

Steady State Power of marked rods (Heat Flux [kW/m^2])

Rod	Initial	After REA
blue	741	1093
red	734	1133
green	733	1129



Full core 3D coupled does not require heat transfer penalty for each rod

Advantages over Legacy Method
using CASCADE-3D / PANBOX 3

- Subchannel-by-Subchannel thermal-hydraulics and Pin-by-Pin fuel rod model
  - Local channel properties (geometry, pressure loss, mixing)
  - Local fuel properties (geometry, density, enrichment, burnup, gap conductance)
  - Local coupling between thermal-hydraulic and thermal models
- Increased resolution of core model
  - No unnecessary conservative assumptions regarding safety limits dependent on burnup
  - No unnecessary bounding assumptions regarding fuel parameters as local parameters are penalized (e.g. gap conductivity = h_{gap})
  - No assumptions regarding hot channel location
- Verification of required but sufficient conservatism based on case specific sensitivity calculations

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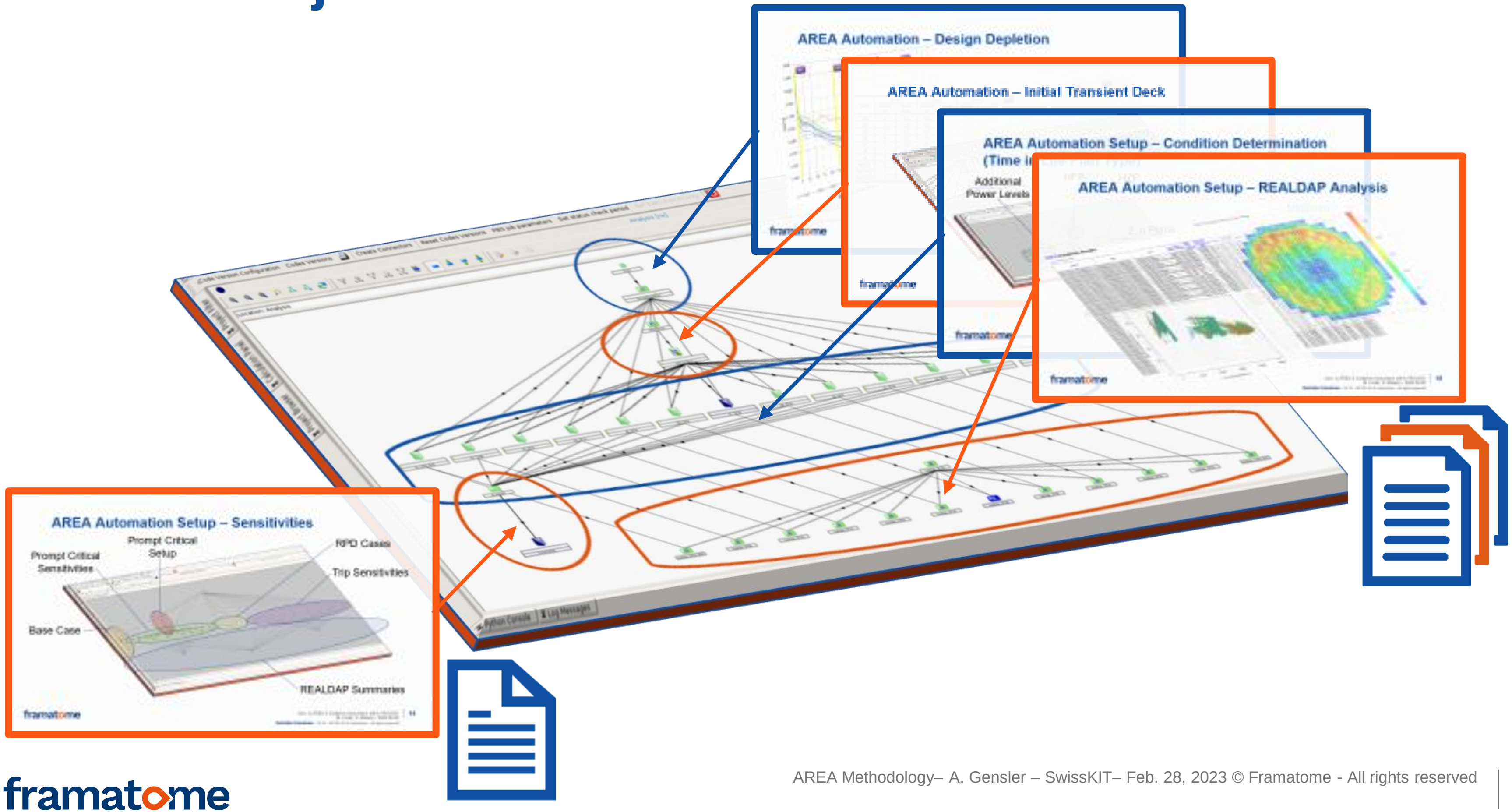
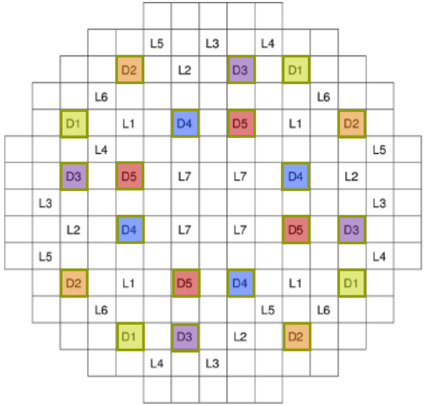
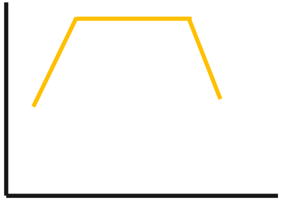
AREA Project Overview



Adaptation to KWU-Type Plants



- Bank Sequences and Load Conditions
  - Multiple control (D-) bank sequences
  - Control (D-) banks move without overlap
  - Movement of total (L-) bank allowed and used
  - Multiple control rod configurations to be considered at given power level
  - Requires pre-selection of limiting cases
- Limitation of Axial Offset (AO)
  - No tech-spec limit enforced on AO (‚AO Barn‘ in Westinghouse plants)
  - Limiting AO is found by setting state on actuation value of
    - PO- or PU-RELEB
    - LOCA/LOFE or LV-limit
  - Non-trivial task as limiting AO depends on power level and control bank configuration
    - Requires iteration of AO until bounding actuation value is reached
    - Requires online simulation of DNB module of PO-RELEB



Adaptation of methodology and automation started at Framatome

Conclusions

- AREA is a state-of-the–art methodology with state-of-the-art code system ARCADIA
- It fulfills the requirements of NRC RG 1.236
- AREA offers multiple advantages over legacy methods
  - Coupled 3D full core analysis with subchannel-by-subchannel and pin-by-pin resolution
  - Use of local fuel and TH parameters
  - Evaluation of fuel safety limits based on fuel/cladding material
- A dedicated automation suite exists for use in the ARCADIA ATLAS GUI
- AREA is approved by US NRC and currently being implemented in the US
- AREA is available for use of Westinghouse type plants
- For application to KWU-type plants adaptation of methodology and automation is required
  - Adaptation project has recently started at Framatome

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