RELAP5 Safety Analyses in Support of the BR2 COBRA Lead Test Assembly Irradiation

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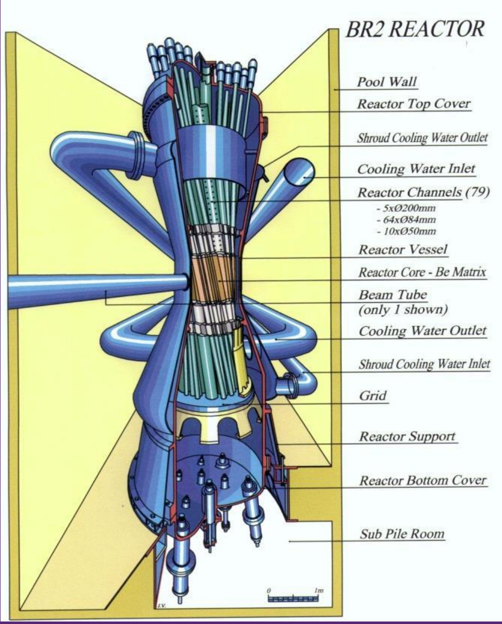
BR2



MTR: 50 - 125 MW_{th}

Water cooled (12 bar)

H_2O + Beryllium moderated

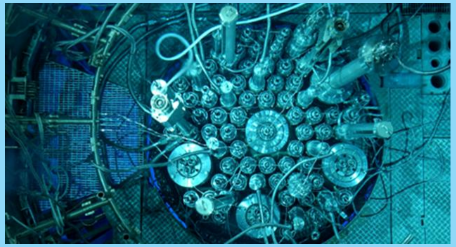
History

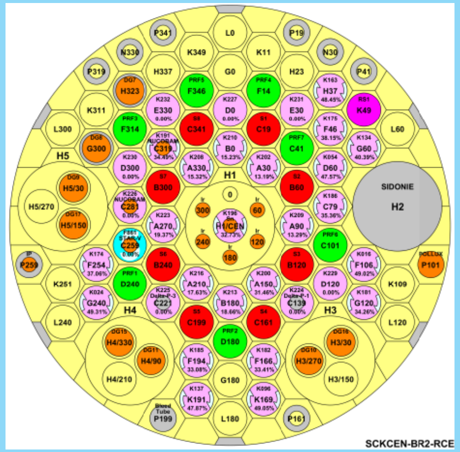
In operation since 1963

Major refurbishments in 1977, 1996 & 2016

4th Beryllium matrix

Core design



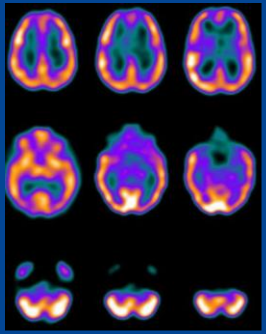


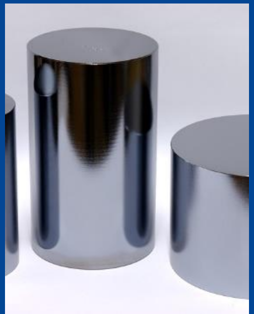
5×8", 64×3.5", 10× 2" channels

Highly flexible configuration

HEU UAl_x driver fuel

BR2 applications





Research & development

Radioisotope production

Silicon doping

COBRA: experimental and licensing process

*COBRA: Conversion Of BR2 – the Alternative

Experimental process (CEE)

BR2 fuel
- UAl_x HEU 1.3g/cc
- 510µm meat – 380µm clad
- Sm_2O_3 + B_4C poison
- STD geometry assy

COBRA-HEU LTA ✔
- UAl_x HEU 1.05g/cc
- 630µm meat – 350µm clad
- Gd & Sm_2O_3 + B_4C poison
- COBRA geometry assy

COBRA-FUTURE ✔
- U_3Si_2 LEU 5.3g/cc
- 630µm meat – 350µm clad
- Gd poison
- E-FUTURE flat plates

COBRA-LEU LTA
- U_3Si_2 LEU 5.3g/cc
- 630µm meat – 350µm clad
- Gd poison
- COBRA geometry assy

(DE) PIE ongoing

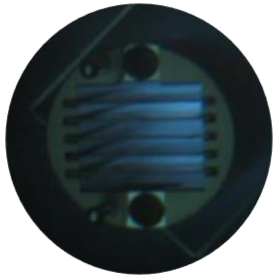
BR2 driver fuel
- UAl_x HEU 1.3g/cc
- 510µm meat – 380µm clad
- Sm_2O_3 + B_4C poison
- STD geometry assy

COBRA driver fuel ✔
- UAl_x HEU 1.05g/cc
- 630µm meat – 350µm clad
- Gd poison 2.5g/assy
- COBRA geometry assy

Converted driver fuel
- U_3Si_2 LEU 5.3g/cc
- 630µm meat – 350µm clad
- Gd poison
- COBRA geometry assy

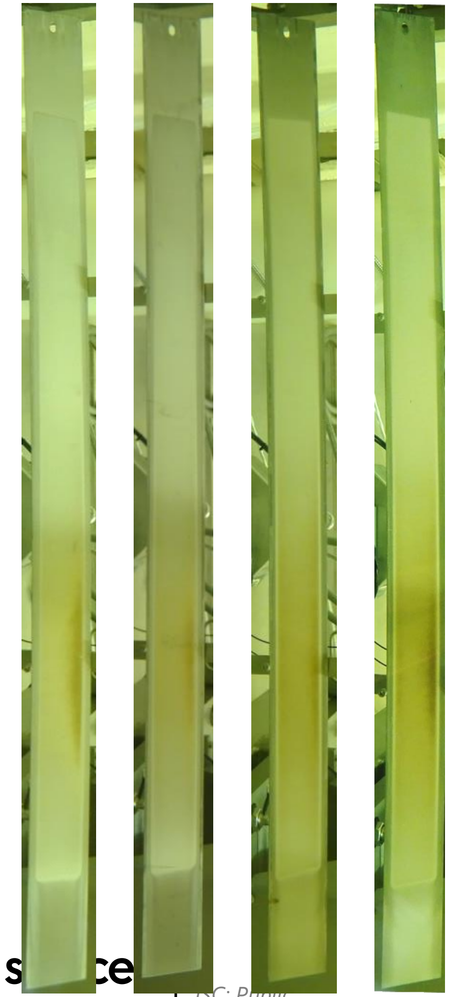
Licensing process (FANC)

COBRA-FUTURE (and more)

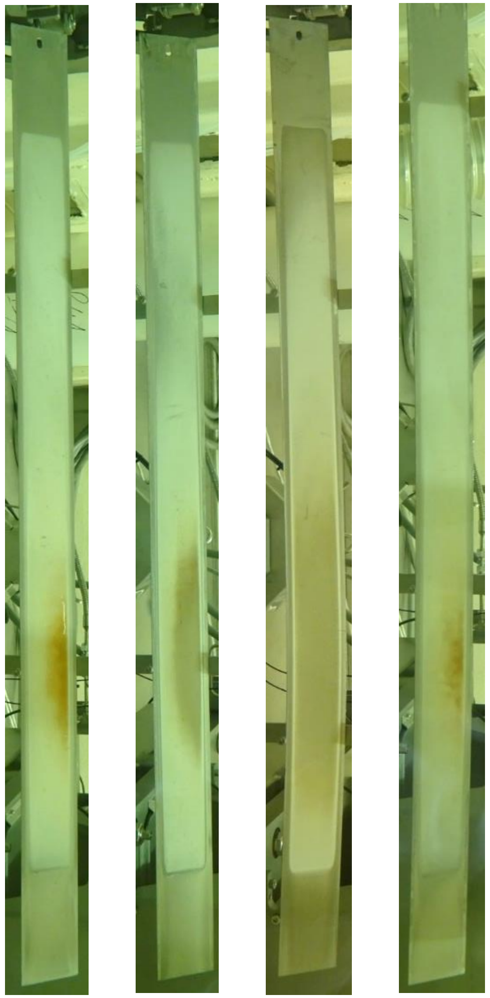


16 HD silicide fuel plates successfully irradiated in the FUTURE-5 basket in BR2

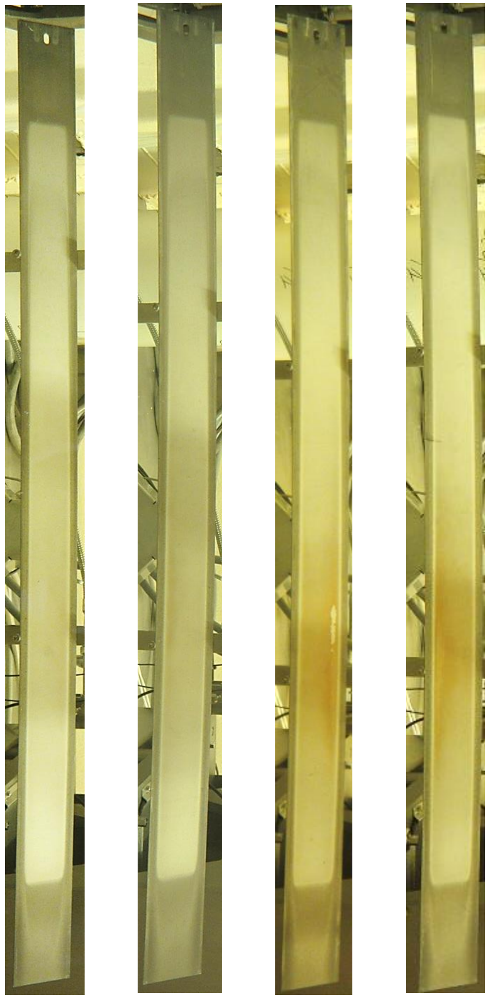
HiPROSIT irradiation
(CERCA) (BR2: 2019-2020)



COBRA-FUTURE irradiation
(BWXT) (BR2: 2020)



FUTURE-HFIR irradiation
(BWXT) (BR2: 2021)



KIMQI-FUTURE irradiation
(KAERI) (BR2: 2021-2022)

**KIMQI-FUTURE image from underwater observation, as cooling is ongoing. Visual exams in LHMA expected in Oct 2022.*

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*COBRA: Conversion Of BR2 – the Alternative

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- Gd & Sm_2O_3 + B_4C poison
- COBRA geometry assy

COBRA-FUTURE
- U_3Si_2 LEU 5.3g/cc
- 630µm meat – 350µm clad
- Gd poison
- E-FUTURE flat plates

COBRA-LEU LTA

COMING SOON!
- U_3Si_2 LEU 5.3g/cc
- 630µm meat – 350µm clad
- Gd poison
- COBRA geometry assy

(DE) PIE ongoing

BR2 driver fuel
- UAl_x HEU 1.3g/cc
- 510µm meat – 380µm clad
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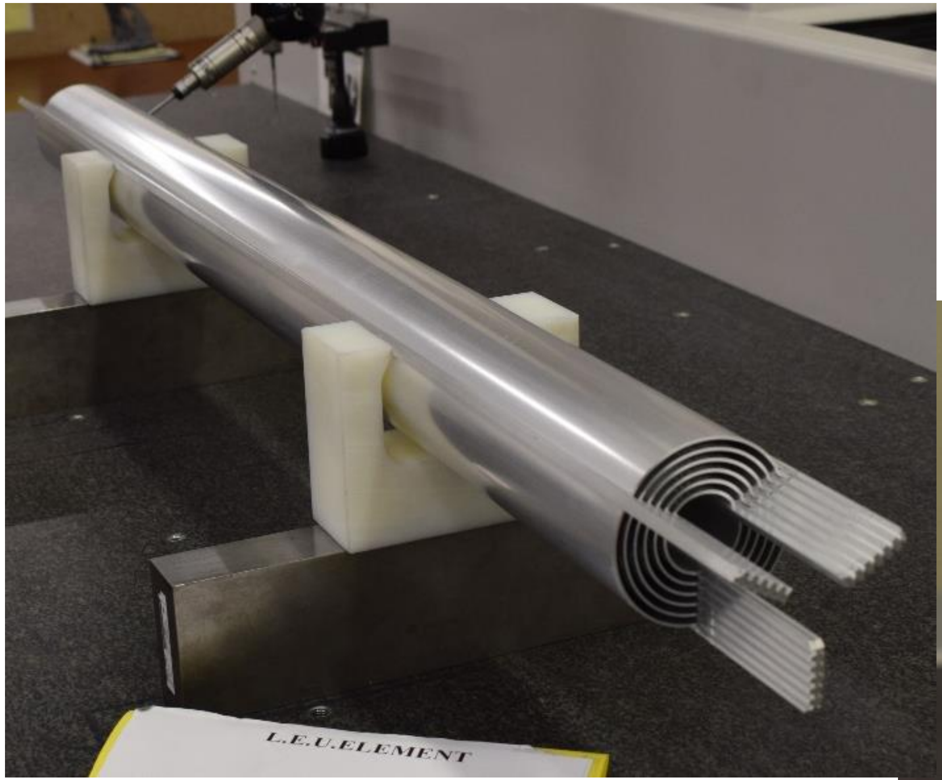
- STD geometry assy

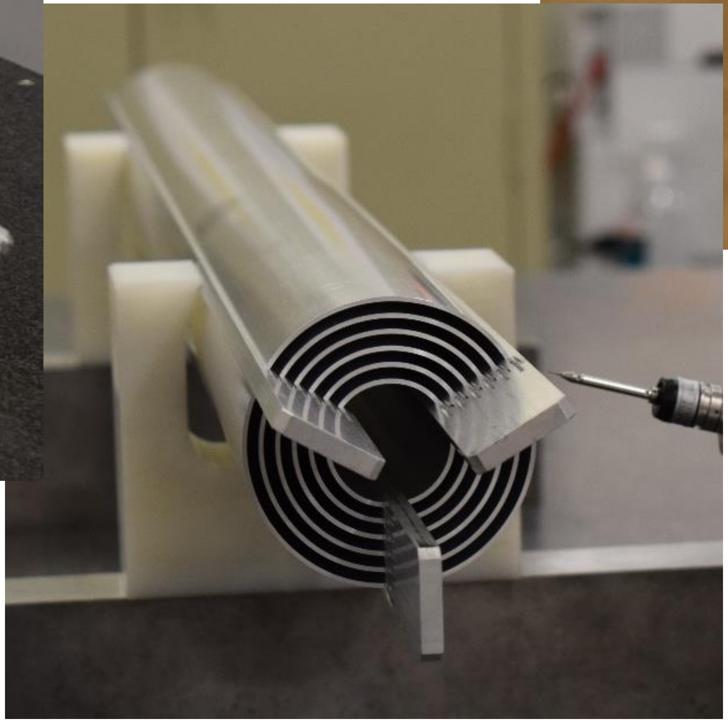
COBRA driver fuel
- UAl_x HEU 1.05g/cc
- 630µm meat – 350µm clad
- Gd poison 2.5g/assy
- COBRA geometry assy

Converted driver fuel
- U_3Si_2 LEU 5.3g/cc
- 630µm meat – 350µm clad
- Gd poison
- COBRA geometry assy

Licensing process (FANC)

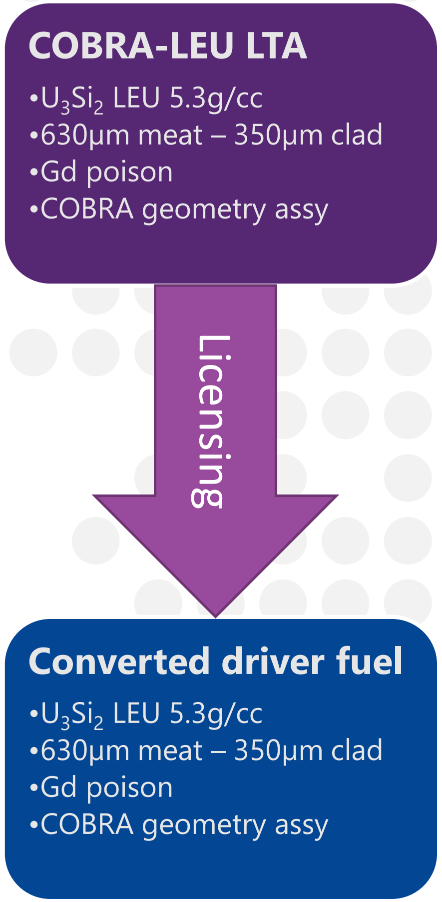
The COBRA-LEU LTAs





COBRA LEU LTA irradiation

- Three Lead Test Assemblies (LTAs)
  - 5.3 g/cc U_3Si_2 LEU with Gd poison
- Expose to typical BR2 irradiation conditions envelope
  - Heat flux up to 470 W/cm^2, avg burnup up to ≈60% ^{235}U
  - Three to four irradiation cycles of 28-35 days
  - Reactivity and hydraulic measurements
  - Visual inspections and wet sipping between cycles
  - Extensive PIE on 2 LTAs after sufficient cooling time
  - Obtain relevant data for fuel qualification and core conversion safety analyses



COBRA LEU LTA experiment approval

- Approval required for LTA experiment via CEE (SCK CEN's Committee for Evaluation of Experiments)
  - Phase 1: Preliminary Design (content table for safety report)
  - **Phase 2: Detailed design and safety report of experiment**
  - Phase 3: Reception tests (and manuals & procedures)
  - Phase 4: REX

Experimental process (CEE)

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COBRA-LEU LTA
- U_3Si_2 LEU 5.3g/cc
- 630µm meat – 350µm clad
- Gd poison
- COBRA geometry assy

CEE phase II: COBRA LEU

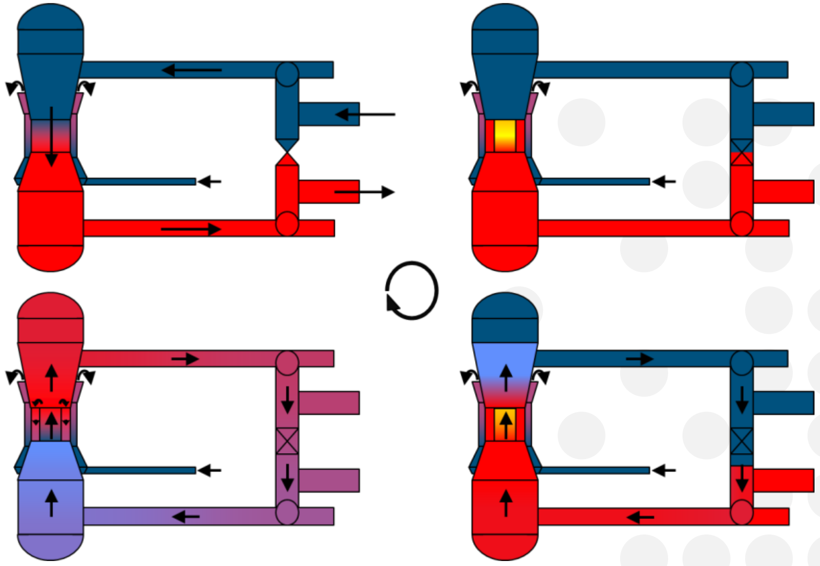
Safety analyses in support of CEE phase II report

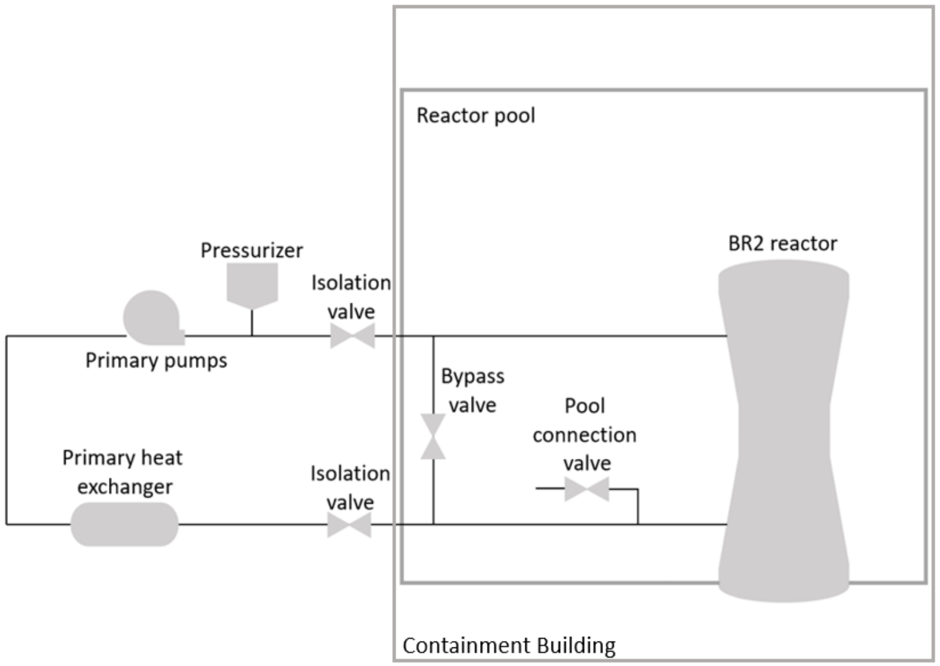
- Extensive review of various safety aspects of LTA experiment
- Particular focus on thermal-hydraulic safety analyses
- BR2 asked ANL to particularly analyze the following scenarios for the COBRA-LEU LTAs:
  - Nominal cooling conditions – allowable heat flux (PLTEMP)
  - Reactivity insertion transients equal to BR2 tech spec limits (PARET)
  - **Core cooling perturbations (RELAP5-3D)**
    - Three BR2 design base transient scenarios selected for RELAP5 analyses

BR2 RELAP5-3D modelling

Overview of analyzed scenarios [1]

- **<u>Test A:</u>** Primary cooling main pumps trip (no shutdown pump takeover)
- <u>Test F:</u> Untimely opening of the pool connection valve leading to primary circuit depressurization with Bypass valve opening
- **<u>Test G:</u>** Untimely opening of the pool connection valve leading to primary circuit depressurization **without** Bypass valve opening

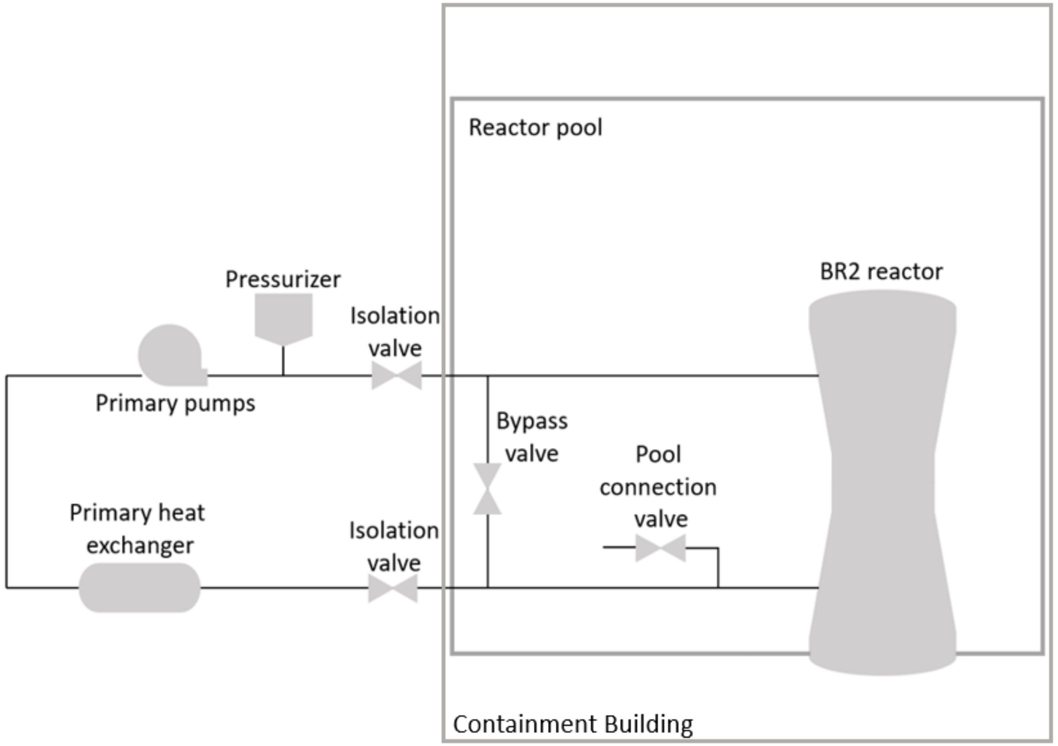




BR2 RELAP5-3D modelling

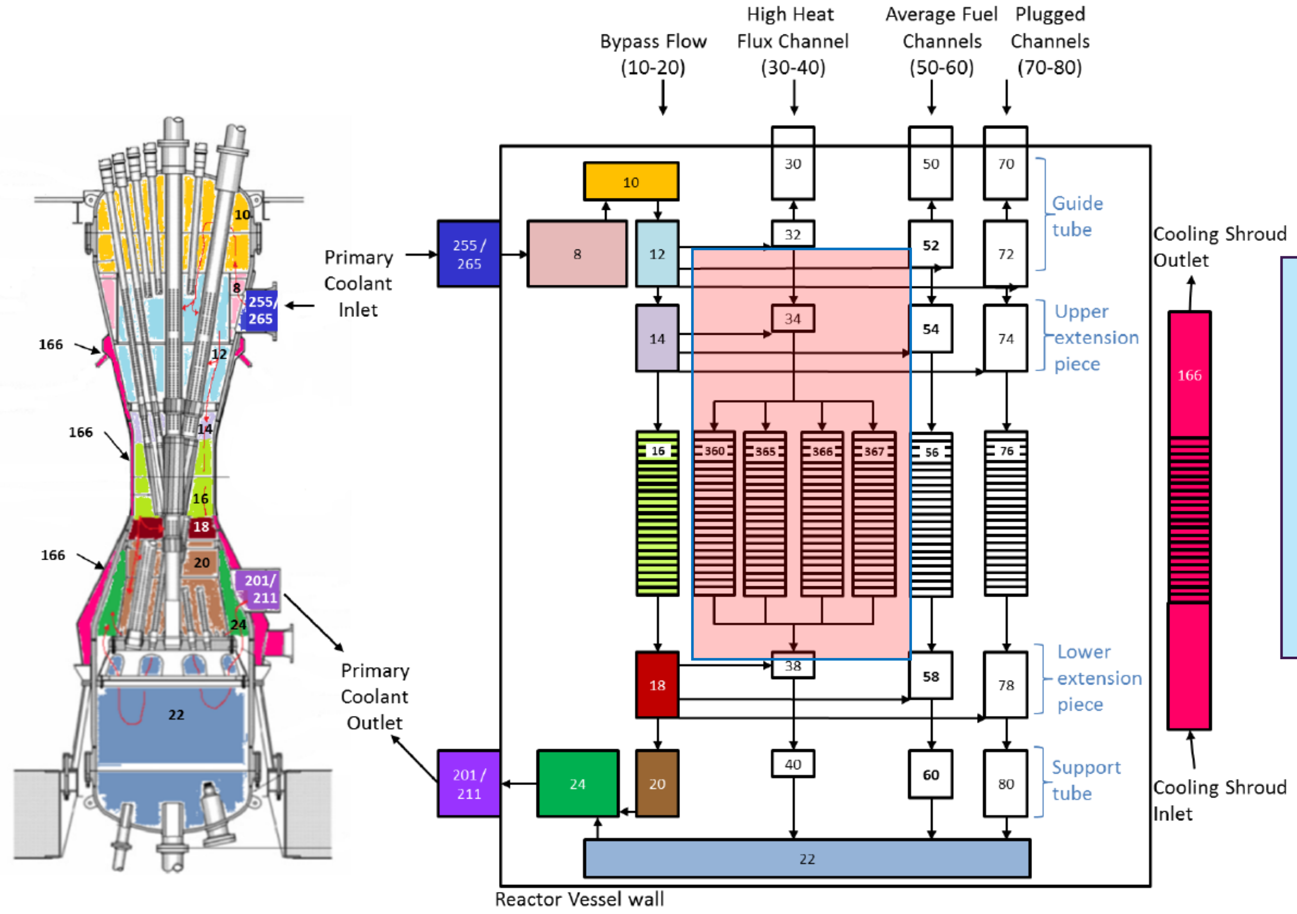
Overview of analyzed scenarios [2]

- Scenarios correspond to historical commissioning tests of BR2 from 1963
- Analyzed by ANL with RELAP5 for 2016 PSR:
  1. Reproduced 1963 Test Results (validation)
  2. Extended to up-to-date plant specs
  3. Beyond design scenarios (see RERTR-2019); (not in scope for LTAs.)
- Prior to current analyses, extensive regression testing of BR2 RELAP5-3D model was done. (see RERTR-2021)

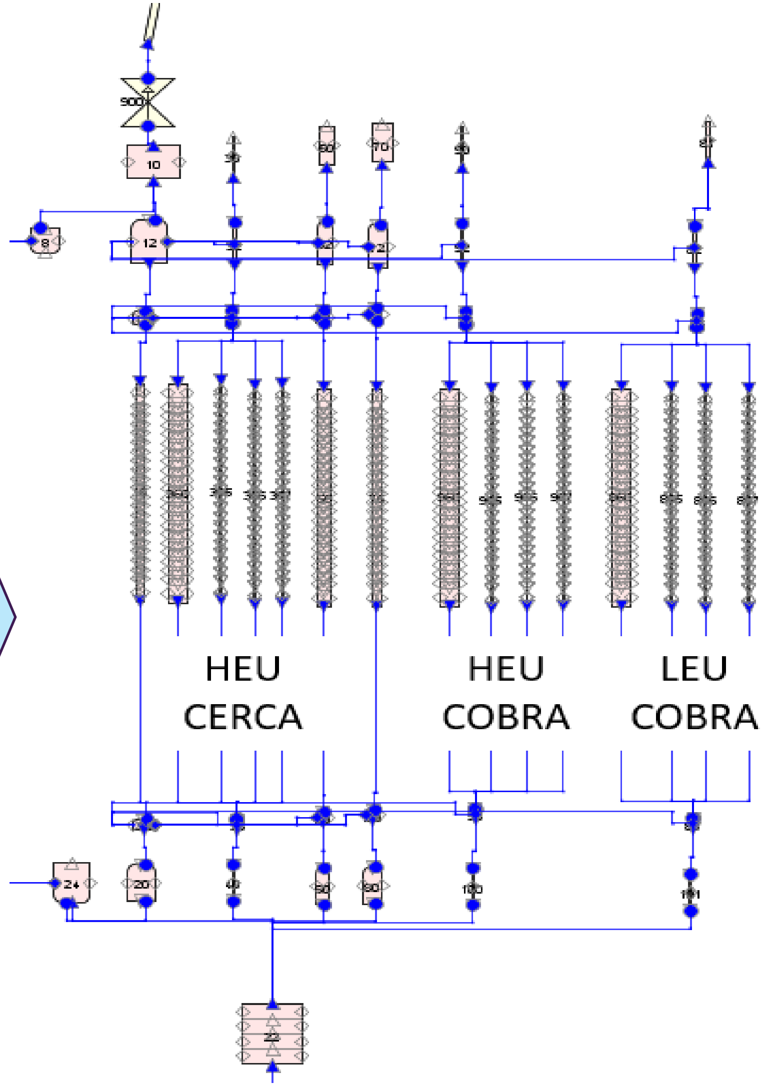


Extension of existing BR2 RELAP5 model

RELAP5 mainly used to investigate flow reversal cooling conditions in hottest fuel element and segments.

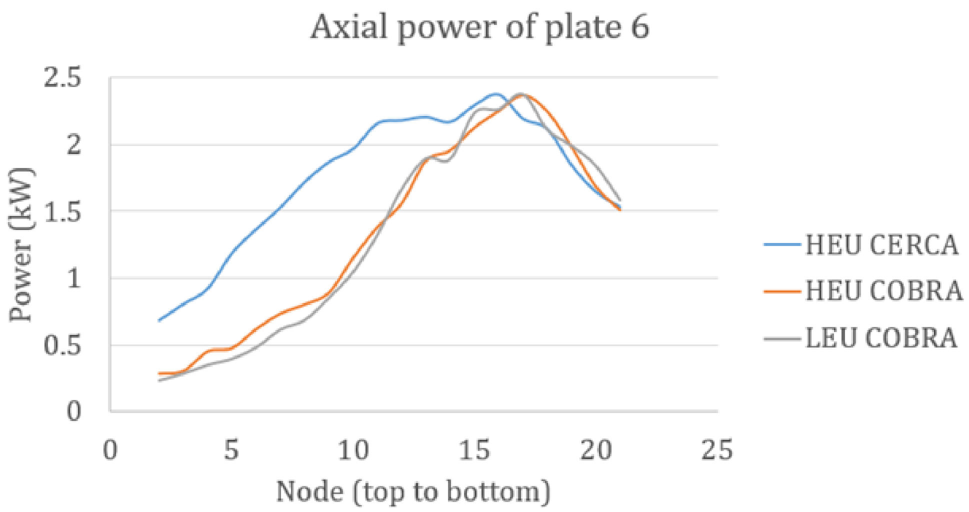


Added COBRA-HEU and LEU side branches for hot FE



Other relevant input data

- COBRA HEU and LEU hot FE axial power profile re-calculated for updated 2026 representative core
  - Different control rod configuration (8 vs 6)
- Material properties for once-burnt fuel element (16% ^{235}U BU)
- LEU silicide (U_3Si_2) thermal conductivity conservatively estimated with DART code



Material properties of fuel plates (once-burnt, ≈16% ^{235}U burnup)

	Thermal Conductivity (k) (W/m-K)	Volumetric Heat Capacity (ρCp) (J/m³-K)
HEU CERCA and HEU COBRA UAlx-Al dispersion	64.1	$2.312*10^6$
COBRA LEU: U_3Si_2 dispersion	**8.7**	$2.302*10^6$
Cladding: AG3NE	130.0	$2.350*10^6$
Oxidation layer (16 µm COBRA, 10.7 µm CERCA)	2.25	$3.203*10^6$

Test A results

Total loss of (forced) flow followed by the opening of the bypass valve

- Without oxidation layer; fuel and cladding temperature acceptable for all three fuel elements

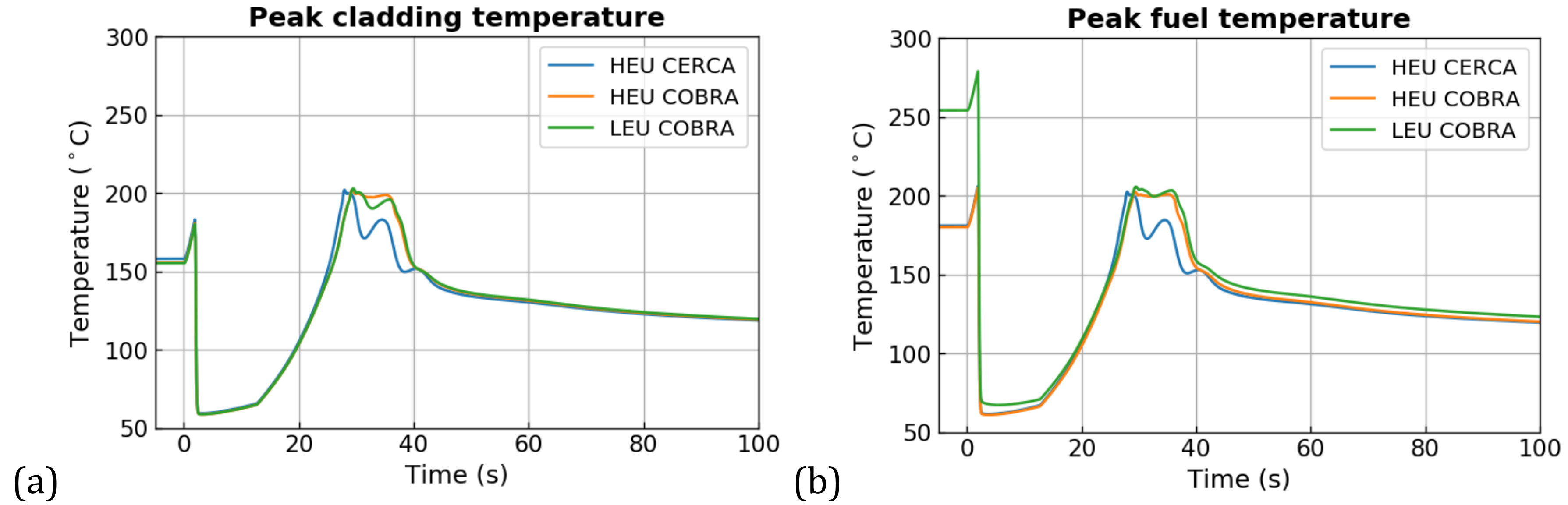
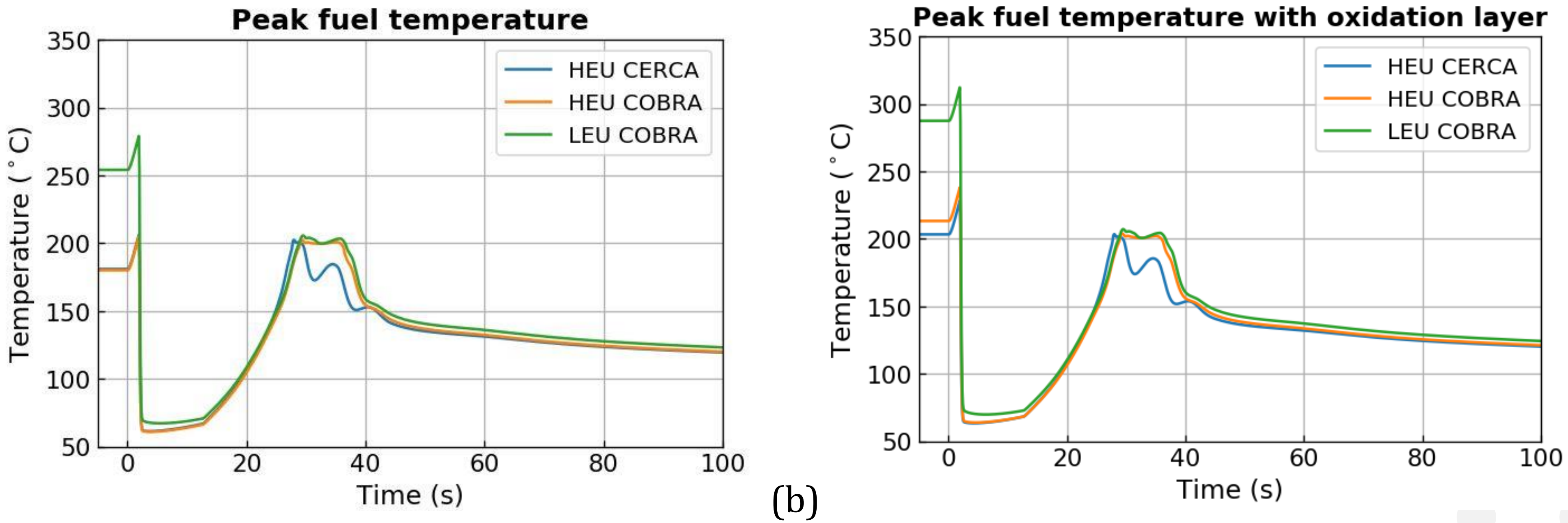


Figure (a) Peak cladding temperatures and (b) peak fuel temperatures in Test A

Test A results

Total loss of (forced) flow followed by the opening of the bypass valve

- Fuel temperature with and without oxidation layer → **no impact after scram**



(a) (b)

Figure a) Peak fuel temperatures without oxidation layer in Test A, b) with oxidation layer

Test G results

Untimely opening of the pool connection valve (total loss of pressure) without opening the bypass valve

- Fuel and clad temperature acceptable for all three fuel elements
- No increased/prolonged nucleate boiling for COBRA LEU (also for test F)

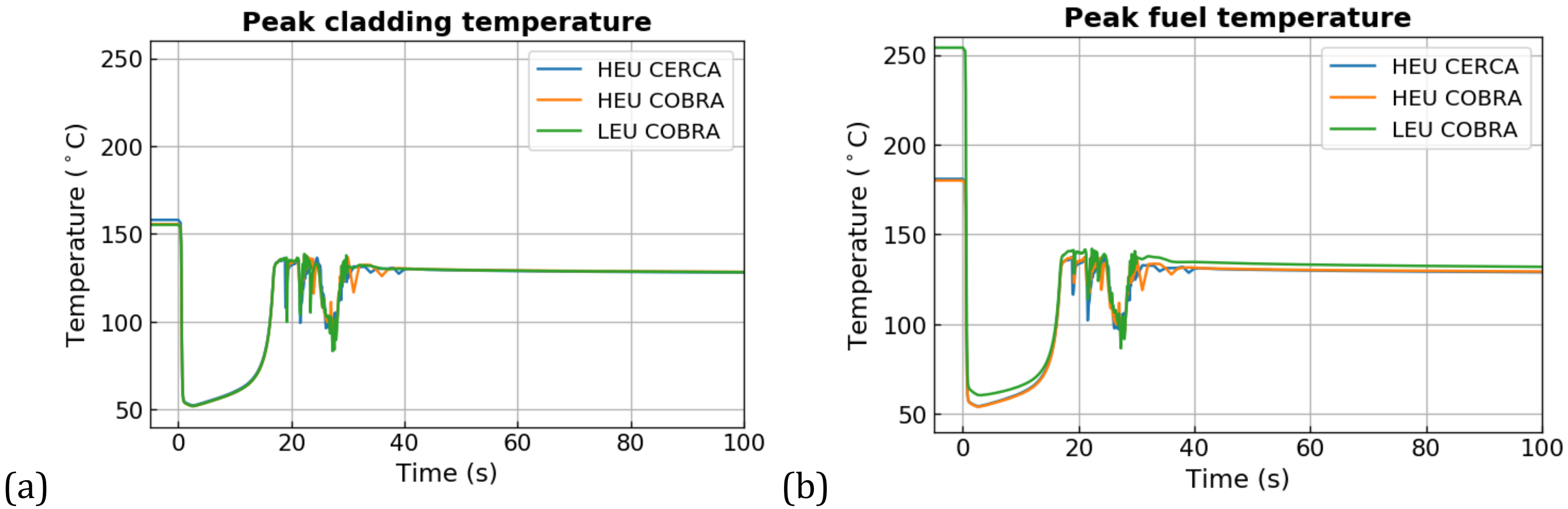


Figure (a) Peak cladding temperatures and (b) peak fuel temperatures in Test G

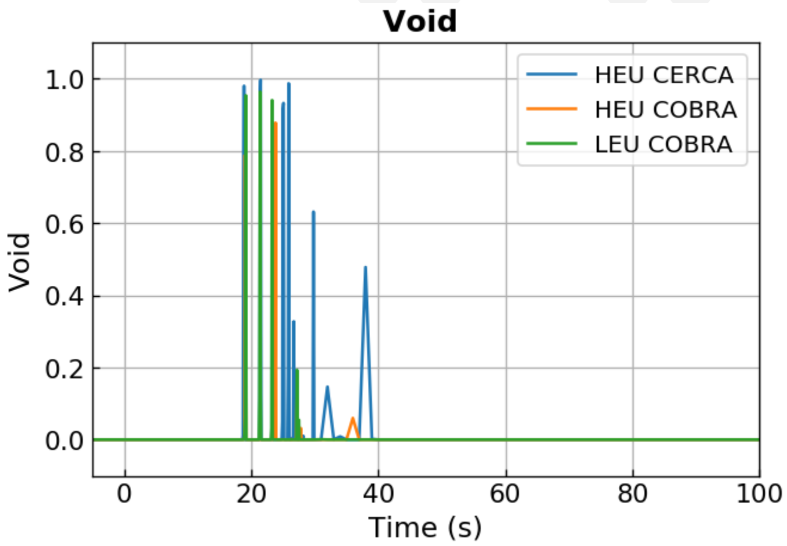


Figure Void in Test G

Conclusion

RELAP5-3D Test A, (F), G results for LTAs

- Some differences between CERCA-HEU and COBRA due to:
  - Axial power profile differences
  - Geometrical changes (slightly reduced flow area of COBRA)
- Transient behavior for COBRA-LEU very similar to COBRA-HEU
  - Gives confidence that COBRA-LEU LTAs are equally safe during flow reversal transients
- Lower thermal conductivity for COBRA-LEU and presence of oxide layer has no impact on peak fuel temperatures during/after flow reversal transients…

Conclusion

U_3Si_2 Thermal conductivity and high heat flux situations

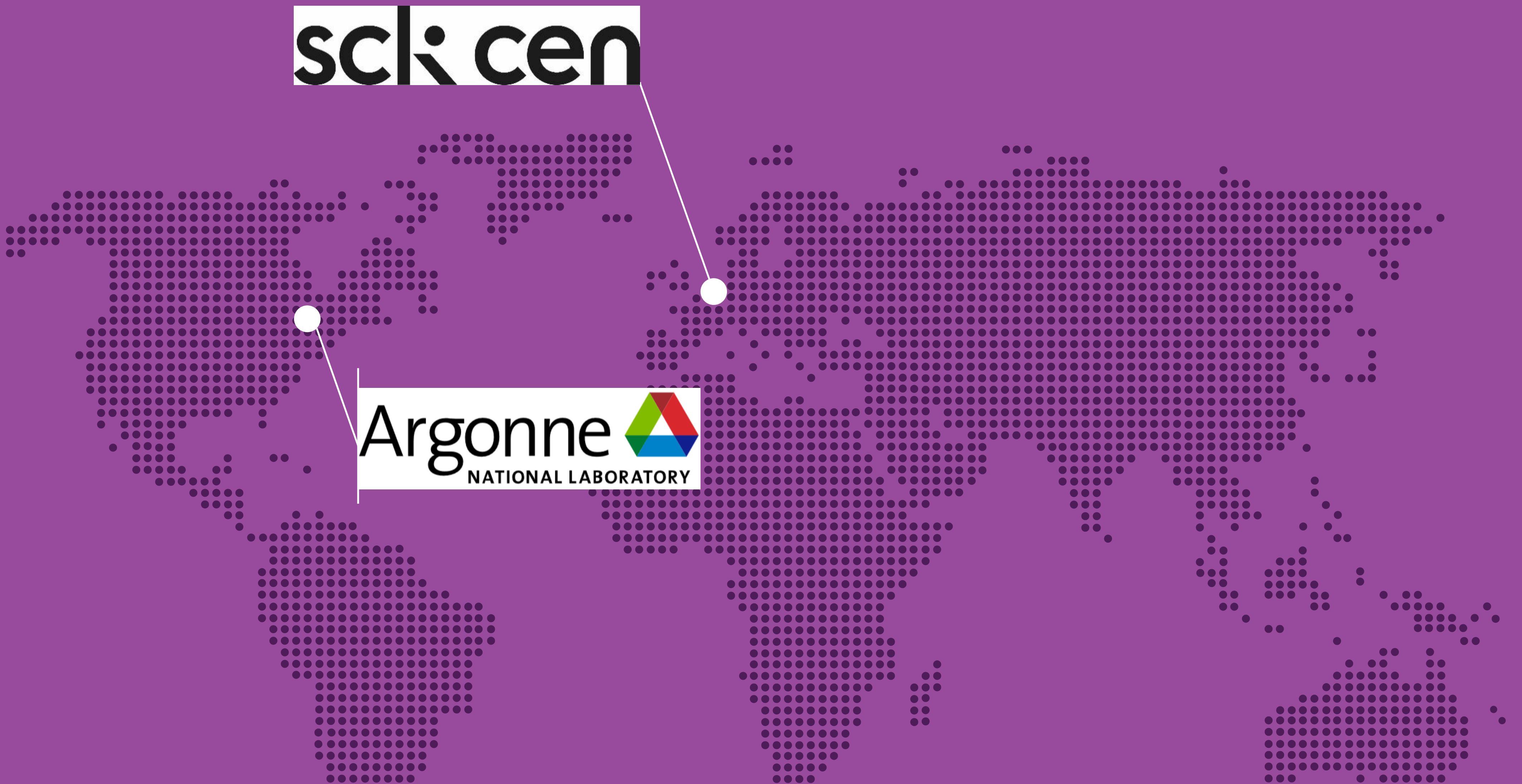
- However, reduced thermal conductivity of irradiated high density U_3Si_2 is a relevant factor in high heat flux situations
  - ANL also looked at nominal cooling conditions (PLTEMP) and reactivity insertion transients (PARET) for once burnt (≈16% U-235 burnup) fuel elements.
  - Results provide confidence that LTA irradiation can be performed safely.
  - Nonetheless, reducing uncertainty on **irradiated** fuel meat thermal conductivity will be important for future BR2 core conversion safety analyses

Conclusion

Future work on BR2 conversion

- Future work on safety analyses
  - Converting the BR2 RELAP model entirely to COBRA fuel and COBRA representative cores
  - More scenario’s to be analyzed than Test A, F & G
  - Several other analyses within the framework of the BR2 conversion safety analysis file (e.g. MCNP, PLTEMP, PARET).

- Experimental work at BR2
  - Irradiate the COBRA-LEU LTAs (!)
  - Post Irradiation Examination
    - Thermal conductivity measurements in COBRA-FUTURE and COBRA LEU LTAs



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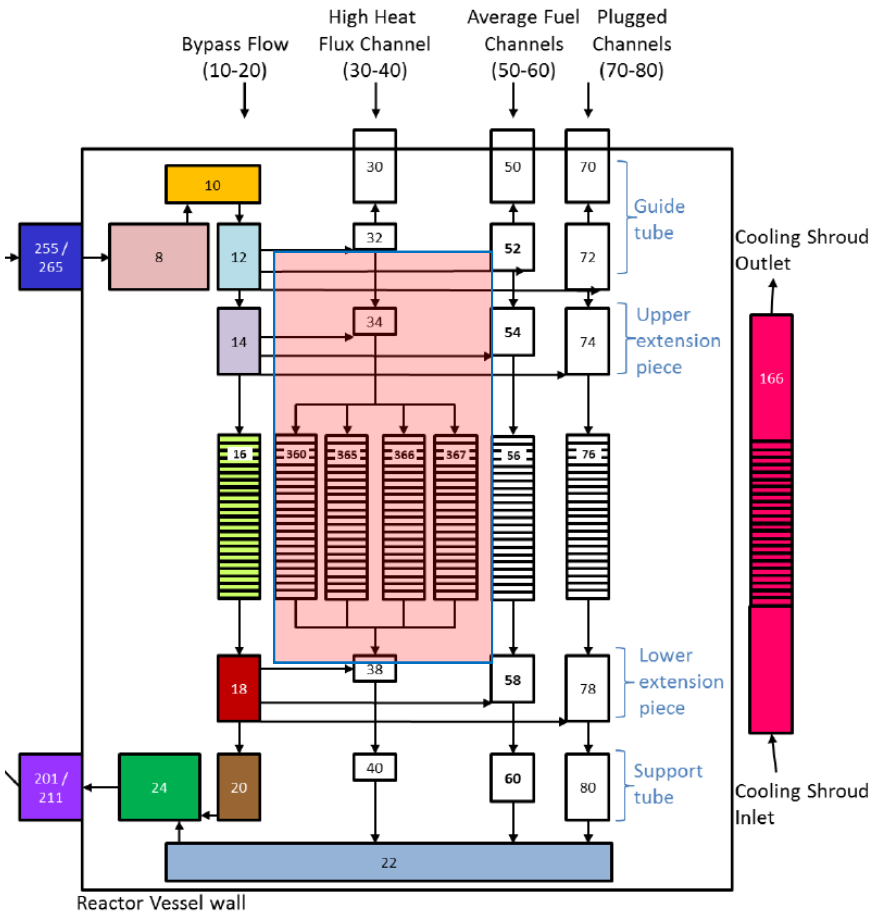
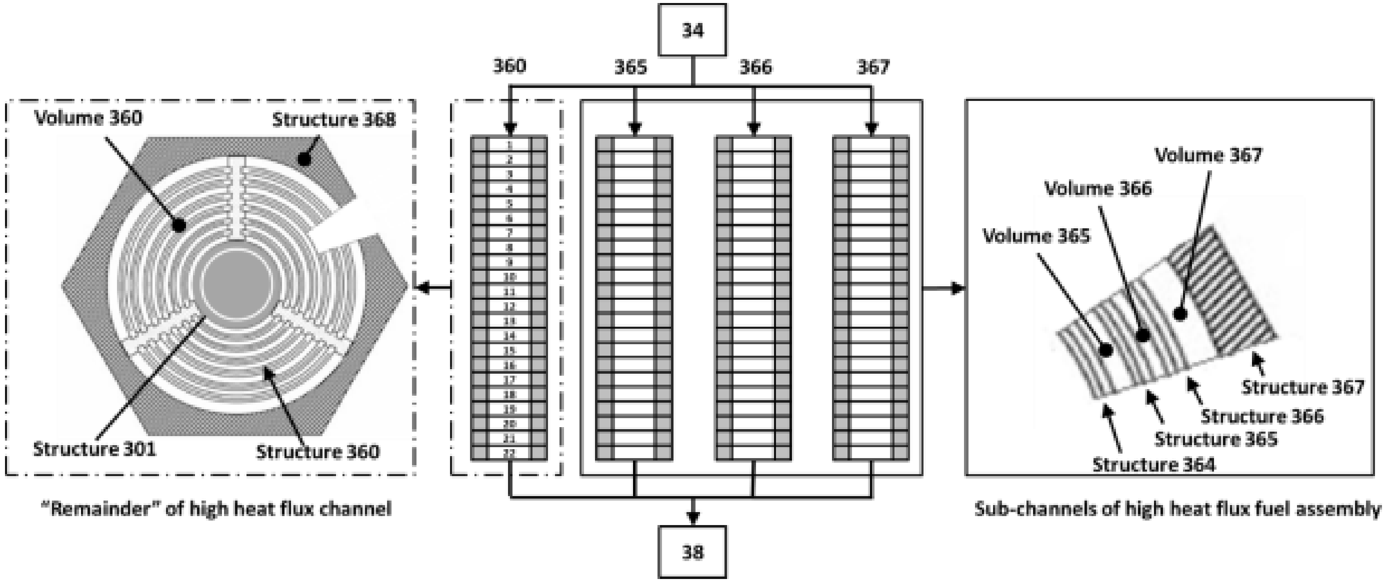
BR2 RELAP5 model hot FE discretization

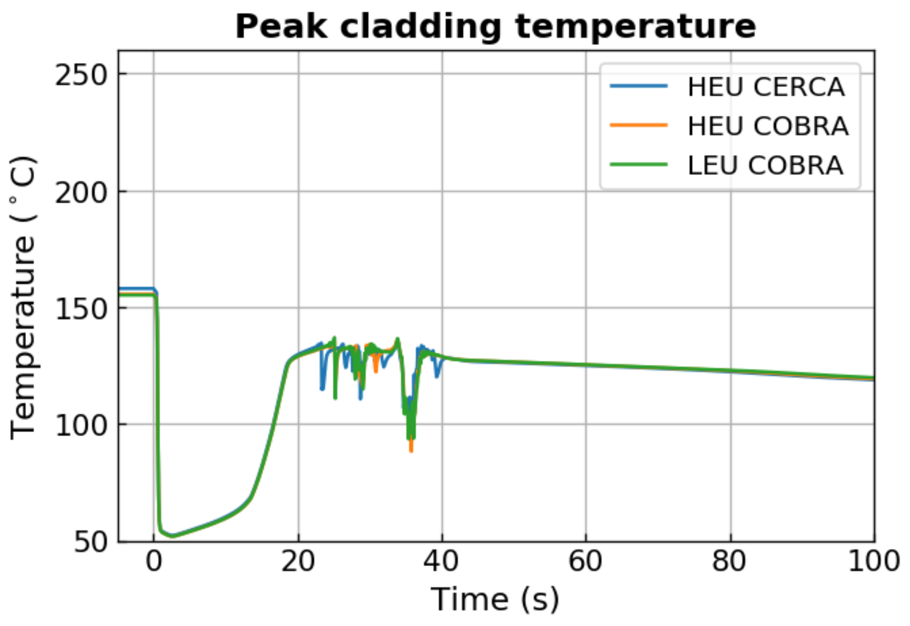




Test F results

Untimely opening of the pool connection valve (total loss of pressure) followed by the opening of the bypass valve

- Fuel and clad temperature acceptable for all three fuel elements



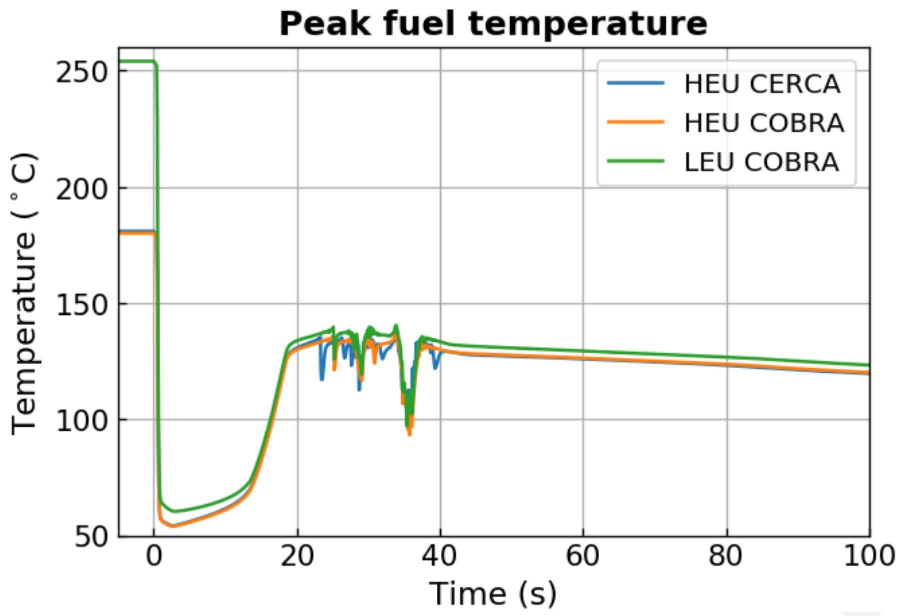


Figure (a) Peak cladding temperatures and (b) peak fuel temperatures in Test F