



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA



Neutronic and Thermal Hydraulic Analyses of ELSY Nuclear Reactor Core

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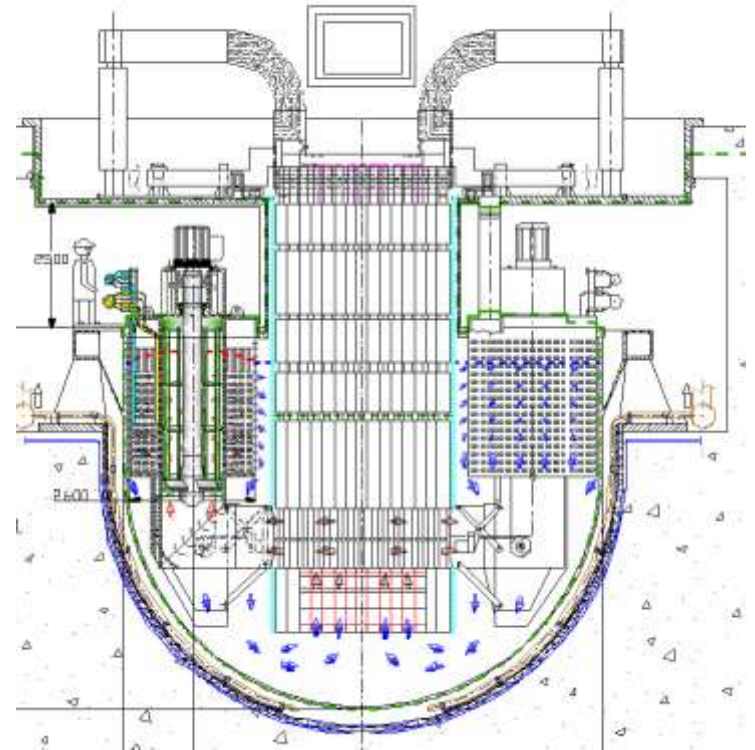


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Introduction

European Lead-cooled System (ELSY)

| | |
|------------------------------|------------------|
| Electrical power | 600 MWe |
| Design of the primary system | Pool type system |
| Thermal efficiency | ~ 40% |
| Primary Coolant | Lead |
| Core inlet temperature | 400 C |
| Core outlet temperature | 480 C |



ELSY, 600 MWe [Cinotti (2007)]

- Neutronic and thermal-hydraulic analyses of the ELSY reactor core during operational conditions.
 - i. Determine the lead temperature based on neutronic and thermal-hydraulic analyses to check whether the design criterion is fulfilled.
 - ii. CFD analyses of the flow in- a single sub-channel and between fuel-assembly to provide feedback to the sub-channel analyses codes in terms of the heat transfer correlations.

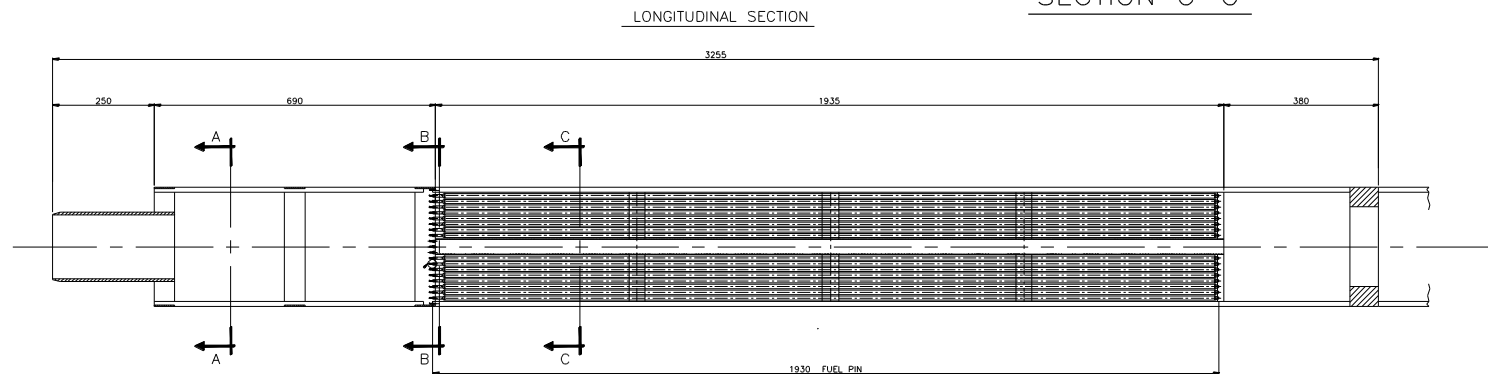
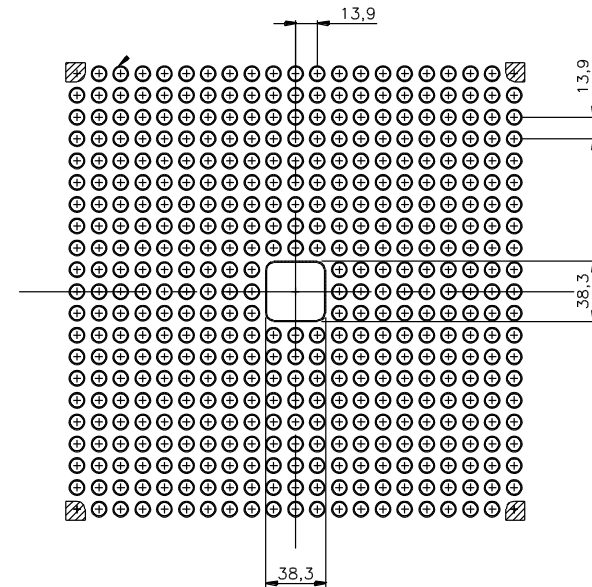
- Analyze the power distribution in the ELSY reactor core based on the neutronic investigation
- Employ an average power per rod based on suggestion from the neutronic analyses for the thermal-hydraulics investigation
- For the neutronic analyses:
By using and comparing deterministic (ERANOS) and stochastic (MCNP) codes:
 - definition of suitable zoning to flat power/FA distribution
 - evaluation of the enrichments
 - evaluation of the BU swing and regulating/control/scram absorber redundant systems
 - **power distributions**
 - performances
- For the thermal-hydraulic analyses:
 - Use of a suitable turbulence model (based on literature review and an in-house validation campaign)
 - Influence of computational domain
 - Determine the flow and temperature distribution in:
 - a single sub-channel
 - between fuel assemblies.

ELSY fuel assembly

(Source: Artioli et al. 2008)

Main parameters:

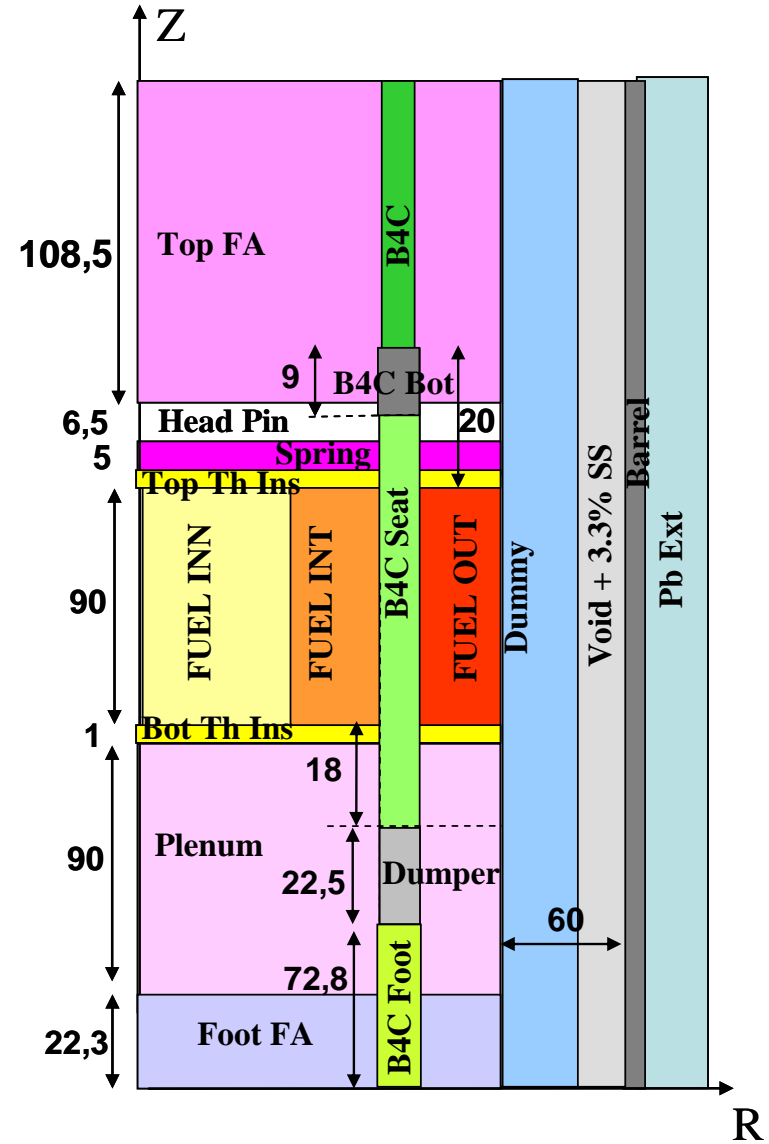
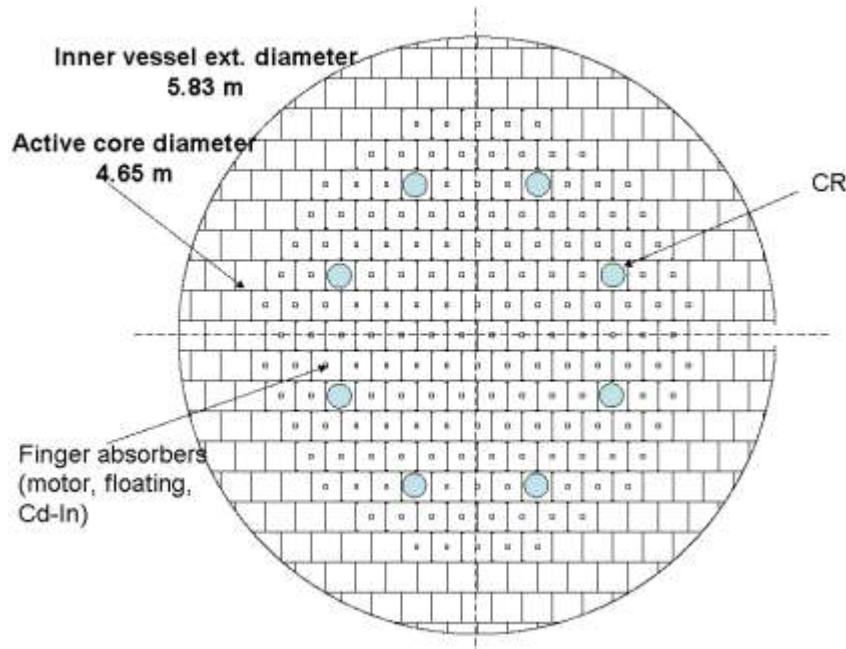
| | | |
|---|--------|----|
| Fuel rod pitch (center-to-center) | 13.9 | mm |
| Rod pitch ratio | 1.3238 | |
| Number of fuel rods in assembly (rod/row number) | 428 | |
| Structural box inner width | 32.30 | mm |
| Structural box wall thickness | 3.00 | mm |
| Clearance between assemblies | 2.10 | mm |
| Assembly pitch (center-to-center) | 294 | mm |
| Total assembly height | 3255 | mm |
| Fuel mass in assembly | ~250 | kg |



Neutronic analyses of the ELSY reactor core

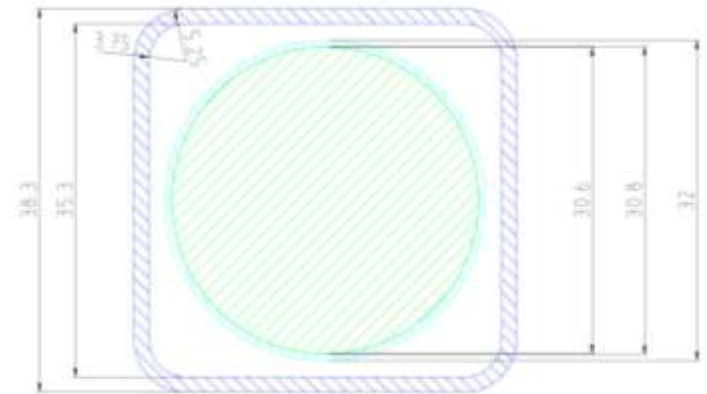
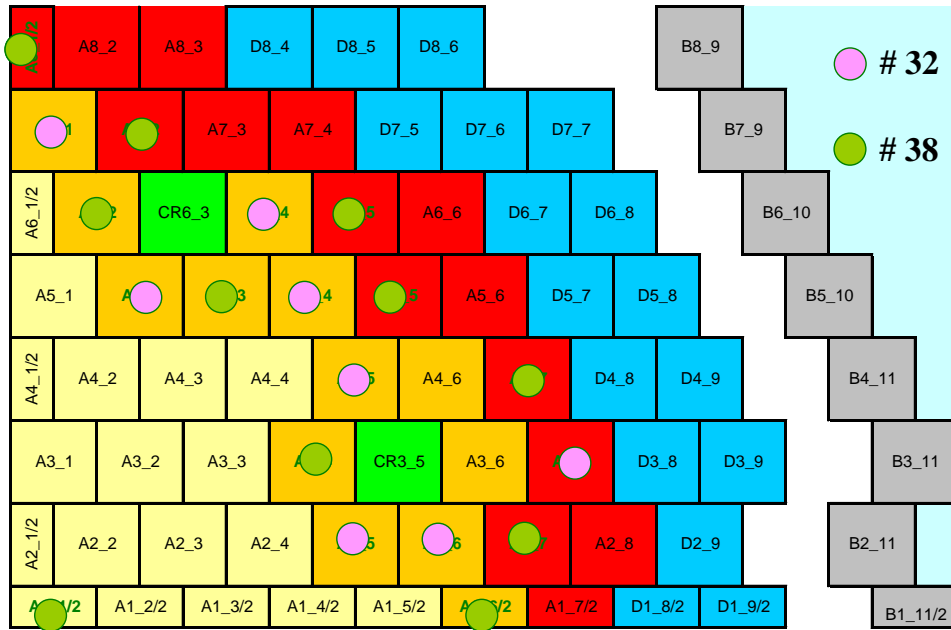
ELSY core

Core schemes



ELSY core

Finger Absorber Rods (FARs)



Positioning of the FARs

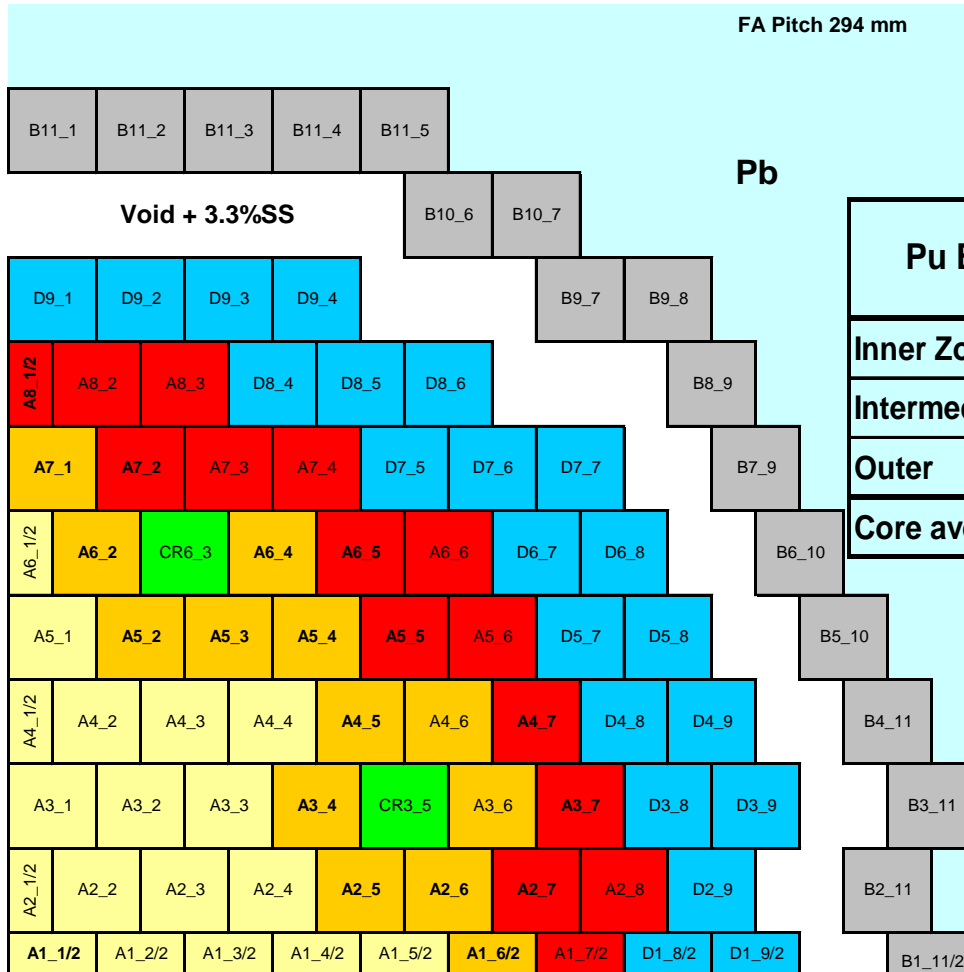
- The 38 green ones are devoted to the compensation/regulation and to the scram
- The 32 pink ones are devoted to the scram
- The 8 CRs are devoted to the shutdown and scram

In normal condition only the 38 green FARs are operating.

They are used in such a way to improve the flattening of the power/FA distribution

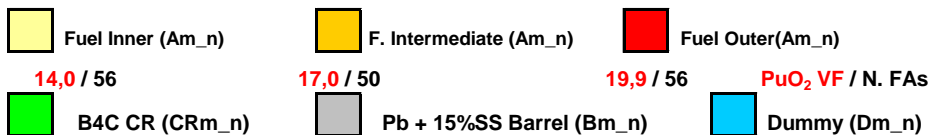
ELSY core

Core enrichment zoning

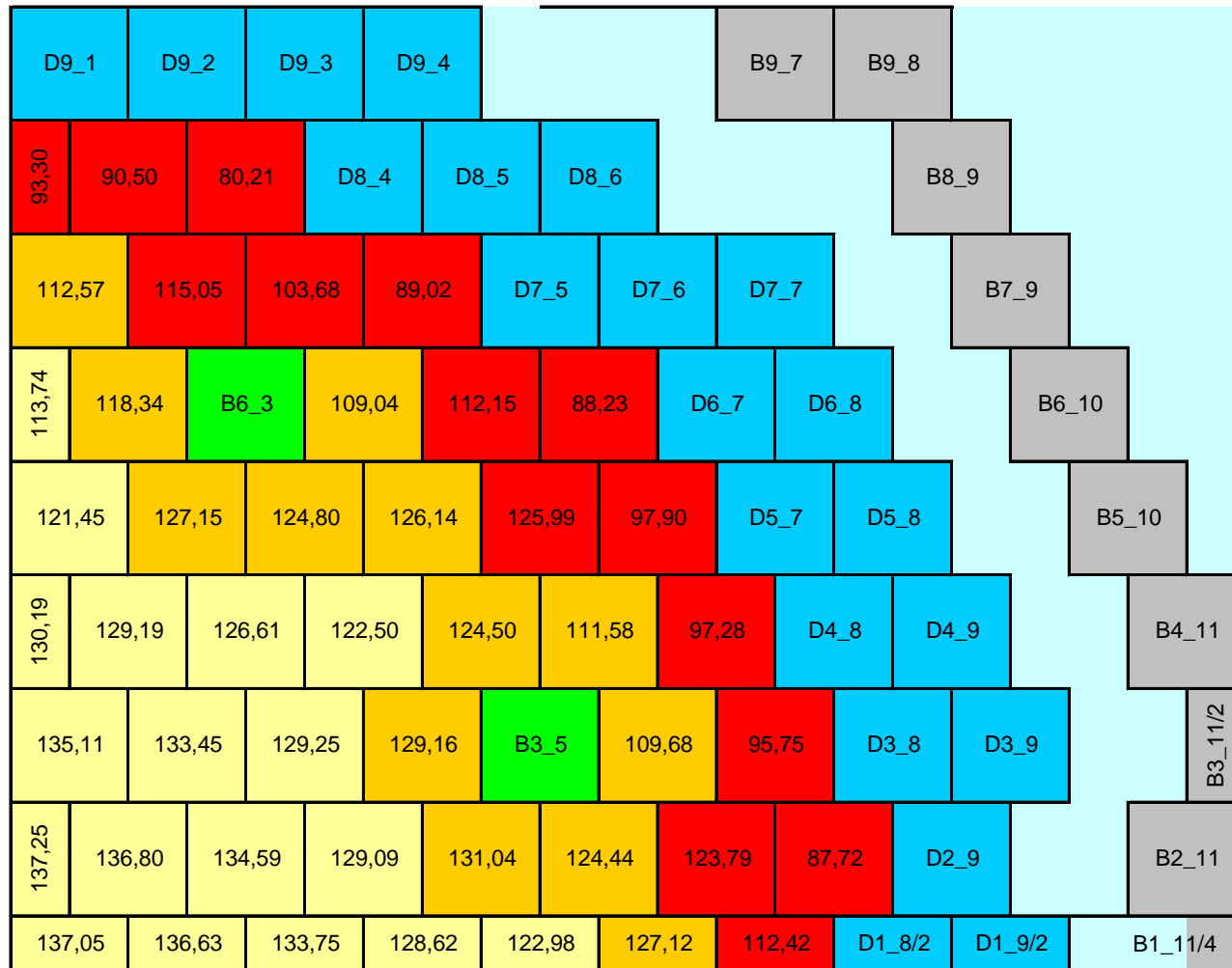


| Pu Enrichments | FAs | PuO ₂ VF | Pu / (U+Pu) | |
|----------------|-----|---------------------|-------------|-------|
| | | [%] | at.% | wt.% |
| Inner Zone | 56 | 14,00 | 14,45 | 14,54 |
| Intermediate | 50 | 17,00 | 17,53 | 17,63 |
| Outer | 56 | 19,90 | 20,50 | 20,61 |
| Core average | 162 | 16,97 | 17,49 | 17,59 |

→ Different enrichment zones allow the possibility of power flattening in a fuel assembly.

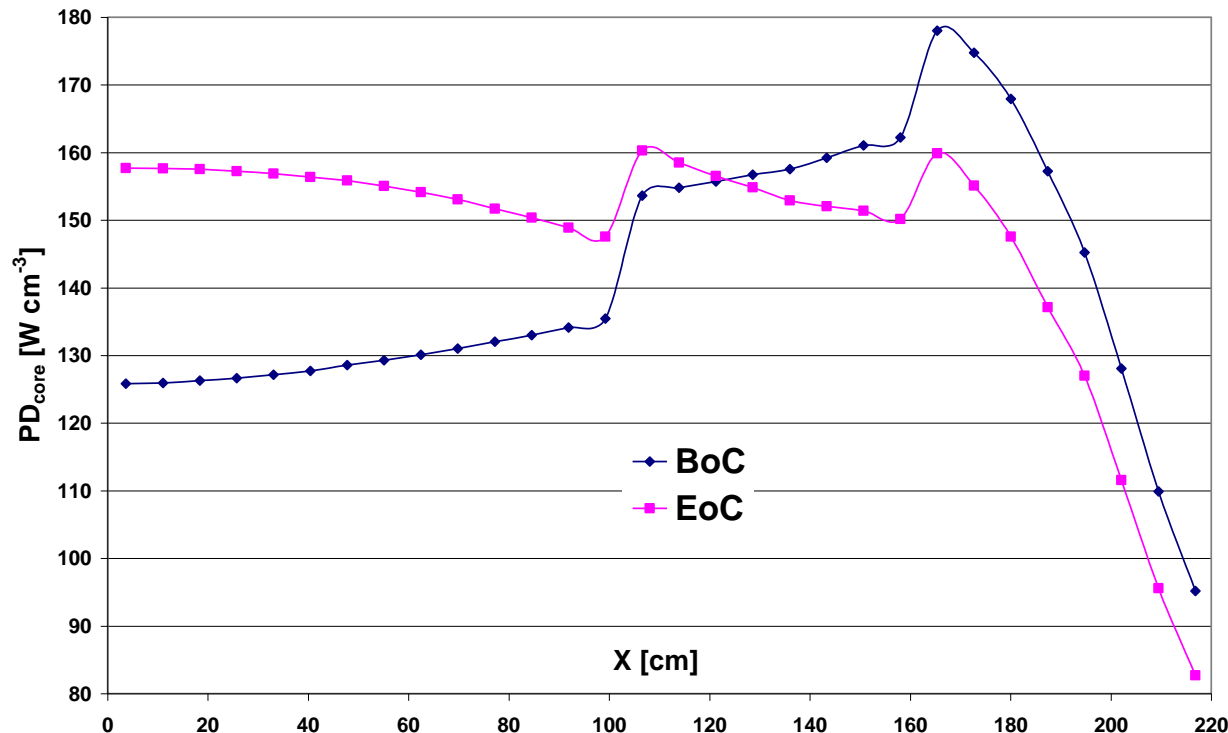


Power/FA distribution at EoC (W cm⁻³)



→ Flattening of Power/FA distribution at the end of cycle is achieved in the inner and intermediate zones (indicated by colors as in slide 11).

Power/FA distribution at EoC ($W\text{ cm}^{-3}$)



→ The “radial” flattening has been optimized, by enrichment zoning, at EoC configuration (pink); the consequent worst (blue) distribution at BoC will be improved by a suitable choice of the FARs, used to compensate for the swing (900 pcm)

→ The employed mean rod power in the thermal-hydraulic analyses is acceptable in the inner and intermediate region with flattened power/FA distribution.

Used for the thermal-hydraulic analyses

| | | |
|-------------------------------------|-------|-----|
| Thermal power | 1500 | MW |
| Active core diameter | 4.65 | m |
| Core height | 0.9 | m |
| H/D | 0.19 | |
| Fuel mass | 42.5 | t |
| Number of Fuel Assemblies | 170 | |
| Mean assembly power | 8.82 | MW |
| Mean rod power | 20.62 | kW |
| Radial power form-factor (allowed) | 1.2 | |
| Coolant inlet temperature | 400 | °C |
| Coolant average outlet temperature | 480 | °C |
| Lead bulk-velocity | 1.5 | m/s |
| Pressure drop on core (expected) | ≤ 0,1 | Mpa |
| Clad maximum temperature (expected) | 550 | °C |

→ The power distribution/FA resulting from the neutronic simulations was simplified (by making it uniform) and applied to the thermal-hydraulic simulations.

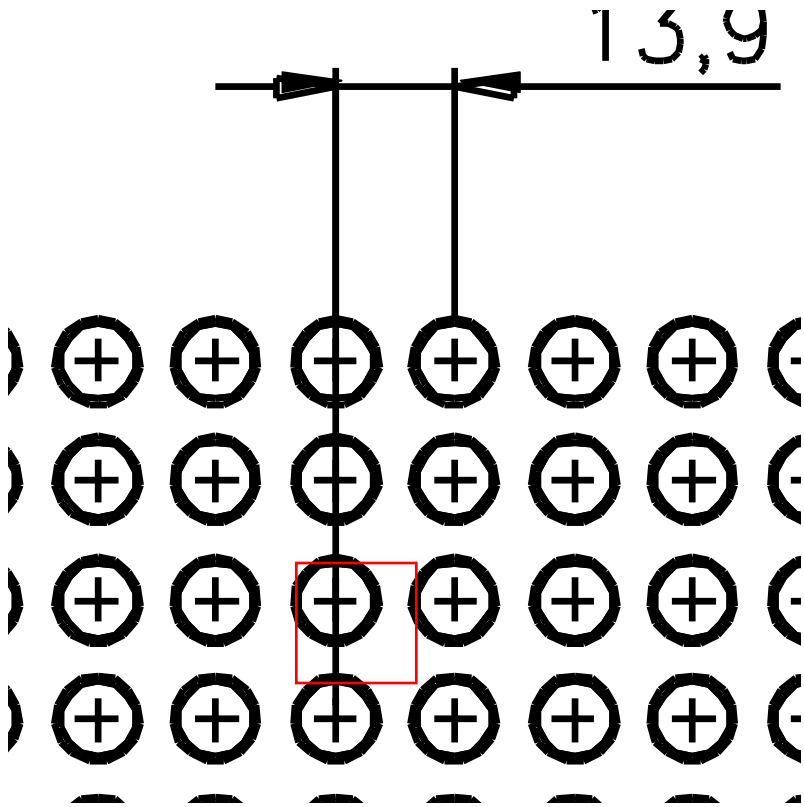
Thermal-hydraulic analyses of the ELSY reactor core

Single sub-channel analyses

Computational model



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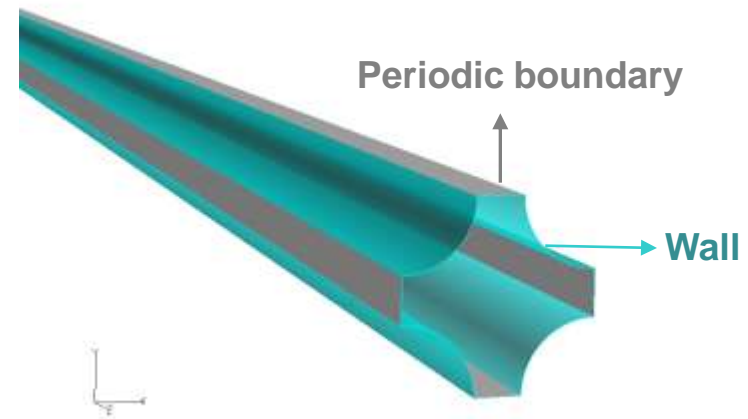


Considered sub-channel (SQUARE arrangement) in computation

Single sub-channel analyses

Computational model

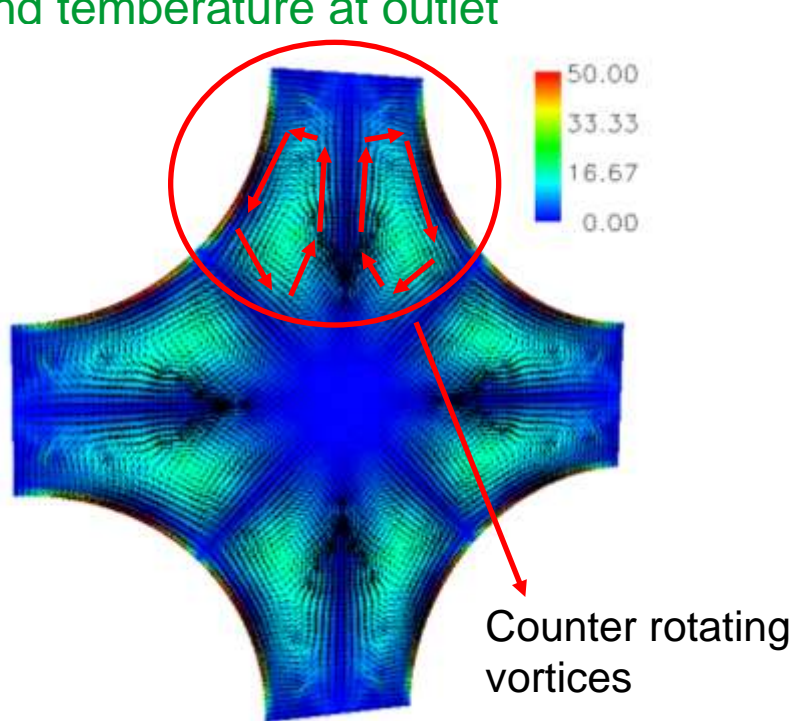
- **Computational Code: CFX-11**
- **Geometry**
 - ELSY rod bundle
 - Length = 900 mm
 - Diameter of tube = 10.5 mm
 - Pitch-to-diameter ratio ~ 1.32
 - Hydraulic diameter = 9.155 mm
- **Boundary conditions**
 - Inlet: Uniform flow velocity of 1.5 m/s
 - Inlet: Fluid temperature = 400 C
 - Outlet: Zero [Pa] static pressure
 - Walls: Uniform surface heat fluxes for the given average power (see slide 15)
- **Working fluid:**
 - Lead with recommended properties as a function of temperatures (from OECD handbook)
- **Pitch-to-diameter ratio**
 - Numerically the ELSY fuel rods are additionally arranged with pitch-to-diameter ratio of 1.1 and 1.2 for heat transfer analyses.



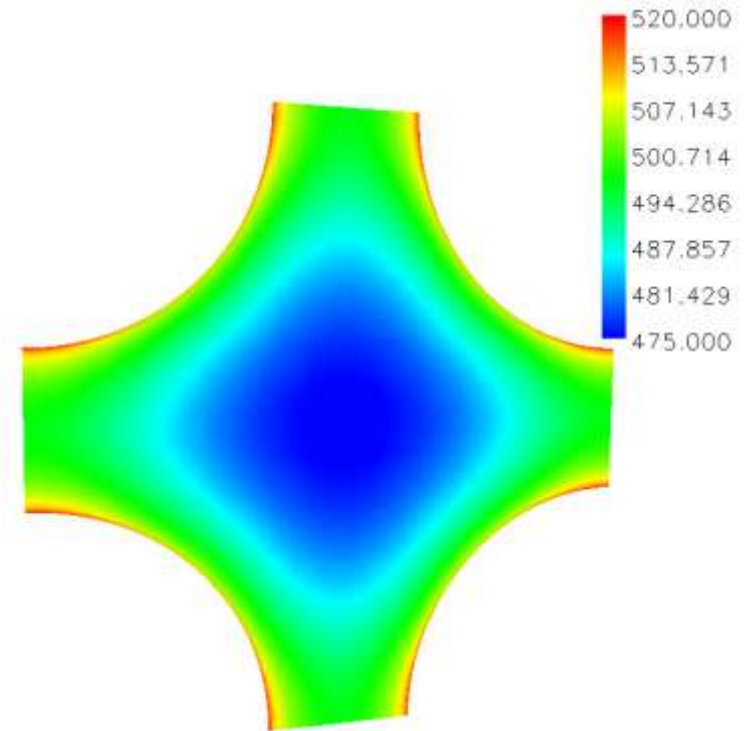
Single sub-channel analyses

Results:

Secondary flow, vorticity
and temperature at outlet



Flow field: velocity vectors and vorticity

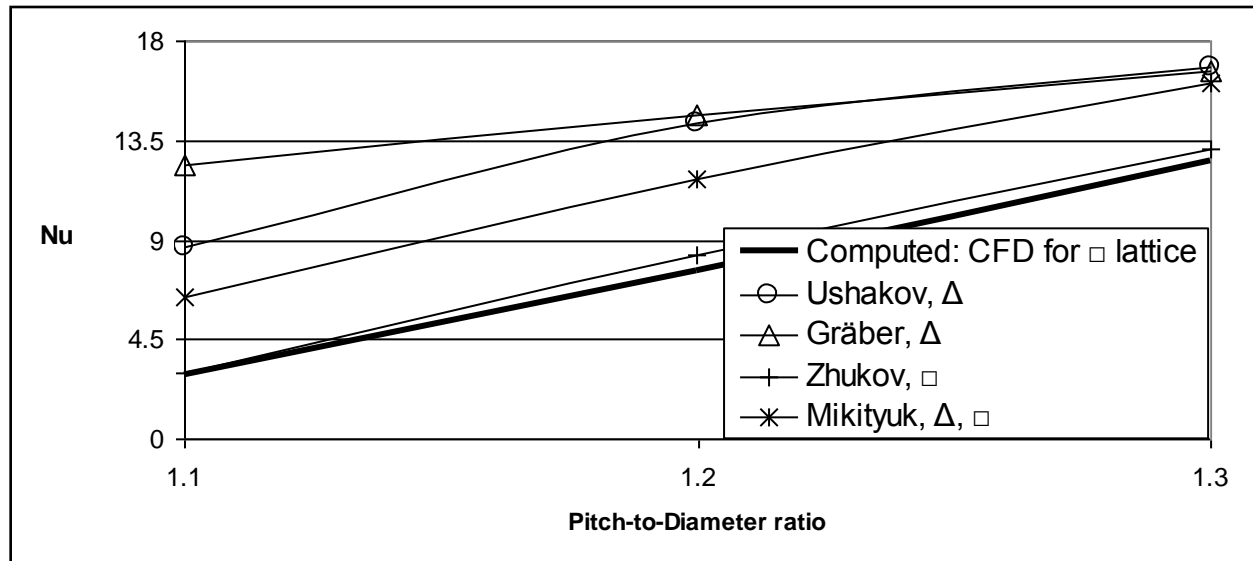


Temperature field [°C]

- Counter rotating pairs of vortices are observed in the smallest gap between fuel rods. These were also observed experimentally by Vonka (1988)
- The outlet temperature of lead in the bulk flow is in between 475 C to 500 C.
- The maximum lead temperature near the surface is close to 520 C.

Single sub-channel analyses

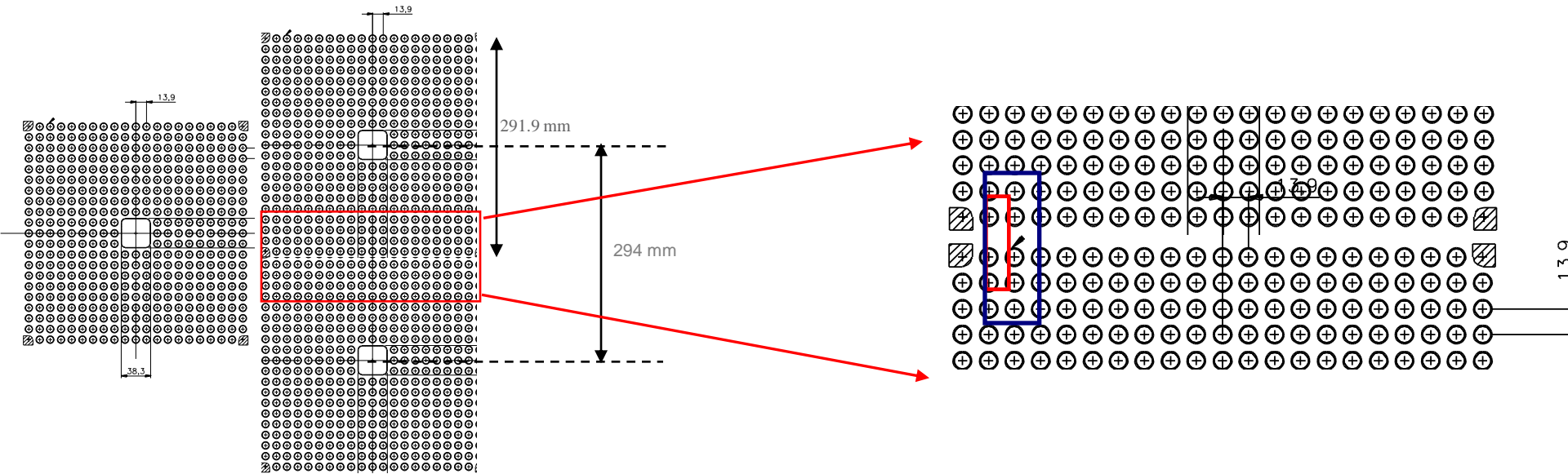
Results:
Heat transfer correlations
(source: Mikityuk (2009))



→ Zhukov correlation is recommended for the square lattice of a bare and liquid metal cooled rod bundle

Inter fuel assembly T-H analyses

Computational model: Small & Large domain



Arrangement of ELSY FA

Selected computational domain
(Small & Large)

Table in previous slide shows that:

Assembly Pitch (Center-to-Center) = 294 mm.

The total breadth or width of the square FA = 291.9 mm (shown in figure 2).

Narrow smallest gap between two neighboring is = 2.1 mm (294-291.9)

Inter fuel assembly T-H analyses

Computational model: Small domain

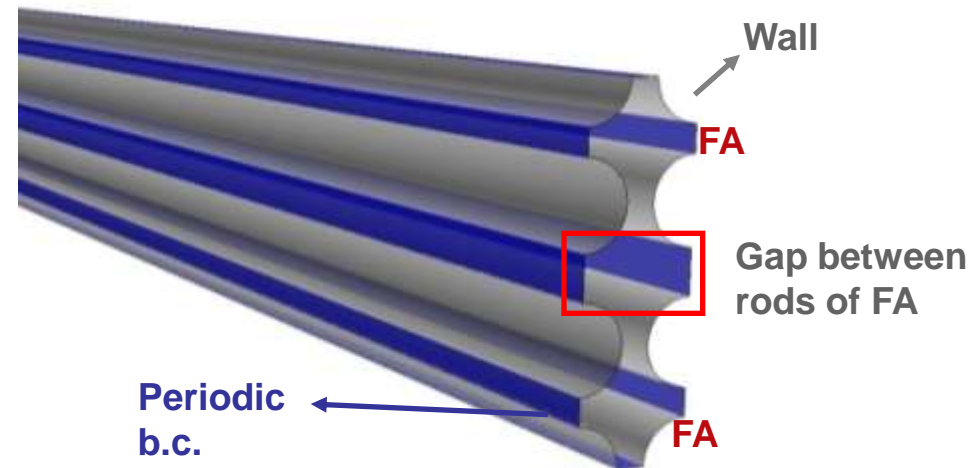
- **Computational Code: CFX-11**
- **Geometry**
 - ELSY rod bundle
 - Length = 900 mm
 - Diameter of tube = 10.5 mm
 - Pitch-to-diameter ratio ~ 1.32
 - **Gap between rods of FA = 5.5 mm**

- **Boundary conditions**

- Inlet: Uniform flow velocity of 1.5 m/s
- Inlet: Fluid temperature = 400 C
- Outlet: Zero [Pa] static pressure
- Walls: Uniform surface heat fluxes for the given average power (see slide 15)

- **Working fluid:**

- Lead with recommended properties as a function of temperature (from OECD handbook)



Inter fuel assembly T-H analyses

Computational model: Large domain

- **Computational Code: CFX-11**

- **Geometry**

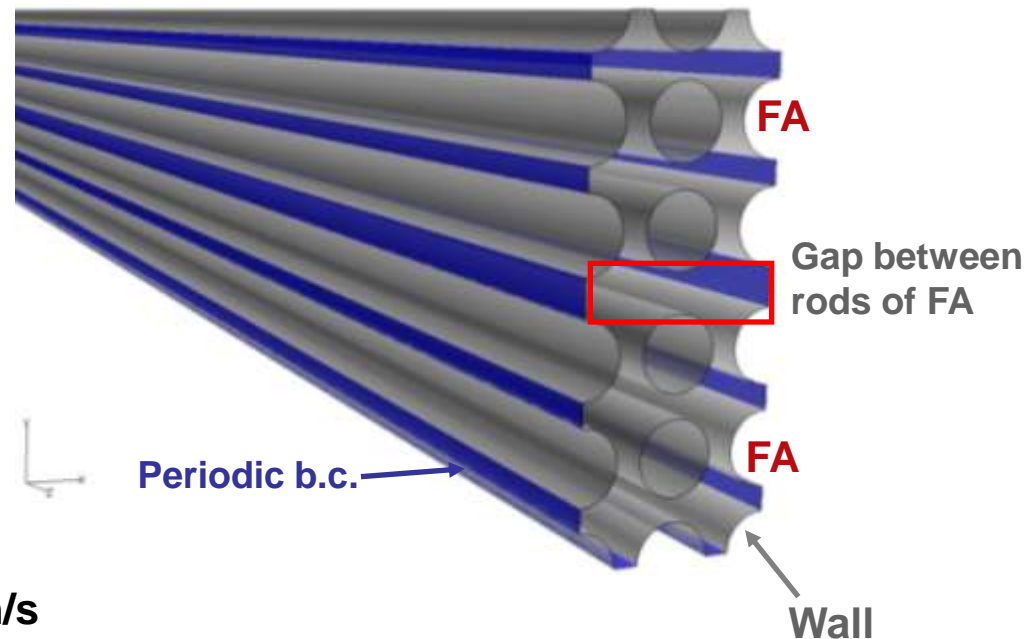
- **ELSY rod bundle**
- **Length = 900 mm**
- **Diameter of tube = 10.5 mm**
- **Pitch-to-diameter ratio ~ 1.32**
- **Gap between rods of FA = 5.5 mm**

- **Boundary conditions**

- **Inlet: Uniform flow velocity of 1.5 m/s**
- **Inlet: Fluid temperature = 400 C**
- **Outlet: Zero [Pa] static pressure**
- **Walls: Uniform surface heat fluxes for the given average power (see slide 15)**

- **Working fluid:**

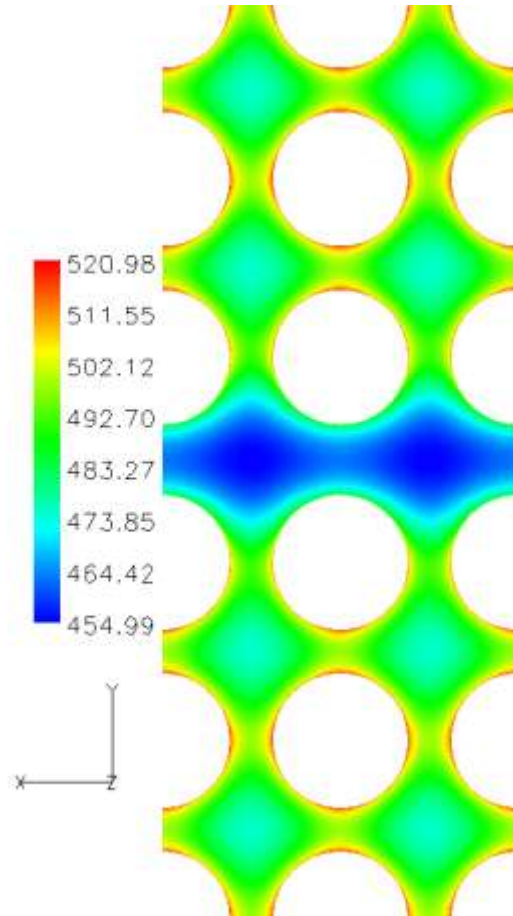
- **Lead with recommended properties as a function of temperature (from OECD handbook)**



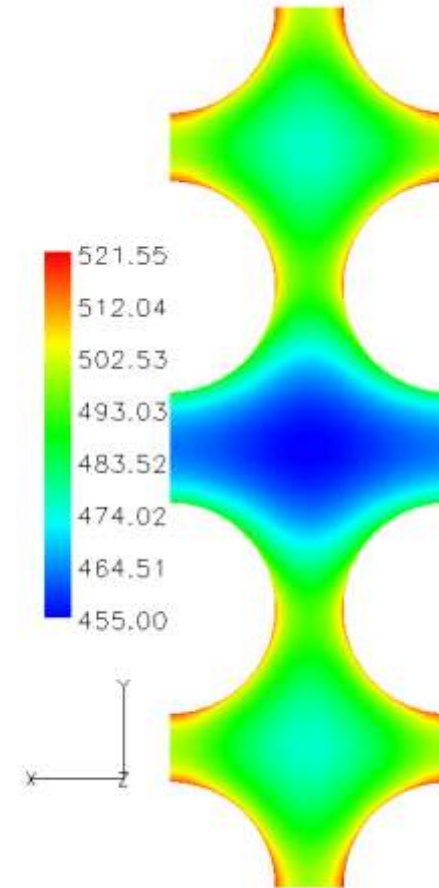
Inter fuel assembly T-H analyses

Results:

Fluid temperature (C) at the outlet



Large domain



Small domain

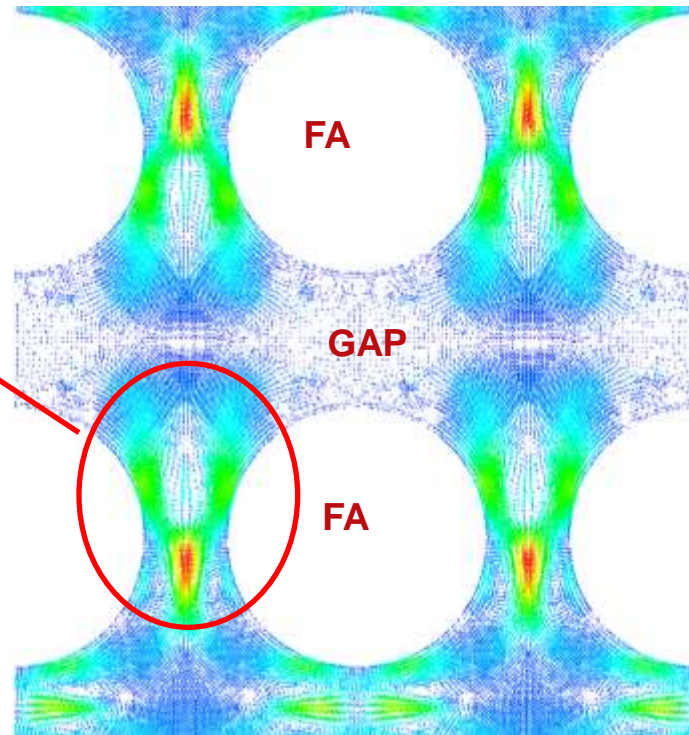
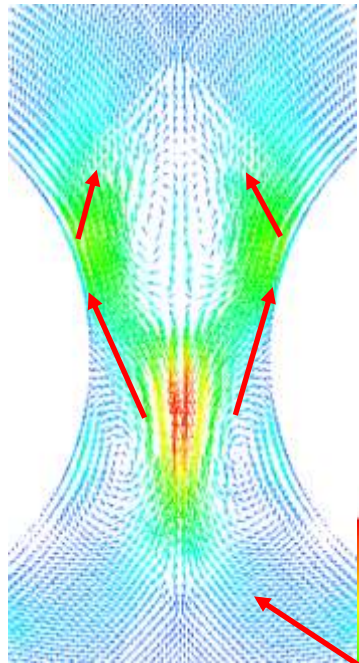
→ Calculated temperatures for small and large domain at the outlet are practically same.

Inter fuel assembly T-H analyses

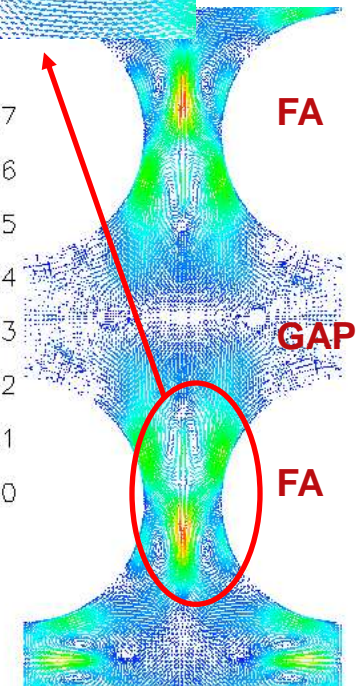
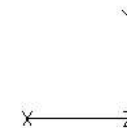
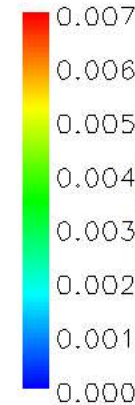
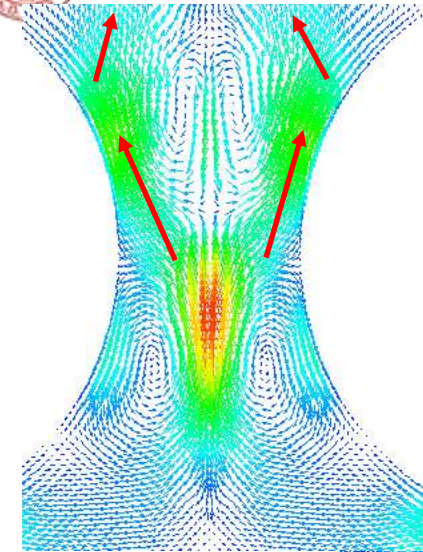
Results:

Cross flow colored with its normalized magnitude for large and small domain

At 200 mm from inlet



Large domain



Small domain

Inter fuel assembly T-H analyses

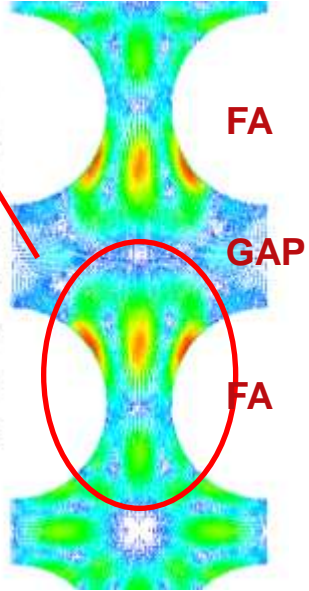
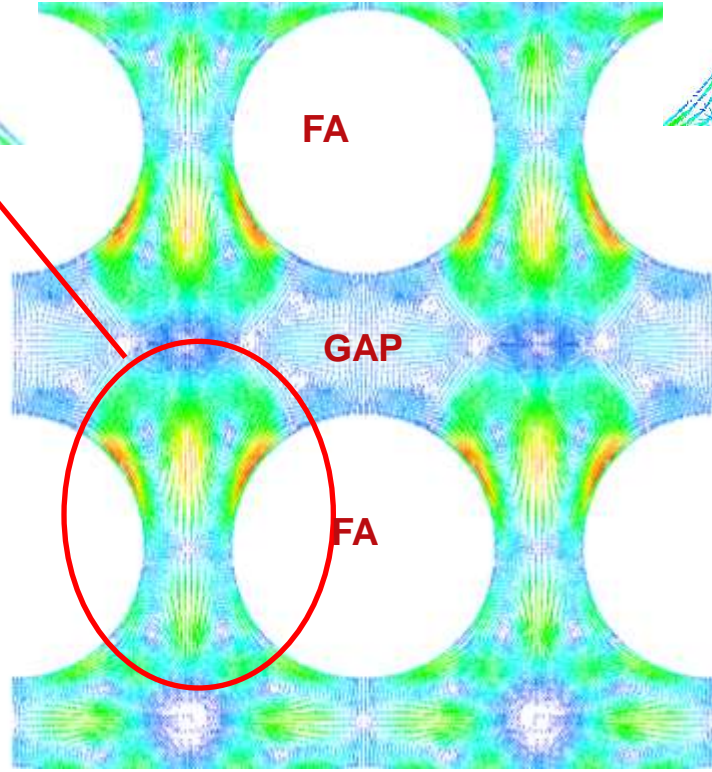
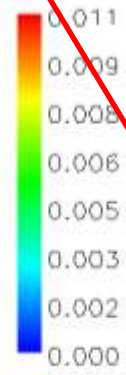
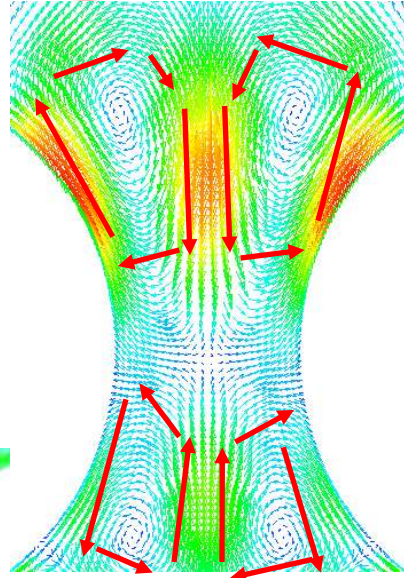
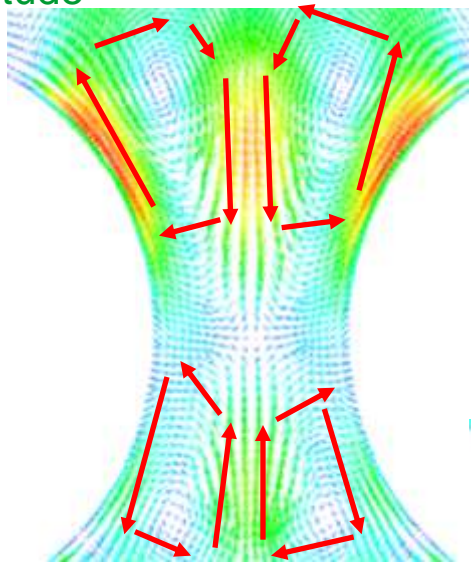
Results: Cross flow colored with its normalized magnitude



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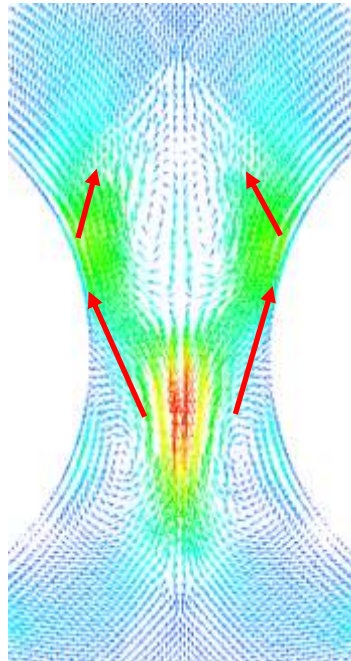


At outlet

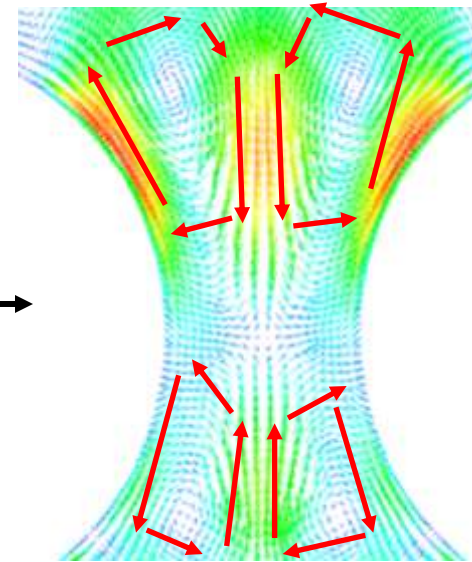


Inter fuel assembly T-H analyses

Results: Flow Development



200 mm from inlet



Outlet (900 mm from inlet)

→ Flow develops along axial direction of bare rod bundle → cross-flow reduces

- Neutronic analyses of the ELSY reactor core show:
 - Possibility of getting a flat power/FA distribution in such a way to have a corresponding uniform coolant T_{out} in the wrapper less option.
 - Uniformity is kept within acceptable limit despite the distribution drift along the sub-cycle. Moreover the uniformity can be improved by an appropriate use of the innovative Finger Absorber Rods.
- Thermal-hydraulic analyses of a bare single sub-channel show:
 - Highest lead temperature at the outlet close to the heated rod is 520 °C
 - Counter rotating vortices at the smallest gap between fuel rods are observed. These were also observed in an experiment from Vonka (1985).
 - The Zhukov's heat transfer correlation is recommended for the square lattice of bare and liquid metal cooled rod bundle.
- Thermal-hydraulic analyses of small and large domain for inter fuel assembly (bare) cross flow show:
 - The highest outlet lead temperature at the smallest gap between two heated fuel rods is close to 520 °C for both the small and large computational domain. This corresponds to that of the single sub-channel analyses.
 - The lowest outlet lead temperature is observed in the largest gap between two consecutive fuel assemblies
 - The highest inter fuel assembly cross flow is of the order of 1% of the maximum axial flow near the inlet.
 - The inter fuel assembly cross flow decreases from inlet to outlet. This can be attributed to the flow development towards outlet from inlet.

Reference



1. Artioli, C., Sarotto, M., and Grasso, G., 2008
Status of the open-square-SA design of the ELSY core
WP2 meeting, Brussels.
2. Cinotti, L., 2007
ELSY Project, The European Lead-cooled System.
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3. Mikityuk, K., 2009
Heat transfer to liquid metal: review of data and correlations for tube bundles
Nucl. Engg. and Design, vol. 239, pp. 680-687 (2009).
4. Vonka, V., 1988
Measurement of secondary flow vortices in a rod-bundle
Nuclear Eng. and Design 106, pp: 191-207.