CFD SIMULATIONS OF SELECTED STEADY-STATE AND TRANSIENT EXPERIMENTS IN SODIUM-COOLED FAST NEUTRON REACTORS

Internship Final Report | Sebastian Gurgacz

24 MARS 2015
PLANDTL Test Facility overview

Identified phenomena in upper plenum to be validated

Methodology

- Turbulent jet validation
- Thermal stratification validation
- PLANDTL modeling general assumptions

PLANDTL heat removal systems

Simulation of steady-state experiments

Simulation of transients experiments
PLANDTL TEST FACILITY OVERVIEW
PLANDTL TEST FACILITY GENERAL OVERVIEW

PLANDTL = Plant Dynamics Test Loop facility

1. Upper plenum
2. Core barrel
3. Direct heat exchanger (DRACS)
4. Upper inner structure
5. Center subassembly
6. Outer subassemblies
7. Interwrapper gap
8. Lower plenum
9. Electromagnetic flow meter
10. Electromagnetic pump
11. Intermediate heat exchanger (PRACS)
12. PRACS coil
13. Main air cooler
14. Air cooler
### PLANDTL MAIN CAPABILITIES

<table>
<thead>
<tr>
<th>Primary loop</th>
<th>Core region</th>
<th>Maximum power, MW</th>
<th>1.2</th>
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<tbody>
<tr>
<td></td>
<td>Number of subassemblies</td>
<td></td>
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<tr>
<td>Upper plenum</td>
<td>Diameter, m</td>
<td></td>
<td>2</td>
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<tr>
<td>Intermediate heat exchanger</td>
<td>Sodium level from bottom, m</td>
<td></td>
<td>2.6</td>
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<tr>
<td></td>
<td>Auxiliary heater power, kW</td>
<td></td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Capacity, MW</td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Maximum flow rate, l/min</td>
<td></td>
<td>1200</td>
</tr>
<tr>
<td>Secondary loop</td>
<td>Main air cooler capacity, MW</td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Maximum flow rate, l/min</td>
<td></td>
<td>700</td>
</tr>
<tr>
<td>Auxiliary cooling system</td>
<td>DRACS</td>
<td>Type</td>
<td>Coil tube type</td>
</tr>
<tr>
<td></td>
<td>Capacity, MW</td>
<td></td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>PRACS</td>
<td>Type</td>
<td>Coil tube type</td>
</tr>
<tr>
<td></td>
<td>Capacity, MW</td>
<td></td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>Maximum flow rate, l/min</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Air cooler capacity, MW</td>
<td></td>
<td>0.3</td>
</tr>
</tbody>
</table>
IDENTIFIED PHENOMENA IN UPPER PLENUM TO BE VALIDATED
The performance of the jets depends on several factors:

- geometry of the nozzle
- outflow initial conditions
- properties of discharged and ambient fluid

\[
\frac{w_c(z)}{w_0} = \frac{3.5}{\sqrt{\frac{z}{b_0} + \alpha_1}}
\]

\[
\frac{w(y, z)}{w_c(z)} = \exp\left(-0.693 \left(\frac{y}{b(z)}\right)^2\right)
\]

\[
\frac{v(y, z)}{w_c(z)} = \frac{1}{\alpha} \left(\frac{\alpha y}{z} - \frac{\alpha y}{z} \tanh^2 \left(\frac{\alpha y}{z}\right) - 0.5 \tanh \left(\frac{\alpha y}{z}\right)\right)
\]

\[
\frac{w_c(z)}{w_0} = \left(\text{erf} \left(\frac{6.257}{z/2b_0}\right)\right)^{\frac{1}{2}}
\]

\[
\frac{w_c(z)}{w_0} = \frac{2.475}{\sqrt{\frac{z}{2b_0}}}
\]

Sources:


Thermal stratification effect is characterized by Froude number. When Fr ≤ 1, the effect is considered to be significant. The importance of thermal stratification increases with lowering of Froude number.

\[ Fr = \frac{w}{\sqrt{g\beta\Delta T D}} \]

Such phenomenon is observed in pool type sodium cooled fast reactors during transients, when cold sodium is injected to hot upper plenum. Thermal stratification can be undesirable effect since it may lead to thermal fatigue of construction materials. Therefore, such phenomenon is widely investigated.
METHODOLOGY
All considered flows in the present study have been assumed incompressible.

\[ \frac{D \rho}{D t} = 0 \]

\[
Ma = \frac{u}{c} = \frac{u}{\sqrt{\frac{\partial \rho}{\partial p}}} \ll 1
\]

Continuity law and Navier-Stokes equations can be simplified to the following form:

\[ \nabla \cdot \vec{u} = 0 \]

\[
\frac{\partial \vec{u}}{\partial t} + \nabla \cdot (\vec{u} \vec{u}) = -\nabla P^0 + \nabla \cdot \tau^0 + F_m^0
\]

\[ \tau^0 = \frac{\mu}{\rho} \nabla \vec{u} + \nu_t (\nabla \vec{u} + \nabla^T \vec{u}) \]

\[ P^0 = \frac{p}{\rho} - gz \]

In the Boussinesq approximation, density is assumed to change linearly as a function of temperature and is treated as variable only in gravitational field. Therefore, one is able to calculate density using formula below:

\[
(\rho(T) - \rho_0)g = \rho_0 g \beta (T - T_0)
\]

\[ \rho_0 = \rho(T_0). \]

\[ \rho(T) = \rho_0 (1 + \beta(T - T_0)) \]

In present study, the value of **maximum error** related to Boussinesq approximation associated with sodium density change is **no more than 1%**.
Specific heat of sodium has been assumed constant, temperature independent and equal to 1270 kJ/kg K. The other necessary properties, have been assumed as temperature dependent and calculated using formulas as follows:

- **density (expressed in kg/m³)**

\[
\rho_{Na} = 1011.8 - 0.22054(273.15 + t_{Na}) - 1.9226 \cdot 10^{-5}(273.15 + t_{Na})^2 + 5.6371 \cdot 10^{-9}(273.15 + t_{Na})^3
\]

- **dynamic viscosity (expressed in kg/m·s)**

\[
\mu_{Na} = \exp\left(-6.4406 - 0.3958 \ln(273.15 + t_{Na}) + \frac{556.835}{273.15 + t_{Na}}\right)
\]

- **thermal conductivity (expressed in W/m·K)**

\[
\lambda_{Na} = 124.67 - 0.11381(273.15 + t_{Na}) + 5.5226 \cdot 10^{-5}(273.15 + t_{Na})^2 - 1.1842 \cdot 10^{-8}(273.15 + t_{Na})^3
\]

- **thermal expansion coefficient (expressed in 1/K)**

\[
\beta_{Na} = 2.02663 \cdot 10^{-5} + 1.06977 \cdot 10^{-7}(273.15 + t_{Na}) - 4.74942 \cdot 10^{-11}(273.15 + t_{Na})^2
+ 4.75913 \cdot 10^{-14}(273.15 + t_{Na})^3
\]

The temperature-averaged values of abovementioned parameters were taken to the calculations.

Source:
Fink J.K., Leibowitz L., "Thermodynamic and Transport Properties of Sodium Liquid and Vapor", Argonne National Laboratory, Ref. ANL-RE-95-2, 1995
The conservation equations for turbulence kinetic energy \( k \) and dissipation rate \( \varepsilon \) are formulated as follows:

\[
\frac{\partial k}{\partial t} + \vec{u} \cdot \nabla k = \nabla \cdot \left( \frac{\nu_t}{\sigma_k} \nabla k \right) - \varepsilon + P + G
\]

\[
\frac{\partial \varepsilon}{\partial t} + \vec{u} \cdot \nabla \varepsilon = \nabla \cdot \left( \frac{\nu_t}{\sigma_\varepsilon} \nabla \varepsilon \right) - C_{\varepsilon 2} \frac{\varepsilon^2}{k} + C_{\varepsilon 1} \frac{P \varepsilon}{k} + C_{\varepsilon 1} C_{\varepsilon 3} G \frac{\varepsilon}{k}
\]

The turbulent viscosity \( \nu_t \) can be calculated using the formula below:

\[
\nu_t = C_\mu \frac{k^2}{\varepsilon}
\]

\( P \), the production of turbulence kinetic energy is calculated using the correlation:

\[
P = \left( \nu_t \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \frac{2}{3} k \delta_{ij} \right) \frac{\partial \bar{u}_i}{\partial x_j}
\]

For assumed incompressible flow, buoyancy effects \( G \) shall be treated by:

\[
G = -\frac{\nu_t}{\Pr_t} \beta_T \bar{g} \cdot \nabla T
\]
The empirical coefficients used in all formulas above are listed in table:

<table>
<thead>
<tr>
<th>$C_\mu$</th>
<th>$\sigma_k$</th>
<th>$\sigma_\varepsilon$</th>
<th>$C_{\varepsilon 1}$</th>
<th>$C_{\varepsilon 2}$</th>
<th>$C_{\varepsilon 3}$</th>
<th>$Pr_t$</th>
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<tbody>
<tr>
<td>0.09</td>
<td>1.0</td>
<td>1.3</td>
<td>1.44</td>
<td>1.92</td>
<td>0</td>
<td>0.9</td>
</tr>
</tbody>
</table>

\[
G = -\frac{\nu_t}{Pr_t} \beta_T g \cdot \nabla T
\]

Stable stratification:
\[
\nabla T > 0 \quad \rightarrow \quad G < 0 \quad \rightarrow \quad C_{\varepsilon 3} = 0
\]

Unstable stratification:
\[
\nabla T < 0 \quad \rightarrow \quad G > 0 \quad \rightarrow \quad C_{\varepsilon 3} = 1
\]

In order to assume the values of boundary conditions for $k$ and $\varepsilon$, the correlations below have been used:

\[
k = \frac{3}{2} (0.1u_0)^2
\]

\[
\varepsilon = \frac{C_\mu \varepsilon}{l_m}
\]

\[
l_m \equiv 0.07D_h
\]
## NUMERICAL SCHEME

<table>
<thead>
<tr>
<th>General</th>
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<tbody>
<tr>
<td>Dimension</td>
<td>2D/3D</td>
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<tr>
<td>Fluid</td>
<td>Water/Sodium</td>
<td></td>
</tr>
<tr>
<td>Mesh</td>
<td>Tetrahedral</td>
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<td>Discretization</td>
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<thead>
<tr>
<th>Discretization</th>
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<tr>
<td>P0/P1 for p</td>
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</tr>
<tr>
<td>P1NC for u, v, w, T, k, (\varepsilon)</td>
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<thead>
<tr>
<th>Time scheme</th>
<th>Implicit</th>
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<tr>
<td>Convection</td>
<td>EF_stab, (\alpha = 1)</td>
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<tr>
<td>Diffusion</td>
<td>2nd order centred</td>
<td></td>
</tr>
<tr>
<td>Pressure solver</td>
<td>Cholesky method</td>
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<tr>
<td>Thermal effects</td>
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<td></td>
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<tr>
<td>Wall law</td>
<td>Logarithmic wall law</td>
<td></td>
</tr>
<tr>
<td>Turbulence</td>
<td>RANS</td>
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<th>Navier-Stokes equations</th>
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<td>Turbulence model</td>
<td>High Reynolds k-(\varepsilon)</td>
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<tr>
<td>(k, \varepsilon) convection</td>
<td>EF_stab, (\alpha = 1)</td>
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</tr>
<tr>
<td>(k, \varepsilon) diffusion</td>
<td>2nd order centred</td>
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</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Turbulence modeling</th>
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<th></th>
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</thead>
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<tr>
<td>Convection</td>
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<tr>
<td>Diffusion</td>
<td>2nd order centred</td>
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<tr>
<td>Wall law</td>
<td>Logarithmic wall law</td>
<td></td>
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<tr>
<td>Turbulence</td>
<td>Turbulent Prandtl Number (Pr_t)</td>
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<tr>
<th>Energy transport equation</th>
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<tr>
<td>Diffusion</td>
<td>2nd order centred</td>
<td></td>
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<tr>
<td>Wall law</td>
<td>Logarithmic wall law</td>
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</tr>
<tr>
<td>Turbulence</td>
<td>Turbulent Prandtl Number (Pr_t)</td>
<td></td>
</tr>
</tbody>
</table>
TURBULENT JET VALIDATION
DIMENSIONS AND ASSUMPTIONS

- $d = 7 \text{ mm}$
- $w_0 = 0.6 \text{ m/s}$
- Non-buoyant jet assumption
- Fluid: water

Three-step approach:

- initialization of the calculations on the coarse mesh, with ambient velocity equals to 0 m/s and uniform nozzle outlet velocity in order to achieve solution $S_c$
- initialization of the calculations on the fine mesh, with solution $S_c$ in order to achieve solution $S_f$
- initialization of the calculations on the very fine mesh, with solution $S_f$ in order to achieve solution $S_v$

<table>
<thead>
<tr>
<th>$\rho_{H_2O}$</th>
<th>$\mu_{H_2O}$</th>
<th>$C_{p_{H_2O}}$</th>
<th>$\lambda_{H_2O}$</th>
<th>$\beta_{H_2O}$</th>
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</thead>
<tbody>
<tr>
<td>$kg/m^3$</td>
<td>$kg/m \cdot s$</td>
<td>$J/kg \cdot K$</td>
<td>$W/m \cdot K$</td>
<td>$1/K$</td>
</tr>
<tr>
<td>992</td>
<td>0.000653</td>
<td>4182</td>
<td>0.58</td>
<td>0.000385</td>
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### Meshing

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<th>Coarse mesh</th>
<th>Fine mesh</th>
<th>Very fine mesh</th>
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<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>Nozzle</td>
<td>1</td>
<td>1.4</td>
<td>1</td>
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<tr>
<td>Outlet field</td>
<td>2</td>
<td>3.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Close field</td>
<td>3.5</td>
<td>7</td>
<td>0.9</td>
</tr>
<tr>
<td>Far field</td>
<td>5</td>
<td>21</td>
<td>5</td>
</tr>
<tr>
<td>Number of elements</td>
<td>80 296</td>
<td>565 693</td>
<td>1 884 531</td>
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RESULTS (1/2)
RESULTS (2/2)
THERMAL STRATIFICATION VALIDATION
Sodium in heating channel

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<tr>
<th>$\rho_{Na}$</th>
<th>$\mu_{Na}$</th>
<th>$\alpha_{Na}$</th>
<th>$\lambda_{Na}$</th>
<th>$\beta_{Na}$</th>
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</thead>
<tbody>
<tr>
<td>$kg/m^3$</td>
<td>$kg/(m \cdot s)$</td>
<td>$J/(kg \cdot K)$</td>
<td>$W/(m \cdot K)$</td>
<td>$1/K$</td>
</tr>
<tr>
<td>880</td>
<td>0.000341</td>
<td>1 270</td>
<td>75</td>
<td>0.000257</td>
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</table>

Sodium in cavity

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<tr>
<th>$\rho_{Na}$</th>
<th>$\mu_{Na}$</th>
<th>$Cp_{Na}$</th>
<th>$\lambda_{Na}$</th>
<th>$\beta_{Na}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$kg/m^3$</td>
<td>$kg/(m \cdot s)$</td>
<td>$J/(kg \cdot K)$</td>
<td>$W/(m \cdot K)$</td>
<td>$1/K$</td>
</tr>
<tr>
<td>884</td>
<td>0.000358</td>
<td>1 270</td>
<td>76</td>
<td>0.000255</td>
</tr>
<tr>
<td>Cavity</td>
<td>Supply channel</td>
<td>Heating channel</td>
<td>Heat exchange wall</td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>----------------</td>
<td>-----------------</td>
<td>--------------------</td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>7.5</td>
<td>1</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>15</td>
<td>3</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

Min 7.5 1 7.5 8
Max 15 3 15 8
PLANDTL MODELING GENERAL ASSUMPTIONS
PLANDTL TEST FACILITY GENERAL OVERVIEW

PLANDTL = Plant Dynamics Test Loop facility

1. Upper plenum
2. Core barrel
3. Direct heat exchanger (DRACS)
4. Upper inner structure
5. Center subassembly
6. Outer subassemblies
7. Interwrapper gap
8. Lower plenum
9. Electromagnetic flow meter
10. Electromagnetic pump
11. Intermediate heat exchanger (PRACS)
12. PRACS coil
13. Main air cooler
14. Air cooler
UPPER PLENUM AND CORE REGION VISUALISATIONS

Flowchart representation

Trio_U CFD

Trio_U subchannel module
MODELING OF UPPER PLENUM

Upper plenum
Coarse mesh: 80
Fine mesh: 60
Very fine mesh: 40
Core outlet
Coarse mesh: 8
Fine mesh: 7
Very fine mesh: 5
Interwrapper inside
Coarse mesh: 7
Fine mesh: 2.3
Very fine mesh: 1.25
Interwrapper outside
Coarse mesh: 7
Fine mesh: 1.3
Very fine mesh: 0.65
Number of core axial divisions
Coarse mesh: 50
Fine mesh: 100
Very fine mesh: 150
Number of elements
Coarse mesh: 740 177
Fine mesh: 3 609 103
Very fine mesh: 13 892 709
MODELING OF CORE REGION (1/2)
Meshing of subassembly depends on number of pins
Number of elements in cladding meshing: 2
Number of equal divisions in interwrapper gap: 2
HEAT REMOVAL SYSTEMS
HEAT REMOVAL SYSTEMS (1/3)

SL = Secondary Loop

1. Upper plenum
2. Core barrel
3. Direct heat exchanger (DRACS)
4. Upper inner structure
5. Center subassembly
6. Outer subassemblies
7. Interwrapper gap
8. Lower plenum
9. Electromagnetic flow meter
10. Electromagnetic pump
11. Intermediate heat exchanger (PRACS)
12. PRACS coil
13. Main air cooler
14. Air cooler
HEAT REMOVAL SYSTEMS (2/3)

PRACS = Primary Reactor Auxiliary Cooling System

1. Upper plenum
2. Core barrel
3. Direct heat exchanger (DRACS)
4. Upper inner structure
5. Center subassembly
6. Outer subassemblies
7. Interwrapper gap
8. Lower plenum
9. Electromagnetic flow meter
10. Electromagnetic pump
11. Intermediate heat exchanger (PRACS)
12. PRACS coil
13. Main air cooler
14. Air cooler
HEAT REMOVAL SYSTEMS (3/3)

DRACS = Direct Reactor Auxiliary Cooling System

1. Upper plenum
2. Core barrel
3. Direct heat exchanger (DRACS)
4. Upper inner structure
5. Center subassembly
6. Outer subassemblies
7. Interwrapper gap
8. Lower plenum
9. Electromagnetic flow meter
10. Electromagnetic pump
11. Intermediate heat exchanger (PRACS)
12. PRACS coil
13. Main air cooler
14. Air cooler
SIMULATION OF STEADY-STATES EXPERIMENTS
**POWER AND FLOW CONDITIONS**

SL = Secondary Loop  
PRACS = Primary Reactor Auxiliary Cooling System  
DRACS = Direct Reactor Auxiliary Cooling System  
SS = Steady-state

<table>
<thead>
<tr>
<th></th>
<th>SL_SS_1</th>
<th>PRACS_SS_1</th>
<th>PRACS_SS_2</th>
<th>DRACS_SS_1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cooling loop</strong></td>
<td>Secondary loop</td>
<td>PRACS</td>
<td>PRACS</td>
<td>DRACS</td>
</tr>
<tr>
<td><strong>Core power, kW</strong></td>
<td>170.5</td>
<td>170.3</td>
<td>128.8</td>
<td>126.7</td>
</tr>
<tr>
<td>Center subassembly</td>
<td>24.4</td>
<td>24.5</td>
<td>18.4</td>
<td>18.1</td>
</tr>
<tr>
<td>Outer subassemblies 1</td>
<td>73.5</td>
<td>73.3</td>
<td>55.2</td>
<td>54.3</td>
</tr>
<tr>
<td>Outer subassemblies 2</td>
<td>72.6</td>
<td>72.5</td>
<td>55.2</td>
<td>54.3</td>
</tr>
<tr>
<td><strong>Coolant flow rate, dm³/min</strong></td>
<td>48.8</td>
<td>54.3</td>
<td>31.5</td>
<td>28</td>
</tr>
<tr>
<td>Center subassembly</td>
<td>7</td>
<td>7.9</td>
<td>4.5</td>
<td>4</td>
</tr>
<tr>
<td>Outer subassemblies 1</td>
<td>20.9</td>
<td>23.2</td>
<td>13.5</td>
<td>12</td>
</tr>
<tr>
<td>Outer subassemblies 2</td>
<td>20.9</td>
<td>23.2</td>
<td>13.5</td>
<td>12</td>
</tr>
<tr>
<td><strong>Coolant inlet temperature, °C</strong></td>
<td>295.8</td>
<td>298.7</td>
<td>305.3</td>
<td>307.5</td>
</tr>
</tbody>
</table>
RESULTS ON SL_SS_1 (1/2)
RESULTS ON SL_SS_1 (2/2)
SIMULATION OF TRANSIENT EXPERIMENTS
<table>
<thead>
<tr>
<th>Time, s</th>
<th>Event</th>
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<tbody>
<tr>
<td>0</td>
<td>Reactor SCRAM</td>
</tr>
<tr>
<td>60</td>
<td>Increase of the flow in DRACS/PRACS loop</td>
</tr>
<tr>
<td>61</td>
<td>Primary loop pump trip, beginning of natural circulation</td>
</tr>
<tr>
<td>80</td>
<td>Launch of the air blower</td>
</tr>
<tr>
<td>110</td>
<td>Maximal flow in DRACS/PRACS loop</td>
</tr>
<tr>
<td>130</td>
<td>Maximum air blower power</td>
</tr>
<tr>
<td>2400</td>
<td>Closing the valve in secondary loop, decrease in the natural circulation rate</td>
</tr>
<tr>
<td>7000</td>
<td>End of simulation</td>
</tr>
</tbody>
</table>
RESULTS ON PRACS_TR_1 (2/2)

Core outlet temperature

Interwrapper gap BI-3

Interwrapper gap BD-1

Temperature, °C

Time, s
**DRACS_TR_1**
**SEQUENCE OF EVENTS**

<table>
<thead>
<tr>
<th>Time, s</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Reactor SCRAM</td>
</tr>
<tr>
<td>60</td>
<td>Increase of the flow in DRACS/PRACS loop</td>
</tr>
<tr>
<td>61</td>
<td>Primary loop pump trip, beginning of natural circulation</td>
</tr>
<tr>
<td>80</td>
<td>Launch of the air blower</td>
</tr>
<tr>
<td>110</td>
<td>Maximal flow in DRACS/PRACS loop</td>
</tr>
<tr>
<td>130</td>
<td>Maximum air blower power</td>
</tr>
<tr>
<td>2400</td>
<td>Closing the valve in secondary loop, decrease in the natural circulation rate</td>
</tr>
<tr>
<td>7000</td>
<td>End of simulation</td>
</tr>
</tbody>
</table>

![Diagram](image)
RESULTS ON DRACs TR_1 (2/2)

Core outlet temperature

Interwrapper gap DA-2

Interwrapper gap BG-4
Measured and calculated results are in good comparison, when Secondary Loop and PRACS experiments are simulated.

Temperature variation at the top of the upper plenum during transients need to be investigated.

Overestimated temperature trends in the interwrapper gap when DRACS is operated need to be investigated.

Simulations on fine and very fine meshes needed in order to investigate influence of interwrapper flow.
Thank you for your attention