Fuel assembly blockage phenomena in LFR: modeling approaches, assumptions, and results

SEARCH / MAXSIMA 2014 International Workshop

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Outline

- Types of fuel SA blockages
- Fuel assembly blockage analysis with SIM-LFR
- Fuel assembly blockage analysis with RELAP5
- Fuel assembly blockage analysis with SIMMER-III
- Fuel assembly blockage CFD analysis with ANSYS
- Fuel assembly blockage CFD analysis with STAR-CCM+
- Conclusions

Types of fuel SA blockages

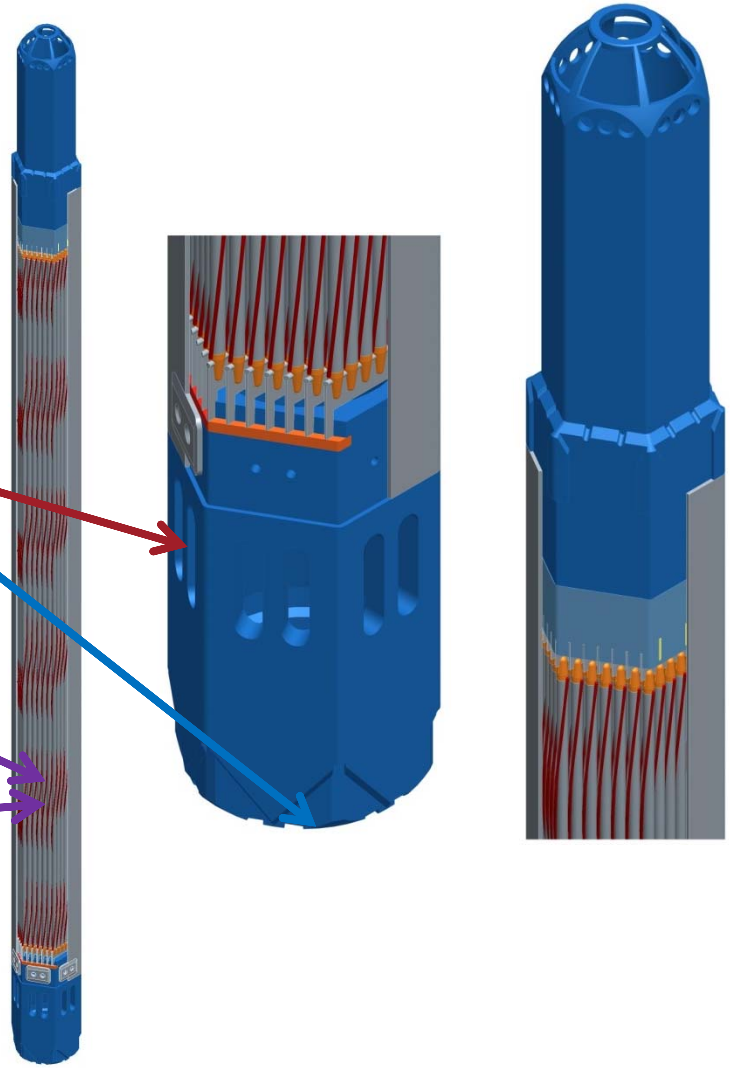
- External

Central hole in SA foot part is blocked, coolant enters only through the side openings

- Internal

Internal blockage inside fuel SA in a form of a thin plate (assumption)

Internal blockage inside fuel SA in a form of a Pb oxide slug (assumption)



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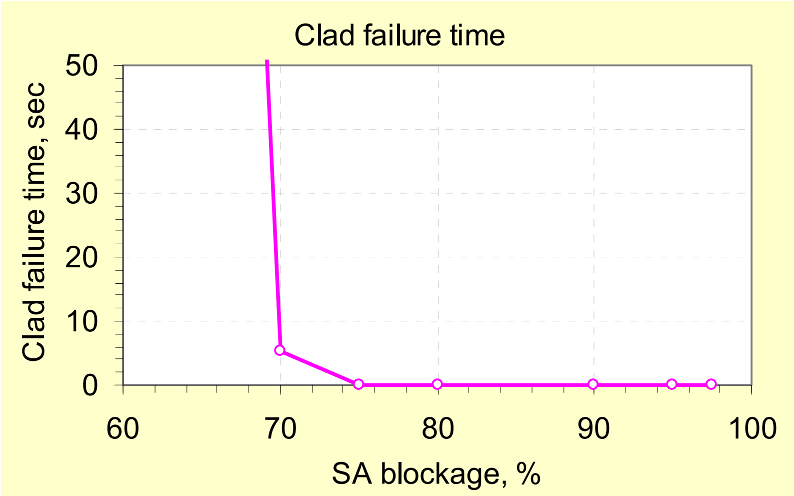
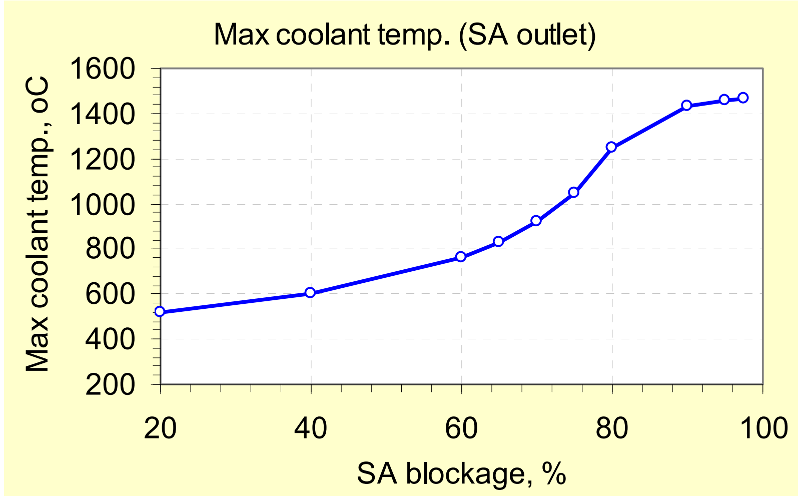
Fuel SA external blockage analysis with SIM-LFR (1)

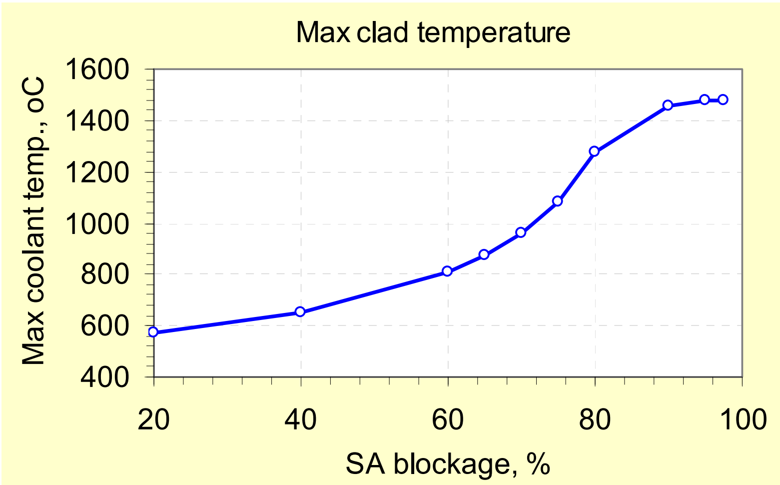
- Hottest fuel SA of the MYRRHA reactor (design 1.4) was taken for the investigation (*unprotected, constant power*);
- It was assumed that the central hole in the foot part of the SA is blocked and thus LBE flow rate is being reduced;
- Fuel SA outlet temperature is assumed to be monitored, but the corresponding signal is assumed to fail in this transient;
- Several different cases were run at EOC conditions, varying the LBE flow blockage from 20% to 97.5% (20, 40, 60, 65, 70, 75, 80, 90, 95 and 97.5% cases).

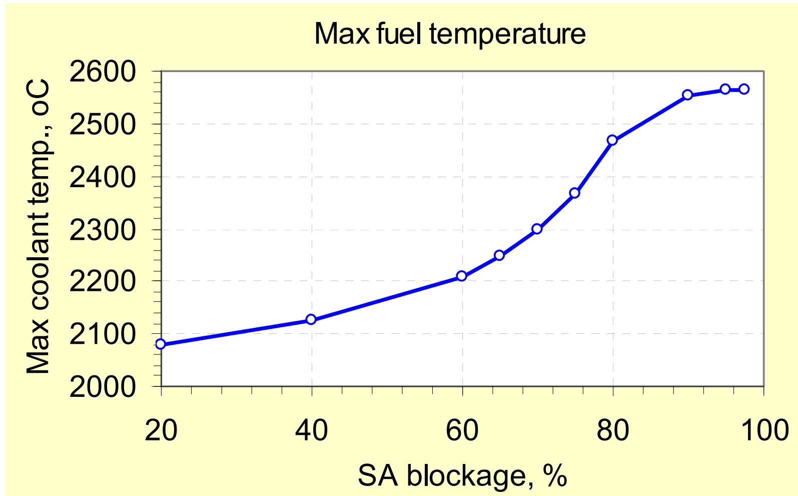
Fuel SA external blockage analysis with SIM-LFR (2)





EOC conditions





Fuel SA external blockage analysis with SIM-LFR (3)

EOC

Blockage	Clad failure time*	Max. cool. SA outlet temp.	Max clad temp (peak pin)	Max fuel temp (peak pin)
%	sec	°C	°C	°C
20	3.9E+10	522	576	2080
40	1.1E+08	599	654	2124
60	7386	760	806	2210
65	266	829	874	2248
70	5.4	920	963	2299
75	0.0	1049	1086	2366
80	0.0	1244	1275	2466
90	0.0	1436	1455	2554
95	0.0	1460	1478	2565
97.5	0.0	1462	1481	2565

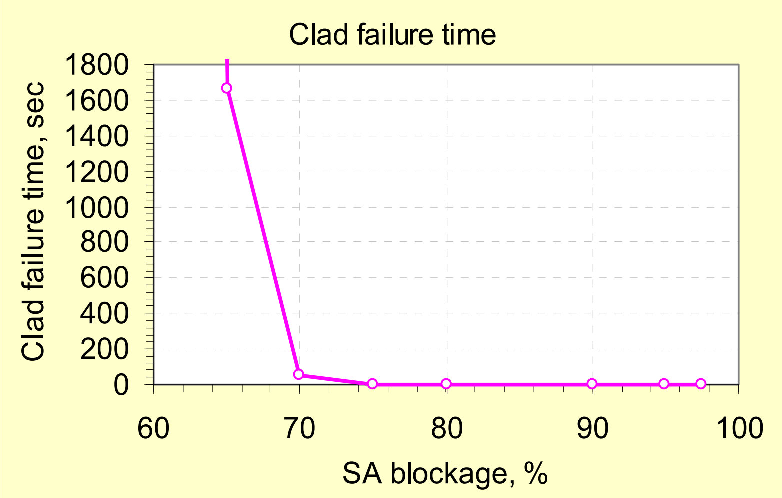
* - max fission gas pressure 5.5 bar

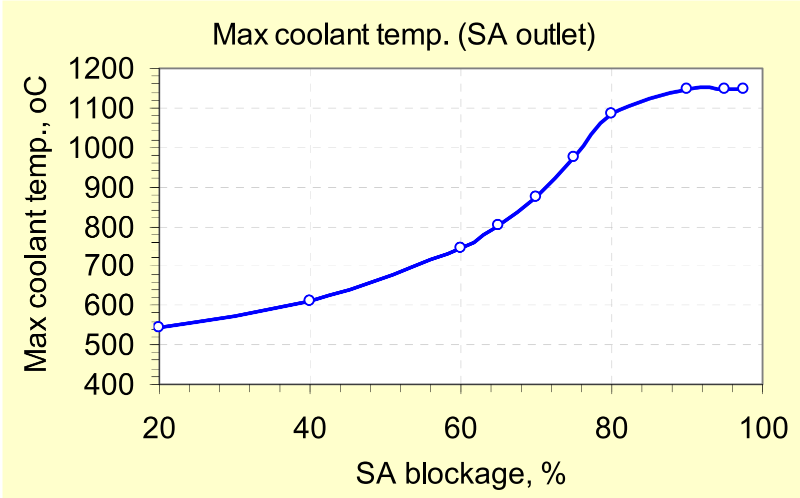
- The critical MYRRHA design will not experience any fuel pin failure for flow blockages of less than 70%, even under unprotected conditions;
- For flow blockages above 70%, clad failures should be expected;
- Clad melting (T_{clad} > 1320°C) should be expected for flow blockages above ~ 80%.

Fuel SA external blockage analysis with SIM-LFR (4)

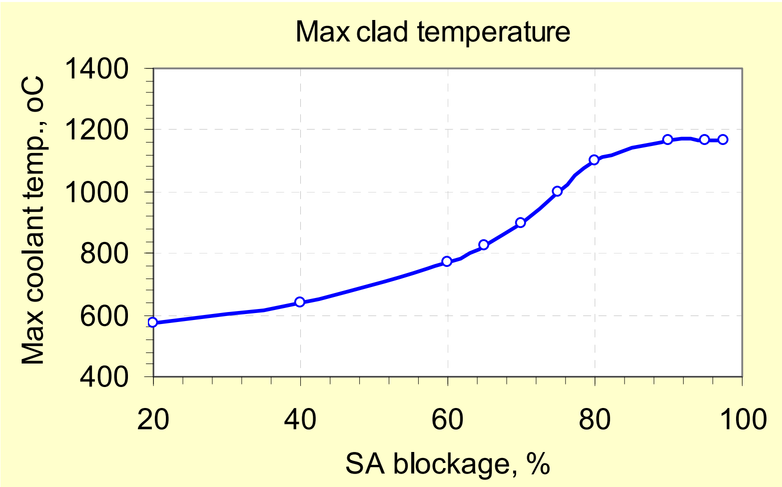
- Hottest fuel SA of the ALFRED reactor was taken for this investigation (*unprotected, constant power*);
- It was assumed that the central hole in the foot part of the SA is blocked and the Pb flow rate is being reduced;
- Fuel SA outlet temperature is assumed to be monitored, but the corresponding signal is assumed to fail in this transient;
- Several different cases were run at BOC & EOC conditions, varying the Pb flow blockage from 20% to 97.5% (20, 40, 60, 65, 70, 75, 80, 90, 95 and 97.5% cases).

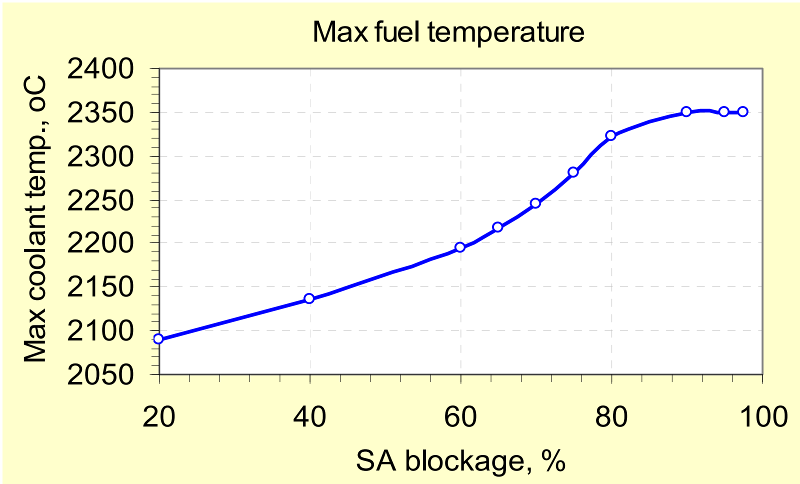
Fuel SA external blockage analysis with SIM-LFR (5)





EOC conditions





Fuel SA external blockage analysis with SIM-LFR (6)

BOC

Blockage	Clad failure time*	Max. cool. SA outlet temp.	Max clad temp (peak pin)	Max fuel temp (peak pin)
%	sec	°C	°C	°C
20	4.00E+10	542	573	2052
40	2.20E+08	608	638	2083
60	4.20E+04	742	771	2162
65	2057	799	826	2194
70	136	873	898	2222
75	0	974	997	2272
80	0	1091	1110	2326
90	0	1158	1176	2359
95	0	1158	1176	2359
97.5	0	1158	1176	2359

* - max fission gas pressure ~18 bar

EOC

Blockage	Clad failure time*	Max. cool. SA outlet temp.	Max clad temp (peak pin)	Max fuel temp (peak pin)
%	sec	°C	°C	°C
20	2.70E+10	545	574	2089
40	1.50E+08	612	641	2136
60	3.00E+04	745	772	2194
65	1661	801	827	2218
70	53	874	898	2245
75	0	974	996	2280
80	0	1084	1103	2322
90	0	1148	1165	2349
95	0	1148	1165	2350
97.5	0	1148	1165	2350

* - max fission gas pressure ~25 bar

- The ALFRED reactor will not experience any fuel pin failure for flow blockages of less than 75%, even under unprotected conditions;
- For flow blockages above 75%, clad failures should be expected;
- Fuel melting is not an issue for ALFRED reactor. Fuel melting temperatures are not reached even in 97.5% SA flow blockage case.

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- Types of fuel SA blockages
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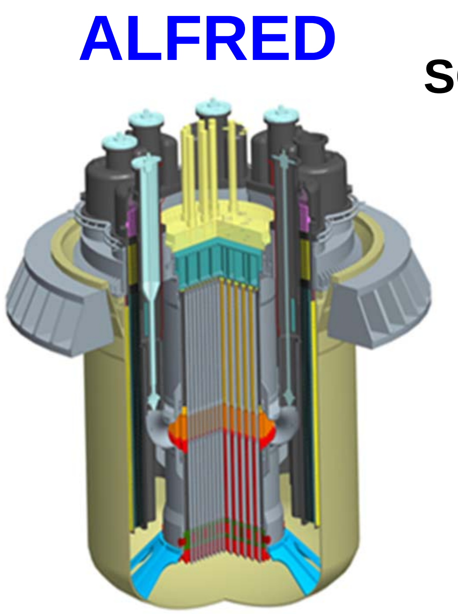
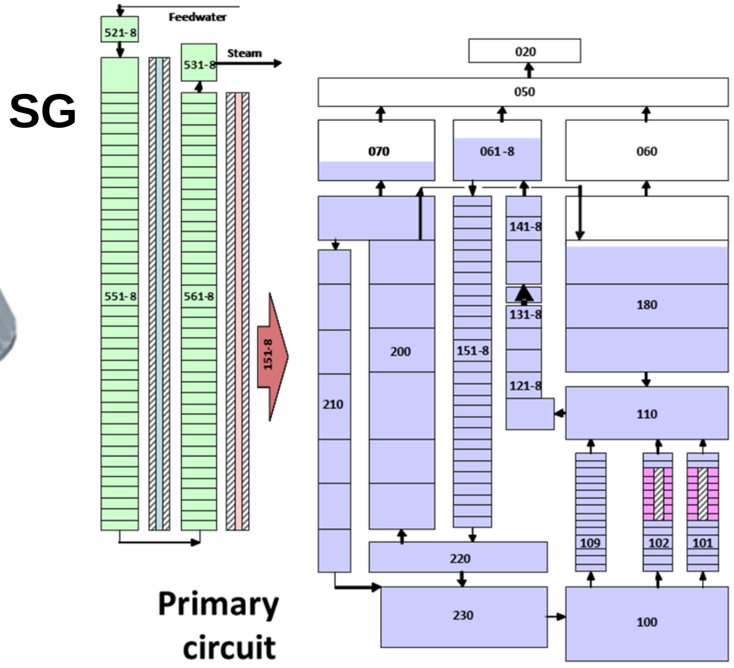
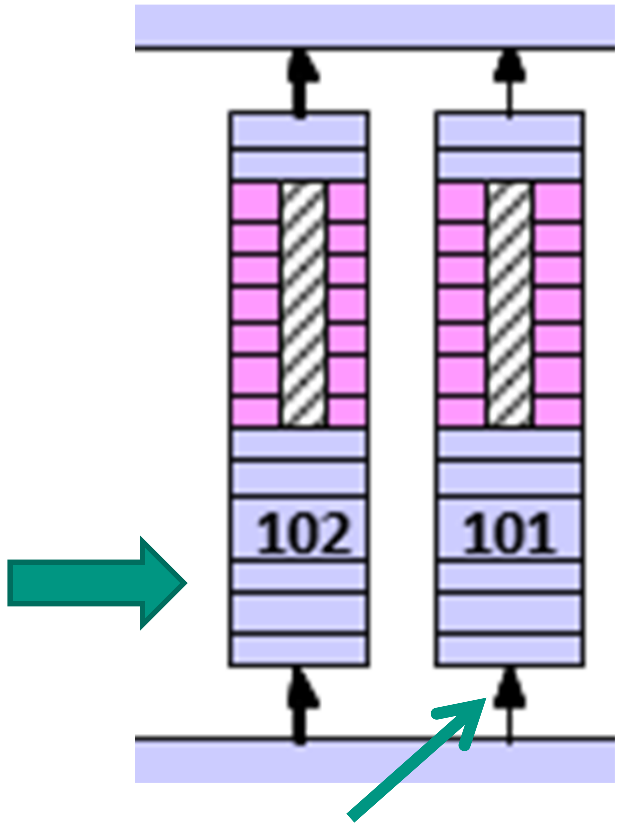
Fuel SA external blockage analysis with RELAP5 (1)



Nodalization scheme





Blockage simulation → Reduction of junction area

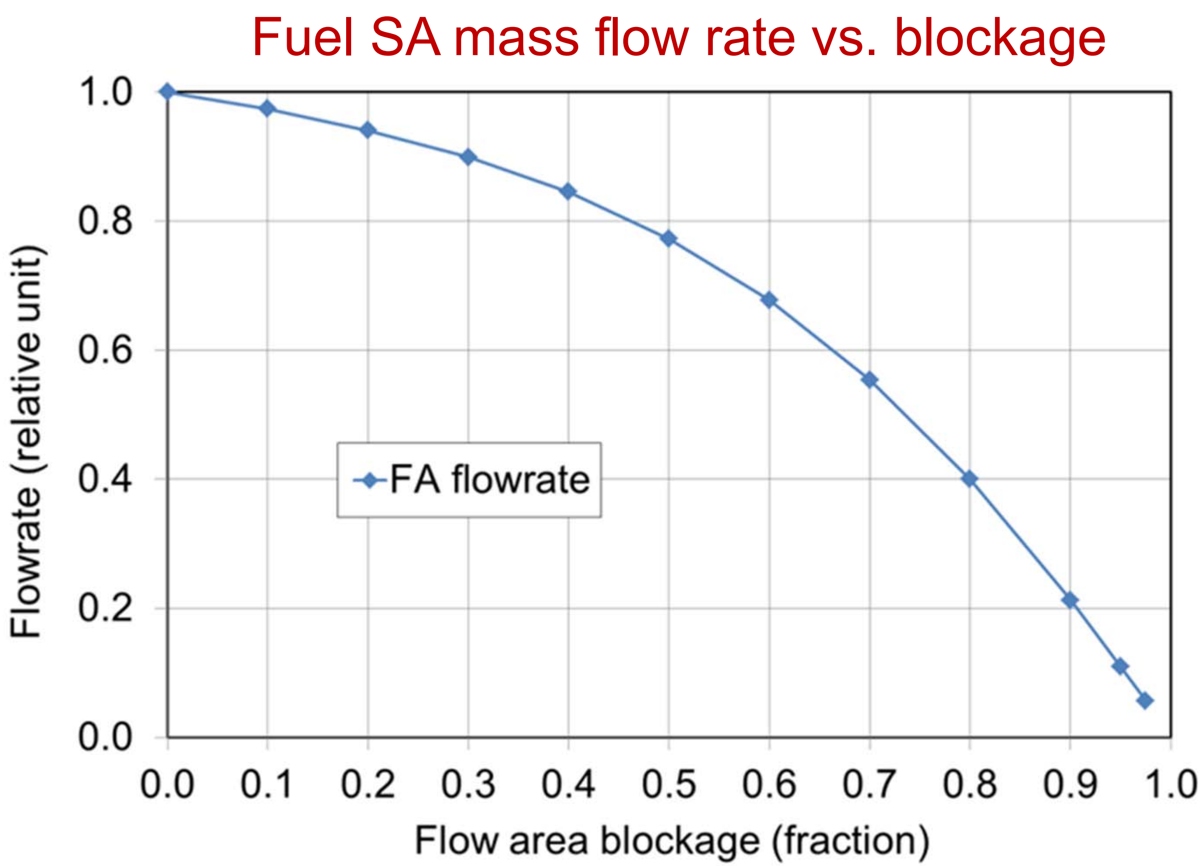
The active core (171 SAs) is represented by:

- 1 fuel SA (101) representing the hottest fuel SA
- 1 average fuel SA (102) representing 170 SAs of the core

Fuel SA external blockage analysis with RELAP5 (2)

- Hottest fuel SA of the ALFRED reactor was taken for this investigation
- Partial blockage of the flow area at the fuel SA inlet was taken into account in this simulation by progressively reducing the inlet section area from 100% down to 2.5%
- Unprotected transient at EOC: no reactor scram on high coolant temperature detection at fuel SA outlet
- Constant core power → no reactivity feedback effects
- For conservative analysis the heat exchange with the six surrounding fuel SAs has been neglected

Fuel SA external blockage analysis with RELAP5 (3)

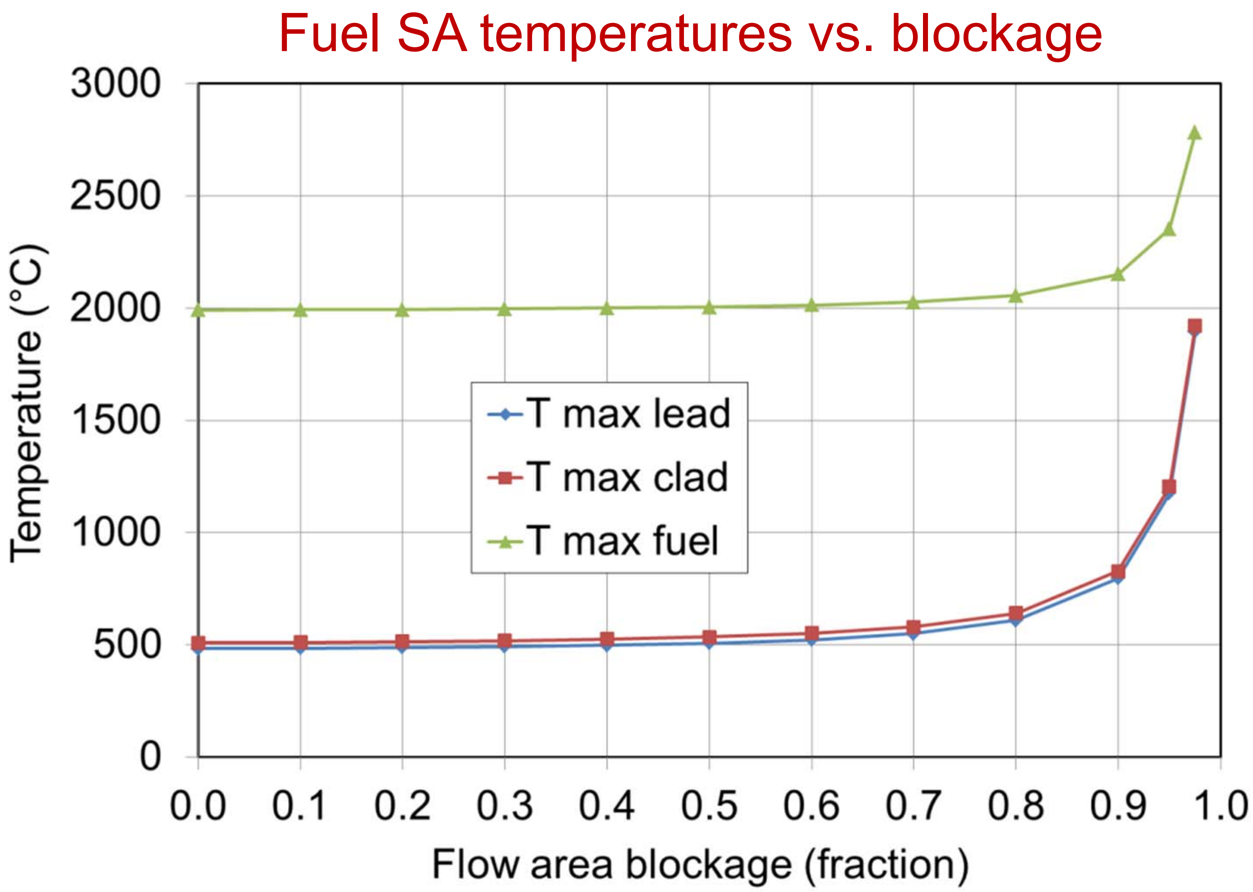


- Total pressure loss through the fuel SA is 1.0 bar
- Pressure loss at the fuel SA inlet (0.22 bar, if no blockage) is simulated by RELAP5 with a constant K factor at the inlet junction

- 80% area blockage results in flow rate reduced down to 40%

Fuel SA external blockage analysis with RELAP5 (4)

- T-clad limit of 700 °C is exceeded for area blockage > 85%
- No clad melting is calculated if area blockage is below 95%



- Fuel melting is calculated if area blockage is above 97.5%
- 50% area blockage could be detected by TCs at fuel SA outlet

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Fuel assembly blockage analysis with SIMMER-III (1)

- Fuel assembly blockage and its consequent fuel pin failure have been studied extensively within SEARCH project for MYRRHA V1.4.

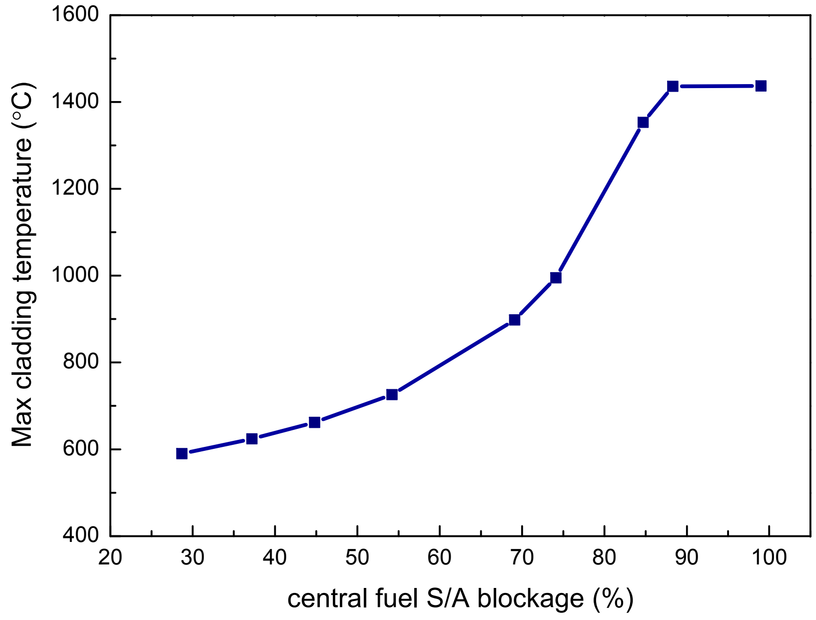
Ref: SEARCH D 5.5 by Li, Chen and Rineiski

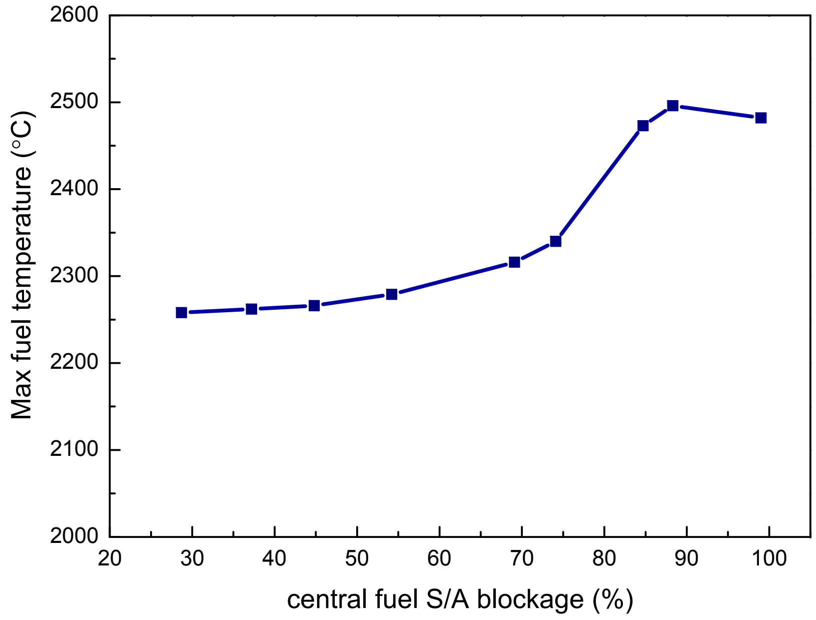
- Further development of pin-bundle model for simulation of coolant sub-channel blockage was initiated and will be applied for the MAXSIMA project.

Ref: HLMC-2013 Conference Paper by Chen, Li and Rineiski

Fuel assembly blockage analysis with SIMMER-III (2)

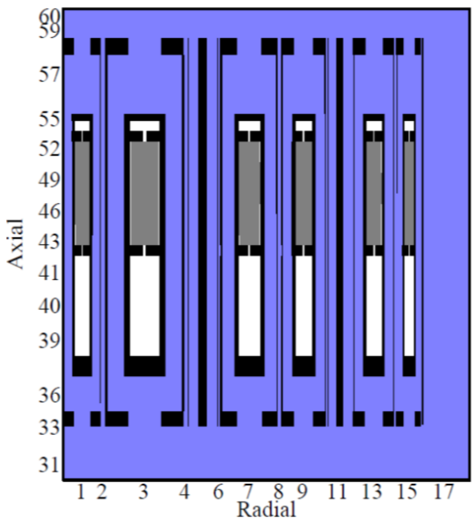
- Parametric blockage studies
- Blockage: pin bundle entrance and uniform blockage
- Wrapper gap flow and heat transfer are considered
- Flow rate blockage as variation parameter





Fuel assembly blockage analysis with SIMMER-III (3)

- Snap shots of material distribution in case of flow rate 88.2% blockage



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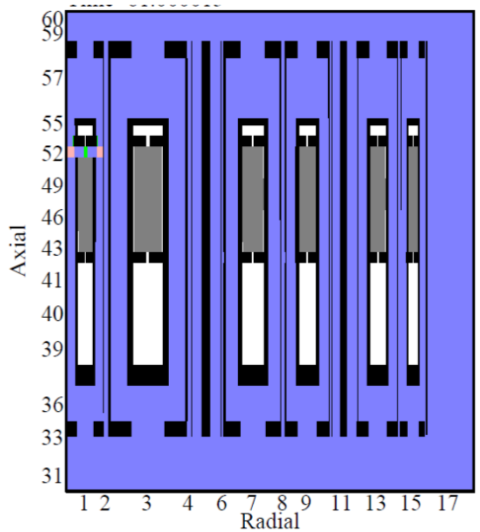

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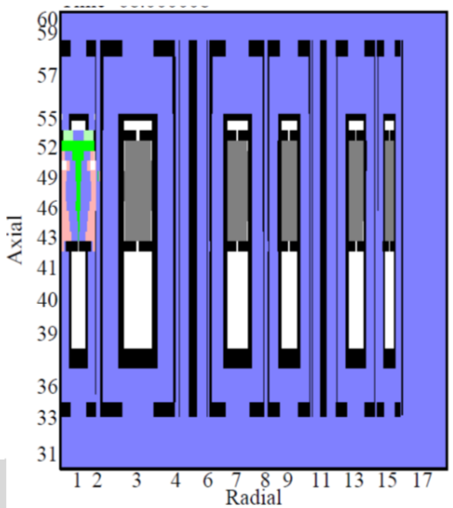

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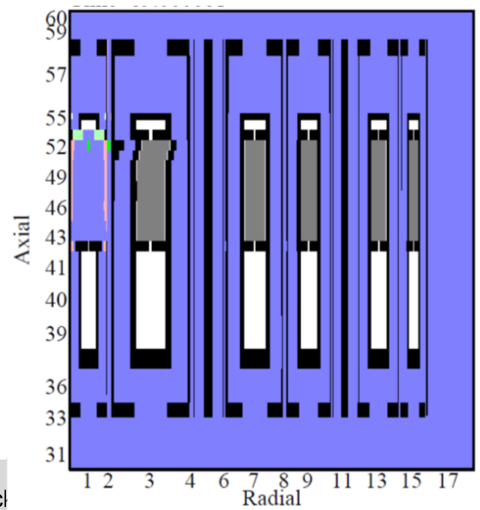

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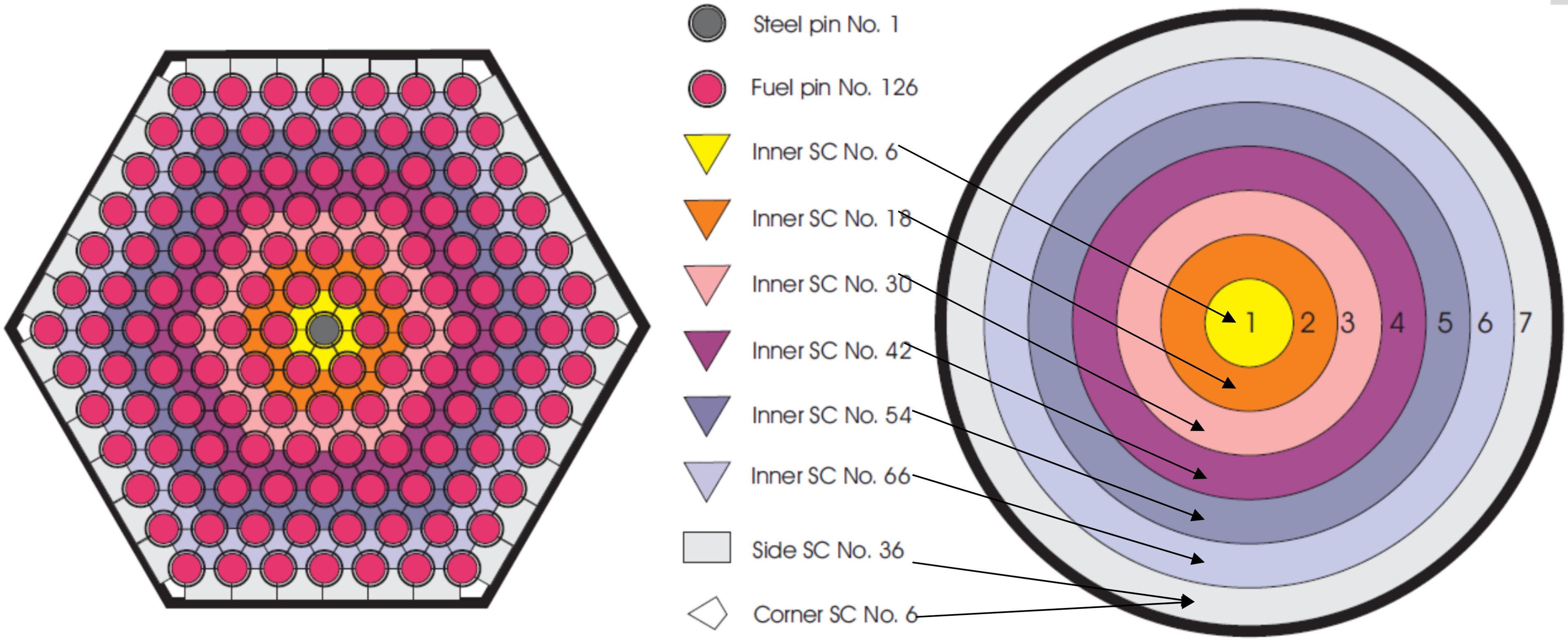
Fuel assembly blockage analysis with SIMMER-III (4)

Pin bundle model development and its geometrical arrangement



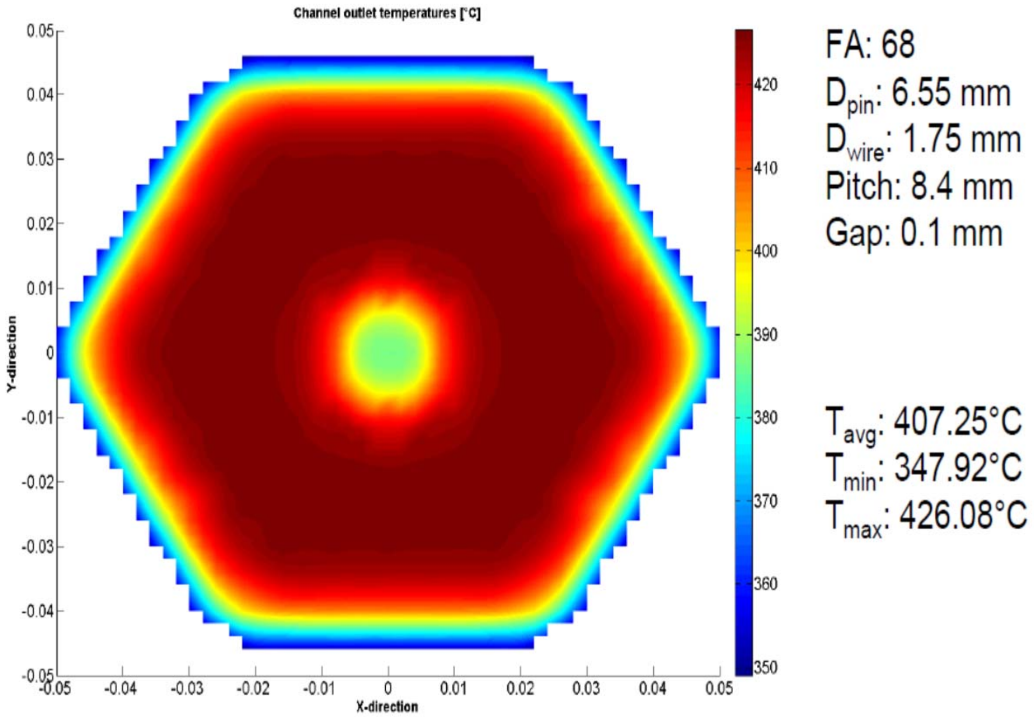
This FA sub-channel model is only applied to the central FA in the current calculation

Pins „smeared“ in the flow rings, e.g. there is 1 steel pin and 1 fuel pin in the first ring

Fuel assembly blockage analysis with SIMMER-III (5)

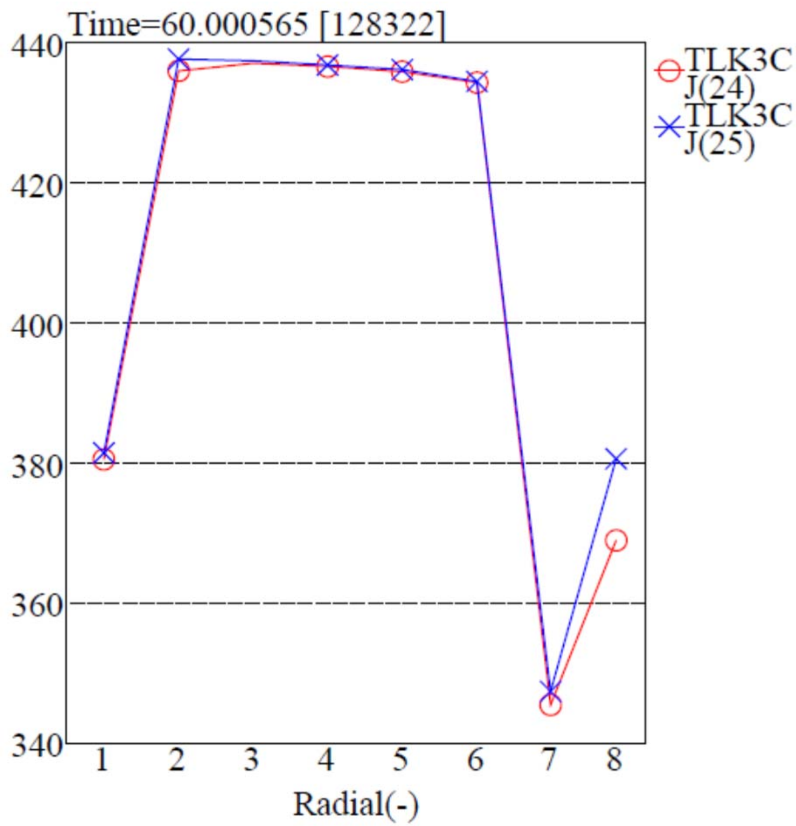
Pin bundle model development and its validation (steady state)

SUBCHANFLOW



T_{av} = 407.3°C, T_{max} = 426.08°C
T_{min} = 347.9°C

SIMMER

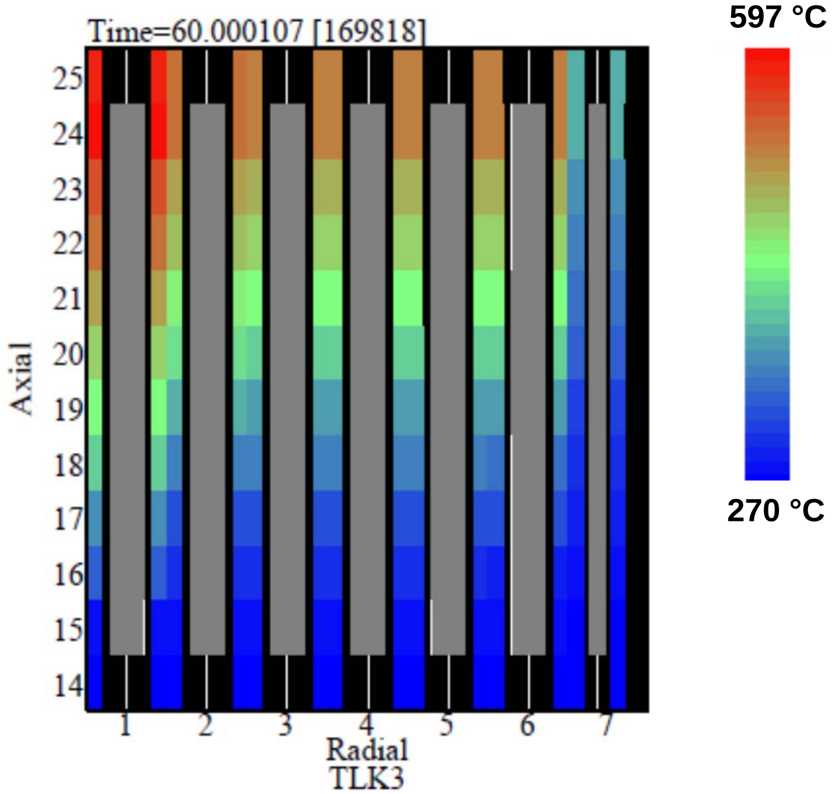


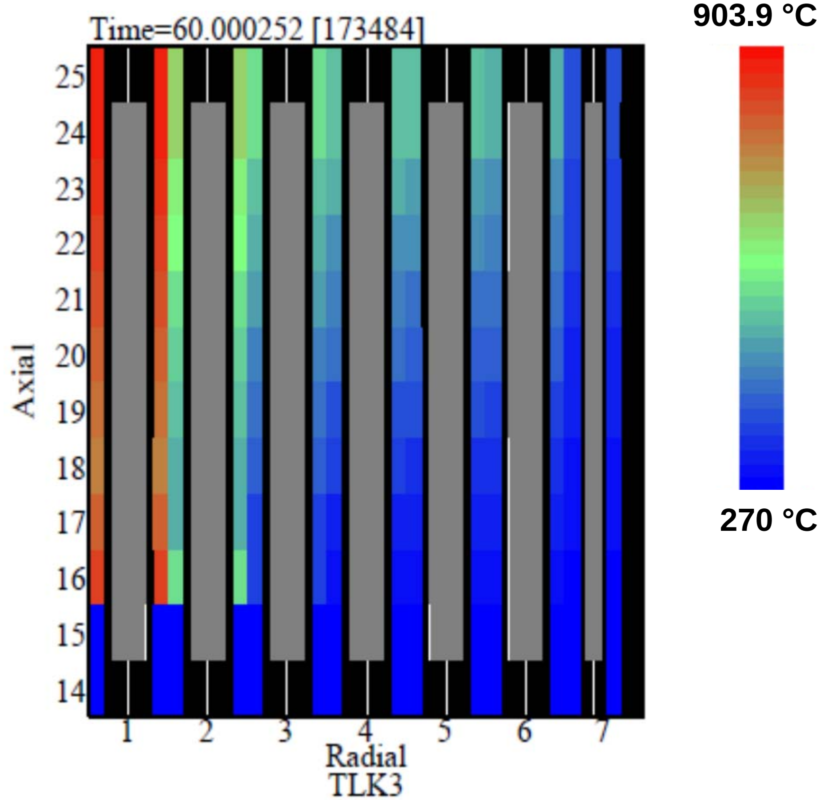
T_{av} = 410.8°C, T_{max} = 437.6°C
T_{min} = 347.4°C

Fuel assembly blockage analysis with SIMMER-III (6)

Preliminary results of the sub-channel blockage

Blockage position: bottom of the active zone, 1 (central) and 3 sub-channel rings blockage (2% and 18% of the flow area)





1-Ring Blockage
Max. coolant temperature increase 62 °C

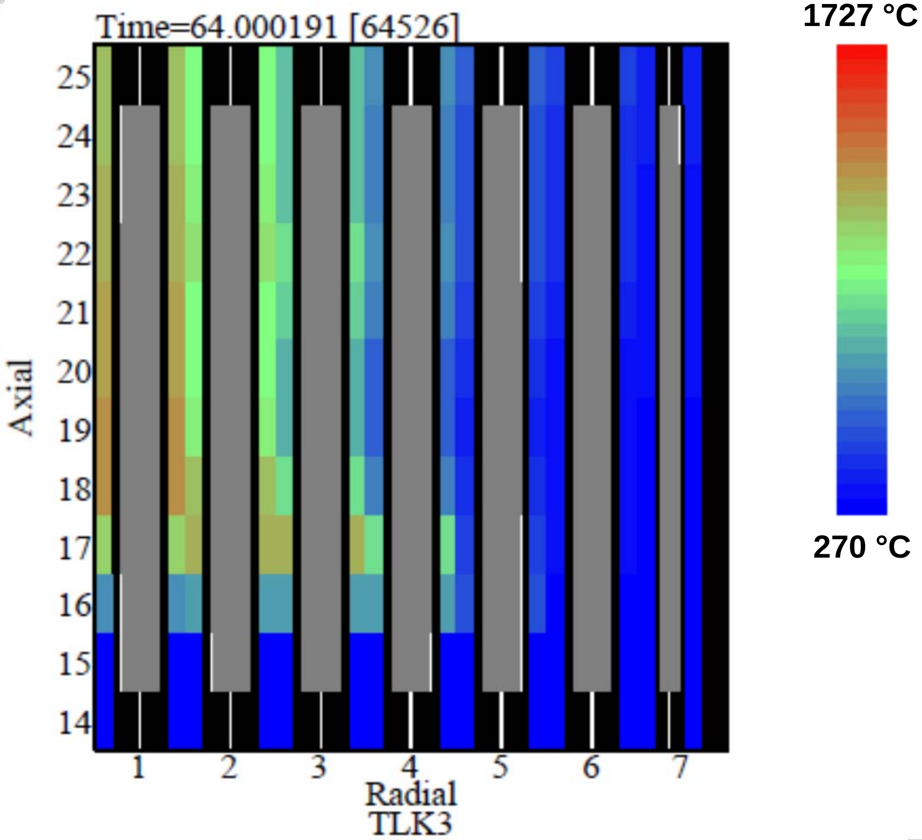
3-Rings Blockage
Max. coolant temperature increase 369 °C

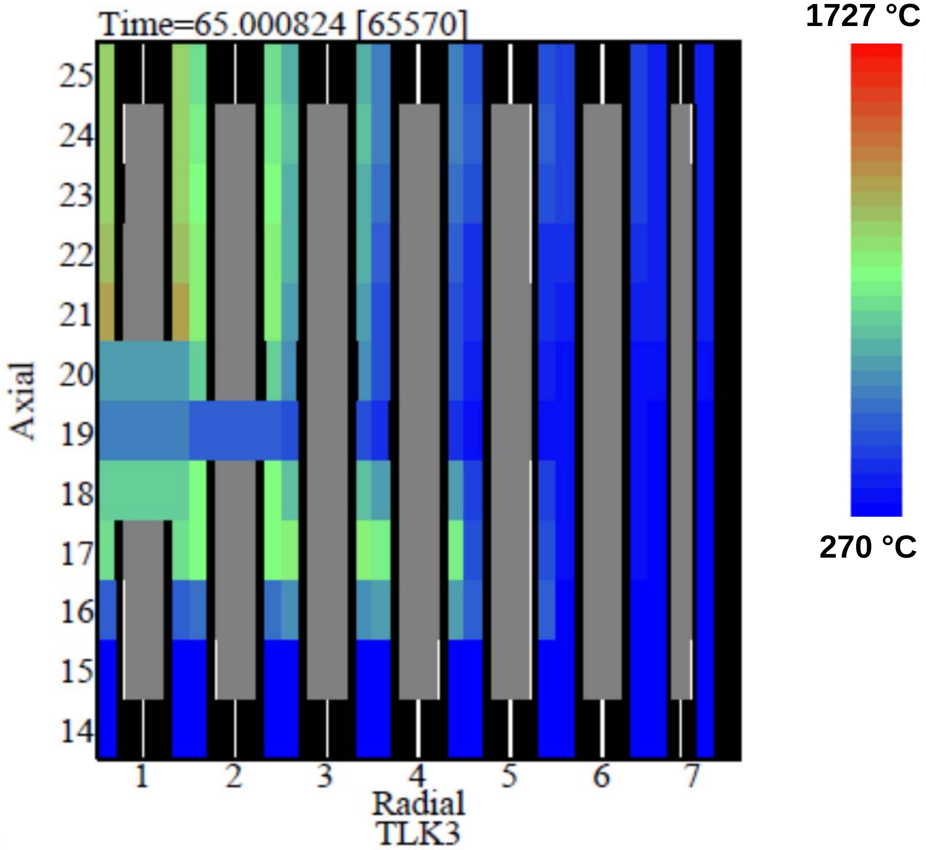
Fuel assembly blockage analysis with SIMMER-III (7)

Preliminary results of the sub-channel blockage

Blockage position: bottom of the active zone, 5 sub-channel rings blockage (50% flow area)

Clad melting takes place between 4 and 5 s after the blockage appears





Fuel assembly blockage analysis with SIMMER-III (8)

- ✓ SIMMER-III results for uniform blockages (all rings of pins) in a MYRRHA fuel assembly: no pin failure until flow rate blockage of ~90%.
- ✓ New SIMMER-III model for partial blockages (few rings of sub-channels) in a fuel assembly: 18% flow area blockage may lead to pin clad failure, while 50% flow area blockage (only 25% flow rate reduction) may lead already to pin melting behind the blockage, but no pin failure (melting) propagation will take place.

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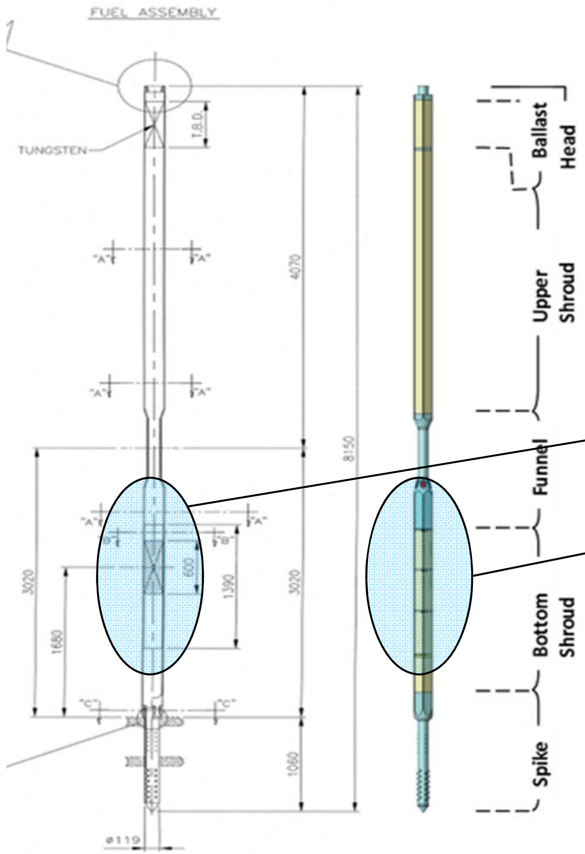
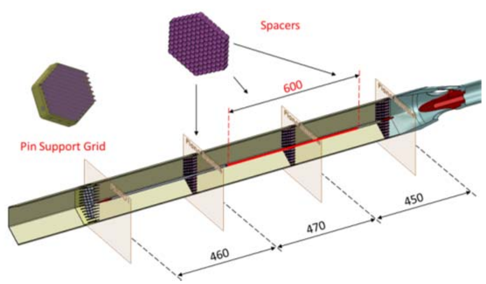
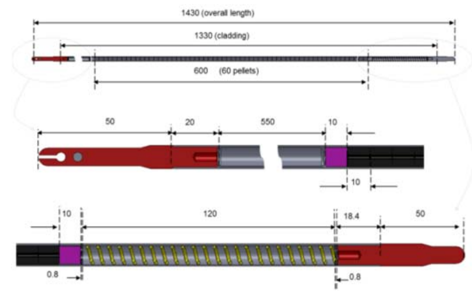
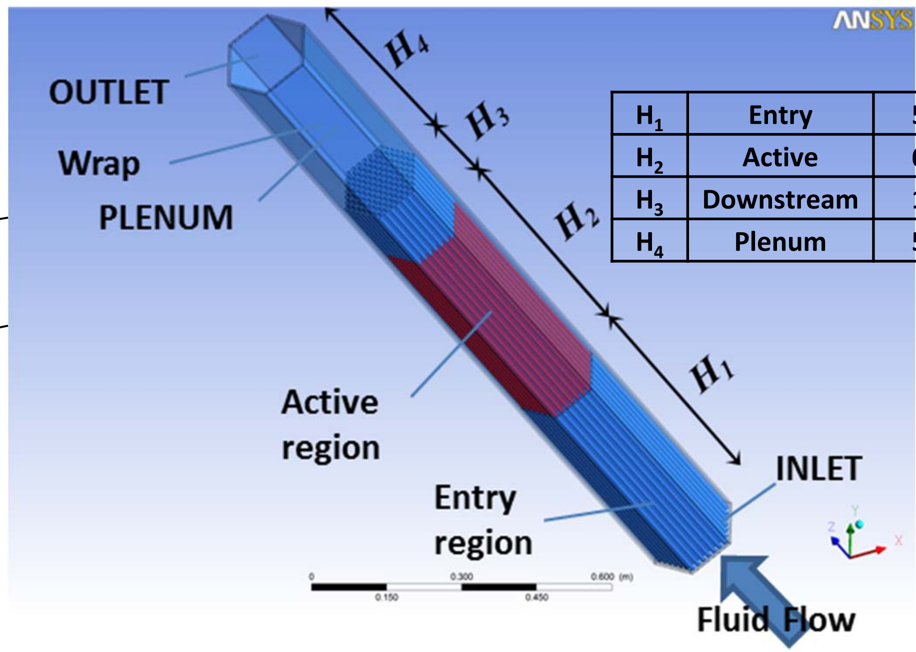
Fuel SA Internal blockage analysis with CFD *1*

A CFD study has been carried out on fluid flow and heat transfer in the HLM-cooled Fuel Pin Bundle of the **ALFRED LFR DEMO**.









H_1	Entry	500 mm
H_2	Active	600 mm
H_3	Downstream	180 mm
H_4	Plenum	500 mm

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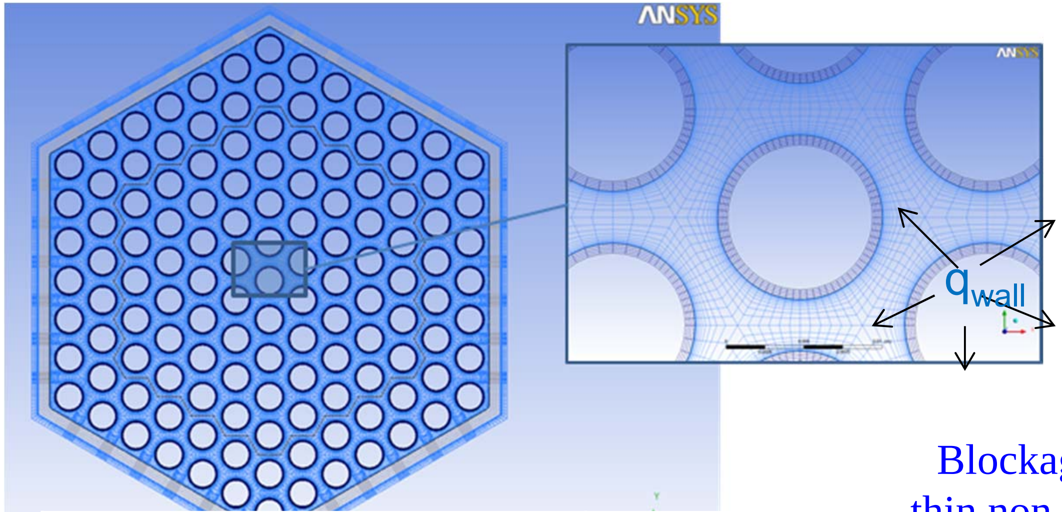
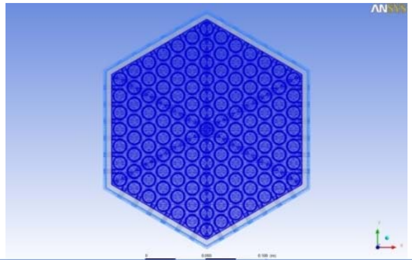
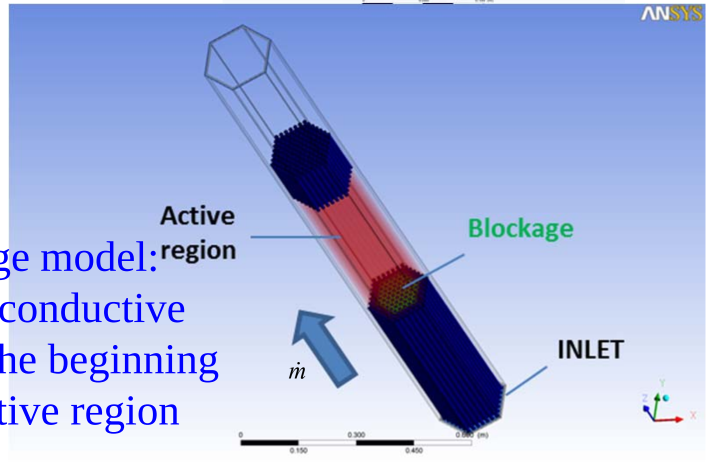
Fuel SA Internal blockage analysis with CFD 2

Models and Methods







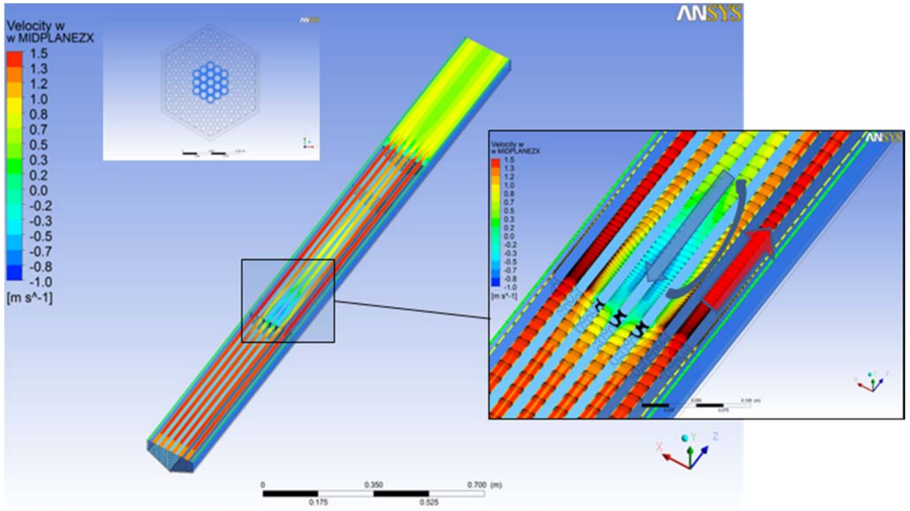
Blockage model: thin non-conductive surface at the beginning of the active region

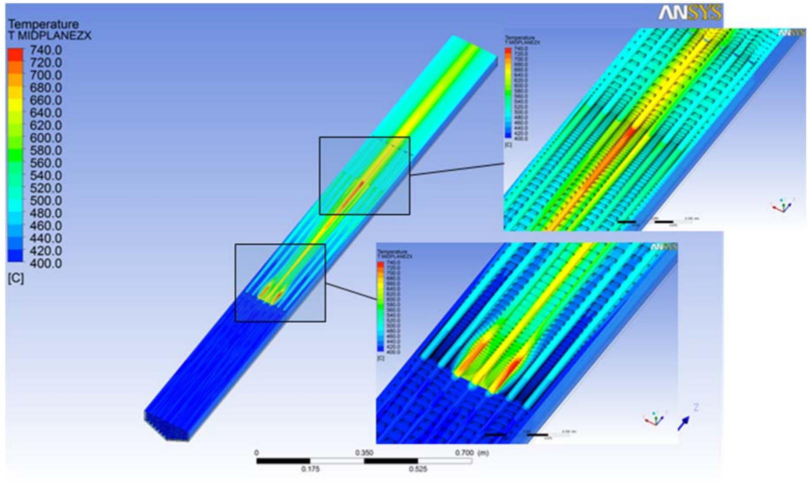
Rod diameter d	10.5 mm
Pitch to diameter ratio p/d	1.32
Number of fuel rods	127
Mean Wall Heat Flux q_{wall}	0.7 MW/m^2
Conservative Wall Heat Flux (for engineering computations)	1 MW/m^2
Active Height L	0.6 m
Lead Inlet Temperature T_{inlet}	400 °C
Lead Outlet Temperature T_{outlet}	470 °C
Lead Bulk Velocity	1.4 m/s
Lead flow average FA	144.1 kg/s
Bypass flow average FA (3%)	2.76 kg/s
Clad Maximum Temperature (expected under nominal conditions)	550 °C

- ✓ ANSYS CFX 13
- ✓ SST k-ω Menter (1994)
- ✓ y^+~1 at the wall
- ✓ N_{nodes}~$22\cdot10^6$ (160 axial)
- ✓ Δt ~1 ms (CFL ~1)
- ✓ q_{wall}=1 MW/m^2

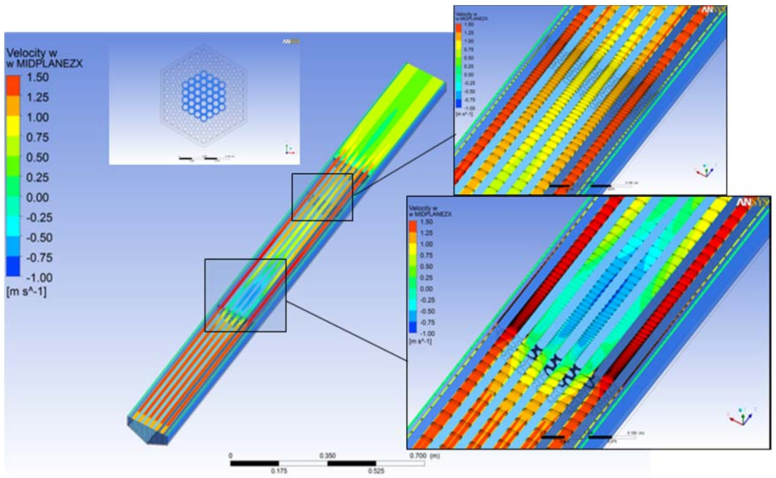
Fuel SA Internal blockage analysis with CFD *3*

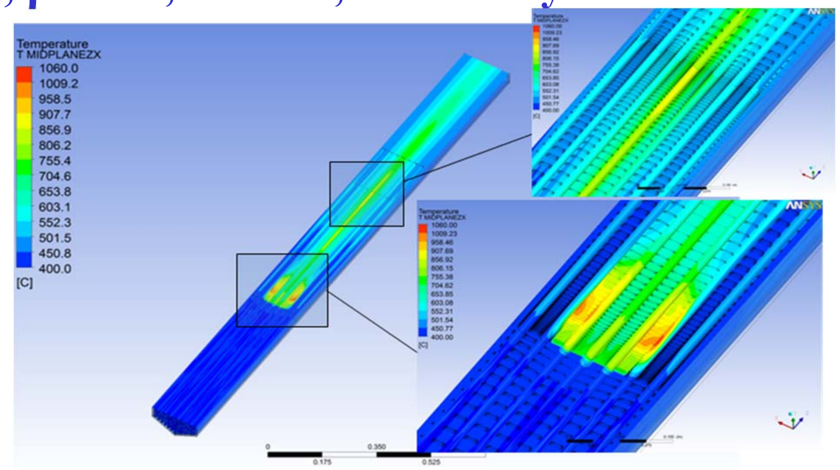
Nblock=19, β(area blockage fraction)=0.15, case 11, stationary





Nblock=37, β=0.29, case 12, stationary

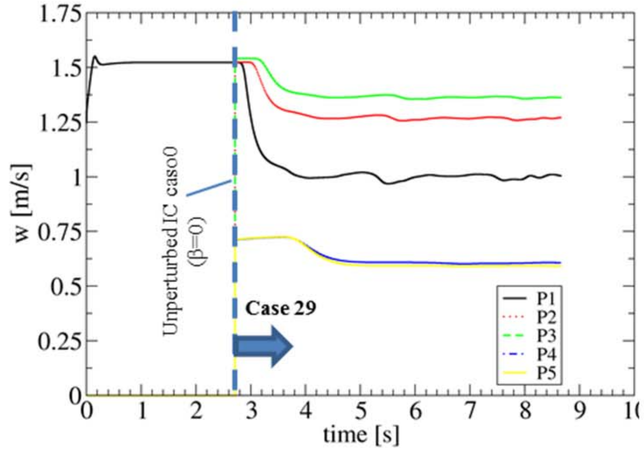


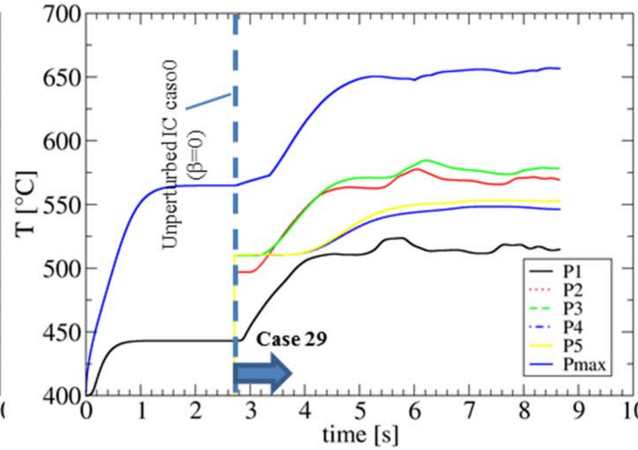


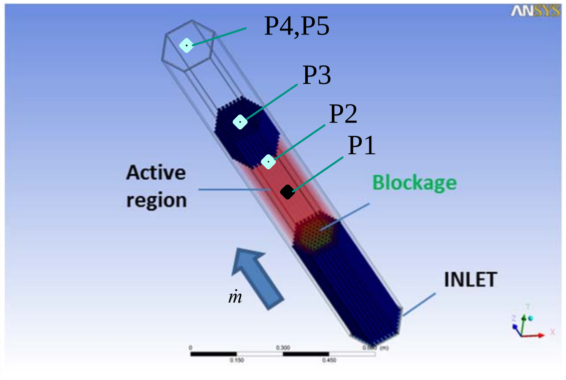
Fuel SA Internal blockage analysis with CFD *4*

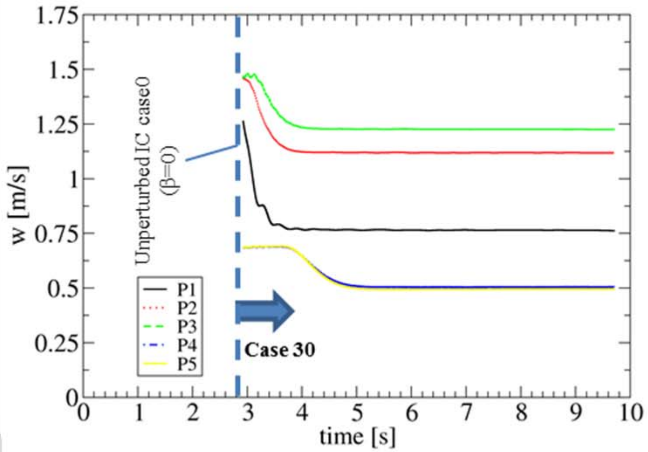
Transient solutions

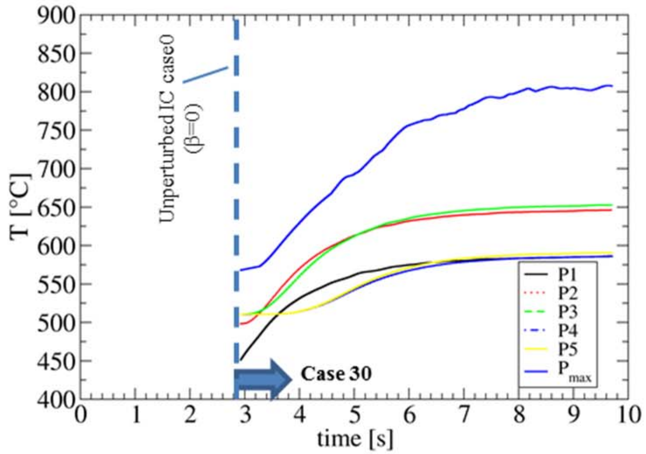
CASE Number	TYPE	BlockTYPE	N_{block}	β	[kg/s]	m/m_0
28	*TRANSIENT*	*CENTRAL*	*1*	*0.008*	*144.14*	*1*
29	*TRANSIENT*	*CENTRAL*	*7*	*0.055*	*144.14*	*1*
30	*TRANSIENT*	*CENTRAL*	*19*	*0.150*	*136.93*	*0.95*

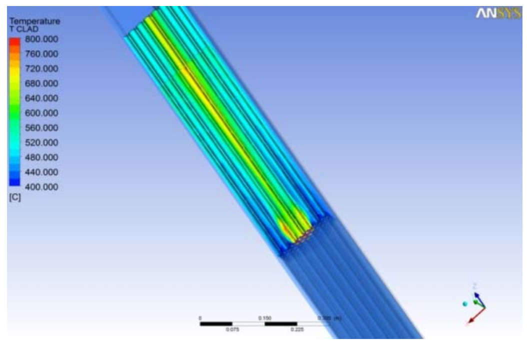








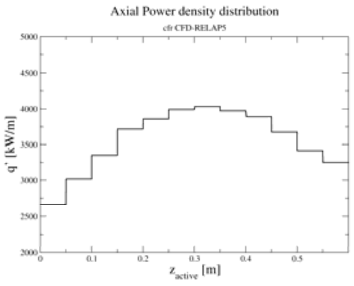




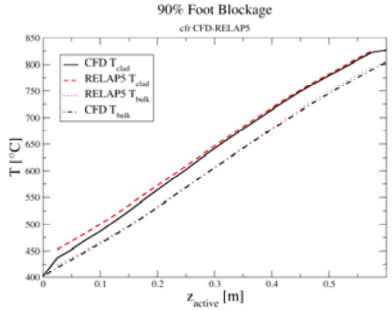
Clad temperature contours for case 30 (N_{block}=19): time = 9 *s*.

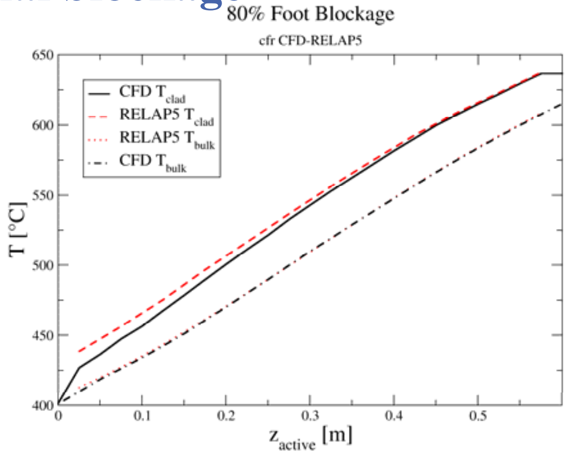
Fuel SA Internal blockage analysis with CFD 5

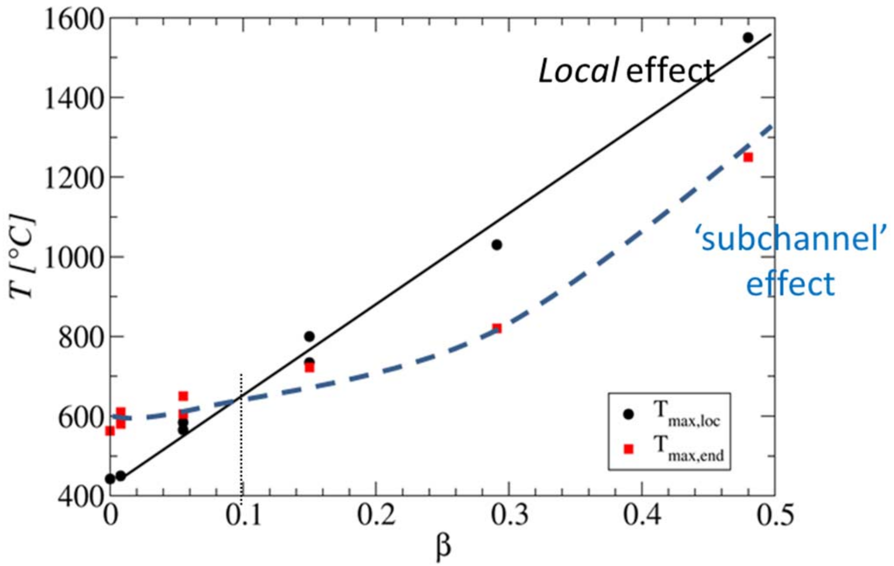
Comparison with RELAP simulation on external blockage



CASE Number	TYPE	BlockTYPE	*β*	*[kg/s]*
CFR80	STATIONARY	FOOT	0.8	69.788
CFR90	STATIONARY	FOOT	0.9	37.066







Overall results from CFD analysis of internal blockage: maximum clad temperature

KIT Karlsruhe Institute of Technology ENEA NRG

Fuel SA Internal blockage analysis with CFD *6*

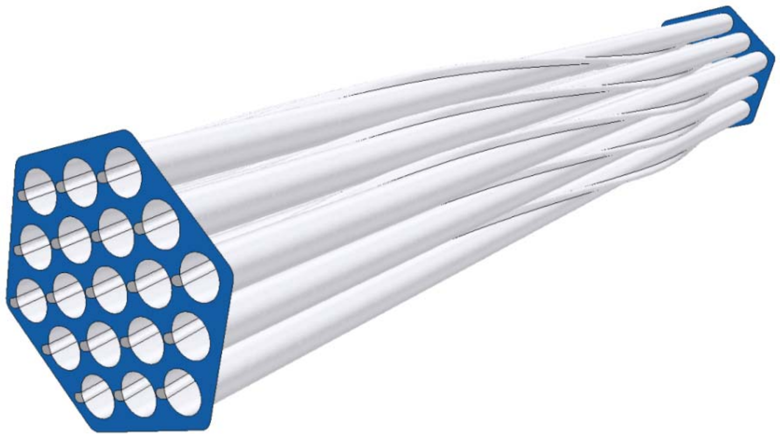
- ✓ A CFD analysis by fully resolved RANS simulations has been carried on **fluid flow and heat transfer in the case of flow blockage in heavy liquid metal cooled fuel assemblies**. The **hexagonal closed ALFRED FA** have been considered for the study. The model includes the different *FA regions* (entry, active, follower, plenum), the *conjugate heat transfer* in the clad and the wrap, the bypass and power released by gamma. All the pins of the FA have been modeled and no special symmetry planes have been considered.
- ✓ Two main effects can be distinguished in a flow blockage: a **local effect** in the wake/recirculation region downstream the blockage and a **global effect** due to the lower mass flow rate in the blocked subchannels; the former effect gives rise to a temperature peak behind the blockage and it **is dominant for large blockages** (β>0.1-0.2), while the latter effect determines a temperature peak at the end of the active region and it is **dominant for small blockages** (β<0.1).
- ✓ ***The blockage area has been placed at the beginning of the active region***, so that both over-mentioned phenomena can fully take place. The mass flow rate at the different degree of blockage has been imposed from preliminary *system code simulations* (minor influence).
- ✓ Results indicate that **a blockage of ~15%** (in terms of area) leads to a maximum clad temperature around **800 °C**, and this condition is reached in a characteristic time of *3-4 s without overshoot*. Local clad temperatures around **1000 °C** can be reached for blockages of **30% or more**.
- ✓ CFD simulations indicate that *Blockages >15% could be detected by putting thermocouples in the plenum region of the FA*.

Outline

- Types of fuel SA blockages
- Fuel assembly blockage analysis with SIM-LFR
- Fuel assembly blockage analysis with RELAP5
- Fuel assembly blockage analysis with SIMMER-III
- Fuel assembly blockage CFD analysis with ANSYS
- Fuel assembly blockage CFD analysis with STAR-CCM+
- Conclusions

Fuel SA blockage CFD analysis with STAR-CCM+ THEADES bundle

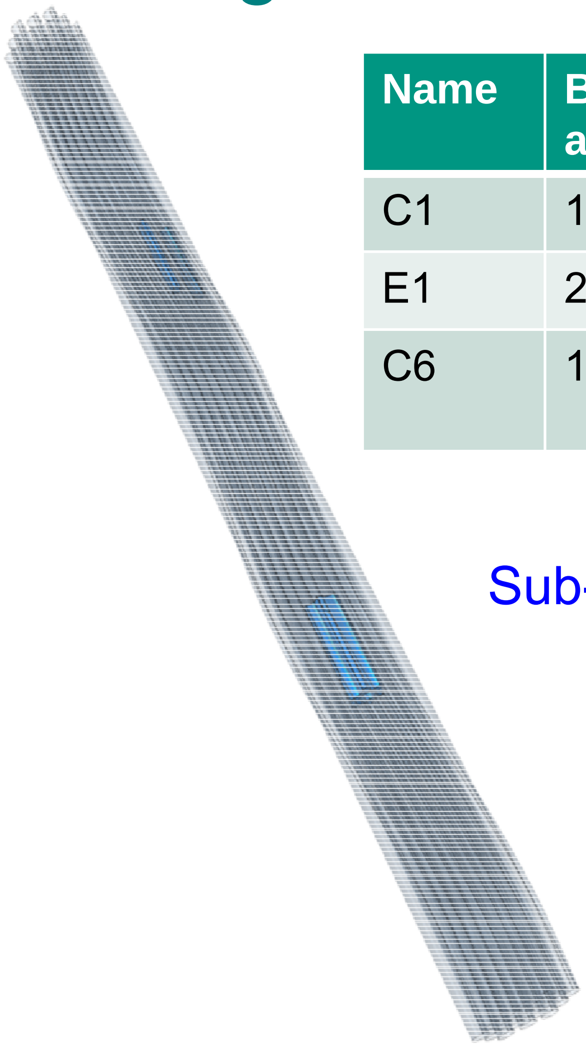
- 19-pin wire-wrapped rod bundle experiment at KIT
- Several internal blockages are implemented
- Numerical sensitivity analysis is performed to reduce the number of experiments
- Influence of the size, location and the conductivity of the blockage.



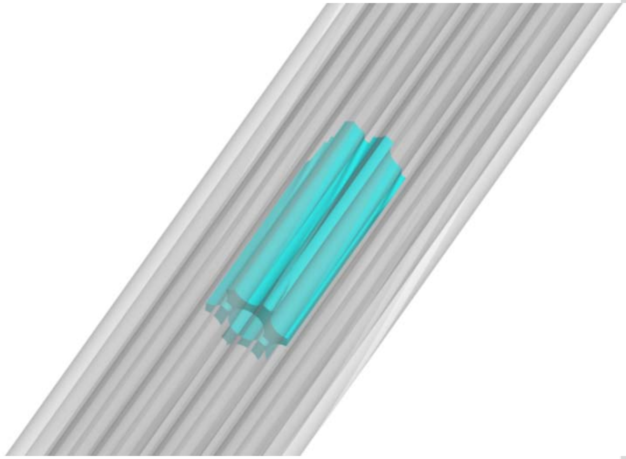
- P_w = wrapping pitch ⟷
- z = streamwise coordinate
  $z = [0, 2 \cdot P_w]$

	KALLA Bundle	MYRRHA
Number of pins	19	127
Pin diameter	8.2 mm	6.55 mm
Pin pitch	10.5 mm	8.4 mm
Wrapping pitch	328 mm	262 mm
Wire diameter	2.2 mm	1.75 mm
Smallest gap	0.1 mm	0.1 mm

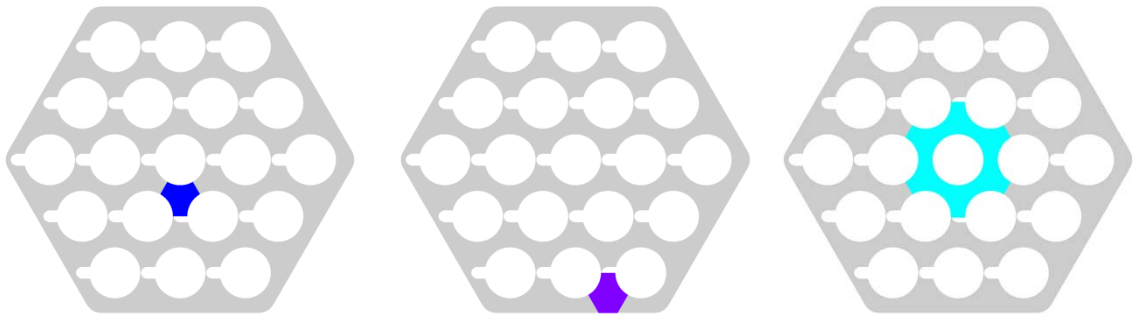
Fuel SA blockage CFD analysis with STAR-CCM+ Blockages



Name	Blocked flow area (%)	Conductivity ($Wm^{-1}K^{-1}$)
C1	1.9	2
E1	2.6	2
C6	11.4	2 12



Sub-channels are blocked between z = ½ P_w and ⅔ P_w



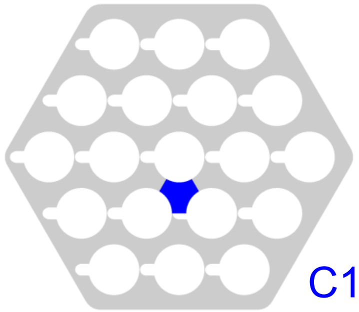
C1 E1 C6

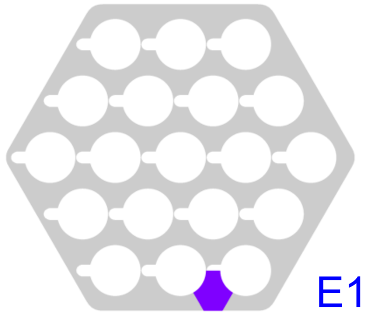
Fuel SA blockage CFD analysis with STAR-CCM+ Computational Setup

	Property
Code	STAR-CCM+
Turbulence model	SST k-ω
Schemes	Segregated flow Segregated heat transfer All second order
Time dependence	Steady state
Working fluid	Lead-Bismuth Eutectic (LBE) Temperature dependent properties
Inlet	Re = $3.78 \cdot 10^4$ (based on sub-channel) T_{in} = 270 °C
Outlet boundary condition	P = 0 Pa
Wire and outer ring rod	Steel solid, no slip walls
Inner ring rod	Boron-Nitride Heat flux of 1.38 MW/m^2 applied at inner rod surface, resulting in a heat flux of 0.924 MW/m^2 at outer cladding
Total power	Total power 0.297 MW

Fuel SA blockage CFD analysis with STAR-CCM+
Single sub-channel blockages

- Unblocked reference case
- Only C1 or E1 blocked
- C1 and E1 blocked at the same axial position



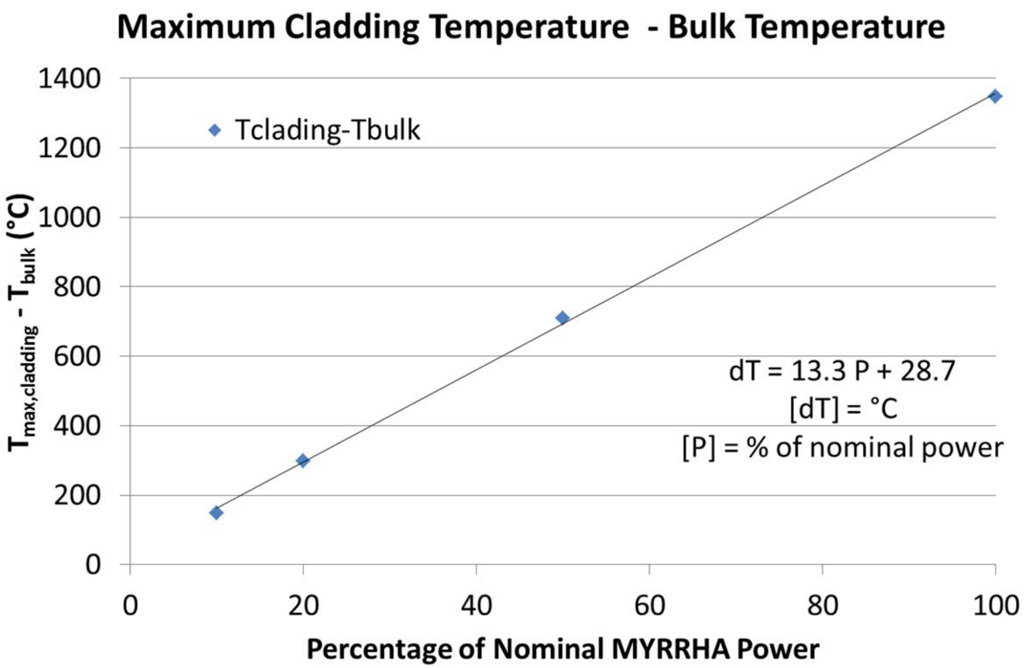


Case	$T_{max,cladding}$ - T_{bulk} (°C)	$T_{max,cladding}$ (°C)	z/P_w
Reference	87	480	2
C1 blocked	211	520	0.63
E1 blocked	170	479	0.63
C1 & E1 blocked	@ C1: 210 @ E1: 170	@C1: 519 @E1: 479	0.63 0.63

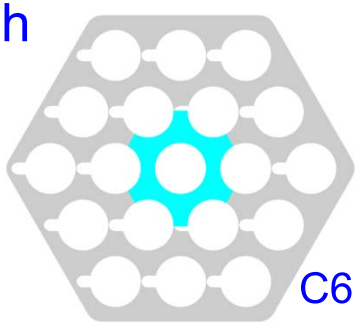
- Temperatures are experimentally feasible.
- C1 and E1 barely influence each other if located at the same axial position. So in one experiment, both C1 and E1 can be blocked.

Fuel SA blockage CFD analysis with STAR-CCM+
Six blocked sub-channels

Case	$T_{max,cladding}$ - T_{bulk} (°C)	$T_{max,cladding}$ (°C)
Reference	87	480
C6 blocked	1349	1655
C6 Blocked, *50% nominal power*	710	998
C6 Blocked, *20% nominal power*	299	576
C6 Blocked, *10% nominal power*	148	422



- Maximum cladding temperature at nominal power is too high
- 10 % of nominal power results in smaller temperature differences than C1 or E1 at nominal power
- Maximum temperature difference approximately scales with the power input.
- Linear fit useful for design of experiments



Fuel SA blockage CFD analysis with STAR-CCM+
Blockage conductivity

- 6 blocked sub-channels with nominal MYRRHA power
- Conductivity is increased from 2 $Wm^{-1}K^{-1}$ (oxides) to 12 $Wm^{-1}K^{-1}$ (LBE)

Case	Blockage Conductivity ($Wm^{-1}K^{-1}$)	$T_{max,cladding} - T_{bulk}$ (°C)	$T_{max,cladding}$ (°C)
Reference	-	87	480
C6 blocked	2	1349	1655
C6 blocked, *high conductivity*	12	597	903

- High conductivity significantly reduces the maximum cladding temperature

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Conclusions (1)

- Two types of SA flow blockages exist: external and internal;

- For **external** blockages case, all codes agree that fuel pin failure occurs when blockage exceeds ~85% of the flow area, while clad melting can be expected when blockage exceeds 90-95% of the flow area. Blockage effects can be detected already starting from ~25% of the flow blockage area;

- For **internal** blockages case, SIMMER-III and all CFD codes show that fuel pin failure occurs already when blockage exceeds ~15% of the flow area. Hot spot is located just behind or even within the blockage. This depends to a great extent on the blockage region thermal conductivity: the higher blockage conductivity, the lower fuel pin clad temperature and the risk for the pin to fail or for the clad to melt;

Conclusions (2)

- In order to re-confirm these predictions of the CFD codes, corresponding R&D activity should be foreseen, experimentally analyzing various possible internal flow blockages in a SA and their formation mechanisms;

- The paramount role when avoiding the SA flow blockages plays oxygen control in a LFR (avoiding formation of lead oxides). In this sense, coolant cleaning from possible oxides and other sorts of debris is a prerequisite preventing them from reaching the active core region.

Acknowledgements

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