Impact of Truly Optimized PWR (TOP) Lattice on Maximum Power of Natural Circulation Reactor

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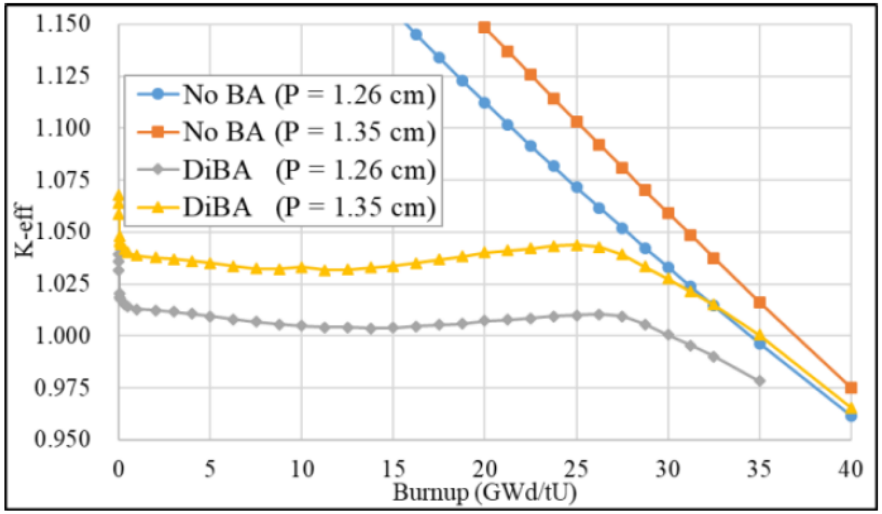
Introduction (1/3)

- **The rise of Small Modular Reactor (SMR)**
  - Reduced capital cost
  - Compact module (modularity)
  - Enhanced safety performance -> enhanced furthermore by passive cooling system
- **Passive cooling SMRs -> natural circulation**
  - Simplify reactor system design
  - Enhances the reactor safety performance
  - Lower mass flow rate -> lower power; affected by
    - Reactor power
    - Fuel Assembly (FA) design
    - Operation state of the heat exchanger
- **Natural circulation vs forced circulation**

Type	Core Flow Distribution
Natural circulation	Automatically adjusted according to the local power and resistance
Forced circulation	Controlled and adjusted by pump power and flow distributor

Introduction (2/3)

- **High performance Soluble-Boron-Free (SBF) SMR**
  - Autonomous Transportable On-demand reactor Module (ATOM)
    - ATOM's neutronic performance is significantly enhanced by using the TOP lattice with the help of Disk-type Burnable Absorber (DiBA).
    - TOP lattice can be achieved by:
      - Increases the pin pitch for a given fuel rod diameter
      - Reduce the fuel rod diameter for a given pitch
    - Not optimized yet in term of the Thermal-Hydraulic (TH) aspect, particularly under passive cooling system (ATOM's cooled with forced circulation)



Criticality behavior of ATOM Core with DiBA[1]

[1] Ha,et al., A Spectral Optimization Study of Fuel Assembly for SBF SMR, KNS Spring meeting, 2020

Introduction (3/3)

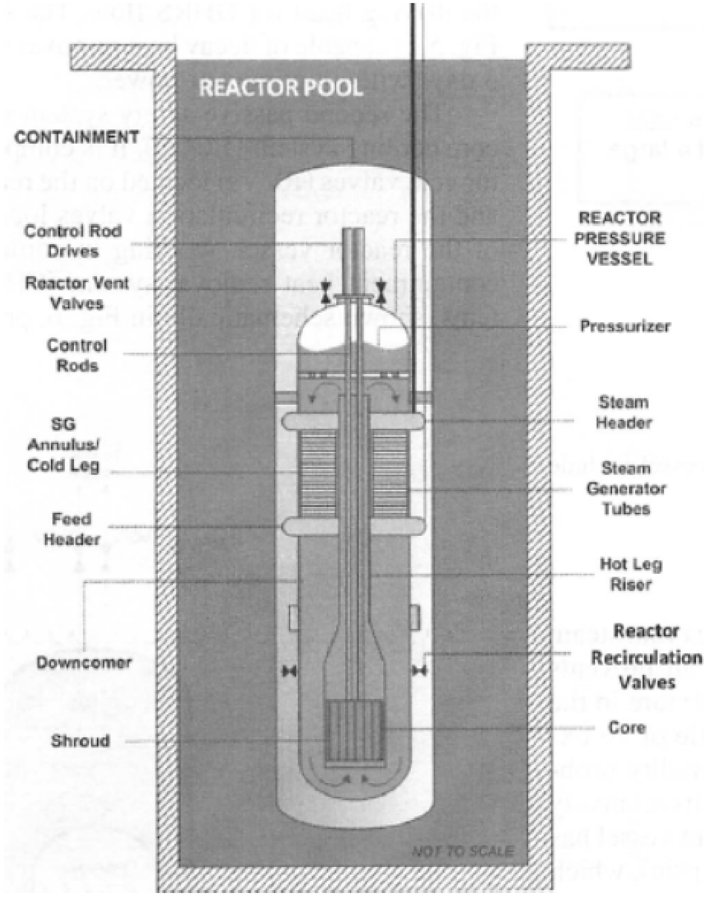
- **NuScale Core**
  - 160 MWt natural circulated SMR based on well-established PWR technology
  - Using soluble-boron to manage the excess reactivity
  - Under US-NRC review for licensing

- **Main Objective**
  - Investigation of TOP implementation on a natural circulation cooled SBF SMR.
  - NuScale Core as the base-model
    - Assuming NuScale Core can be successfully converted to the SBF core.
  - Fuel pin pitch is varied to observe the impact of the reduced pressure drop to the improvement of the system mass flow rate and reactor power under the constraint of same temperature difference.
  - Preliminary step to find the TOP lattice for SBF SMR cooled with natural circulation.

Calculation Method (1/10)

- **Key parameter of NuScale reactor:**

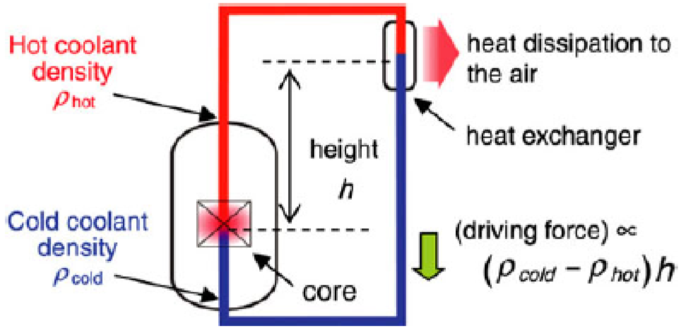
Parameter	Value
Core power	160 MWt
Height of active core	2 m
System pressure	12.75 MPa
Inlet temperature	531.5 K
Best estimate flow	587.15 kg/s
Core average coolant velocity	0.82 m/s
Number of FA	37
FA pitch	21.5 cm
Fuel rod pitch	1.26 cm
Fuel rod diameter	0.95 cm
Cladding thickness	0.061cm
Cladding material	m5
Number of space grid	5
Once through HCSG	
Number of helical tubes per NPM	1380
Tube column per NPM	21
Primary pressure	14.5 MPa
Secondary pressure	3.45 MPa
Steam flow	67 kg/s
Steam temperature	574.8 K
Feedwater temperature	422 K
Tube outer diameter	15.875 mm
Tube thickness	1.27 mm
Total heat transfer area	1665.57 m^2

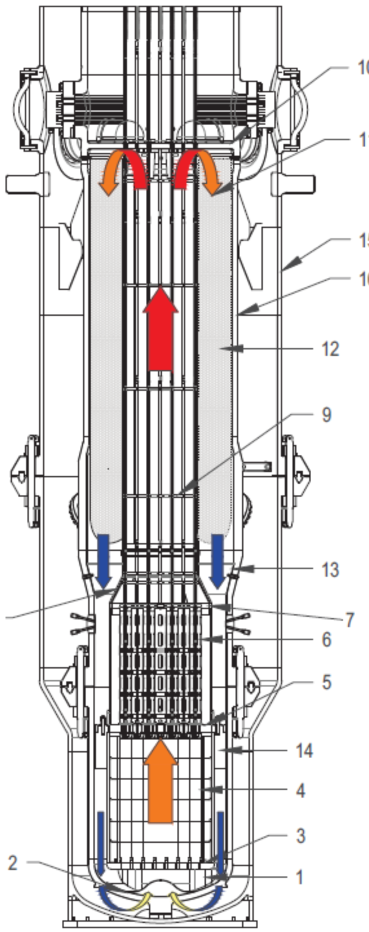


Calculation Method (2/10)

- **Several conditions being considered:**
  - The analysis will be done within the primary circulation loop
  - The reactor is modelled (thermal-hydraulically) as consisting of laterally closed parallel channels
  - Axial power distribution -> chopped cosine function
  - Steady state natural-circulation system:

$$P_{buoyancy} = P_{resistance}$$
$$f(\Delta T, Height) = f(\dot{m}, pitch, geometry)$$





No.	Description
1	Core support blocks in downcomer
2	Downcomer to lower plenum turn
3	Core support blocks in downcomer
4	Upper core plate
5	Core support blocks in downcomer
6	Control rod assembly guide tubes
7	Control rod assembly guide tube support plate
8	Riser transition
9	Control rod dive shaft support
10	Pressurizer baffle
11	Upper riser turn to annulus
12	Downcomer through steam generator
13	Downcomer transition
14	Upper core support block
15	Containment vessel
16	Reactor vessel

Primary reactor coolant flowing path of NuScale; Copyright by NuScale Power, LLC.

Calculation Model (3/10)

- **Core mass flow rate model of natural circulation**

One dimensional primary loop momentum equation:

$$\sum_k L_k \frac{\partial G_k}{\partial t} = \Delta P_{pump} - \Delta P_{loss} + \Delta P_{buoyancy}$$

– Driving force : No pump -> buoyancy force (density difference between hot and cold pool)

$$\Delta P_{loss} = \Delta P_{buoyancy}$$

– $\Delta \mathrm{P}_{\mathrm{buoyancy}}$ -> system driving force

$$\Delta P_{buoyancy} = (\rho_{cold} - \rho_{hot}) g \Delta H$$

where ΔH is the thermal center difference.

– ΔP_{lost} -> primary system resistance head

$$\Delta P_{loss} = \Delta P_{lowplenum} + \Delta P_{core} + \Delta P_{riser} + \Delta P_{upplenum} + \Delta P_{SG} + \Delta P_{downcomer}$$

– Core pressure drop can be calculated as follow:

$$\Delta P_{core} = \Delta P_{inlet} + \Delta P_{friction} + \Delta P_{spacer} + \Delta P_{outlet}$$

where

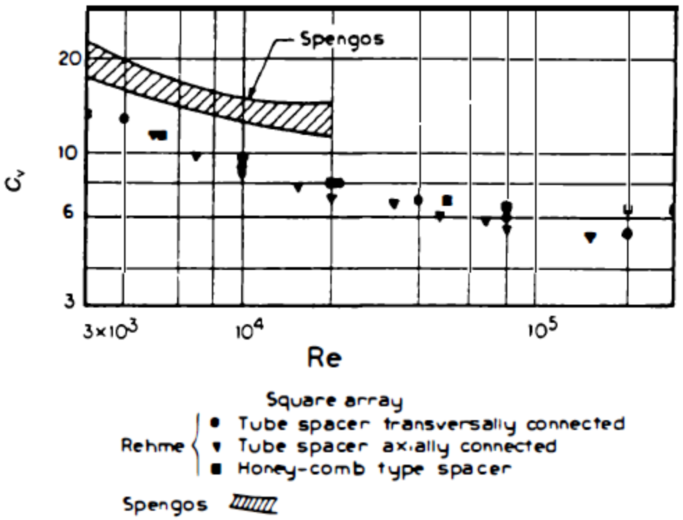
$$\Delta P_{inlet} + \Delta P_{oulet} = (K_{inlet} + K_{oulet}) \frac{1}{2} \rho v^2,$$

$$\Delta P_{fric} = f_{core} \frac{L_{core}}{De_{core}} \frac{1}{2} \rho v^2$$

Calculation Model (4/10)

- **The spacer grid pressure drop is calculated using Rehme's correlation (Honeycomb type) as follow:**

$$\Delta P_{spacer} = N_{spacer} C_v \left(\frac{\rho V_v^2}{2}\right)\left(\frac{A_s}{A_v}\right)^2$$



- Dalle Denne's Correlation:

$$Cv = MIN[3.5 + \frac{73.14}{\mathrm{Re}^{0.264}} + \frac{2.79x10^{10}}{\mathrm{Re}^{2.79}}, \frac{2}{(\frac{A_s}{A_v})^2}]$$

A_s= projected frontal area of spacer
A_v= unrestricted flow area
C_v= drag coefficient
V_v=average bundle fluid velocity
V_s= velocity in the spacer region
t = grid thickness
N_{spacer}= Number of spacer grid

$$A_s = 2\left(Pitch * t - \frac{t^2}{2}\right)$$

$$A_v = Pitch^2 - \frac{\pi D^2}{4}$$

$$V_v = V_s \frac{A_v - A_s}{A_v}$$

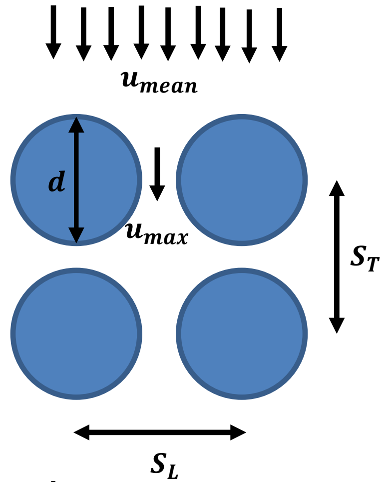
$$V_s = \frac{m_{dot}}{\rho(A_v - A_s)}$$

$$De = \frac{4[Pitch^2 - \pi r^2]}{\pi D}$$

$$Re = \frac{D_e V_v}{v}$$

Calculation Model (5/10)

- There are two types of the helical coil tube configurations:
  - In-line configuration

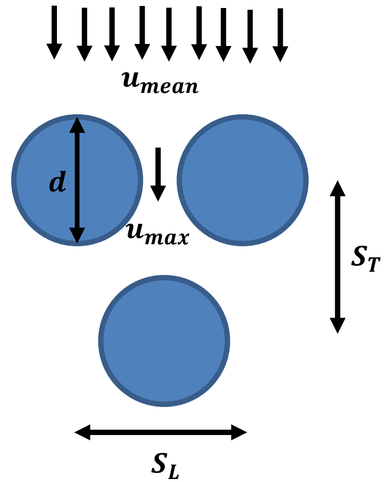


Two option for pressure drop calculation:

a. Zukauskas and Ulinkskas (1988)
   a. 3 different pitch to diameter ratio (1.25,1.5 and 2.0)

b. Gaddis and Gnielinski (1985)
   a. More general over a large range of P/D

  - Staggered configuration



S_L= Longitudinal pitch
S_T= Transversal pitch
u_{mean}= free stream/mean velocity
u_{max}= maximum velocity in the minimum cross-section area
d= Tube outer diameter

Calculation Model (6/10)

- **In the current mode inline configuration is assumed. The pressure drop for the in-line bundle configuration can be calculated using Gaddis-Gnielinski Correlation as follow:**
  - Drag Coefficient:

$$\xi = \xi_{lam} + (\xi_{turb} + f_n)[1 - \exp(-\frac{\mathrm{Re}_d + 1000}{2000})],$$

$$\xi_{lam} = 280\pi \frac{(b^{-0.5} - 0.6)^2 + 0.75}{a^{1.6}(4ab - \pi)\mathrm{Re}_d},$$

$$\xi_{turb} = \frac{f_t}{\mathrm{Re}_d^{0.1(\frac{b}{a})}},$$

$$f_t = [0.22 + \frac{1.2(1 - (\frac{0.94}{b}))^{0.6}}{(a - 0.85)^{1.3}}]10^{0.47}(\frac{b}{a} - 1.5) + 0.03(a-1)(b-1),$$

$$f_n = \frac{1}{a^2}(\frac{1}{N} - \frac{1}{10});\ for 5 \le N \le 10$$

$$f_n = 0;\ for N \ge 10$$

Calculation Model (7/10)

- **Gaddis-Gnielinski Correlation**
  - Euler Number:

$$Eu = \zeta N$$

  - Pressure Drop:

$$P = Eu\frac{1}{2}\rho u_{maxs}^{2}$$

$$u_{maxs} = \left(\frac{a}{a-1}u_{mean}\right)$$

Other:

$$D_e^{HCSG} = \left(\frac{4a}{\pi} - 1\right)d; b > 1$$

$$D_e^{HCSG} = \left(\frac{4ab}{\pi} - 1\right)d; b < 1$$

$$Re_d = \frac{D_e^{HCSG} u_{max}\rho}{\mu}$$

a= Transversal pitch to outer diameter ratio $\left(\frac{S_T}{d}\right)$ b= Longitudinal pitch to outer diameter ratio $\left(\frac{S_L}{d}\right)$ ζ= Drag Coefficient ζ_{lam}= Drag coefficient contribution from laminar flow ζ_{turb}= Drag coefficient contribution from turbulent flow Eu = Euler Number f_n = inlet and oulet effects D_e^{HCSG}= HCSG equivalent diameter	S_L= Longitudinal pitch S_T= Transversal pitch u_{mean}= free stream/mean velocity u_{max}= maximum velocity in the minimum cross-section area d= Tube outer diameter N = Number of tube column Re = Reynold number μ= coolant dynamic viscosity

Calculation Model (8/10)

- **PHX heat transfer model**
  - Helical coil type
  - Modelled with several simplifications, with predetermined secondary side condition (uncoupled)
  - heat generated in the core = heat transferred to the heat exchanger

$$\frac{1}{R_{SG}} = \frac{Q}{A_h \Delta T_m}, A_h = N_{tubes} P_h^{tubes}\ l, P_h^{tubes} = \pi D_o$$

$$\Delta T_m = \frac{\Delta T_{\max} - \Delta T_{\min}}{\ln \frac{\Delta T_{\max}}{\Delta T_{\min}}},$$

$$G\frac{\partial h}{\partial z} = \frac{q'' P_h}{A},$$

$$G\frac{(h(T_z^{primary}) - h(T_{z-1}^{primary}))}{z_i - z_{i-1}} - \frac{\left(T_z^{primary} - T_z^{\sec ondary}\right)P_h}{R_{SG} A} \square\ 0$$

h: coolant enthalpy
P_h^{tube}: helical tubes heated perimeter
A_f: flow area
R_{sg}: thermal resistance
A_h: total heat transfer area
Q: total heat to be transferred to secondary side
ΔT_{max} and ΔT_{min}: maximum and minimum temperature difference between primary and secondary side
l: tube length
D_0: outer diameter of helical tubes

- **For simplification, it is assumed that the heat transfer at lower plenum, upper plenum and down comer is negligibly small**

Calculation Model (9/10)

- **Closed parallel multi-channel model**
  - N uniform, vertical, interconnected, parallel channel
  - Single fuel assembly -> a basic channel unit
  - The pressure drop balance equation for each channel:

$$\Delta P_{ch,n} = P_{ch,n}^{in} - P_{ch,n}^{out}$$

$$\Delta P_{ch,1} = \Delta P_{ch,2} = \Delta P_{ch,n}; n = 1,2,3,\ldots N$$

  - The mass conservation equation for each channel:

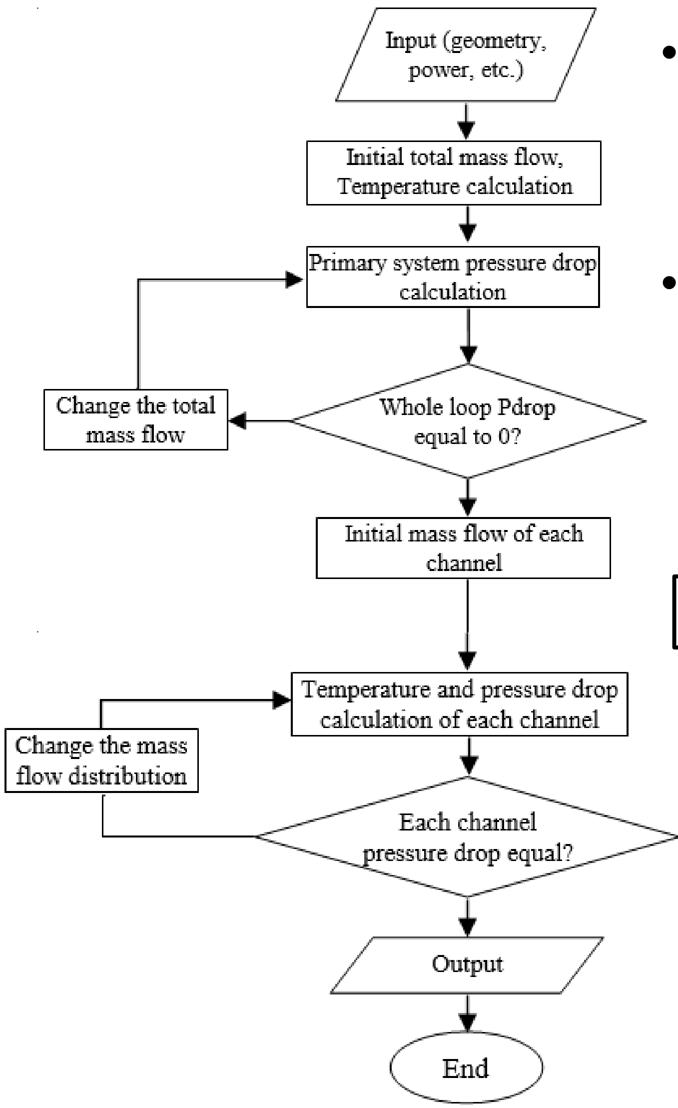
$$W_{total} = W_1 + W_2 + \cdots + W_n; n = 1,2,3,\ldots N$$

  - The energy conservation equation for each channel:

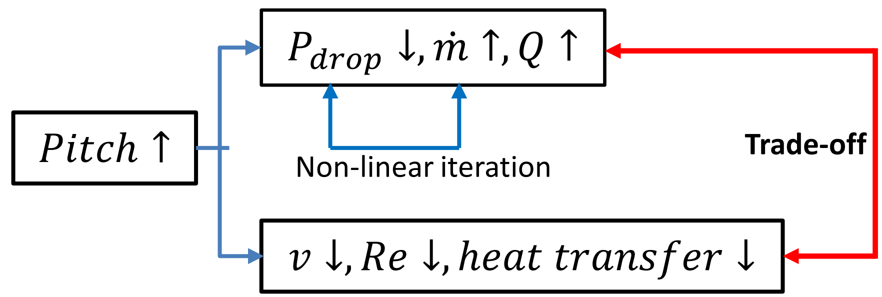
$$Q_n = W_n\left(h_{out,n} - h_{in,n}\right); n = 1,2,3,\ldots N$$

- ❑ Mass flow rate and enthalpy rise of each channel can be determined by solving above equations
- ❑ Chopped cosine function is utilized to determine the axial power distribution

Calculation Model (10/10)



- In the primary system pressure drop circulation:
  - Core pressure drop and temperature calculation
- Non-linear iteration:
  - Pitch ↑ core pressure drop ↓ mass flow rate ↑ core pressure drop ↑



Numerical Result (1/2)

- **Due to lack of several key parameters, the pressure drop model need to be adjusted with the constraints as follow:**
  - Buoyancy force (known) = total pressure drop
  - Core Pressure drop ratio to the total Pressure drop = 30%
  - Reference NuScale mass flow: 587.15 kg/s
  - Steady state primary circulation pressure drop equation:

$$\Delta P_{buoyancy} - (\Delta P_{lowplenum} + \Delta P_{core} + \Delta P_{riser} + \Delta P_{upplenum} + \Delta P_{SG} + \Delta P_{downcomer}) = 0$$

$$\Delta P_{buoyancy} - (\Delta P_{core} + \Delta P_{SG} + \Delta P_{lossform}) = 0$$

  - It is known that:

$$\Delta P_{core} = \Delta P_{inlet} + \Delta P_{friction} + \Delta P_{spacer} + \Delta P_{outlet}$$

  - Therefore:

$$\Delta P_{buoyancy} - (\Delta P_{inlet} + \Delta P_{friction} + \Delta P_{spacer} + \Delta P_{outlet} + \Delta P_{SG} + \Delta P_{lossform}) = 0$$

  - Pressure drop model adjustment:

$$\Delta P_{buoyancy} - (\Delta P_{inlet} + \Delta P_{friction} + x\Delta P_{spacer} + \Delta P_{outlet} + y\Delta P_{SG} + \Delta P_{lossform}) = 0$$

Numerical Result (2/2)

- Effect of the pitch size to the reactor power
  - Fixed coolant inlet and outlet temperature
  - Fixed height between core and HCSG

Constant $P_{buoyancy}$

Parameter	Pitch (cm)				Change to the original pitch (%)	
	Reference	1.26	1.35	1.4	1.35 cm	1.4 cm
Equivalent core radius (cm)	73.78	73.78	79.04	81.95	7.12	11.07
P_{drop}^{core}(Pa)	N/A	2332.40	1587.70	1293.40	-31.93	**-44.55**
P_{drop}^{HCSG}(Pa)	N/A	5090.50	5772.30	6041.70	13.39	18.69
P_{drop}^{others} (Pa)*	N/A	443.992	506.83	531.77	14.15	19.77
Mass flow, $\dot{m}$(kg/s)	587.15	587.06	627.23	642.48	6.84	9.44
$v_{coolant}^{core}$(m/s)	0.861	0.869	0.732	0.666	-15.76	-23.39
$T_{hot}(C)$	310.00	310.00	310.00	310.00	0.00	0.00
$T_{cold}(C)$	258.11	258.87	258.87	258.87	0.00	0.00
Q (MWt)	162.23	160.00	170.94	175.11	6.84	**9.44**

$*$ P_{drop}^{others} is the pressure drop contribution from the other components, such as riser, lower and upper plenum.

- As the core average coolant speed is reduced, CHF may be reduced too resulting in lower DNBR.
- Lower coolant speed -> lower CHF -> lower DNBR

Conclusion and Future Studies

- **Conclusion**
  - Preliminary investigation of the TOP lattice application to the natural-circulated SBF SMR has been performed.
  - Core pressure drop ratio affects the percentage of power gain.
  - Under the same temperature difference as the constraint, the reactor power can be increased by 6.8% and 9.4% utilizing 1.35 cm and 1.4 cm fuel pin pitch.

- **Further studies**
  - Comprehensive TH-analysis need to be performed to determine the optimal TOP lattice for natural circulation cooled SBF SMR.
    - CHF analysis (function of the flow diameter, pressure and coolant speed)
    - Detailed Sub-channel analysis (interior, edge, corner section)
    - Pressure drop model validation
  - Designing the natural-circulated SBF SMR based on the NuScale Core (on-going)

Thank you for your attention