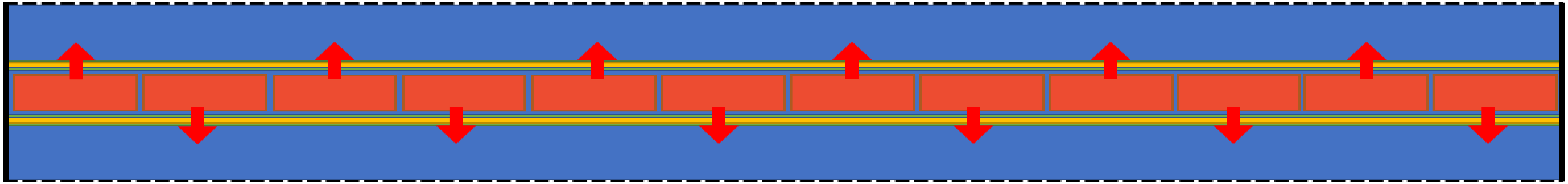
Heat Loss and Neutron Economy Analysis for Heavy Water Reactor Lattice without Insulating Calandria Tube

Faruk Celik , Douglas A. Fynan

Department of Nuclear Engineering,
Ulsan National Institute of Science and Technology (UNIST)
farukcelik@unist.ac.kr, dfynan@unist.ac.kr

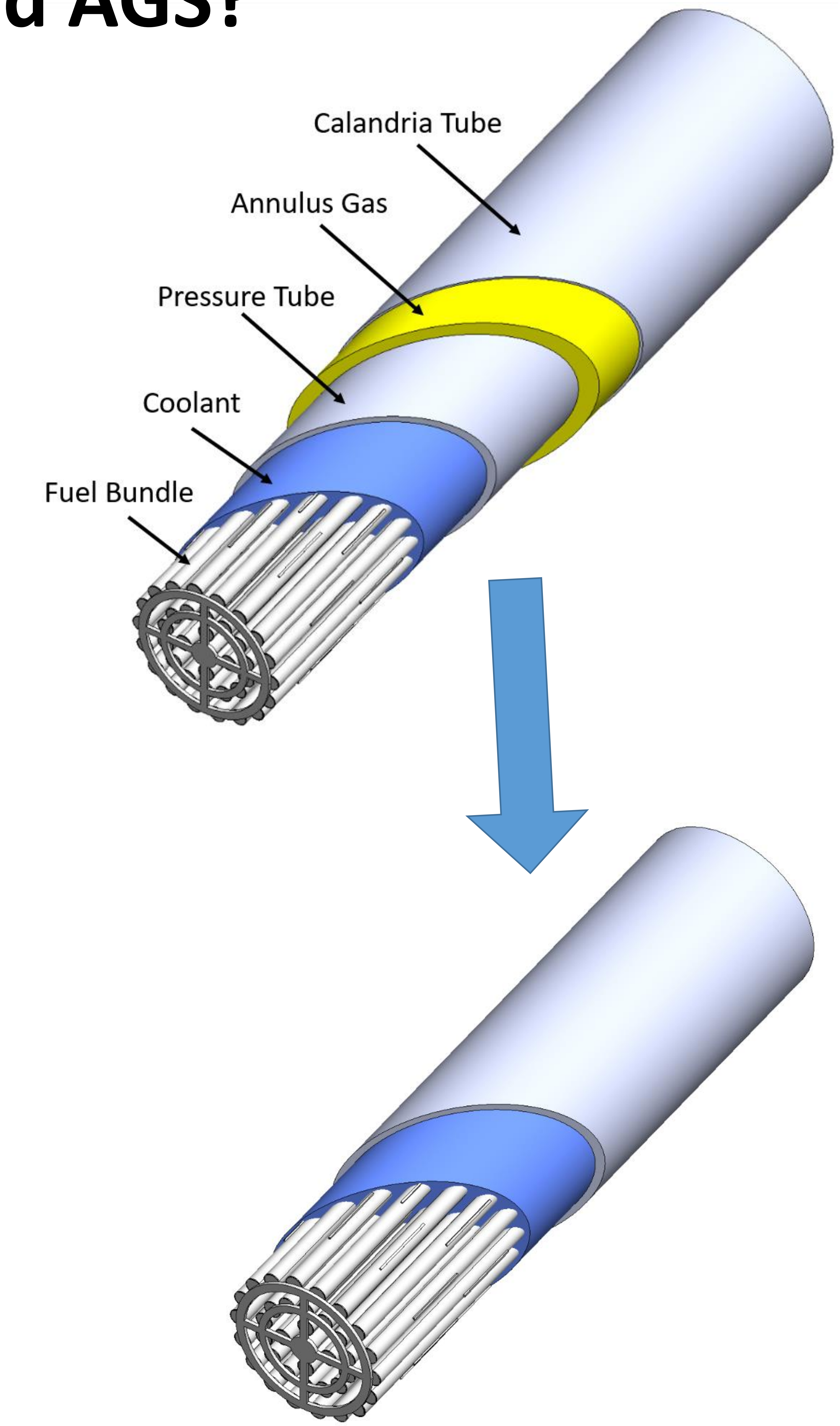
Introduction

- Most heavy water power reactors (HWRs) are the pressure-tube type where the fuel channels and high-temperature coolant are separated from the low-pressure and low-temperature heavy water moderator by a pressure-retaining boundary
- The heat loss from channel to heavy water moderator is minimized by pressure tube (PT), insulating gas annulus (usually CO_2) and calandria tube (CT) in pressure-tube type HWRs
- ~**5%** of the fission reaction Q-value is still lost to the moderator primarily from direct gamma-ray and neutron heating (~98.5 MWt for CANDU-6)
- Only in pressure-vessel type HWRs (Agesta, MZFR, Atucha-I, Atucha-II) can the neutron and gamma heating of the moderator be converted to useable energy by maintaining the moderator temperature above 200 °C and rejecting heat to the feedwater heaters



Design Trade-off Question: What if we remove the CT and AGS?

- Negative Attributes of CT and CO_2:
  - All in-core structures are parasitic absorbers of neutrons affecting neutron economy
  - The reactivity worth of 8.5 tons mass of 380 CTs is -9 mk
  - Zr alloys become activated with long-lived ^{93}Zr (1.5×10^6 year $T_{1/2}$), so the CTs become high-level waste after plant decommissioning
  - Reactors that have large Zr inventories produce more hydrogen (or deuterium) gas during severe accidents
  - The annulus gas system (AGS) and supporting subsystems adds to plant complexity
  - Production of activation product ^{14}C in the AGS contributes to the release of radioactive effluent from CANDU reactors
  - Leakage of CO_2 into the moderator has caused rapid precipitation of moderator soluble poison that if went undetected would have resulted in the loss of guaranteed shutdown state *
- **Design Trade-off Question**: What are the heat loss and neutron economy drawbacks/benefits if we remove the CT and AGS?



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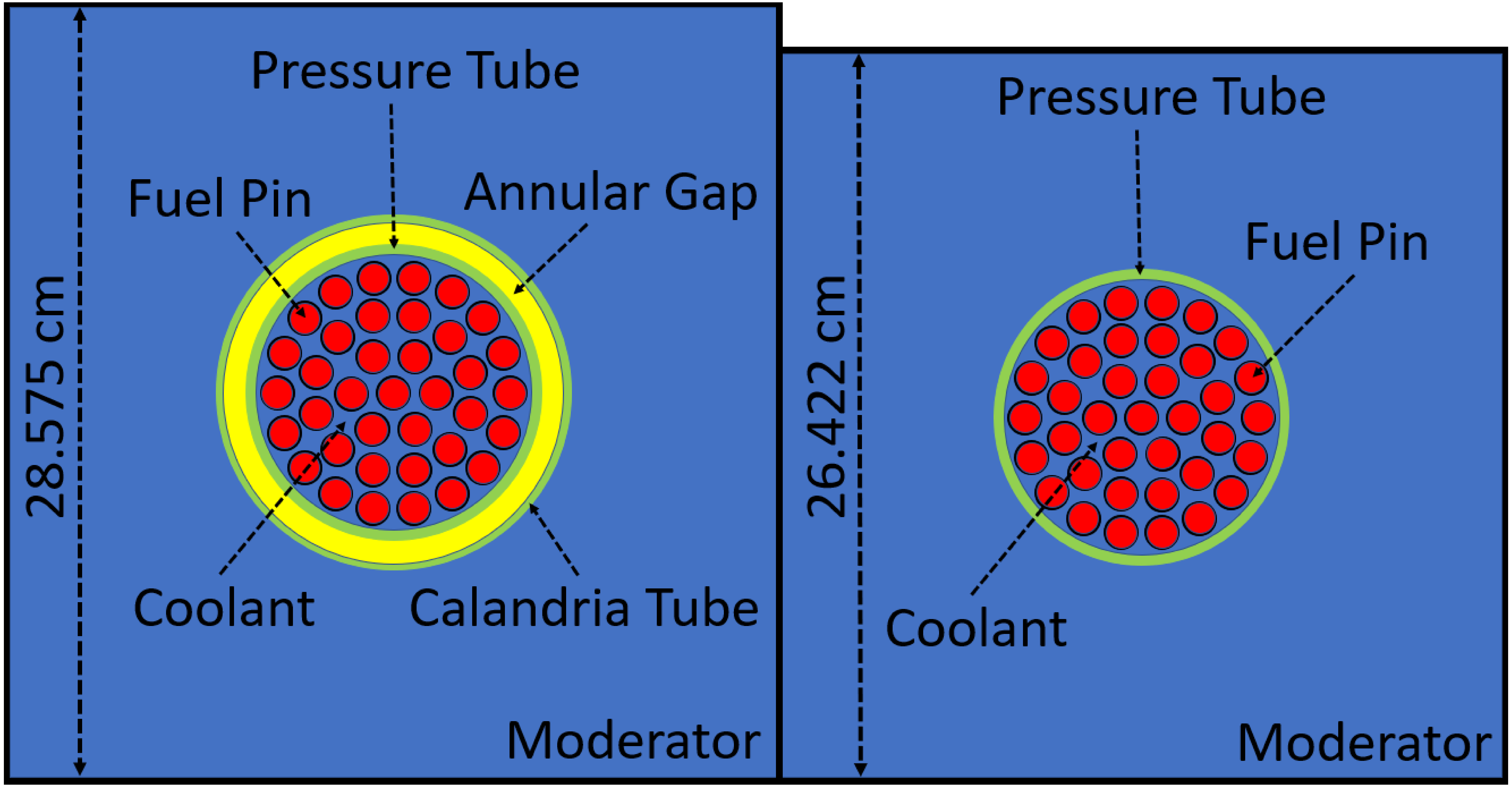
*D.W. Evans, J. Price, D. Swami, E. Fracalanza , M.E. Brett, F.V. Puzzuoli, A. Garg, O. Herrmann, A. Rudolph, C. Stuart, G. Glowa, J. Smee, "Gadolinium Depletion Event in a CANDU Moderator - Causes and Recovery", Nuclear power plant conference, Canada, 2010.

Insulated CANDU-6 Lattice versus Uninsulated Channel



Fuel Channel Heat loss Model

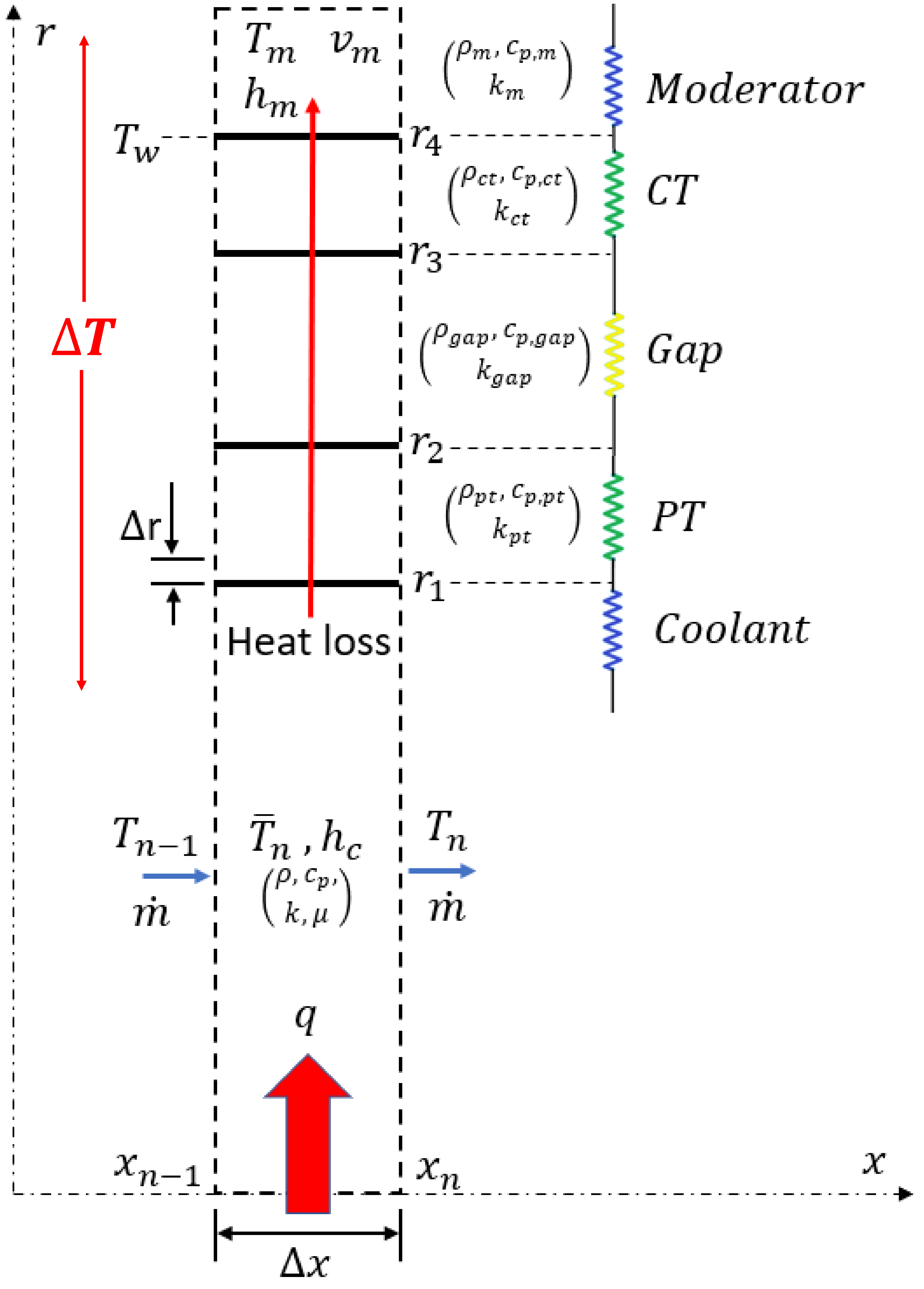
- TH analysis of the fuel channel and heat loss was performed for insulated (traditional CANDU lattice) and uninsulated case (CT + CO_2 gas removed)
- Developed 1D channel flow model using control volume (CV) approach coupled to 1D radial heat conduction model to quantify heat loss
- Axial coolant temperature profile is solved using finite differencing solution for steady-state mass and energy balance through iterative Gauss-Seidel (GS) update of an initial value problem

$$\dot{m}c_p\frac{dT}{dx} = \dot{q}(x) + 2\pi(T_m - T)/\Omega$$

$$T_n^{j+1} = T_{n-1}^{j} + \frac{1}{\dot{m}c_p}\left(q - 2\pi\Delta x\left(\bar{T}_n^{j} - T_m\right)/\Omega\right)$$

$\boldsymbol{\Delta T}$

Overall thermal resistance



Transient Radial Heat Conduction Routine for Wall-to-Moderator Heat Transfer

- Raleigh # is dependent on the CT outer wall temperature (T_w) for heat transfer to moderator
- Recursive relationship between heat loss, radial temperature profile, and wall heat transfer coefficient
- The recursive problem is solved using finite differencing solution of the one-dimensional unsteady-state heat conduction governing equation through iterative GS update of a boundary value problem (BVP)

$$\frac{\partial T_r}{\partial t} = a\left(\frac{1}{r}\frac{\partial T_r}{\partial r} + \frac{\partial^2 T_r}{\partial r^2}\right)$$

$$T_{r,k}^{i} = \alpha T_{r,k-1}^{i+1} + \varphi T_{r,k}^{i+1} + \gamma T_{r,k+1}^{i+1}$$

$$bT_{r,1}^{i} - \alpha \bar{T}_n = (\varphi b - \alpha)T_{r,1}^{i+1} + (\alpha b + \gamma b)T_{r,2}^{i+1}$$

$$T_{r,K-1}^{i} - \gamma d T_m = (\alpha + \gamma)T_{r,K-2}^{i+1} + (\varphi - \gamma d)T_{r,K-1}^{i+1}$$

$$Ra = \frac{g\beta(T_w - T_m)L_c^3\rho^2 c_p}{\mu k}$$

Nu-based coefficient for free + forced convection

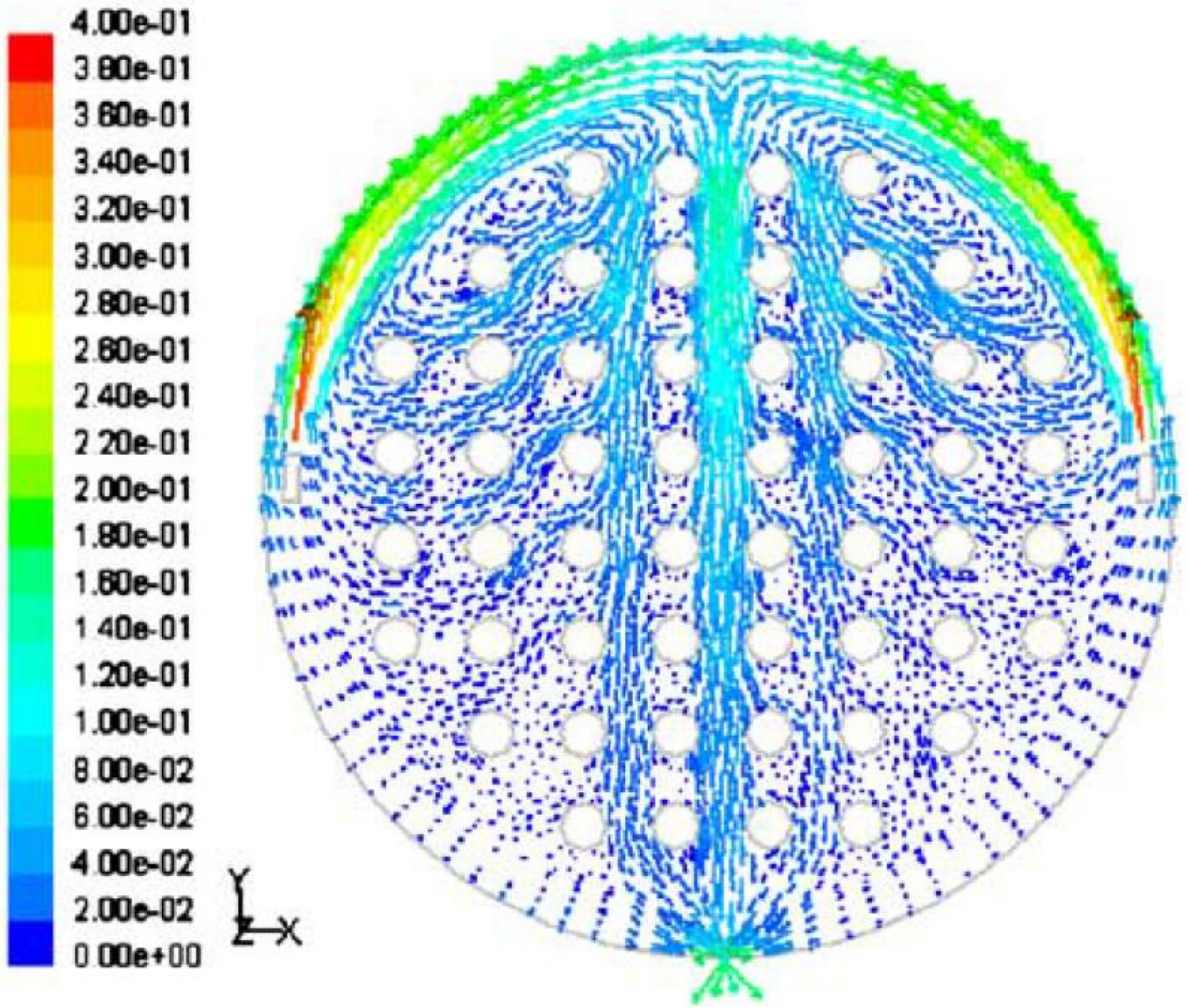
$$Nu_m = \frac{h_m D_h}{k} = \left(Nu_{free}{}^3 + Nu_{force}{}^3\right)^{\frac{1}{3}}$$

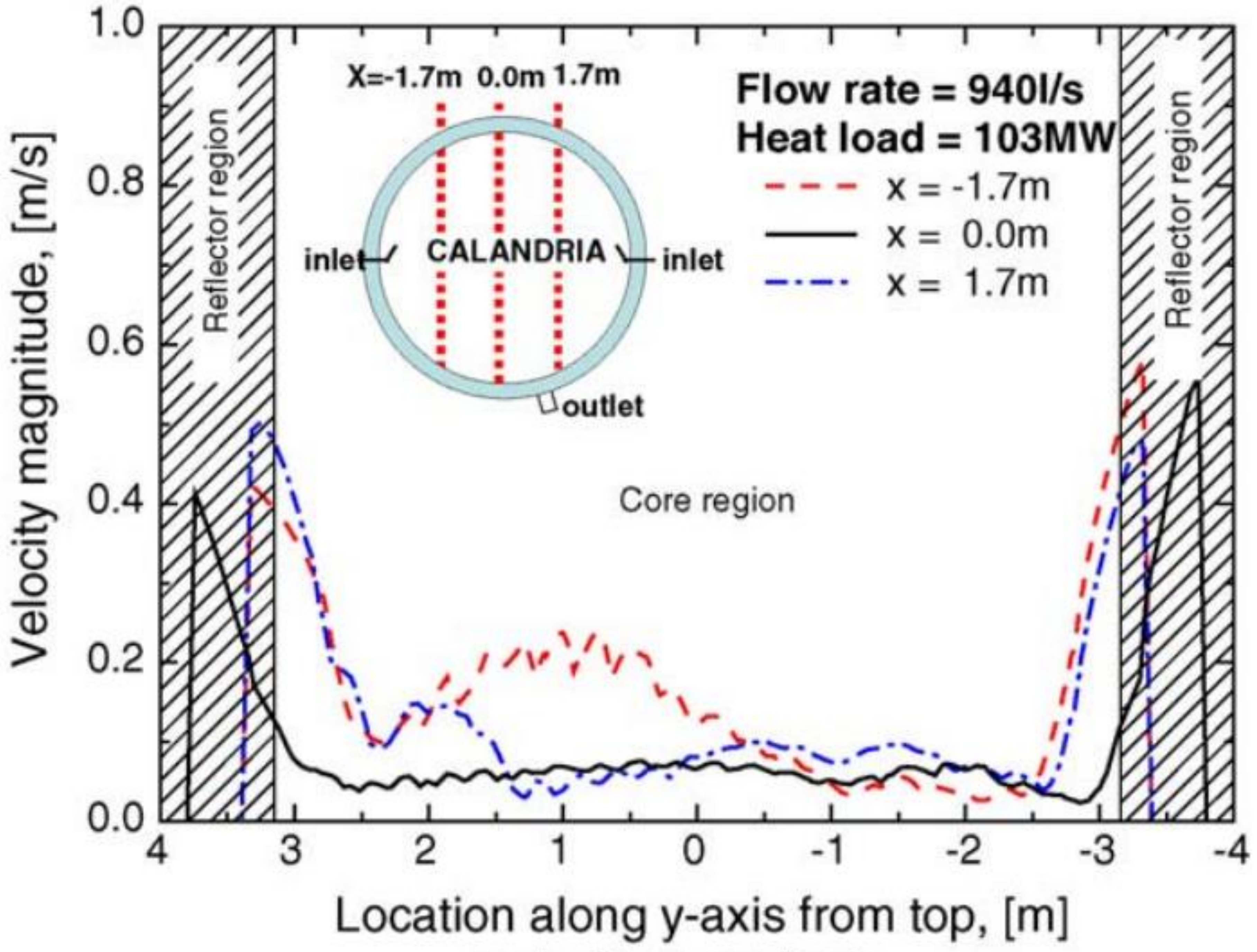
$$Nu_{free} = \left(0.6 + \frac{0.387 Ra^{\frac{1}{6}}}{\left[1 + \left(\frac{0.559}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right)^2$$

$$Nu_{force} = 0.3 + \frac{0.62 Re^{\frac{1}{2}} Pr^{\frac{1}{3}}}{\left[1 + \left(\frac{0.4}{Pr}\right)^{\frac{2}{3}}\right]^{\frac{1}{4}}}\left[1 + \left(\frac{Re}{282000}\right)^{\frac{1}{2}}\right]$$

Parameters of Heat Loss Analysis

- In an actual operating CANDU calandria, the moderator temperature and flow velocities follow complex three-dimensional distributions
- v_m = 0.01 m/s (min), 0.1 m/s (average), 0.5 m/s (max/limiting case) for parametric study of heat loss
- 3 channel powers: 3 MWt, 5.4 MWt (average), 6.8 MWt (high power channel)





velocity magnitude

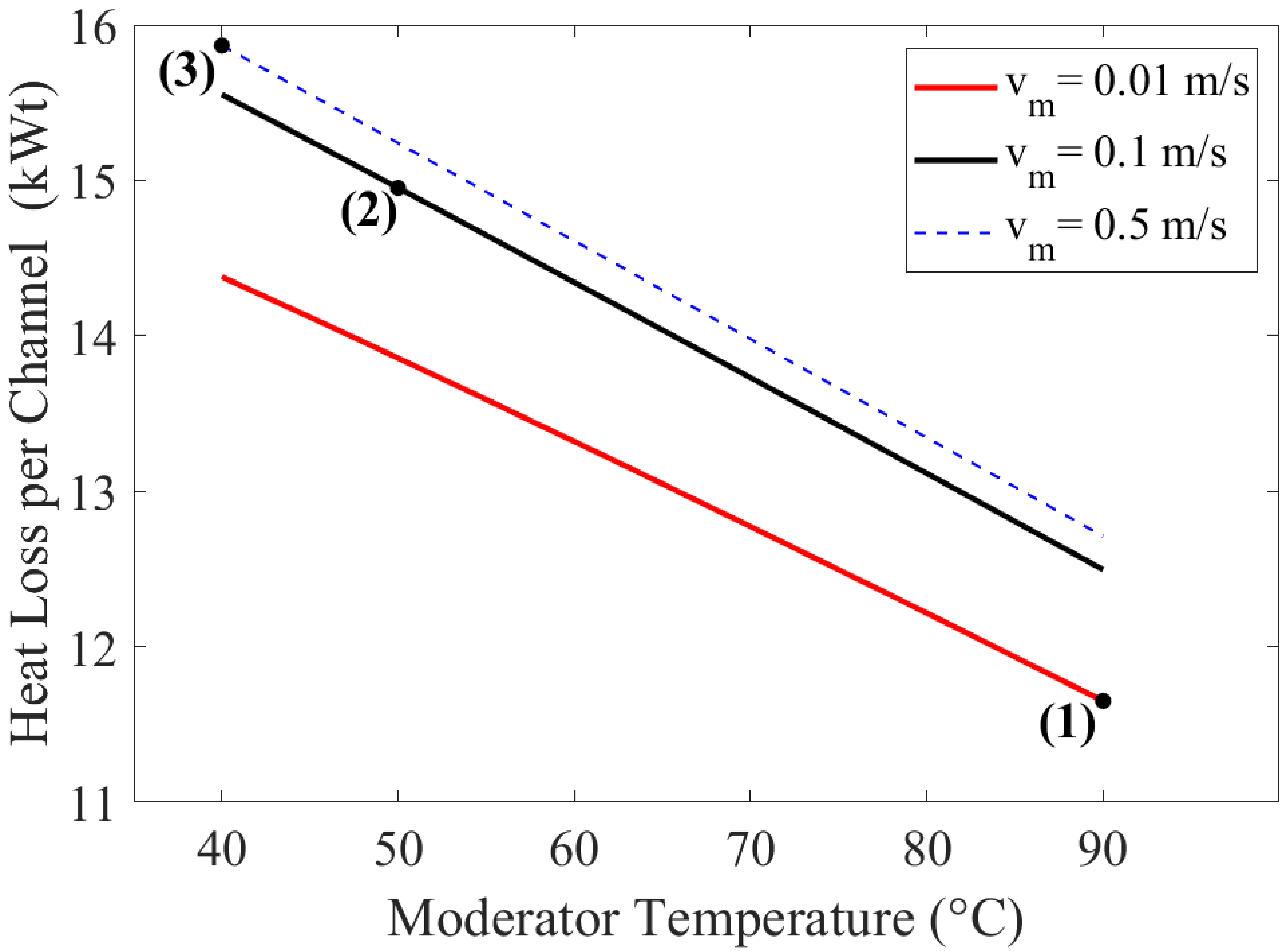
Reference : M. Kim, S.O. Yu, H.J. Kim “Analyses on fluid flow and heat transfer inside Calandria vessel of CANDU-6 using CFD”, Nuclear Engineering and Design, Vol. 236, pp. 1155-1164, 2006.

Heat Loss from Insulated Channel (CANDU-6 lattice)

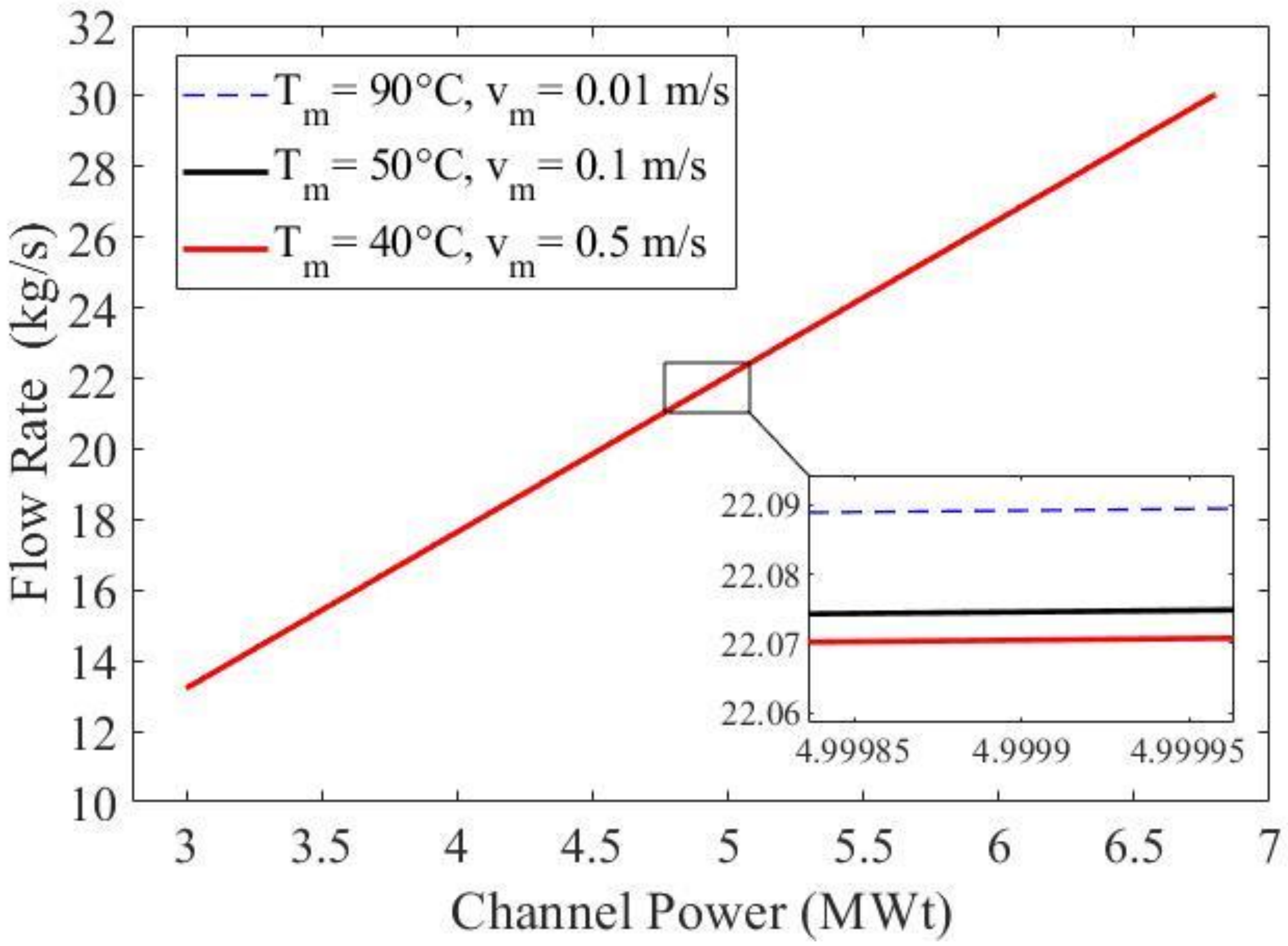
- **overall thermal resistance:**

$$\boldsymbol{\Omega} = \frac{1}{r_1 h_c} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{k_{pt}} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_{gap}} + \frac{\ln\left(\frac{r_4}{r_3}\right)}{k_{ct}} + \frac{1}{r_4 h_m}$$

- Thermal resistance of the annulus gas is dominant (low thermal conductivity *k)*
- Moderator velocity changes the heat transfer coefficient at the CT outer wall
- Moderator velocity affects the heat loss between 5% to 10%
- Heat loss is small for insulated channel (~0.2% - 0.5% of channel power)
- Similar to other values in literature (code validated)



Coolant Flow Rates for Insulated Channel: Linear Relationship with Channel Power



- Finite differencing code solves for the steady-state coolant mass flow rate that satisfies the inlet/outlet BCs: 266 °C to 310 °C at 10.5 MPa

- Coolant velocity only affects heat loss through the Re in DB heat transfer coefficient at the PT inner wall which is a very small component of the overall thermal resistance

$$Nu = \frac{h_c D_h}{k} = 0.023 Re^{0.8} Pr^{0.3}$$

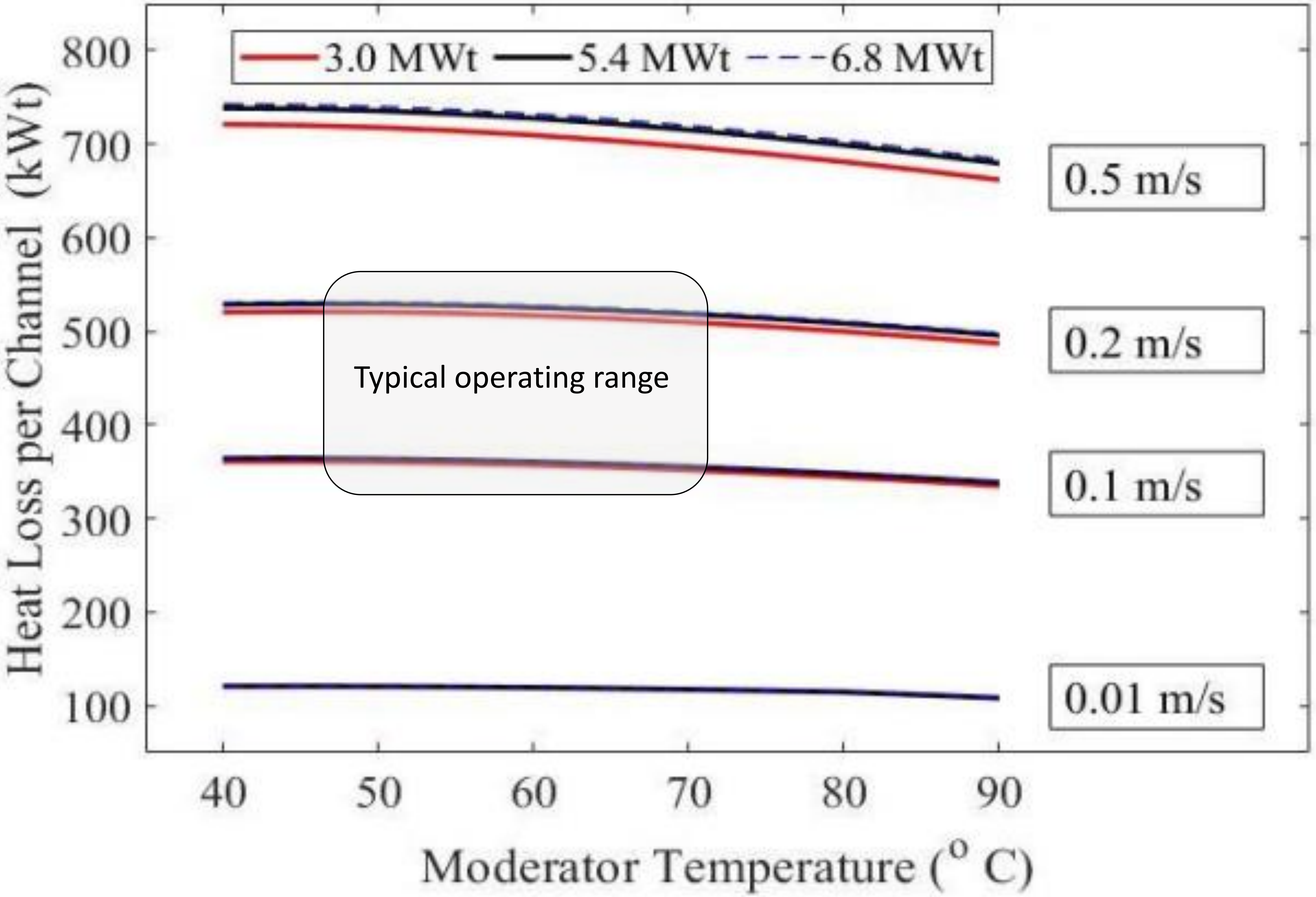
- The heat loss from an insulated channel has minimal effect on channel flow rate and coolant energy balance

Heat Loss for Uninsulated Channel

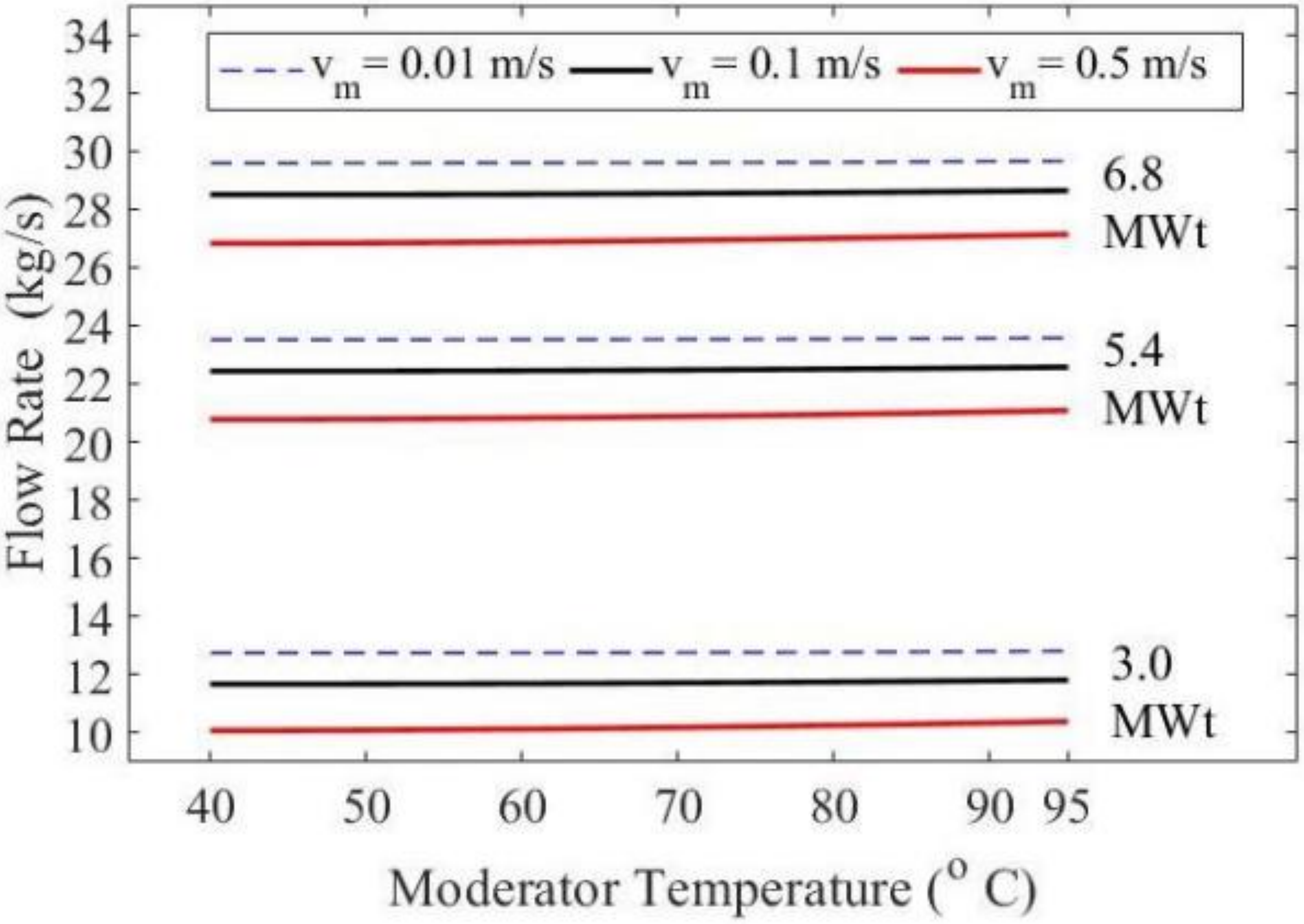
- The heat transfer coefficient of the PT outer wall is the dominant parameter of the thermal resistance

$$\Omega = \frac{1}{r_1 h_c} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{k_{pt}} + \frac{1}{r_2 h_m}$$

- Heat loss is a strong function of v_m
- Some dependence on Re of coolant flow (higher Re for the high-power channels)
- Heat loss is between 1.8% - 24% of channel power
- Average conditions: 6.5% - 9.4% of channel power
- Operating conditions of the moderator cooling system should be optimized to minimize heat loss



The Coolant Flow Rates for Uninsulated Channel are Coupled to Heat Loss

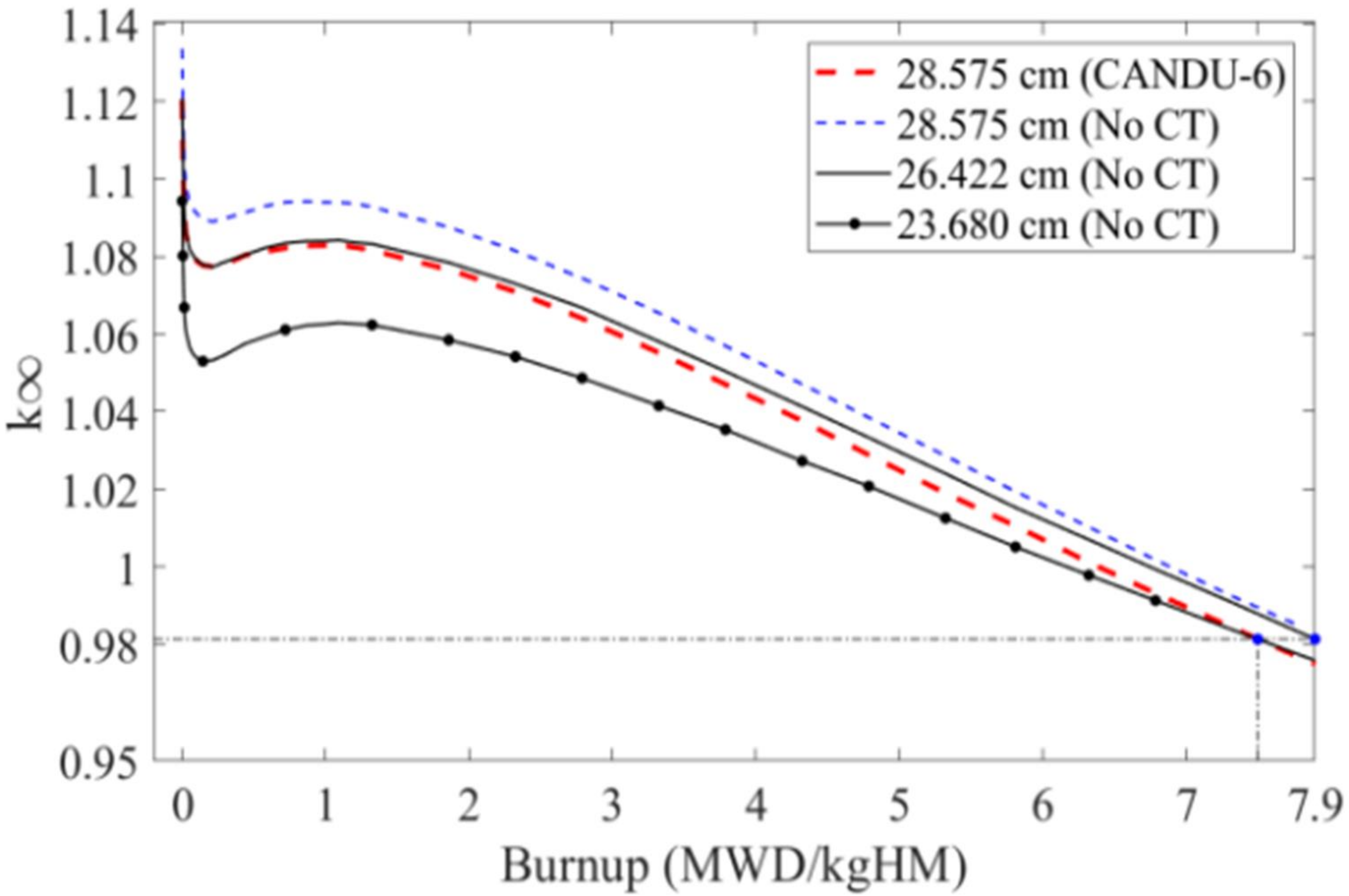


- The mass flow rate to achieve 266 °C/310 °C inlet/outlet temperature is sensitive to channel power but insensitive to moderator temperature

- Need to provide flow orificing for each channel matching channel power and heat loss

Neutronic Benefits of Removing CT

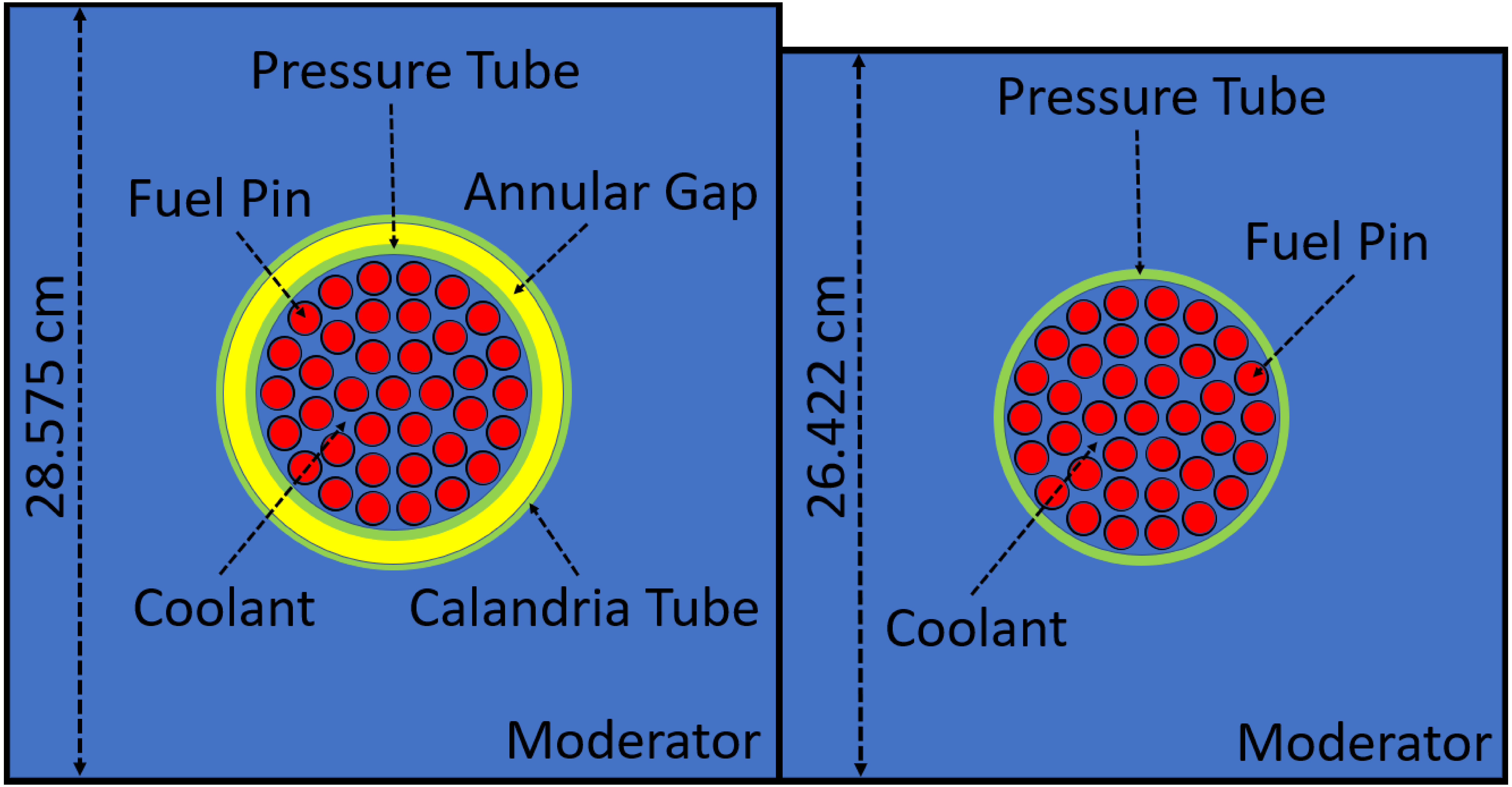
Optimal Lattice Pitch of Uninsulated Channel and Increased Discharge Burnup



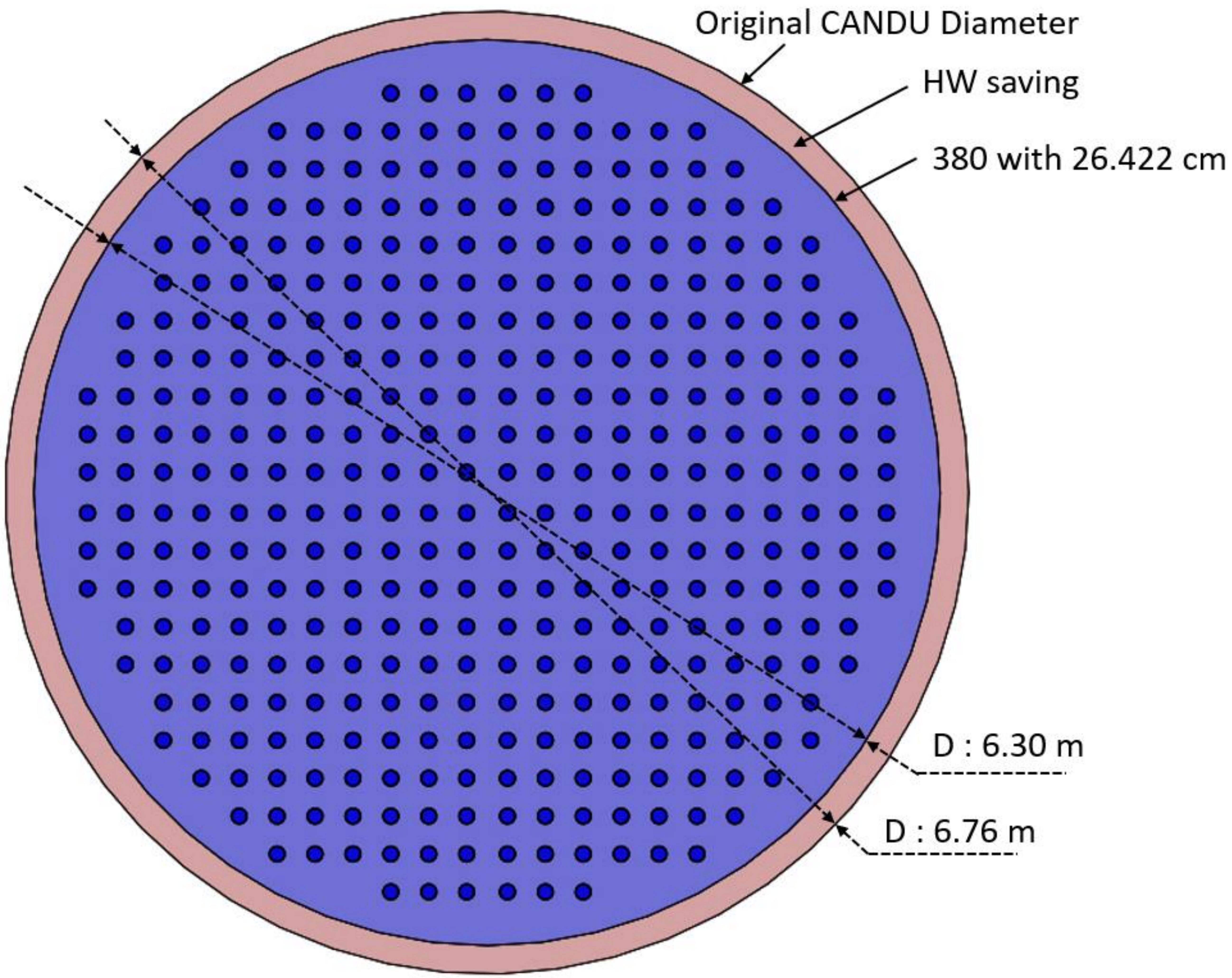
- The UNIST Monte Carlo MCS was used for infinite-lattice criticality calculations and depletion to identify the optimal lattice pitch of the uninsulated channel
- The lattice pitch was iterated to find **the optimal pitch** which is **26.422 cm**
- Reactivity diverges after Pu peak due to enhanced Pu breeding (no parasitic loss in CT) and possible spectrum shift
- The new optimal lattice pitch provides the **increased discharge burnup** (**5.3%**) and significant heavy water savings

Optimal Lattice Pitch of Uninsulated Channel

- Two-unit cell geometries for the CANDU-6 lattice and uninsulated channel.



Heavy Water Savings and Power Uprating



- A 380-channel core can be constructed with 7% less calandria diameter relative to the CANDU-6 diameter (preserving the thickness of radial reflector region)

- **Heavy water savings** will be about **~21 tons**

- Because of the additional heat loss the power downrate will be between 6.7% to 10% which can be compensated by 5.3% increase in discharge burnup

Heavy Water Savings and Power Uprating

- Retaining the outer diameter of the CANDU-6 calandria vessel, more channels can be added using the same heavy water inventory

- We estimate 460 channels with 26.42 cm pitch can be incorporated into CANDU-6 calandria

- Represents **net power uprate** between **+13%** to **+9%** despite the increased heat loss

Parameter	Unit	Candu	No CT	
#Fuel Channels	-	380	380	460
Power (3)	MWt	2052	2052	2484 (+432)
Nuclear HL	MWt	98.7	~98.7	~119.5
Convective HL(1)	MWt	5.2	135.1	163.5
Convective HL(2)	MWt	5.7	201.0	243.3
Total HL(1)	MWt	103.9	233.8	283.0
Total HL(2)	MWt	104.4	299.7	362.8
C. Tank Dia.	m	6.76	6.30	6.76
Mod. Volume	m^3	184.1	164.6	188.1
$D_2$0 Saving	m^3	-	+19.5	-4
$D_2$0 Saving	ton	-	+21.5	-4.4

(1) Assuming T_m = 70 °C and v_m = 0.1 m/s
(2) Assuming T_m = 50 °C and v_m = 0.2 m/s
(3) Assuming 5.4 MWt average channel power

Conclusions and Future Works

- Heat loss from uninsulated pressure tubes to the heavy water moderator is the same magnitude as the unavoidable heat loss from nuclear sources (gamma and neutron heating)

- Without parasitic CT in-core structures, neutron economy is improved allowing for a decrease in lattice pitch (from 28.575 cm to 26.422 cm) and increased discharge burnup by over 5%

- New cores with the optimized lattice pitch can be designed with :
  - heavy water savings and nominal net electric power downrate relative to the 380-channel CANDU-6 reference
  - a net power uprate exceeding 10% by adding more channels (460 total) to a calandria with the same heavy water inventory

- Other discussion points: PT operating temperature < 200 °C for uninsulated case (~250 °C for insulated). How does reduced PT temperature affect irradiation growth/PT sagging?

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