Loading Pattern Optimization for OPR-1000 by Simulated Annealing with a Screening Technique using Pin-wise Vision Transformer Model

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Contents

Introduction

Background

➢ Loading pattern (LP) optimization

- Aims to **extend cycle length** and **improve reactor safety**.

➢ Traditional methods

- **Simulated annealing (SA)**[1], Dynamic programming[2], Direct search[3], Backward diffusion[4], Linear programming[5], Genetic Algorithms[6], Particle swarm optimization[7] etc.
- **SA** requires tons of evaluations, increasing the demand for **fast surrogate models**.
  - **Screening technique**[8]:
    - Evaluate the surrogate model's bias and deviation.
    - Candidates significantly better or worse than the SA criteria are accepted or rejected **without 3D calculations**.

1) Kropaczek, D.J., Turinsky, P.J., 1991. In-core nuclear fuel management optimization for pressurized water reactors utilizing simulated annealing. Nucl. Technol. 95 (1), 9-32.
2) Wall, I., Fenech, H., 1965. The application of dynamic programming to fuel management optimization. Nucl. Sci. Eng. 22, 285-297.
3) Motoda, H., Herczeg, J., Seseonske, A., 1975. Optimization of refueling schedule for light water reactors. Nucl. Technol. 25, 477-496.
4) Chao, Y.A., Hu, C.W., Suo, C.A., 1986. A theory of fuel management via backward diffusion calculation. Nucl. Sci. Eng. 93 (1), 78-87.
5) Okafor, K.C., Aldemir, T., 1988. Construction of linear empirical core models for pressurized water reactor in-core fuel management. Nucl. Technol. 81, 381-391.
6) Yamamuto, A., 1997. A quantitative comparison of loading pattern optimization methods for in-core fuel management of PWR. J. Nucl. Sci. Technol. 34 (4), 339-347.
7) Babazadeh, D., Boroushaki, M., Lucas, C., 2009. Optimization of fuel core loading pattern design in a VVER nuclear power reactors using Particle Swarm Optimization (PSO). Ann. Nucl. Energy 36, 923-930.
8) Park, T.K., Joo, H.G., Kim, C.H., Lee, H.C., 2009. Multiobjective loading pattern optimization by simulated annealing employing discontinuous penalty function and screening technique. Nucl. Sci. Eng. 162, 134-147.

Previous Research (1/2)

➢ SA using screening technique

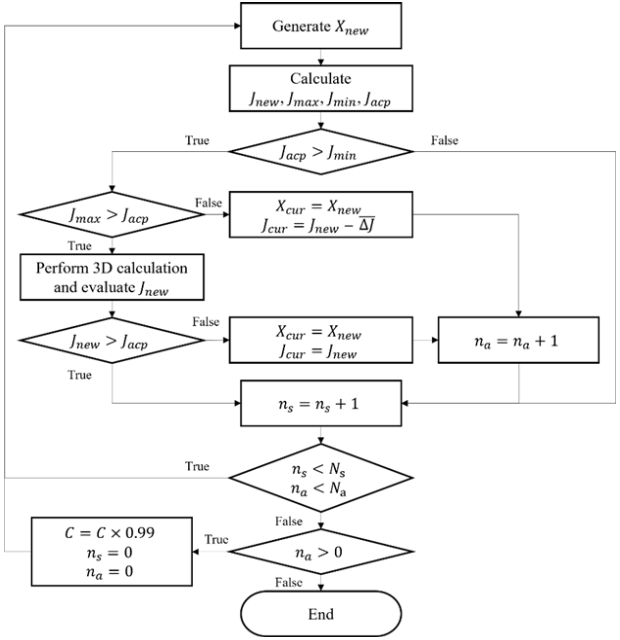
- Evaluate **bias($\overline{\delta J}$)** and **standard deviation(σ)** between objective values of surrogate model and 3D calculations.
- Skip 3D calculation if the surrogate result is beyond $\pm 3\sigma$ from SA criteria.
  - $J_{\max/\min} = J_{new} - \overline{\Delta J} \pm 3\sigma$

$$p = \begin{cases} 1 & (\Delta f < 0) \\ \exp\left(-\frac{\Delta f}{C}\right) & (\Delta f > 0) \end{cases} \quad \longrightarrow \quad J_{acp} = J_{cur} - C \ln \xi$$

Transition probability in metropolis algorithm Acceptance criteria of Simulated Annealing

➢ Multi-Objective function design

- Combined score that **penalizes in peaking factor and cycle length**
  - $J(X) = J_{PF}(X) + J_{CYC}(X)$
  - $J_{PF}(X) = \begin{cases} 1 + \frac{1}{PF^2}\left(PF(X) - PF_{\lim}\right)^2 & \left(PF(X) > PF_{\lim}\right) \\ 0 & \left(PF(X) < PF_{\lim}\right) \end{cases}$
  - $J_{CYC}(X) = \begin{cases} 1 + \frac{1}{CYC^2}\left(CYC(X) - CYC_{\lim}\right)^2 & \left(CYC(X) < CYC_{\lim}\right) \\ 0 & \left(CYC(X) > CYC_{\lim}\right) \end{cases}$



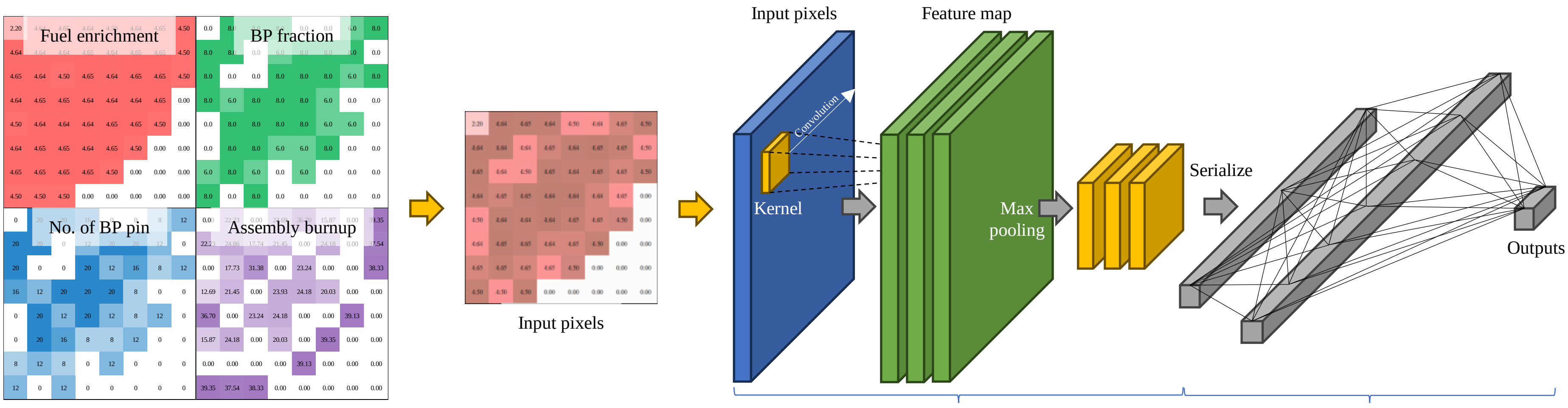
Flow chart of Simulated Annealing with screening technique.

Ref.) Park, T.K., Joo, H.G., Kim, C.H., Lee, H.C., 2009. Multiobjective loading pattern optimization by simulated annealing employing discontinuous penalty function and screening technique. Nucl. Sci. Eng. 162, 134-147.

Previous Research (2/2)

➢ Application of Assembly-wise CNN for Screening

- Processes 2D data by extracting local features through convolution layer.
- Effective for capturing neighborhood patterns in images.
- Limitation:
  - Focuses only on **local regions**, making it difficult to model global relationships.
  - Predicts only at the **assembly level**, losing pin-wise details.



Ref.) Jang, H., Shin, H.C., Kim, D., Lee, H.C., 2020. Application of convolutional neural network to fuel loading pattern optimization by simulated annealing. Korea Nuclear Society Virtual Autumn Meeting.

Objective

- Construct training and validation datasets
  - Training datasets: Random generated and near-optimal data created via SA.
  - Extrapolated validation dataset: Model validation with unseen data.

- Develop pin-wise Vision Transformer (ViT) models
  - Fast and accurate prediction of core parameters for OPR-1000 cores.

- Accelerate LP optimization using ViT-guided SA
  - Evaluates the bias and deviation of the model to filter out clearly good or bad candidates.

- Perform multi-cycle optimization for OPR-1000 cores
  - Maintaining inter-cycle consistency and comparing different candidate generation methods.

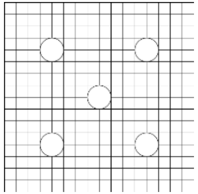
Methodology

Fuel Assembly Types for Datasets

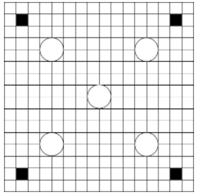
➢ Reference of assembly patterns

- Hanbit Unit 3 (YGN3): Based on **NDR**[1]
- Ulchin Unit 5 (UCN5): Based on **annular fuel evaluation paper**[2]

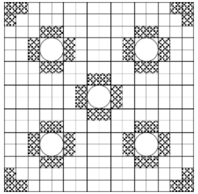
➢ Enrichment zoning pattern and burnable poison arrangement



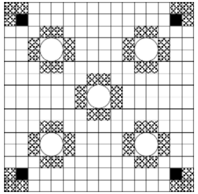
YGN3: A0, B0, FC, GC
UCN5: A0
Custom: -



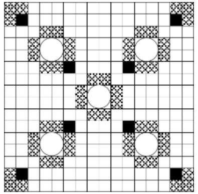
YGN3: B2
UCN5: -
Custom: -



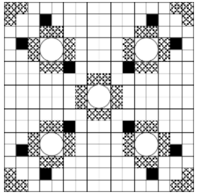
YGN3: C0, D0, E0, F0
UCN5: B0, C0, D0, E0, F0
Custom: H0, I0, J0



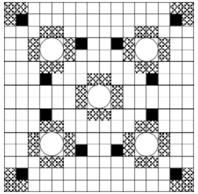
YGN3: F1, GH1
UCN5: -
Custom: H1, I1, J1



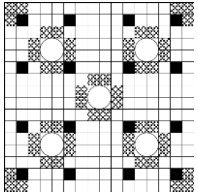
YGN3: B1, C1, D1, E1, E2, F2, GH2
UCN5: B1, E1, F1
Custom: H2, I2, J2



YGN3: -
UCN5: E2, F2
Custom: -



YGN3: F3, GH3
UCN5: D2
Custom: H3, I3, J3



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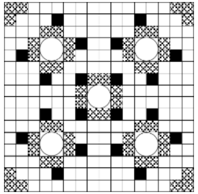
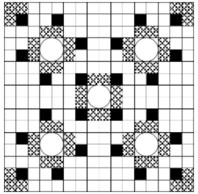
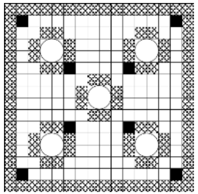
UCN5: -
Custom: H4, I4, J4



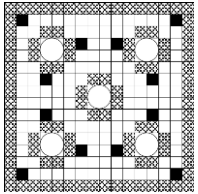
YGN3: F5, G5, GH5
UCN5: -
Custom: H5, I5, J5



YGN3: F6, GH6
UCN5: -
Custom: H6, I6, J6



YGN3: D2
UCN5: B2
Custom: -



YGN3: -
UCN5: C1
Custom: -

○ Water hole
□ Normal fuel rod
▩ Zoned fuel rod
■ Burnable poison fuel rod

1) 1996. Nuclear design report for Yonggwang nuclear power plant unit 3 cycle 2. KAERI/TR-605/96, Korea Atomic Energy Research Institute.
2) Zhang, L., 2009. Evaluation of high power density annular fuel application in Korean OPR-1000 reactor. Master's thesis, Massachusetts Institute of Technology.

Fuel Assembly Types – YGN3

- **C01 and C02**: Based on **NDR[1].**
  - **A0 – D2** were used for **C01** fresh fuel assemblies and **E0 – E2** were used for **C02** fresh fuel assemblies.
- **C03 – C16**: Based on **loading pattern design paper[2].**
  - **FXs** were used for **18-month equilibrium cores** (**C03 – C10**).
  - **GXs** were used for **24-month equilibrium cores** (**C11 – C16**).

Name	Enrichment [wt.% ^{235}U]		No. of rods (Zoned / BP)	BP fraction [wt.% Gd_2O_3]	Name	Enrichment [wt.% ^{235}U]		No. of rods (Zoned / BP)	BP fraction [wt.% Gd_2O_3]
	Normal	Zoned				Normal	Zoned		
A0	1.30	-	- / -	-	F1	4.65	4.10	52 / 4	6.0
B0	2.37	-	- / -	-	F2	4.65	4.10	52 / 8	6.0
B1	2.36	1.30	52 / 8	4.0	F3	4.65	4.10	52 / 12	6.0
B2	2.37	-	- / 4	4.0	F4	4.65	4.10	52 / 16	8.0
C0	2.87	2.35	52 / -	-	F5	4.65	4.10	52 / 20	8.0
C1	2.87	2.36	52 / 8	4.0	F6	4.65	4.10	52 / 24	8.0
D0	3.35	2.87	52 / -	-	GC	2.90	-	- / -	-
D1	3.36	2.85	52 / 8	4.0	G5	4.75	4.45	52 / 20	8.0
D2	3.35	2.87	100 / 8	4.0	GH1	4.95	4.45	52 / 4	8.0
E0	4.08	3.61	52 / -	-	GH2	4.95	4.45	52 / 8	8.0
E1	4.08	3.61	52 / 8	6.0	GH3	4.95	4.45	52 / 12	8.0
E2	3.60	3.11	52 / 8	6.0	GH4	4.95	4.45	52 / 16	8.0
FC	2.20	-	- / -	-	GH5	4.95	4.45	52 / 20	8.0
F0	4.65	4.10	52 / -	-	GH6	4.95	4.45	52 / 24	8.0

Assembly types are colored according to the cycle in which they were introduced as a fresh fuel.

1) 1996. Nuclear design report for Yonggwang nuclear power plant unit 3 cycle 2. KAERI/TR-605/96, Korea Atomic Energy Research Institute.
2) Lee, J., Lee, H.C., 2023. Loading pattern design and economic evaluation for 24-month cycle operation of OPR-1000 in Korea. Nuc. Eng. Technol. 55 (3), 1167-1180.

Fuel Assembly Types – Others

➢ UCN5 C01 – C04

Ref) Zhang, L., 2009. Evaluation of high power density annular fuel application in Korean OPR-1000 reactor. Master's thesis, Massachusetts Institute of Technology.

Name	Enrichment [wt.% ^{235}U]		No. of rods (Zoned / BP)	BP fraction [wt.% Gd_2O_3]	Name	Enrichment [wt.% ^{235}U]		No. of rods (Zoned / BP)	BP fraction [wt.% Gd_2O_3]
	Normal	Zoned				Normal	Zoned		
A0	1.42	-	- / -	-	D2	4.43	3.93	52 / 12	6.0
B0	2.92	2.42	52 / -	-	E0	4.50	4.00	52 / -	-
B1	2.92	2.43	52 / 8	6.0	E1	4.50	4.00	52 / 8	6.0
B2	2.92	2.43	100 / 8	6.0	E2	4.50	4.01	52 / 12	6.0
C0	3.43	2.93	52 / -	-	F0	4.50	4.01	52 / -	-
C1	3.43	2.93	100 / 12	6.0	F1	4.50	4.01	52 / 8	6.0
D0	4.42	3.93	52 / -	-	F2	4.50	4.01	52 / 12	6.0

Assembly types are colored according to the cycle in which they were introduced as fresh fuel.

➢ Custom types

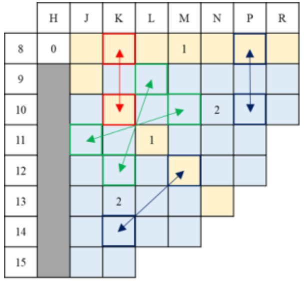
- Created using **enrichment** and **BP fraction** set **not used in YGN3 or UCN5**.

Name	Enrichment [wt.% ^{235}U]		No. of rods (Zoned / BP)	BP fraction [wt.% Gd_2O_3]	Name	Enrichment [wt.% ^{235}U]		No. of rods (Zoned / BP)	BP fraction [wt.% Gd_2O_3]	Name	Enrichment [wt.% ^{235}U]		No. of rods (Zoned / BP)	BP fraction [wt.% Gd_2O_3]
	Normal	Zoned				Normal	Zoned				Normal	Zoned		
H0	4.30	3.80	52 / -	-	I0	4.80	4.30	52 / -	-	J0	4.80	4.30	52 / -	-
H1	4.30	3.80	52 / 4	6.0	I1	4.80	4.30	52 / 4	8.0	J1	4.80	4.30	52 / 4	7.0
H2	4.30	3.80	52 / 8	6.0	I2	4.80	4.30	52 / 8	8.0	J2	4.80	4.30	52 / 8	7.0
H3	4.30	3.80	52 / 12	6.0	I3	4.80	4.30	52 / 12	8.0	J3	4.80	4.30	52 / 12	7.0
H4	4.30	3.80	52 / 16	6.0	I4	4.80	4.30	52 / 16	8.0	J4	4.80	4.30	52 / 16	7.0
H5	4.30	3.80	52 / 20	6.0	I5	4.80	4.30	52 / 20	8.0	J5	4.80	4.30	52 / 20	7.0
H6	4.30	3.80	52 / 24	6.0	I6	4.80	4.30	52 / 24	8.0	J6	4.80	4.30	52 / 24	7.0

Datasets for Model Training and Validation

➢ Training dataset

- **Random generation (RG)**
  - Created using YGN3 reference cores from NDR (C01, C02) and LP design paper (C03 – C16).
    - Assembly swapping and rotation are conducted randomly.
  - Generated with a relaxed constraint (max-F_{xy} < 5.0) to cover diverse cases during the SA process.
  - 5,000 cases per cycle (**Total 80,000 cases**)
- **Near-optimal (NO)**
  - Generated **using SA** Guided by pin-wise ViT model pre-trained with the RG dataset.
  - Used **modified objective function** to collect **longer cycle length** or **lower peaking factor** LPs.
  - 300 cases per cycle (**Total 4,800 cases**)
- The **final model** was trained using **both RG and NO datasets**.



Methods of swapping assembly position

$$J_{PF}(X)=\frac{\left(PF(X)-PF_{ref}\right)^3}{PF_{ref}^{\ 2}\left|PF_{ref}-PF(X)\right|}\qquad J_{CYC}(X)=\frac{\left(CYC_{ref}-CYC(X)\right)^3}{CYC_{ref}^{\ 2}\left|CYC_{ref}-CYC(X)\right|}$$

Modified objective functions for NO search

➢ External validation (EV) dataset

- Designed to **verify model performance** on LPs that include **unseen fuel assemblies during training**.
- Created by **replacing several assembly types** in RG dataset LPs with UCN5 or custom assemblies.
  - **Total 3,000 cases**
- **Random generation** using **UCN5 C01 – C04** cores
  - 100 cases for cycle 1, 200 cases for others
  - **Total 700 cases**

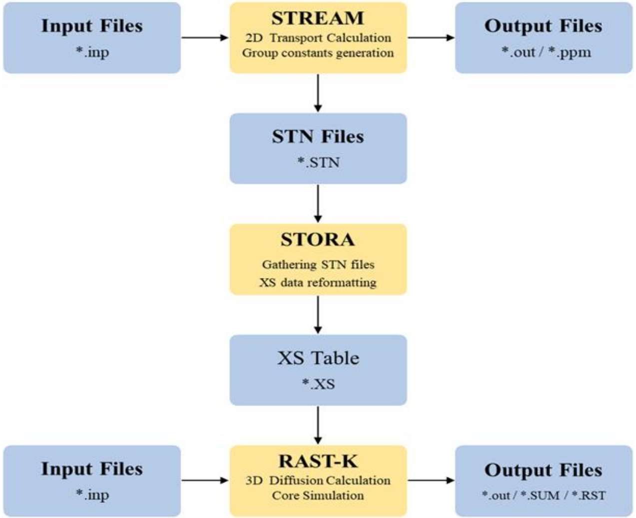
Core Parameters Calculation

➢ Calculation code

- STREAM/RAST-K v2, two step nodal diffusion code system
- Developed by UNIST CORE.

➢ Core parameters

- Cycle length: EFPDs when the CBC is 10 ppm.
- Peaking factor: max-F_{xy} during the cycle.



Flowchart of STREAM/RAST-K v2 code system

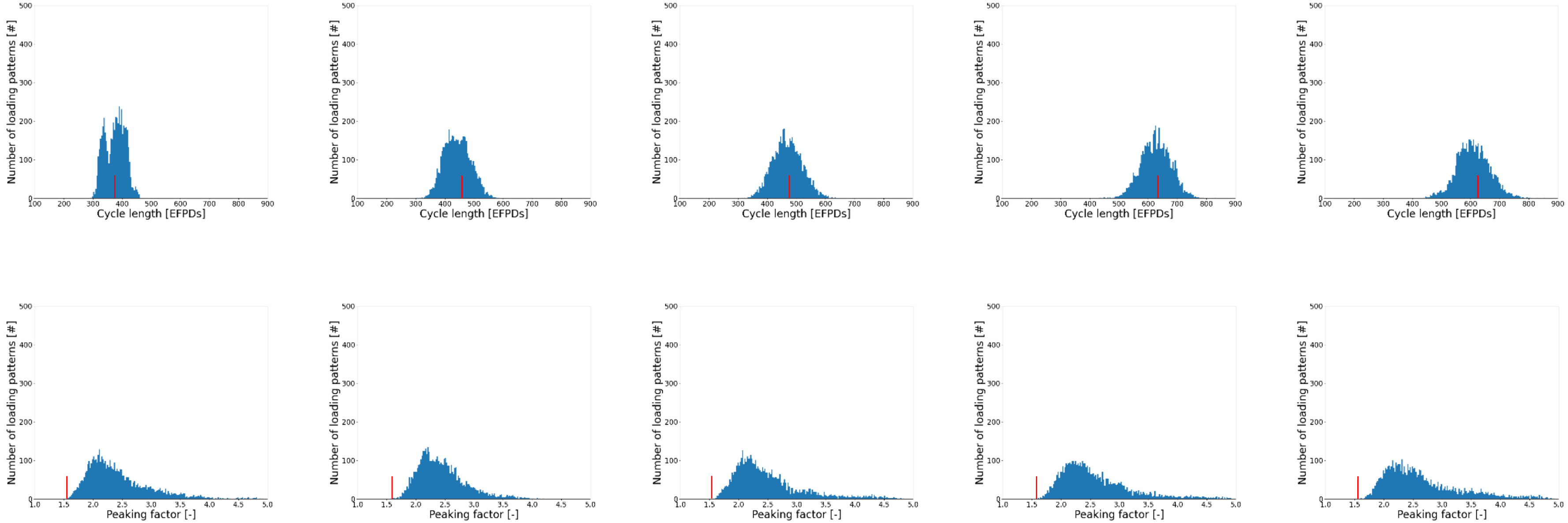
Ref.) Park, J., Jang, J., Kim, H., Et Al., 2020. RAST-K v2-three dimensional nodal diffusion code for pressurized water reactor core analysis. Energies, 13:6324.

Core Parameter Distribution of RG Dataset

Cycle 1 | Cycle 3 | Cycle 10 | Cycle 11 | Cycle 16

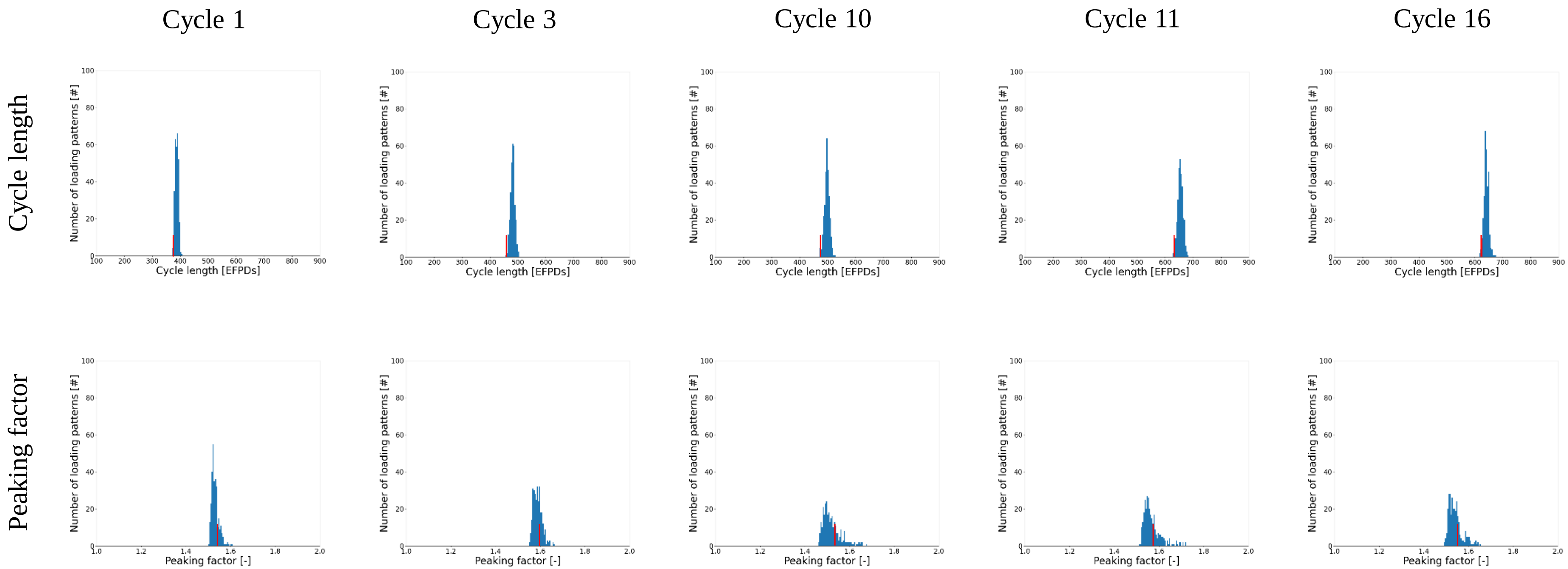
Cycle length

Peaking factor



The red line shows the core parameters of the reference core loading pattern.

Core Parameter Distribution of NO Dataset



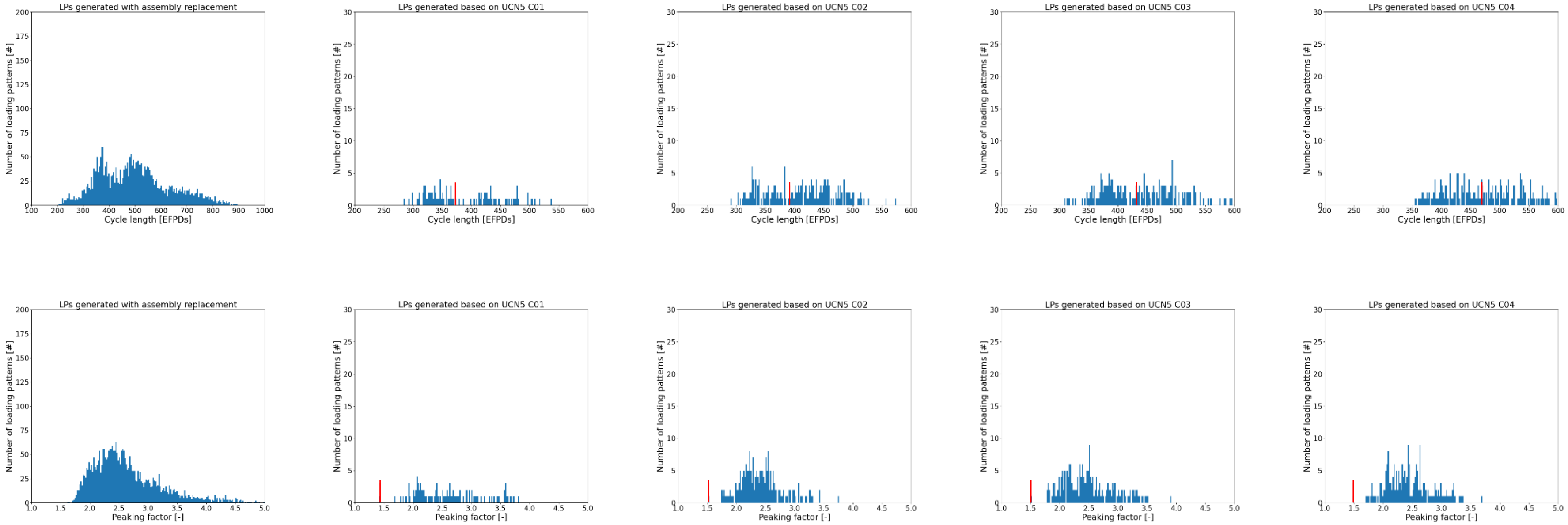
The red line shows the core parameters of the reference core loading pattern.

Core Parameter Distribution of EV Dataset

Modified LPs | UCN5 C01 | UCN5 C02 | UCN5 C03 | UCN5 C04

Cycle length

Peaking factor

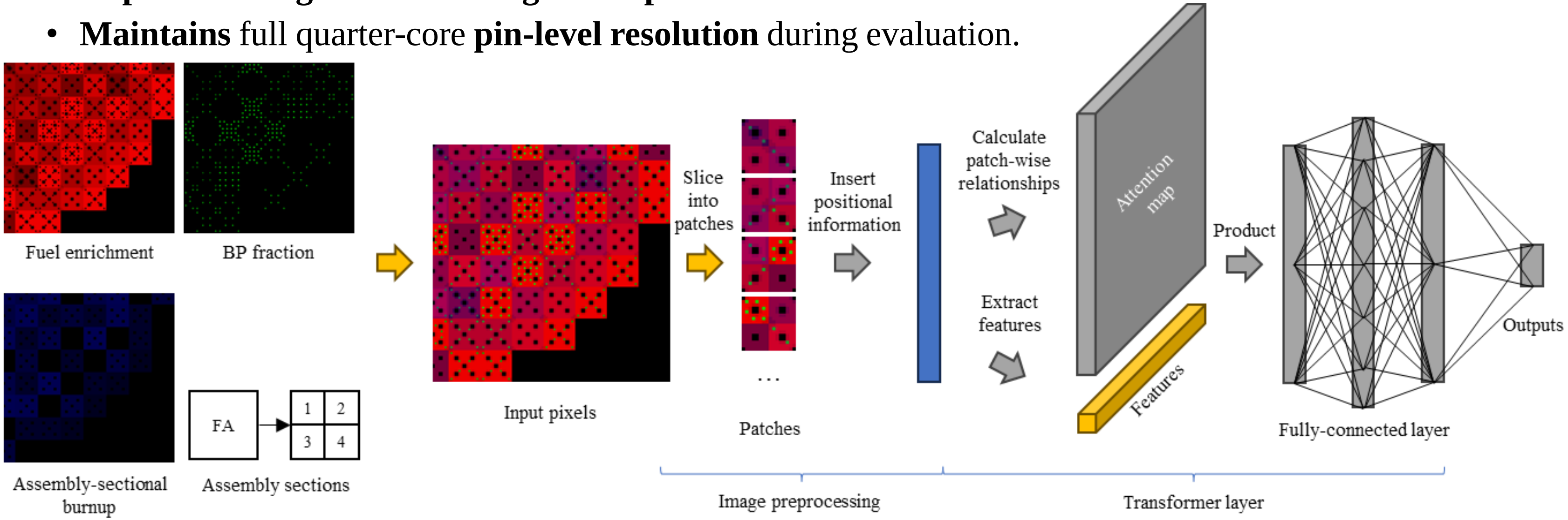


The red line shows the core parameters of the reference core loading pattern.

Pin-wise Vision Transformer Model

➢ Characteristics of the pin-wise ViT model

- Divides input images into small patches and treats them as a sequence of tokens.
- Applies self-attention to model **global relationships** across all patches.
- Advantages:
  - **Captures** both **global** and **fine-grained pin-wise features**.
  - **Maintains** full quarter-core **pin-level resolution** during evaluation.



Ref.) Kolesnikov, A., Dosovitskiy, A., Weissenborn, D., Et al., 2021. An image is worth 16x16 words: transformers for image recognition at scale. ICLR.

Comparison of CNN and ViT Models

➢ Model hyperparameters

- In the CNN model, hyperparameters mainly control the convolutional structure.
  - Ef.) the number of layers and kernel sizes.
- The ViT model focuses on patch size, the number of attention heads, and transformer depth.
- Predicting **cycle length is relatively easier**, while predicting **pin peaking factor is more challenging**.
- **Separate models with different levels of complexity** were trained for each target.

➢ Number of model parameters

- Pin-wise ViT model has **fewer model parameters** than CNN.
- Enables **faster training** and **quicker evaluation** during LP optimization.

Target value	Assembly-wise CNN	Pin-wise ViT
Cycle length	3,406,593	1,696,129
Pin power peaking factor	4,275,073	3,685,401

Number of trainable parameters for each model.

Model Training Process

➢ Model training strategy

- Loss function: **Mean squared error (MSE) loss**.
- Optimizer: **AdamW**, Scheduler : **ReduceLROnPlateau**
- Dataset splitting
  - Training : Validation : Test = **8 : 1 : 1**
- Training phases
  - Pretraining with RG dataset to **learn global LP characteristics**.
  - Fine-tuning with NO dataset to **improve model accuracy in the optimal region**.

➢ Model training resources

- GPU: NVIDIA RTX 2080 Ti (12 GB memory).
- Training time:
  - Cycle length evaluation model: ~ 8 hrs (CNN: ~ 15 hrs)
  - Peaking factor evaluation model: ~ 16 hrs (CNN: ~ 19 hrs)
  - Fine-tuning: ~4 hrs per model
- Framework: PyTorch 2.0 with CUDA

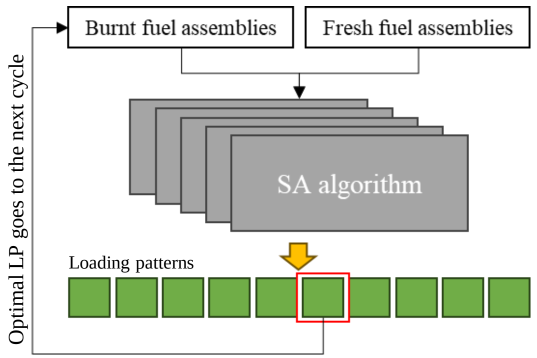
Optimal LPs Generation Method

➢ LP candidate generation

- Type fix
  - **Preserve the number of fresh fuel assembly types**.
  - Keeps overall U-235 mass unchanged.
- Enrichment fix
  - **Allow fresh fuel assembly type conversion** only if normal and zoned **fuel enrichment is identical**. (Ef. B0 ↔ B2)
  - Enables **limited flexibility** while maintaining fuel economy.
- Free type change
  - **Allow any conversion of fresh fuel assembly types within the fresh fuel assembly set**.
  - Offers **maximum flexibility** but may **affect cost and reactivity**.

➢ LP optimization process

- **Initial LP**: Random generation LP based on reference.
- **Burnt fuel assemblies**: Taken from the previous cycle's optimized LP.
- **Optimization method**:
  - SA is performed 1**0 times independently** for each LP candidate generation method.
  - The LP with **the longest cycle length** is selected as the optimal LP for each method.
  - The selected optimal LP is passed to the next cycle as the **basis for burnt fuel assemblies**.



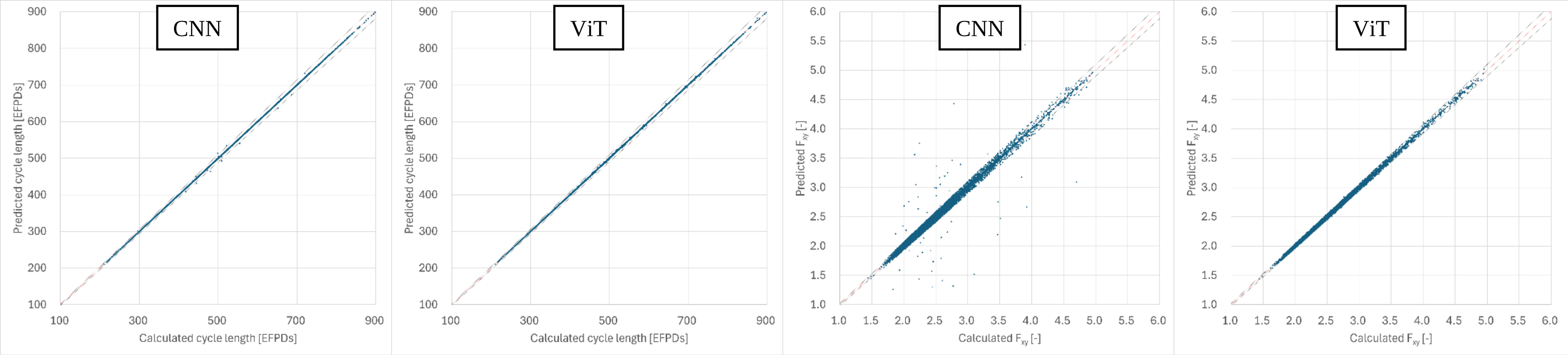
LP optimization process

Results

Model Accuracy – CNN vs. ViT

➢ Error metric comparison

Model architecture	Cycle length evaluation model		Peaking factor evaluation model	
	RMS of relative error	Max. absolute value of relative error	RMS of relative error	Max. absolute value of relative error
CNN	0.13%	3.47%	3.30%	67.3%
ViT	0.11%	0.82%	0.73%	4.02%



Model prediction – Code calculation for cycle length

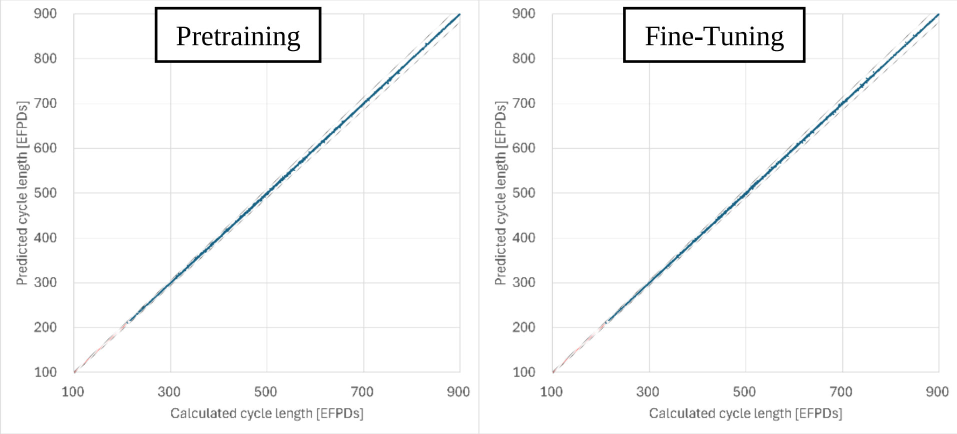
Model prediction – Code calculation for peaking factor

The **red line** indicates **perfect agreement** between **model prediction and code calculation**.
Black lines represent the **±2% relative error** bounds.

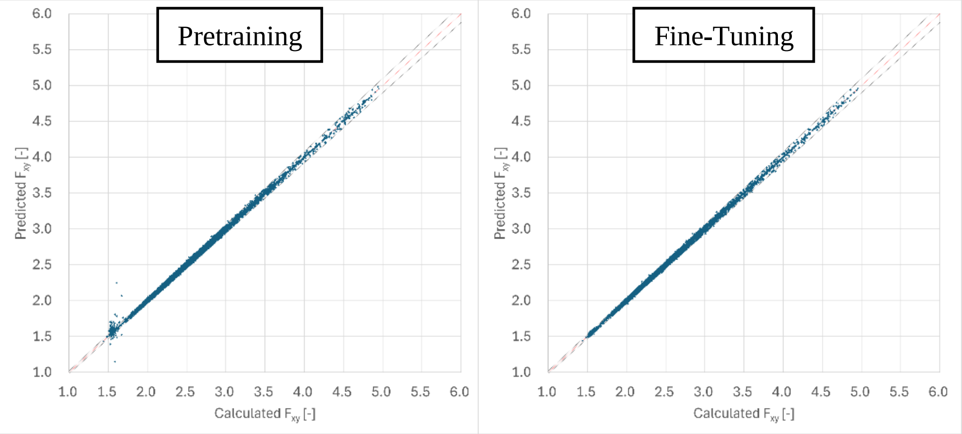
Model Accuracy – Pretraining vs. Fine-Tuning

➢ Error metric comparison

Model architecture	Cycle length evaluation model		Peaking factor evaluation model	
	RMS of relative error	Max. absolute value of relative error	RMS of relative error	Max. absolute value of relative error
Pretraining	0.11%	0.82%	1.36%	40.3%
Fine-Tuning	0.11%	0.82%	0.71%	3.27%



Model prediction – Code calculation for cycle length



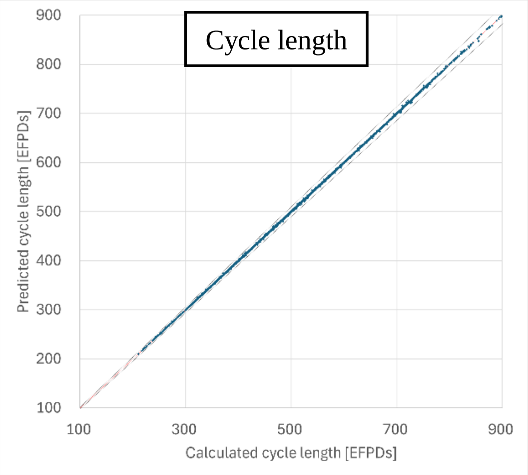
Model prediction – Code calculation for peaking factor

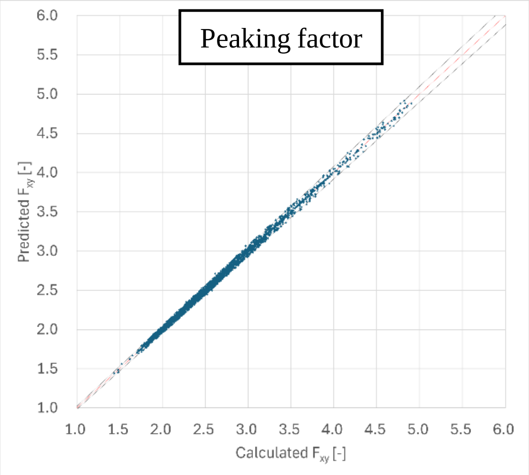
The **red line** indicates **perfect agreement** between **model prediction and code calculation**.
Black lines represent the **±2% relative error** bounds.

Model Accuracy – External Validation

➢ Error metric comparison

Dataset	Cycle length evaluation model		Peaking factor evaluation model	
	RMS of relative error	Max. absolute value of relative error	RMS of relative error	Max. absolute value of relative error
RG+NO	0.11%	0.82%	0.73%	4.02%
EV	0.16%	0.90%	0.94%	4.39%





Model prediction – Code calculation with external validation dataset

The **red line** indicates **perfect agreement** between **model prediction and code calculation**.
Black lines represent the **±2% relative error** bounds.

Results of SA – Type Fix (1/2)

➢ YGN3 Cycle 01

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	25	10924	10949	99.8	3.0	1094.9	374.2	1.5007
2	20	10073	10093	99.8	2.4	1009.3	373.4	1.5011
3	24	10489	10513	99.8	2.9	1051.3	373.7	1.5390
4	18	10045	10063	99.8	2.2	1006.3	374.4	1.5347
5	23	10352	10375	99.8	2.8	1037.5	375.1	1.4965
6	21	10488	10509	99.8	2.6	1050.9	374.4	1.5347
7	16	9768	9784	99.8	2.0	978.4	374.9	1.5258
8	25	10614	10639	99.8	3.0	1063.9	374.7	1.5276
9	21	10276	10297	99.8	2.6	1029.7	374.5	1.5377
10	24	10787	10811	99.8	2.9	1081.1	373.9	1.5351
Avg.	**21.7**	**10381.6**	**10403.3**	**99.8**	**2.6**	**1040.3**	**374.3**	**1.5233**
Reference (NDR)							**373.2**	**1.5412**

➢ YGN3 Cycle 16

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	15	9758	9773	99.8	2.5	1248.8	627.0	1.5381
2	22	10242	10264	99.8	3.6	1311.5	627.2	1.5473
3	21	10310	10331	99.8	3.4	1320.1	626.4	1.5503
4	21	10357	10378	99.8	3.4	1326.1	626.4	1.5438
5	20	10060	10080	99.8	3.3	1288.0	626.5	1.5351
6	15	9672	9687	99.8	2.5	1237.8	626.7	1.5468
7	15	9565	9580	99.8	2.5	1224.1	625.9	1.5434
8	15	9637	9652	99.8	2.5	1233.3	626.3	1.5423
9	21	10234	10255	99.8	3.4	1310.4	625.7	1.5497
10	18	9973	9991	99.8	3.0	1276.6	626.9	1.5490
Avg.	**18.3**	**9980.8**	**9999.1**	**99.8**	**3.0**	**1277.7**	**626.5**	**1.5446**
Reference (NDR)							**625.5**	**1.5512**

* Efficiency = # of ViT evaluation / # of total evaluation
** Estimated time w/o ST = average time of RAST-K calculation * # of total evaluation

Results of SA – Type Fix (2/2)

➢ UCN5 C01

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	19	9991	10010	99.8	1.9	834.2	**373.7**	**1.4988**
2	24	10650	10674	99.8	2.3	889.5	371.5	1.4857
3	27	10849	10876	99.8	2.6	906.3	371.5	1.4857
4	20	10229	10249	99.8	2.0	854.1	372.9	1.5020
5	23	10566	10589	99.8	2.2	882.4	373.2	1.4961
6	23	10578	10601	99.8	2.2	883.4	371.5	1.4857
7	28	11345	11373	99.8	2.6	947.8	373.5	1.4872
8	29	11294	11323	99.7	2.7	943.6	372.5	1.4897
9	27	10939	10966	99.8	2.6	913.8	372.9	1.5020
10	20	10325	10345	99.8	2.0	862.1	373.0	1.4989
Avg.	**24.0**	**10676.6**	**10700.6**	**99.8**	**2.3**	**891.7**	**372.6**	**1.4932**
Reference (NDR)							**370.8**	**1.5039**

➢ UCN5 C04

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	26	10623	10649	99.8	2.9	1005.7	453.6	1.5162
2	27	10751	10778	99.7	3.0	1017.9	453.2	1.5089
3	23	10354	10377	99.8	2.6	980.1	**454.7**	**1.5120**
4	19	10082	10101	99.8	2.2	954.0	454.5	1.5013
5	24	10619	10643	99.8	2.7	1005.2	454.5	1.5052
6	23	10466	10489	99.8	2.6	990.6	453.7	1.5009
7	18	10154	10172	99.8	2.1	960.7	454.3	1.5082
8	20	10341	10361	99.8	2.3	978.5	454.0	1.5071
9	19	10083	10102	99.8	2.2	954.1	454.5	1.5070
10	22	10532	10554	99.8	2.5	996.8	**454.7**	**1.5120**
Avg.	**22.1**	**10400.5**	**10422.6**	**99.8**	**2.5**	**984.4**	**454.2**	**1.5075**
Reference (NDR)							**452.7**	**1.5171**

* Efficiency = # of ViT evaluation / # of total evaluation
** Estimated time w/o ST = average time of RAST-K calculation * # of total evaluation

Optimal LPs – Type Fix

	YGN3 C01		YGN3 C02		YGN3 C10		YGN3 C16		UCN5 C01		UCN5 C04	
	CL [EFPDs]	PF [-]	CL [EFPDs]	PF [-]	CL [EFPDs]	PF [-]	CL [EFPDs]	PF [-]	CL [EFPDs]	PF [-]	CL [EFPDs]	PF [-]
Reference	373.2	1.5412	275.8	1.5442	475.9	1.5349	625.5	1.5512	370.8	1.5039	452.7	1.5171
Optimal LP	375.1	1.4965	278.8	1.5359	479.5	1.5297	627.2	1.5473	373.7	1.4988	454.7	1.5120

Core performance parameters of the optimal LPs.

Reference

YGN3 C01

	H	J	K	L	M	N	P	R
8	A0	B1	B2	A0	B2	B1	C1	D0
9		B0	A0	D2	A0	B2	C1	C0
10		A0	C1	A0	C1	A0	D2	B0
11		D2	A0	C1	A0	D2	D0	
12		A0	C1	A0	C1	D1	B0	
13		B2	A0	D2	D1	C0		
14		C1	D2	D0	B0			
15		C0	B0					

YGN3 C02

	H	J	K	L	M	N	P	R
8	B1	C1	E2	B1	D0	B0	E2	D2
9		C0	B2	C0	C1	B0	D2	E0
10		B2	E2	B2	E2	C1	E2	B0
11		C0	B2	D2	C1	D1	E0	
12		C1	E2	C1	E1	D2	D0	
13		B0	C1	D1	D2	C1		
14		D2	E2	E0	D0			
15		E0	B0					

YGN3 C10

	H	J	K	L	M	N	P	R
8	FC	F0	F5	F5	F4	F5	F4	F0
9		F0	F5	F5	F2	F3	F3	F3
10		F5	F5	F5	F0	F5	F3	F5
11		F5	F5	F5	F3	F0	F0	
12		F2	F0	F3	F5	F2	F3	
13		F3	F5	F0	F2	F5		
14		F3	F3	F0	F3			
15		F3	F5					

YGN3 C16

	H	J	K	L	M	N	P	R
8	GC	GH4	GH6	GH6	GH5	GH5	GH4	GH1
9		GH5	GH2	GH5	GH1	GH3	GH2	GH5
10		GH2	GH5	GH5	GH5	GH5	GH2	GH5
11		GH5	GH5	GH5	GH2	GH3	GH5	
12		GH1	GH5	GH2	GH4	GH1	GH5	
13		GH3	GH5	GH3	GH1	GH5		
14		GH2	GH2	GH5	GH5			
15		GH5	GH5					

UCN5 C01

	H	J	K	L	M	N	P	R
8	A0	A0	A0	B1	A0	A0	B1	C0
9		A0	C1	A0	C1	A0	C1	B0
10		C1	A0	B1	A0	B2	C1	B0
11		A0	B1	A0	B2	A0	C0	
12		C1	A0	B2	B1	C1	B0	
13		A0	B2	A0	C1	C0		
14		C1	C1	C0	B0			
15		B0	B0					

UCN5 C04

	H	J	K	L	M	N	P	R
8	D2	E2	F2	D2	D2	F1	D2	E0
9		E1	D2	E0	F2	D0	F2	E0
10		D2	F2	E2	E1	E1	F1	E2
11		E0	E2	D2	D0	D0	F0	
12		F2	E1	D0	F2	F1	E1	
13		D0	E1	D0	F1	D0		
14		F2	F1	F0	E1			
15		E0	E2					

Type fix

YGN3 C01

	H	J	K	L	M	N	P	R
8	A0	B1	B2	A0	B1	B2	C1	D0
9		B0	A0	D2	A0	C1	B2	C0
10		A0	C1	A0	C1	A0	D2	B0
11		D2	A0	C1	A0	D2	D0	
12		A0	C1	A0	C1	D1	B0	
13		C1	A0	D2	D1	C0		
14		B2	D2	D0	B0			
15		C0	B0					

YGN3 C02

	H	J	K	L	M	N	P	R
8	B1	C1	E2	A0	B2	B1	E2	D0
9		B0	C0	D2	A0	C1	B2	E0
10		C0	E2	B2	E2	C1	E2	B0
11		D2	B2	C1	C1	E0	D0	
12		A0	E2	C1	E1	D1	B0	
13		C1	C1	E0	D1	C0		
14		B2	E2	D0	B0			
15		E0	B0					

YGN3 C10

	H	J	K	L	M	N	P	R
8	FC	F0	F5	F5	F4	F5	F4	F0
9		F0	F5	F5	F2	F3	F3	F3
10		F5	F5	F5	F5	F2	F3	F5
11		F5	F5	F5	F3	F0	F0	
12		F2	F5	F3	F5	F2	F3	
13		F3	F2	F0	F2	F5		
14		F3	F3	F0	F3			
15		F3	F5					

YGN3 C16

	H	J	K	L	M	N	P	R
8	GC	GH4	GH6	GH6	GH5	GH5	GH4	GH1
9		GH5	GH2	GH5	GH2	GH3	GH2	GH5
10		GH2	GH5	GH5	GH5	GH5	GH2	GH5
11		GH5	GH5	GH5	GH1	GH3	GH5	
12		GH2	GH5	GH1	GH4	GH1	GH5	
13		GH3	GH5	GH3	GH1	GH5		
14		GH2	GH2	GH5	GH5			
15		GH5	GH5					

UCN5 C01

	H	J	K	L	M	N	P	R
8	A0	A0	A0	B1	A0	A0	B1	C0
9		A0	C1	A0	C1	A0	C1	B0
10		C1	A0	B1	A0	B2	C1	B0
11		A0	B1	A0	B2	A0	B0	
12		C1	A0	B2	B1	C1	C0	
13		A0	B2	A0	C1	C0		
14		C1	C1	B0	C0			
15		B0	B0					

UCN5 C04

	H	J	K	L	M	N	P	R
8	D2	E2	F2	D2	D2	D2	F1	E0
9		E1	D2	E0	F2	D0	F2	E0
10		D2	F2	E2	E1	E1	F1	E2
11		E0	E2	D2	D0	D0	F0	
12		F2	E1	D0	F2	F1	E1	
13		D0	E1	D0	F1	D0		
14		F2	F1	F0	E1			
15		E0	E2					

Optimal LPs – Enrichment Fix

	YGN3 C01		YGN3 C02		YGN3 C10		YGN3 C16		UCN5 C01		UCN5 C04	
	CL [EFPDs]	PF [-]	CL [EFPDs]	PF [-]	CL [EFPDs]	PF [-]	CL [EFPDs]	PF [-]	CL [EFPDs]	PF [-]	CL [EFPDs]	PF [-]
Reference	373.2	1.5412	275.8	1.5442	475.9	1.5349	625.5	1.5512	370.8	1.5039	452.7	1.5171
Optimal LP	375.9	1.5309	278.8	1.5311	478.9	1.5152	628.2	1.5425	373.5	1.4935	455.7	1.5122

Core performance parameters of the optimal LPs.

YGN3 C01

Reference

	H	J	K	L	M	N	P	R
8	A0	B1	B2	A0	B2	B1	C1	D0
9		B0	A0	D2	A0	B2	C1	C0
10		A0	C1	A0	C1	A0	D2	B0
11		D2	A0	C1	A0	D2	D0	
12		A0	C1	A0	C1	D1	B0	
13		B2	A0	D2	D1	C0		
14		C1	D2	D0	B0			
15		C0	B0					

Type fix

	H	J	K	L	M	N	P	R
8	A0	B1	B2	A0	B0	B1	C1	D0
9		B0	A0	D2	A0	C1	B2	C0
10		A0	C1	A0	C0	A0	D2	B0
11		D2	A0	C1	A0	D2	D0	
12		A0	C0	A0	C1	D1	B0	
13		C1	A0	D2	D1	C0		
14		B2	D2	D0	B0			
15		C0	B0					

YGN3 C02

Reference

	H	J	K	L	M	N	P	R
8	B1	C1	E2	B1	D0	B0	E2	D2
9		C0	B2	C0	C1	B0	D2	E0
10		B2	E2	B2	E2	C1	E2	B0
11		C0	B2	D2	C1	D1	E0	
12		C1	E2	C1	E1	D2	D0	
13		B0	C1	D1	D2	C1		
14		D2	E2	E0	D0			
15		E0	B0					

Type fix

	H	J	K	L	M	N	P	R
8	B1	C1	E2	A0	B2	B1	E2	D0
9		B1	D2	A0	E2	B1	C1	E0
10		D2	E2	A0	B2	A0	E2	B0
11		A0	A0	C1	C1	E0	D0	
12		E2	B2	C1	E1	D1	B0	
13		B1	A0	E0	D1	C0		
14		C1	E2	D0	B0			
15		E0	B0					

YGN3 C10

Reference

	H	J	K	L	M	N	P	R
8	FC	F0	F5	F5	F4	F5	F4	F0
9		F0	F5	F5	F2	F3	F3	F3
10		F5	F5	F5	F0	F5	F3	F5
11		F5	F5	F5	F3	F0	F0	
12		F2	F0	F3	F5	F2	F3	
13		F3	F5	F0	F2	F5		
14		F3	F3	F0	F3			
15		F3	F5					

Type fix

	H	J	K	L	M	N	P	R
8	FC	F1	F5	F5	F4	F5	F4	F1
9		F0	F5	F5	F2	F3	F2	F3
10		F5	F5	F5	F5	F2	F2	F5
11		F5	F5	F5	F3	F2	F0	
12		F2	F5	F3	F4	F1	F4	
13		F3	F2	F2	F1	F5		
14		F2	F2	F0	F4			
15		F3	F5					

YGN3 C16

Reference

	H	J	K	L	M	N	P	R
8	GC	GH4	GH6	GH6	GH5	GH5	GH4	GH1
9		GH5	GH2	GH5	GH1	GH3	GH2	GH5
10		GH2	GH5	GH5	GH5	GH5	GH2	GH5
11		GH5	GH5	GH5	GH2	GH3	GH5	
12		GH1	GH5	GH2	GH4	GH1	GH5	
13		GH3	GH5	GH3	GH1	GH5		
14		GH2	GH2	GH5	GH5			
15		GH5	GH5					

Type fix

	H	J	K	L	M	N	P	R
8	GC	GH4	GH5	GH6	GH5	GH5	GH4	GH1
9		GH5	GH1	GH6	GH2	GH3	GH2	GH5
10		GH1	GH5	GH5	GH5	GH4	GH2	GH5
11		GH6	GH5	GH5	GH2	GH3	GH5	
12		GH2	GH5	GH2	GH4	GH1	GH4	
13		GH3	GH4	GH3	GH1	GH5		
14		GH2	GH2	GH5	GH4			
15		GH5	GH5					

UCN5 C01

Reference

	H	J	K	L	M	N	P	R
8	A0	A0	A0	B1	A0	A0	B1	C0
9		A0	C1	A0	C1	A0	C1	B0
10		C1	A0	B1	A0	B2	C1	B0
11		A0	B1	A0	B2	A0	C0	
12		C1	A0	B2	B1	C1	B0	
13		A0	B2	A0	C1	C0		
14		C1	C1	C0	B0			
15		B0	B0					

Type fix

	H	J	K	L	M	N	P	R
8	A0	A0	A0	B1	A0	A0	B1	C0
9		A0	C1	A0	C2	A0	C2	B0
10		C1	A0	B1	A0	B2	C1	B0
11		A0	B1	A0	B2	A0	B0	
12		C2	A0	B2	B1	C1	C0	
13		A0	B2	A0	C1	C0		
14		C2	C1	B0	C0			
15		B0	B0					

UCN5 C04

Reference

	H	J	K	L	M	N	P	R
8	D2	E2	F2	D2	D2	F1	D2	E0
9		E1	D2	E0	F2	D0	F2	E0
10		D2	F2	E2	E1	E1	F1	E2
11		E0	E2	D2	D0	D0	F0	
12		F2	E1	D0	F2	F1	E1	
13		D0	E1	D0	F1	D0		
14		F2	F1	F0	E1			
15		E0	E2					

Type fix

	H	J	K	L	M	N	P	R
8	D1	E2	F2	D2	D2	F2	D0	E0
9		E1	D2	E1	F2	D0	F2	E0
10		D2	F2	E2	E1	E1	F1	E2
11		E1	E2	D2	D1	F0	D1	
12		F2	E1	D1	F2	F1	E1	
13		D0	E1	F0	F1	D0		
14		F2	F1	D1	E1			
15		E0	E2					

Optimal LPs – Free Type Change

	YGN3 C01		YGN3 C02		YGN3 C10		YGN3 C16		UCN5 C01		UCN5 C04	
	CL [EFPDs]	PF [-]	CL [EFPDs]	PF [-]	CL [EFPDs]	PF [-]	CL [EFPDs]	PF [-]	CL [EFPDs]	PF [-]	CL [EFPDs]	PF [-]
Reference	373.2	1.5412	275.8	1.5442	475.9	1.5349	625.5	1.5512	370.8	1.5039	452.7	1.5171
Optimal LP	378.1	1.5269	279.7	1.5346	481.9	1.5349	631.5	1.5508	376.6	1.4942	454.3	1.5072

Core performance parameters of the optimal LPs.

YGN3 C01

Reference

	H	J	K	L	M	N	P	R
8	A0	B1	B2	A0	B2	B1	C1	D0
9		B0	A0	D2	A0	B2	C1	C0
10		A0	C1	A0	C1	A0	D2	B0
11		D2	A0	C1	A0	D2	D0	
12		A0	C1	A0	C1	D1	B0	
13		B2	A0	D2	D1	C0		
14		C1	D2	D0	B0			
15		C0	B0					

Type fix

	H	J	K	L	M	N	P	R
8	A0	B1	B2	A0	B2	C1	C1	D0
9		B0	A0	C0	A0	B2	C1	C0
10		A0	D2	C1	A0	D2	D2	B0
11		C0	C1	C1	A0	C0	D0	
12		A0	A0	A0	C1	D1	B0	
13		B2	D2	C0	D1	C0		
14		C1	D2	D0	B0			
15		C0	B0					

YGN3 C02

Reference

	H	J	K	L	M	N	P	R
8	B1	C1	E2	B1	D0	B0	E2	D2
9		C0	B2	C0	C1	B0	D2	E0
10		B2	E2	B2	E2	C1	E2	B0
11		C0	B2	D2	C1	D1	E0	
12		C1	E2	C1	E1	D2	D0	
13		B0	C1	D1	D2	C1		
14		D2	E2	E0	D0			
15		E0	B0					

Type fix

	H	J	K	L	M	N	P	R
8	B1	C1	E2	A0	B2	B1	E2	D0
9		B1	D2	A0	E2	B1	C1	E0
10		D2	E2	A0	A0	A0	E2	B0
11		A0	A0	C1	A0	E0	D0	
12		E2	A0	A0	E1	D1	B0	
13		B1	A0	E0	D1	C0		
14		C1	E2	D0	B0			
15		E0	B0					

YGN3 C10

Reference

	H	J	K	L	M	N	P	R
8	FC	F0	F5	F5	F4	F5	F4	F0
9		F0	F5	F5	F2	F3	F3	F3
10		F5	F5	F5	F0	F5	F3	F5
11		F5	F5	F5	F3	F0	F0	
12		F2	F0	F3	F5	F2	F3	
13		F3	F5	F0	F2	F5		
14		F3	F3	F0	F3			
15		F3	F5					

Type fix

	H	J	K	L	M	N	P	R
8	FC	F1	F5	F5	F4	F5	F4	F1
9		F1	F5	F5	F2	F3	F2	F3
10		F5	F4	F5	F5	F2	F2	F5
11		F5	F5	F4	F3	F2	F0	
12		F2	F5	F3	F4	F1	F4	
13		F3	F2	F2	F1	F5		
14		F2	F2	F0	F4			
15		F3	F5					

YGN3 C16

Reference

	H	J	K	L	M	N	P	R
8	GC	GH4	GH6	GH6	GH5	GH5	GH4	GH1
9		GH5	GH2	GH5	GH1	GH3	GH2	GH5
10		GH2	GH5	GH5	GH5	GH5	GH2	GH5
11		GH5	GH5	GH5	GH2	GH3	GH5	
12		GH1	GH5	GH2	GH4	GH1	GH5	
13		GH3	GH5	GH3	GH1	GH5		
14		GH2	GH2	GH5	GH5			
15		GH5	GH5					

Type fix

	H	J	K	L	M	N	P	R
8	GC	GH4	GH6	GH6	GH5	GH5	GH4	GH1
9		GH5	GH1	GH6	GH2	GH3	GH2	GH5
10		GH1	GH5	GH5	GH5	GH4	GH2	GH6
11		GH6	GH5	GH5	GH2	GH3	GH5	
12		GH2	GH5	GH2	GH4	GH1	GH4	
13		GH3	GH4	GH3	GH1	GH5		
14		GH2	GH2	GH5	GH4			
15		GH5	GH6					

UCN5 C01

Reference

	H	J	K	L	M	N	P	R
8	A0	A0	A0	B1	A0	A0	B1	C0
9		A0	C1	A0	C1	A0	C1	B0
10		C1	A0	B1	A0	B2	C1	B0
11		A0	B1	A0	B2	A0	C0	
12		C1	A0	B2	B1	C1	B0	
13		A0	B2	A0	C1	C0		
14		C1	C1	C0	B0			
15		B0	B0					

Type fix

	H	J	K	L	M	N	P	R
8	A0	A0	A0	B1	A0	C1	B1	C0
9		A0	B1	B0	C1	A0	B1	B0
10		B1	A0	B1	A0	B2	C1	B0
11		B0	B1	A0	B2	A0	C0	
12		C1	A0	B2	B1	C1	B0	
13		A0	B2	A0	C1	C0		
14		B1	C1	C0	B0			
15		B0	B0					

UCN5 C04

Reference

	H	J	K	L	M	N	P	R
8	D2	E2	F2	D2	D2	F1	D2	E0
9		E1	D2	E0	F2	D0	F2	E0
10		D2	F2	E2	E1	E1	F1	E2
11		E0	E2	D2	D0	D0	F0	
12		F2	E1	D0	F2	F1	E1	
13		D0	E1	D0	F1	D0		
14		F2	F1	F0	E1			
15		E0	E2					

Type fix

	H	J	K	L	M	N	P	R
8	D1	E2	F2	D2	D2	F2	D0	E0
9		E1	D1	E1	F2	D0	F2	E0
10		D1	F1	E2	E1	E1	F1	E2
11		E1	E2	D2	D1	F0	D1	
12		F2	E1	D1	F2	F1	E1	
13		D0	E1	F0	F1	D0		
14		F2	F1	D1	E1			
15		E0	E2					

Conclusion

➢ Pin-wise Vision Transformer Model

- Trained with both **random generation** and **near-optimal** datasets.
- Achieved **high accuracy** in predicting core parameters.

Dataset	Cycle length evaluation model		Peaking factor evaluation model	
	RMS of relative error	Max. absolute value of relative error	RMS of relative error	Max. absolute value of relative error
RG+NO	0.11%	0.82%	0.73%	4.02%
EV	0.16%	0.90%	0.94%	4.39%

Model error metrics with training dataset (RG+NO) and external validation dataset (EV)

➢ Simulated Annealing using pin-wise ViT-based screening

- **Generated optimal LPs** for each cycle and core using **three different methods**.
  - SA process takes **~ 4 hours with single core environment**.
  - All methods successfully found LP with **longer cycle length** and **lower peaking factor** than the reference.
  - Optimal LPs were found even with **different cycles or reactor units of OPR-1000**.

Thank you ☺

Results of SA – Type Fix (1/3)

➢ YGN3 Cycle 01

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	25	10924	10949	99.8	3.0	1094.9	374.2	1.5007
2	20	10073	10093	99.8	2.4	1009.3	373.4	1.5011
3	24	10489	10513	99.8	2.9	1051.3	373.7	1.5390
4	18	10045	10063	99.8	2.2	1006.3	374.4	1.5347
5	23	10352	10375	99.8	2.8	1037.5	**375.1**	**1.4965**
6	21	10488	10509	99.8	2.6	1050.9	374.4	1.5347
7	16	9768	9784	99.8	2.0	978.4	374.9	1.5258
8	25	10614	10639	99.8	3.0	1063.9	374.7	1.5276
9	21	10276	10297	99.8	2.6	1029.7	374.5	1.5377
10	24	10787	10811	99.8	2.9	1081.1	373.9	1.5351
Avg.	**21.7**	**10381.6**	**10403.3**	**99.8**	**2.6**	**1040.3**	**374.3**	**1.5233**
Reference (NDR)							**373.2**	**1.5412**

➢ YGN3 Cycle 02

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	20	10279	10299	99.8	1.5	686.6	276.9	1.5422
2	21	10362	10383	99.8	1.5	692.2	277.3	1.5277
3	25	10601	10626	99.8	1.8	708.4	277.3	1.5424
4	24	10557	10581	99.8	1.5	646.6	275.9	1.5410
5	20	10321	10341	99.8	1.3	632.0	276.0	1.5292
6	17	9984	10001	99.8	1.3	666.7	277.7	1.5275
7	25	10617	10642	99.8	1.5	650.3	276.0	1.5360
8	17	10017	10034	99.8	1.3	668.9	**278.8**	**1.5359**
9	24	10649	10673	99.8	1.5	652.2	276.1	1.5293
10	22	10445	10467	99.8	1.4	639.7	276.6	1.5303
Avg.	**21.5**	**10383.2**	**10404.7**	**99.8**	**1.4**	**664.4**	**276.8**	**1.5342**
Reference (NDR)							**275.8**	**1.5442**

* Efficiency = # of ViT evaluation / # of total evaluation

** Estimated time w/o ST = average time of RAST-K calculation * # of total evaluation

Results of SA – Type Fix (2/3)

YGN3 Cycle 10

Index	No. of LP evaluations: RAST-K	No. of LP evaluations: ViT	No. of LP evaluations: Total	Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
1	19	10004	10023	99.8	2.3	1002.3	479.5	1.5297
2	23	10410	10433	99.8	2.8	1043.3	476.2	1.5200
3	24	10731	10755	99.8	2.9	1075.5	476.0	1.5298
4	22	10339	10361	99.8	2.7	1036.1	479.5	1.5299
5	25	10526	10551	99.8	3.0	1055.1	476.8	1.5268
6	22	10322	10344	99.8	2.7	1034.4	476.1	1.5296
7	19	10056	10075	99.8	2.3	1007.5	476.9	1.5281
8	20	10353	10373	99.8	2.5	1037.3	477.1	1.5241
9	16	9606	9622	99.8	2.0	962.2	476.7	1.5319
10	18	9910	9928	99.8	2.2	992.8	476.9	1.5281
Avg.	**20.8**	**10225.7**	**10246.5**	**99.8**	**2.5**	**1024.7**	**477.2**	**1.5278**
Reference (NDR)							**475.9**	**1.5349**

YGN3 Cycle 16

Index	No. of LP evaluations: RAST-K	No. of LP evaluations: ViT	No. of LP evaluations: Total	Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
1	15	9758	9773	99.8	2.5	1248.8	627.0	1.5381
2	22	10242	10264	99.8	3.6	1311.5	627.2	1.5473
3	21	10310	10331	99.8	3.4	1320.1	626.4	1.5503
4	21	10357	10378	99.8	3.4	1326.1	626.4	1.5438
5	20	10060	10080	99.8	3.3	1288.0	626.5	1.5351
6	15	9672	9687	99.8	2.5	1237.8	626.7	1.5468
7	15	9565	9580	99.8	2.5	1224.1	625.9	1.5434
8	15	9637	9652	99.8	2.5	1233.3	626.3	1.5423
9	21	10234	10255	99.8	3.4	1310.4	625.7	1.5497
10	18	9973	9991	99.8	3.0	1276.6	626.9	1.5490
Avg.	**18.3**	**9980.8**	**9999.1**	**99.8**	**3.0**	**1277.7**	**626.5**	**1.5446**
Reference (NDR)							**625.5**	**1.5512**

* Efficiency = # of ViT evaluation / # of total evaluation

** Estimated time w/o ST = average time of RAST-K calculation * # of total evaluation

Results of SA – Type Fix (3/3)

➢ UCN5 Cycle 01

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	19	9991	10010	99.8	1.9	834.2	373.7	1.4988
2	24	10650	10674	99.8	2.3	889.5	371.5	1.4857
3	27	10849	10876	99.8	2.6	906.3	371.5	1.4857
4	20	10229	10249	99.8	2.0	854.1	372.9	1.5020
5	23	10566	10589	99.8	2.2	882.4	373.2	1.4961
6	23	10578	10601	99.8	2.2	883.4	371.5	1.4857
7	28	11345	11373	99.8	2.6	947.8	373.5	1.4872
8	29	11294	11323	99.7	2.7	943.6	372.5	1.4897
9	27	10939	10966	99.8	2.6	913.8	372.9	1.5020
10	20	10325	10345	99.8	2.0	862.1	373.0	1.4989
Avg.	**24.0**	**10676.6**	**10700.6**	**99.8**	**2.3**	**891.7**	**372.6**	**1.4932**
Reference (NDR)							**370.8**	**1.5039**

➢ UCN5 Cycle 04

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	26	10623	10649	99.8	2.9	1005.7	453.6	1.5162
2	27	10751	10778	99.7	3.0	1017.9	453.2	1.5089
3	23	10354	10377	99.8	2.6	980.1	454.7	1.5120
4	19	10082	10101	99.8	2.2	954.0	454.5	1.5013
5	24	10619	10643	99.8	2.7	1005.2	454.5	1.5052
6	23	10466	10489	99.8	2.6	990.6	453.7	1.5009
7	18	10154	10172	99.8	2.1	960.7	454.3	1.5082
8	20	10341	10361	99.8	2.3	978.5	454.0	1.5071
9	19	10083	10102	99.8	2.2	954.1	454.5	1.5070
10	22	10532	10554	99.8	2.5	996.8	454.7	1.5120
Avg.	**22.1**	**10400.5**	**10422.6**	**99.8**	**2.5**	**984.4**	**454.2**	**1.5075**
Reference (NDR)							**452.7**	**1.5171**

* Efficiency = # of ViT evaluation / # of total evaluation
** Estimated time w/o ST = average time of RAST-K calculation * # of total evaluation

Results of SA – Enrichment Fix (1/3)

➢ YGN3 Cycle 01

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	16	9907	9923	99.8	1.6	826.9	375.5	1.5410
2	20	10359	10379	99.8	2.0	864.9	375.9	1.5309
3	19	10034	10053	99.8	1.9	837.8	373.9	1.5246
4	21	10143	10164	99.8	2.0	847.0	374.8	1.5267
5	22	10593	10615	99.8	2.1	884.6	374.5	1.5247
6	22	10563	10585	99.8	2.1	882.1	373.8	1.5218
7	22	10444	10466	99.8	2.1	872.2	374.3	1.5409
8	17	9991	10008	99.8	1.7	834.0	374.9	1.5362
9	18	9964	9982	99.8	1.8	831.8	374.7	1.5270
10	22	10507	10529	99.8	2.1	877.4	375.3	1.5252
Avg.	**19.9**	**10250.5**	**10270.4**	**99.8**	**1.9**	**855.9**	**374.8**	**1.5299**
Reference (NDR)							**373.2**	**1.5412**

➢ YGN3 Cycle 02

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	17	9836	9853	99.8	1.3	656.9	278.8	1.5311
2	19	10059	10078	99.8	1.4	671.9	278.2	1.5285
3	18	10055	10073	99.8	1.3	671.5	278.2	1.5285
4	23	10744	10767	99.8	1.6	717.8	276.9	1.5366
5	16	9706	9722	99.8	1.2	648.1	277.3	1.5304
6	16	9811	9827	99.8	1.2	655.1	277.0	1.5368
7	25	10756	10781	99.8	1.8	718.7	278.8	1.5311
8	18	9976	9994	99.8	1.2	610.7	276.7	1.5259
9	16	9652	9668	99.8	1.2	644.5	277.2	1.5335
10	20	10063	10083	99.8	1.3	616.2	276.9	1.5242
Avg.	**18.8**	**10065.8**	**10084.6**	**99.8**	**1.3**	**661.2**	**277.6**	**1.5307**
Reference (NDR)							**275.8**	**1.5442**

* Efficiency = # of ViT evaluation / # of total evaluation

** Estimated time w/o ST = average time of RAST-K calculation * # of total evaluation

Results of SA – Enrichment Fix (2/3)

➢ YGN3 Cycle 10

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	20	10277	10297	99.8	2.5	1029.7	477.3	1.5186
2	23	10528	10551	99.8	2.8	1055.1	476.9	1.5169
3	25	10653	10678	99.8	3.0	1067.8	**478.9**	**1.5152**
4	17	9799	9816	99.8	2.1	981.6	478.4	1.5331
5	24	10478	10502	99.8	2.9	1050.2	478.9	1.5286
6	21	10321	10342	99.8	2.6	1034.2	478.3	1.5292
7	25	10777	10802	99.8	3.0	1080.2	477.0	1.5240
8	17	9825	9842	99.8	2.1	984.2	476.6	1.5223
9	21	10460	10481	99.8	2.6	1048.1	476.6	1.5262
10	19	9981	10000	99.8	2.3	1000.0	478.9	1.5286
Avg.	**21.2**	**10309.9**	**10331.1**	**99.8**	**2.6**	**1033.1**	**477.8**	**1.5246**
Reference (NDR)							**475.9**	**1.5349**

➢ YGN3 Cycle 16

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	15	9620	9635	99.8	2.5	1231.1	626.2	1.5492
2	15	9582	9597	99.8	2.5	1226.3	626.1	1.5366
3	18	9849	9867	99.8	3.0	1260.8	**628.2**	**1.5425**
4	23	10388	10411	99.8	3.7	1330.3	627.4	1.5363
5	18	10049	10067	99.8	3.0	1286.3	625.8	1.5231
6	18	10016	10034	99.8	3.0	1282.1	627.8	1.5315
7	19	10104	10123	99.8	3.1	1293.5	628.1	1.5319
8	21	10391	10412	99.8	3.4	1330.4	626.0	1.5253
9	20	10264	10284	99.8	3.3	1314.1	625.7	1.5243
10	14	9629	9643	99.9	2.4	1232.2	626.5	1.5488
Avg.	**18.1**	**9989.2**	**10007.3**	**99.8**	**3.0**	**1278.7**	**626.8**	**1.5350**
Reference (NDR)							**625.5**	**1.5512**

* Efficiency = # of ViT evaluation / # of total evaluation

** Estimated time w/o ST = average time of RAST-K calculation * # of total evaluation

Results of SA – Enrichment Fix (3/3)

➤ UCN5 Cycle 01

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	28	10999	11027	99.7	2.6	918.9	373.3	1.4989
2	21	10430	10451	99.8	2.0	870.9	371.5	1.5012
3	20	10163	10183	99.8	1.9	848.6	371.9	1.4853
4	24	10404	10428	99.8	2.3	869.0	372.9	1.5024
5	25	10501	10526	99.8	2.4	877.2	372.6	1.4985
6	24	10848	10872	99.8	2.3	906.0	**373.5**	**1.4935**
7	29	11105	11134	99.7	2.7	927.8	372.9	1.5031
8	27	11236	11263	99.8	2.6	938.6	370.9	1.4896
9	23	10700	10723	99.8	2.2	893.6	370.9	1.4957
10	19	10226	10245	99.8	1.9	853.8	372.8	1.4957
Avg.	**24.0**	**10661.2**	**10685.2**	**99.8**	**2.3**	**890.4**	**372.3**	**1.4964**
Reference (NDR)							**370.8**	**1.5039**

➤ UCN5 Cycle 04

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	21	10439	10460	99.8	2.6	1046.0	455.4	1.5101
2	19	9950	9969	99.8	2.2	941.5	453.0	1.5161
3	26	11082	11108	99.8	2.9	1049.1	453.9	1.5101
4	22	10609	10631	99.8	2.5	1004.0	454.7	1.5090
5	27	10982	11009	99.8	3.0	1039.7	454.9	1.5074
6	27	11113	11140	99.8	3.2	1114.0	455.5	1.5130
7	28	11279	11307	99.8	3.3	1130.7	**455.7**	**1.5122**
8	22	10344	10366	99.8	2.5	979.0	452.7	1.5158
9	19	9964	9983	99.8	2.3	998.3	455.5	1.5095
10	22	10471	10493	99.8	2.5	991.0	453.4	1.5094
Avg.	**23.3**	**10623.3**	**10646.6**	**99.8**	**2.7**	**1029.3**	**454.5**	**1.5113**
Reference (NDR)							**452.7**	**1.5171**

* Efficiency = # of ViT evaluation / # of total evaluation

** Estimated time w/o ST = average time of RAST-K calculation * # of total evaluation

Results of SA – Free Type Change (1/3)

➢ YGN3 Cycle 01

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	19	10274	10293	99.8	1.9	857.8	377.2	1.5397
2	23	10516	10539	99.8	2.2	878.3	377.7	1.5260
3	18	10060	10078	99.8	1.8	839.8	374.1	1.5310
4	18	10126	10144	99.8	1.8	845.3	374.1	1.5364
5	17	9766	9783	99.8	1.7	815.3	375.1	1.5398
6	18	10102	10120	99.8	1.8	843.3	375.8	1.5254
7	21	10235	10256	99.8	2.0	854.7	373.3	1.5408
8	24	10431	10455	99.8	2.3	871.3	376.8	1.5399
9	20	10037	10057	99.8	1.9	838.1	**378.1**	**1.5269**
10	24	10786	10810	99.8	2.3	900.8	373.9	1.5274
Avg.	**20.2**	**10233.3**	**10253.5**	**99.8**	**2.0**	**854.5**	**375.6**	**1.5333**
Reference (NDR)							**373.2**	**1.5412**

➢ YGN3 Cycle 02

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	25	10995	11020	99.8	1.8	734.7	280.2	1.5398
2	24	10674	10698	99.8	1.7	713.2	277.5	1.5301
3	17	9810	9827	99.8	1.3	655.1	278.6	1.5336
4	19	10278	10297	99.8	1.4	686.5	277.7	1.5367
5	19	10048	10067	99.8	1.4	671.1	277.7	1.5309
6	21	10360	10381	99.8	1.5	692.1	278.8	1.5365
7	16	9896	9912	99.8	1.2	660.8	277.2	1.5349
8	25	10615	10640	99.8	1.8	709.3	278.9	1.5302
9	23	10434	10457	99.8	1.6	697.1	279.6	1.5351
10	17	9925	9942	99.8	1.3	662.8	**279.7**	**1.5346**
Avg.	**20.6**	**10303.5**	**10324.1**	**99.8**	**1.5**	**688.3**	**278.6**	**1.5342**
Reference (NDR)							**277.2**	**1.5442**

* Efficiency = # of ViT evaluation / # of total evaluation

** Estimated time w/o ST = average time of RAST-K calculation * # of total evaluation

Results of SA – Free Type Change (2/3)

YGN3 Cycle 10

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	24	10880	10904	99.8	2.9	1090.4	477.4	1.5238
2	22	10364	10386	99.8	2.7	1038.6	479.3	1.5154
3	17	9738	9755	99.8	2.1	975.5	476.7	1.5233
4	21	10324	10345	99.8	2.6	1034.5	477.9	1.5227
5	17	9747	9764	99.8	2.1	976.4	477.3	1.5311
6	16	9886	9902	99.8	2.0	990.2	480.9	1.5343
7	23	10562	10585	99.8	2.8	1058.5	**481.9**	**1.5349**
8	21	10375	10396	99.8	2.6	1039.6	478.8	1.5192
9	25	10602	10627	99.8	3.0	1062.7	480.8	1.5246
10	24	10439	10463	99.8	2.9	1046.3	479.4	1.5287
Avg.	**21.0**	**10291.7**	**10312.7**	**99.8**	**2.6**	**1031.3**	**479.0**	**1.5258**
Reference (NDR)							**475.9**	**1.5349**

YGN3 Cycle 16

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	21	10214	10235	99.8	3.4	1307.8	627.3	1.5399
2	21	10517	10538	99.8	3.4	1346.5	626.4	1.5472
3	23	10348	10371	99.8	3.7	1325.2	630.9	1.5325
4	17	9920	9937	99.8	2.8	1269.7	625.9	1.5447
5	19	9949	9968	99.8	3.1	1273.7	626.8	1.5455
6	20	10180	10200	99.8	3.3	1303.3	630.2	1.5453
7	17	9736	9753	99.8	2.8	1246.2	625.9	1.5366
8	20	10207	10227	99.8	3.3	1306.8	631.4	1.5420
9	23	10623	10646	99.8	3.7	1360.3	631.2	1.5461
10	24	10468	10492	99.8	3.9	1340.6	**631.5**	**1.5508**
Avg.	**20.5**	**10216.2**	**10236.7**	**99.8**	**3.4**	**1308.0**	**628.8**	**1.5431**
Reference (NDR)							**625.5**	**1.5512**

* Efficiency = # of ViT evaluation / # of total evaluation
** Estimated time w/o ST = average time of RAST-K calculation * # of total evaluation

Results of SA – Free Type Change (3/3)

➢ UCN5 Cycle 01

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	28	10883	10911	99.7	2.6	909.3	372.8	1.4987
2	28	11123	11151	99.7	2.6	929.3	370.9	1.4998
3	24	10546	10570	99.8	2.3	880.8	374.9	1.4951
4	23	10757	10780	99.8	2.2	898.3	376.2	1.5026
5	24	10546	10570	99.8	2.3	880.8	371.2	1.4987
6	22	10255	10277	99.8	2.1	856.4	371.8	1.4937
7	24	10470	10494	99.8	2.3	874.5	374.8	1.4935
8	21	10172	10193	99.8	2.0	849.4	371.3	1.4904
9	23	10588	10611	99.8	2.2	884.3	372.7	1.4945
10	25	10642	10667	99.8	2.4	888.9	376.6	1.4942
Avg.	**24.2**	**10598.2**	**10622.4**	**99.8**	**2.3**	**885.2**	**373.3**	**1.4961**
Reference (NDR)							**370.8**	**1.5039**

➢ UCN5 Cycle 04

Index	No. of LP evaluations			Efficiency* [%]	Calculation time [hrs]	Estimated time w/o ST** [hrs]	Cycle Length [EFPDs]	Peaking Factor [-]
	RAST-K	ViT	Total					
1	22	10584	10606	99.8	2.5	1001.7	453.5	1.5132
2	27	10849	10876	99.8	3.0	1027.2	452.7	1.5022
3	25	10743	10768	99.8	2.8	1017.0	454.3	1.5072
4	23	10422	10445	99.8	2.6	986.5	453.8	1.5150
5	25	10578	10603	99.8	2.8	1001.4	454.2	1.5024
6	21	10140	10161	99.8	2.4	959.7	453.8	1.5041
7	24	10864	10888	99.8	2.7	1028.3	453.5	1.5079
8	20	10047	10067	99.8	2.3	950.8	454.3	1.5076
9	25	10877	10902	99.8	2.8	1029.6	452.8	1.5128
10	21	10369	10390	99.8	2.4	981.3	453.3	1.5121
Avg.	**23.3**	**10547.3**	**10570.6**	**99.8**	**2.6**	**998.3**	**453.6**	**1.5085**
Reference (NDR)							**452.7**	**1.5171**

* Efficiency = # of ViT evaluation / # of total evaluation

** Estimated time w/o ST = average time of RAST-K calculation * # of total evaluation