GMDH-based 3-D Power Reconstruction for Increment of MDNBR Margin

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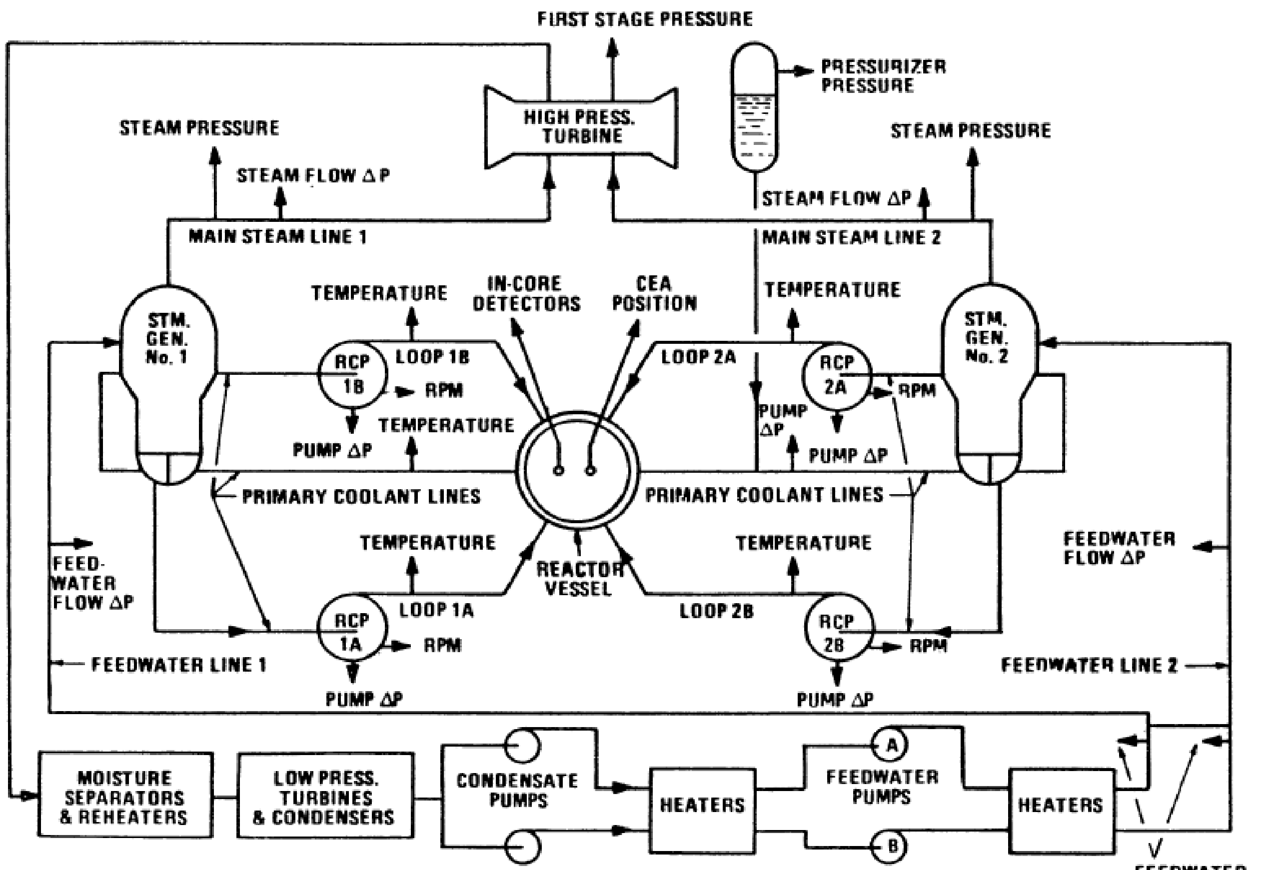
Introduction

GMDH-based 3-D Power Reconstruction for Increment of MDNBR Margin

COLSS Introduction

- **COLSS (Core Operating Limit Surveillance System)**
  - **Real-time digital Core monitoring system software**

FIGURE 2-3
COLSS SENSOR LOCATIONS



NOTE:
RCP = REACTOR COOLANT PUMP

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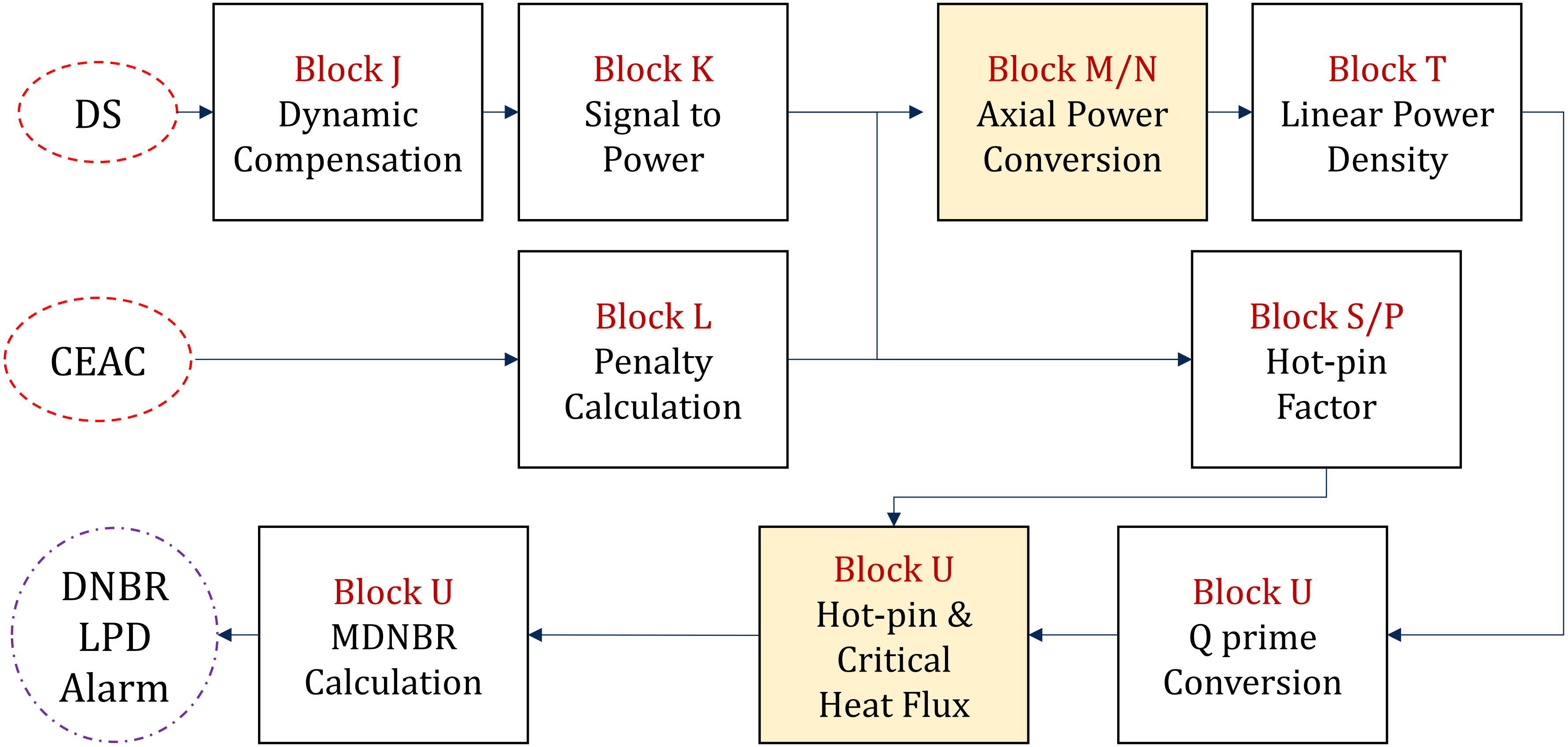
COLSS Introduction

- **Input**
  - **Primary/Secondary coolant measurements (from Sensors)**
    - Coolant Temperature, Pressure, and Flowrate
  - **In-core detector signal (from ICI)**
  - **Control rod position (from CEAC)**
- **Output**
  - **Operation margin & exceeding alarm (to operators)**
    - MDNBR, LPD, ASI, Tilt
- **Motivation of this study**
  - **1-D conservative MDNBR margin**
    - COLSS is using 1-dimensional Fourier spline fitting
      - Averaging all radial distribution of ICI signals
    - Using conservative penalty factors with respect to control rod position and azimuthal tilt
  - **OPR-1000, has 45 ICIs & 5 SPND per ICI**

COLSS DNBR

- **Multi-block structure**
  - **From Signal to DNBR**



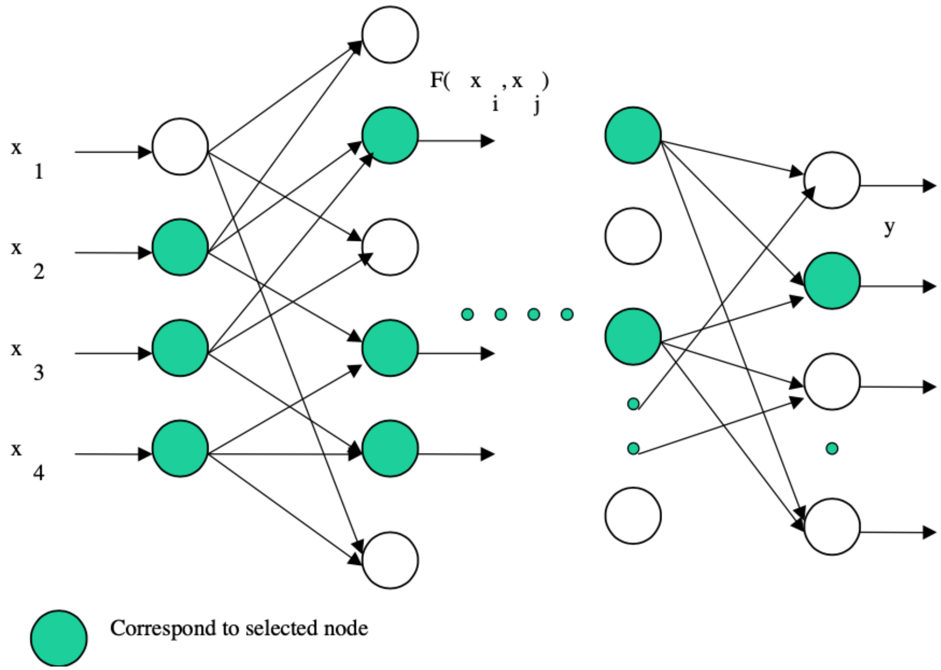
3-D Power Distribution Reconstruction

via GMDH polynomial model

GMDH

- **Trained regression model using Ivakhnenko polynomial**

$$p(x_1, x_2) = a_0 + a_1x_1 + a_2x_2 + a_3x_1^2 + a_4x_2^2 + a_5x_1x_2$$



- **GMDH_A**
  - **Reconstruct assembly axial power distribution**
- **GMDH_H**
  - **Reconstruct hot-pin power distribution**

GMDH model configuration

- **Trained regression model using Ivakhnenko polynomial**

$$z^{(1)} = a_0^{(1)} + a_1^{(1)} x_1 + a_2^{(1)} x_2 + a_3^{(1)} x_1^2 + a_4^{(1)} x_2^2 + a_5^{(1)} x_1 x_2 \qquad \text{2}^{\text{nd}} \text{ Order}$$

$$\downarrow$$

$$z^{(2)} = a_0^{(2)} + a_1^{(2)} z_1^{(1)} + a_2^{(2)} z_2^{(1)} + a_3^{(2)} z_1^{(1)2} + a_4^{(2)} z_2^{(1)2} + a_5^{(2)} z_1^{(1)} z_2^{(1)} \qquad \text{4}^{\text{th}} \text{ Order}$$

$$\downarrow$$

$$\ldots$$

$$z^{(5)} = a_0^{(5)} + a_1^{(5)} z_1^{(4)} + a_2^{(5)} z_2^{(4)} + a_3^{(5)} z_1^{(4)2} + a_4^{(5)} z_2^{(4)2} + a_5^{(5)} z_1^{(4)} z_2^{(4)} \qquad \text{32}^{\text{th}} \text{ Order}$$

- **Model hyperparameters**
  - **N_layer = 5**
  - **N_cutoff = 50**
  - **Loss function**

$$\boldsymbol{Mean}\left(\frac{|P_{GMDH(xy,z)} - P_{RK(xy,z)}|}{P_{RK(xy,z)}}\right)$$

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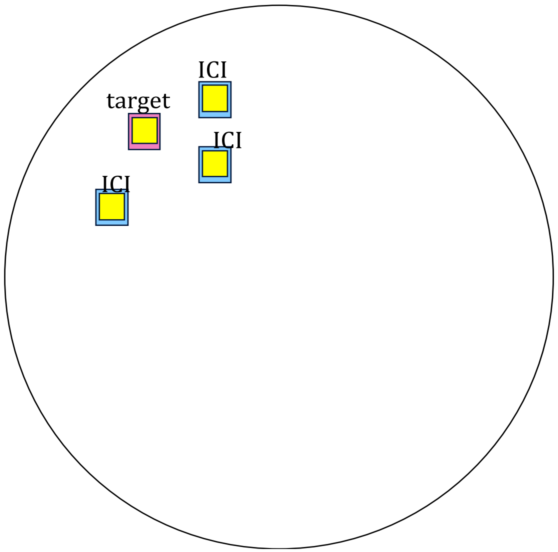
Data Acquisition

- **Training data configuration**
  - **X_data (N_data , N_FA, 20)**
    - Detector power from **nearby Four ICI** [MW]
  - **Y_data (N_data , N_FA, 40)**
    - Assembly axial power distribution [W/cm^3]
    - Hot-pin power distribution [W/cm^3]



- **Data Acquisition**
  - **Detector signal module in 2-step code STREAM/RAST-K**
    - Detector power are used
  - **Dataset domain**
    - OPR-1000 cycle 1
    - Fixed Burnup step (9,0 GWD/MtU)
    - Core Power is sampled in 60% ~ 100%
    - CR position (R5 & R4) are set following corresponding PDIL of Core Power

3-D Assembly Power Distribution (APD) : $GMDH_A$

- **Train set domain :**
  - BU : 9.0 GWd/MtU
  - CR : 0 ~ 381 cm insert
  - Power : 60 ~ 100%
- **ARO case :**
  - BU : 9.0 GWd/MtU
  - Power : 99%
- **Relative Error [%]**
  - Max : 0.277
  - Min : -2.212
  - RMS : 0.284

GMDH radial Dist.
BU : 9.000 GWD/MtU , I_z: 39

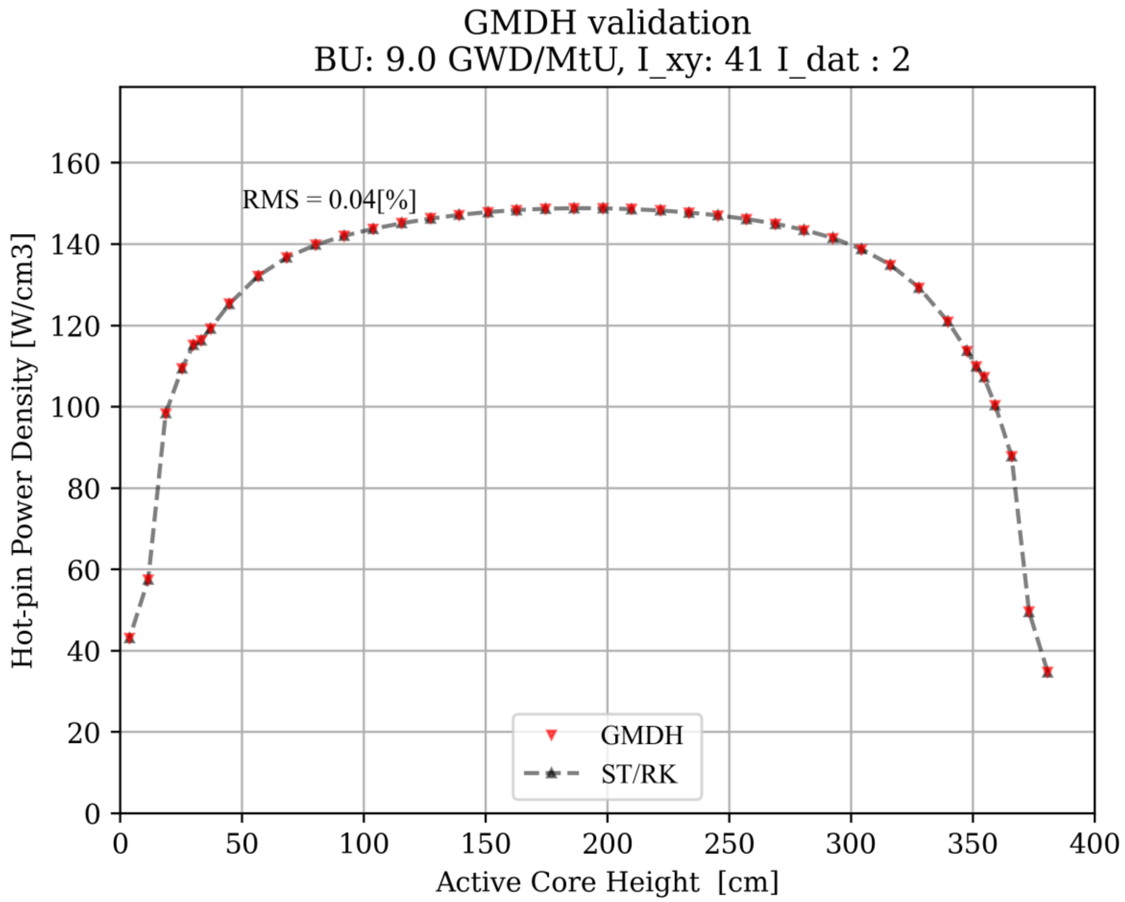
	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P
15						22.088 22.120 -0.145	23.409 23.433 -0.101	23.242 23.263 -0.091	23.102 23.101 0.002	22.065 22.091 -0.118					
14				24.417 24.416 0.003	33.560 33.566 -0.018	36.492 36.478 0.037	35.939 35.925 0.042	34.658 34.620 0.110	35.890 35.917 -0.076	36.482 36.486 -0.010	33.673 33.675 -0.007	26.035 26.048 -0.049			
13			27.860 27.849 0.040	37.339 37.370 -0.082	38.844 38.949 -0.270	39.487 39.513 -0.065	37.193 37.195 -0.005	33.574 33.597 -0.068	37.195 37.200 -0.013	39.522 39.536 -0.036	38.909 38.998 -0.230	37.416 37.417 -0.002	27.773 27.780 -0.027		
12		26.013 26.020 -0.027	37.454 37.458 -0.011	41.552 41.673 -0.292	40.905 40.792 0.277	37.465 37.465 0.000	37.124 37.387 -0.708	28.069 28.117 -0.170	37.109 37.387 -0.749	37.491 37.485 0.016	40.776 40.781 -0.014	41.586 41.657 -0.172	37.313 37.353 -0.108	24.198 24.206 -0.034	
11		33.315 33.320 -0.015	37.291 37.304 -0.035	41.185 41.241 -0.134	43.145 43.089 0.129	40.041 40.029 0.031	39.073 39.063 0.024	36.283 36.313 -0.082	39.028 39.080 -0.133	40.020 40.031 -0.027	43.125 43.074 0.118	41.198 41.218 -0.047	37.174 37.207 -0.090	33.150 33.163 -0.038	
10	21.941 21.980 -0.179	35.760 35.751 0.026	39.312 39.303 0.024	37.207 37.202 0.013	39.606 40.482 -2.212	36.075 36.074 0.003	36.744 36.763 -0.051	39.882 39.921 -0.098	36.776 36.783 -0.020	36.067 36.066 0.002	40.088 40.453 -0.911	37.188 37.152 0.097	39.278 39.264 0.034	35.753 35.743 0.027	21.951 22.003 -0.238
9	22.958 22.928 0.132	35.729 35.728 0.001	37.039 37.020 0.051	38.440 38.416 0.063	39.970 40.004 -0.084	36.841 36.848 -0.019	39.433 39.421 0.031	36.517 36.562 -0.124	39.363 39.371 -0.022	36.807 36.804 0.008	39.759 39.963 -0.514	38.392 38.383 0.024	37.056 37.017 0.104	35.700 35.703 -0.011	23.318 23.355 -0.161
8	23.156 23.166 -0.042	34.523 34.528 -0.013	33.798 33.871 -0.215	28.154 28.193 -0.140	36.321 36.320 0.002	39.960 39.949 0.027	36.780 36.744 0.097	41.456 41.453 0.006	36.792 36.741 0.140	39.949 39.948 0.003	36.319 36.313 0.017	28.235 28.185 0.175	33.819 33.870 -0.148	34.526 34.531 -0.013	23.142 23.166 -0.104
7	23.302 23.340 -0.162	35.744 35.732 0.032	37.039 37.009 0.081	38.401 38.396 0.013	39.857 39.976 -0.297	36.821 36.804 0.045	39.365 39.374 -0.023	36.542 36.562 -0.056	39.403 39.419 -0.041	36.833 36.846 -0.035	39.907 39.999 -0.230	38.401 38.406 -0.015	37.071 37.025 0.126	35.688 35.696 -0.021	22.949 22.939 0.044
6	21.969 22.006 -0.169	35.770 35.741 0.080	39.265 39.269 -0.008	37.161 37.160 0.003	39.742 40.470 -1.831	36.073 36.080 -0.019	36.774 36.789 -0.041	39.923 39.925 -0.006	36.733 36.767 -0.093	36.048 36.077 -0.078	39.927 40.473 -1.366	37.187 37.183 0.013	39.287 39.293 -0.014	35.732 35.747 -0.041	21.925 21.976 -0.234
5		33.179 33.191 -0.036	37.214 37.223 -0.025	41.215 41.230 -0.035	43.123 43.085 0.086	40.040 40.040 -0.001	39.100 39.087 0.033	36.326 36.316 0.028	39.123 39.062 0.156	40.020 40.018 0.005	43.119 43.070 0.115	41.165 41.221 -0.135	37.298 37.290 0.022	33.273 33.278 -0.015	
4		24.209 24.211 -0.007	37.293 37.336 -0.115	41.688 41.667 0.051	40.787 40.788 -0.003	37.490 37.495 -0.011	37.320 37.395 -0.200	28.158 28.115 0.151	37.262 37.373 -0.296	37.438 37.444 -0.016	40.865 40.765 0.245	41.670 41.649 0.050	37.402 37.406 -0.010	26.008 26.006 0.008	
3			27.761 27.787 -0.091	37.452 37.449 0.007	38.873 39.006 -0.343	39.527 39.544 -0.043	37.214 37.219 -0.013	33.444 33.602 -0.473	37.193 37.199 -0.016	39.490 39.501 -0.028	38.882 38.926 -0.113	37.283 37.315 -0.084	27.851 27.840 0.039		
2				26.056 26.053 0.014	33.652 33.658 -0.018	36.464 36.497 -0.090	35.862 35.898 -0.100	34.664 34.626 0.110	35.888 35.891 -0.007	36.482 36.472 0.030	33.517 33.523 -0.017	24.413 24.413 0.000			
1						22.067 22.091 -0.111	23.099 23.110 -0.046	23.251 23.260 -0.040	23.417 23.438 -0.087	22.079 22.107 -0.125					

MAX	0.277
MIN	-2.212
RMS	0.284

GMDH
RAST-K
Rel. Diff.[%]

Hot-pin Power Distribution (HPD) : $GMDH_H$

- **Train set domain :**
  - **BU : 9.0 GWd/MtU**
  - **CR : 0 ~ 381 cm insert**
  - **Power : 60 ~ 100%**
- **ARO case :**
  - **BU : 9.0 GWd/MtU**
  - **Power : 99%**
- **Relative Error [%]**
  - **RMS : 0.04**



3-D Assembly Power Distribution (APD) : $GMDH_A$

- **Train set domain :**
  - BU : 9.0 GWd/MtU
  - CR : 0 ~ 381 cm insert
  - Power : 60 ~ 100%
- **Rodded case :**
  - BU : 9.0 GWd/MtU
  - CR : 275 cm inserted
  - Power : 67%
- **Relative Error [%]**
  - Max : 0.874
  - Min : -0.688
  - RMS : 0.142

GMDH radial Dist.
BU : 9.000 GWD/MtU , I_z: 39

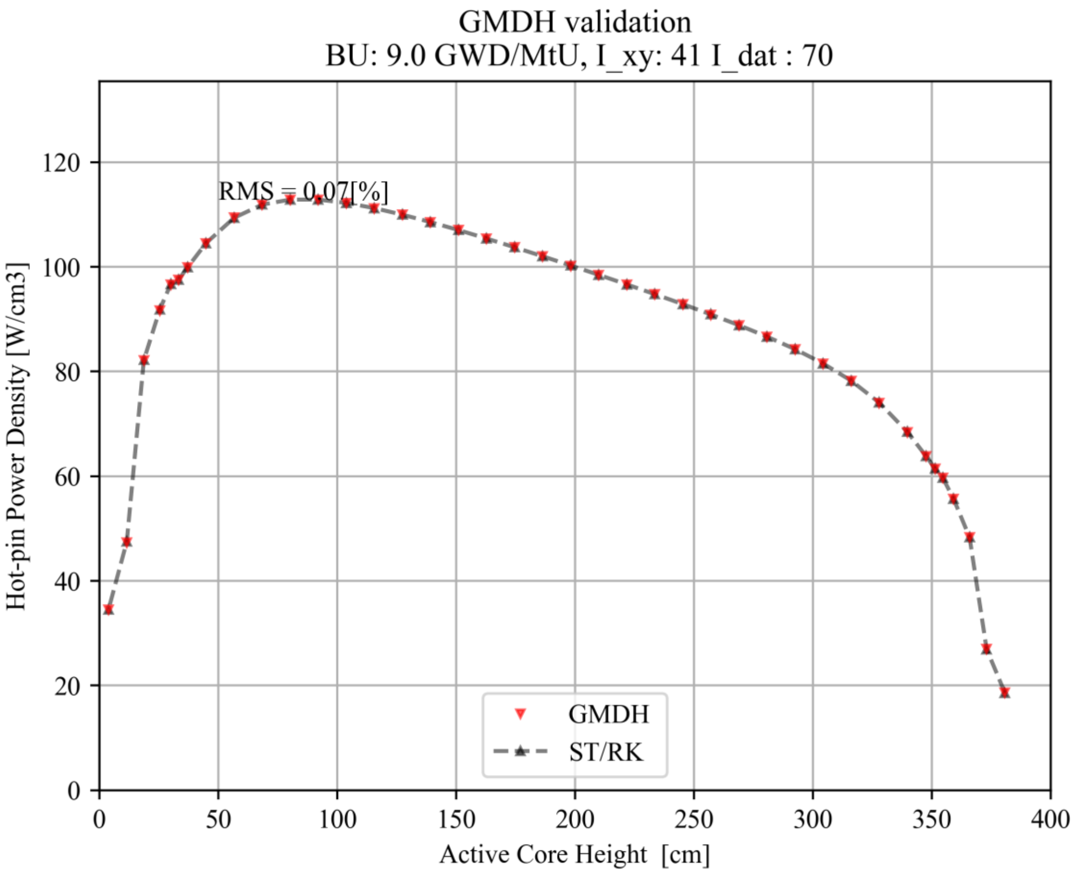
	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P
15						25.960 25.926 0.129	27.793 27.803 -0.037	27.648 27.653 -0.019	27.415 27.399 0.056	25.881 25.891 -0.039					
14				28.182 28.188 -0.022	38.784 38.792 -0.021	42.625 42.633 -0.019	42.206 42.202 0.009	41.146 41.138 0.019	42.195 42.192 0.007	42.610 42.639 -0.069	38.913 38.914 -0.002	30.066 30.063 0.012			
13			31.956 31.989 -0.103	42.824 42.822 0.004	45.215 45.090 0.277	46.106 46.109 -0.006	43.737 43.732 0.012	39.808 39.812 -0.010	43.724 43.734 -0.023	46.163 46.133 0.065	45.200 45.144 0.124	42.874 42.875 -0.002	31.902 31.909 -0.022		
12		30.032 30.034 -0.005	42.924 42.923 0.002	47.993 47.865 0.267	45.927 45.956 -0.063	43.634 43.642 -0.018	43.115 43.176 -0.142	34.084 34.109 -0.075	43.012 43.169 -0.364	43.659 43.662 -0.007	45.854 45.969 -0.252	47.851 47.846 0.011	42.801 42.803 -0.005	27.953 27.949 0.016	
11		38.524 38.523 0.001	42.890 42.888 0.005	47.540 47.527 0.028	49.735 49.688 0.094	46.681 46.698 -0.036	46.846 46.806 0.086	43.534 43.538 -0.008	46.771 46.823 -0.112	46.699 46.699 -0.000	49.752 49.670 0.164	47.453 47.500 -0.100	42.778 42.777 0.002	38.344 38.344 -0.001	
10	25.857 25.864 -0.027	42.148 41.779 0.874	45.875 45.880 -0.009	43.349 43.348 0.003	45.163 45.199 -0.081	42.468 42.465 0.006	43.873 43.877 -0.009	47.371 47.366 0.012	43.905 43.899 0.014	42.446 42.456 -0.024	45.292 45.150 0.314	43.292 43.290 0.005	45.843 45.835 0.018	42.339 42.403 -0.152	25.851 25.891 -0.152
9	27.267 27.263 0.017	41.970 41.982 -0.028	43.001 42.893 0.252	45.735 45.731 0.010	46.810 46.916 -0.225	43.956 43.965 -0.021	46.369 46.380 -0.024	43.089 43.058 0.070	46.322 46.324 -0.003	43.932 43.913 0.042	46.830 46.881 -0.108	45.664 45.691 -0.059	43.023 42.891 0.306	41.944 41.951 -0.017	27.673 27.712 -0.143
8	27.538 27.527 0.041	41.026 41.025 0.003	40.502 40.489 0.033	33.946 33.853 0.274	43.529 43.531 -0.004	47.412 47.404 0.016	43.263 43.271 -0.017	48.730 48.768 -0.078	43.270 43.267 0.007	47.374 47.403 -0.061	43.517 43.523 -0.014	34.009 33.844 0.485	40.497 40.488 0.024	41.029 41.028 0.002	27.539 27.526 0.046
7	27.648 27.694 -0.168	41.976 41.985 -0.021	43.011 42.886 0.289	45.693 45.706 -0.030	46.887 46.892 -0.011	43.911 43.913 -0.006	46.331 46.327 0.010	43.019 43.059 -0.092	46.372 46.377 -0.011	43.958 43.963 -0.012	46.754 46.910 -0.333	45.717 45.720 -0.006	42.865 42.894 -0.067	41.950 41.944 0.014	27.265 27.281 -0.057
6	25.873 25.894 -0.080	41.708 41.767 -0.143	45.841 45.839 0.003	43.291 43.298 -0.017	44.868 45.177 -0.688	42.469 42.472 -0.006	43.913 43.906 0.015	47.335 47.367 -0.066	43.863 43.882 -0.043	42.466 42.470 -0.009	44.979 45.193 -0.475	43.327 43.327 -0.000	45.859 45.869 -0.023	42.394 42.414 -0.047	25.858 25.860 -0.010
5		38.381 38.376 0.011	42.836 42.795 0.097	47.514 47.513 0.002	49.753 49.682 0.143	46.701 46.709 -0.017	46.850 46.831 0.042	43.545 43.541 0.009	46.780 46.805 -0.054	46.678 46.688 -0.021	49.596 49.669 -0.147	47.519 47.507 0.027	42.888 42.874 0.032	38.477 38.476 0.001	
4		27.956 27.954 0.009	42.792 42.783 0.020	47.885 47.856 0.061	46.146 45.974 0.372	43.652 43.673 -0.047	43.285 43.175 0.256	34.067 34.108 -0.119	43.051 43.169 -0.273	43.623 43.620 0.007	46.017 45.926 0.197	47.704 47.840 -0.285	42.849 42.865 -0.039	30.020 30.020 -0.001	
3			31.938 31.915 0.070	42.942 42.910 0.073	45.231 45.152 0.174	46.130 46.142 -0.025	43.747 43.757 -0.022	39.861 39.826 0.088	43.744 43.738 0.013	46.098 46.098 0.000	45.109 45.066 0.095	42.762 42.762 0.001	31.948 31.980 -0.101		
2				30.069 30.067 0.007	38.892 38.893 -0.002	42.658 42.652 0.014	42.165 42.168 -0.007	41.153 41.146 0.018	42.166 42.164 0.005	42.630 42.627 0.007	38.736 38.744 -0.021	28.182 28.186 -0.014			
1						25.880 25.892 -0.046	27.363 27.410 -0.171	27.642 27.650 -0.030	27.812 27.809 0.009	25.942 25.913 0.112					

MAX	0.874
MIN	-0.688
RMS	0.142

GMDH
RAST-K
Rel. Diff.[%]

Hot-pin Power Distribution (HPD) : $GMDH_H$

- **Train set domain :**
  - **BU : 9.0 GWd/MtU**
  - **CR : 0 ~ 381 cm insert**
  - **Power : 60 ~ 100%**
- **Rodded case :**
  - **BU : 9.0 GWd/MtU**
  - **CR : 275 cm inserted**
  - **Power : 67%**
- **Relative Error [%]**
  - **RMS : 0.07**



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3-D Assembly Power Distribution (APD) : $GMDH_A$

▪ Power conversion via Fourier spline (Block M)

- **Unit conversion W/cm³ -> BTU/ft³-sec**

#	COLSS Fourier Spline	GMDH
1	Averaging PHI(45,5)-> CHI(1,5)	Reshape PHI(45,5) -> PHIG(177,20)
2	Calculation Fourier spline fitting	Calculation of pre-trained GMDH
3	$L(J+1) = 100 \times \frac{CHI(J)}{\sum_{J=1}^{5} CHI(J)}$ $A(I) = \sum_{J=1}^{7} [H(I,J) \times L(J)]$ $H(I,J)$ = Fourier weighting coefficients $APKD(I) = \sum_{K=1}^{5} [SPLIN(I,K) \times A(K)]$ $SPLIN(I,K)$ = Fourier series matrix $\boldsymbol{APKD(I)}$ **= 40 node axial power dist.**	$APKD3D(I_{xy}, I_z) = GMDH\left(PHIG(I_{xy}, :)\right)$ $\boldsymbol{APKD(I) = APKD3D(I_{xy,max}, I_z)}$

MDNBR Calculation

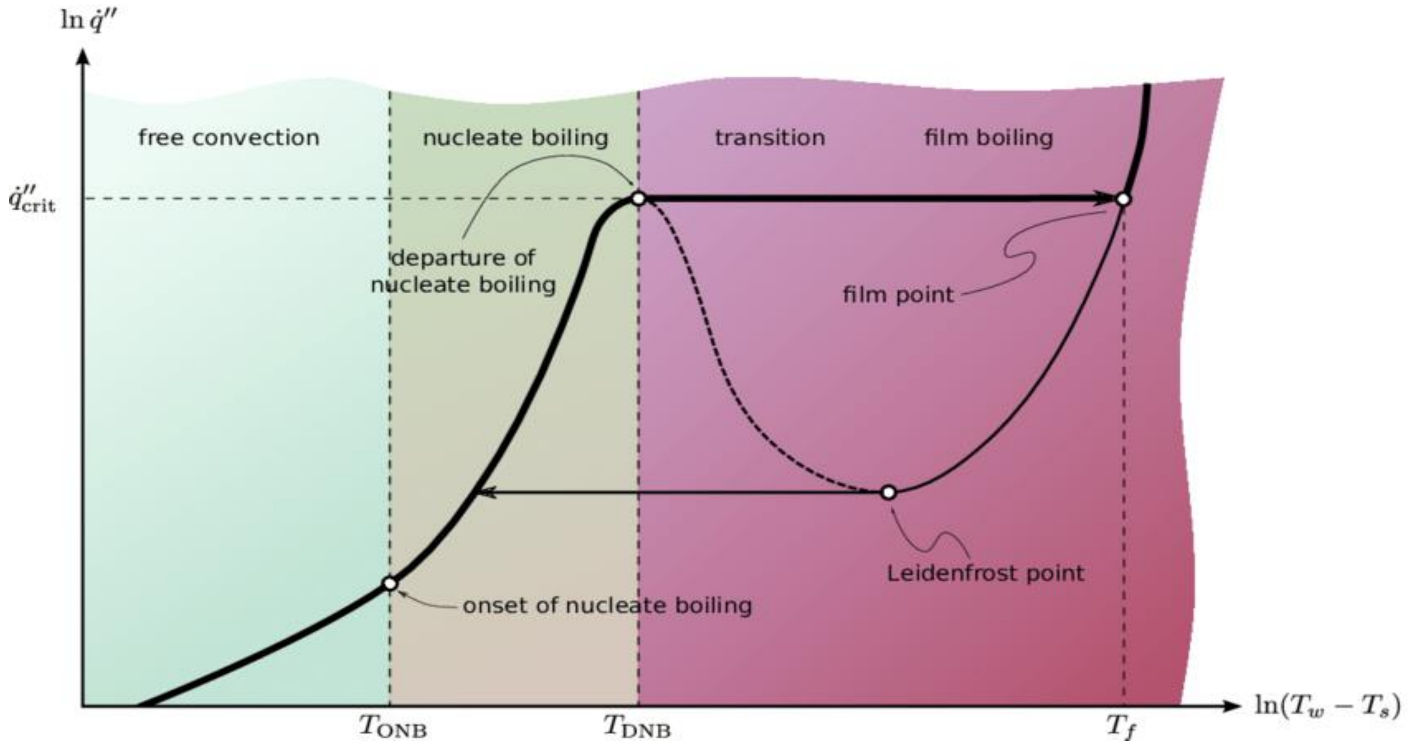
COLSS 1-D vs 3-D

DNBR

- **Departure of Nucleate Boiling Ratio**

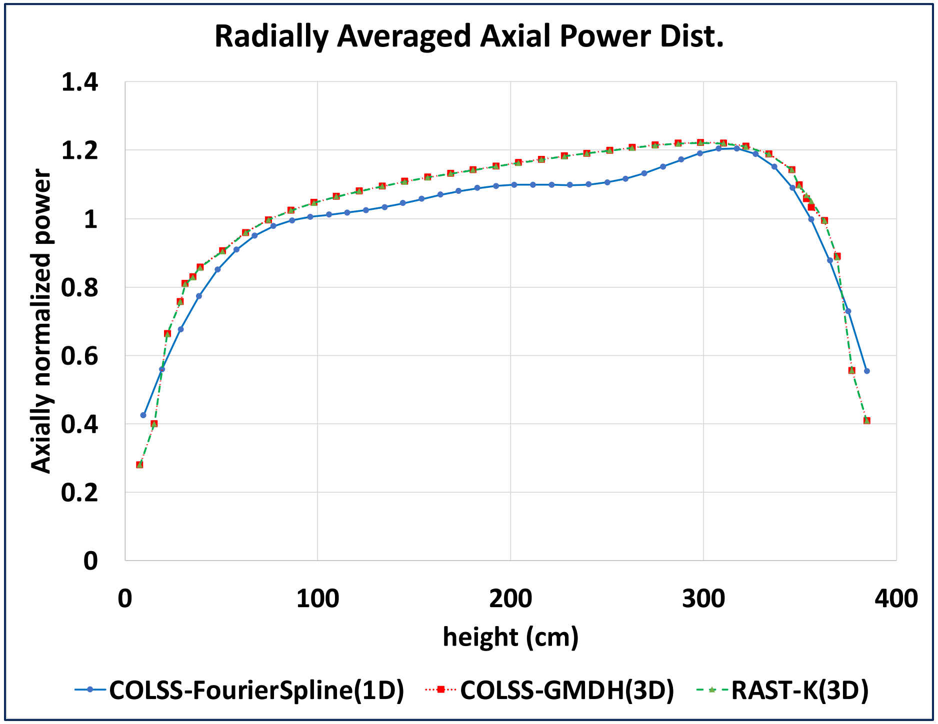
$$MDNBR = \frac{q''_{Crit}}{F_v \times (q''_{hot-pin})}$$

$$q''_{chf} = \dot{m}h_{fg}(T_{sat} - T_{sub})\ , F_v = \frac{Q_{actual}}{q''_{uniform} \times area}$$



Validation case configuration

- **COLSS sample case**
  - **9.0 GWD/MtU, 65% Core relative power, ARO from COLSS sample input**
  - **Input signal : Detector power from RAST-K**
    - **GMDH-results just follow the RAST-K results**

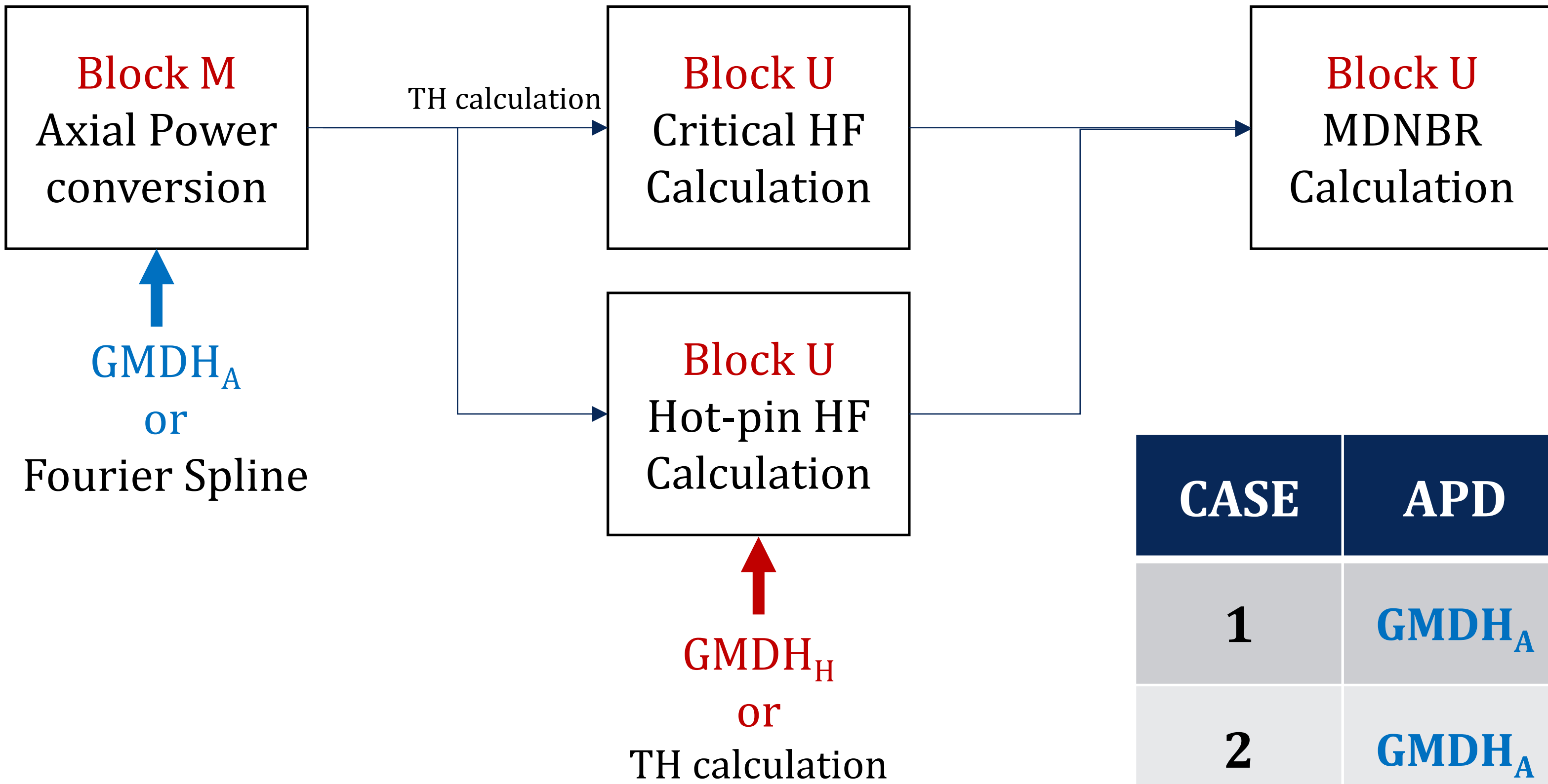


ASI [-]		
Fourier	$GMDH_A$	RAST-K
-0.0539	-0.0647	-0.0647

Azimuthal Tilt [-]		
Fourier	$GMDH_A$	RAST-K
0.02914	0.03090	0.03090

COLSS MDNBR Calculation

- **DNBR margin increment test**

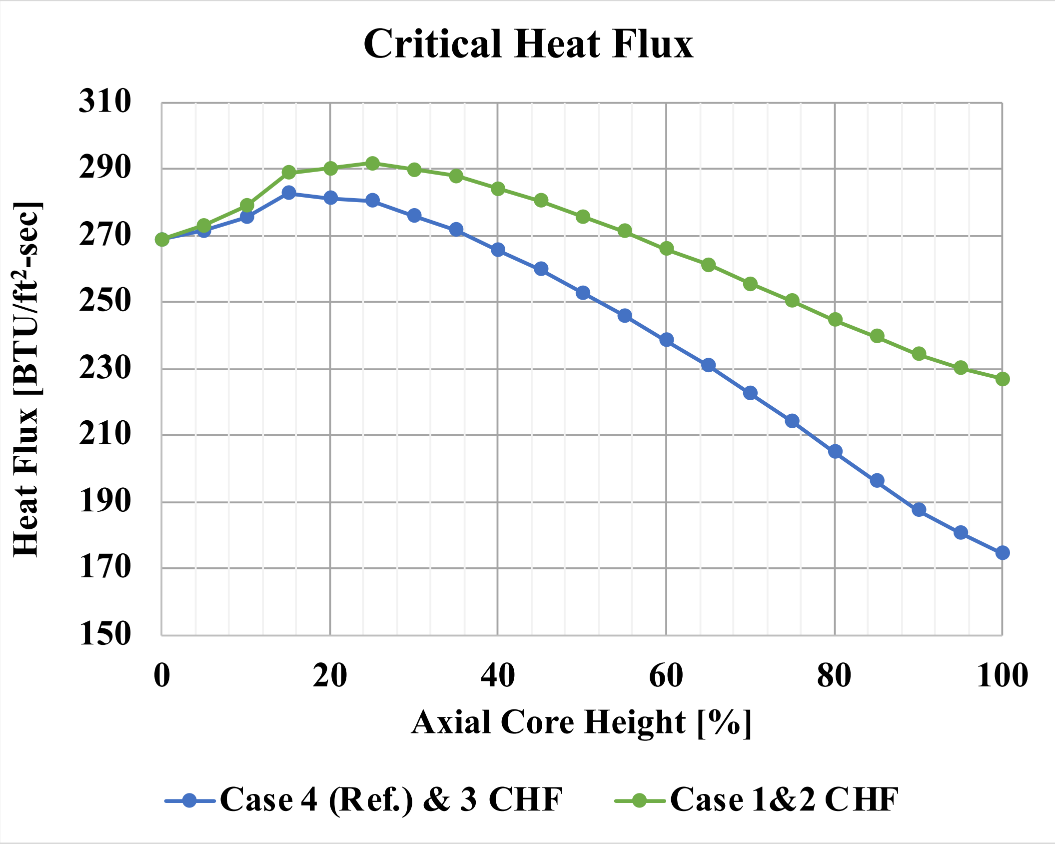


CASE	APD	HPD
1	GMDH$_A$	GMDH$_H$
2	GMDH$_A$	TH calc
3	Fourier	GMDH$_H$
4(ref)	Fourier	TH calc

COLSS MDNBR Calculation

▪ Critical Heat Flux (CHF)

- **CHF are resulted from APD and coolant information**
  - **Fourier spline method with integral radial penalty factor**
  - **3-D GMDH method without penalty factor**

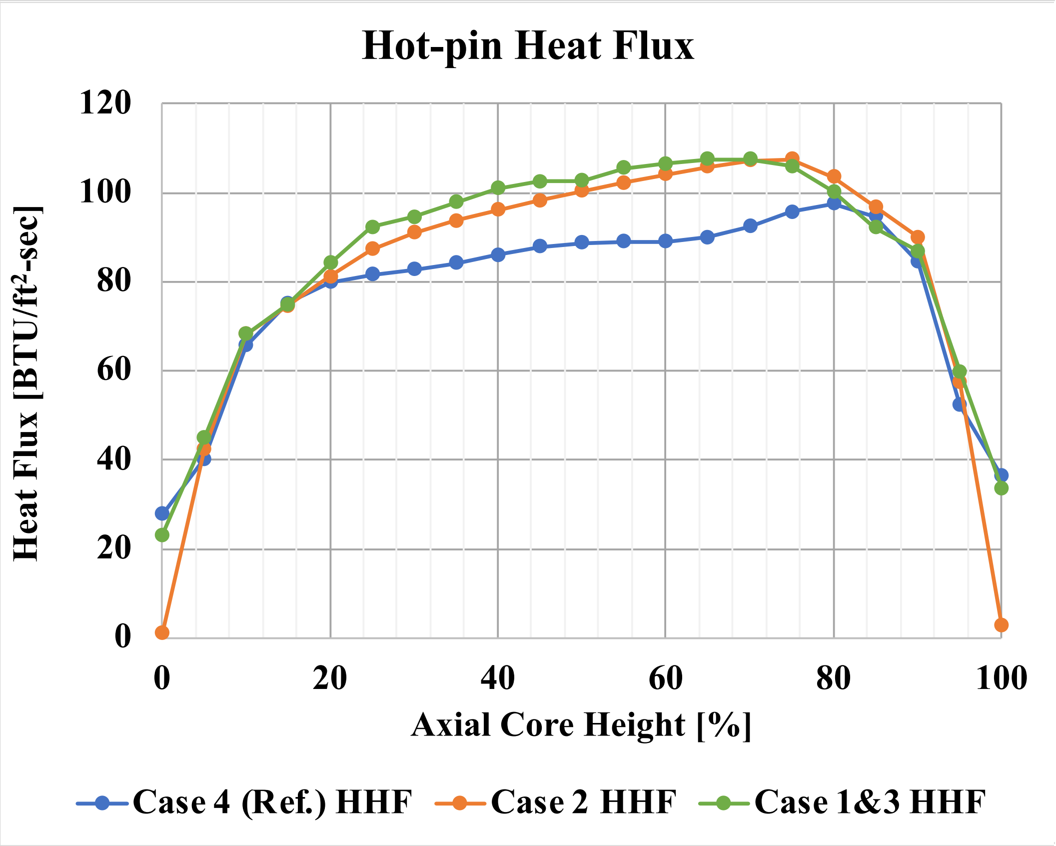


CASE	APD	HPD
1	$GMDH_A$	$GMDH_H$
2	$GMDH_A$	TH calc
3	Fourier	$GMDH_H$
4(ref)	Fourier	TH calc

COLSS MDNBR Calculation

▪ Hot-pin Heat Flux (HHF)

- **HHF are resulted from APD and coolant information**
  - TH calculation integrates TH properties to APD
  - GMDH method directly converts HPD to HHF

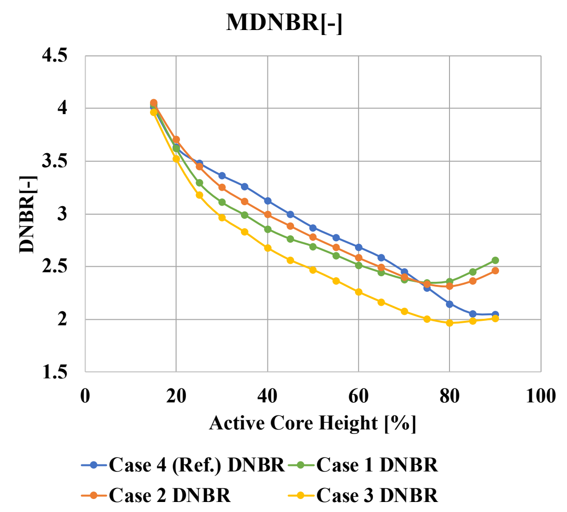


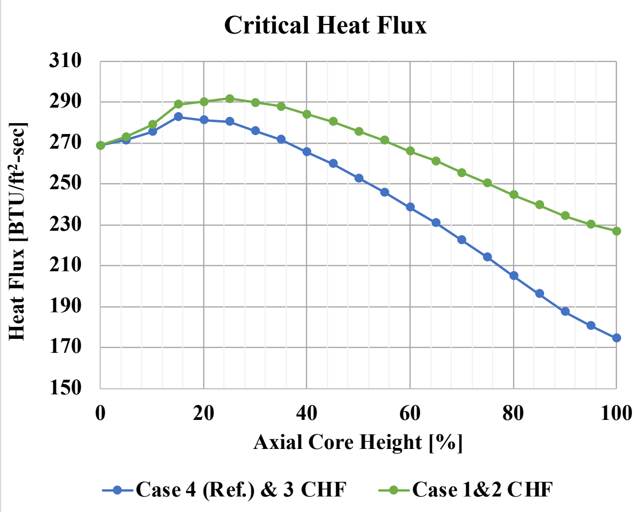
CASE	APD	HPD
1	$GMDH_A$	$GMDH_H$
2	$GMDH_A$	TH calc.
3	Fourier	$GMDH_H$
4(ref)	Fourier	TH calc.

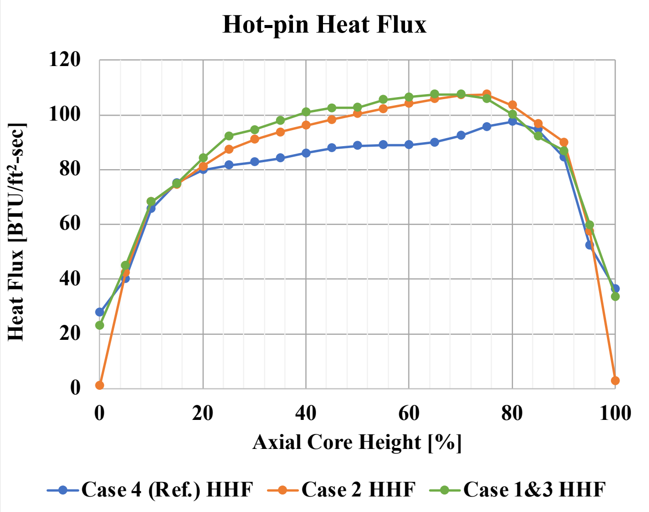
COLSS MDNBR Calculation

- **DNBR margin increment by case**

CASE	APD	HPD	MDNBR	Rel. Margin Increment	CHF [BTU/ft²-sec]	HHF [BTU/ft²-sec]	Position of DNBR [cm]
1	$GMDH_A$	$GMDH_H$	2.3457	14.60%	250.18	105.03	320
2	$GMDH_A$	-	2.3163	13.17%	244.58	103.53	340
3	Fourier	$GMDH_H$	1.9686	-3.82%	196.30	100.28	320
4(ref)	Fourier	-	2.0468	-	187.43	84.40	340







Uncertainty Analysis

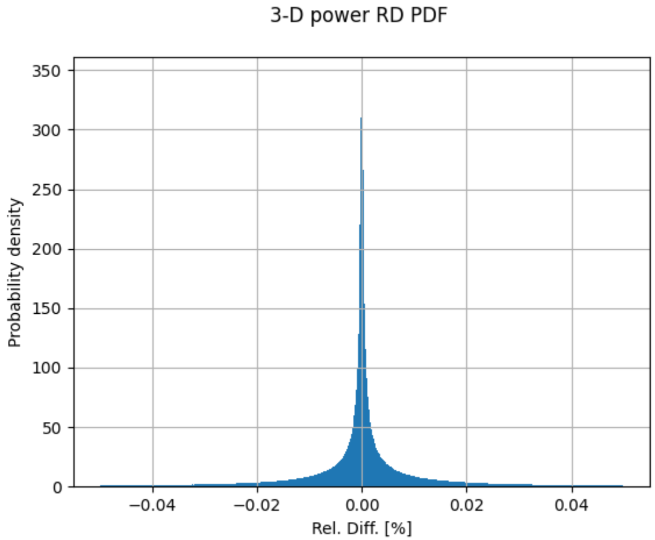
Best estimate

GMDH Uncertainty quantification

- **Model uncertainty using Test dataset (N_test = 4,000)**
  - **Calculation of relative difference between**
    Model Prediction (GMDH) and Y-data (RAST-K)

$$RD[\%] = \frac{P_{GMDH(xy,z)} - P_{RK(xy,z)}}{P_{RK(xy,z)}} \times 100\%$$

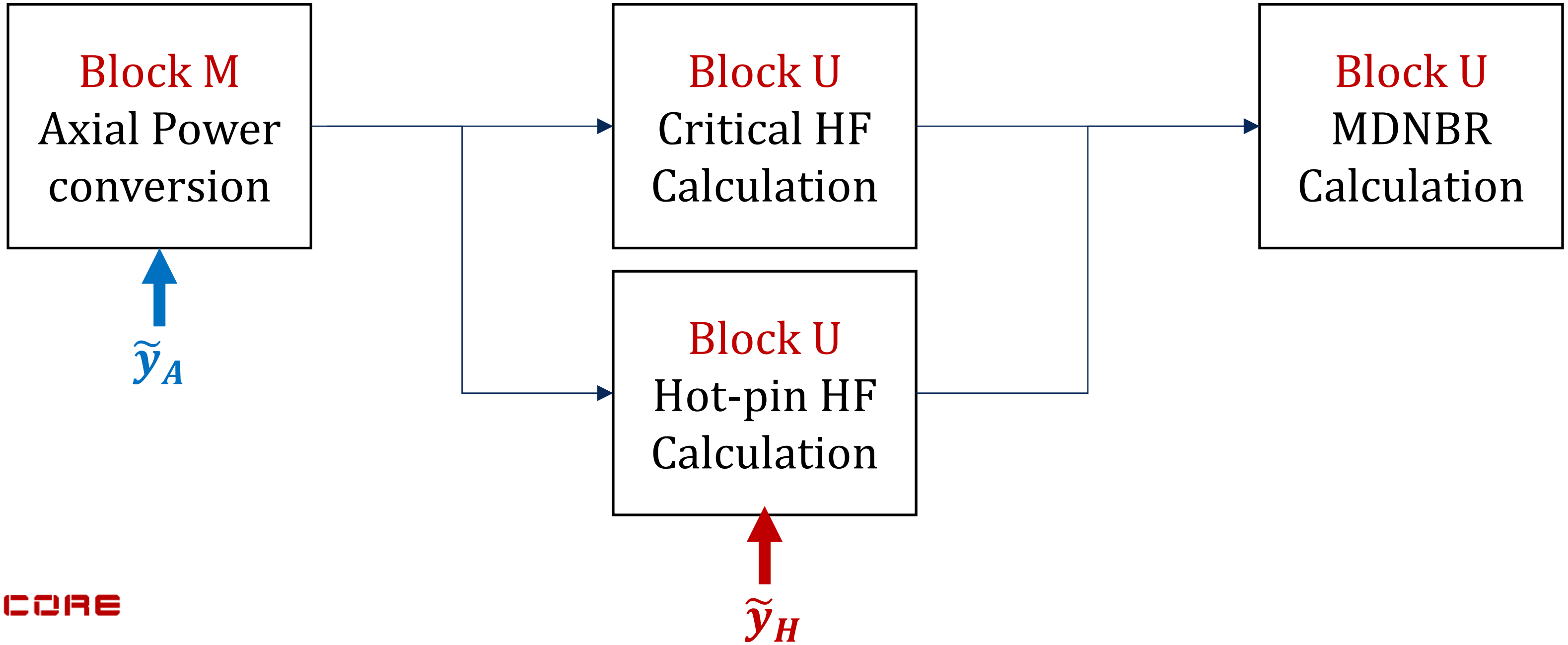
  - **Shapiro-Wilk Normality test of RD histogram (p-value = 0.001)**
    - **Non-parametric uncertainty quantification**



99% Non-parametric interval		
Model	Lower Limit (20^{th} Value)	Upper Limit (3980^{th} Value)
$GMDH_A$ (for 3-D APD)	-0.3889 %	0.3505 %
$GMDH_H$ (for HPD)	-0.6593 %	0.7438 %

Uncertainty adjusted COLSS MDNBR

- **MDNBR from perturbed GMDH results**
  - **10,000 perturbation of model**
    - $\tilde{y}_A = \mathrm{GMDH_A} + N(0, \sigma^*)$
      - $\sigma^* = \sigma_{lower,,A} / k_{99\%}$
    - $\tilde{y}_H = \mathrm{GMDH_H} + N(0, \sigma^*)$
      - $\sigma^* = \sigma_{lower,,H} / k_{99\%}$
  - **Conservatively lowest MDNBR values are chosen**



Uncertainty adjusted COLSS MDNBR Calculation

▪ DNBR margin increment by case

- The results in parenthesis are nominal value

CASE	APD	HPD	MDNBR	Rel. Margin Increment	CHF [BTU/ft^2-sec]	HHF [BTU/ft^2-sec]
1	$GMDH_A$	$GMDH_H$	2.3150 (2.3457)	13.10% (14.60%)	250.39 (250.18)	107.38 (105.03)
2	$GMDH_A$	-	2.2983 (2.3163)	12.29% (13.17%)	244.13 (244.58)	104.15 (103.53)
3	Fourier	$GMDH_H$	1.9434 (1.9686)	-5.05% (-3.82%)	204.93 (196.30)	101.47 (100.28)
4(ref)	Fourier	-	2.0468	-	187.43	84.40

▪ Computing resources (Time & memory)

Computing Resources	COLSS original (Case 4)	COLSS w. GMDH (Case 1)
Data reading time [ms]	20 ~ 25	1,300
Calculation time [ms]	1 ~ 2	5 ~ 10
Used memory [MB]	1.6	16 ~ 17

Conclusion

- **The operational margin for MDNBR, as calculated via 3-D power reconstruction GMDH, increased by 13.10%, including model uncertainty.**
- **Unlike the COLSS method, the GMDH method does not need the information of control rod positions when synthesizing power distribution.**
- **The required memory of GMDH model is about 20MB, the specification of FPGA for COLSS should match that in practical.**

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