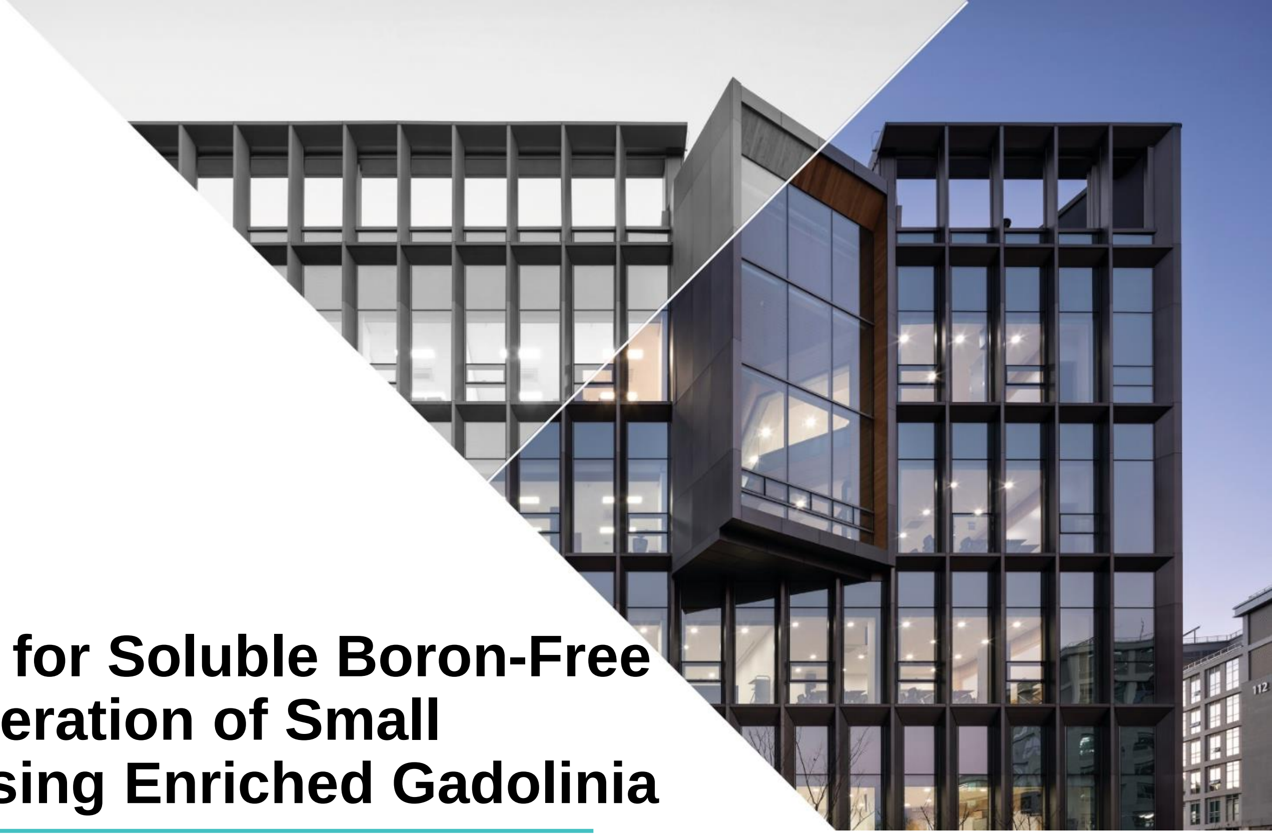

# Core Design Study for Soluble Boron-Free and Long-cycle Operation of Small Modular Reactor using Enriched Gadolinia

UNIST CORE Lab.

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- **Conclusion**
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# Introduction

## -Computation code system
## -Single pin-cell calculation

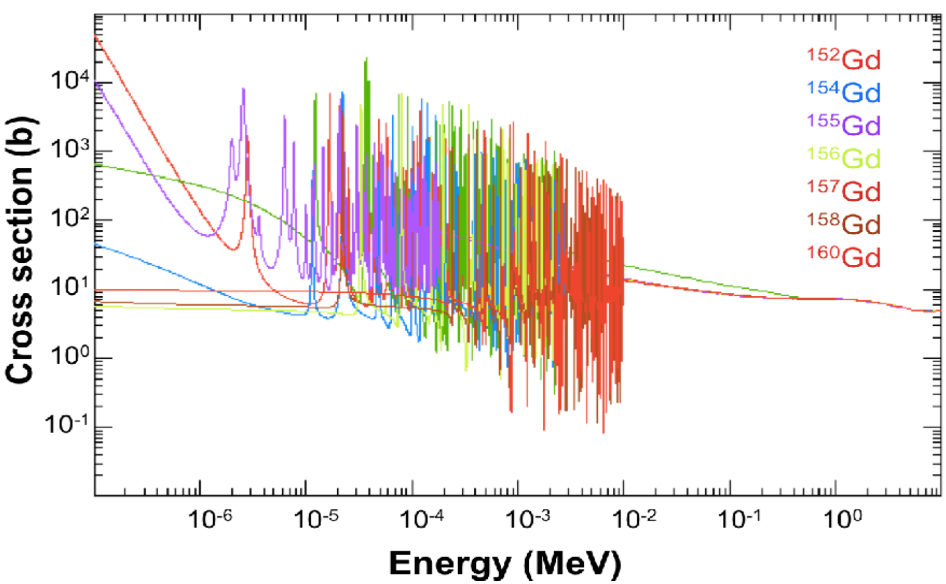
# Introduction

- **Small modular reactors(SMRs)**
  - **Carbon neutrality, safety and flexibility**
- **Soluble boron-free (SBF) operation**
  - **Elimination of the CVCS**
  - **Simplification of the reactor design**
  - **More negative MTC**
  - **Increased use of burnable absorbers and control rods**
- **Burnable absorbers (CSBA, CIMBA, and HIGA)**
  - **Thermal property issue**
  - **Manufacturing and regulatory challenges**

**→Enriched gadolinia**
  - **Solution for SBF and long-cycle operation**

# Introduction

- **Gadolinia ($UO_2$-$Gd_2O_3$)**
  - **Large thermal neutron absorption XS**
  - **Commercial nuclear power plants**
  - **High melting point (2,693 K)**
  - **Thermal property issue**
    - Increasing content of $Gd_2O_3$




| Isotope | Natural isotopic abundance (%) | Absorption XS (barns) |
|---|---|---|
| Gd-152 | 0.20 | 10 |
| Gd-154 | 2.18 | 80 |
| **Gd-155** | **14.80** | **61,000** |
| Gd-156 | 20.47 | 2 |
| **Gd-157** | **15.65** | **255,000** |
| Gd-158 | 24.84 | 2.4 |
| Gd-160 | 21.86 | 0.8 |

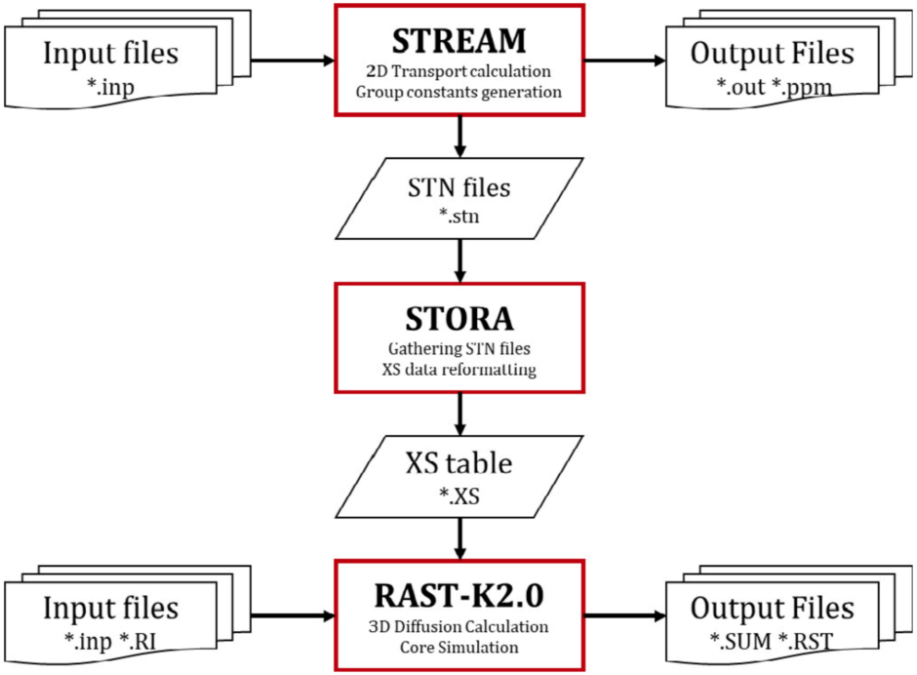
# Computation code system developed by UNIST CORE

## ▪ STREAM

- Neutron transport analysis code
- 2D lattice physics code
- Group constants generation
- Method of characteristics (MOC)

## ▪ RAST-K

- Neutron diffusion analysis code
- Unified nodal method (UNM)
- Multi-group coarse mesh finite difference (CMFD) acceleration

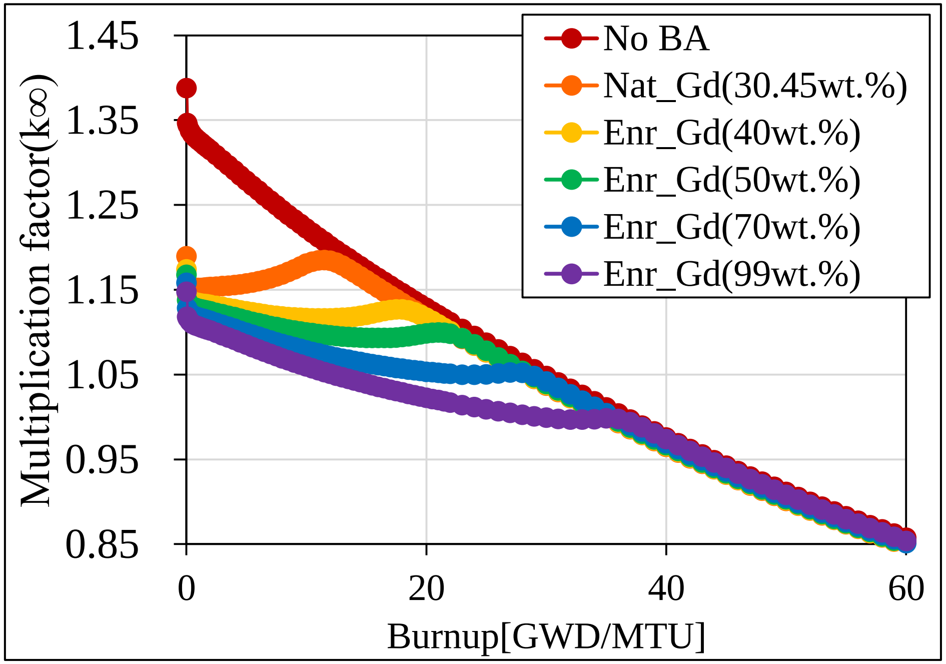



**Flowchart of STREAM/RAST-K 2.0 code system**

# Enriched gadolinia calculation with STREAM

## ▪ Single pin-cell gadolinia calculation

- **Gadolinia($Gd_2O_3$) content is limited to 6-8 wt.% in commercial reactor**
- **Different enrichment levels were tested, with a maximum content of 8 wt.%**

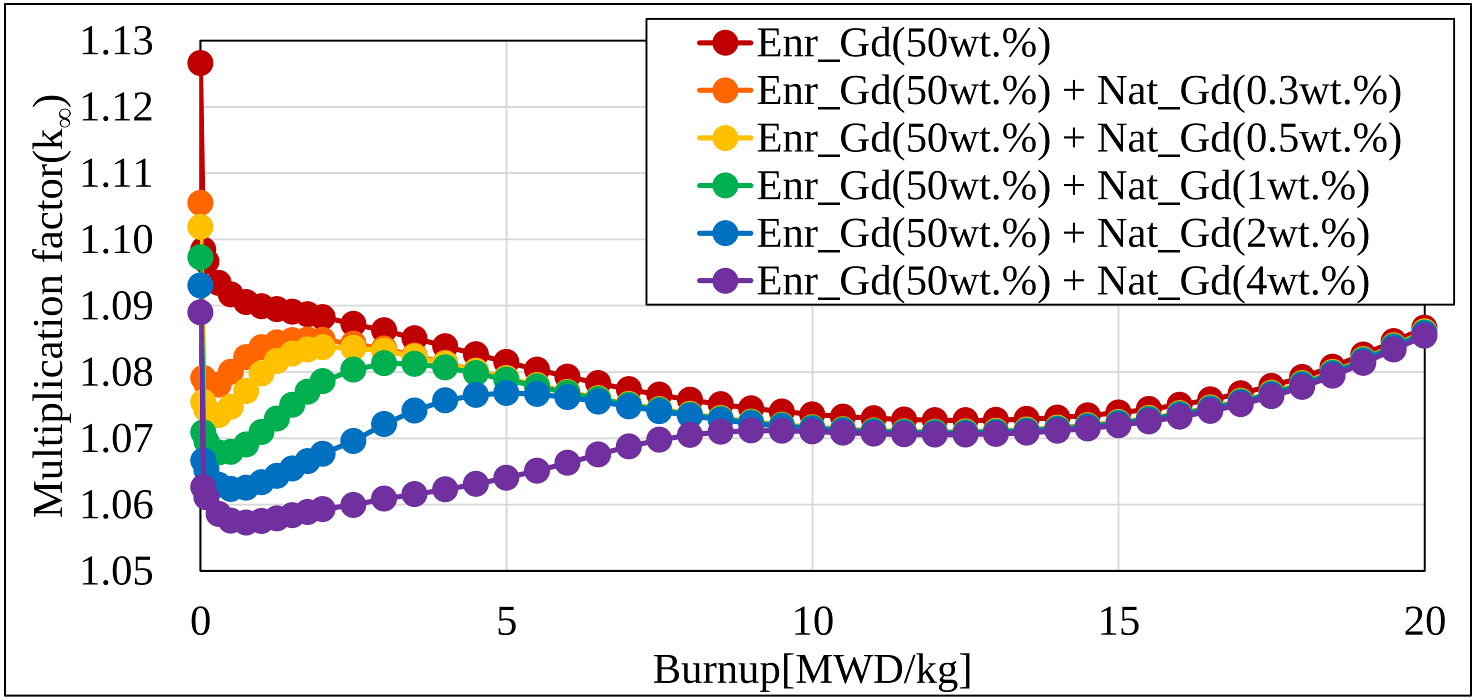



**Comparison of $k_\infty$ for various gadolinia enrichment**

| Isotope | Abundance (%) | | | | | |
|---|---|---|---|---|---|---|
| Gd-152 | 0.20 | 0.17 | 0.14 | 0.11 | 0.09 | 0.00 |
| Gd-154 | 2.18 | 1.88 | 1.57 | 1.22 | 0.94 | 0.03 |
| **Gd-155** | 14.80 | 19.44 | 24.30 | 28.97 | 34.02 | 48.12 |
| Gd-156 | 20.47 | 17.66 | 14.72 | 11.63 | 8.83 | 0.29 |
| **Gd-157** | 15.65 | 20.56 | 25.70 | 31.03 | 35.98 | 50.88 |
| Gd-158 | 24.84 | 21.43 | 17.86 | 14.30 | 10.71 | 0.36 |
| Gd-160 | 21.86 | 18.86 | 15.72 | 12.74 | 9.43 | 0.31 |
| Sum of $^{155,157}Gd$ | 30.45 | 40 | 50 | 60 | 70 | 99 |

# Enriched + natural gadolinia calculation with STREAM

- **Only enriched gadolinia**
  - **Difficult to control high excess reactivity at BOC**
- **Mix of enriched gadolinia and low-content natural gadolinia**
  - **Combined with 0.3 ~ 4 wt.% content of natural gadolinia**




**Comparison of $k_\infty$ for various natural gadolinia contents**

# Core design

**-Core design parameter**
**-Fuel assembly design**
**-Core design**

# Core design parameter

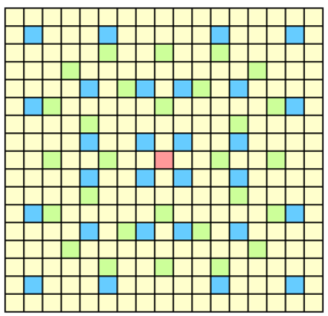
| Parameter | Value |
|---|---|
| Thermal power | $520MW_{th}$ |
| Number of FAs | 69 |
| Fuel enrichment | < 4.95 wt.% $^{235}U$ |
| Control rod material | AIC |
| Reflector material | Stainless steel |
| Active fuel height | 240 cm |
| Total loading | 21.613 MTU |
| Multiplication factor ($k_{eff}$) | $1.005 < k_{eff} < 1.015$ |
| 3D pin peaking factor ($F_q$) | $F_q < 2.5$ |
| Axial Shape Index (ASI) | -0.4 < ASI < +0.4 |
| Isothermal temperature coefficient | ITC < 0 pcm/˚C |
| Shutdown margin | SDM > 3000 pcm |
| Target cycle length | ~30 months |

- **SDM limit was determined based on the mPower reactor design**
  - **Geometries (17 × 17 square-type assemblies)**
  - **Uranium enrichment (< 5 wt.%)**
  - **Active core height of 200 cm**

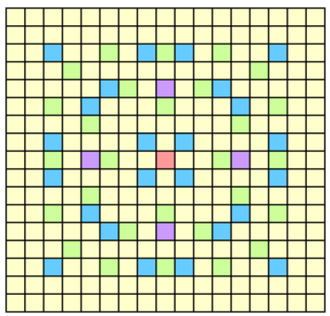
# Fuel assembly design

- **Use of many CRs to manage excess reactivity**
  - **Power concentration at the bottom of the core**
  - **Leading to higher ASI and axial asymmetry**

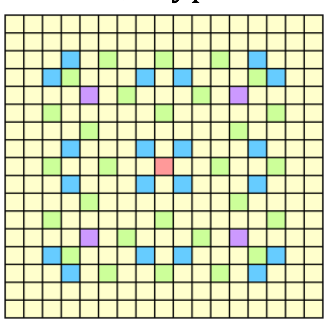
- **Maximizing the use of BA rods to manage excess reactivity**
  - **Difference of maximum and minimum within 5,000 pcm**



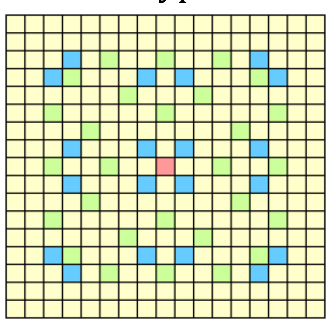
A,C type



B type



D type



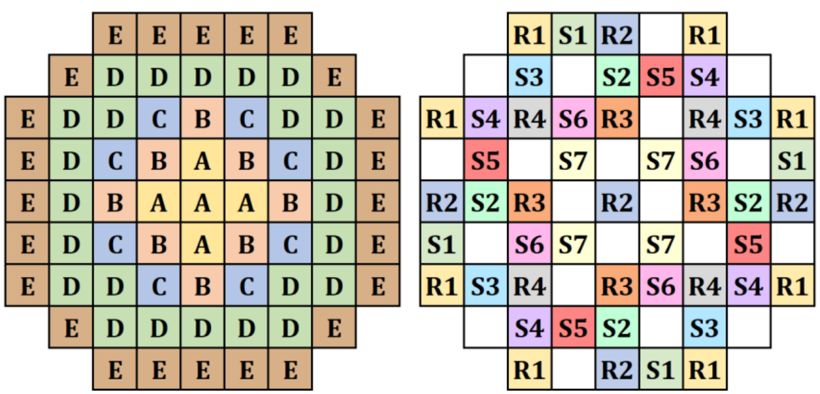
E type

| | |
|---|---|
| (yellow) | $UO_2$ pin |
| (red) | Instrumentation tube |
| (green) | Guide tube |
| (blue) | Enriched gadolinia pin ($UO_2$-$Gd_2O_3$) |
| (purple) | Natural gadolinia pin ($UO_2$-$Gd_2O_3$) |

| Fuel type | A | B | C | D | E |
|---|---|---|---|---|---|
| $^{235}$U enrichment [wt.%] | 4 | 4 | 4 | 4.5 | 4.95 |
| Number of gadolinia pin (Enriched + Natural) | 28 | 24+4 | 28 | 20+4 | 20 |
| $^{155,157}$Gd enrichment [wt.%] | 70 | 70 | 70 | 50 | 70 |
| Content of natural gadolinia [wt.%] | - | 4 | - | 2 | - |
| $^{235}$U in $UO_2$-$Gd_2O_3$ [wt.%] | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 |

# Fuel assembly design

- **Core design**
  - **Homogeneous axial composition**
  - **Fuel with a multiplication factor less than unity was used in the center**
  - **Higher $^{235}U$ enrichment was used in peripheral regions**
  - **Ag-In-Cd is used in regulating banks to minimize the impact of control rod burnup**
  - **$B_4C$ is used in shutdown banks to enhance the shutdown margin**



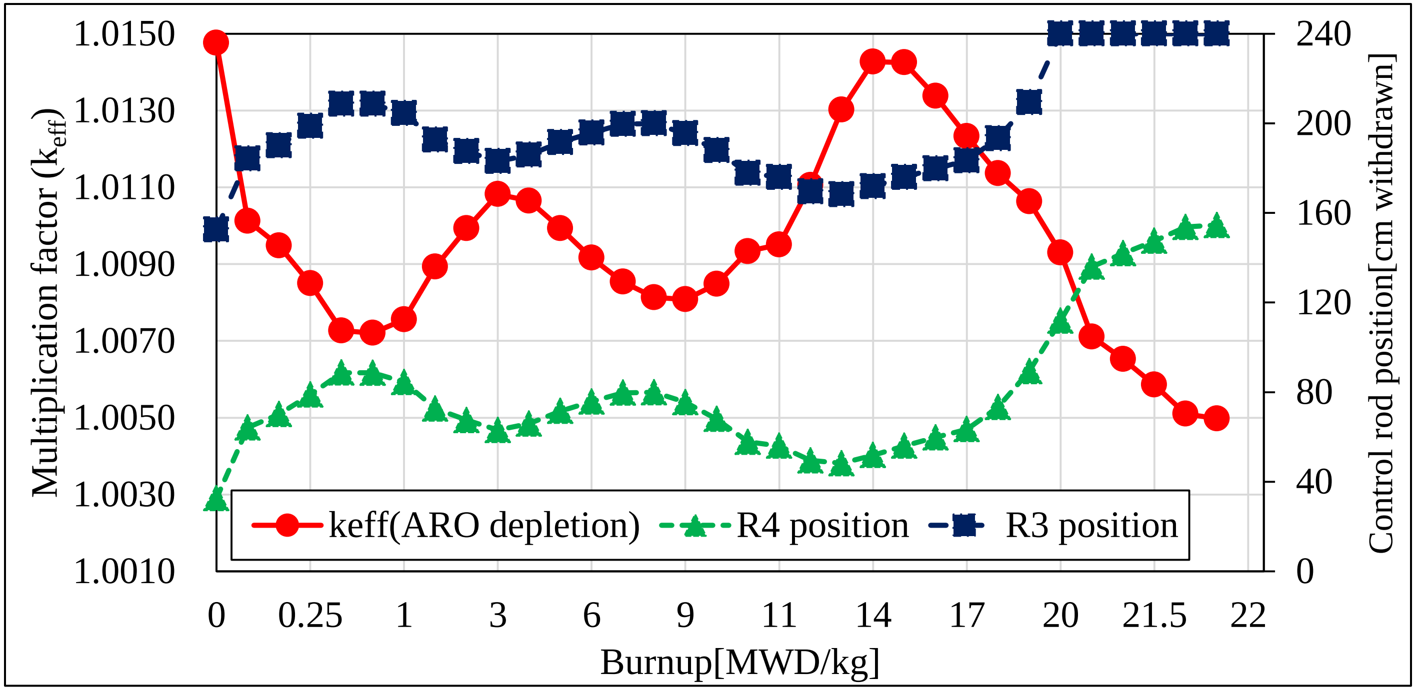

**Loading pattern and control rod pattern**

| Fuel type | A | B | C | D | E |
|---|---|---|---|---|---|
| $^{235}U$ enrichment [wt.%] | 4 | 4 | 4 | 4.5 | 4.95 |
| Number of gadolinia pin (Enriched + Natural) | 28 | 24+4 | 28 | 20+4 | 20 |
| $^{155,157}Gd$ enrichment [wt.%] | 70 | 70 | 70 | 50 | 70 |
| Content of natural gadolinia [wt.%] | - | 4 | - | 2 | - |
| $^{235}U$ in $UO_2$-$Gd_2O_3$ [wt.%] | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 |

# Numerical results

# Numerical results

- **Effective multiplication factor ($k_{eff}$)**
  - **ARO depletion state and critical positions of regulating banks**
  - **1.005 < $k_{eff}$ < 1.015**
  - **Discharging burnup of 21.8 MWd/kg**
  - **Long-cycle operation goal of 30 months**




**$k_{eff}$ and critical control rod position from core depletion calculation**

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# Numerical results

- **Axial shape index (ASI) and 3D pin peaking factor ($F_q$)**
  - **ARO depletion and rod operation states**
  - **-0.35 < ASI < +0.35 / $F_q$ < 2.5**
  - **Power concentration increased at the bottom during rod operation**


**Axial shape index (ASI) and 3D pin peaking factor ($F_q$)**

# Numerical results

## ▪ Radial and Axial power distribution

- **Maximum control rod insertion at BOC**
- **Core's central region with low-enrichment fuel**
- **Regulating banks R4 and R3 were withdrawn from the bottom of the core by 32.59 cm and 152.59 cm, respectively**
- **Power in R4 decreased by 31.3%, while R3 showed a 1.9% decrease**

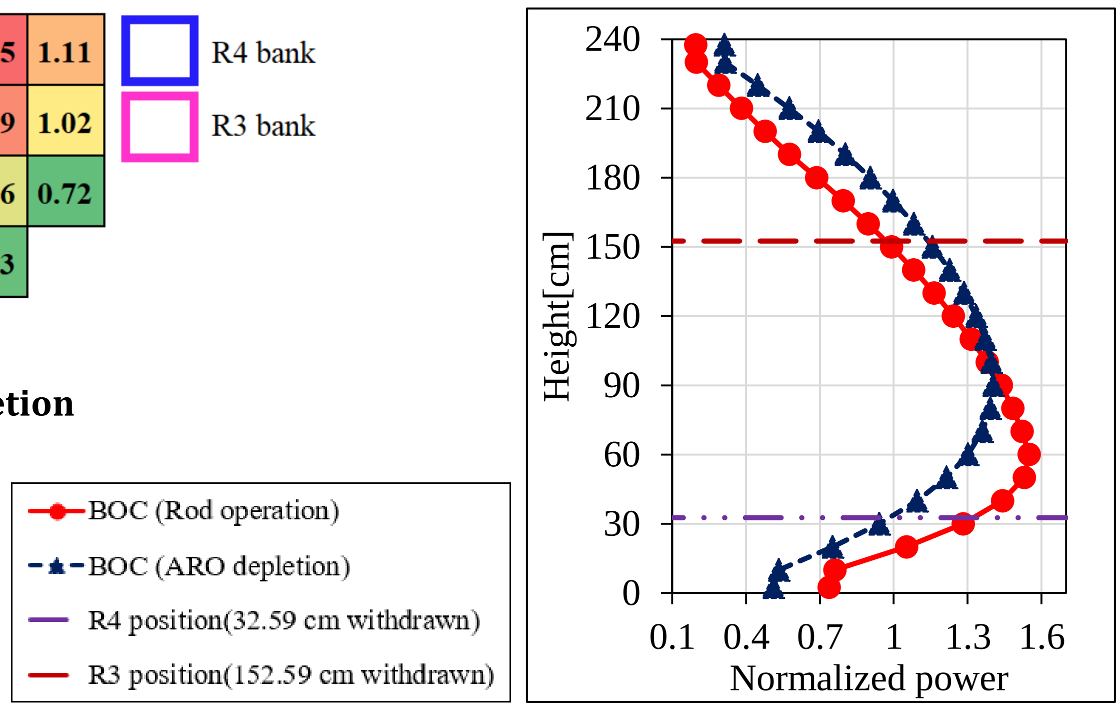
| | | | | |
|---|---|---|---|---|
| 0.91 | 0.96 | 1.05 | 1.19 | 1.00 |
| 0.96 | 0.98 | 1.14 | 1.15 | 0.94 |
| 1.05 | 1.14 | 1.15 | 1.01 | 0.68 |
| 1.19 | 1.15 | 1.01 | 0.76 | |
| 1.00 | 0.94 | 0.68 | | |

| | | | | |
|---|---|---|---|---|
| 0.97 | 1.00 | 1.03 | 1.25 | 1.11 |
| 1.00 | 0.99 | 1.10 | 1.19 | 1.02 |
| 1.03 | 1.10 | 0.79 | 0.96 | 0.72 |
| 1.25 | 1.19 | 0.96 | 0.73 | |
| 1.11 | 1.02 | 0.72 | | |

R4 bank

R3 bank

**Radial power distribution in ARO depletion and rod operation states at BOC**

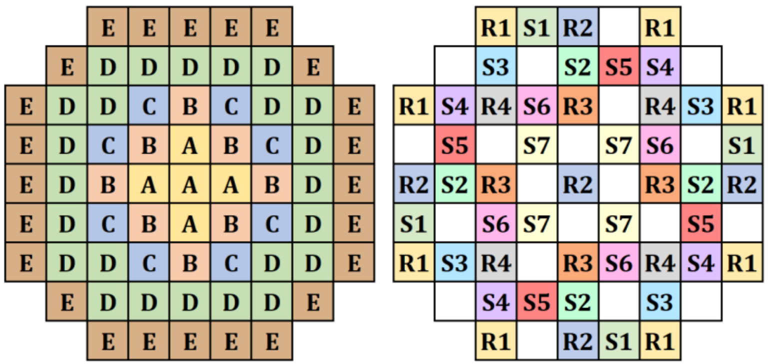



**Axial power distribution at BOC**

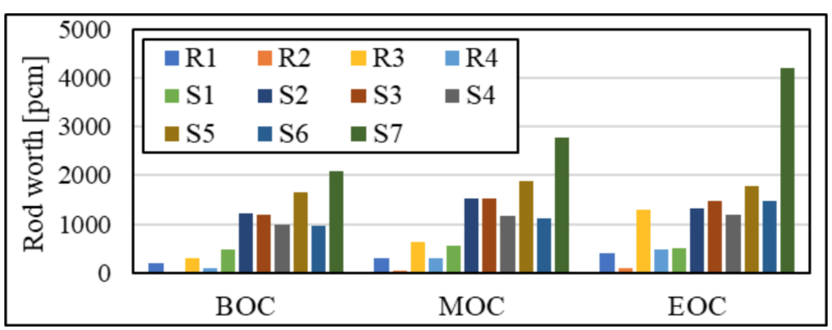
# Shutdown margin and reactivity coefficients calculation

- **HFP → HZP →CZP**
  - **Positive reactivity**

  **(Power defect, xenon burnout, Doppler effect and isothermal defect)**




**Loading pattern and control rod pattern**




**Rod worth by location of regulating & shutdown bank**

| State | BOC [pcm] | MOC [pcm] | EOC [pcm] |
|---|---|---|---|
| All-rod-in worth (1) | 31,466 | 33,319 | 34,894 |
| Worth of worst stuck rod (2) | 2,080 | 2,764 | 4,294 |
| Uncertainty of rod worth (3) = (1) * 10% | 3,146 | 3,331 | 3,489 |
| Rod worth for criticality (4) | 1,455 | 925 | 495 |
| Engineering error (5) | 100 | 100 | 100 |
| Real worth (6) = (1) – [(5) + (4) + (3) + (2)] | 24,685 | 26,199 | 26,516 |
| Power defect from HFP (EQ xenon) to HZP (NO xenon) (7) | 3,796 | 4,013 | 4,510 |
| Isothermal defect (8) (HZP to CZP) | 7,599 | 4,833 | 5,356 |
| Engineering error (9) | 100 | 100 | 100 |
| Total defect (10) = (7) + (8) + (9) | 11,495 | 9,846 | 9,966 |
| Shutdown margin (11) = (6) – (10) | 13,190 | 17,253 | 16,550 |

| CASE | EFPD [day] | Xe | Sm | State | FTC [pcm/°C] | MTC [pcm/°C] | ITC [pcm/°C] |
|---|---|---|---|---|---|---|---|
| BOC | 0 | EQ | TR | HFP | -2.62 | -56.68 | -59.60 |
| | | NO | NO | HZP | -3.02 | -57.01 | -60.03 |
| | | NO | NO | CZP | -3.24 | -12.31 | -15.56 |
| MOC | 451 | EQ | TR | HFP | -2.86 | -53.06 | -54.99 |
| | | NO | NO | HZP | -3.47 | -52.62 | -56.09 |
| | | NO | NO | CZP | -3.57 | -7.43 | -11.00 |
| EOC | 901 | EQ | TR | HFP | -3.17 | -54.99 | -58.16 |
| | | NO | NO | HZP | -3.80 | -53.82 | -57.62 |
| | | NO | NO | CZP | -3.85 | -3.52 | -7.37 |

# Conclusion

# Conclusion

- **Enriched gadolinia**
  - **SBF and long-cycle operation without new burnable absorber**
  - **Thermal conductivity**
  - **With low-content natural gadolinia flattens the reactivity curve**
  - **Discharging burnup of 21.8 MWD/kg over a 30 months**

- **Core design**
  - **Homogeneous axial composition**
  - **Effective multiplication factor : $1.005 < k_{eff} < 1.015$**
  - **Peaking factor : $F_q < 2.5$**
  - **Axial shape index : $-0.35 < ASI < +0.35$**
  - **Shut down margin : SDM > 3,000 pcm**
  - **Isothermal temperature coefficient : ITC < 0 pcm/°C at all condition**

# Conclusion

- **Future work**
  - **Optimization of the number/location/enrichment of gadolinia rods**
  - **Improvement in reactor core loading pattern**
  - **Improvement in control rod pattern**
  - **Use of LEU+**
  - **Investigate innovative burnable absorbers, reflectors**
  - **Economic efficiency for gadolinia enrichment**
    - Enriched gadolinia in the core's central region
    - Natural gadolinia in the core's outer region

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