



# i-SMR 혁신형 핵연료 및 무봉산운전

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장 도 익

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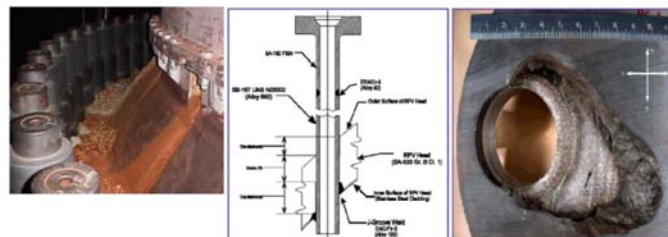
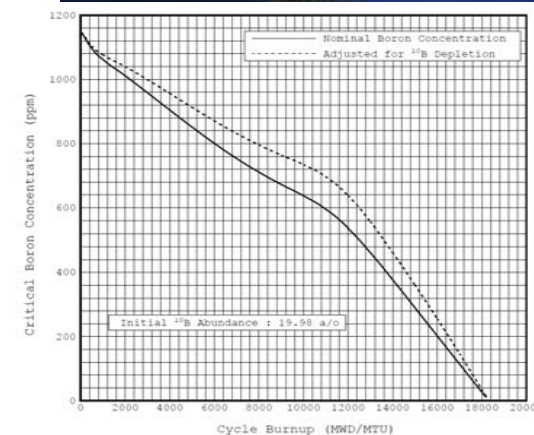
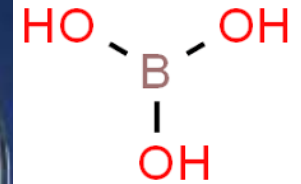
# 무봉산 운전 개요

## ● Soluble Boron is prevalent to control excess reactivity in PWR

- High absorption cross section of B-10 (3840 barn @ 0.0253 eV)
- Uniform reactivity control
- Naturally abundant
- Reduce control rod operation

## ● Soluble Boron( $H_3BO_3$ ) also has cons

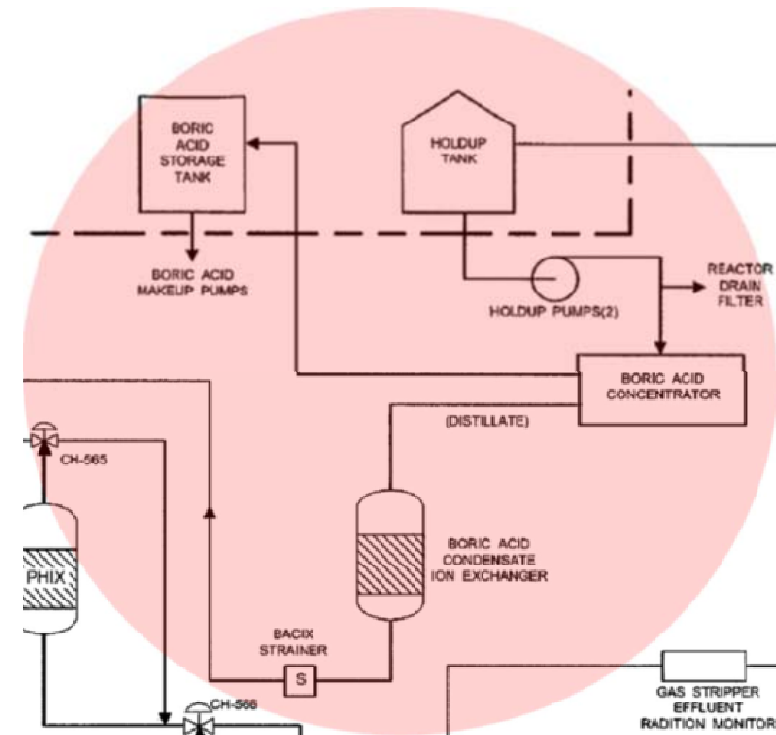
- Safety concerns of boron dilution
- Results in more positive MTC
- RCS with boric acid is more susceptible to corrosion
- Requires a large CVCS
- Crud Induced Power Shift(CIPS)



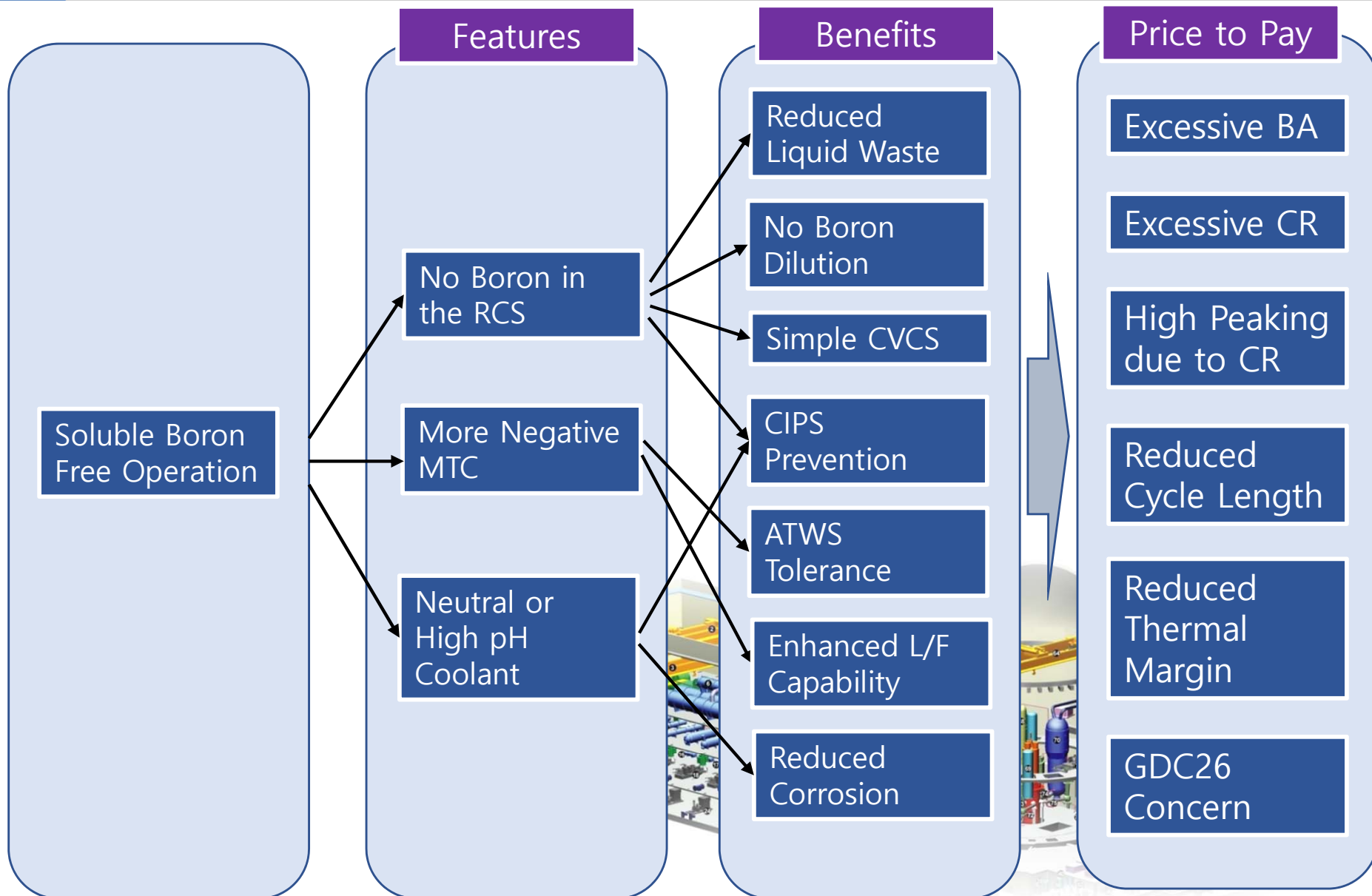
# 무봉산 운전 개요

## ● Soluble Boron Free (SBF) Operation in SMR

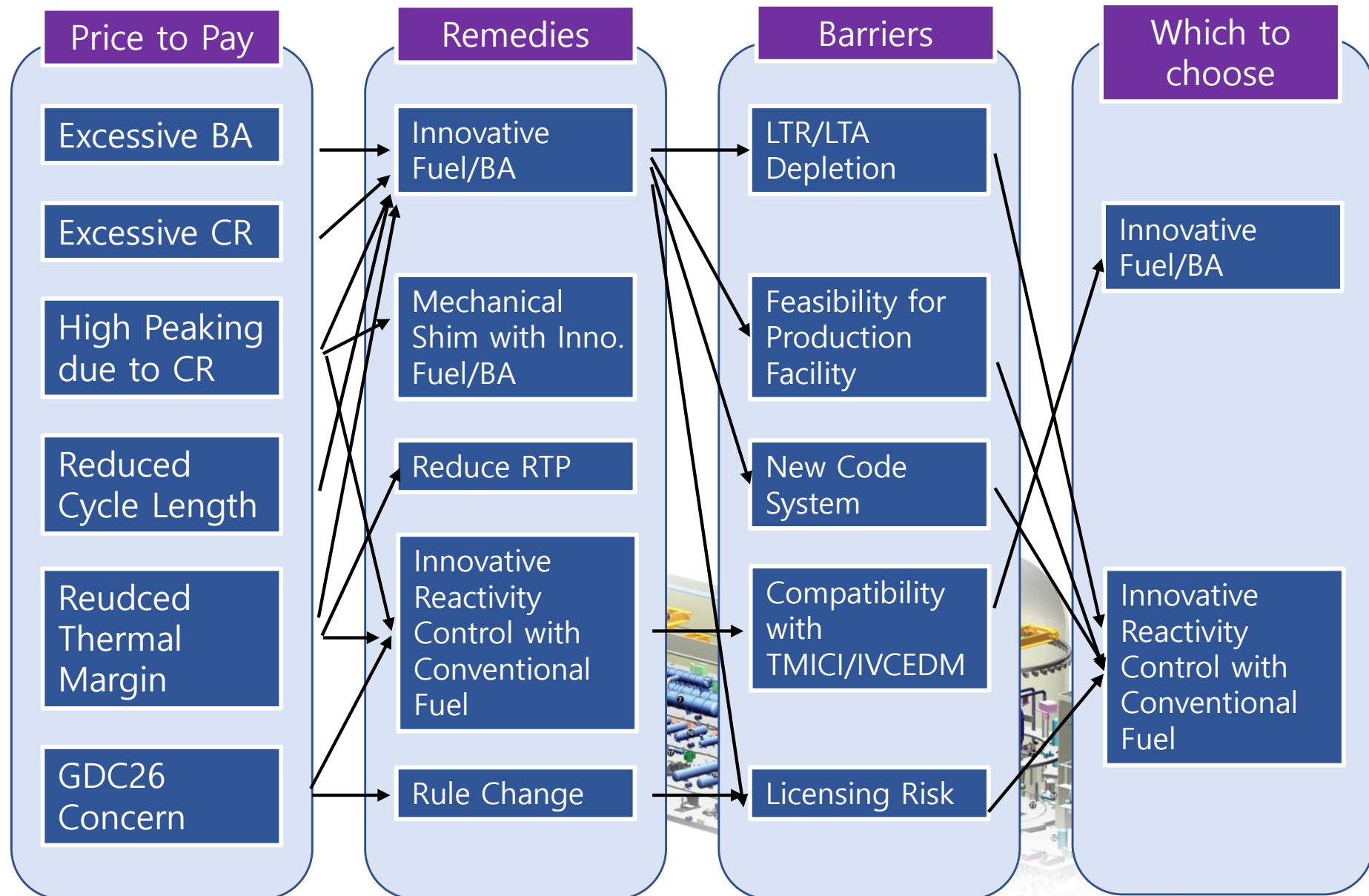
- Appropriate for smaller reactor size
  - Favorable to modular concept
  - Simple CVCS
- Enhanced Safety
  - More Negative MTC
  - Remove concerns of boron dilution transient
- Reduce operator's burden



# 무붕산 운전 요구사항

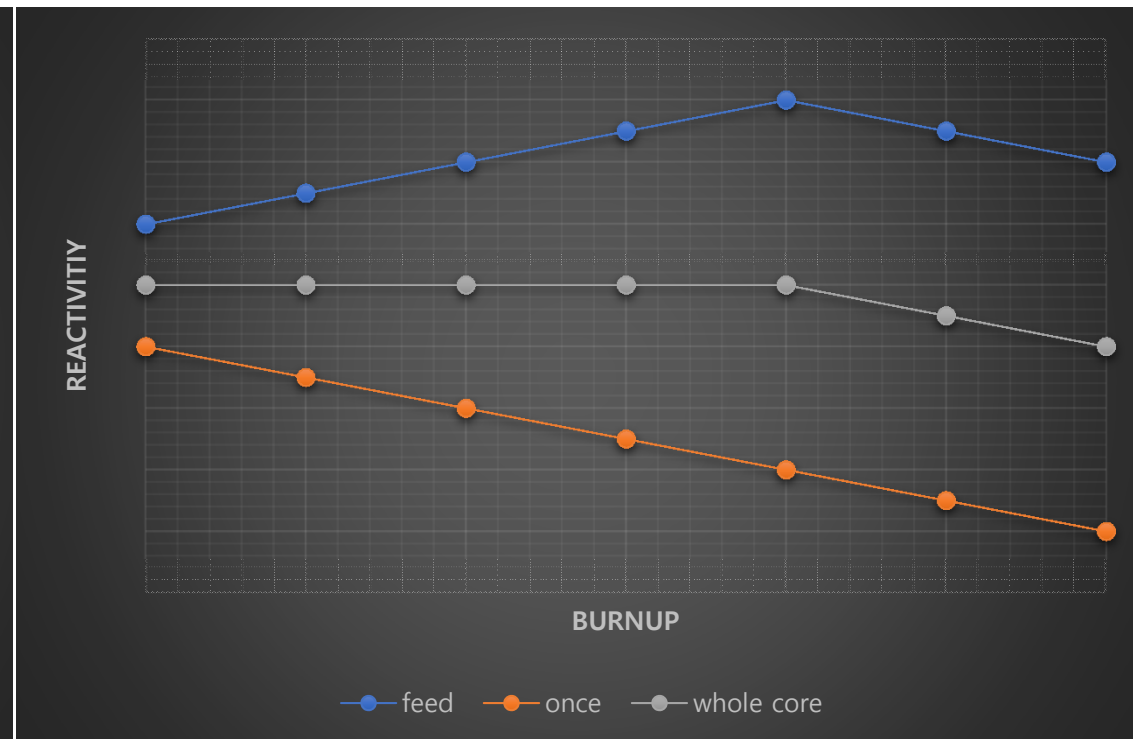


# 무봉산운전 요구사항



# 무봉산운전 요구사항

## Favorable reactivity behavior of fuel assemblies and BAs for SBF



1-Batch Core

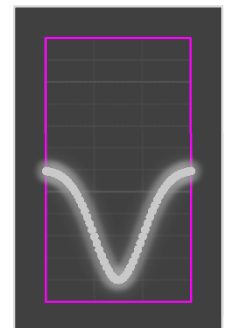


2-Batch Core

To control the speed of BA depletion is essential for SBF



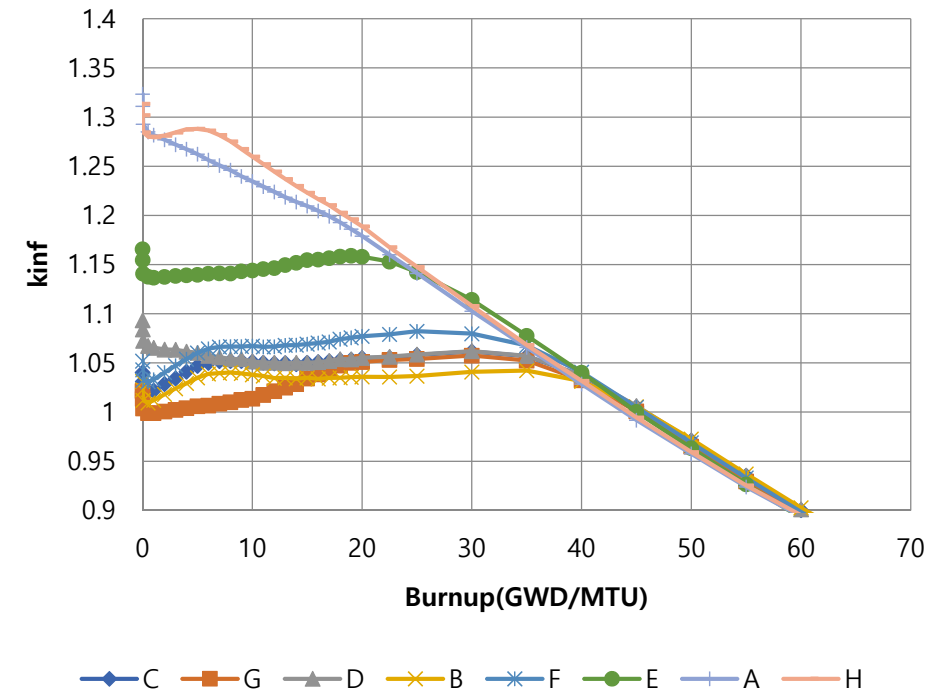
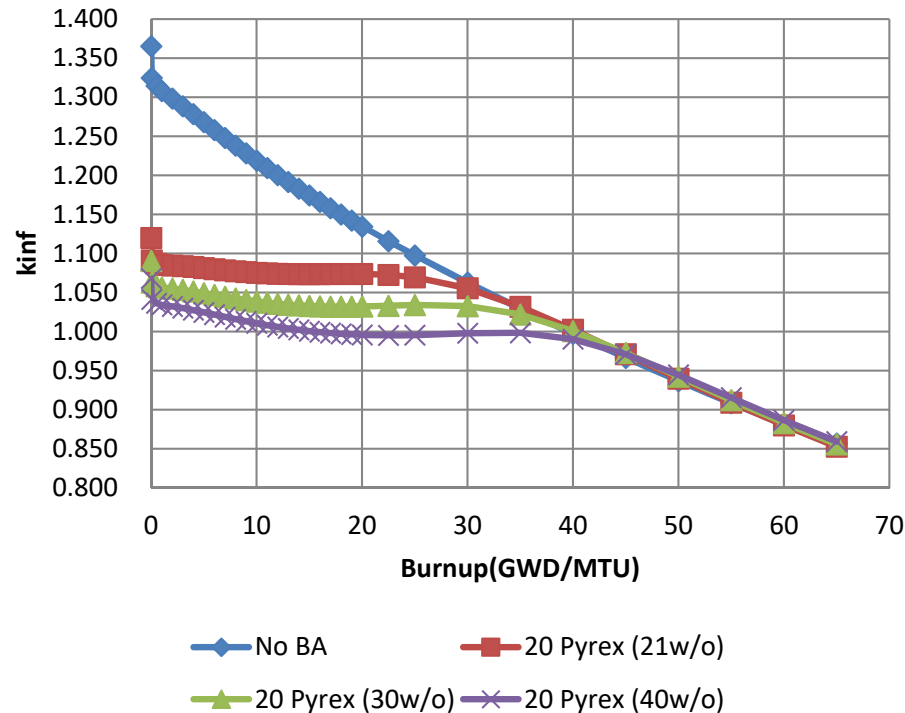
To control the self-shielding effect of BA is essential



KEPCON

# 무봉산운전요구사항

## Favorable reactivity behavior of fuel assemblies and BAs for SBF



**How to control self-shielding**



- ❖ Increase absorber material content
  - ✓ Combined BA usage (IFBA+Gd, Gd+Er)
  - ✓ Increase absorber weight percent
  - ✓ Enrich absorber isotope (B-10, Gd-155,157)
- ❖ Isolate absorber material
  - ✓ External rod (Solid BA Rod, BigT, DLBA)
  - ✓ In-fuel separation(CsBA, DiBA)



# 무봉산운전 요구사항

## ❖ Major SMR Design Comparison

Reactor	FAs	CEA No.	RCP Flow	Soluble Boron	CEDM
mPower	69	57	Forced	X	IV, Top
NuScale	37	16	Natural	O	EV, Top
SMART	57	25	Forced	O	EV, Top
SMR-160	37	37	Natural	X	EV, Top
W-SMR	89	37	Forced	O	IV, Top
BWRX-300	60	57	Natural	X	EV, Bottom
i-SMR	69	49~61	Forced	X	IV, Top

## ❖ SBF operation requires a large portion of CEA in the core

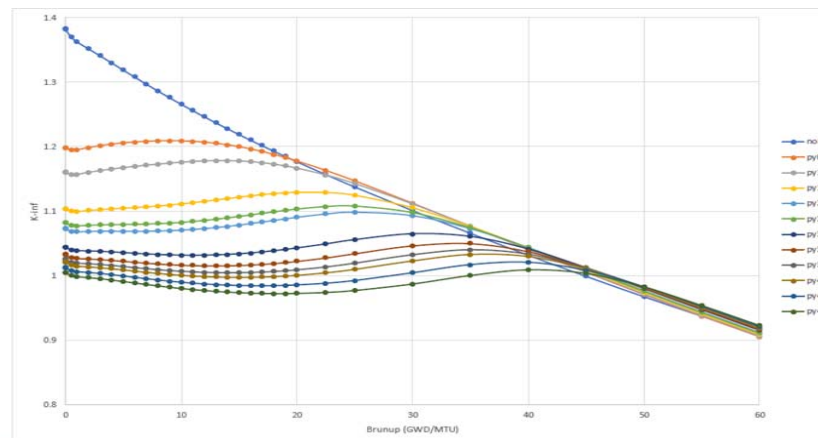
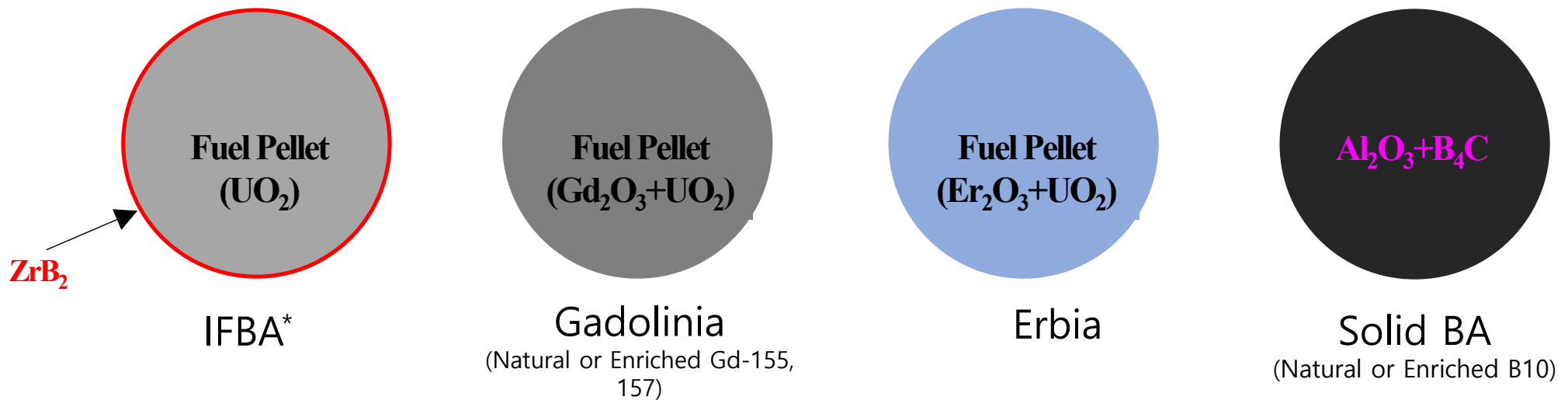
- ✓ Excess reactivity control using CEA
- ✓ Increase in control rod requirement due to absence of boron and more negative MTC throughout a cycle

## ❖ Excessive number of IV-CEDM causes undesirable flow restriction

## ❖ TMICI requires a reasonable number of unrodded FAs depending on ICI location

# 무봉산운전 가연성흡수봉

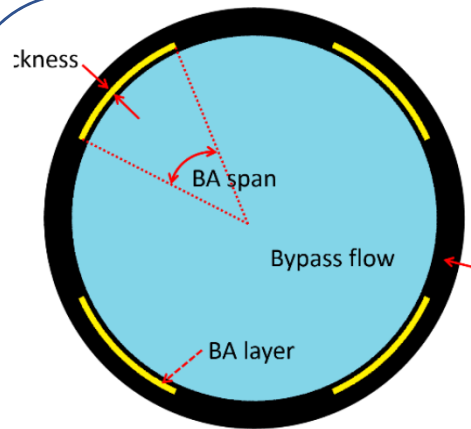
- Conventional (Proven) burnable absorber for SBF



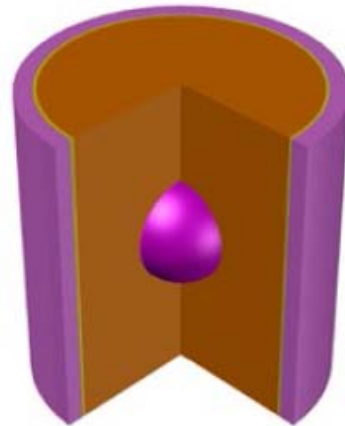
\*WEC proprietary

# 무봉산운전 가연성흡수봉

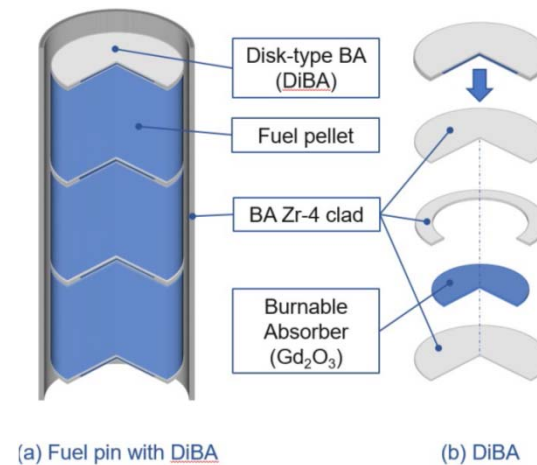
## Novel burnable absorber design for SBF



BigT-fAHR



CsBA

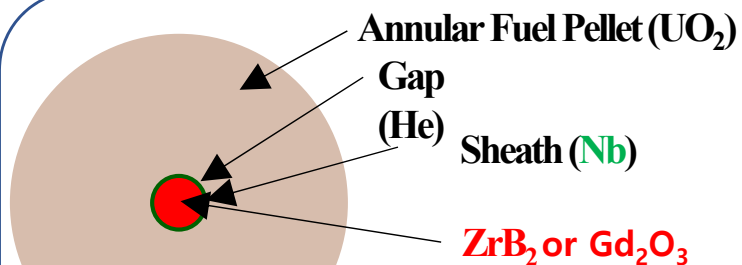


(a) Fuel pin with DiBA

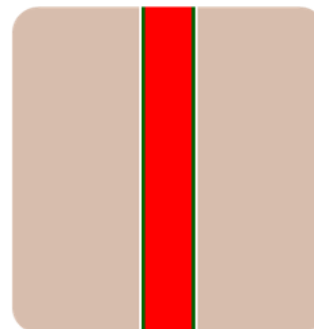
(b) DiBA

DiBA

KAIST

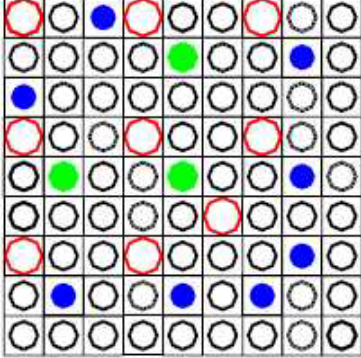
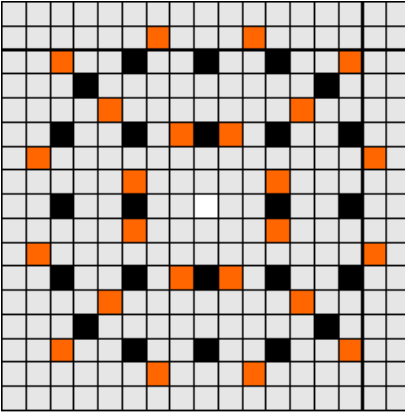
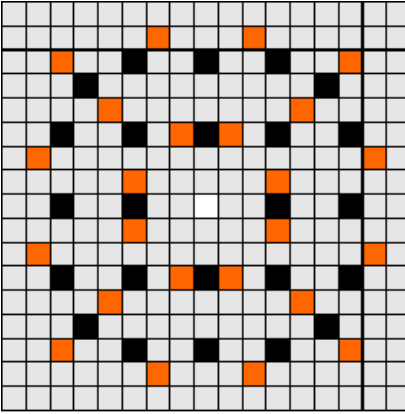
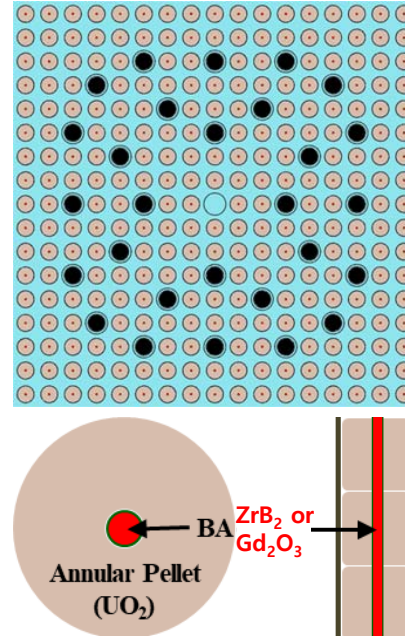
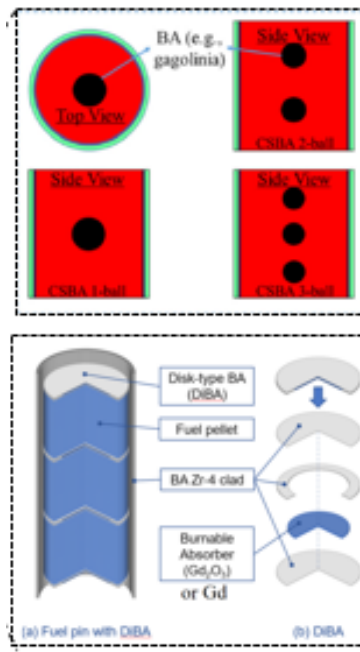


CIMBA



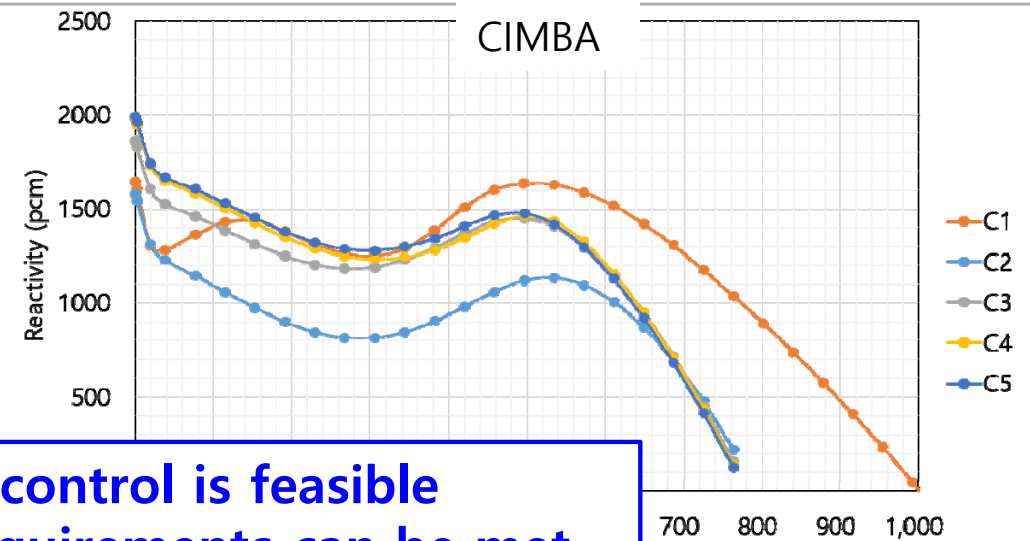
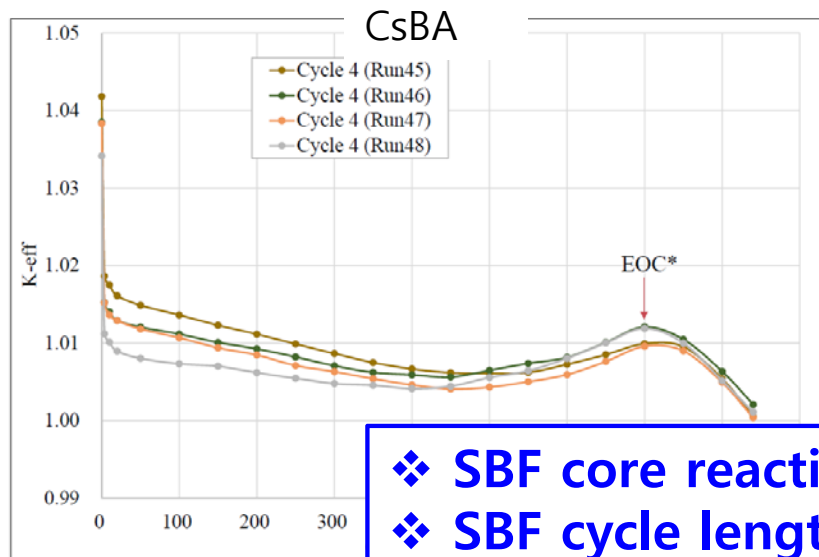
CRI

# 무봉산운전 가연성흡수봉

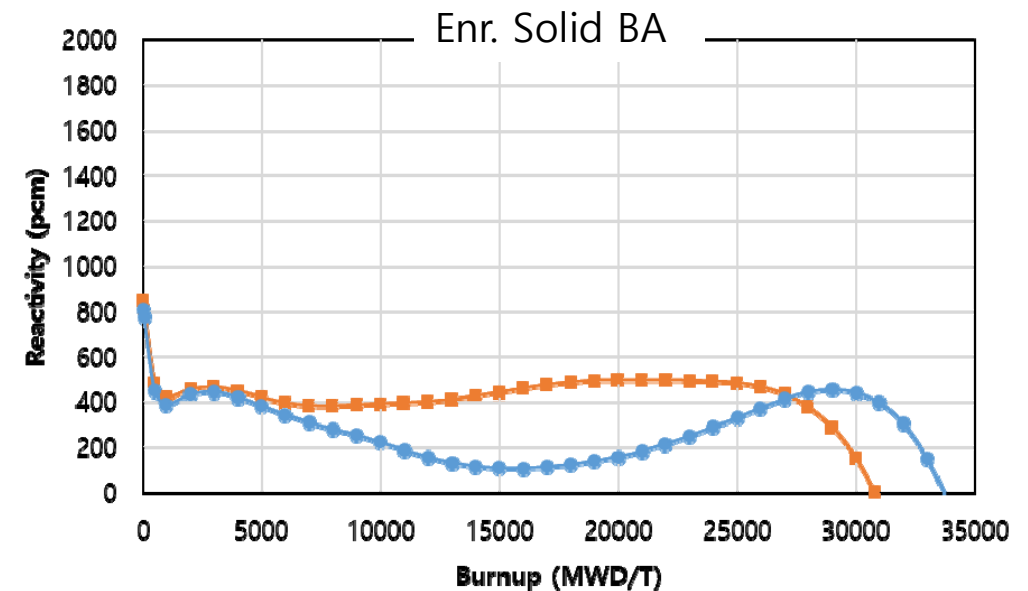
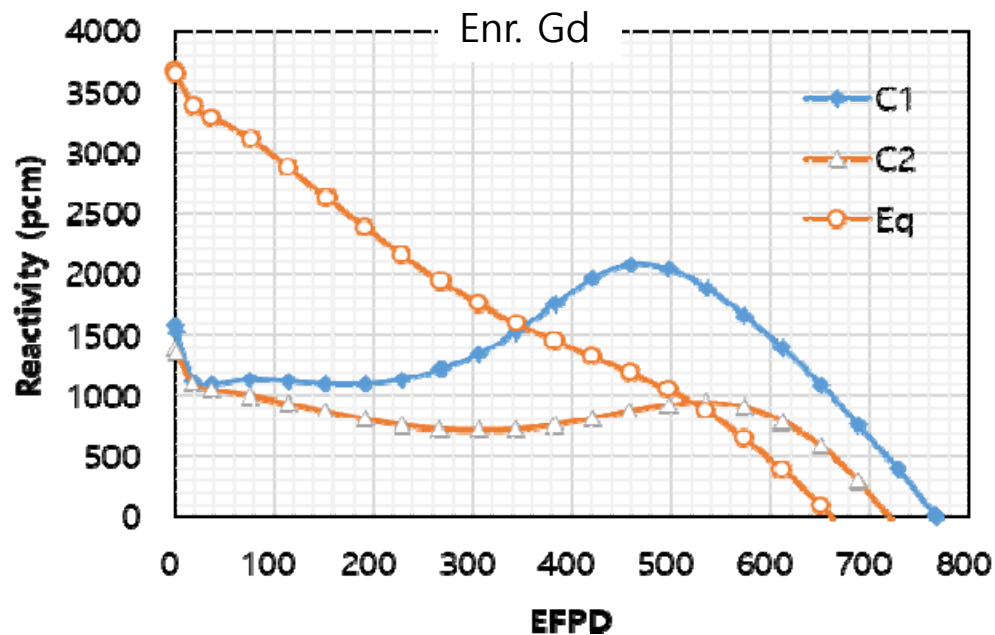
	Solid BA	Enriched Gadolinia	CIMBA*-ZrB <sub>2</sub> /Gd <sub>2</sub> O <sub>3</sub>	CsBA & DiBA
Concept	 			
Features	<ul style="list-style-type: none"> <li>▪ U-Loading ↓ (8%)</li> <li>▪ Peaking Factor ↑ (20%)</li> <li>▪ Large Negative MTC(HFP)</li> <li>▪ Commercial Applicability - Easy</li> </ul>	<ul style="list-style-type: none"> <li>▪ Enriched Gd155,157</li> <li>▪ Peaking Factor ↑ (20%)</li> <li>▪ Less Negative MTC(HFP)</li> <li>▪ Commercial Applicability - Easy</li> </ul>	<ul style="list-style-type: none"> <li>▪ Fuel Centerline Temp ↓</li> <li>▪ Low Peaking Factor</li> <li>▪ Large Negative MTC(HFP)</li> <li>▪ Commercial Applicability - Medium</li> </ul>	<ul style="list-style-type: none"> <li>▪ Fuel Centerline Temp ↓</li> <li>▪ Low Peaking Factor</li> <li>▪ Less Negative MTC(HFP)</li> <li>▪ Commercial Applicability - Difficult</li> </ul>

\* CIMBA utilizes proven technology of annular pellets in WEC plants and VVER and its fabrication technology is based on ICI manufacturing and a test product has been built to verify its mass production recently

# 무봉산운전 가연성흡수봉



- ❖ SBF core reactivity control is feasible
- ❖ SBF cycle length requirements can be met

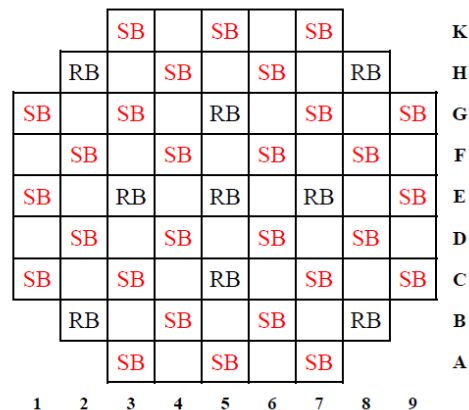




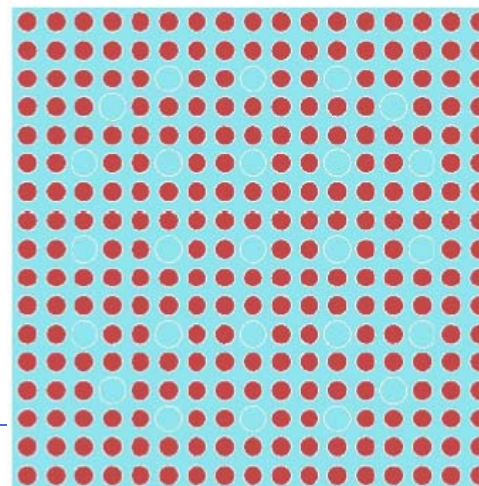
# 무봉산운전 핵연료집합체

- Conventional fuel is also available for SBF operation with enhanced performance characteristics to meet thermal margin and mechanical compatibility
- TOP fuel is proposed in KAIST to reduce required CEAs for SBF
  - To increase H/U ratio, increase the pin pitch or decrease the fuel rod diameter
  - Better neutron economy
  - Less negative MTC enables reduced SDM requirement
  - Checker-board CEA pattern is feasible
  - Long-term approach is necessary

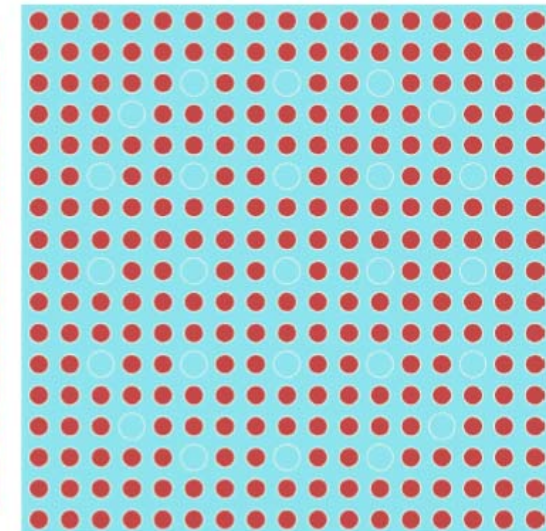
TOP CEA	
CEA No.	37 (Checker-board)
CEA Mat.	SS or Mn+B4C(enriched B-10)
CEA Finger	24/33



1.26 cm of pin pitch  
0.41 cm of fuel radius



1.40 cm of pin pitch  
0.41 cm of fuel radius



\*TOP: Truly Optimized PWR (TOP) lattice design

# 무봉산운전 2차 반응도 제어

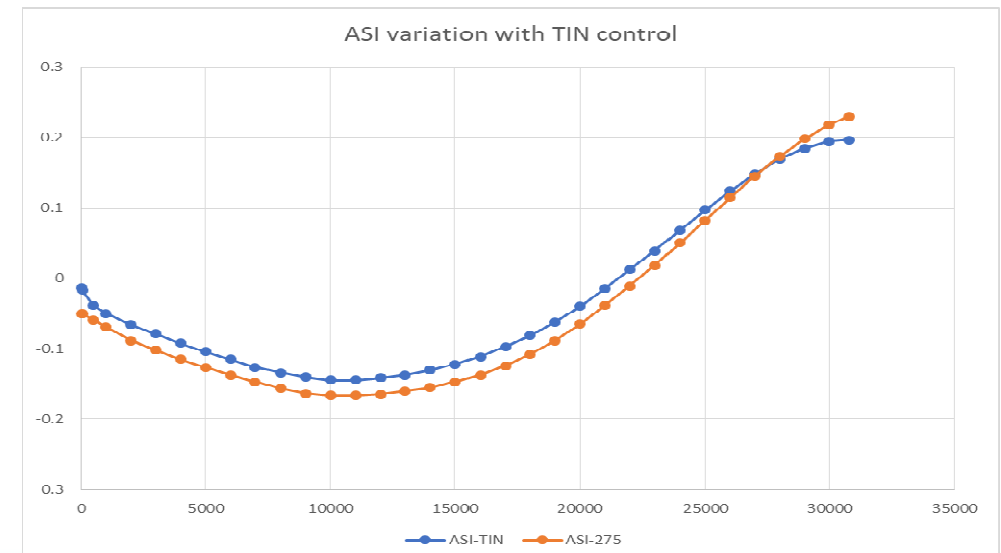
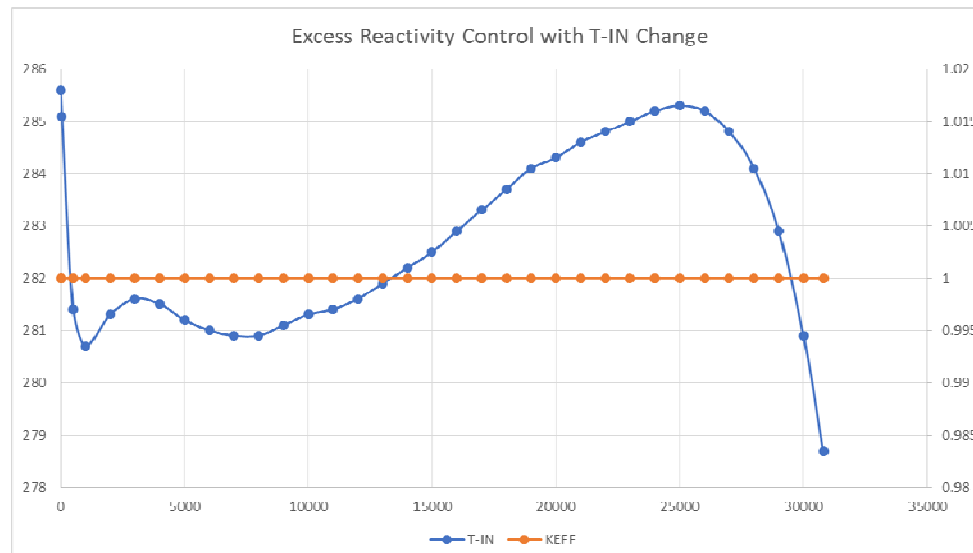
## GDC26 – RCS redundancy and capability

- Two independent reactivity control system of different design principle
- The second RCS shall be capable of reliably controlling the rate of reactivity changes resulting from planned normal power changes...



## Reactivity control with inlet temperature control is feasible

- Depletion with Inlet Temperature Control with reactivity deadband of  $\pm 20$  pcm
- Criticality can be achieved with ease
- Xenon reactivity compensation is not covered



# 무봉산운전 2차 반응도 제어

## ○ GDC 27 – Combined RCS capability

- The reactivity control systems shall be designed to have a combined capability, in conjunction with poison addition by the ECCS... (core cooling capability)



## ○ Emergency Boration System

- CAREM
- Requires boron injection and removal system
- Enhance safety during normal operation

## ○ Hydraulic CRDM

- mPower
- Loss of flow drives CRDM into the core by gravity

## ○ SLIS –Standby Liquid Injection System

- BWR

## ○ Absorber ball injection system

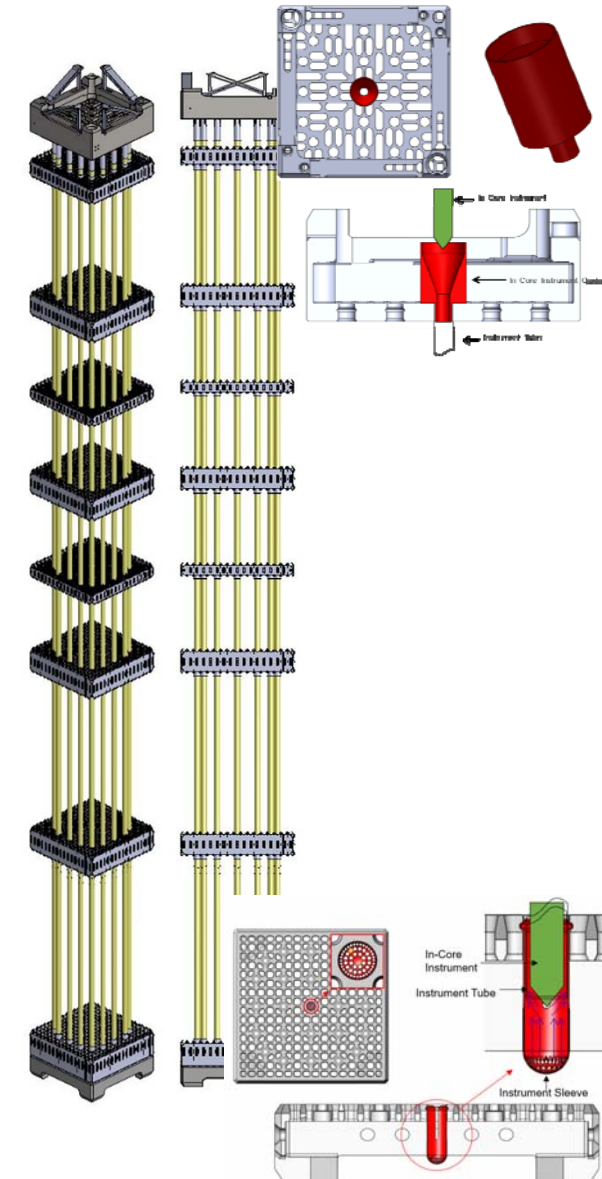
- Conceptual design
- Requires additional guide tubes for absorber balls



# i-SMR 핵연료 개요

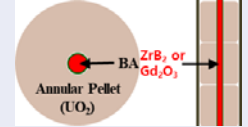
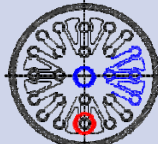
## i-SMR 핵연료 성능목표

항 목	성능목표
• 전체구조	. 2.4m 유효연료길이, 17x17 연료봉 배열, <b>TM-ICI 수용</b>
• 연소성능	. 연료봉 62 GWD/MTU (Peak Rod Burn-up)
• 열적성능	. 핵연료 열적 여유도 15%이상 확보
• 내진설계	. <b>0.5g 포괄부지 지진요건 만족</b>
• 재질	. <b>HANA-6 또는 고유소재 적용</b>
• 신뢰성	. SMART(HIPER17) 고유핵연료 설계기술 활용 . 수명말(End of Life) 특성 고려하여 설계(지지격자 등) . 내마모/고강도 부품 설계(피복관, 안내관 등)
• 내진성능	. 충격강도 향상 지지격자 . 지지격자 수량 및 위치 최적 배치 . 고강도 안내관 적용, 안내관 개수 증가, 지지격자-골격체 연결 형상 개선
• 열적여유도	. 혼합날개 형상 및 패턴 최적설계 . 중간지지격자 및 혼합지지격자 수량 및위치 최적 배치 . 고성능 피복관 및 소결체 적용



# i-SMR 핵연료 개요

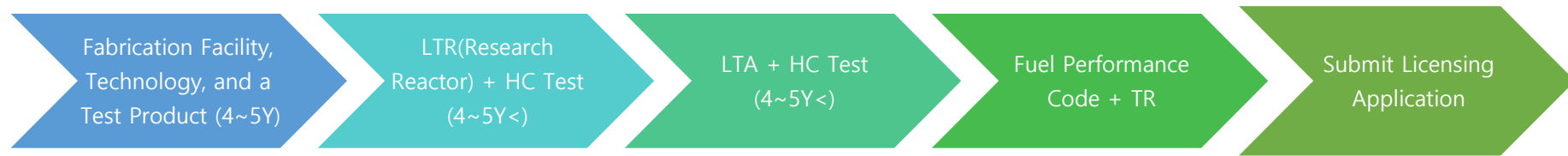
## i-SMR Burnable Absorber and CEA Design Candidates

BA type	A	B	C
Absorber Material	$Gd_2O_3 / Al_2O_3 + B_4C$	$Gd_2O_3$ (enriched Gd-155,157)	CIMBA( $ZrB_2$ or $Gd_2O_3$ ) (Variably enriched B-10)
Absorber Design	Conventional	Conventional	Novel 
ICI Location	Peripheral IT 	Central IT	Central IT
No. of CEA Availability	61	53	49
CEA Material	$AlC + B_4C$ (Natural B-10)	$AlC + B_4C$ (Enriched B-10)	$AlC + B_4C$ (Enriched B-10)
CEA finger	23	24/28(CRI)	24/28(CRI)
Licensing risk	low	Medium	Medium

# 무봉산운전 인허가 현안

## Uncertainty in licensing of novel BA pellet

- New kind of pellet requires a long period for commercial application (>15Y)
- Two-track approach is desirable for new kind of BA for early deployment of i-SMR



※ Verification for the feasibility of mass production and quality control is required

## GDC26 – RCS redundancy and capability

- Two independent reactivity control system of different design principle
- The second RCS shall be capable of reliably controlling the rate of reactivity changes resulting from planned normal power changes...

## GDC 27 – Combined RCS capability

- The reactivity control systems shall be designed to have a combined capability, in conjunction with poison addition by the ECCS... (core cooling capability)

# 요약

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- ◉ **SBF operation is a favorable option for SMR**
- ◉ **SBF core excess reactivity control is feasible through conventional or conceptual BAs**
- ◉ **For i-SMR fuel assembly, two-track approach is desirable**
  - Employment of proven technology for the early deployment of i-SMR
  - Long term approach for the development of innovative fuel assemblies or burnable absorbers
- ◉ **SBF Licensing issue should be tackled at the early stage of i-SMR design**
  - Development of PDC applicable to SMR



Thank you.

