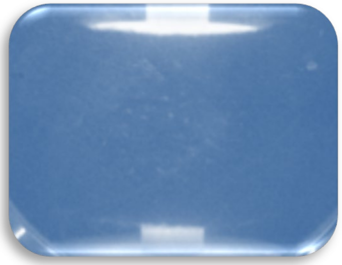
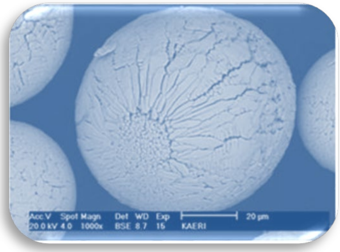
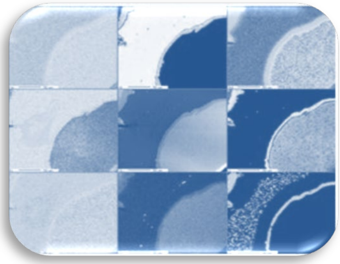
KNS 워크샵
2021. 10. 20







무붕산 운전을 위한 가연성 흡수체 핵연료 개발 및 조사시험 계획

류호진

KAIST 원자력 및 양자공학과

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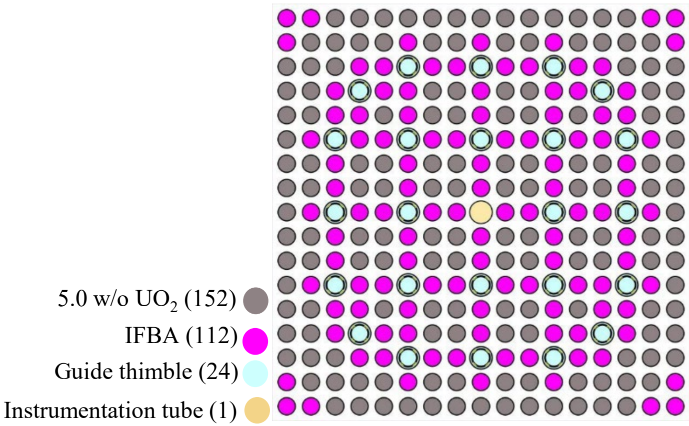
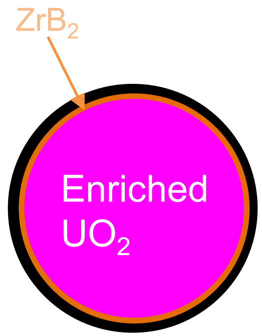
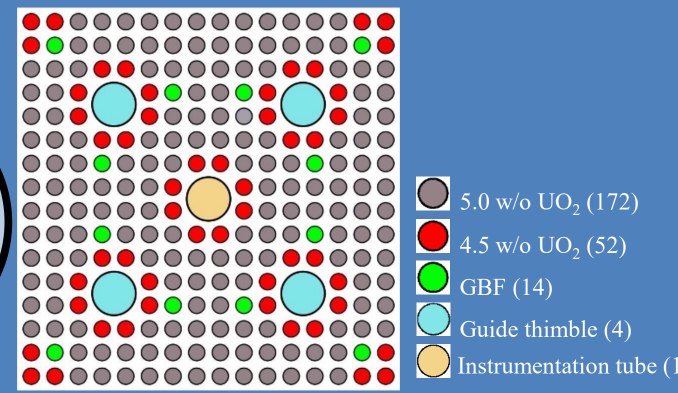
Current Burnable Absorber Fuel Designs







Integral Fuel Burnable Absorber (IFBA)

- **Westinghouse**
- 600 nm sprayed coating
- Relatively low σ_a → high # FRs
- He gas emission → internal rod pressure

$$^{10}_{5}\mathrm{B} + ^{1}_{0}\mathrm{n} \rightarrow ^{4}_{2}\mathrm{He} + ^{7}_{3}\mathrm{Li}$$

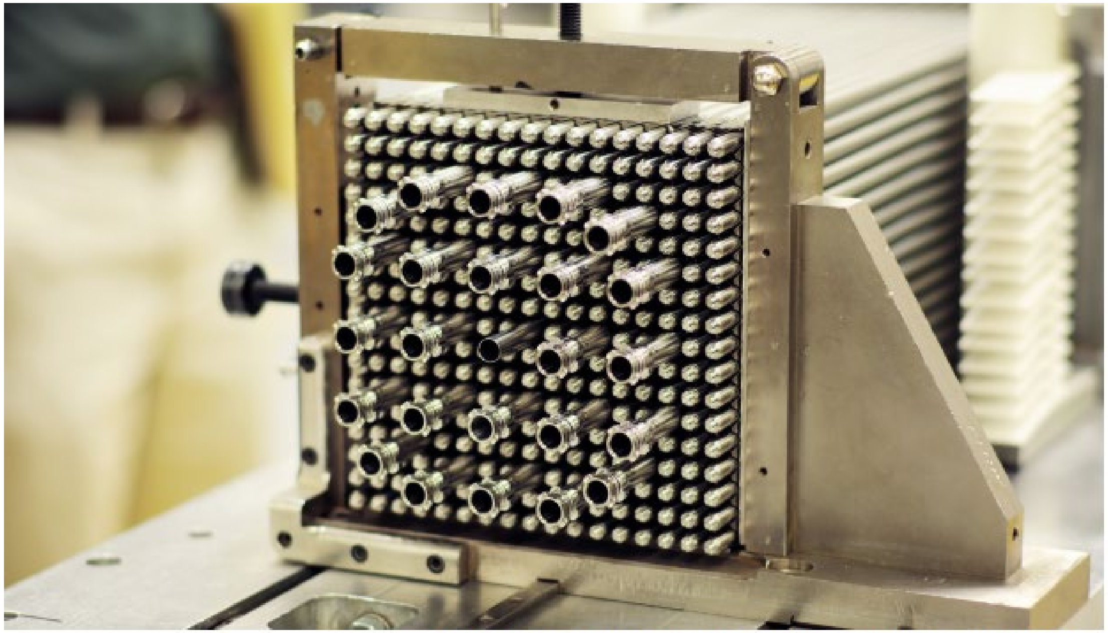
Urania-Gadolinia (6-10 wt%)

- **Combustion Engineering (CE)**
- Relatively high σ_a → low # FRs
- Presence of highly neutron absorbing radioisotope → EOC penalty
- Mixed with fuel → affect its physical properties
- Fast burn-out → limited excess reactivity control (fuel cycle length)

Simmons et al., Nuclear Technology 80 (1988) 343-348
IAEA-TECDOC-844, " Characteristic and use of Urania-Gadolinia fuel" , 1995.

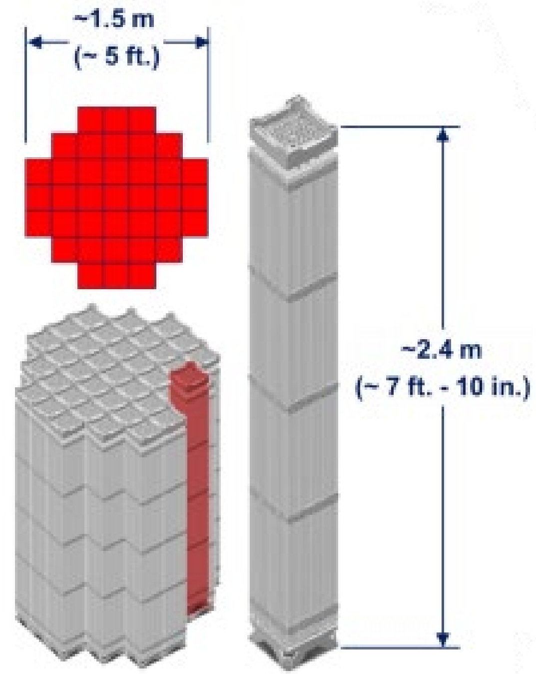
EOC: End of Cycle, **FR**: Fuel Rods, σ_a: thermal neutron absorption cross section

Fuel for NuScale SMR



The fuel uses an established 17x17 fuel rod array with 24 guide tubes

The NuScale SMR will utilize a core of 37 fuel bundles

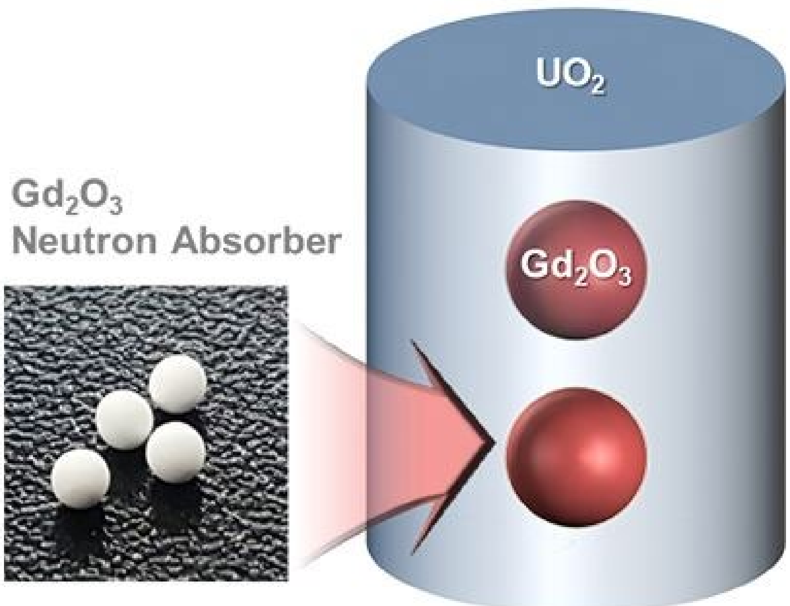


- **To reduce the beginning-of-life moderator coefficient**
  - The burnable absorber rod is mechanically similar to fuel rods but consists of gadolinium oxide (Gd_2O_3) mixed in enriched UO_2 in the central rod portion (axially) and enriched UO_2 at the top and bottom.

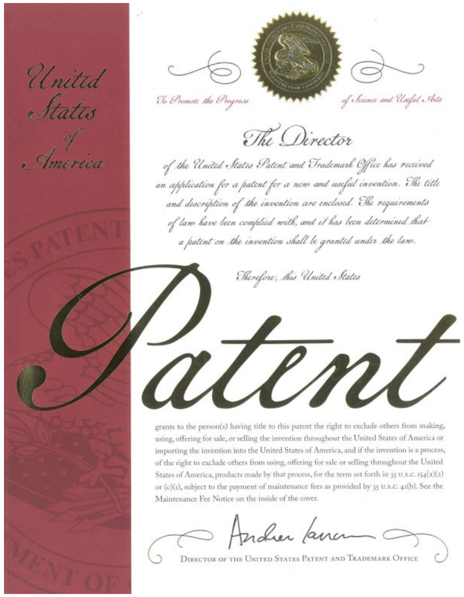
http://us.areva.com/home/liblocal/docs/Catalog/PWR/ANP-U-631-V1-16-ENG-NuScale.pdf

Introduction – Advanced Fuel for SMR

KAIST Breakthroughs
Biannual Engineering Research Webzine



Innovative Neutron Absorber Fuel

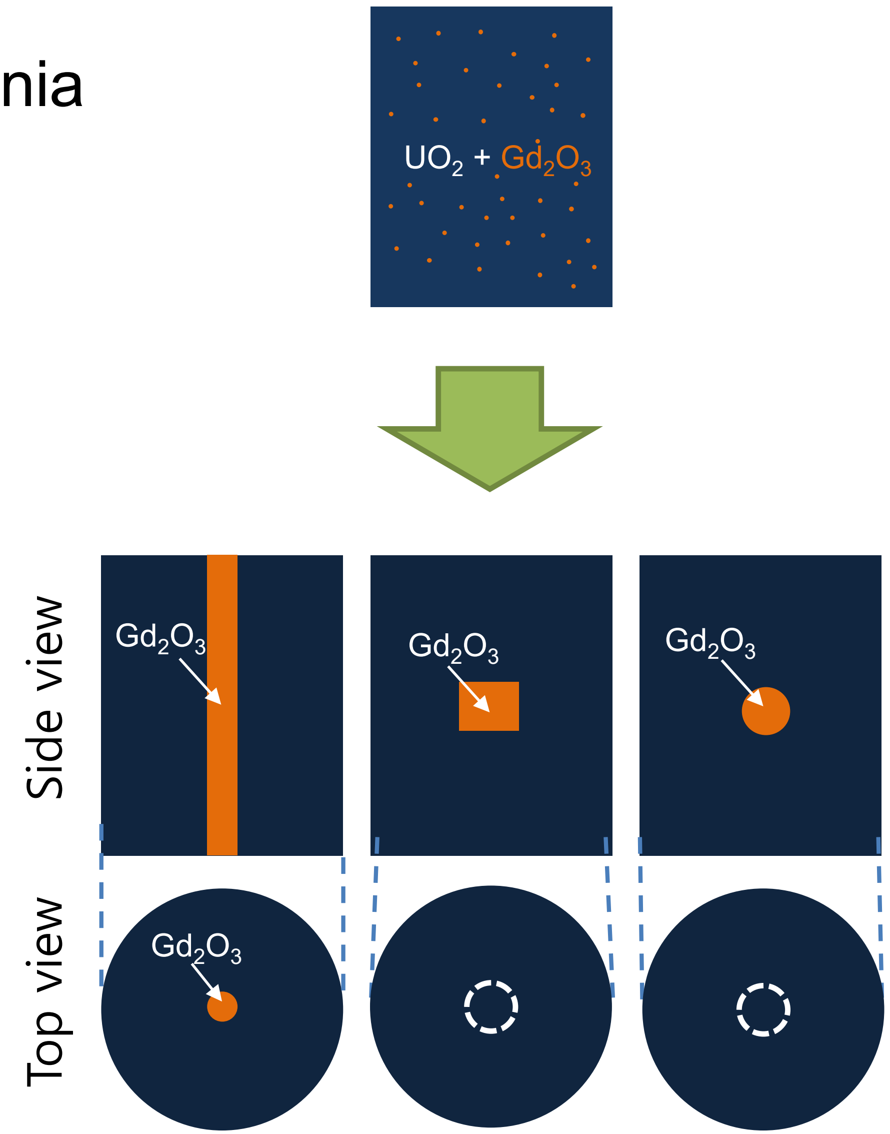


<u>특허등록현황</u>

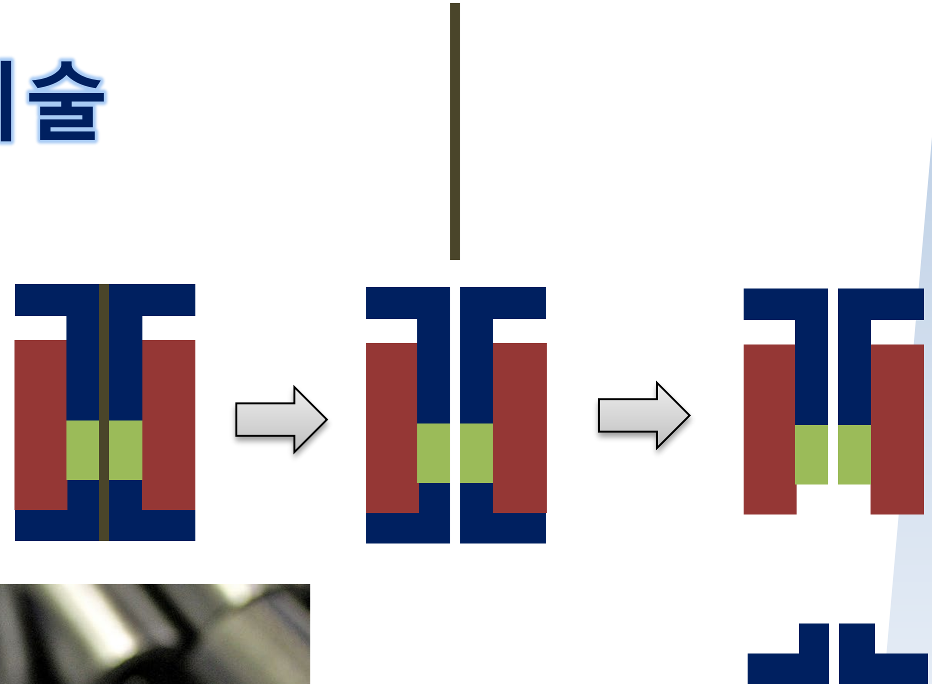
- **핵연료 복합소결체 및 이의 제조방법, 2018. 11. 28 (류호진, 김용희)**
- **국부의 가연성흡수체를 포함하는 핵연료 소결체, 2020. 4. 20 (김용희 류호진)**
- **미국 특허 11049625 (2021.06.29)**

Design Concepts

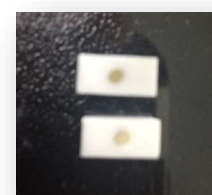
❖ Lumping gadolinia in the oxide pellet



중심 hole 펠렛 상용기술



러시아 VVER UO_2 핵연료 펠렛



중심 위치 유지 가능

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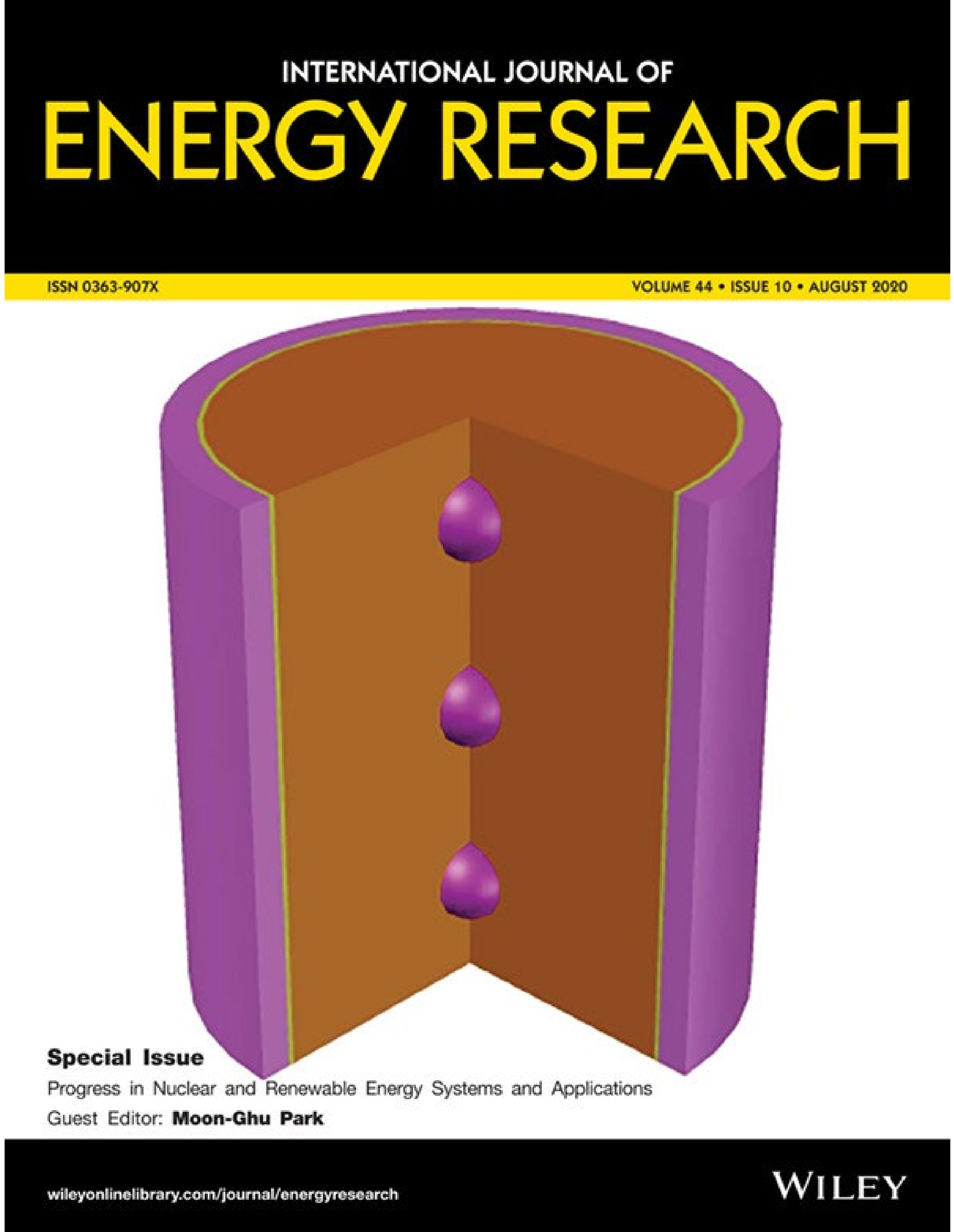

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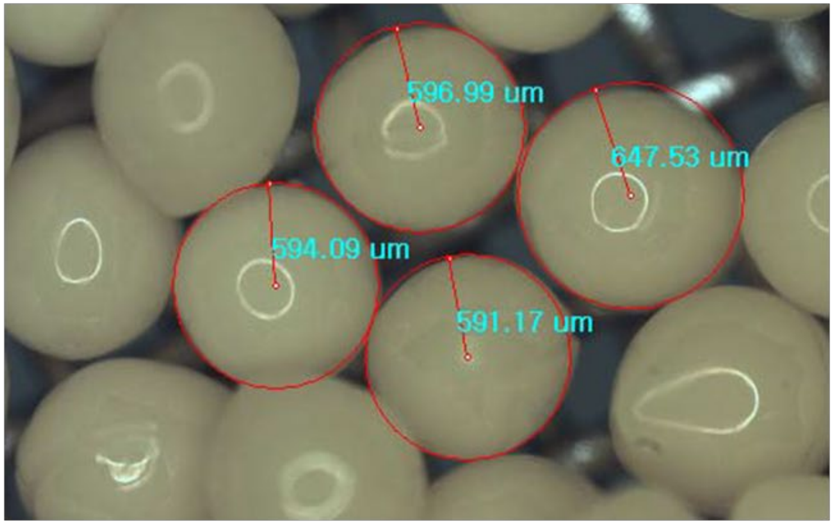
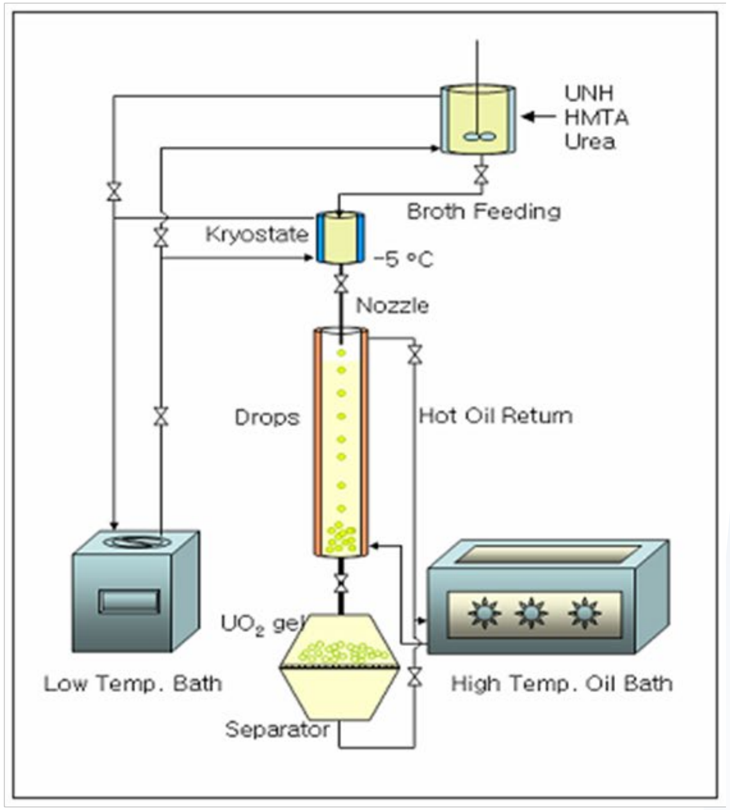
구형 산화물 대량생산 기술 1

- UO3 Intermediate Particle Preparation Using the Sol-Gel Process by KAERI

TRISO 핵연료 Kernel 제조기술 확립





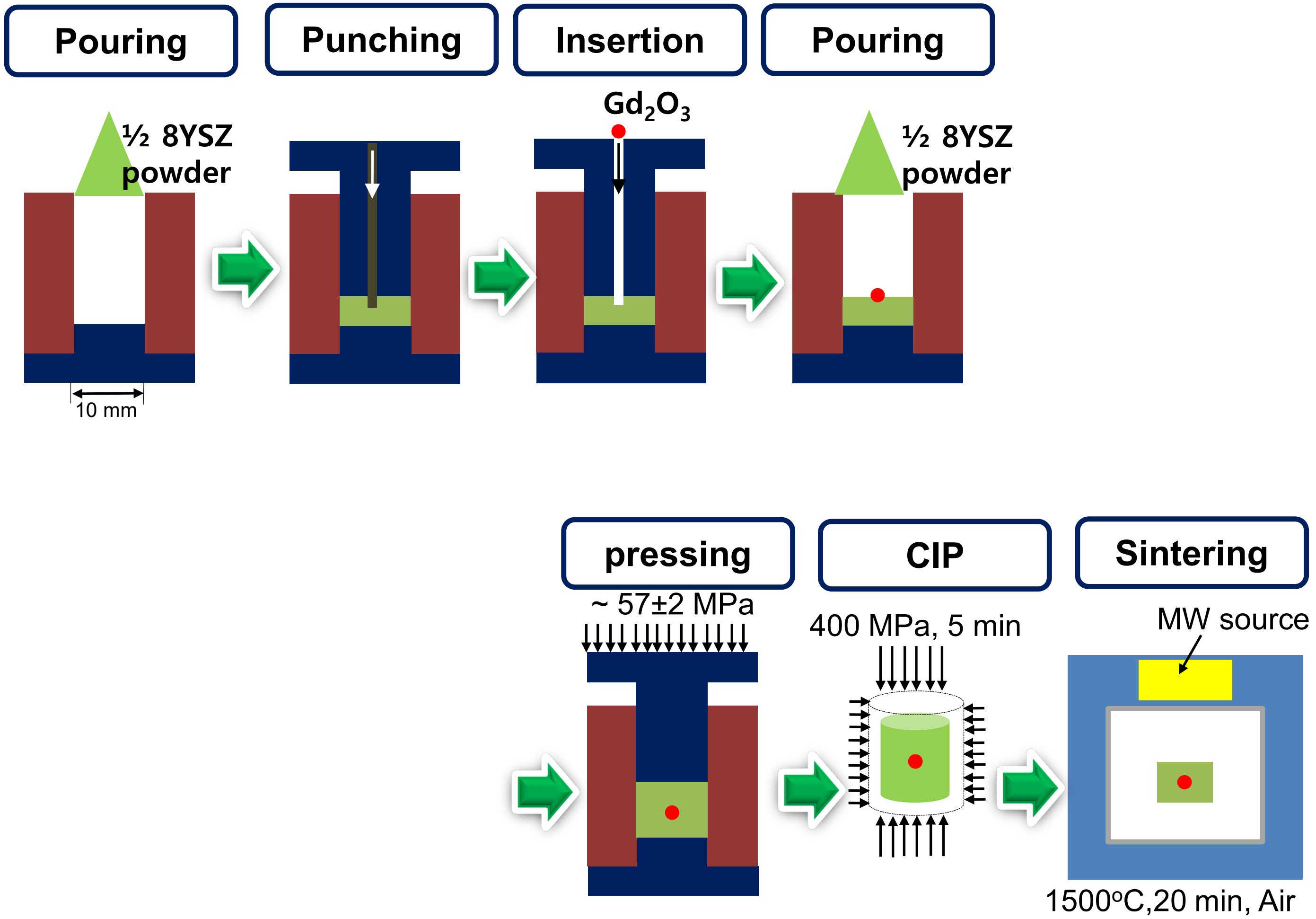
구형 산화물 대량생산 기술 2

- ❖ 세라믹 슬러리 캐스팅 상용화 되어 있음 (drip casting)

- ❖ Gd_2O_3는 비방사성 물질로 대량생산 가능

실제 제조된 Gd_2O_3

Methods (Fabrication of oxide pellets containing lumped Gd_2O_3 spherical particle)



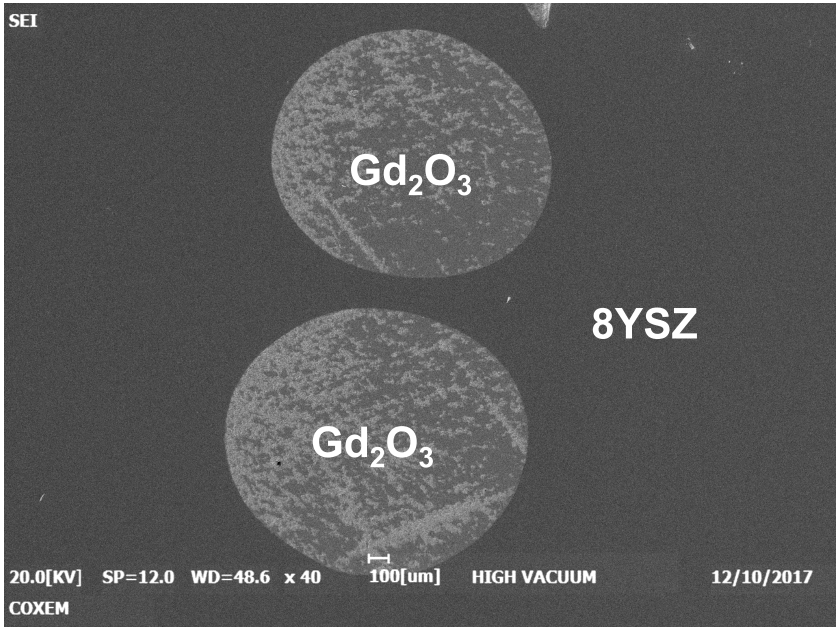
CIP: Cold isostatic pressing

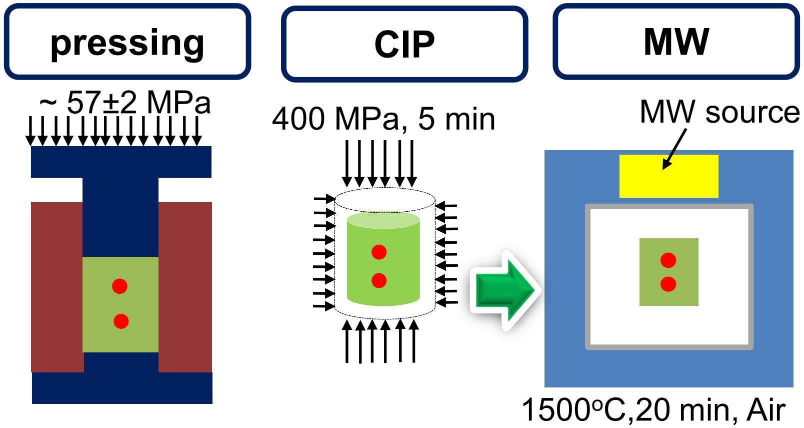
8YSZ pellet containing 2 lumped Gd_2O_3

Gd_2O_3

Drying: 120°C, 12 h

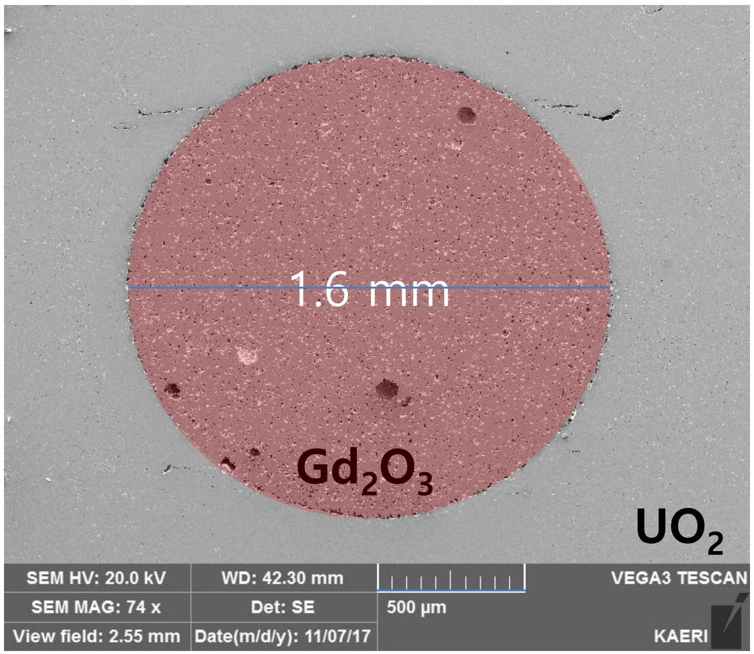
Sintering: 1400°C for 2 hr

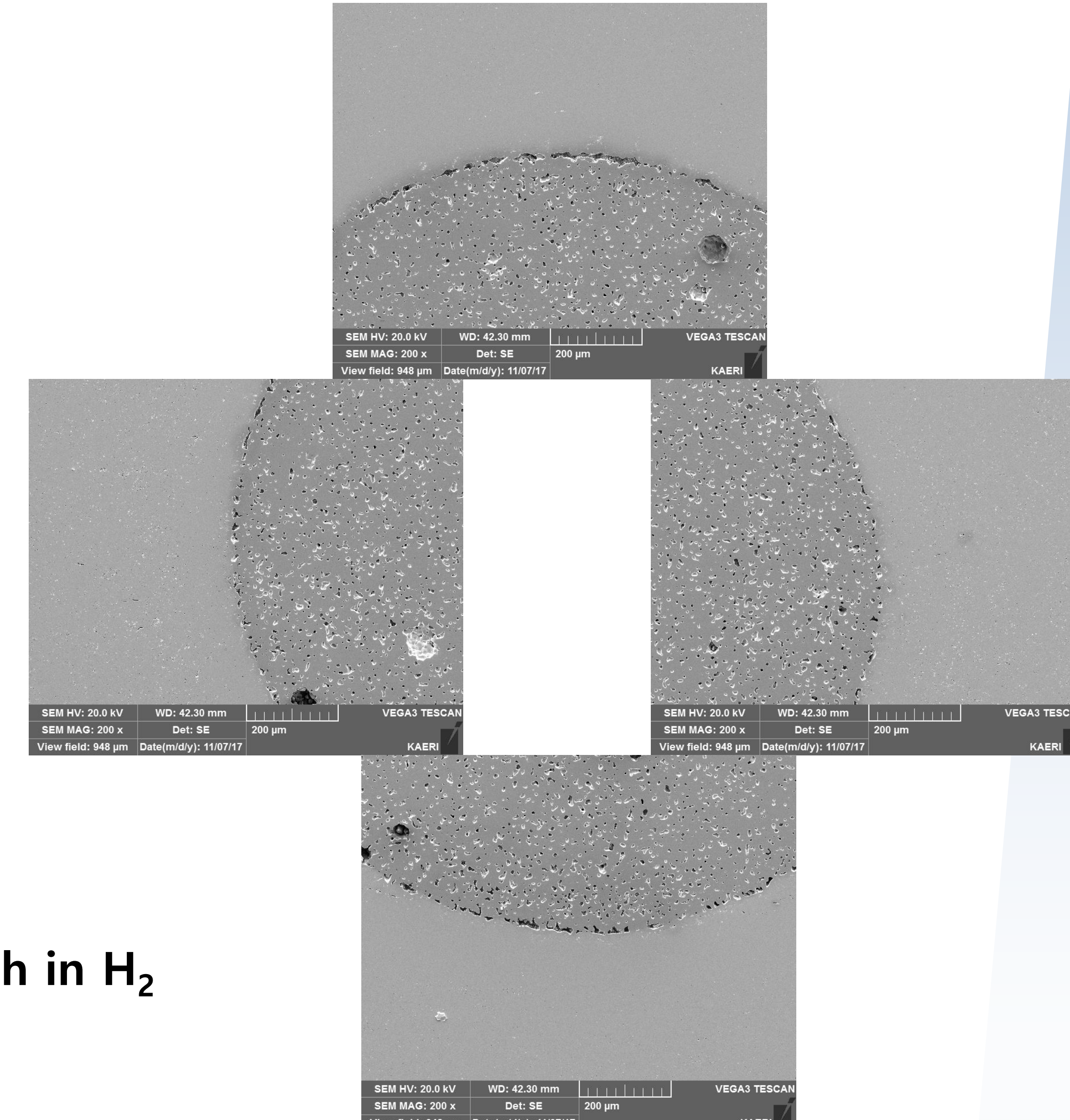




UO_2 이용 1700°C 소결 후 미세조직

제작성 및 고온 안정성 양호



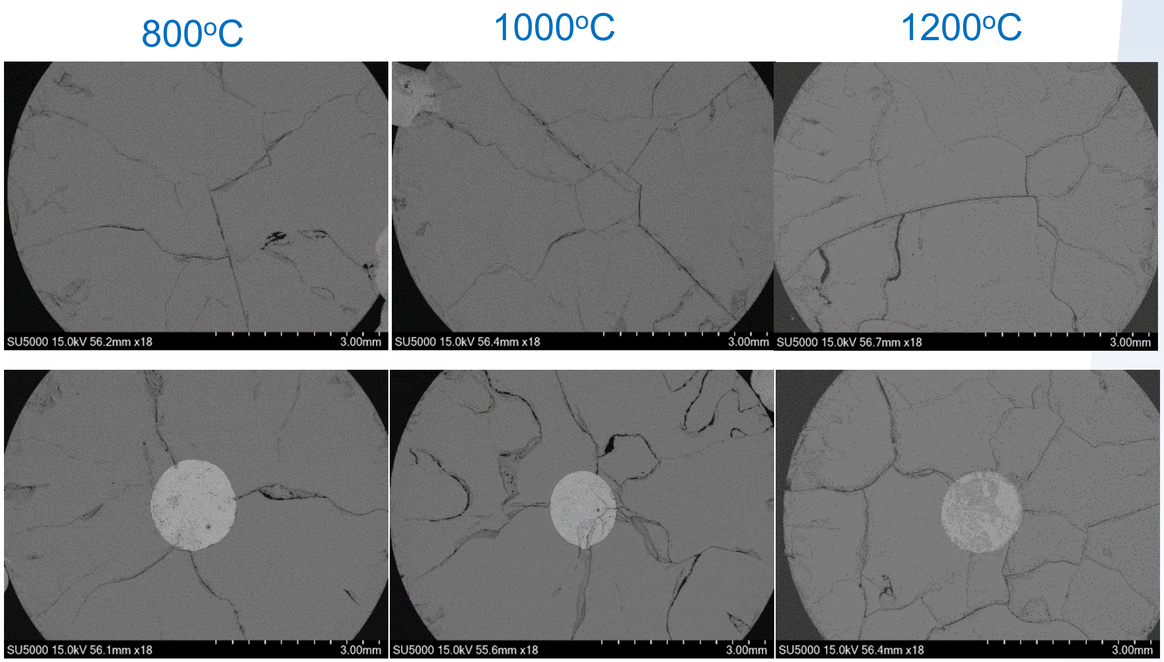


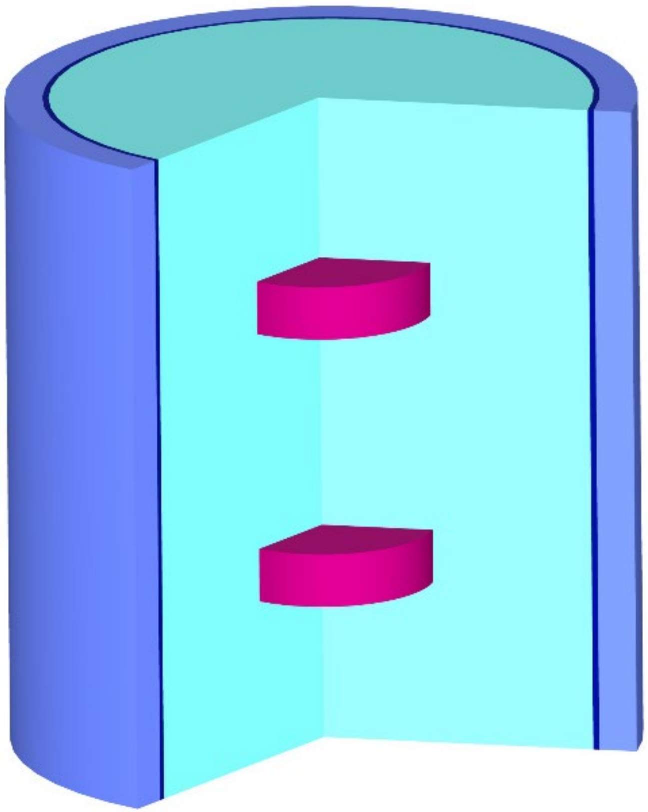
Sintering conditions : 1700°C / 4h in H_2

Quenching of lumped BA fuel design

- **Design:**
  - 8YSZ pellet with 1400°C pre-sintered Gd_2O_3 spherical particle
- **Conditions:**
  - T(800°C, 1000°C, and 1200°C), holding time (30 min)
- **Structure:**
  - No-relocation of Gd_2O_3 sphere was observed

Dimensions of 8YSZ pellets with Gd_2O_3 spherical particle. (mm)	
Gd_2O_3	1.72±0.01
8YSZ Pellet	4.57±0.05 H×7.51±0.02 D

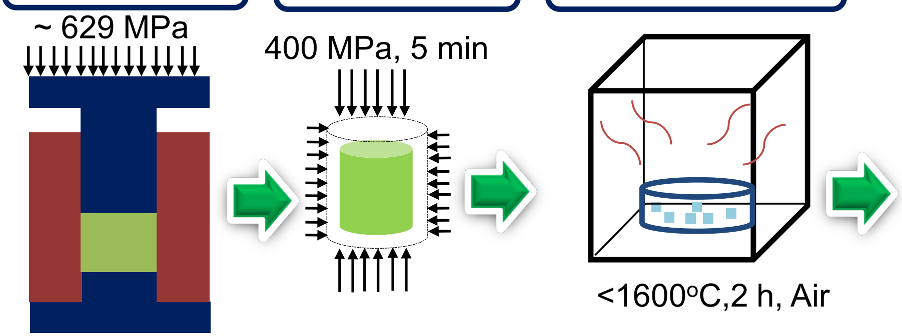




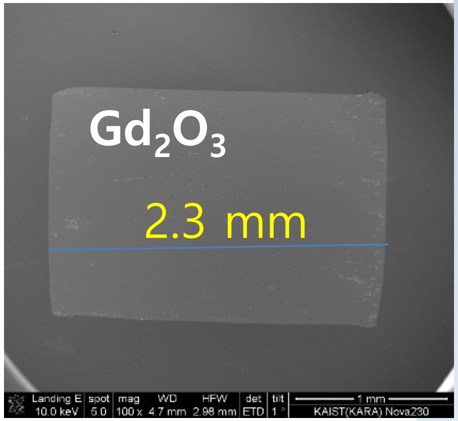
구형 대신 디스크형 제작 용이

Gd_2O_3 3 mm mini-pellets by powder metallurgy

pressing → **CIP** → **Box furnace**

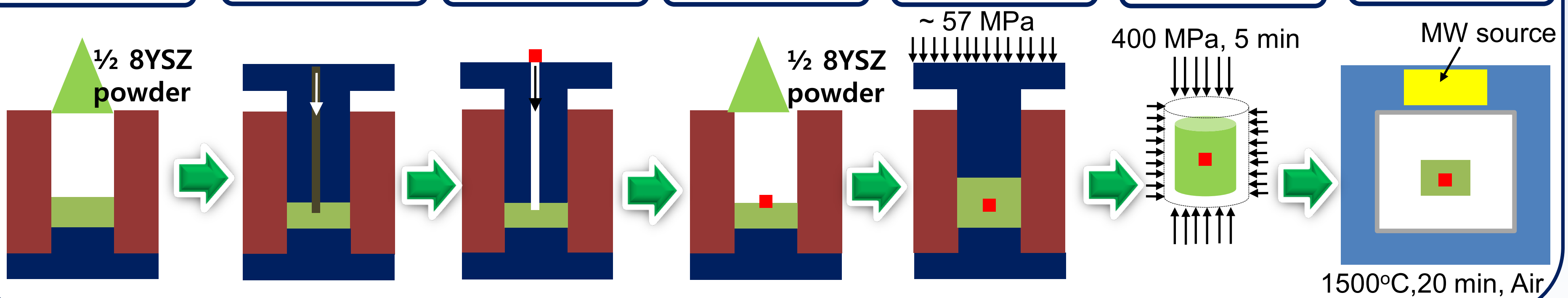


Density: Archimedes

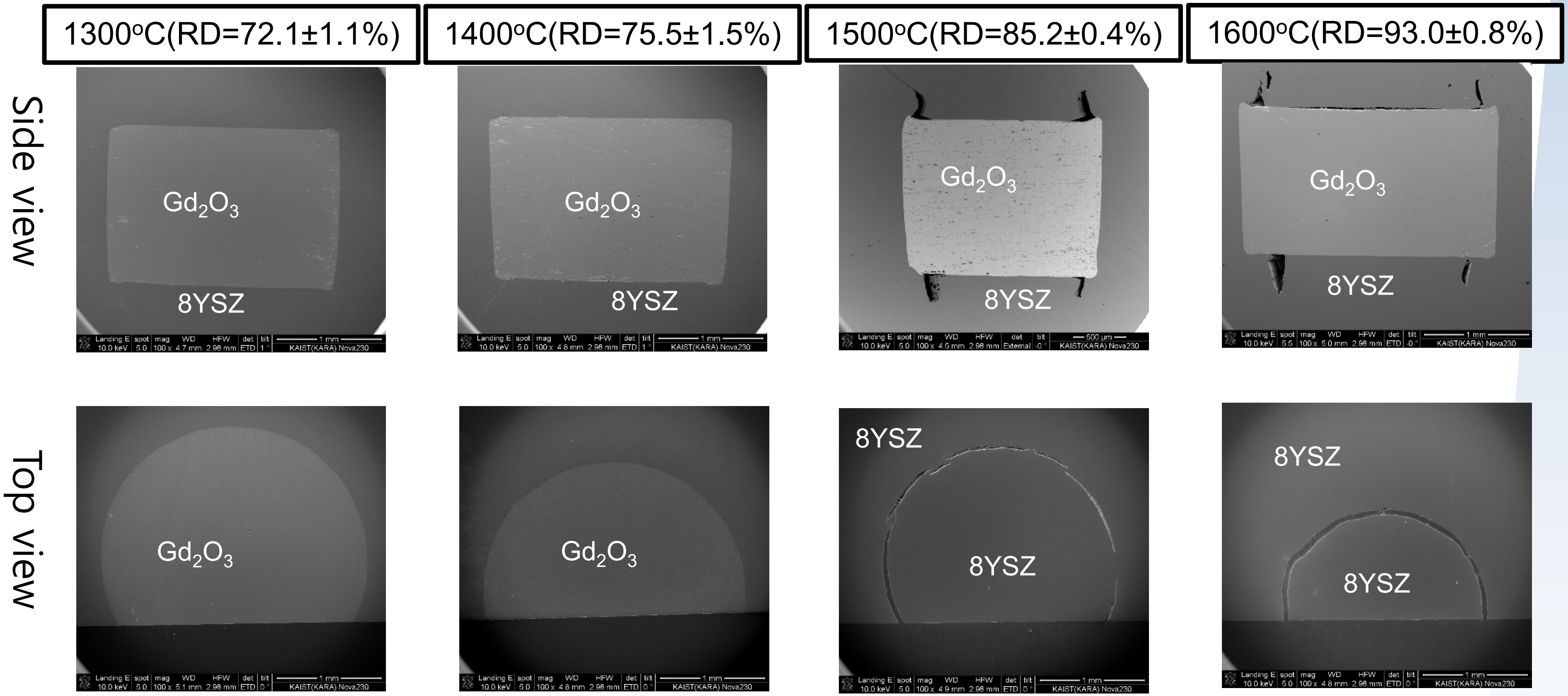


Pellet containing lumped Gd_2O_3 mini-pellet

Pouring → **Punching** → **Insertion** → **Pouring** → **pressing** → **CIP** → **소결**



Gd_2O_3 디스크 소결 제조성 평가



(at least 3 samples were characterized)

No interfacial cracks in 1400°C or less sintered mini-pellets

Mistarihi, et al. (2018).
International Journal of Energy Research, **42**(6), 2141-2151

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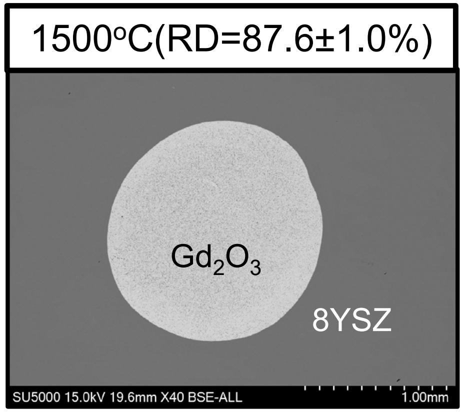
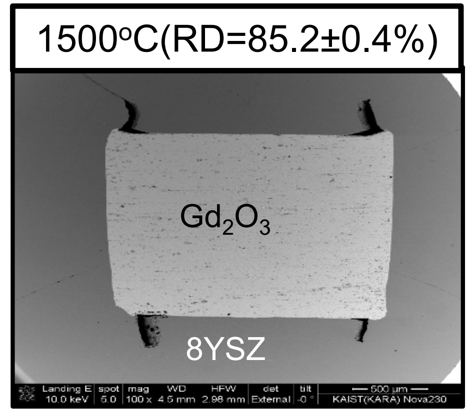
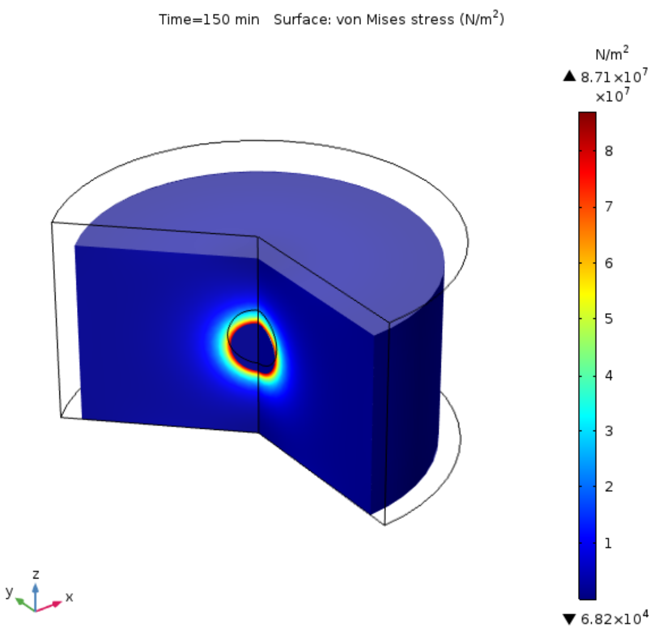
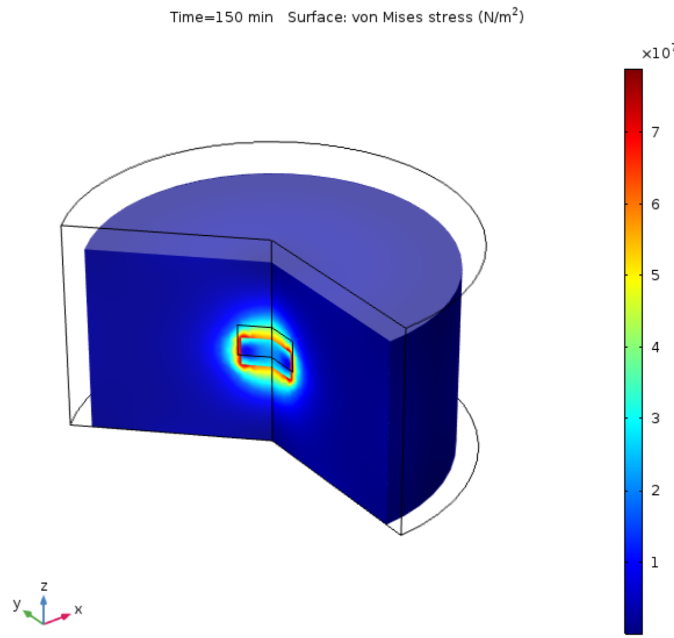
Gd_2O_3 디스크 소결 제조성 평가 – FEM 계산









Mistarihi et al. (2021).
Frontiers in Energy Research, ***9***, 104.

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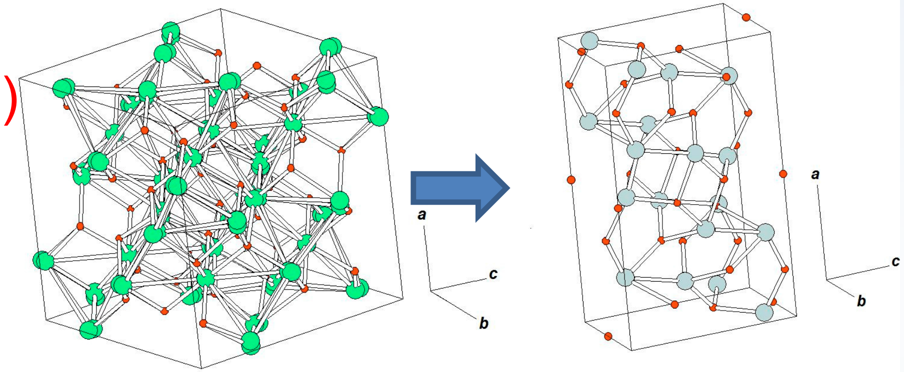
Lumped Gd_2O_3 BA fuel design challenges

- Fabrication process:
  - Formation of interfacial cracks/gap
    - Phase transformation of Gd_2O_3
    - Different shrinkage & sintering rate of the Gd_2O_3 and UO_2
    - Thermal expansion mismatch
- Fuel performance:
  - Melting of Gd_2O_3
  - Gd_2O_3 relocation
  - Unknown irradiation behaviour of Gd_2O_3 (swelling, or amorphization)

	Gd_2O_3	UO_2
Structure	Cubic →monoclinic @ T > 1250°C	Cubic
D ($g \cdot cm^{-3}$)	7.403	10.96
MT(°C)	2330	2860
E (GPa)	150.2	87.4
$\alpha \times 10^{-6}(K^{-1})$	10.5	12.0

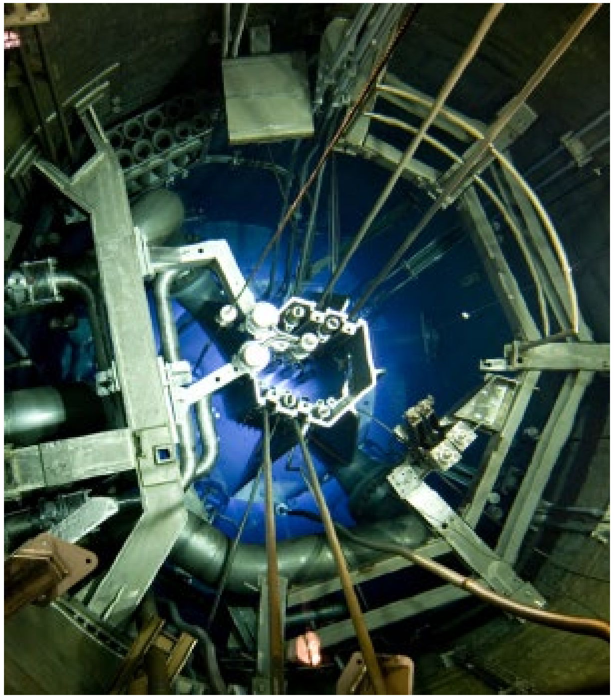
D: Density, E: Modulus of elasticity, MT: Melting point, α : thermal expansion Coefficient



IAEA-TECDOC-844, " Characteristic and use of Urania-gadolinia fuel" , 1995.
S.C. Atkinson, Crystal structures and phase transition in the rare earth oxides, Ph.D thesis, University of Salford, 2013

하나로 조사시험 추진 계획

- 목적: LTA 또는 LTR 시험 가능성 검증
- 2022년 하반기 착수 추진 – OR 조사공 활용 ($3x10^{14}$ /cm^2-s)
- 목표 연소도: 30,000 MWd/MTU (연간 8000-9000 MWd/MTU)
  - 평균선출력: 35~45 kw/m
- 미니연료봉 당 UO_2 펠렛 5개 장입 가능
  - 핵물질 사용 및 펠렛 제조를 위한 KAERI/KNF 협조 추진



하나로 조사시험 캡슐

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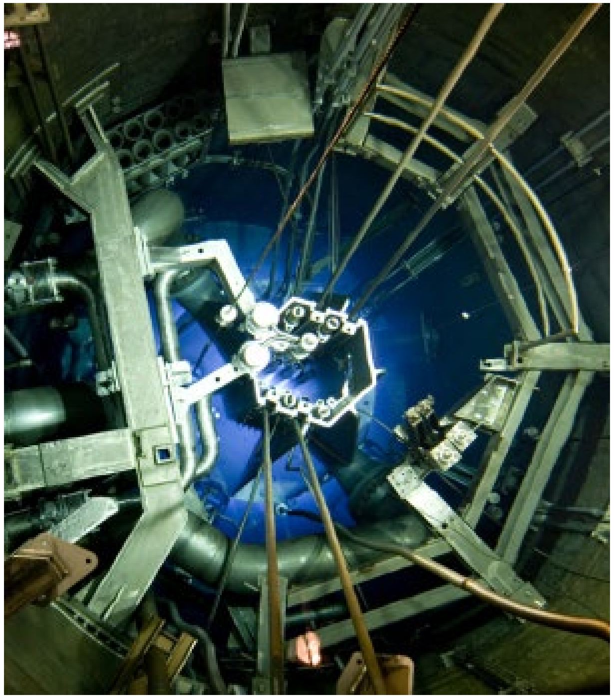


하나로 조사시험 캡슐

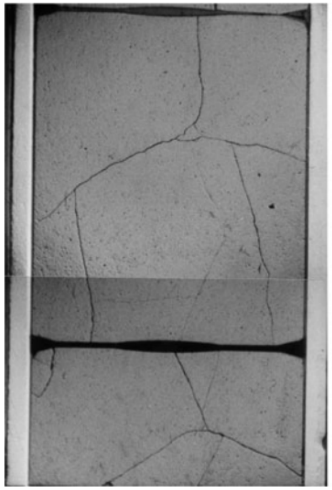
조사후 시험 (PIE) 추진 계획

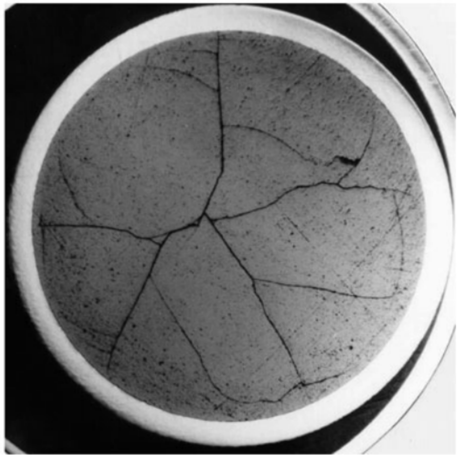
❖ 목적: CSBA 핵연료 건전성 평가

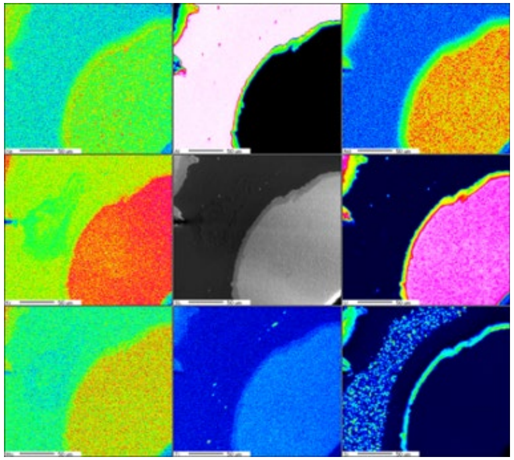
❖ KAERI IMEF 핫셀 시설 활용

❖ 주요 평가 항목

- Gamma scan을 이용한 위치별 연소도 평가
- LVDT를 이용한 변형 및 팽윤 측정
- X-CT를 이용한 파손 거동 측정
- OM, SEM을 이용한 균열, 석출물, 반응층 형성 측정
- EPMA를 이용한 반응층 조성 분석







Gd 산화물의 조사 특성

❖ Review of irradiation studies [1-3]:

Radiation	Max. Fluence (ions/cm^2)	Gd Compound	Results
Au (2.25 GeV)	5×10^{13}	Gd_2O_3	Phase transformation
Au (4 MeV)	10^{15}	Gd_2O_3	Phase transformation
Ne (400 KeV)	10^{16}	$Gd_2Hf_2O_7$ $Gd_2Ti_2O_7$	Amorphous

❖ Irradiation deformation mechanisms:

– Gd_2O_3: formation of anti-frenkel defects → cluster to dislocation loops → re-arrangments of cations into monoclinic structure. [4]

– Gd compounds: cation size ratio → formation of Pyrochlor or fluorite structure → fluorite are more radiation resistant (more space to accommodate lattice disorder). [5]

Phase transformation of Gd_2O_3 by irradiation

[1] Lang et al., Nucl. Instruments Methods Phys. Res. Sec. B 326 (2014) 121-125
[2] Mejai et al., Appl. Phys. Lett. 107 (2015)
[3] Wen et al., Nucl. Inst. Methods Phys. Res. Sec. B 287 (2012) 130-134
[4] Chen et al., Appl. Phys. Lett. 112 (2018)
[5] Sickafus et al., Science 289 (2000) 748-751

Thank you for kind attention