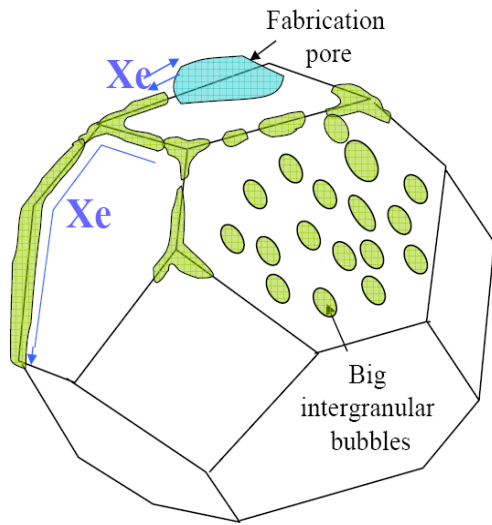
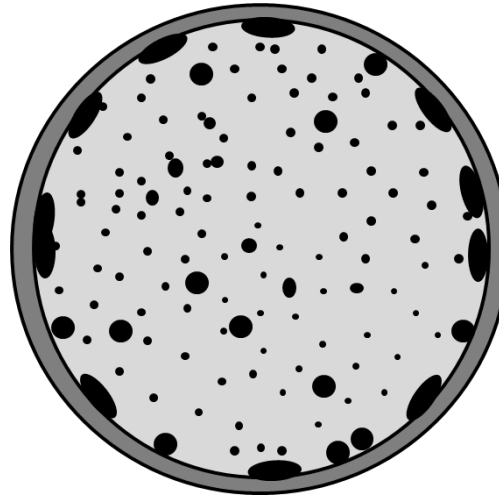


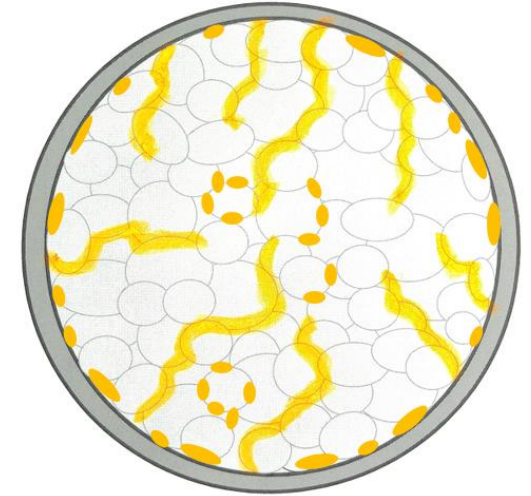
미소셀 소결체 기체방출에 대한 정성적 분석: UO₂ 소결체 기체방출 경험을 사용



UO₂ 결정립
(10 μ m)



세라믹 셀
(80~115 μ m)



금속 셀
(167~531 μ m)

후쿠시마 1호기 (2011.3.12) 수소폭발



20만명 긴급 대피



7만명 이상, 아직도 피난 생활

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Over 70,000 live in evacuation 7 years after Fukushima disaster

Source: Xinhua 2018-03-11 23:04:50

TOKYO, March 11 (Xinhua) -- More than 70,000 people are still living as evacuees seven years following triple disasters that hit Fukushima and its neighboring areas on March 11,



기체(+불활성 원소) 방사능 물질이 문제

Table 1. Classification of fission products (FP).

Group	Major elements	Characteristics for leakage and transport	Leakage rate (>2350°C)
Volatile FP (+noble gas)	Xe, Kr, I, Cs, Sb, Te	<ul style="list-style-type: none"> - High volatility - Very easily leaked from fuel pellet - Move very long distance in the environment 	100%
Semi-volatile FP	Mo, Ba, Rh, Pd, Tc	<ul style="list-style-type: none"> - Medium volatility - Easily leaked from fuel pellet - Move long distance in the environment 	50-100%
Low-volatile FP	Ru, Ce, Sr, Y, Eu, Nb, La	<ul style="list-style-type: none"> - Low volatility - Difficult to be leaked from fuel pellet - Move short distance in the environment 	3-10%
Non-volatile FP	Zr, Nd, Pr	<ul style="list-style-type: none"> - No volatility - Very difficult to be leaked from fuel pellet 	Not measured
Actinides	U, Pu	<ul style="list-style-type: none"> - Different leakage depending on nuclides - Move short distance in the environment 	U: at most 10% Pu: less than 1%

구양현 등, "Radioactivity release from the Fukushima accident and its consequences: A review," *Progress in Nuclear Energy*, 74 (2014) 61.

격납고 파괴 시, **기체** 방사능 물질은 **누출**



누출된 기체 방사능 물질: 원자 개수 매우 Big

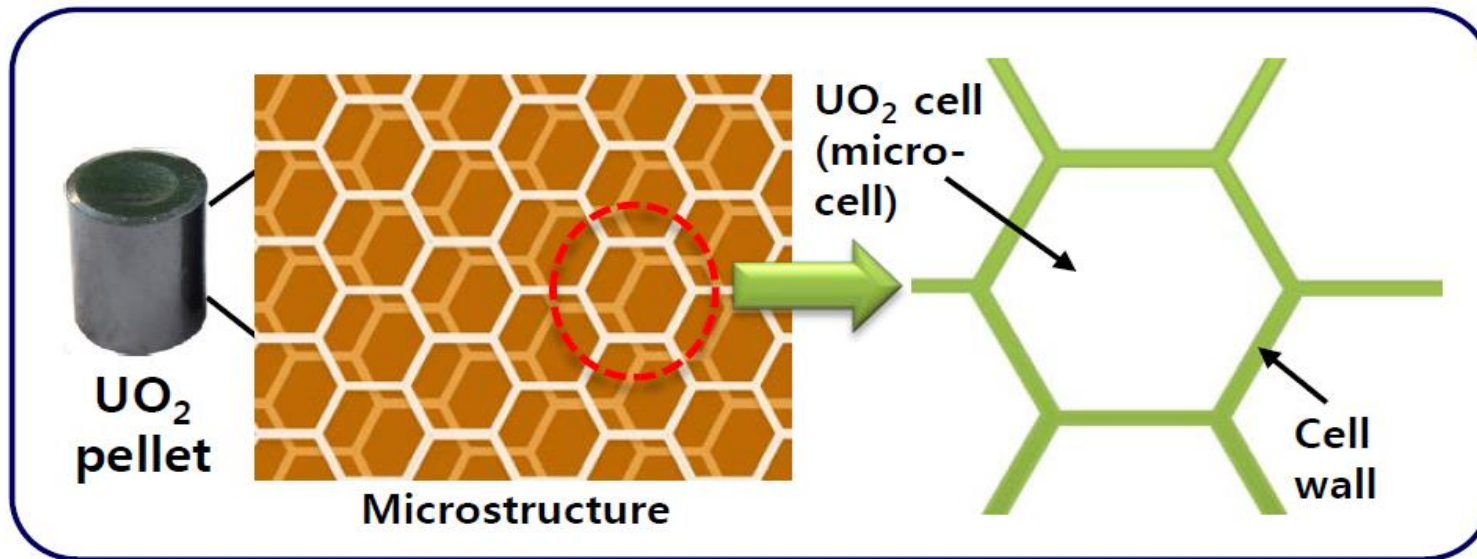
Table 2. Summary of source terms released into the atmosphere from units 1-3.

		^{133}Xe	^{131}I	^{137}Cs
Half life, $t_{1/2}$		5.2 day	8.0 day	30.2 yr
Decay constant ($0.693/t_{1/2}$), (1/sec)		1.54×10^{-6}	1.00×10^{-6}	7.27×10^{-10}
Inventory	Isotope number	7.80×10^{24}	6.40×10^{24}	$(1.05-1.13) \times 10^{27}$
	Activity (Bq)	1.20×10^{19}	6.40×10^{18}	$(7.60-8.20) \times 10^{17}$
	Mass (kg)	1.7	1.4	238.8-257.0
Source term into the atmosphere, Bq (Release into the ocean not included)	Activity (Bq)	$(0.60-1.90) \times 10^{19}$	$(0.7-5.0) \times 10^{17}$	$(1.0-5.0) \times 10^{16}$
	Mass (kg)	0.85-2.7	0.015-0.11	2.9-17.0
	Fraction (%)	50-159 [*])	1.1-7.9	1.2-6.6

구양현 등, "Radioactivity release from the Fukushima accident and its consequences: A review," Progress in Nuclear Energy, 74 (2014) 61.

미소셀 (Micro-cell) 소결체

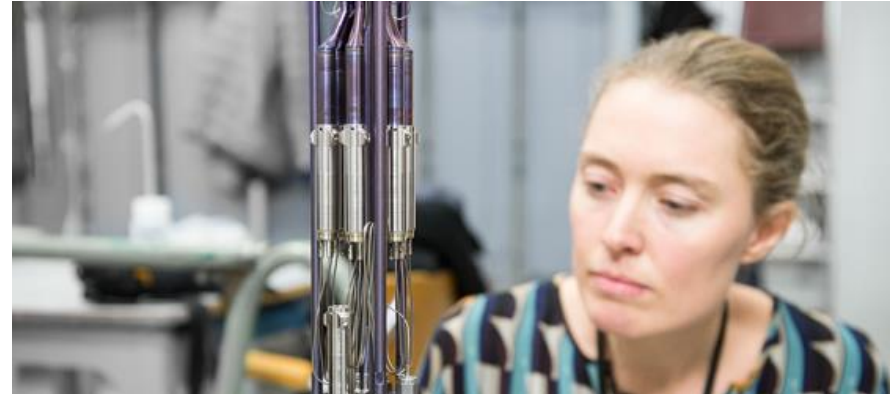
- 세라믹 미소셀 소결체: SiO_2 based 세라믹 물질로 Wall 구성
- 금속 미소셀 소결체: Cr, Mo 금속으로 Wall 구성



Halden 연구로 연소시험: 2016-2018

- 상용로 연소시험 경험: 없음
- **Halden 연구로 연소시험**
 - 연소도: **16,000 MWD/MTU**
 - **PIE 자료** 확보 필요

- IFA-790 (Thor Energy 협력): 봉 2개
- **Pin #08: 세라믹 미소셀 소결체 (0.6wt%Si-Ti-O)**
+ CrAlFe/Cr coated Zry cladding
- **Pin #11: 금속 미소셀 소결체 (5vol%Cr)**
+ CrAl coated Zry cladding



Thor Energy
Scandinavian Advanced Technology

Thorium Fuel: Second round of test irradiation underway in Norway

Oslo, Norway **January 6, 2016** The second phase of a five-year trial-operation of thorium based nuclear fuels has commenced in Norway. An international consortium established* in 2011 and led by *Thor Energy* is undertaking a sophisticated test-irradiation campaign in order to quantify the performance of the fuel and to qualify it for commercial use. The first thorium fuel specimens were loaded into the Norwegian fuel-testing reactor operated by the *Institute for Energy Technology* in Halden in April 2013, and the second round, now under way, is intended to verify test results and is a further step towards commercializing thorium as a supplement fuel in conventional nuclear reactors.

The second phase of thorium irradiation in the Halden reactor consists of 12 fuel pins in a new, fully instrumented test fuel rig. It consists of three variants of ThAdd fuel, which are uranium-based pins with small fractions of thorium, four reference pins as well as two pins with Accident Tolerant Fuel from Korea Atomic Energy Research Institute **KAERI**. The irradiation will produce a great deal of unique data from a number of parameters that describes how the fuel ceramic behaves as it operates for long periods in a

현재, 연소시험 자료 제한적, PIE 자료 없음

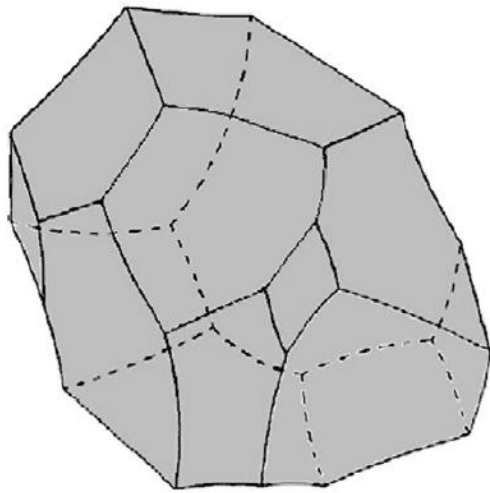


Wall (<5vol%)을 제외한,
"나머지 UO_2 matrix에서는 기체
거동이 동일하다는 전제"

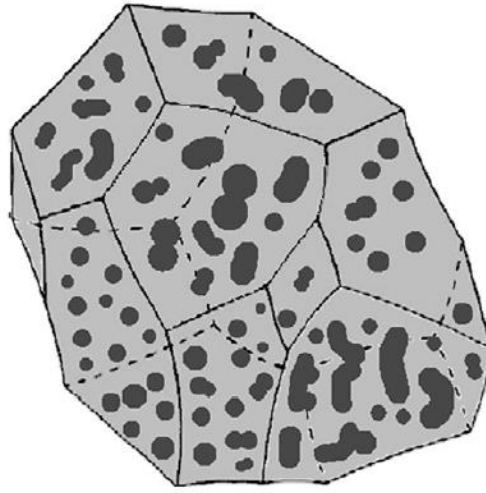
UO_2 소결체의 기체 방출률 기준
으로, 미소셀 소결체의 상대적인
방출률 추정

UO₂ 소결체: 기포형성 → 연결 → 기체방출

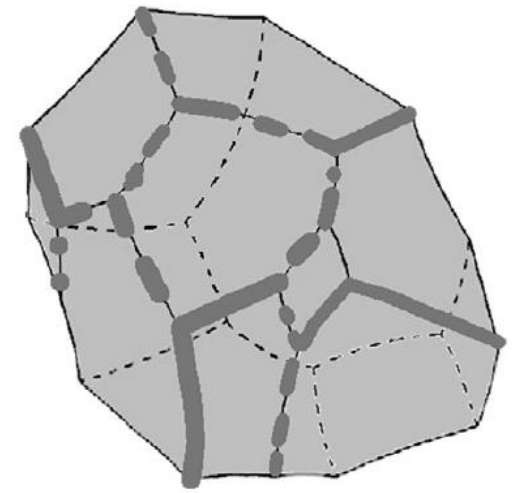
기본 전제: 모든 Grain(결정립)에서 기체방출 가능



(a)



(b)



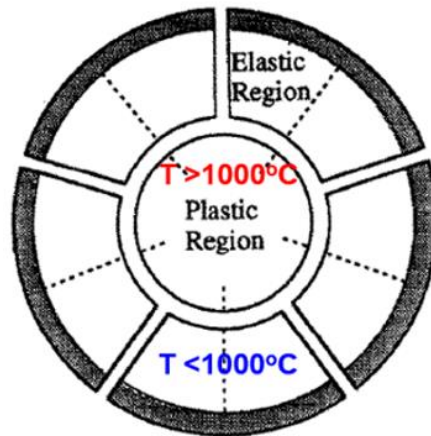
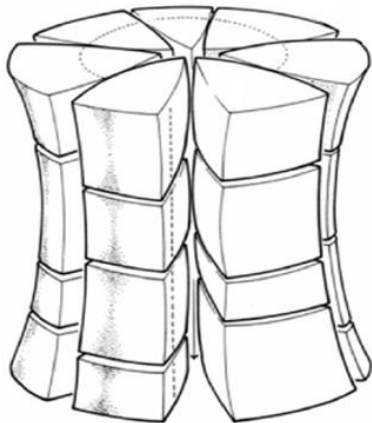
(c)

M. Tonks et al. / Journal of Nuclear Materials 504 (2018) 300–317

UO₂ 소결체: 노내에서 Crack 형성

- Crack 형성: $T_{CL} < 1000^{\circ}\text{C}$ (Elastic region)
- Crack 비형성: $T_{CL} > 1000^{\circ}\text{C}$ (Plastic region)

$T_{CL} < 1000^{\circ}\text{C}$



$T_{CL} > 1000^{\circ}\text{C}$

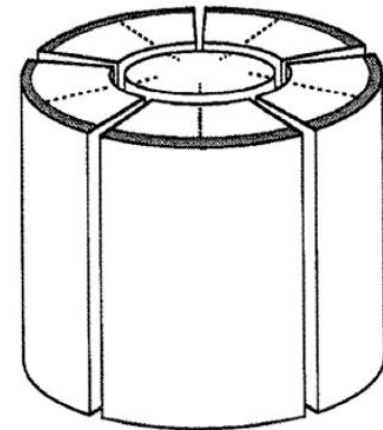
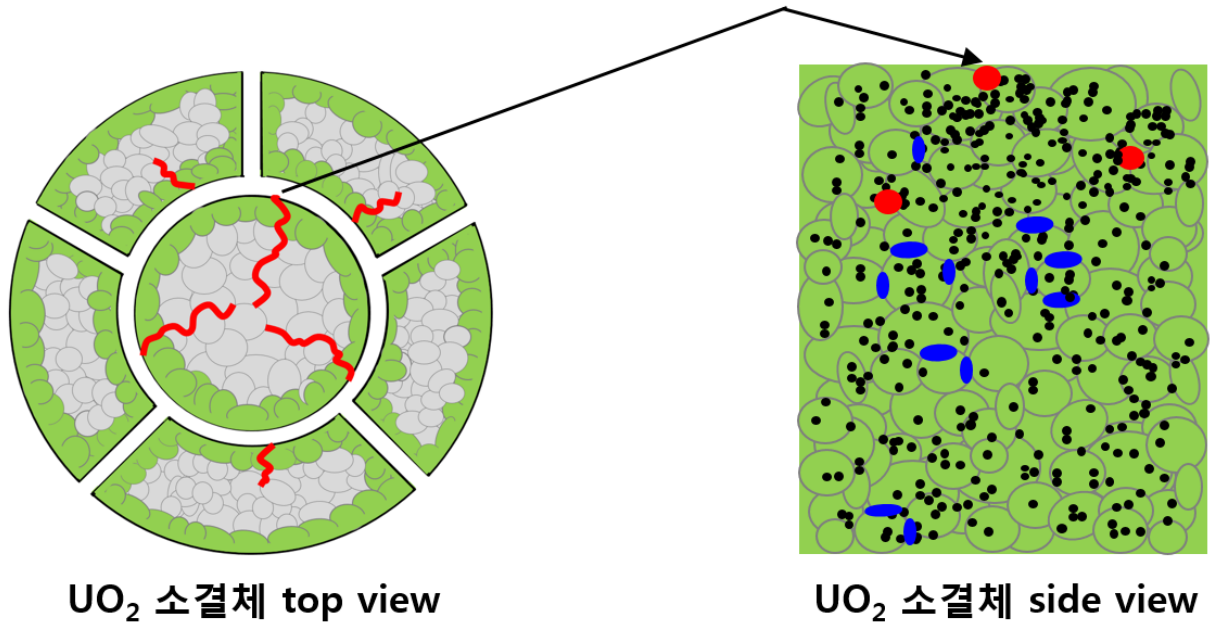


Fig. 2. Schematic geometry of cracked fuel pellet and each annulus.
Y.-H. Koo et al. / Journal of Nuclear Materials 209 (1994) 62–78

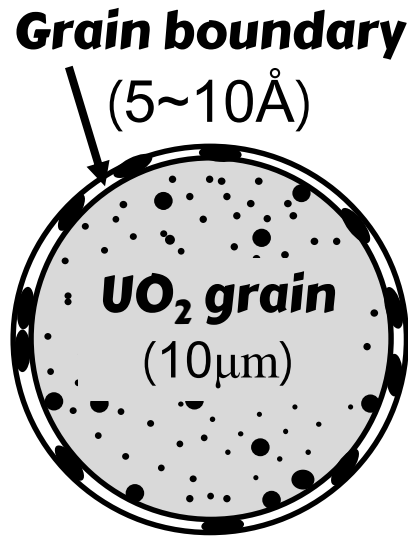
UO₂ 소결체: 기체 방출 경로, 방출률 (f_{UO_2})

- 표면에 노출된 Grains에서는 직접 방출: **녹색 Grains**
- 내부 Grains에서는 Release path로 방출: **붉은색 paths**

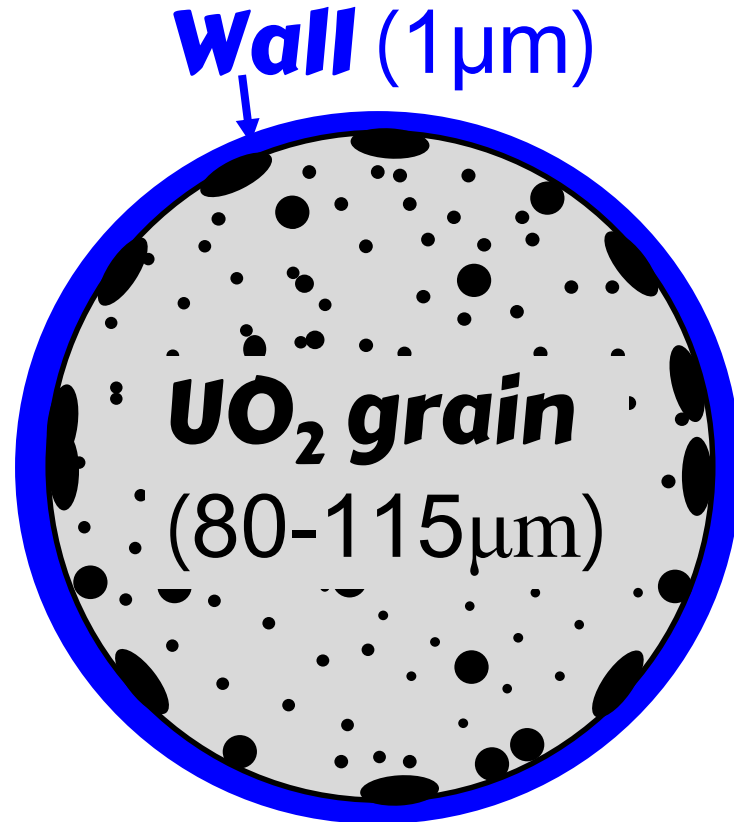


20kW/m로 연소되는 조건에서, 기체 방출률: f_{UO_2}

세라믹 미소셀, UO_2 결정립과 비교



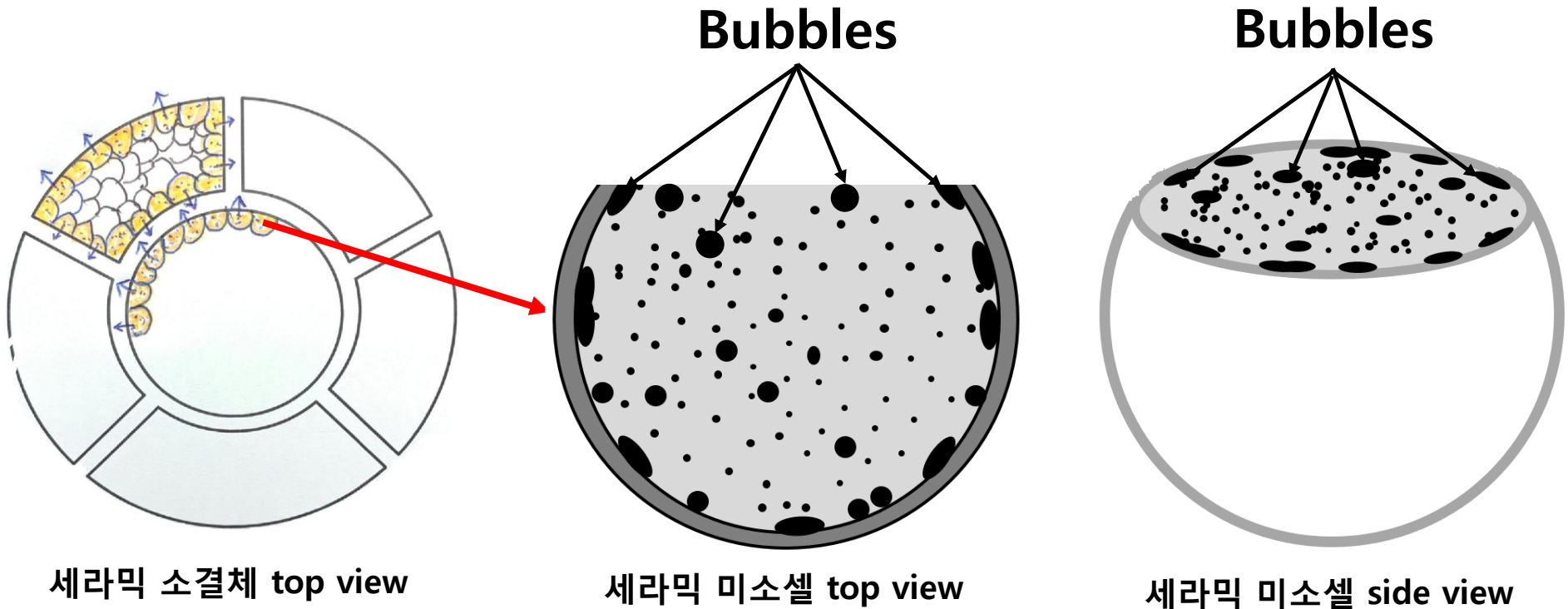
UO_2 결정립



세라믹 미소셀

세라믹 미소셀: 기체방출 경로

표면에 노출된 matrix에서 gas atoms 확산으로 외부 방출:
전체 셀 중에서 표면에 노출된 셀의 비율이 중요



세라믹 미소셀: 셀 크기, 노출된 셀 갯수

분석방법	분석항목	금속 셀	세라믹 셀
3D 계산*	셀 평균 크기 (μm)	345.10	115.19
2D 이미지 분석**	셀 평균 크기 (μm)	265.46	88.61
	단위면적당 cell 수(개/ mm^2)	14.72	132.90

* 2D 이미지 분석 결과를 이용하여, 소결체 내부에 존재하는 셀 평균 크기 3D 계산

** 2D 이미지를 이용하여, 소결체 외면 및 균열 단면에 노출되는 셀에 대한 정보 분석

김동주, "미소셀 크기 및 분포 분석", 2018. 7. 13.

세라믹 미소셀: 방출률 (20kW/m) $< 0.24 f_{\text{UO}_2}$

- UO_2 소결체 (모든 결정립에서 기체방출): 방출률 = f_{UO_2}
- 세라믹 (24% 셀(결정립)에서만 방출): 방출률 $< 0.24 f_{\text{UO}_2}$

Linear power: 20kW/m , $T_{\text{CL}} < 1000^\circ\text{C}$, number of cracks(n_c): 10

Pellet radius(r): 4.1mm, pellet height(h): 9.8mm

Cell size($2r_c$): 115.19 μm , cells/area: 132.90/ mm^2

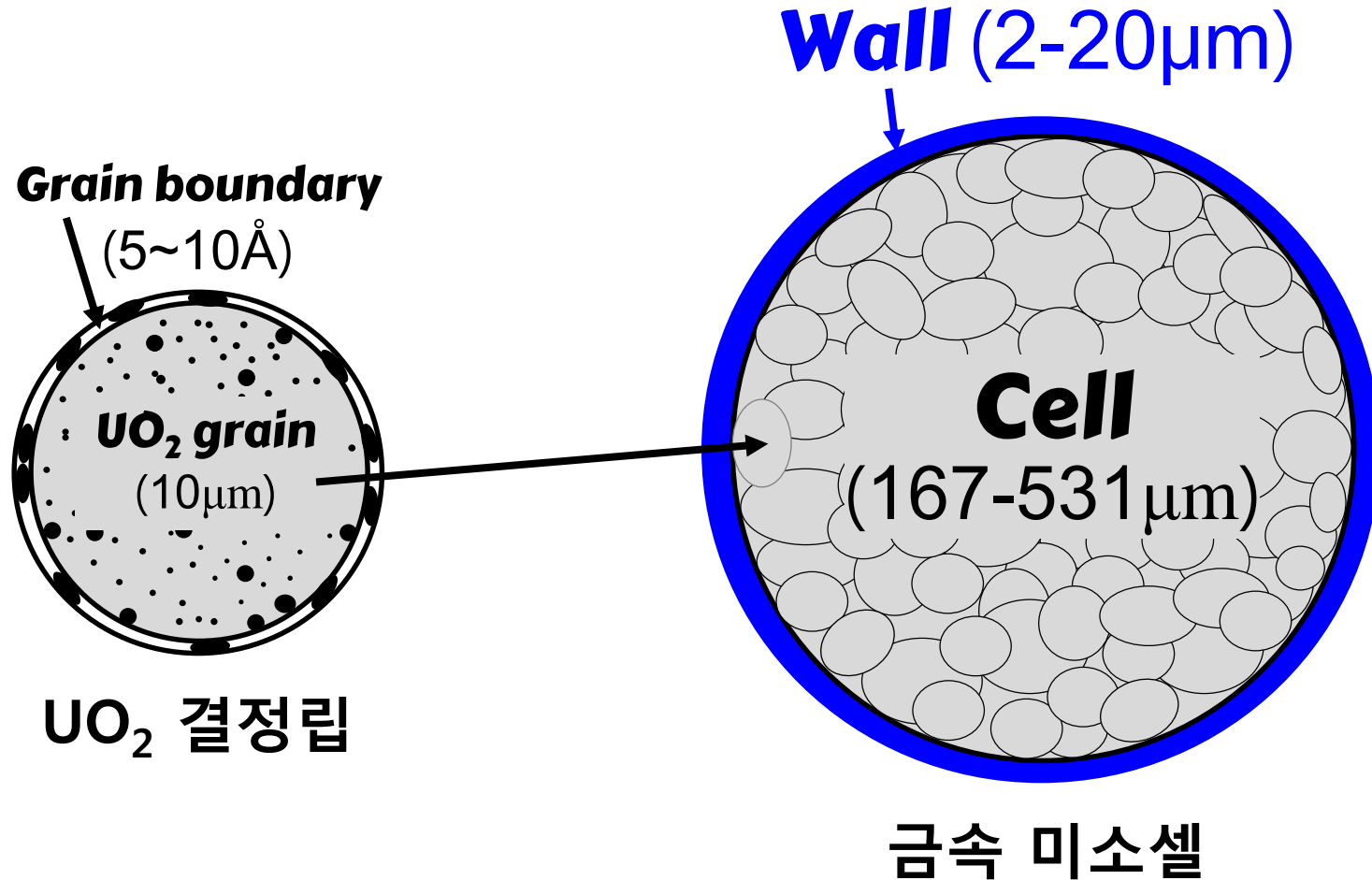
Total surface area: $2\pi r^2(\text{top/bottom}) + 2\pi r h(\text{outer}) + n_c 2rh(\text{cracked area}) = 1161.5 \text{ mm}^2$

Total number of cells in a pellet: $\pi r^2 h / (4\pi r_c^3/3) = 649910$

Total number of cells exposed to the open surface: $132.90 \times 1161.50 = 154363$

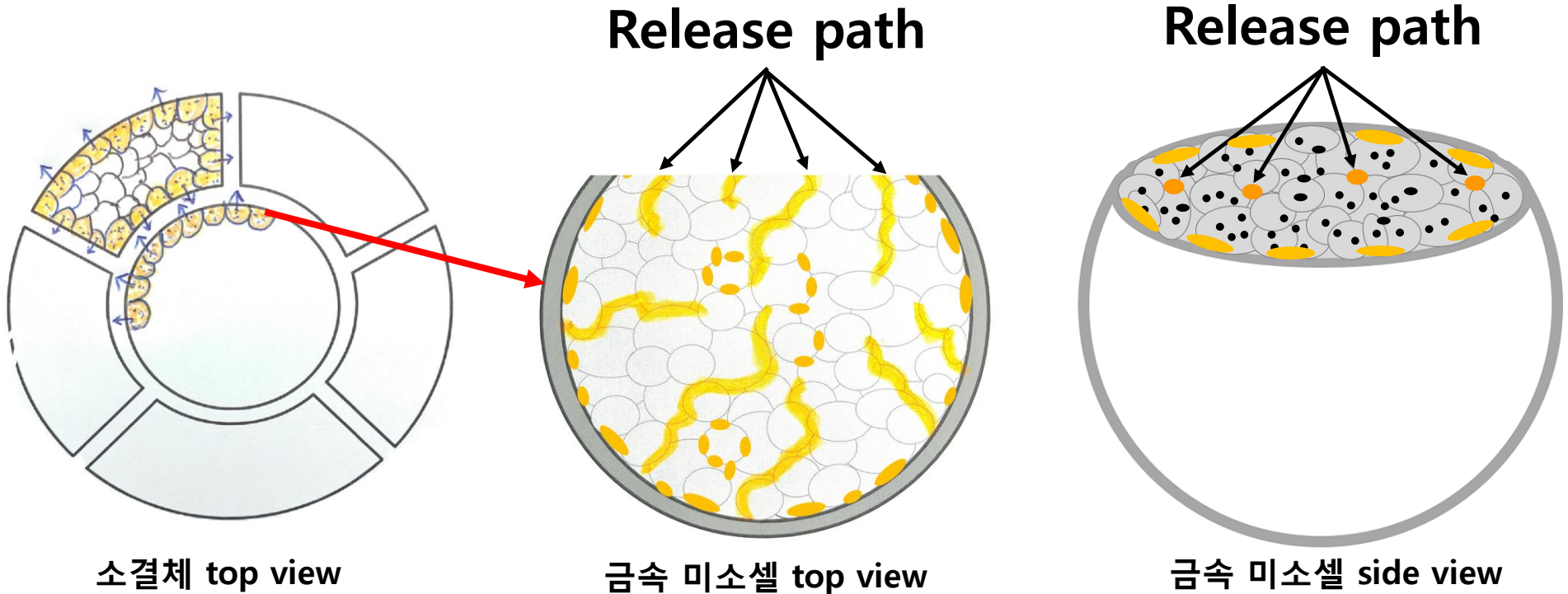
Fraction of cells exposed to the open surface in a pellet: $154363 / 649910 = 0.24$

금속 미소셀: UO_2 결정립과 비교



금속 미소셀: 기체방출 경로

표면에 노출된 matrix에서 gas atoms 확산 및 결정립계에 형성된
Release path: 전체 셀 중에서 표면에 노출된 셀의 비율이 중요



금속 미소셀: 셀 크기, 노출된 셀 갯수

분석방법	분석항목	금속 셀	세라믹 셀
3D 계산*	셀 평균 크기 (μm)	345.10	115.19
2D 이미지 분석**	셀 평균 크기 (μm)	265.46	88.61
	단위면적당 cell 수(개/ mm^2)	14.72	132.90

* 2D 이미지 분석 결과를 이용하여, 소결체 내부에 존재하는 셀 평균 크기 3D 계산

** 2D 이미지를 이용하여, 소결체 외면 및 균열 단면에 노출되는 셀에 대한 정보 분석

김동주, "미소셀 크기 및 분포 분석", 2018. 7. 13.

금속 미소셀: 방출률 (20kW/m) $< 0.17 f_{\text{UO}_2}$

- UO_2 소결체 (모든 결정립에서 기체방출): 방출률 = f_{UO_2}
- 세라믹 (17% 셀(결정립)에서만 방출): 방출률 $< 0.17 f_{\text{UO}_2}$

Linear power: 20kW/m , $T_{\text{CL}} < 1000^\circ\text{C}$, number of cracks(n_c): 10

Pellet radius(r): 4.1mm, pellet height(h): 9.8mm

Cell size($2r_c$): 345.10 μm , cells/area: 14.72/ mm^2

Total surface area: $2\pi r^2(\text{top/bottom}) + 2\pi r h(\text{outer}) + n_c 2r h(\text{cracked area}) = 1161.5 \text{ mm}^2$

Total number of cells in a pellet: $\pi r^2 h / (4\pi r_c^3/3) = 100776$

Total number of cells exposed to the open surface: $14.72 \times 1161.50 = 17097$

Fraction of cells exposed to the open surface in a pellet: $17097 / 100776 = 0.17$

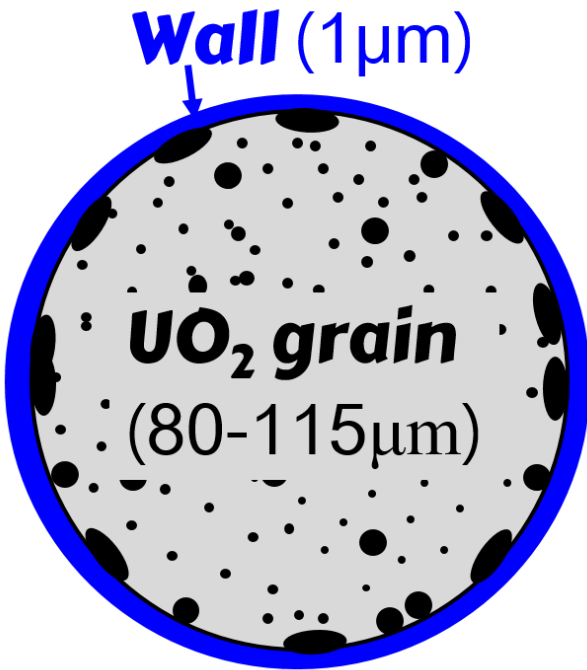
요약: 미소셀 기체방출, 정성적 분석

동일 선출력(20kW/m), 기체방출률 : $\text{UO}_2 > \text{세라믹} > \text{금속}$

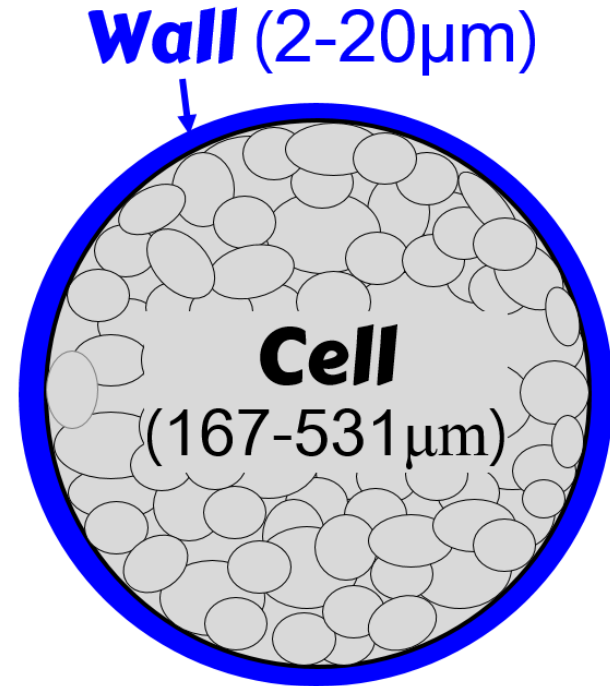
	UO_2 소결체	세라믹 미소셀 소결체 (2vol% Si-Ti-O)	금속 미소셀 소결체 (5vol% Mo)
표면 노출 셀 비율		24% (셀 크기 $115\mu\text{m}$)	17% (셀 크기 $345\mu\text{m}$)
기체 방출률	f_{UO_2}	$f_{\text{세라믹}} < 0.24 f_{\text{UO}_2}$	$f_{\text{금속}} < 0.17 f_{\text{UO}_2}$

조사후시험에서 확인할 내용

1) 연소 중 셀 wall의 존재 여부, 2) Crack pattern 및 개수



세라믹 미소셀



금속 미소셀