

(KNS Workshop) 사고저항성 핵연료: 단기 및 장기 전략

표면개질(coating, ODS) ATF 개발 현황

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핵연료안전연구부

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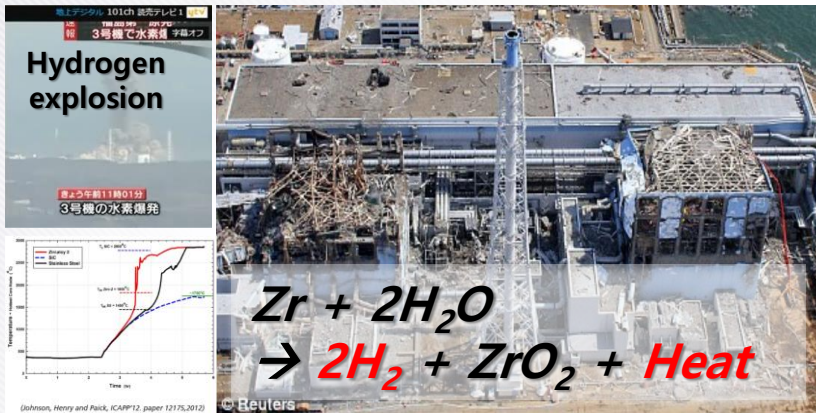
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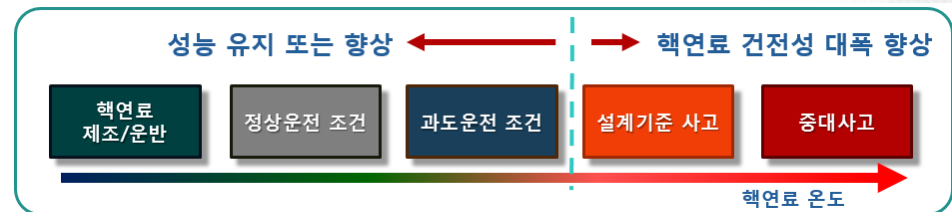
01 사고저항성 핵연료 개념

» 사고저항성핵연료(Accident Tolerant Fuel, ATF)



Fukushima Daiichi Accident ('11.03)

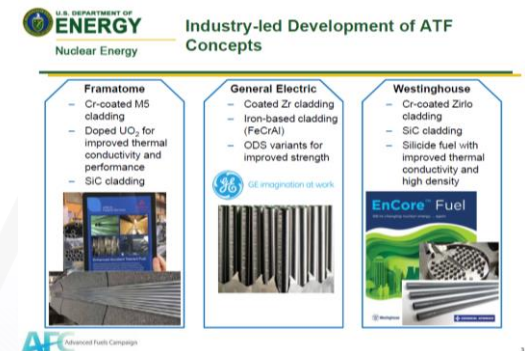
- ✓ 원전의 냉각기능이 손실된 상태에서 UO_2 -Zr 핵연료 대비 상대적으로 핵연료의 건전성을 장시간 동안 유지할 수 있는 핵연료 (중대사고 시 사고전개 지연, 대처시간 확보)
- ✓ 동시에, 원전의 정상/과도 운전에서도 핵연료의 성능이 UO_2 -Zr 핵연료와 동등 또는 우수한 핵연료



- ✓ ATF는 국제기구와 주요 원전 가동국들이 역량을 동원해 개발중인 원자력 핵심 안전 기술로 조기 실용화를 위한 경쟁 체계 돌입
- ✓ 향후 가동 원전의 모든 핵연료는 ATF가 되어야 함 → "Game Changer"

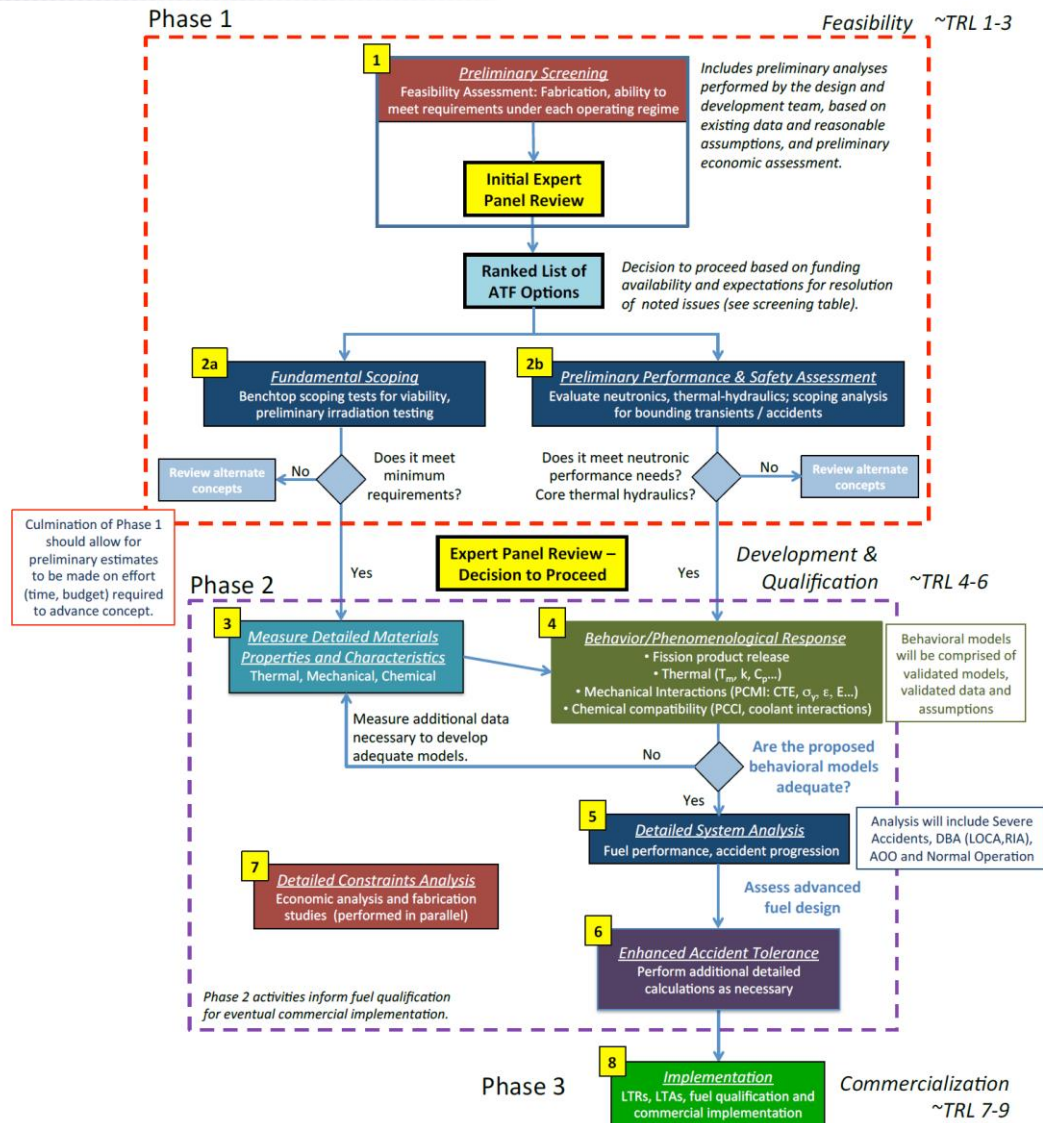


ATF Stakeholder Collaboration



01 사고저항성 핵연료 개발

» 사고저항성 핵연료 개발 전략(TRL base)

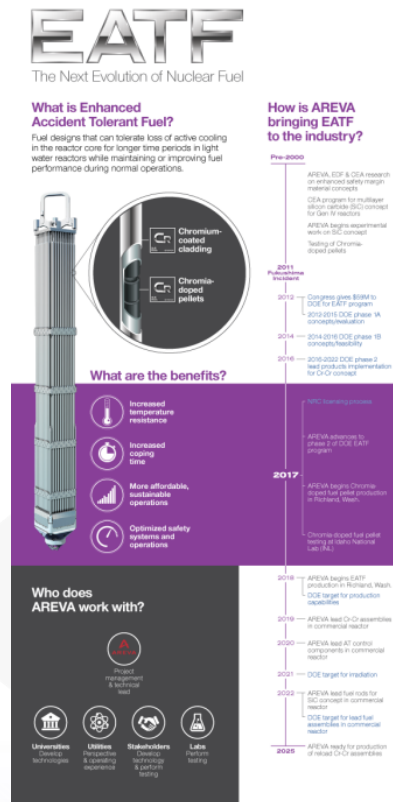
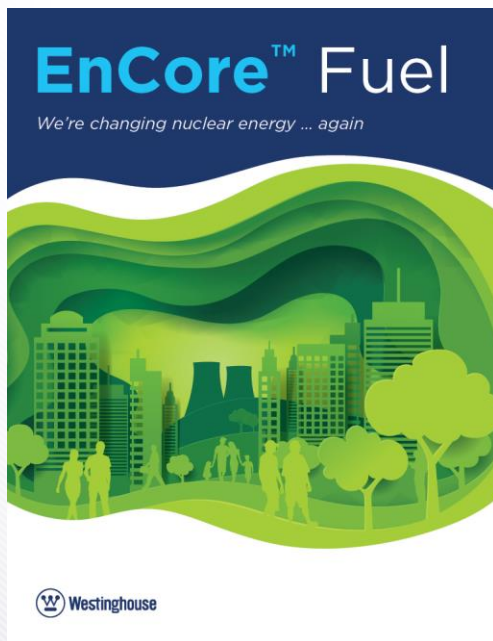


- I. Fabrication/Manufacturability**
Associated Performance Attributes
a. Manageable fissile material content
b. Compatible with large-scale production needs (material availability, fabrication techniques, waste, etc.)
c. Compatible with quality and uniformity standards
d. Ease of licensing
Considerations
Millions of clad/year
Approximately 300 million pellets/year
Economics: cost of raw materials and fabrication process, maximum cycle length, waste disposal
Current fabrication plant enrichment limits
- II. Normal Operation and AOOs**
Associated Performance Attributes
a. Utilization or burnup (12-, 18-, or 24-month cycle)
b. Thermal-hydraulic interaction
c. Reactivity control systems interaction
d. Mechanical strength, ductility (BOL and after irradiation)
e. Thermal behavior (conductivity, specific heat, melting)
f. Chemical compatibility (fuel cladding) and stability
g. Chemical compatibility with and impact on coolant chemistry
h. Fission product behavior
Considerations
Overall neutronics
Linear heat generation rate to centerline melt
Power ramp, $\sim 100 \text{ W/m} \cdot \text{min}^{-1}$
Reduced flow [departure from nucleate boiling (DNB)]
Flow-induced vibrations
Surface roughness effects
Safe shutdown: earthquake
External pressure ($\sim 2750 \text{ psi}$, 10% above PWR design pressure)
Axial growth (less than upper nozzle gap)
- III. Postulated Accidents (Design Basis)**
Associated Performance Attributes
a. Thermal-hydraulic interaction
b. Reactivity control systems interaction
c. Mechanical strength, ductility
d. Thermal behavior (conductivity, specific heat, melting)
e. Chemical compatibility and stability (e.g., oxidation behavior)
f. Fission product behavior
g. Combustible gas production
Considerations
Prompt reactivity insertion
Post-DNB behavior ($T > 800^\circ\text{C}$ for Zr-UO₂ system)
Loss-of-coolant conditions
Thermal shock behavior
Steam reactions ($\sim 1000^\circ\text{C}+$)
- IV. Severe Accidents (Beyond Design Basis)**
Associated Performance Attributes
a. Mechanical strength, ductility
b. Thermal behavior (conductivity, specific heat, melting)
c. Chemical compatibility and stability (including high-temperature steam interaction)
d. Fission product behavior
e. Combustible gas production
Considerations
Thermal shock behavior
Chemical reactions
Combustible gas release
Fission product release
Long-term stability in degraded state
Retention of coolable geometry
- V. Used Fuel Storage, Transportation, and Disposition**
Associated Performance Attributes
a. Mechanical strength, ductility
b. Thermal behavior
c. Chemical stability
d. Fission product behavior
Considerations
Handling, placement, and drying loads
Future reprocessing potential

01 단기적용을 위한 ATF 기술 현황

» 단기적용 ATF 기술은 성능향상도는 낮지만 상용화가 용이

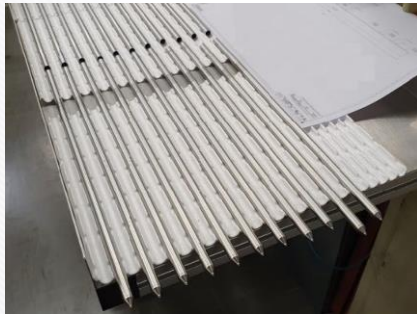
- ❖ Coated (Cr, Cr-alloy, AMOR) Zr cladding (PWR)
 - Framatome, Westinghouse, GE-GNF, Rosatom, CN, KO
- ❖ 성능개선(열전도도 등) UO_2 : Framatome, Westinghouse, CN, KO
- ❖ Fe-base cladding (BWR) : GE-GNF, Rosatom, JP, CN, KO



01 중·장기적용을 위한 ATF 기술 대상 요약

» 단기적용 ATF 기술 대비 높은 성능향상도 연구개발 추진

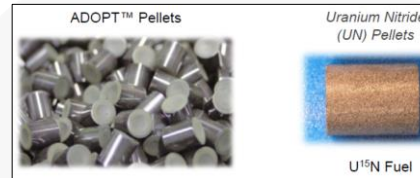
- ❖ **Coated Zr cladding, inner coating** : Framatome, CEA, Mitsubish, **CN, KO**
- ❖ **SiC cladding, channel box** : Framatome, CEA, General Atomics, ORNL, INL, Hitachi, **CN, KO**
- ❖ **Fe-base cladding, FeCrAl-ODS** : GE/GNF, JAEA, Hitachi, Toshiba, **CN, KO**
- ❖ **Fuel pellet with improved thermal conductivity** : Framatome, Westinghouse, INL, **CN, KO**
- ❖ **High U density pellet** : Westinghouse, LANL, INL, KTH, USTA, Rensselaer, **CN, KO**
- ❖ **Accident Tolerant Control Rod** : CRIEPI, Framatome, Westinghouse, Rosatome, **CN, KO**



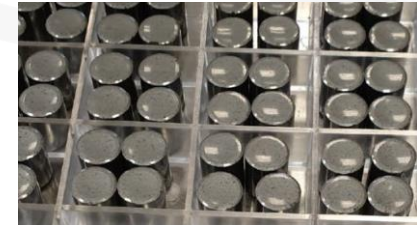
<Coated rods, Framatome>



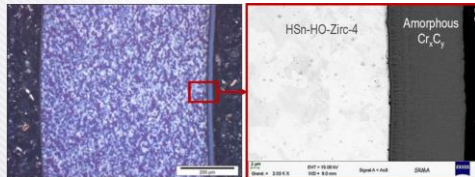
<SiC rodlets, Framatome>



<Advanced pellet, Westinghouse>



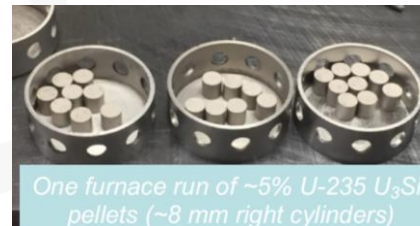
<Cr-variant pellet with high thermal conductivity, Framatome>



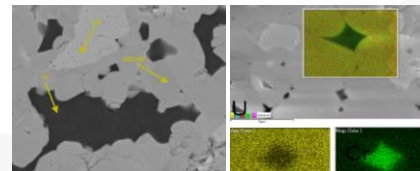
<Cladding inner coating, CEA>



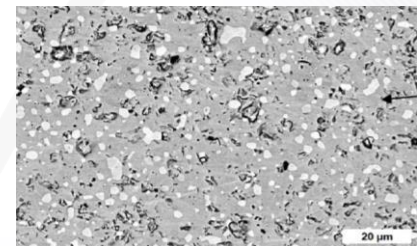
<SIGA™ SiC composite, GA>



<U₃Si₂ pellet, LANL>



<CrN/Cr-doped UN pellet, KTH/Rensselaer>



<UO₂-UB₂ pellet with high thermal conductivity, Westinghouse>

01 사고저항성 핵연료 개발에 대한 신규 정책

» EU Taxonomy의 원자력 정책 변화

- ❖ **EU Taxonomy** : EU는 2050년 기후중립 달성을 위한 장기전략인 '유럽 그린딜'의 일환으로 '환경적으로 지속가능한 경제활동 분류체계'(EU Taxonomy of green, sustainable activities, 이하 EU Taxonomy)를 제정하고 '22.1.1부터 적용'
 - ✓ 당초 원자력과 가스 발전은 회원국간 견해 차이로 EU Taxonomy에 포함되지 못했으나 열띤 논쟁을 거쳐 '엄격한 조건'을 전제로 Taxonomy에 추가 ('22.2.1)
- ❖ **원자력 포함 주요 내용** : 'Supplementary Climate Delegated Act'는 지속가능한 에너지체계로의 전환을 가능케 한다는 차원에서 3개 원자력 활동을 Taxonomy에 추가하고 조건을 명시

내용		주요 조건	
		공통	활동
1	연료주기 폐기물을 최소화한 혁신 원자력 전력 생산시설의 연구/개발/실증/설치	(1) '포괄적인 안전 및 폐기물 관리 요건'을 갖춘 EU 회원국 내에서 수행 (2) 해당 회원국은 EC에 5년마다 각 사업에 대해 보고	-
2	'최선의 가용기술'을 적용한 신규 원전 (열/수소 생산용 포함)의 건설 및 안전 운영		• '45년까지 건설 허가를 받은 것에 한정 • '25년부터는 사고저항성연료 (ATF) 사용
3	기존 원전의 수명연장 을 위한 개조		• '40년까지 승인 받은 것에 한정 • '25년부터는 사고저항성연료 (ATF) 사용

*'25년 ATF 사용 조건은 EU 내에서의 ATF 개발 상황을 고려해 충분히 달성 가능하다고 판단되어 부가된 것으로 평가됨.
 이 '25년 조건은 EC의 정기적 검토시 기술 진전을 고려해 수정될 수 있음.

* BAT (best available technology)에 ATF가 포함됨

02 KAERI의 ATF 피복관 개발 전략

» 국외 개발 목표와 국내 산업계의 요구를 적극 반영



Fuels with **enhanced accident tolerance** are those that, in comparison with the standard UO_2 -Zr system, can **tolerate loss of active cooling** in the core for a **considerably longer time period** (depending on the LWR system and accident scenario) while maintaining or improving the fuel performance during normal operations.

Improved Reaction Kinetics with Steam

- Decreased heat of oxidation
- Lower oxidation rate
- Reduced hydrogen production (or other combustible gases)
- Reduced hydrogen embrittlement of cladding

Improved Fuel Properties

- Lower fuel operating temperatures
- Minimized cladding internal oxidation
- Minimized fuel relocation/dispersion
- Higher fuel melt temperature

**Enhanced
Tolerance to Loss
of Active Core
Cooling**

Improved Cladding Properties

- Resilience to clad fracture
- Robust geometric stability
- Thermal shock resistance
- Higher cladding melt temperature
- Minimized fuel-cladding interactions

Enhanced Retention of Fission Products

- Gaseous fission products
- Solid/liquid fission products

5 지금보다 2배 안전한 「사고저항성 핵연료」 개발 2017.11

- (목적) 핵연료의 내구성을 2배 강화하는 등 성능을 개선하여 사고 발생시 진행을 최대 5시간 지연시켜 폴돈타임 확보

【 사고저항성 핵연료 성능 향상 】

기술적 개선사항	성능 향상
① 핵연료 피복관 크롬(Cr) 코팅	① (강도) 물리적 내구성 2배 증가
② 핵연료 내부구조 개선	② (수소생성) 수소발생량 99% 감소
	③ (운전온도) 18% 하락 (1,100°C→900°C)

- (계획) 원자력연구원·한국원자력연료와 협업하여 핵심기술 개발 중(~18)이며, '25년 상용화를 목표로 하고 있음

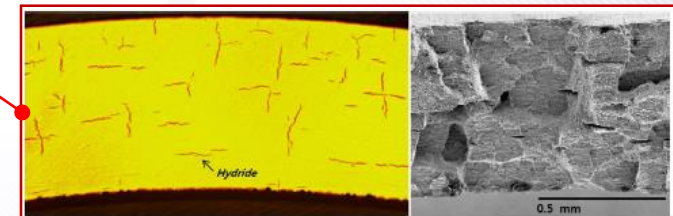
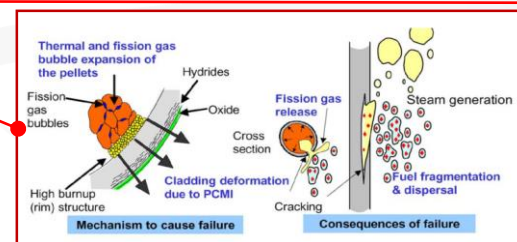
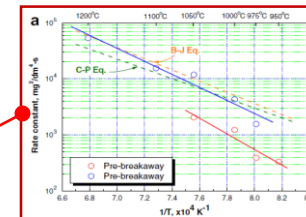
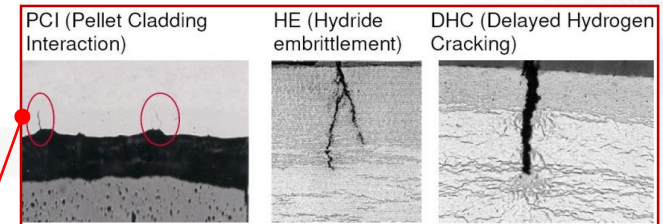
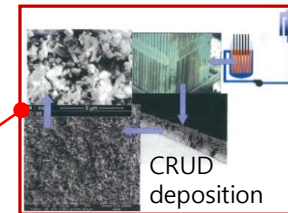
기관	단기적용 피복관
AREVA	Cr coated M5
Westinghouse	Cr coated ZIRLO
General Electric	APMT(FeCrAl), amor coating
KAERI(with KHNP and KNF)	Cr, CrAl, FeCrAl/Cr coating and ODS treatment on Zr tube

02 KAERI의 ATF 피복관 개발 전략

» 현 핵연료와의 양립성과 개발 기술의 유용성



Performance parameters		Commercial Zr alloy cladding
Manufacturability		• Optimized
Normal condition	Corrosion	• No problem (Oxide Thickness < 100nm)
	Creep	• No problem (Hoop Strain < 1%)
	Irradiation growth	• No problem (Shoulder gap closure)
	Wear resistance	• No problem (Wear damage < 10% in thickness)
	PCMI/PCI	• PCMI/PCI failure related to the hydride (hydrogen pick-up during corrosion)
DBA	LOCA	• Severe oxidation and hydrogen generation • Ballooning & Burst • Limitation (PCT < 1204°C, ECR < 17%)
	RIA	• PCMI failure related to the hydride
BDBA		• Severe oxidation and hydrogen generation • Melting problem
Spent fuel storage	Failure mechanism	• Brittle behavior by hydride • Hydride re-orientation problem (Fuel-clad interface temp.; drying: < 570°C, storage: < 400°C) (Clad hoop stress; < 90MPa)

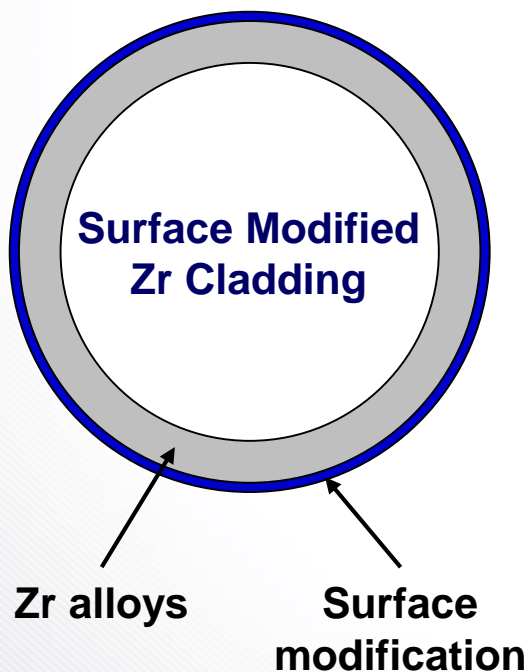


02 KAERI의 ATF 피복관 개발 전략

» 기술개발 방향

- ✓ 기존 피복관을 활용하면서 산화저항성과 변형저항성을 증가
→ 상용화의 용이성 및 경제성 향상(기존 설비, 소재 활용)

□ Concept



❖ Issues to be addressed

- Oxidation resistance
- Thermal conductivity
- Thermal expansion coefficient
- Phase stability up to high temperature
- Adhesion to the matrix
- Neutron economy
- Irradiation susceptibility
- Tube fabricability
- Unknowns

02 KAERI의 ATF 피복관 개발 전략

» 코팅용 소재 적용성 검토

ASTM STP 1543, 2014 / available online at www.astm.org

Materials	Phase Transformation Temperature, °C	Melting Point, °C	Thermal Expansion Coefficient ($\times 10^{-6}$ K)	Thermal Conductivity, W/mK	Thermal Neutron Absorption, Barns
Y ₂ O ₃	None	2690	8.1	1.0	1.28(Y) 0.0002(O)
SiO ₂	Depends on pressure	1600	12.3	1.3	0.177(Si) 0.0002(O)
ZrO ₂	M(970)/T(1205)/cubic	2130	10.1	1.8-3.0	0.182(Zr) 0.0002(O)
Cr ₂ O ₃	None	2400	90	-	3.05(Cr) 0.0002(O)
Cr ₃ C ₂	None	1895	10.3	13	3.05(Cr) 0.0035(C)
SiC (CVD)	None	2545	<5	330	0.177(Si) 0.0035(C)
ZrN	None	1960	7.24	10	0.185(Zr) 1.9(N)
ZrC	None	3540	7.01	12	0.185(Zr) 0.0035(Cr)
Cr	None	1907	4.9	93.9	3.05(Cr)
Si	None	1414	2.6	149	0.177(Si)
Zr	HCP(863)/BCC	1850	7.2	22	0.185(Zr)

02 KAERI의 ATF 피복관 개발 전략

» 코팅/표면처리 기술 검토 및 적용기술

Plasma spray



Cold spray



Arc ion plating



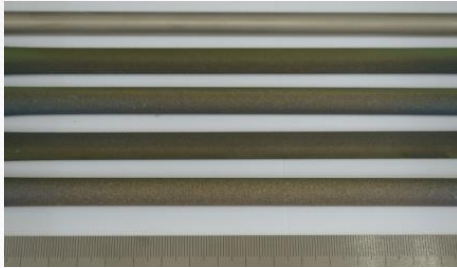
3D printing



03 KAERI의 ATF 피복관 개발 현황

» Plasma spray: Cr coating

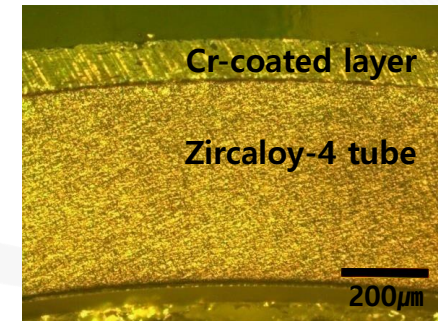
Cr-Plasma Spray Coating



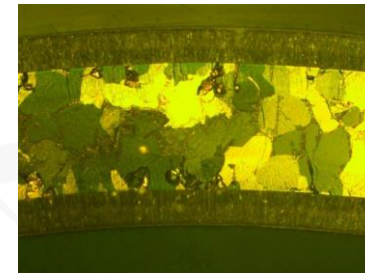
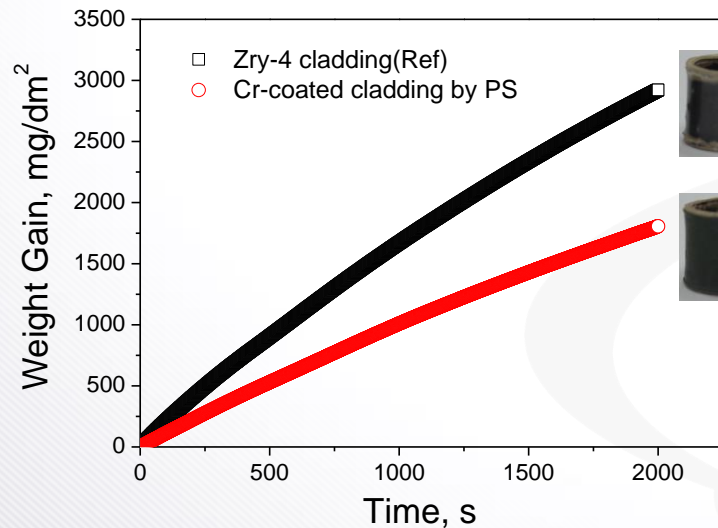
Surface Polishing after Coating



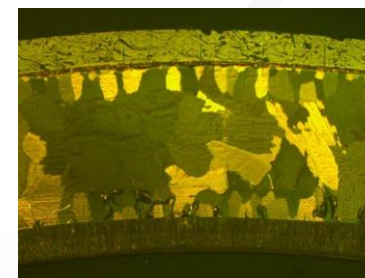
Cross-sectional observation



Oxidation behavior at 1200°C steam condition



← ZrO₂
← α-Zr(O)
← Prior β-Zr
← α-Zr(O)
← ZrO₂



← Cr-coated layer
← α-Zr(O)
← Prior β-Zr
← α-Zr(O)
← ZrO₂

03 KAERI의 ATF 피복관 개발 현황

» Cold spray: Cr, FeCrAl coating

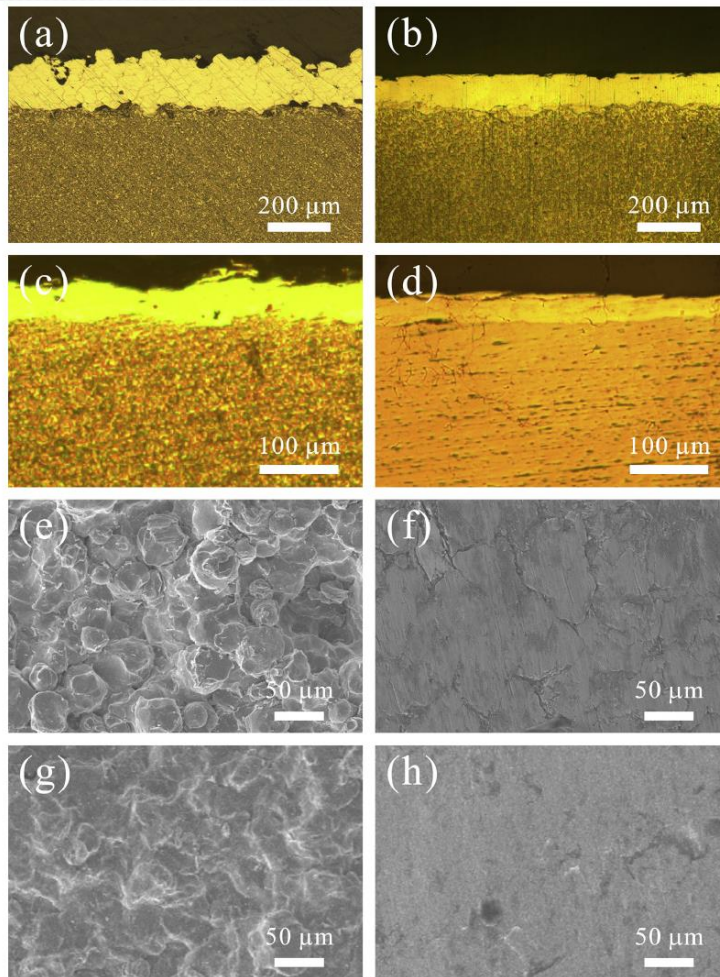


Fig. 1. OM images of a cross-sectioned FeCrAl-coated plate sample (a) before and (b) after cold rolling, and a cross-sectioned Cr-coated plate sample (c) before and (d) after cold rolling. Plane view SEM images of a FeCrAl-coated plate sample (e) before and (f) after cold rolling, and a Cr-coated plate sample (g) before and (h) after cold rolling.

Journal of Nuclear Materials 482 (2016) 75-82

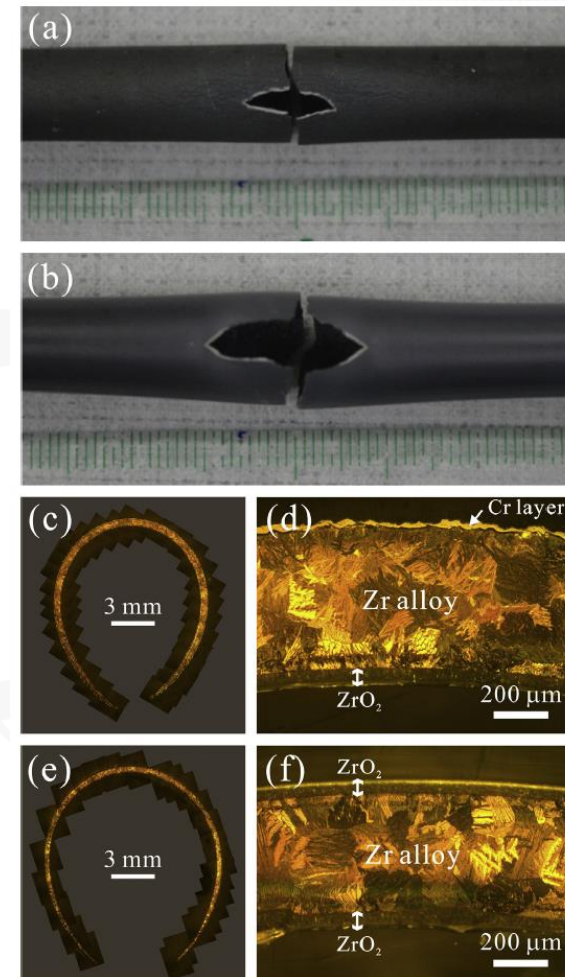


Fig. 5. Photographs of the ballooned regions and burst openings of Zr cladding specimens (a) with and (b) without Cr coating after integral LOCA and mechanical testing. (c, e) Optical microscopy images of cross sections at the burst mid-planes of a Cr-coated and uncoated Zr cladding tube, respectively. (d, f) Optical microscopy images of the cross-sections 180° from the burst opening of a Cr-coated and uncoated Zr cladding tube, respectively.

03 KAERI의 ATF 피복관 개발 현황

» Arc ion plating(AIP): Cr coating

Surface & Coatings Technology 280 (2015) 256–259

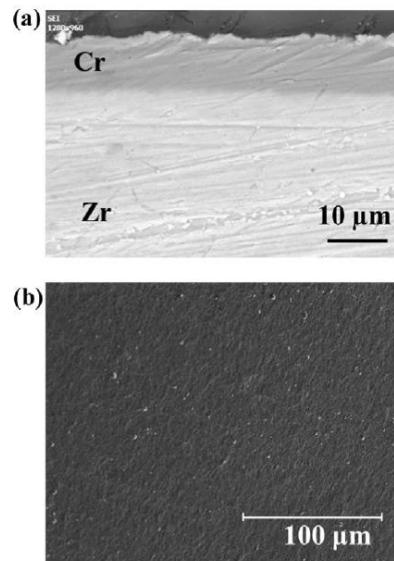


Fig. 2. (a) Cross-sectional SEM image showing a dense and adherent Cr layer on Zircaloy-4 cladding. (b) SEM surface micrograph of the Cr coated Zircaloy-4.

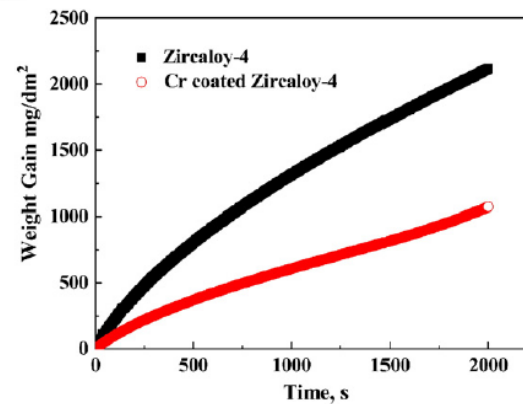


Fig. 3. Corrosion behaviors of the pristine and Cr-coated Zircaloy-4 in 1473 K steam for 2000 s.

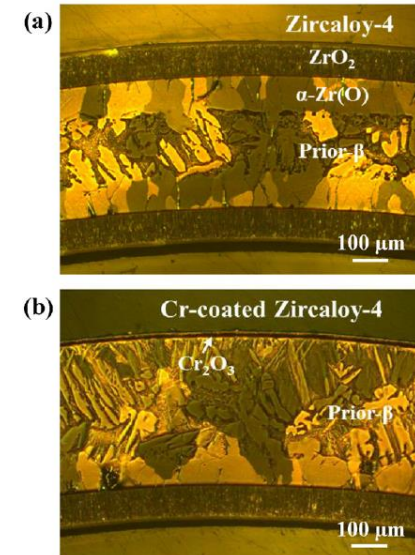


Fig. 4. Reflected light optical micrographs of the oxides formed on the (a) Zircaloy-4 and (b) Cr-coated Zircaloy-4 in 1473 K steam for 2000 s.

Accident Tolerant Fuel Development: Promise, Status, and Challenges

Presented at
Fuel Reliability Program Winter Technical Advisory Committee Meeting
7th EPRI/INL/DOE Joint Workshop On Accident Tolerant Fuel

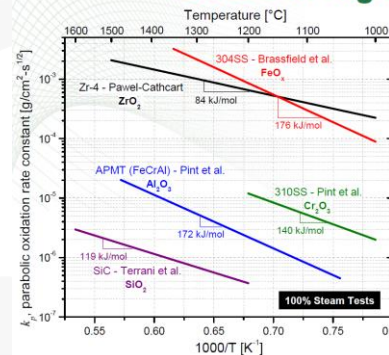
Kurt Terrani
Oak Ridge National Laboratory

AFC Advanced Fuels Campaign

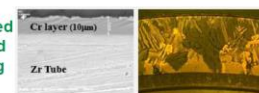
terrani@ornl.gov
Feb 22, 2018



The Basis Of Accident Tolerant Fuel Cladding Technologies Are Materials That Form Protective Oxides In High Temperature Steam

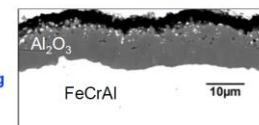


Cr-coated
Zr-based
cladding



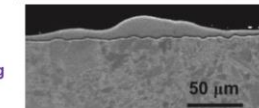
1200°C
0.6 h
KAERI

FeCrAl
cladding



1475°C
4 h

SiC/SiC
cladding



1700°C
4 h

OAK RIDGE
National Laboratory

B.A. Pint, K.A. Terrani, Y. Yamamoto, L.L. Snead, "Material Selection for Accident Tolerant Fuel Cladding," Metall. Mater. Trans. E. 2(3) (2015) 190–196

03 KAERI의 ATF 피복관 개발 현황

» 3D printing: Cr coating

Journal of Nuclear Materials 465 (2015) 531- 539

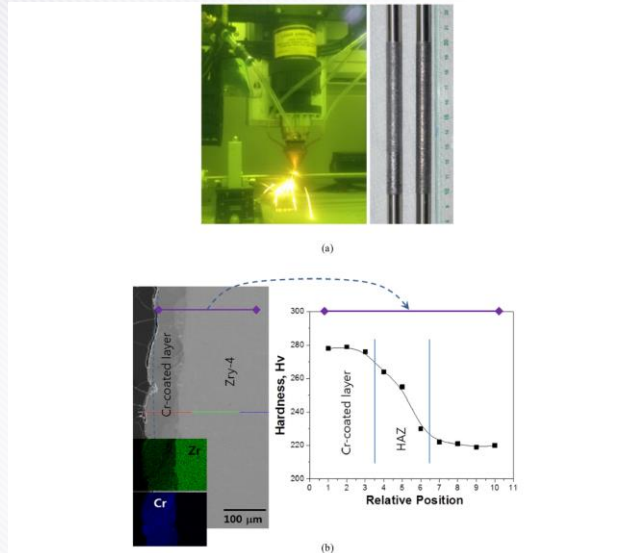


Fig. 4. A diagram of the 3D laser coating process supplying the Cr powder and the surface appearance of the sample (a), and cross-sectional analysis and micro-hardness variations of the Cr-coated Zircaloy-4 cladding tube (b).

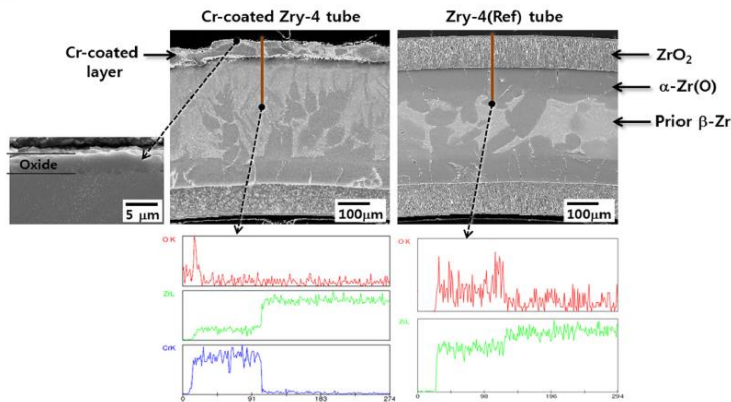


Fig. 7. Cross-sectional SEM observation of the Cr-coated Zircaloy-4 cladding tube using 3D laser coating and the reference Zircaloy-4 cladding tube after the high-temperature oxidation test at 1200 °C for 2000 s in a steam environment.

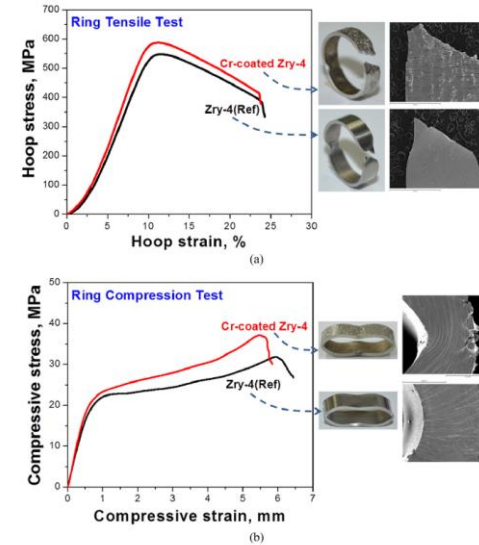


Fig. 5. Ring tensile test results and appearance of the Cr-coated Zircaloy-4 cladding tube (a), ring compression test results, and appearance of the Cr-coated Zircaloy-4 cladding tube (b).

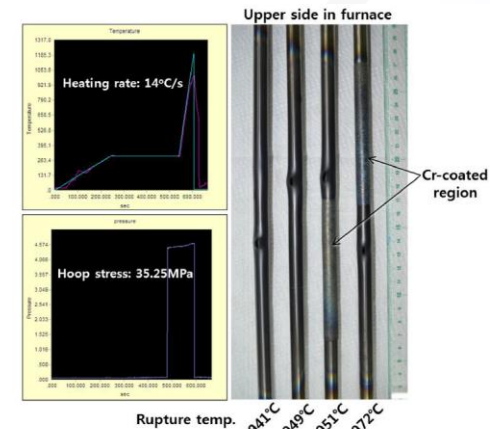


Fig. 9. Profile of heating rate and internal pressure during the LOCA simulation test, and the surface appearance of the tested tube samples of non-coated Zircaloy-4 and partially Cr-coated Zircaloy-4 cladding tubes.

03 KAERI의 ATF 피복관 개발 현황

» 3D printing: ODS 기술

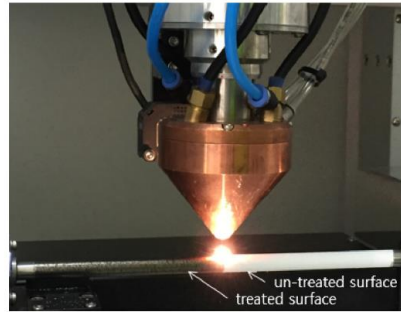


Fig. 1. Appearance of ODS treatment using laser technology on commercial Zircaloy-4 cladding tube surface.

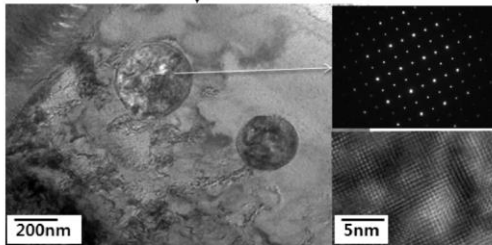
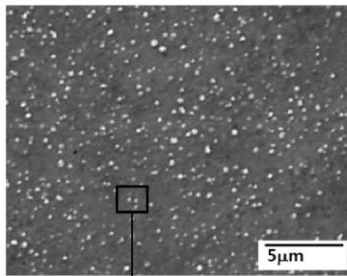


Fig. 5. High-magnification observations and structure analysis of Y_2O_3 particles incorporated in the Zircaloy-4 cladding matrix.

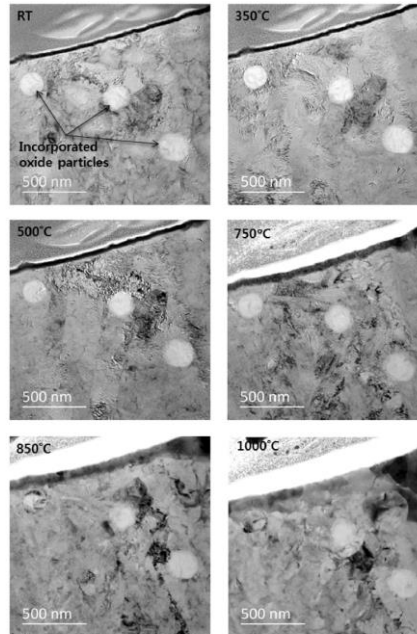


Fig. 6. High-magnification observations by in-situ TEM of Y_2O_3 particles incorporated in the Zircaloy-4 cladding matrix from RT to 1000°C.

Additive Manufacturing 22 (2018) 75–85

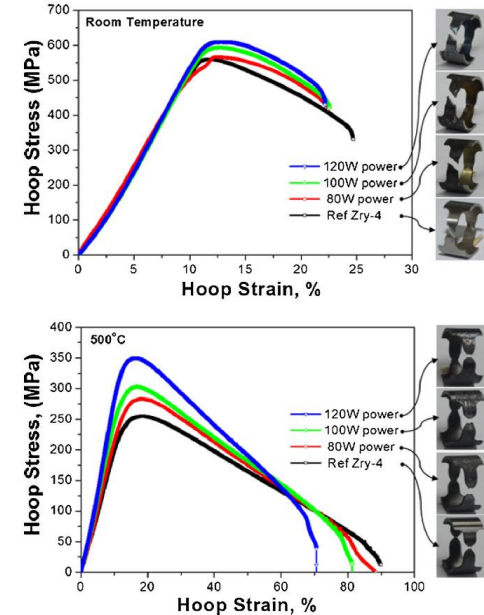


Fig. 8. Engineering stress-strain curves and fractured images of the laser-processed Zircaloy-4 and reference Zircaloy-4 samples.

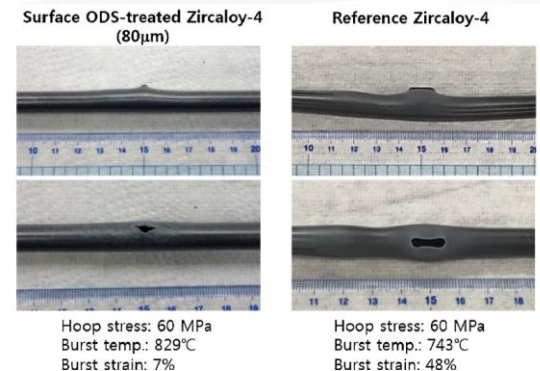


Fig. 9. Appearances of ballooning and ruptured samples of the surface ODS-treated Zircaloy-4 and reference Zircaloy-4 cladding tubes after the LOCA simulation test.

03 KAERI의 ATF 피복관 개발 현황

» 내산화 소재: CrAl 합금

FIG. 1 Corrosion behavior of CrAl binary alloy and Zircaloy-4 tested in PWR simulated loop at 360°C: (A) weight change as a function of test time, (B) weight gain after 660-day test.

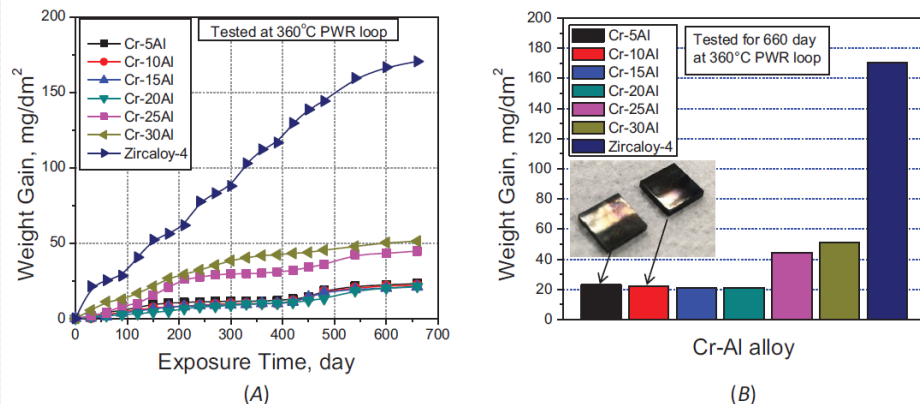
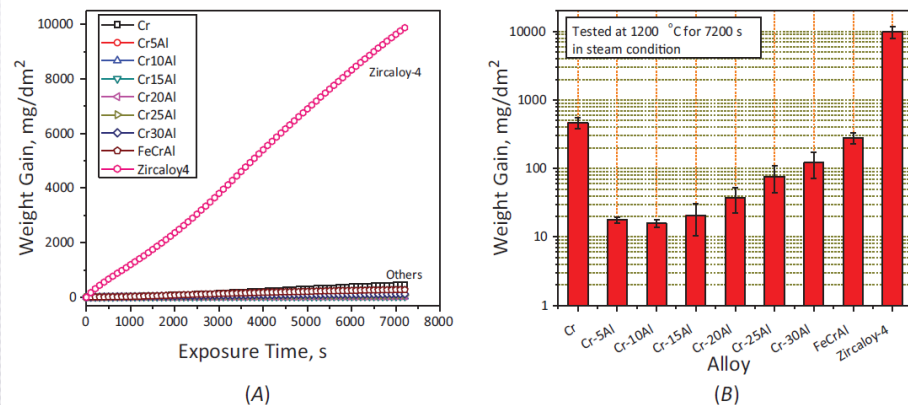


FIG. 2 High-temperature oxidation behavior of pure Cr, CrAl binary alloy, FeCrAl alloy, and Zircaloy-4 tested at 1,200°C steam conditions: (A) weight change as a function of test time, (B) weight gain after 7,200-s test.



ASTM STP 1622, 2021 / available online at www.astm.org

FIG. 4 High-temperature oxidation behavior of Cr-10Al binary alloy: (A) weight change as a function of test time at 900 to 1,400°C, (B) additional Cr-10Al alloy test result in Arrhenius plot of the parabolic weight gain rate constants.

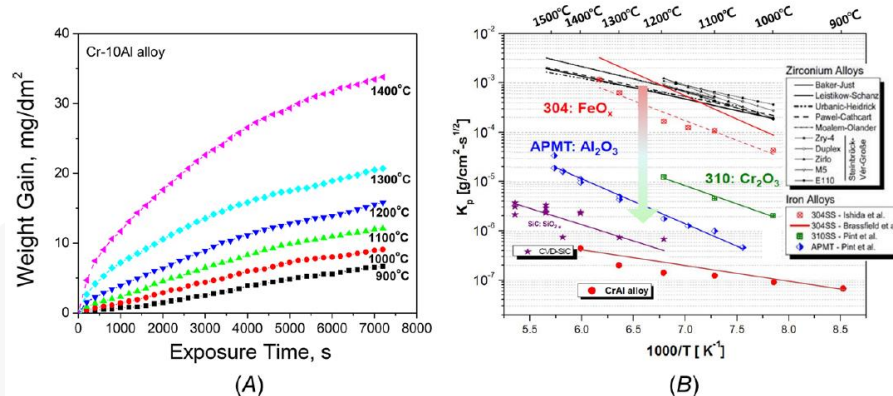
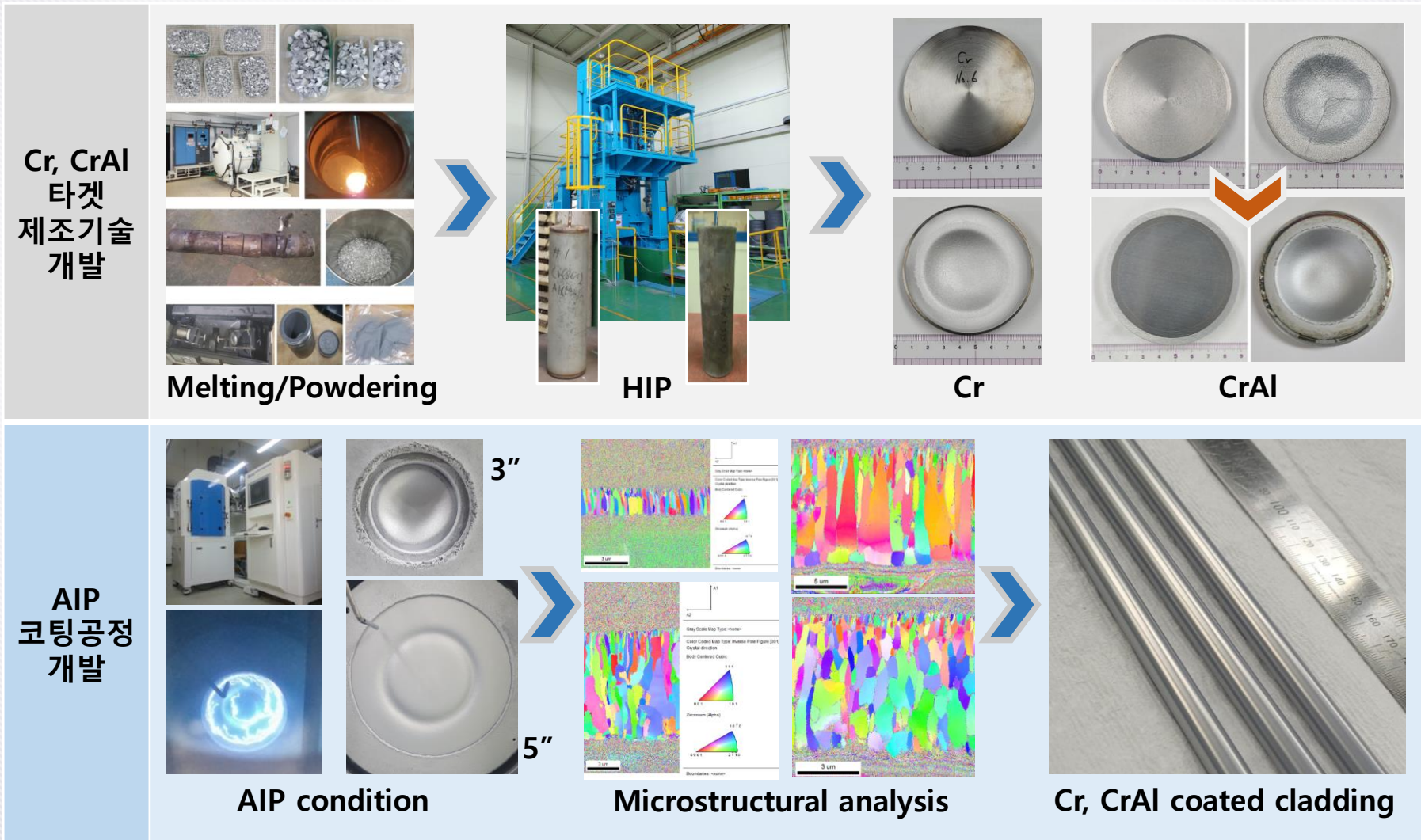


FIG. 10 Appearance of the Zircaloy-4 cladding and Cr-12Al-coated cladding tube after one-cycle irradiation test in the Halden reactor.



03 KAERI의 ATF 피복관 개발 현황

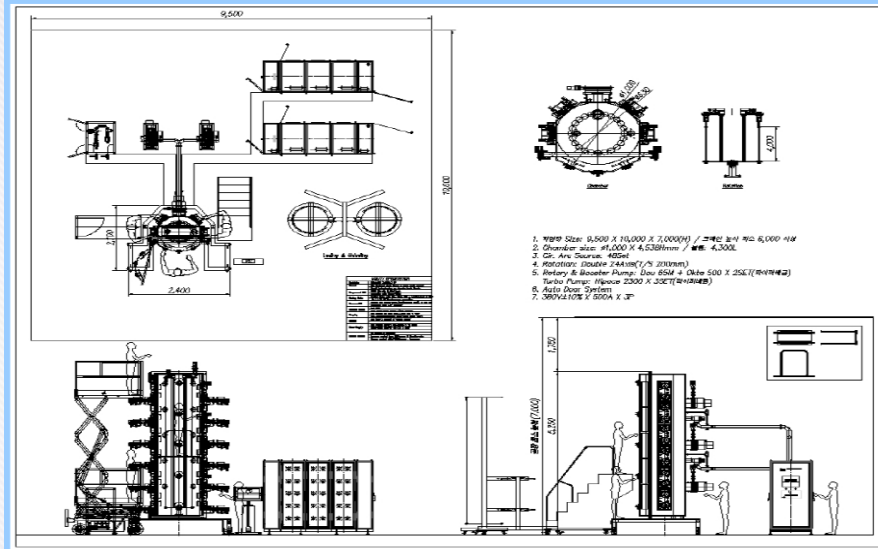
» 내산화 소재 AIP 코팅: Cr, CrAl 타겟 제조 및 AIP 공정 고도화



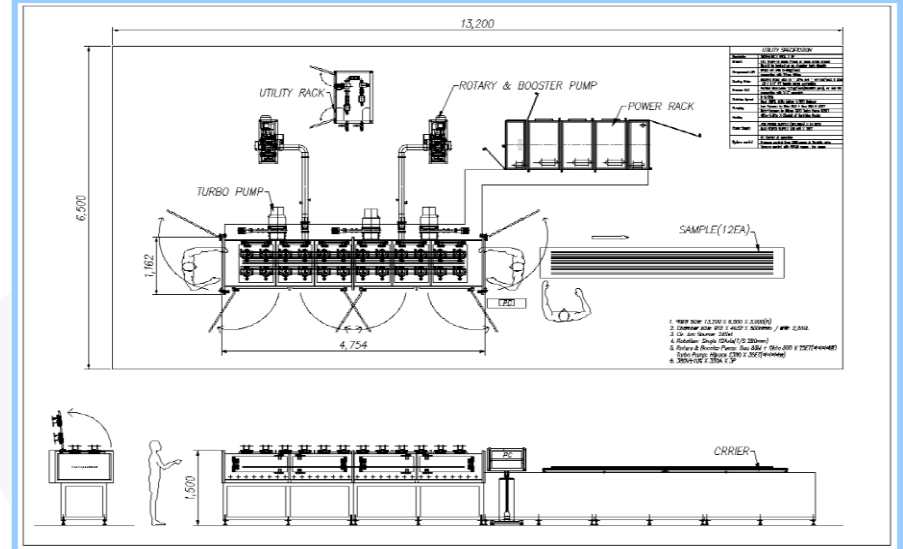
03 KAERI의 ATF 피복관 개발 현황

» AIP 코팅: 4m급 AIP 장치 설계 및 KNF에 제공(2018.07)

Vertical Type



Horizontal Type



재원 / 공정 부분			TYPE	
NO	항 목	기 준	Horizontal Type	Vertical Type
1	Lay-Out	설치 기준	13,200 X 6,500 X 3,000(H)	9,500 X 10,000 X 7,000(H)
2	Electricity	설치 기준	380V X 350A	380V X 500A
3	Chamber Volume		약 2,200 L	약 4,300 L
4	장 입 량	1 Batch	12 EA	24 EA
5	Tact Time	1 Batch	10 시간(편 측 40μm) Single (자전) 회전 방식	20 시간(편 측 40μm) Double (자전 + 공전) 회전 방식
6	생 산 량	1일, 20시간	24 EA (1일 / 2 Batch)	24 EA (1일 / 1 Batch)
7	Target 소모	5' 원형, 15T	4 Batch	2 Batch
8	Source	T/T, T/S	T/T= 350, T/S= 280(T/S 변경 가능)	T/T= 350, T/S= 200
9	Heater	Chamber Temp	300°C Cartridge Heater 채용(32Set)	400°C Sheath Heater 채용(10Set)
10	Jig Guide Unit	4M Tube 치점 보완	Tube 치점 보완 Guide Unit 구성	Guide Unit 미 구성
11	Jig 방식	4M Tube	별도 Jig Unit 구성	개별 Jigging

제작 부분			TYPE	
NO	항 목	기 준	Horizontal Type	Vertical Type
1	제작 방식	제작 & 시운전	완제품 납품 당사 내 제작 & 시운전 완료	Sub Assembly 조립 후 납품 처 현장 조립 완료
2	제작 및 설치 공 간	설치 기준	실내 공간 (길이 또는 폭) 13M 이상	천장 높이 7M 이상 확보 필요
3	제작 시간	조립 기준	현역 업체 주변, 부품 수급 용이	부품 수급 및 시정 조치 시간 소요
4	SET-UP	해제 및 이동	SET-UP 기간 필요 Chamber 분리 가능, 이동 편이	SET-UP 기간 불 필요 Chamber 일체형, 이동 불편
5	양 산 성	현 재	제작 공간 등 제약 없어 양산 용이	양산 방법 모색 (제작 공간 등 제약 사항 제거)
6	제작 원가	Chamber Size Source 수량	원가 절감 (기준 사항과 비례)	원가 상승 (기준 사항과 비례)

정비 부분			TYPE	
NO	항 목	기 준	Horizontal Type	Vertical Type
1	정비 방식 및 공간	작 업 자	지상 작업	고소 작업
2	정비 능력	작 업 자	정비 공간 제한 적어 능력 총괄 가능	정비 공간 및 고소 작업 자 탑승 제한
3	정비 시간	작 업 자	정비 시간 단축 (정비 방식 용이 및 능력 총괄)	정비 시간 늘어남 (정비 공간 및 고소 작업 자 탑승 제한)
4	Target 교체 시간	미 숙련 자 (1인) 15set 교체 시간 (3분)	약 1 시간 30 분 이내 (Target 교체 24 EA) (Target 교체 24 EA)	약 3 시간 이상 (Target 교체 48 EA) (고소 작업으로 더 늘어남)
5	위험 성	작 업 자	위험 요소 제거 개선 여지	환경 특성상 위험 요소 제거 어려움 (작업자 고소 작업 및 공기 낙하)
6	기 자 재	작 업 자	기 자재 불 필요	고소 작업 자 또는 동등 기 자재 필요

03 KAERI의 ATF 피복관 개발 현황

» AIP+3D printing: CrAl, FeCrAl 코팅/ODS *Journal of Nuclear Materials* 510 (2018) 93-99

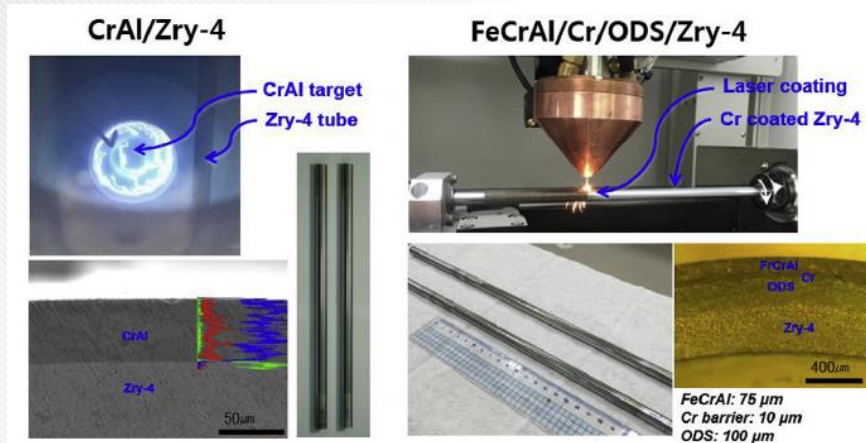


Fig. 2. Manufacturing example of surface modification technology using arc ion plating and 3D laser process.

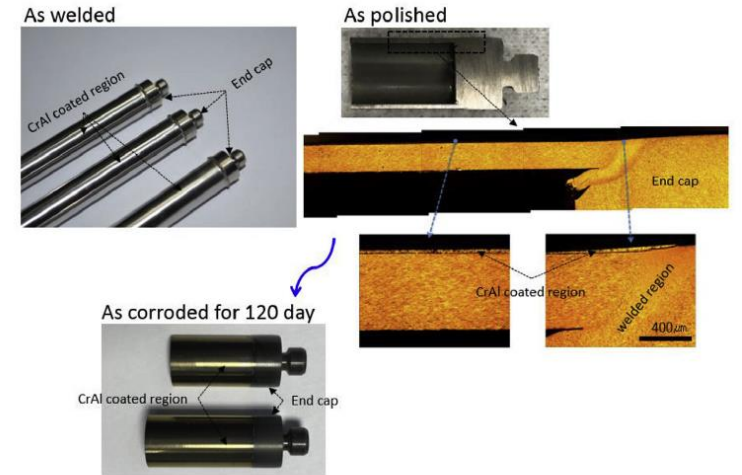


Fig. 4. Microstructure and corrosion behavior at the weld zone of CrAl-coated Zry-4 cladding.

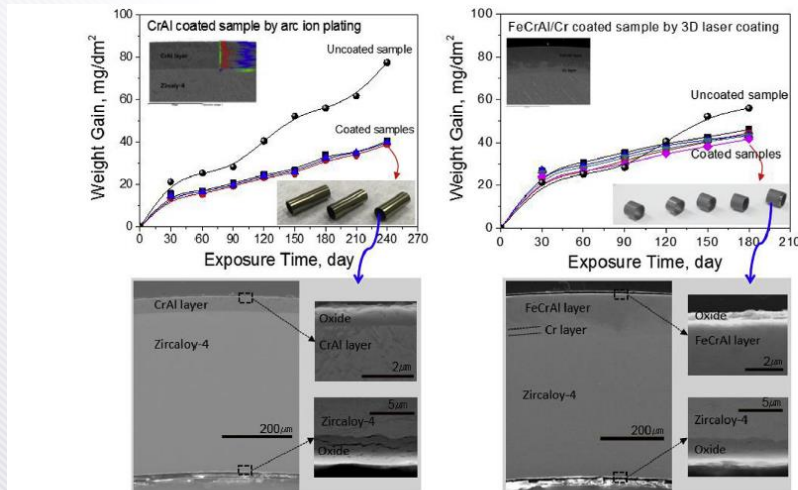


Fig. 3. Corrosion behavior and cross-sectional observation of surface-modified Zry-4 cladding in PWR simulation loop condition at 360 °C.

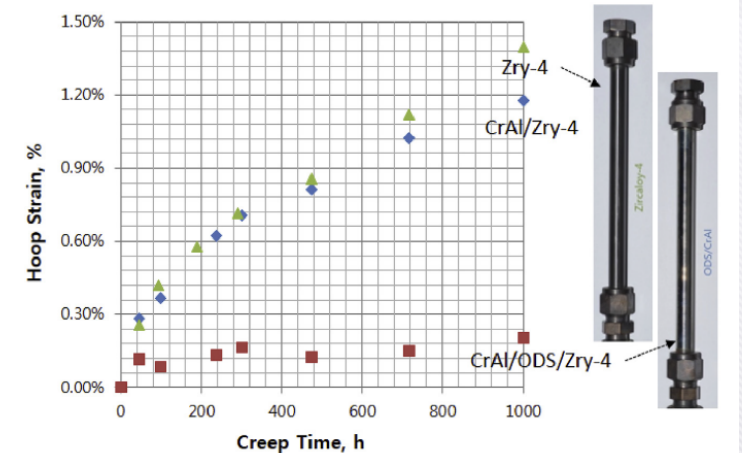


Fig. 5. Creep behavior of surface-modified Zry-4 cladding at 380 °C for 1000 h in air.

03 KAERI의 ATF 피복관 개발 현황

» AIP+3D printing: CrAl, FeCrAl 코팅/ODS [Journal of Nuclear Materials 510 \(2018\) 93-99](#)

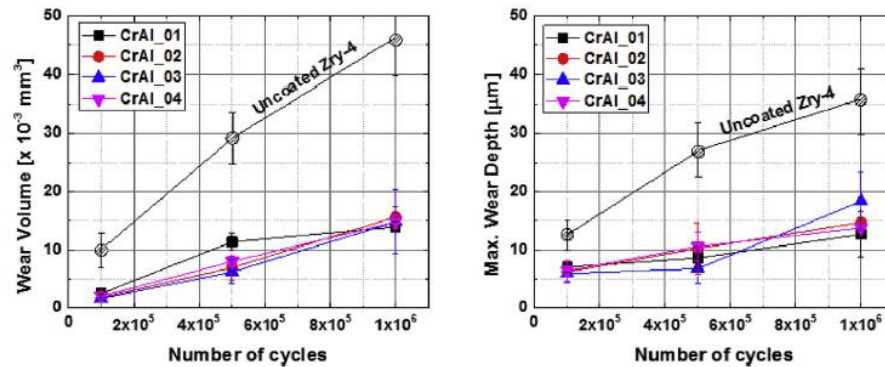


Fig. 6. Wear properties of CrAl-coated Zry-4 and uncoated Zry-4 claddings at room temperature in water.

CrAl coated Zry-4 cladding by arc ion plating

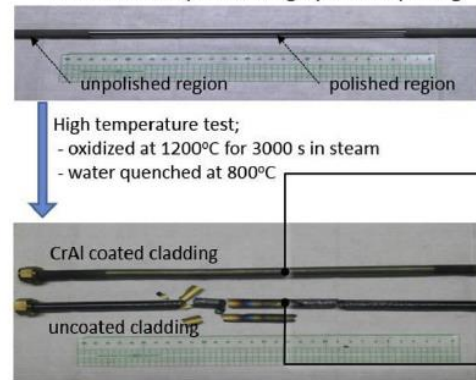


Fig. 7. High temperature oxidation and water quenching behavior of CrAl-coated Zry-4 cladding and uncoated Zry-4 cladding.

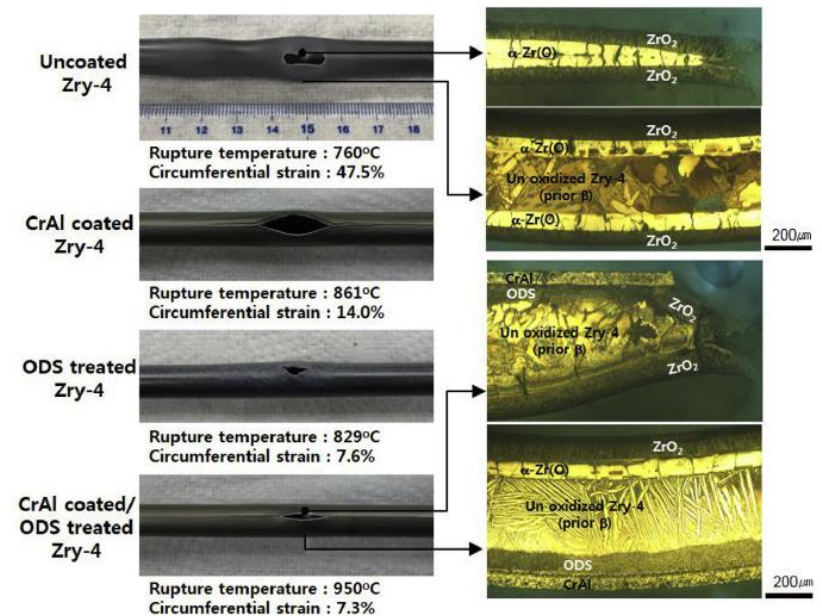
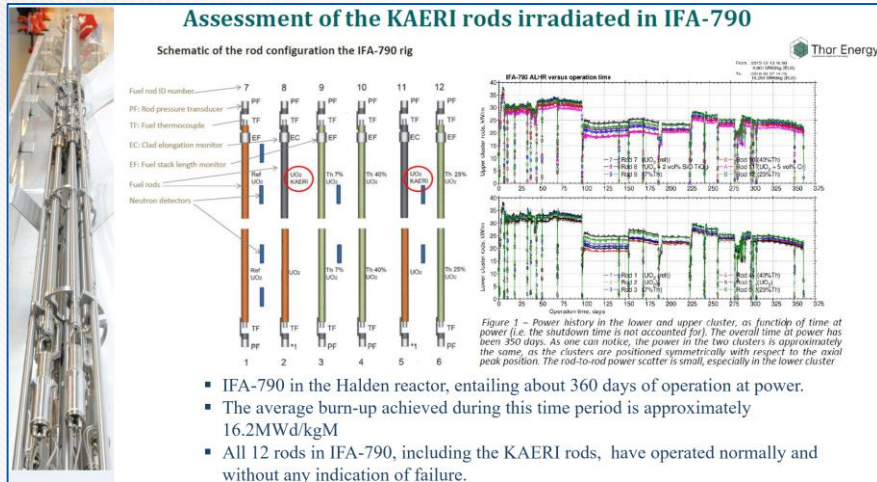


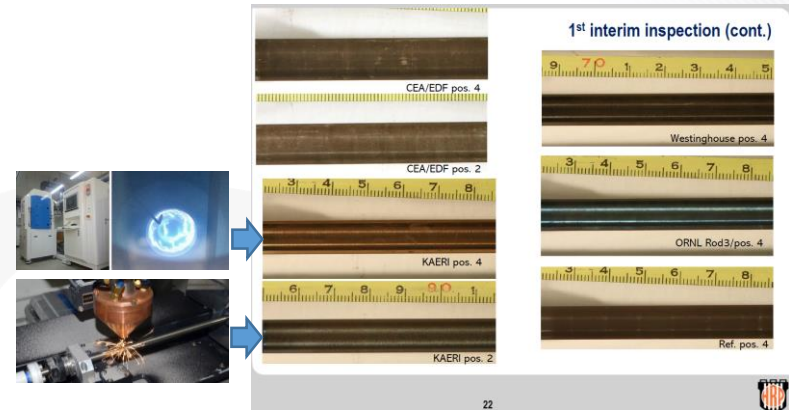
Fig. 8. Cladding behavior after LOCA simulation test of surface-modified Zry-4 cladding and uncoated Zry-4 cladding.

03 KAERI의 ATF 피복관 개발 현황

» AIP+3D printing: 연구로 연소시험



↓ ~5 MWd/kgU (~135 FPD) 피복관 건전성 및 우수한 내부식성 확인



↑ ~16 MWd/kgU (~360 EFPD)

피복관 건전성 확인

- CrAl coated Zircaloy by AIP
- FeCrAl coated Zircaloy by 3DP

INITIAL RESULTS FROM THE ACCIDENT TOLERANT CLADDING TEST IFA-796

Target operating conditions and instrumentation

The irradiation will last for 4-5 years with a target burn-up of ~ 40 MWd/kg UO_2 with a target linear heat rate of 25 kW/m.

The water chemistry is 4.6 ppm Li with boron addition aimed at maintaining a pH300 of ~7.3.

Assembly instrumentation

- 3 inlet thermocouples
- 3 outlet thermocouples
- 3 downcomer thermocouples
- 4 Rh (+ 1 V) neutron detectors at four different elevations 100 mm ac fuel stack

Rod instrumentation

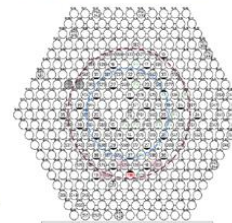
- cladding elongation (EC) on FeCrAl rod

- 6 rods > 5 segmented (4 segments)
 - 100 mm active fuel stack
 - fuelled with ~7.3 wt% enrichment UO_2

General core map

Irradiation started in July, 2017

- Genly start-up, ~ 14 kW/m ALHR
- Ring 6, surrounded by CRs



IFC CORE LOADING No. 238, 2017/08/04

Segment	CEA/EDF	KAERI	Westinghouse	ORNL	EPRI	Ref.
Top	Rod 1	Rod 2	Rod 3	Rod 4	Rod 5	Rod 6
Top-mid	Zr-7 μm Cr	Zr-40 μm Cr alloy (CrAl)	Zr-40 μm Cr (CrAl)	FeCrAl-1	Mo-Zr2Nb	Zr-4
Bottom-mid	MS-15 μm Cr	Zr-15 μm Cr/FeCrAl	FeCrAl-2		Mo-Zr2Nb	Zr-4
Bottom	MS-7 μm Cr	Zr-15 μm Cr/FeCrAl	FeCrAl-2		Mo-Zr2Nb	Zr-4

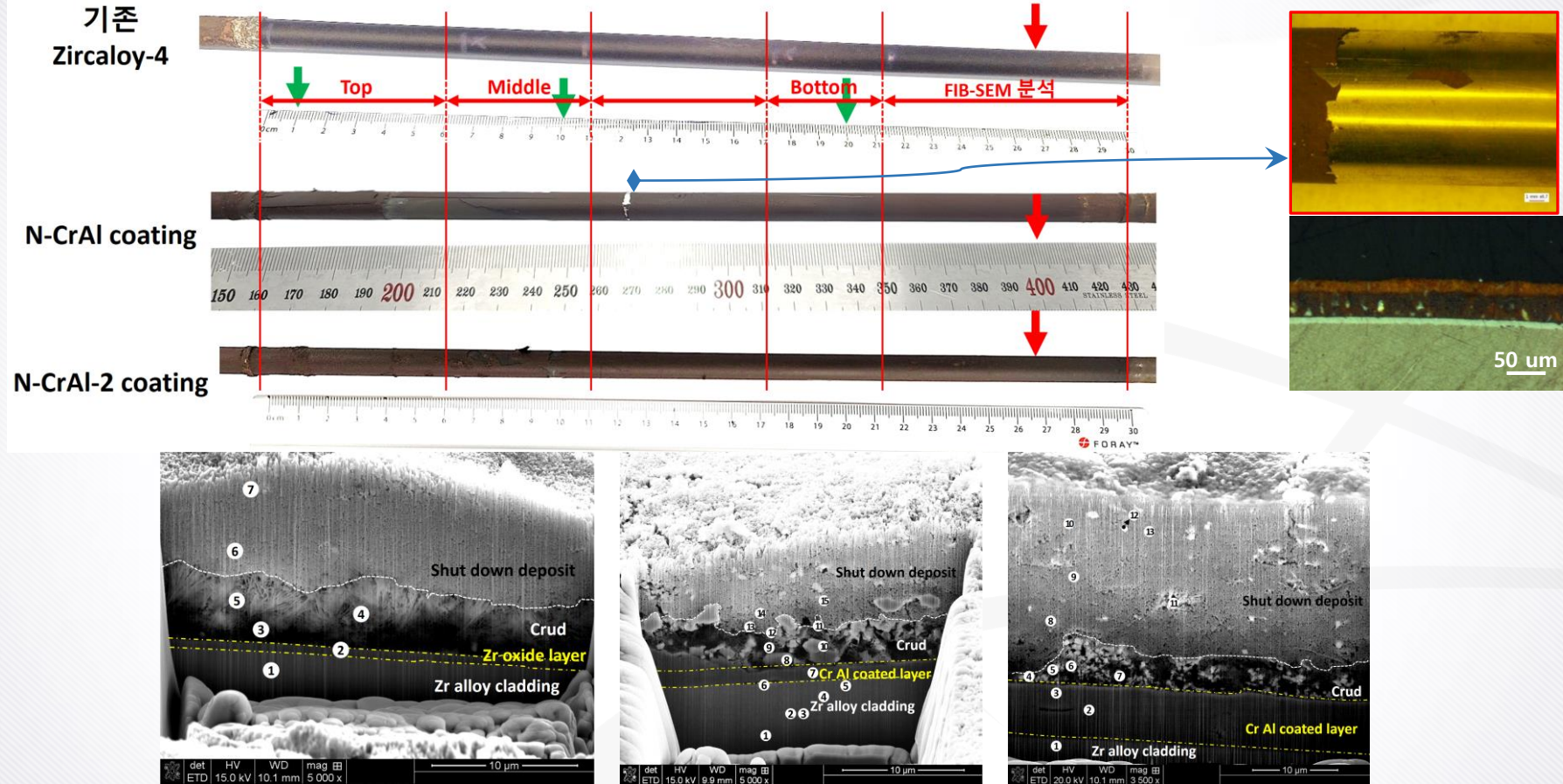
Test rods

Segment	CEA/EDF	KAERI	Westinghouse	ORNL	EPRI	Ref.
Top	Rod 1	Rod 2	Rod 3	Rod 4	Rod 5	Rod 6
Top-mid	Zr-7 μm Cr	Zr-40 μm Cr alloy (CrAl)	Zr-40 μm Cr (CrAl)	FeCrAl-1	Mo-Zr2Nb	Zr-4
Bottom-mid	MS-15 μm Cr	Zr-15 μm Cr/FeCrAl	FeCrAl-2		Mo-Zr2Nb	Zr-4
Bottom	MS-7 μm Cr	Zr-15 μm Cr/FeCrAl	FeCrAl-2		Mo-Zr2Nb	Zr-4



03 KAERI의 ATF 피복관 개발 현황

» AIP coating: CRUD 침적거동 (울산과기대 수행)



03 KAERI의 ATF 피복관 개발 현황

» KAERI의 coating/surface modification 성과

Nuclear Science
2018

State-of-the-Art Report on Light Water Reactor Accident-Tolerant Fuels

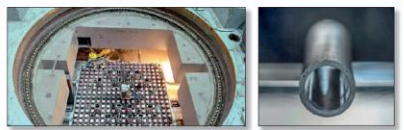


Table 10.1. Summary of coating systems properties

Institution	Coating system	Fabrication	Normal operation	Accidental behaviour
AREVA-CEA-EDF	Cr (5-20 μm)	PVD Full-length prototype ongoing	Extremely low corrosion + H pickup Similar mechanical behaviour as uncoated Very good adherence Cr-Zr interface stable under ion irradiation Increased wear resistance	Significantly reduced HT steam oxidation Increased post-quench ductility Strengthening effect of Cr – reduced HT creep, reduced ballooning Very adherent and no or very limited cracking after significant clad creep/ballooning Zr-Cr eutectic (1 330°C) behaviour TBD
KAERI	Cr Cr-Al FeCrAl (40-80 μm)	PVD (ion plating) Three-dimensional laser coating	Extremely low corrosion + H pickup Increased strength and reduced ductility Very good adherence Increased wear resistance	Significantly reduced HT steam oxidation (up to 1 400°C) Increased post-quench ductility Strengthening effect of Cr – reduced HT creep, reduced ballooning Fe-Zr eutectic around 900°C (use of barrier layer)
IFE-Halden/ CNL	CrN (1-4 μm)	PVD Commercially available (full-length)	Extremely low corrosion + H pickup Good adherence Increased wear resistance Minor cracking of coating observed after irradiation	Reduced HT steam oxidation Some cracking of coating observed during HT steam oxidation Very adherent during HT burst test but significant cracking at burst/balloon location
	TiAlN CrAlN (1-4 μm)	PVD Commercially available (full-length)	Dissolves in water Poor adherence	Cracking and delamination observed after HT steam oxidation
KIT	MAX phases (Ti_2AlC ; Cr_2AlC) (~5 μm)	PVD Difficult to obtain correct stoichiometry + microstructure	No data Potential dissolution of Ti_2AlC in water (Al_2O_3)	Similar HT steam oxidation resistance of Ti_2AlC to uncoated Zr4 Reduced HT steam oxidation of Cr_2AlC
UIUC	Cr-Al (~1 μm)	PVD	Difficult to interpret results (deposits) Reduced corrosion but weight loss for FeCrAl (dissolution of Al_2O_3)	Slight reduction in HT steam oxidation at 700°C
	FeCrAl (~1 μm)			Negligible effect at 1 200°C steam (too thin) Fe-Zr eutectic ~900°C
PSU	TiN / TiAlN (~10 μm)	PVD (multi-layer coating)	Low corrosion + H pickup if surface TiN	No data

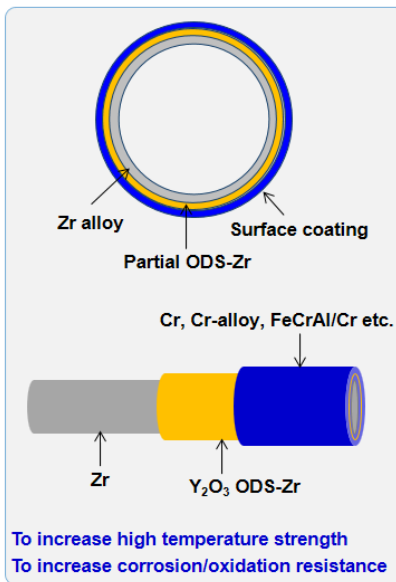
03 KAERI의 ATF 피복관 개발 현황(요약)

» 단기적용 원천기술 확보(TRL 4)

사고저항성 핵연료 피복관 개발기술 요약

표면개질
(코팅/ODS)
피복관

- 성능 목표 : 상용 피복관 대비 고온산화 저항성 100배, 고온변형 저항성 2배 향상
- 달성 수단 : Cr, CrAl, FeCrAl 합금기반 내산화 코팅 기술, ODS 강화 표면처리 기술
- 개발 기술 : 설계기준 사고시 산화속도 100배, 변형량 2배 이상 저감하는 피복관 표면처리 고유 원천기술(특허) 확보 (경쟁 기술 대비 높은 산화저항성, 세계 최고 수준)



Type	Partial ODS		Coating		Remarks (target)
	oxide type	method	material	method	
1	-	-	Cr, CrAl	Arc ion plating/Cold spray/3D printing	Corrosion
1-1	Y ₂ O ₃	Laser beam scanning	Cr, CrAl	Arc ion plating/Cold spray	Strength and Corrosion
2	-	-	Cr/FeCrAl	Arc ion plating for Cr, 3D laser coating/Cold spray for FeCrAl	Corrosion
2-1	Y ₂ O ₃	Laser beam scanning	Cr/FeCrAl	Arc ion plating for Cr, 3D laser coating/Cold spray for FeCrAl	Strength and Corrosion

03 KAERI의 ATF 피복관 개발 현황(요약)

» 사고저항성 핵연료 피복관 독자 기술 소유권(특허) 확보

분야	지적재산권				
	분류	명칭	국가	등록년월(번호)	비고(내용)
코팅 및 표면개질 피복관	특허	고온 내산화성 및 내부식성이 우수한 금속 코팅막 및 이의 제조방법	대한민국	2020.09(10-2161584)	AIP로 Cr코팅
	특허	고온 내산화성이 향상된 지르코늄 합금 피복관 및 이의 제조방법	대한민국 미국 일본	2019.09(10-2029284) 2021.09(11118260) 2021.12(6999810)	AIP로 CrAl코팅
	특허	내식성이 우수한 크롬-알루미늄 이원계 합금 및 이의 제조방법	대한민국 미국	2016.12(10-1691916) 2020.10(10808307)	코팅용 CrAl 소재
	특허	CrAl 2원계 합금 스퍼터링 타겟 및 이의 제조방법	대한민국	2019.08(10-2011141)	코팅용 CrAl 타겟
	특허	레이저를 이용한 금속소재의 산화물 분산 강화 방법	대한민국 일본 미국 프랑스	2014.05(10-1393323) 2015.09(5808731) 2016.05(9346125) 2017.09(299044)	3DP ODS 기술
	특허	표면에 혼합층을 포함하는 코팅층이 형성된 지르코늄 합금 및 이의 제조방법	대한민국 프랑스	2014.06(10-1405396) 2020.01(2992331)	3DP 코팅 기술
	특허	다층구조 핵연료 피복관 및 이의 제조방법	대한민국	2016.02(10-1595436)	FeCrAl 코팅

04 향후 계획

» 단기적용 원천기술(특허등록)을 산업체와 공동으로 상용화 기술 개발

2-1-1 사고저항성 향상 혁신 핵연료 소재 부품 개발 및 상용화(TRL8)

<'12~'21>
4, 5차 원연사과제
사고저항성핵연료
원천기술(TRL4)

세부기술	단위 과제 내용, 기간 및 과제별 연계 체계							
	'22	'23	'24	'25	'26	'27	'28	'29
과기부	(과) 21-13 사고저항성 핵연료 혁신 소재 설계기술 개발 - 혁신 소재 설계 - 혁신소재 제조 - 혁신소재 성능 평가							
				(과) 21-14 사고저항성 핵연료용 혁신 원료소재 제조기술 개발 - 혁신 원료소재 제조기술 개발 - 소재 성능 검증 - 상용 원료소재 제조				
				(과) 21-11 사고저항성 혁신핵연료 소재 부품 기술 개발 - 소재/부품 제조 공정 설계/구축 - 소재/부품 시제품 제조 - 혁신핵연료 부품시제품 제조 - 사고조건 안전 성능 시험 - 혁신 핵연료 부품 종합 시험				
				(과) 21-12 사고저항성 혁신핵연료 안전 성능 평가 기술 개발 - 해석기술 설계 - 리스크 정보 활용 통합해석체계 구축 - 정상상태 안전 성능 시험 - 혁신 핵연료 성능모델 개발 - 혁신 핵연료 안전기여도 평가				
산업부	Task 6 사고저항성 핵연료 공동 연구협력 - 상세 협력방안 도출 - 성능 시험자료 비교 검증 - 사고저항성 혁신 핵연료 Gate check - ATF 안전기여도 평가							
	Task 1. 사고저항성 향상 핵연료 상용 검사 기술 개발 - 상용 핵연료 비파괴 검사 기술 개발 - 조사재 비파괴 검사 기술							
	Task 2 사고저항성 향상 핵연료 상용 제조 기술 개발 - 상용 시제품 제조 - 상용 대량 제조 기술 개발			Task 3. 사고저항성 향상 핵연료 제조/검사 기술 최적화 - 상용 제조기술 최적화 및 상용제품 제조 - 상용 검사기술 최적화				
	Task 4. 사고저항성 향상 핵연료 노내성능 시험 및 DB 구축 - 노외 성능 시험 - 연구로/상용로 연소시험 - 노내 성능 검사/검증 - 조사재 성능시험							
	Task 5. 사고저항성 향상 핵연료 설계기술 개발 - 노외성능모델 개발 - 노내 성능모델 및 코드 이식 - 성능모델/코드 개선/검증 - 인허가보고서							

감사합니다.