Experience in manufacturing a disposal canister

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OUTLINE

1. 서론
2. 해외 처분용기 개발 현황
3. KAERI approach: 처분용기 제작
4. KAERI approach: 장기 부식 시험
5. 처분용기 수명 예측
6. 결론

서론

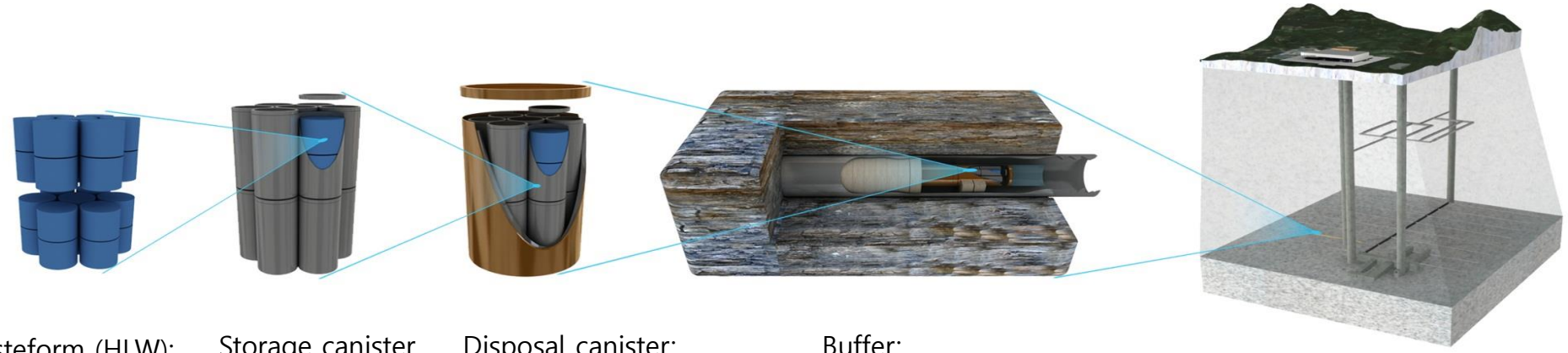
- 심층처분[Deep geological disposal], 공학적방벽, **처분용기**
  - 원자력안전위원회 고시 제2015-021호 [**고준위방사성폐기물 심층처분시설에 관한 일반기준**]
  - ✓ 제2조(정의) 1. **'심층처분'**이란 방사성폐기물을 사람의 접근과 방사성 핵종의 생태계 유입이 제한될 수 있도록 지하 깊은 곳의 안정한 지층구조에 처분하여 인간 생활권으로부터 영구히 **격리(isolation)**시키는 것을 말한다.
  - ✓ 제2조(정의) 4. **'공학적 방벽'**이란 처분환경에서 방사성폐기물의 유출과 처분시설로의 지하수 침투 또는 사람의 침입을 제한하는 역할을 하는 인공물로서 포장용기, **처분용기**, 완충재, 처분고 구조물, 뒤채움재 등을 포함한다.
  - ✓ 제13조(공학적 방벽) ① 심지층처분시설의 **공학적 방벽은** 방사성폐기물에 대하여 처분시설에서 방사성핵종의 유출을 장기간 제한할 수 있는 **처분용기**를 포함하여야 한다

서론

❖ **KAERI deep geological repository**
- ✓ **KBS-3 type** in granite, based on the **KURT study site**
- ✓ Multiple barrier system/defense-in-depth/ALARA

Engineered Barrier System

Natural Barrier System



Wasteform (HLW):
Monazite ceramic

Storage canister

Disposal canister:
Copper-Cast iron
Cold Spray Coating

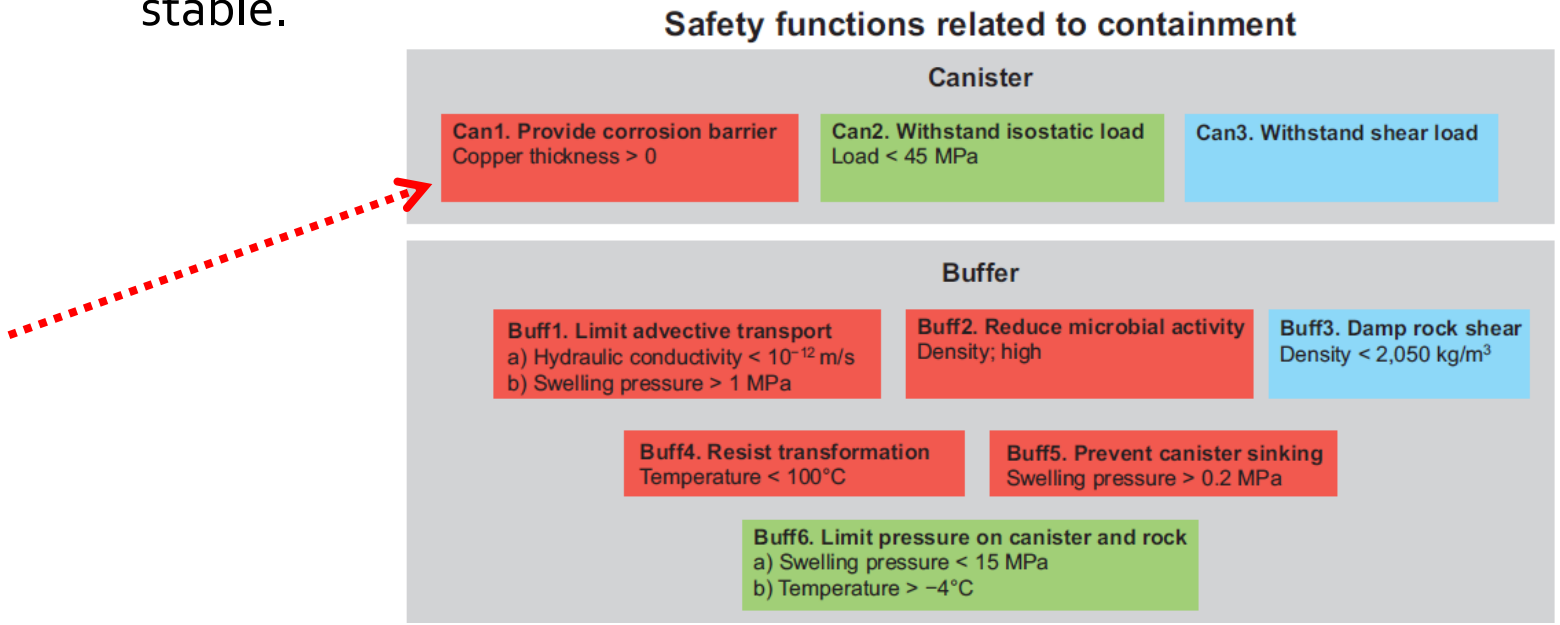
Buffer:
Ca-bentonite
Domestic, Kyeongju

Geology: granite
KURT study site

A-KRS, concept of a multi-barrier system

서론

- Safety Principles for the **KBS-3 repository**
  - **The primary safety function of the barrier is to contain the fuel within a canister**
  - The secondary safety function of the barrier is to retard a potential release from the repository
  - The engineered barrier shall be made of naturally occurring material that are stable.



서론

- **연구의 목적**
  - 고준위폐기물 처분을 위한 10 mm 정도 두께의 **구리용기를 실규모로 제작할** 수 있는 방법을 개발하자.
  - 구리용기의 역할은 **부식**에 대한 방벽: **장기 부식 시험 결과를 축적하자**
  - **처분환경**에 대한 **충분한 이해를 위한 자료를 축적하자**
  - 구리용기의 수명이 **10,000년을** 보장하는가? 이를 예측하기 위한 **전산 프로그램을 개발하자**

해외 처분용기 개발 현황

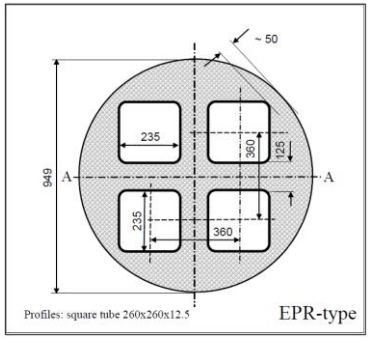
- 각국의 고준위폐기물, 처분환경과 처분용기

고준위폐기물	국가	암반 및 지하수 포화정도	처분용기 재질
사용후핵연료	스웨덴	화강암, 포화 지역	구리-주철
	핀란드	화강암, 포화 지역	구리-주철
	미국-Yucca	응회암, 불포화 지역	Nickel alloy-22
	KAERI	KURT 화강암, 포화 지역	구리-주철
	캐나다	화강암/퇴적암, 포화 지역	구리-주철
유리고화체	프랑스	퇴적암, 포화 지역	탄소강
	일본	화강암/퇴적암, 포화 지역	탄소강
	스위스	화강암/퇴적암, 포화 지역	탄소강

해외 처분용기 개발 현황

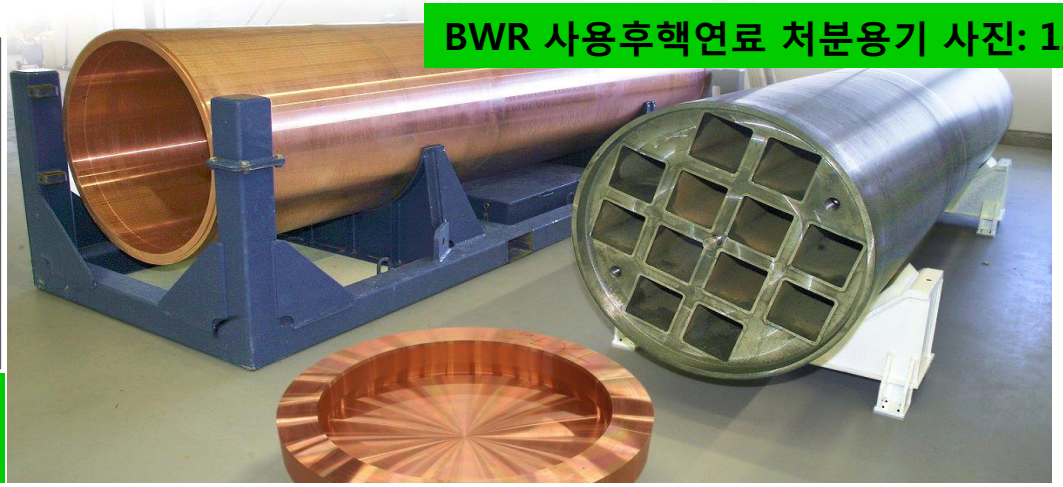
- **스웨덴/핀란드 처분용기 개요**
  - 구리-주철 이중용기: **구리층 두께 49 mm**/직경 1,050 mm/길이 5,223 mm, **PWR SNF 4 다발**
  - 구리 소요량: **약 10톤 [약 1 m³]**
- 스웨덴/핀란드의 처분용기 제작 방법: **3가지 방법** 개발 중
  - **스웨덴 SKB**: Extrusion (**스코틀랜드** Wyman Gordon Ltd), Forging (**스웨덴** Scana Steel Bjorneborg)
  - **핀란드 POSIVA**: Pierce-and-Drawing (**독일** Vallourec & Mannesmann), 이 방법은 바닥까지 동시에 제작 가능
  - Copper billet: 핀란드 Luvata Pori Oy

PWR 사용후핵연료 처분용기 단면: 4다발



Thickness of copper tube: 50 mm
Weight of copper tube: roroughly 10 tons

BWR 사용후핵연료 처분용기 사진: 12다발



해외 처분용기 개발 현황

- 스웨덴/핀란드의 처분용기의 **문제점**
  - 캐나다 NWMO의 분석에 따르면, 화강암반 처분조건에서 1**백만년 동안 예상되는 구리 부식 두께는 1.27 mm에 불과**
  - 그러나, 스웨덴과 핀란드의 처분용기의 구리 층 **두께는 50 mm**

❖ **Huge amount of copper for the canister**

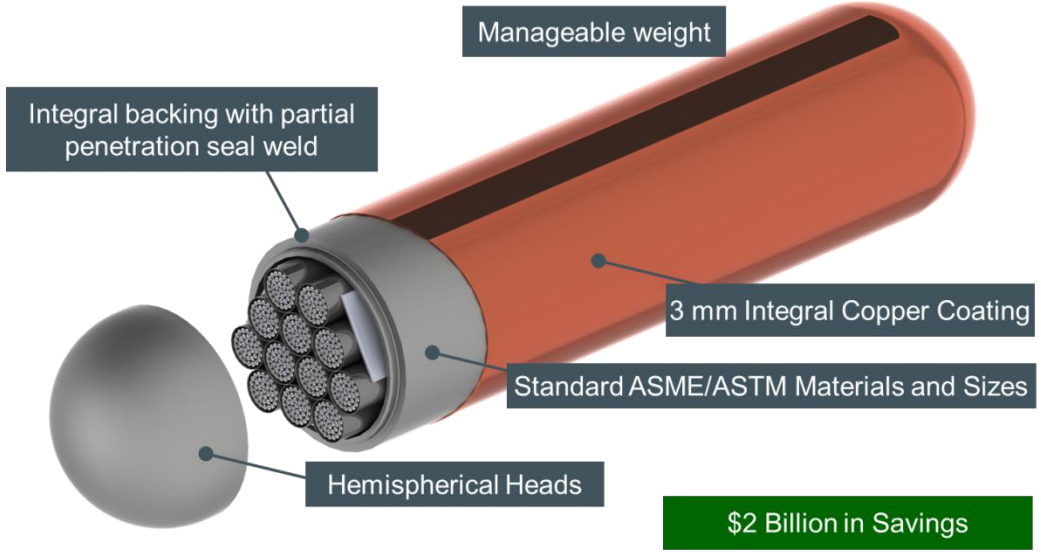
- ✓ KBS-3V, SKB: 12,000 MTU SNF (6,000 canisters), **roughly 10 tons of copper per canister**
- ✓ Our case: **75,000 MTU SNF (37,500 canisters) require around 375,000 tons of copper**.
- ✓ The density of copper: around 9 tons/m^3. Thus, total volume of copper for the canisters: **41,000 m^3**.
- ✓ Volume of a swimming pool: 50 m x 25 m x 2 m = **2,500 m^3**
- ✓ For the final disposal of 75,000 MTU PWR SNF, **we need 16 large swimming pools filled with copper** based on the Swedish canister

해외 처분용기 개발 현황

- **캐나다 NWMO 처분용기 개요**
  - 구리-주철 이중용기: **구리층 두께 3 mm**/직경 600 mm/길이 2,500 mm, **CANDU SNF 48 다발**
  - 구리 소요량: 초기 설계 25 mm -> 3 mm 두께 **(20억달러 절약, 주장)**
- **캐나다의 처분용기 제작 방법**
  - **Body 부분**: **Electrodeposition**
  - **Welding 부분**: **Cold Spray Coating (KAERI 최초 개발 착수)**
  - 스위스 Nagra, 영국 RWM, 체코 Surao 공동연구 진행 중

CANDU 사용후핵연료 처분용기: 48다발

Thickness of copper tube: 3 mm
Lifetime of copper shell: 1.0 million years



KAERI Approach: 처분용기 제작

- **What is the solution?**
  - ✓ According to Canadian approach, **NWMO estimates** the corrosion depth of copper under the very similar disposal conditions to be **1.27 mm for 1 million years**. Also, the thickness of the disposal container is 3 mm.
  - ✓ **Since 2007**, KAERI develops a new technique for manufacture a copper layer over nodular cast iron. It is **a cold spray coating**.
  - ✓ According to our design, **we need a 10 mm copper layer**.
  - ✓ We are trying to develop a cold spray coating machine for a large size copper canister. So far, we can make around 400 mm x 1200 mm size canister with 10 mm thick copper layer.
  - ✓ If we succeed, **we can save more than 80% of copper**.
  - ✓ For the successful application of this new technique, **we have to demonstrate the corrosion resistance of cold sprayed copper**.

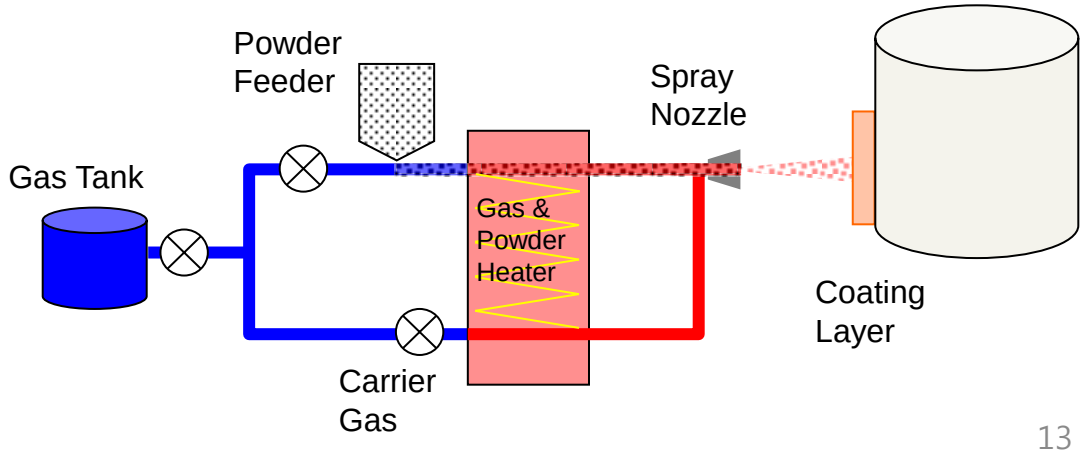
KAERI Approach: 처분용기 제작

	KOREA-KAERI	SWEDEN-SKB FINLAND-POSIVA
Disposal wastes	PWR SNF &Ceramic HLW[1]	BWR & PWR SNF
Canister Lifetime (year)	< 1,000	< 100,000
Disposal canister •Materials •Manufacturing •Dimension(cm) •Weight(ton) •Thickness(mm) •Welding Method	 •Cu-Fe[3] •Cold Spray Coating[4] •D103x H173 •7.2 •Cu 10 •Cold Spray Coating	 •Cu-Fe[3] •Forging, Extruding, Pierce-and-Draw •D105xH484 •BWR 25, PWR 27 •Cu 50 •Friction Stir Welding
Protective Layer •Corrosion Rate	Cu < 1 um/year -> 0.2 um/year	Cu < 0.5 um/year[2]
Buffer	Ca-bentonite	Na-bentonite
Disposal site •Rocks •Depth (m) •Water condition •Oxygen condition •Temperature (°C)	 •Granite •500 •Saturated •Oxy-free •100	 •Granite •500 •Saturated •Oxy-free •100

KAERI Approach: 처분용기 제작

◆ **Cold Spray Coating Technique이란?**

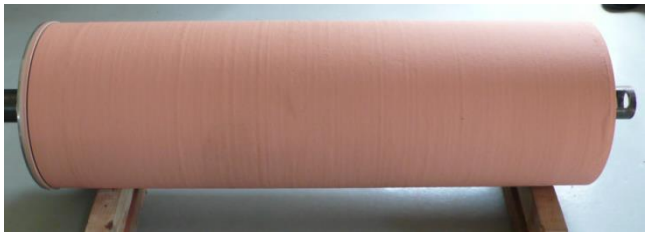
- **Copper powder**: 1 to 50 μm in diameter, heated to about 400°C prior to feeding.
- Carrier gas: Inert gas at a supersonic speed of **400 to 450 m/sec** through a nozzle. Heated to **around 550°C before mixing**.
- **Coatin**g: achieved by plastic deformation of metal particles.
- Merits:
  - **Avoids oxidation** or phase transition of metal
  - Minimizes the thermal impact on a substrate
  - Creates a thick coating layer with low residual stress



KAERI Approach: 처분용기 제작

Disposal Canister: manufacturing /2012-2015/

- **Cold Spray Copper canister**
  - ✓ KAERI designed several kinds of 50 mm copper-cast iron disposal canisters for PWR and CANDU spent fuels based on extruding **from 2003 to 2006**.
  - ✓ Compared with the lifetime of 100,000 years, the thickness of 50 mm seems to be over-designed.
  - ✓ KAERI team tried to find **a new technique** to manufacture a thinner copper canister **since 2007**. And the Cold Spray Coating (CSC) method provided a good performance copper layer and showed a good engineering feasibility.
  - ✓ **In 2015, a large-size disposal canister, 400 mm in diameter and 1,200 mm in height, was manufactured with a thickness of 8 mm(after machining).**

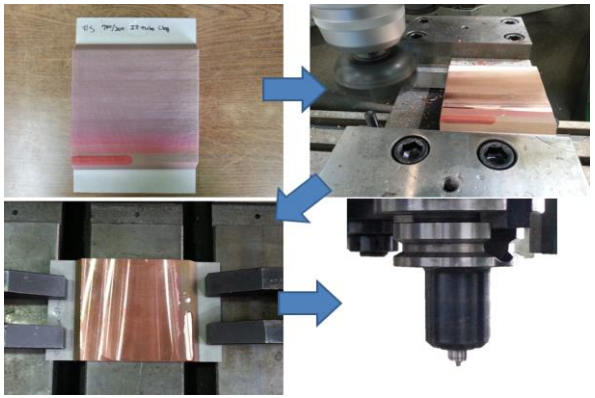


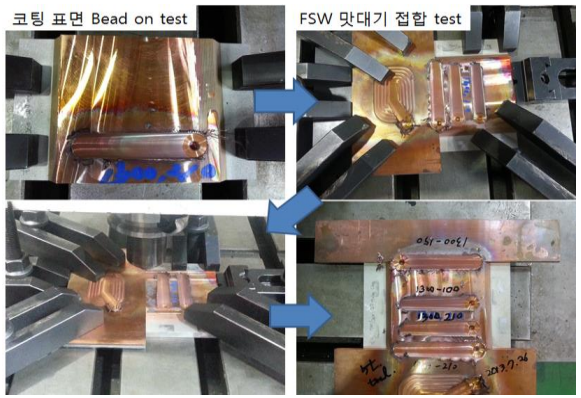
KAERI Approach: 처분용기 제작

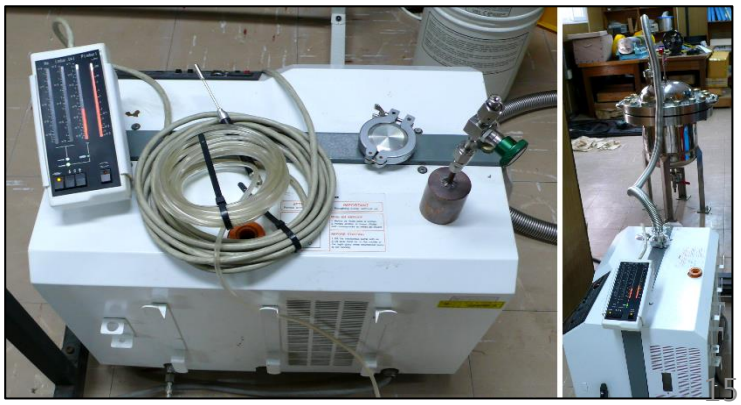
Disposal Canister: welding /2012-2015/

- **Cold Spray Coating (CSC)**
  - ✓ KAERI tested the sealing performance of CSC between both CSC copper body vs. normal copper lid and normal copper lid vs. cast nodular iron body
  - ✓ Their sealing performance was checked by a Helium leak tester.

- **Friction Stirred Welding (FSW)-스웨덴 방식**
  - ✓ KAERI tested FSW between 10 mm thick CSC Cu coating and normal cu plate to get a sealing method of a disposal canister.
  - ✓ Before the FSW test, Bead-On test was done on the CSC Cu plate.







KAERI Approach: 장기 부식 시험

Disposal Canister: corrosion test

- KAERI has conducted three kinds of long-term corrosion experiment,
  - More than **400 identical corrosion cells** were put in a sealed bottle(Lab test), in a constant flowing column(KURT 2nd), or in a chamber(3rd – 5th).

2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017

Lab. Test: finished

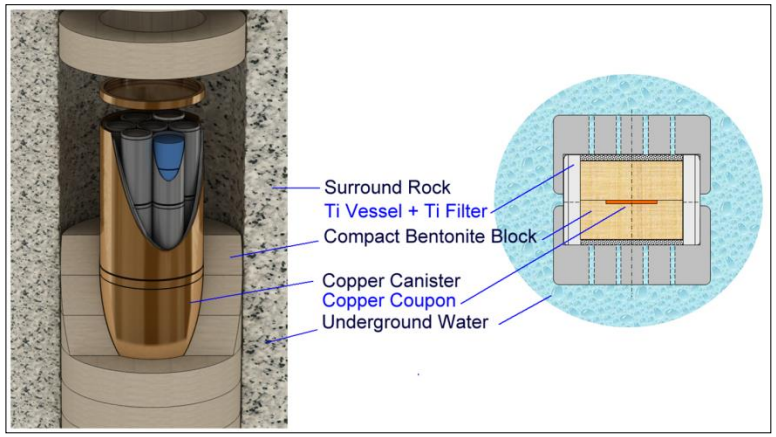
KURT 2nd: finished

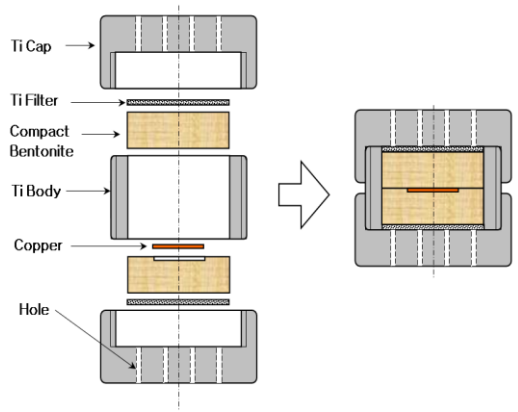
KURT 3rd – 5th: on-going

KAERI Approach: 장기 부식 시험

Disposal Canister: corrosion test

- **Corrosion specimen: five kinds of metal**
  - ✓ Shape: coin type coupon /**wrought copper, CSC copper, Titanium, Stainless steel, Cast Iron**/
  - ✓ Size: 15 mm in diameter, 1.0 mm thick, 177 mm^2 of surface area
- Buffer: two kinds of bentonite
  - ✓ Size: 30 mm in diameter, 10 mm thick
  - ✓ Material: domestic Ca- bentonite/MX-80 Na-bentonite
    - Dry density: 1.6 g/㎤
    - Hydraulic conductivity: 7.6 x 10^{-14} m/sec
- Corrosion Cell
  - ✓ Material: Ti
  - ✓ 12 openings(D 3.0 mm) on top and bottom cell for groundwater exchange
  - ✓ Temperature: 70℃ and 30 ℃
  - ✓ Groundwater: from a borehole in the KURT





KAERI Approach: 장기 부식 시험

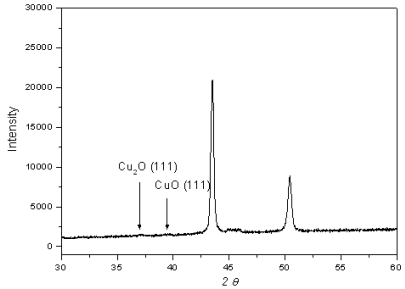
Disposal Canister: corrosion test

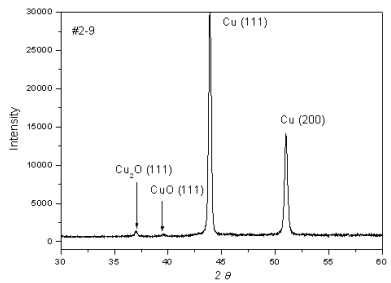
- 1st corrosion test: Lab test (for 2 yrs, 2008 – 2010)
  - ✓ Specimen: Tafa CSC, CS CSC, Extrude & Forging Cu, 6:4 Brass, Al bronze
  - ✓ Corrosion condition: 70℃, closed system(350 ml glass bottle)
  - ✓ Water: - 200 m deep borehole at the KURT

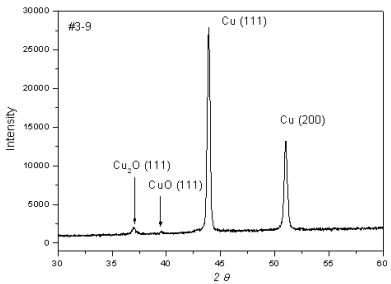
Sample no.	Sampling Date	Borehole depth (m)	Sampling depth (m)	Temp. (℃)	pH	Eh (mV)	EC (μS/cm)	DO (mg/L)	TDS (mg/L)
TB-10	07-6-22 0:00	200	140~150	15.4	8.10	-384	159	0.02	246.6

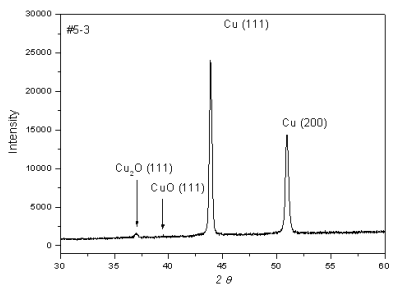
Concentration (mg/L)											
Na	K	Ca	Mg	SiO^{2}	Cl-	SO_4^{2-}	NO^{3-}	F-	HCO_3^-	CO_3^{2-}	HCO_3+CO_3
16.5	0.38	17.2	1.72	41.3	2.18	6.97	0.23	3.41	78.4	0.00	78.4

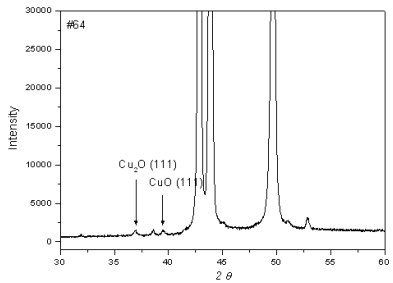
- Corrosion rate: 0.10 ~ 0.15 um/yr
- Corrosion product: Cu_2O, CuO

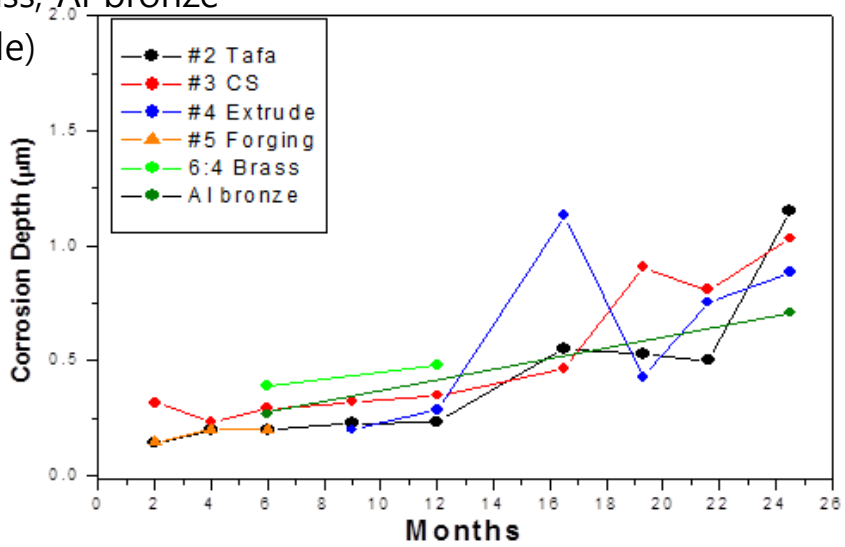










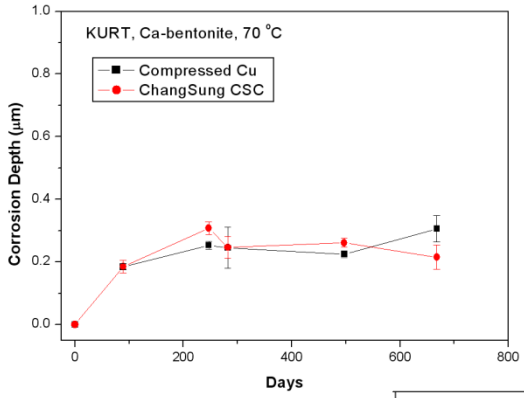


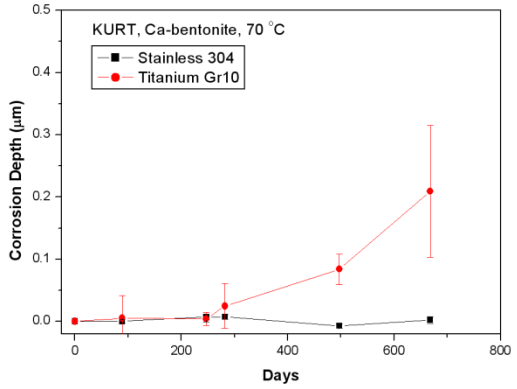
	Corrosion rate, ㎛/year			
	All Period	R	12 Months	R
Tafa CSC(#2)	4.088E-01	0.862	9.702E-02	0.907
CS CSC(#3)	4.088E-01	0.908	7.629E-02	0.589
Cu(#4,#5)	3.687E-01	0.928	1.321E-01	0.875
Naval Bass(#6)	1.814E-01			
Al Bronze(#7)	2.851E-01			
Copper(Total)	3.760E-01	0.875	1.471E-01	0.507

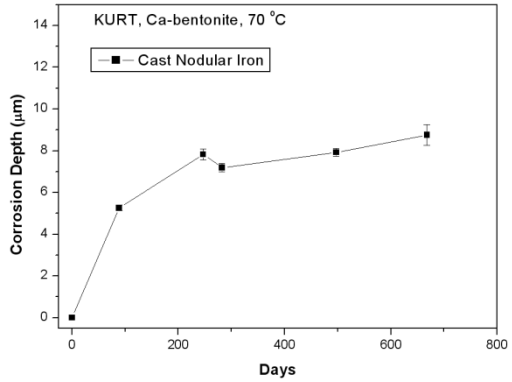
KAERI Approach: 장기 부식 시험

Disposal Canister: corrosion test

- **Very long-term corrosion test at KURT**
  - ✓ Results from the second set: 670 days [2014]
  - ✓ **We plan to publish an interim report** on the long-term corrosion experiment this year.







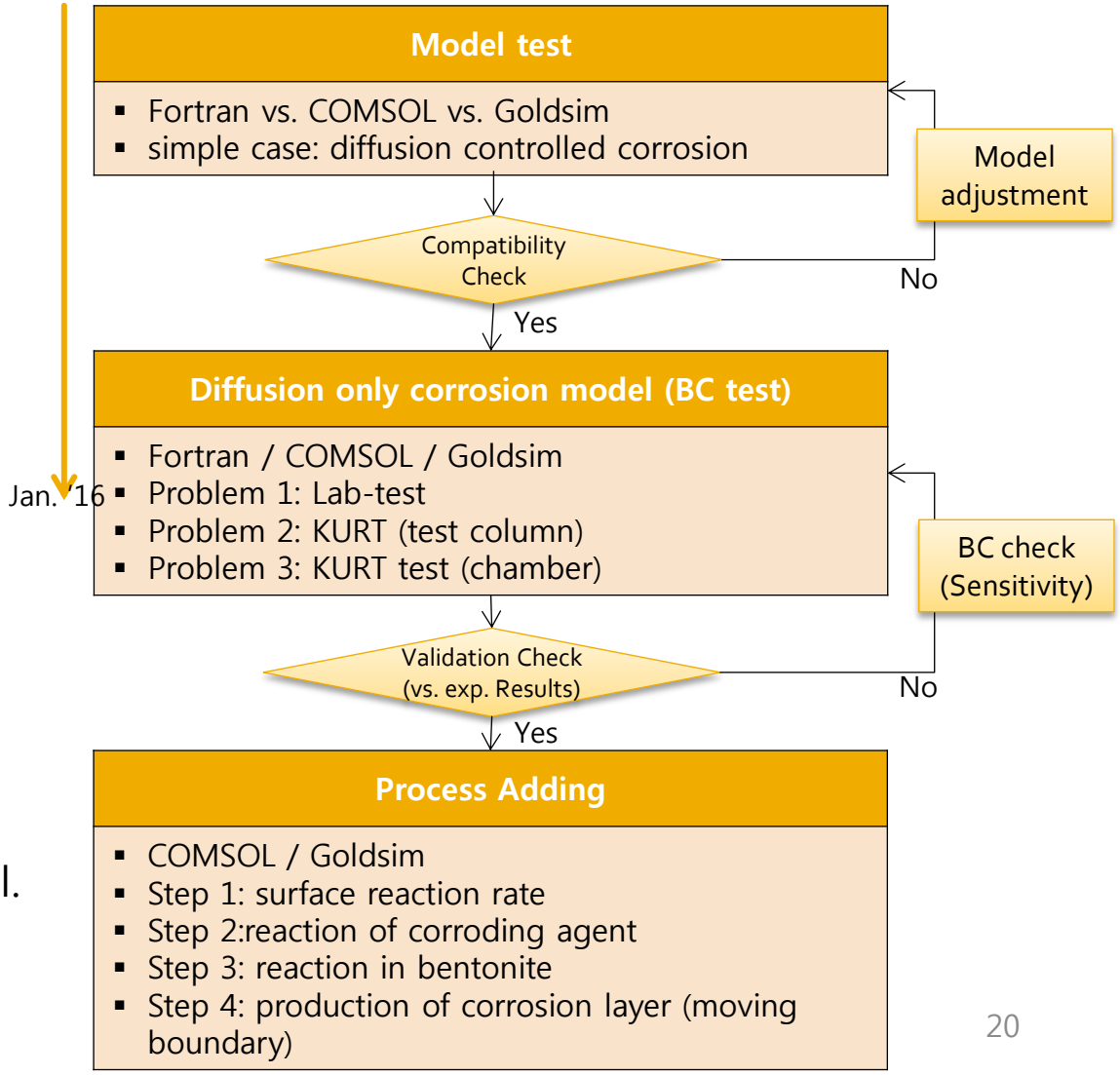
처분용기 수명 예측

Modeling Strategy

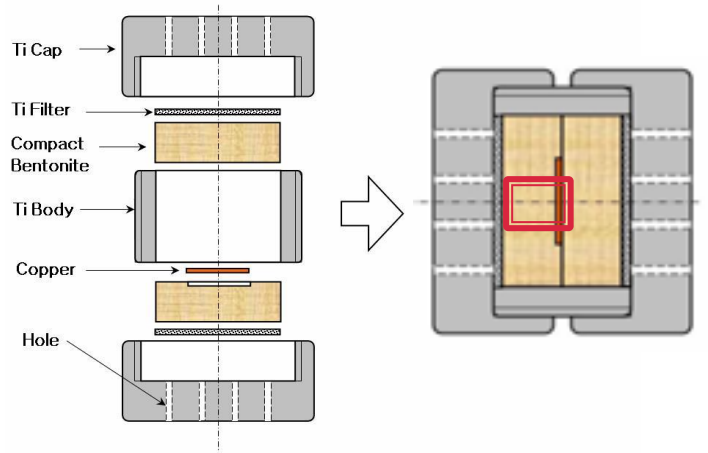
- After meeting with UWO experts, our modeling strategy changed from developing our own corrosion solver to using a commercial tool.
- COMSOL and Goldsim are selected.

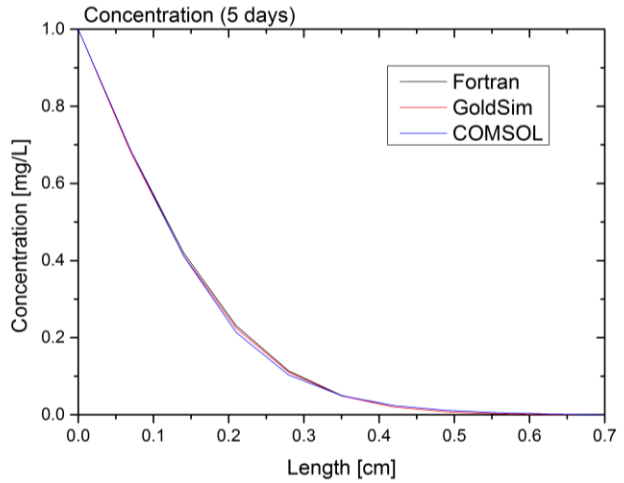
Goldsim

- Mass balance
- Advective & diffusive mass transport, chain decay, dissolution, sorption etc.
- Finally, the corrosion model will be coupled with a safety assessment model.

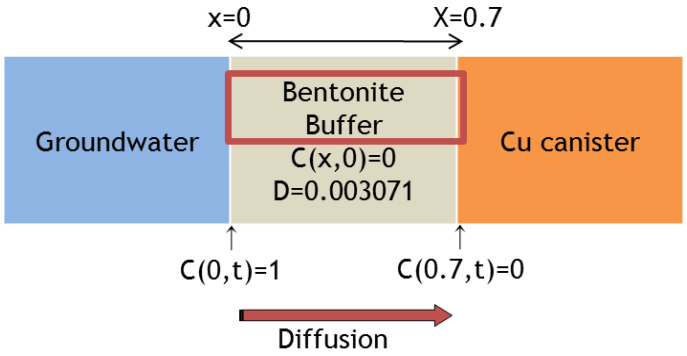


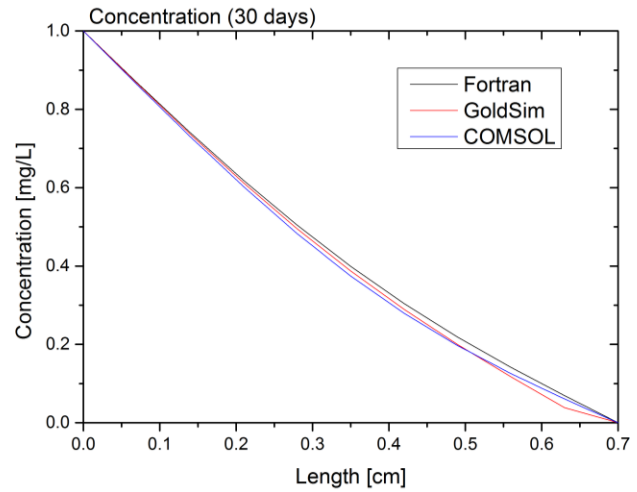
처분용기 수명 예측





Model test





결론

❖ **10년간의 연구 경험을 바탕으로 다음과 같은 결론을 도출:**

1. 고준위폐기물 처분용기 재료로서 다양한 물질(구리-주철, 탄소강, 니켈 합금-22, 티타늄 등)이 연구되고 있음. 국내 발생 고준위폐기물 특성과 지질 조건을 고려할 경우 **구리-주철 이중구조 처분용기가** 바람직함.
2. 구리 용기 제조법으로 여러가지 방법이 스웨덴과 핀란드에서 개발 중이나 10 mm 두께의 용기 제작에는 부적절함. **KAERI에서는 Cold Spray Coating법을** 이용하여 직경 400 mm, 길이 1,200 mm의 중규모 용기 제작에 성공하였음.
3. 구리 용기의 **general corrosion rate을 측정하기** 위해 KURT 지하수 환경(저산소 조건)에서 장기 부식 시험(최소 10년 계획)을 수행하고 있음. 중간결과, 지하수에 노출된 1년 경과 후에는 거의 부식이 진행되고 있지 않음.
4. **COMSOL/GOLDSIM을 이용하여 처분용기의 수명 예측을** 위한 전산 프로그램 개발 중. 부식 메커니즘과 단위 모델은 캐나다 웨스턴 대학과 기술교류. 검증도 캐나다 NWMO 등과 계획 중.
5. 처분용기의 **상용화는 처분사업에서 매우 중요함**. 1개 제작비가 수억원. 1만개 이상 소요될 것으로 판단. 제작-인허가-실증 시험에 소요되는 기간 등을 고려하면, 즉각 상용화 계획이 수립되어야 함. 스웨덴/핀란드 방식의 제작법에 대해서도 적극적으로 검토하여야 함.
6. 인허가를 위해서는 **처분심도(지하 500 m) 환경(환원환경)에서의 장기 부식 시험**이 반드시 수행되어야 함.