# Design and Material Selection for Leak-before Break Nature of Double Walled Once Through Steam Generators in Lead-bismuth Cooled Fast Reactors

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# Outlook



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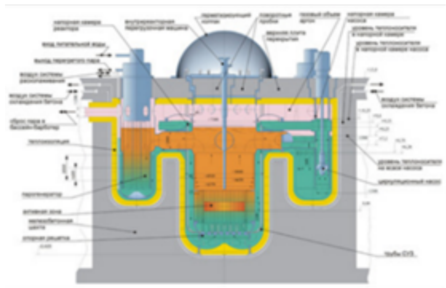
# Gen-IV Lead/Lead-Bismuth Cooled Fast Reactors



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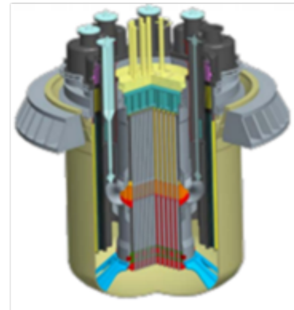

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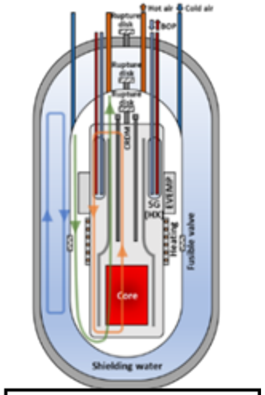


MicroUranus

- **Micro and modular design** can enhance the safety and the economic feasibility of Gen-Ⅳ reactor because of its passive safety system and its productivity.
- The micro modular reactor (MMR) can be a solution to where a large-scale nuclear power plant is inappropriate to be constructed.
- **Heavy liquid metals (HLMs)** including lead or lead-bismuth have a high boiling point which is one of a salient advantage to the safety issues, and they are transparent to neutron.
- LFR can **cool the decay heat** by natural circulation in accident situation, thus, it is **safe** in the case of station black out or other severe accidents.
- UNIST starts a R&D project to develop a unified lead-bismuth cooled MMR which could be operated over 40 years without fuel refueling: **MicroUranus**.

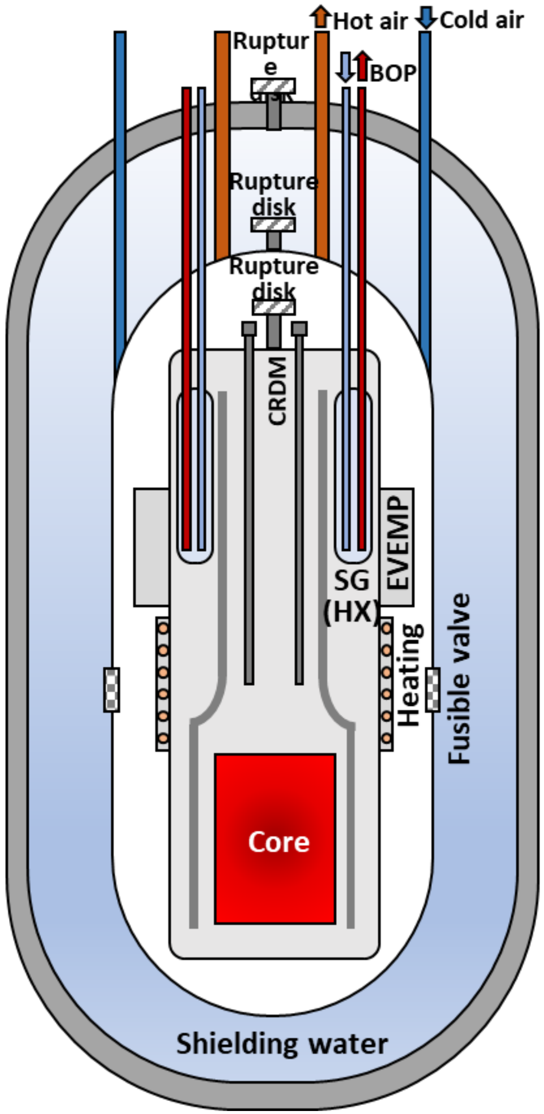
[1] Y. Shin et al. (2015), [2] A. Alemberti (2018), [3] World Nuclear News (2017)

# Concept of MicroUranus Reactor

- Coolant
  - Lead-Bismuth Eutectic (LBE)
    - ✓ Advantage
      - Transparent to the fast neutron
      - Good thermal-hydraulic characteristics
      - High boiling point and low melting point
    - ✓ Disadvantage
      - Polonium-210 (Leak Before Break (LBB))

- **<u>No need to replace nuclear fuel for 40 years</u>**

- Issues in materials for fuel cladding/structure
  - **<u>Steam generator design for enhanced safety and efficiency.</u>**
  - Adequate material selection
  - Damage tolerant design

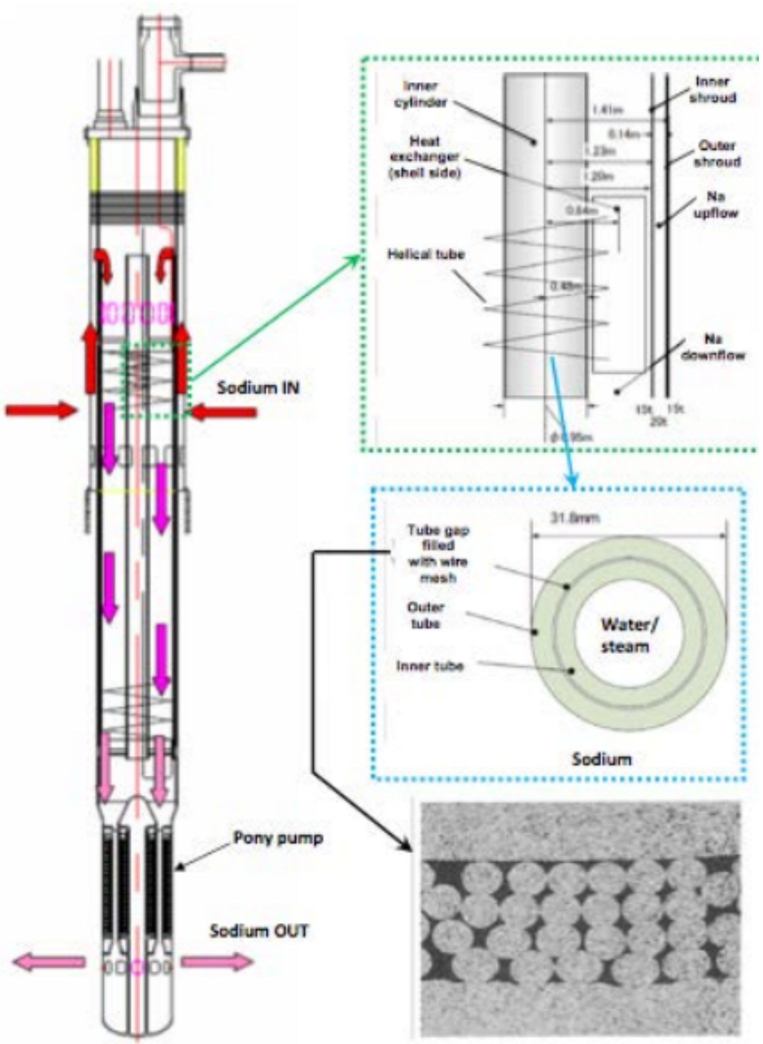


# Double wall tube steam generator

- A **steam generator** in reactor system is one of key components for various application. Also it should have enough safety margin to protect any leakage of primary coolant (LBE) or heat of fuel during operation.

- In sodium-cooled fast reactor (SFR), a **double wall tube steam generator** design was adopted to separate reactive metal coolant from water/steam inside of steam generator.

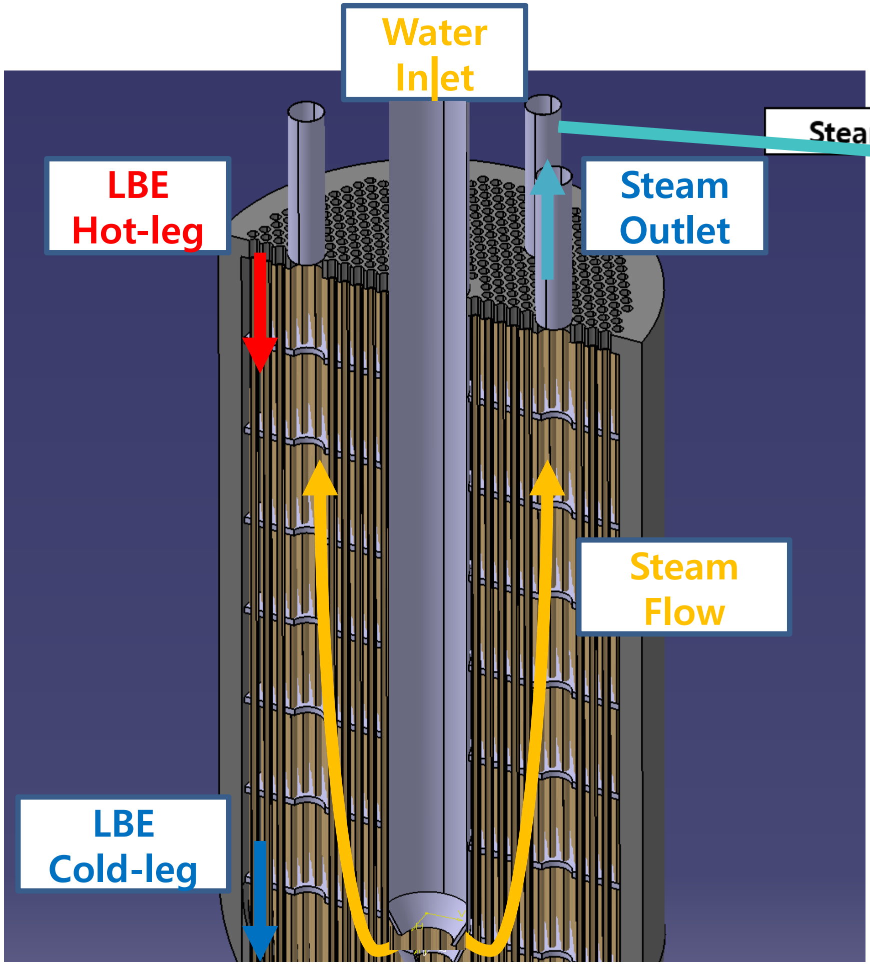
- In this study, the design of steam generator with **double wall concept for MicroUranus** has been proposed, the concept in the view of
  - Structural design
  - Material selection

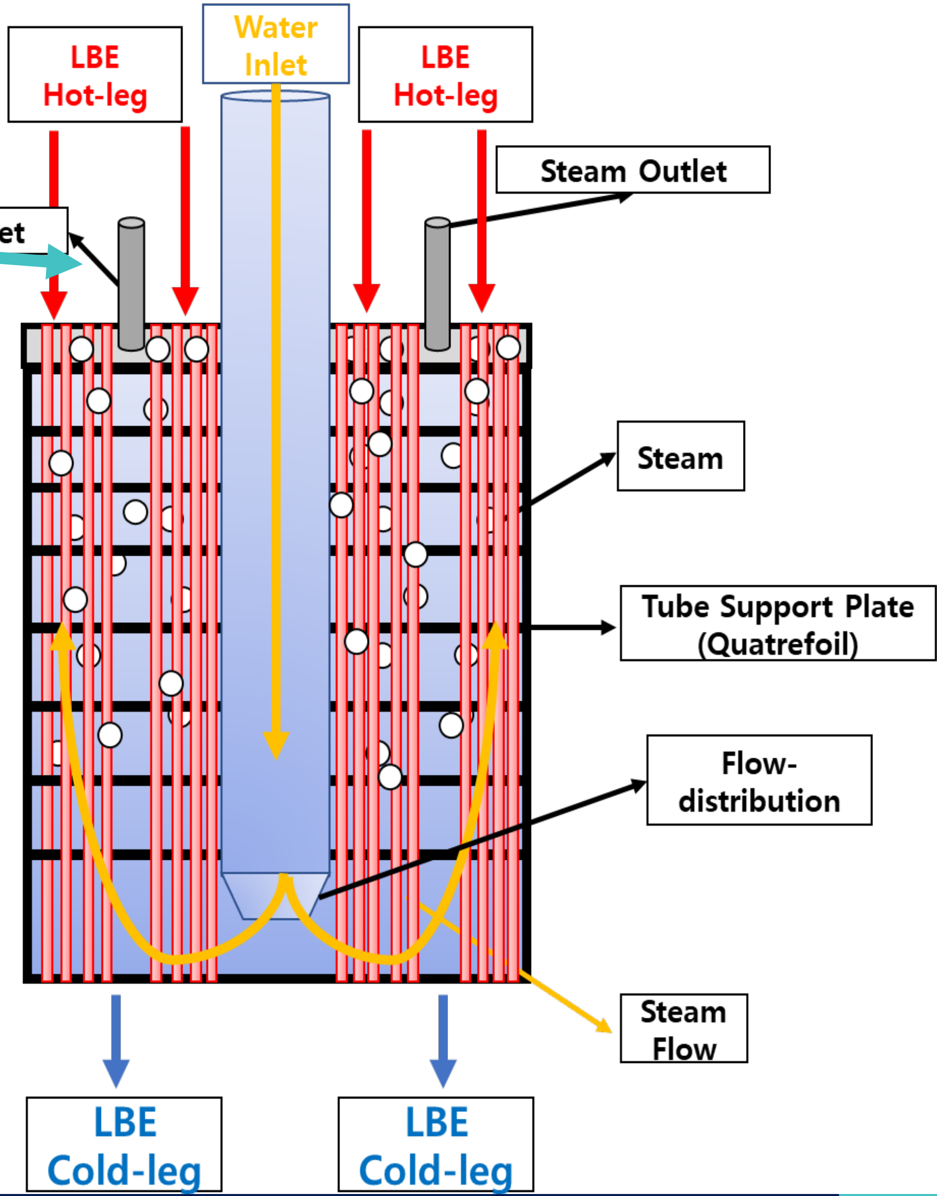



Double wall steam generator concept in SFR

# Overview of steam generator structure - #1

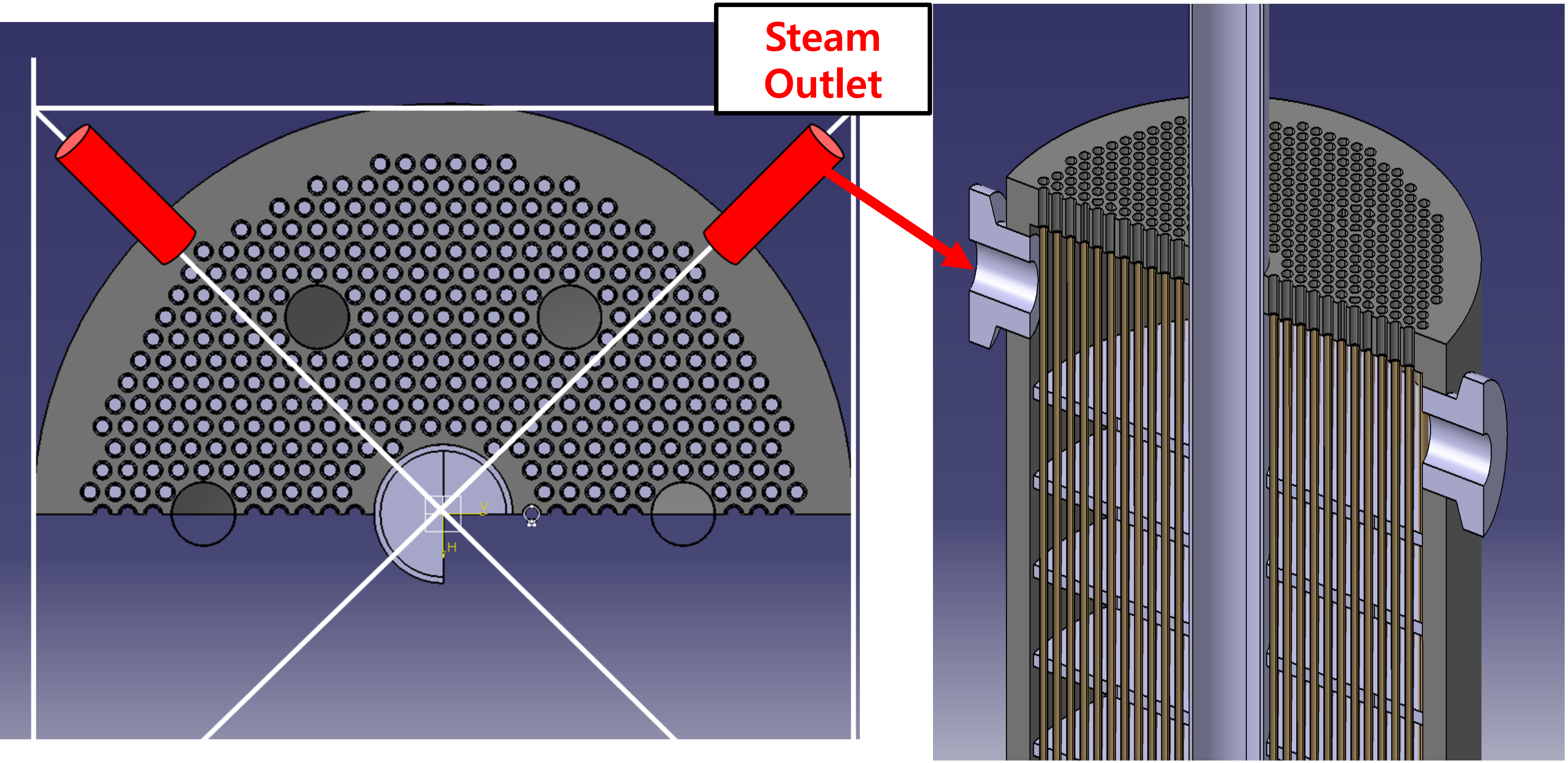
- **Full design of steam generator**



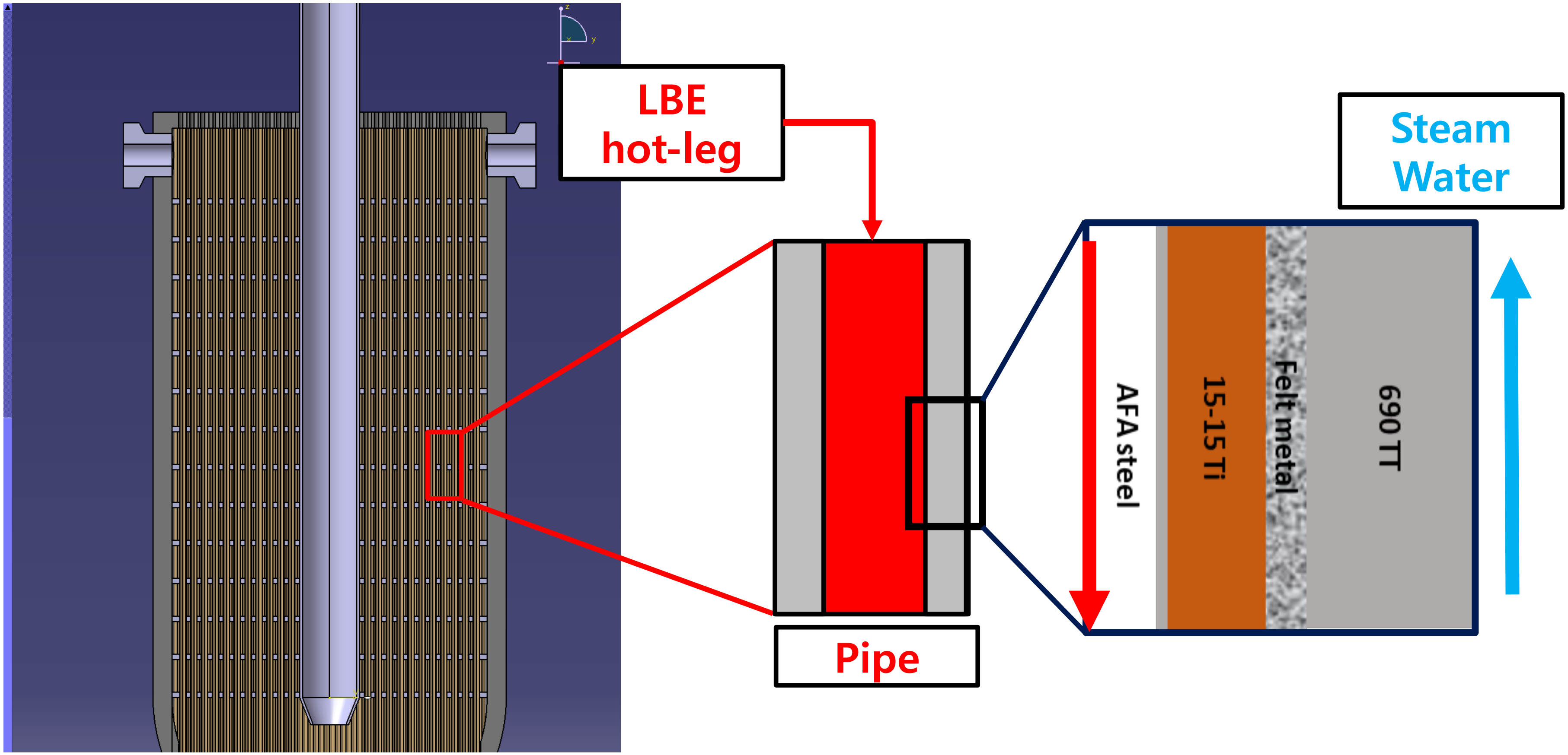



# Overview of steam generator structure - #2

- **<u>Full design of steam generator</u>**



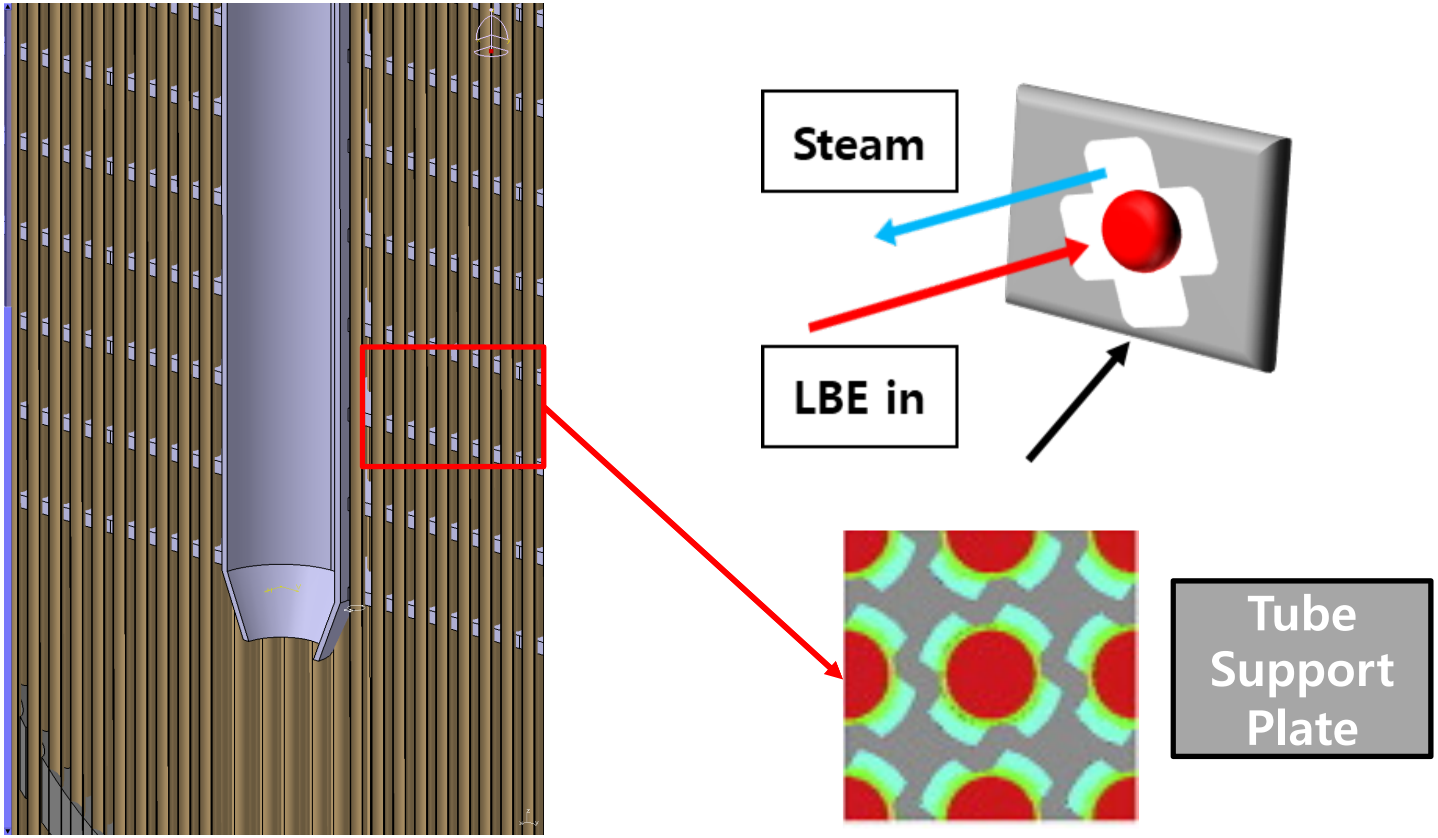
# Double walled once-through steam generator (DWOTSG)




- **<u>Once-through type</u>** is proposed for steam generator
  - Allows **<u>easier installation</u>** of the double-wall tubes.
  - Creates an **<u>empty space</u>** that can compromise LBE to steam heat transfer.

# Structural design of MicroUranus steam generator

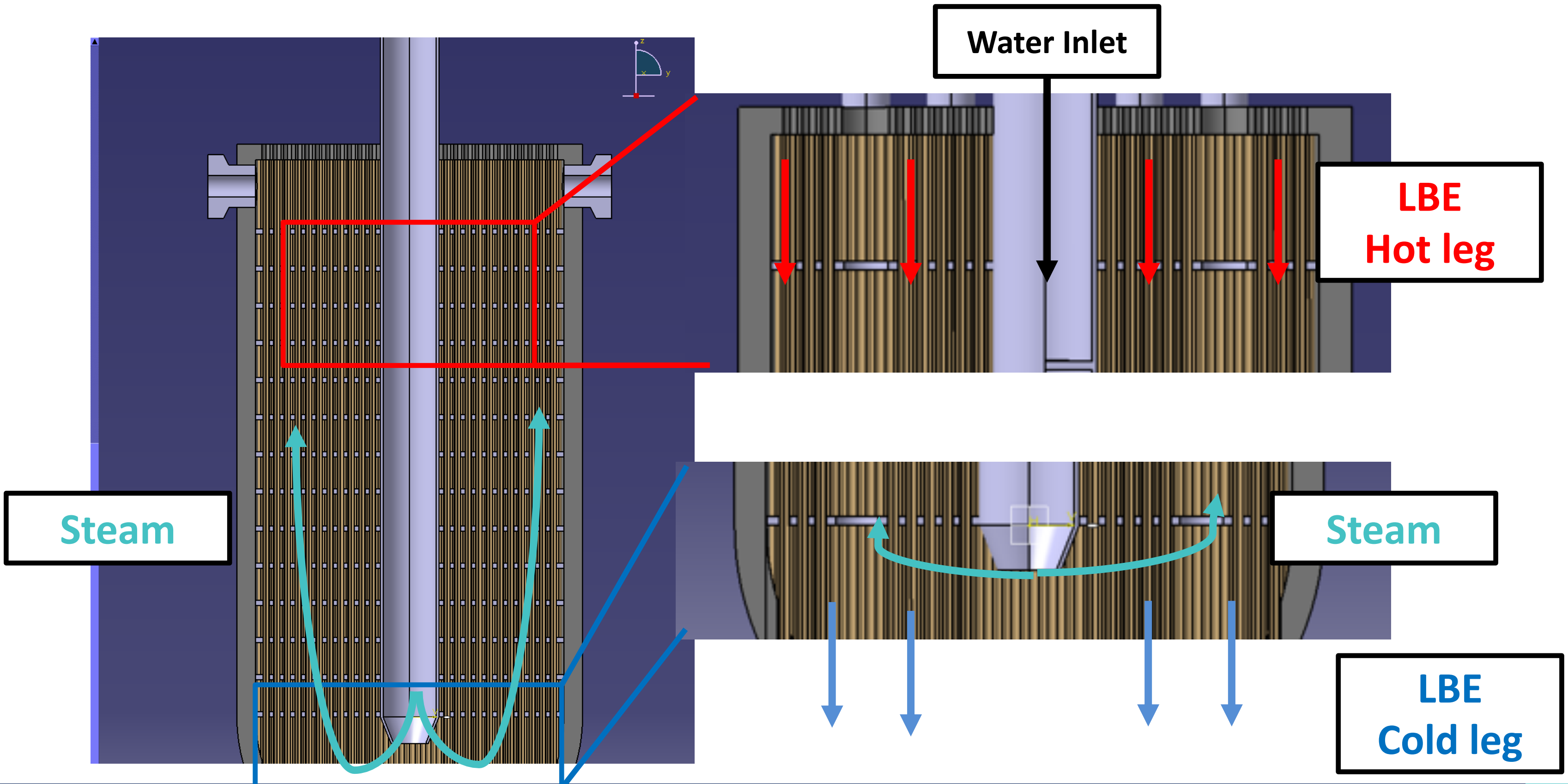
- **Minimize flow-induced vibration** damage
  - **Tube support plate formed quatrefoil** design can minimize flow-induced vibration damage by minimizing the vibration of tube.
  - Also it could prevent the contact of steam generator tubes.




MicroUranus double wall once through steam generator

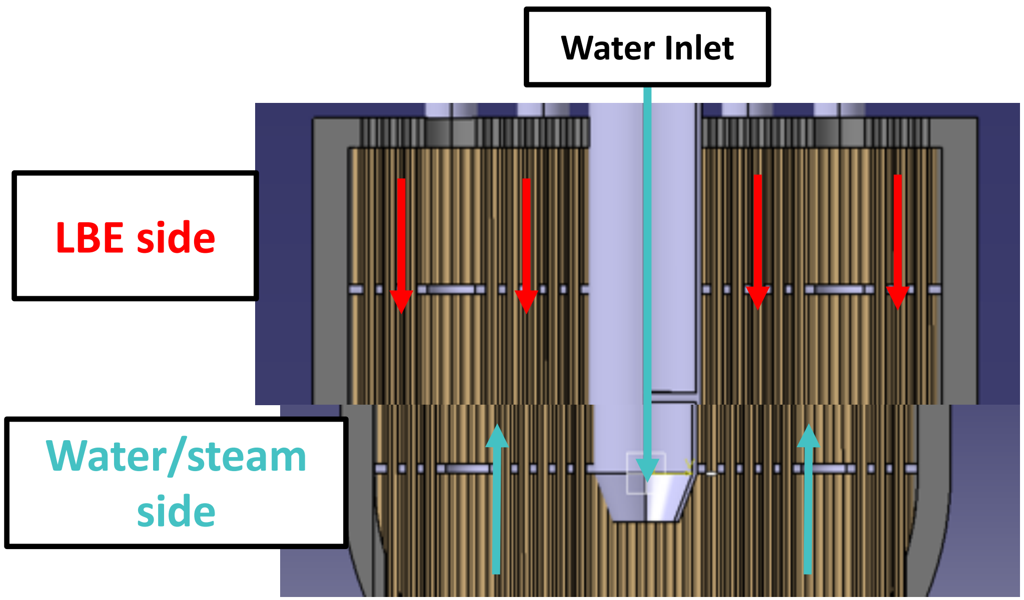
# Structural design of MicroUranus steam generator

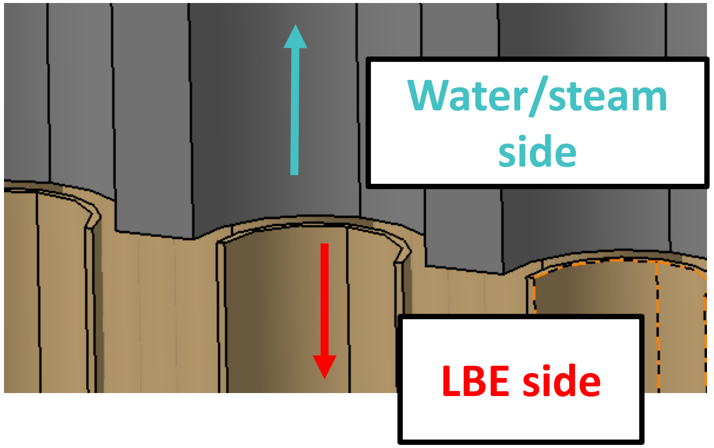
- **Optimized coolant flow path**
  - LBE **flows downward** along the tube side; **opposite to the steam flow** along the shell-side → maximizing the heat transfer
  - This design is more suitable for **online-monitoring of tube wall damage**, **inspection**, and **maintenance** of DWOTSG compared to the other steam generator designs.



# LBB design of MicroUranus steam generator

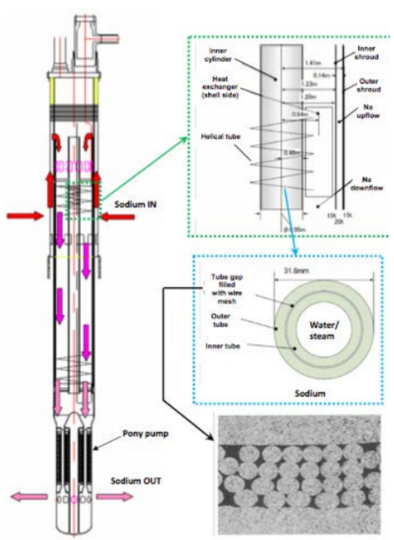
- **Leak Before Break**
  - **Various types of leak detection** methods are considered.
    - ✓ Leak detection system based on **measuring of Nitrogen-16 activity.**
    - ✓ **Ultrasonic leak detector could be helpful to find** leakages in tube.
  - **LBB under compressive stress**
    - ✓ **No liquid metal embrittlement on LBE side**.
    - ✓ **No stress corrosion cracking on water/steam side**.
    - ✓ Finally, adequate margin to failure by uniform corrosion



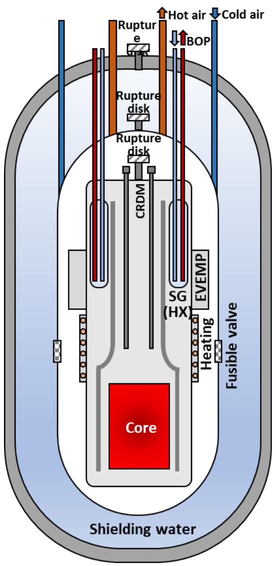



# LBE side material selection for double wall tube

- Several materials are considered for steam generators tubes of MMRs; Alumina Forming Austenitic (AFA) steels, etc.
- Among several candidates, AFA steels show good corrosion resistance to LBE environment.
- Austenitic stainless steels are known to have higher corrosion resistance at temperature below 400 °C which is the operation temperature of steam generator of MicroUranus.
- Several studies were reviewed to evaluate the compatibility of AFA steels to steam generator of MicroUranus.



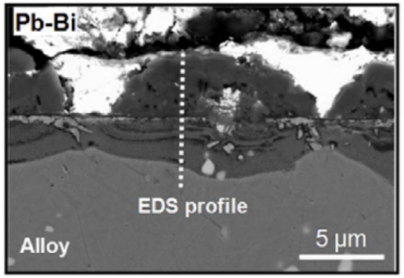

**Double wall steam generator concept in SFR**



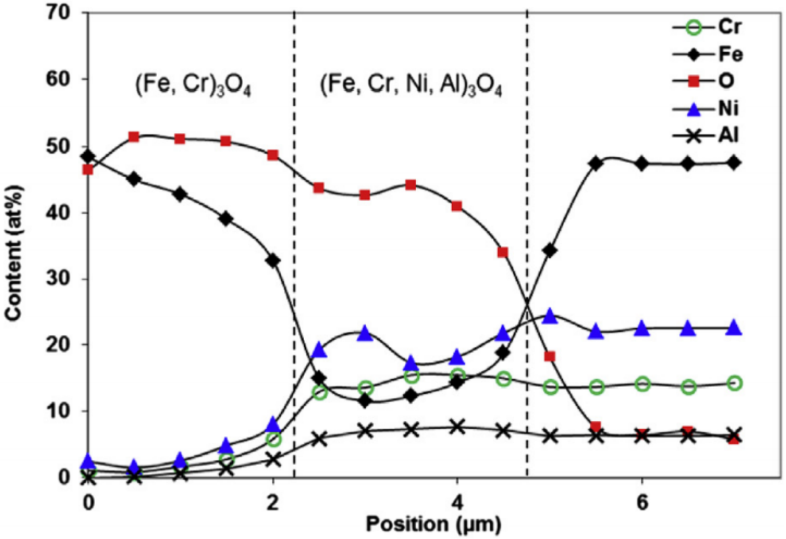

**Schematic figure of MicroUranus**

# Review: ORNL - corrosion test result of AFA steels

- There is almost **no dissolution zone** at the interface.
- Corrosion layer does not **evenly cover the steel surface.**
- **Oxidation** appears to be the dominant degradation mechanism even if it is not the corrosion layer.
- The oxide layer in contact with LBE is composed of a Fe-Cr oxide, the thickness of this layer reaches 10 μm.
- At the interface with the substrate Fe-Cr-Ni-Al oxide is formed.



(a)



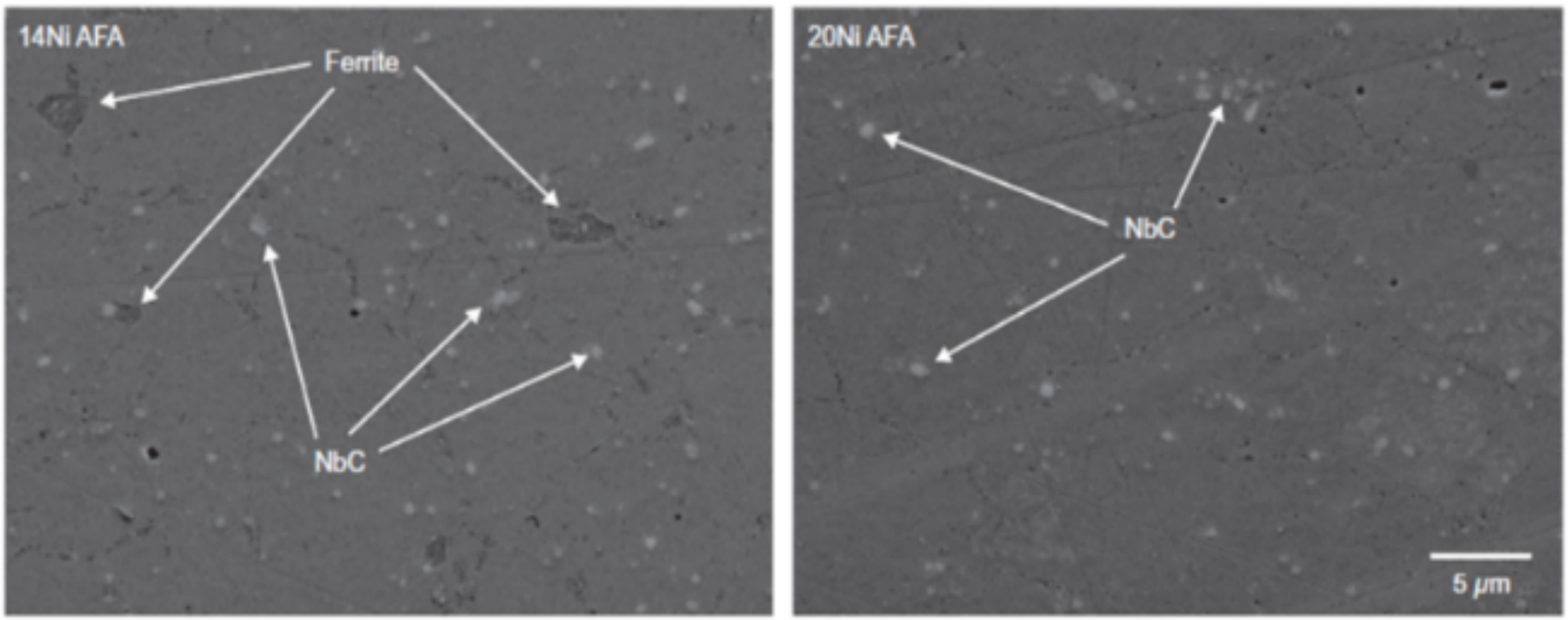
(b)

**SEM Photograph of polished cross section of OC-4 material after immersed in LBE for 190 h at 520 °C [1]**

[1] M. Roy et al. (2016)

# Review: KTH - Manufacturing process

- Two AFA steels were casted in a vacuum furnace; 14Ni AFA and 20Ni AFA steels.
- The casted metals were rolled up to 1 x 8 mm size through 8 steps.
- After each step, each metals were heat treated at 1,050 ℃.
- According to the SEM images, there exist Ni-Al precipitate, NbC carbides in the material.




**NbC particles with secondary phase, ferrite, in 14Ni AFA steel**

# Review: KTH - corrosion test result of AFA steels

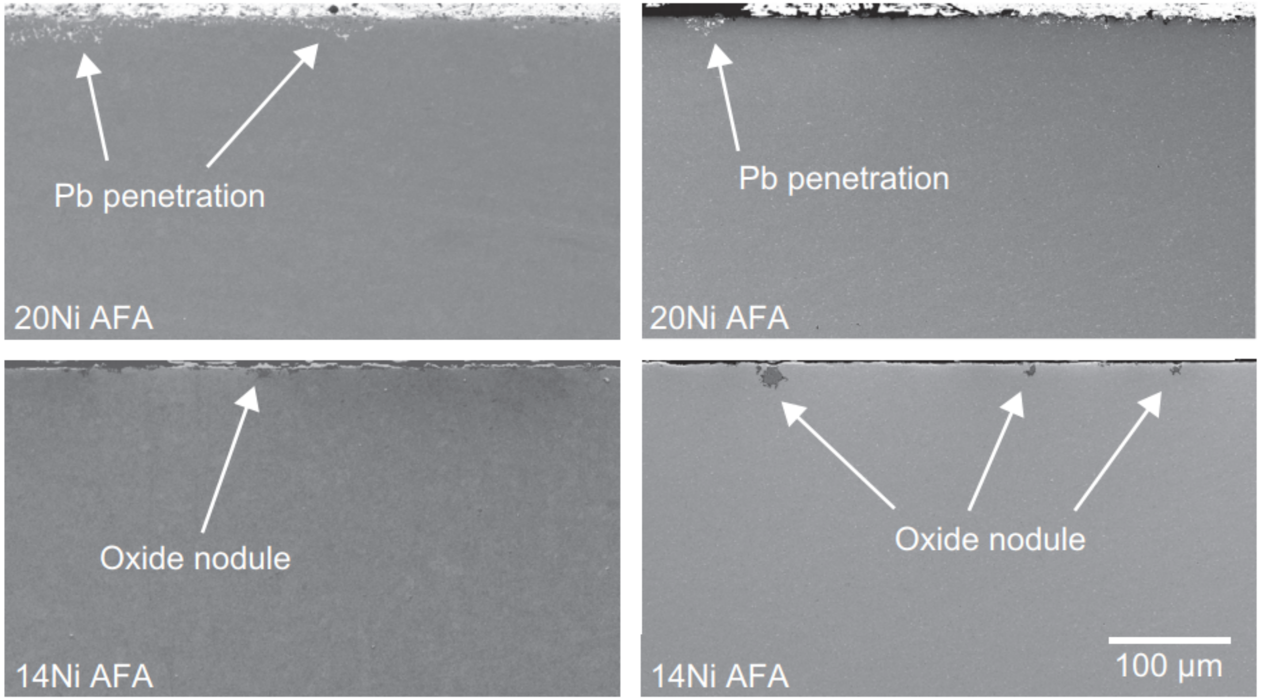
- Experimental condition
  - Liquid lead (Pb) environment
  - Oxygen concentration : $10^{-7}$ wt.% in the liquid lead controlled using a gas mixture consisted of Ar, $H_2$ and $H_2O$
  - 550 ℃ for 3,000 and 8,760 hours.

**Summary of KTH results from the corrosion test in Pb for 3000 h (left) and 8760 h (right) at 550 °C**

| Alloy | 3000 h | | | 8760 h | | |
|---|---|---|---|---|---|---|
| | Protective oxide | Dissolution attack | Nodular oxidation | Protective oxide | Dissolution attack | Nodular oxidation |
| 20Ni AFA | Partially | 10 ~ 20 $\mu m$ | Yes (<10 $\mu m$) | Partially | 10 ~ 20 $\mu m$ | Yes (<20 $\mu m$) |
| 14Ni AFA | Yes (<100 nm) | No | Yes (<10 $\mu m$) | Yes | No | Yes (<20 $\mu m$) |

# Review: KTH - corrosion test result of AFA steels

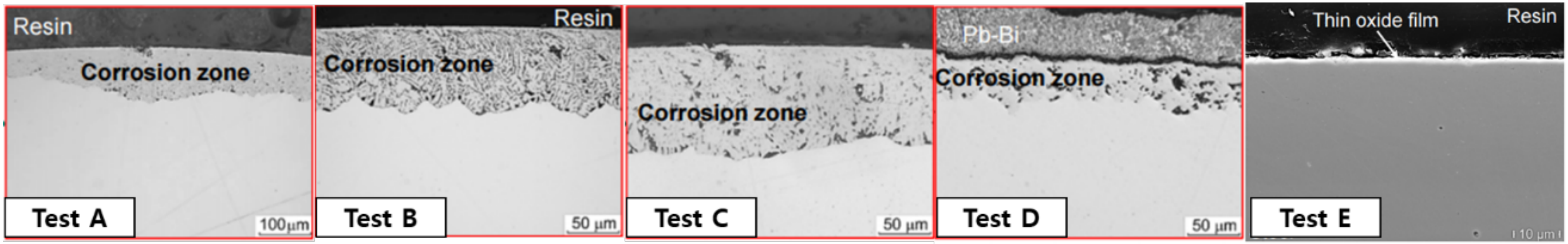
- **20Ni AFA steel exhibited partial attacks** into protective oxide layers, **dissolution attacks and nodular oxidations.**
- **14Ni AFA steel was not attacked by liquid lead**, regardless of exposure time. However, **nodular oxidation was observed** also in 14Ni AFA materials.




**Cross section images of the materials exposed in Pb for 3,000 h (left) and 8,760 h (right) at 550 ℃**

# Review: KIT - corrosion test result of AFA steels (#1-AlNbC)

- Experimental condition
  - Lead bismuth eutectic environment
  - Oxygen concentration – from $10^{-12}$ wt.% to $10^{-6}$ wt.%
  - 550 ℃ for 3,000 and 8,760 hours
  - Material (Made by USDT)
- At low dissolved oxygen concentration (from $10^{-12}$ wt.% to $10^{-8}$ wt.%)
  - **Dissolution attack** occurred in every cases.
  - **Corrosion zone was formed along with depleted Ni and Cr region.**
- At high dissolved oxygen concentration ($10^{-6}$ wt.% )
  - **$Al_2O_3$ layer was observed, dissolution attack was not occurred.**



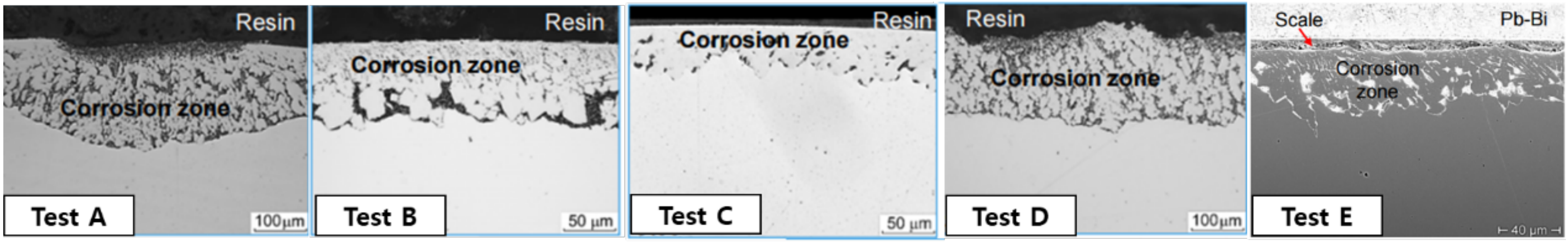

Corrosion test results of #1-AlNbC depending on dissolved oxygen

# Review: KIT - corrosion test result of AFA steels (#3-Al)

- At dissolved oxygen concentration from $10^{-12}$ wt.% to $10^{-6}$ wt.%
  - **Dissolution attack occurred in every cases.**

- It seems that the added **Al and NbC** contributes to the formation of **protective oxide layer** that impedes the oxidation and dissolution of metal ions into liquid metal.

- **Alloying elements should be considered carefully** including common elements like Al and other elements which could enhance the formation of oxide layer such as $Al_2O_3$.




Corrosion test results of #3-Al depending on dissolved oxygen concentration

# Compatibility of AFA steels for MicroUranus S/G

- From the review, we found that current AFA steels **might not be suitable for long-term operation of 40 years**.
- We selected a set of new chemical composition of **Alumina-Forming Super Austenitic (AFSA) steel with Al addition**, as shown in Table.

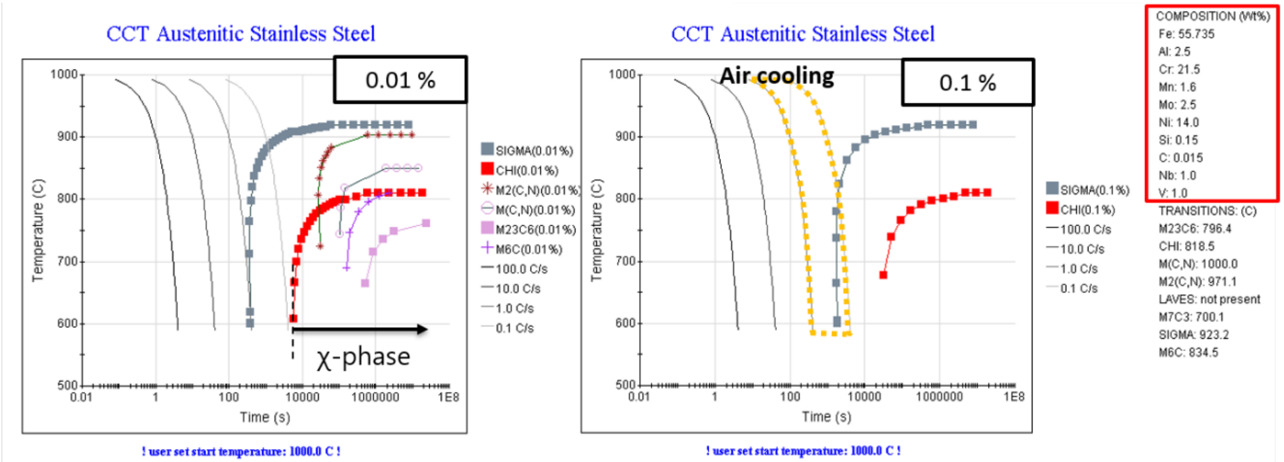
**Comparison of chemical composition of AFA steels applicable to LFR's**

| wt.% | Fe | Cr | Al | Ni | Mn | Mo | Si | Nb | C |
|---|---|---|---|---|---|---|---|---|---|
| ORNL (OC-4) | Bal. | 14 | 3.5 | 25 | 2 | 2 | 0.15 | 2.5 | 0.1 |
| KTH (20Ni AFA) | Bal. | 14.2 | 2.47 | 19.7 | 1.64 | 2.43 | 0.18 | 0.87 | 0.08 |
| KTH (14Ni AFA) | Bal. | 14.4 | 2.49 | 13.9 | 1.60 | 2.50 | 0.19 | 0.89 | 0.08 |
| KIT (#1-AlNbC) | Bal. | 11.7 | 2.32 | 18.0 | 0.0887 | 1.99 | 0.401 | 0.577 | 0.0086 |
| KIT (#3-Al) | Bal. | 11.7 | 2.90 | 18.0 | 0.118 | 2.00 | 0.377 | <0.01 | 0.0300 |
| UNIST (AFAS #1) | Bal. | 18 | 2.50 | 25 | 1 | 5 | 1 | 1 | - |
| UNIST (AFAS #1) | Bal. | 16 | 2.50 | 25 | 1 | 5 | 1 | 1 | - |

[1] I.V. Gorynin et al. (1999)

# Alumina-Forming Super Austenitic (AFSA) steel - Development

- **Alumina-Forming Super Austenitic (AFSA) steel**
  - Super Austenitic Stainless Steel contains high content of Cr (more than 20 wt.%).
  - We **reduced the amount of Cr for better deformability** during material processing.
  - The **chemical compositions of AFSA steel are close to other AFA material from other research institution.**



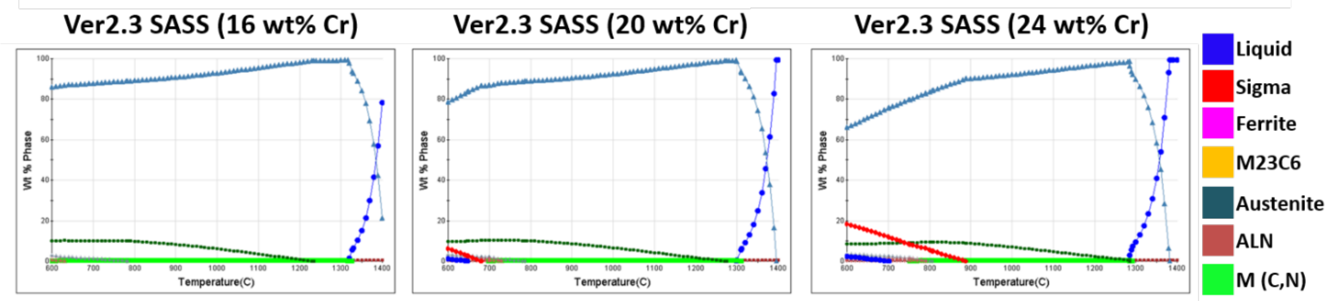




**Fig. UNIST AFSA steel Ingot Sample and result of JMatPro Calculation**

# Alumina-Forming Super Austenitic (AFSA) steel - Manufacturing process

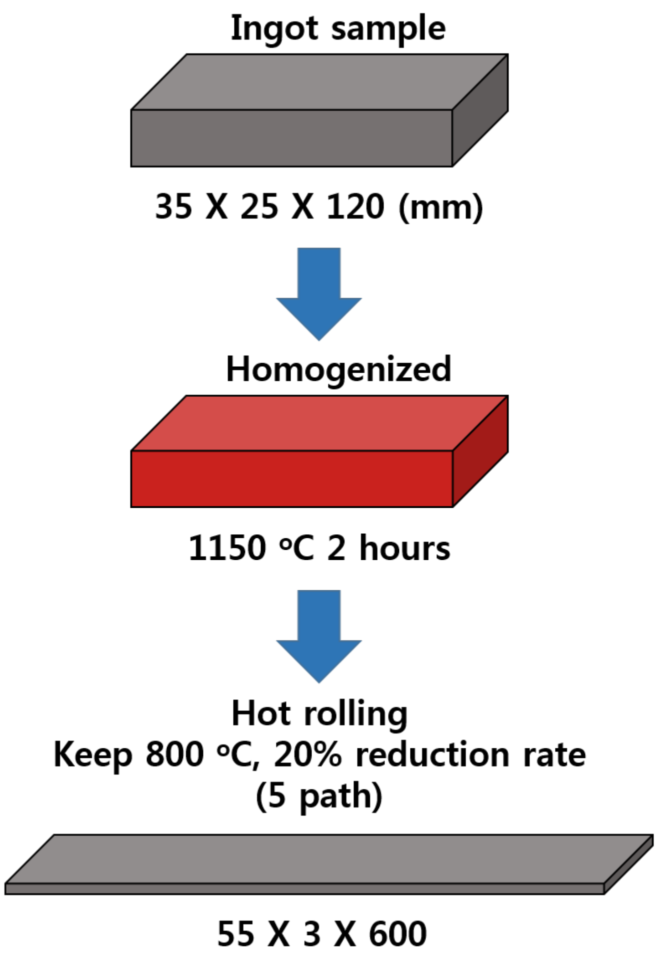



Fig. Process schematic ( Width X thickness X length)

- The material compositions were analyzed by thermodynamic calculation software, JMatPro, in order to confirm designed chemistry of the materials.
- After the experimental alloys were melted initially by arc-melting, it was solidified by furnace-cool.
- After removing surface sludges and impurity spots from ingots, induction melting process was applied to produce homogeneous compositions of the materials.
- Ingots from induction melting were produced by furnace-cool.
- The thick plates was **hot rolled** into 3 mm thickness plates.
- **Water quenching** was introduced to avoid formation of sigma phases.

# Alumina-Forming Super Austenitic (AFSA) steel - Optical Microscopy

- SEM image of AFSA steel.
  - Average grain size of material was about 30 micro meters and several precipitates were observed.
  - Those precipitates were revealed as iron-chrome-molybdenum intermetallic phase which could be sigma phase.

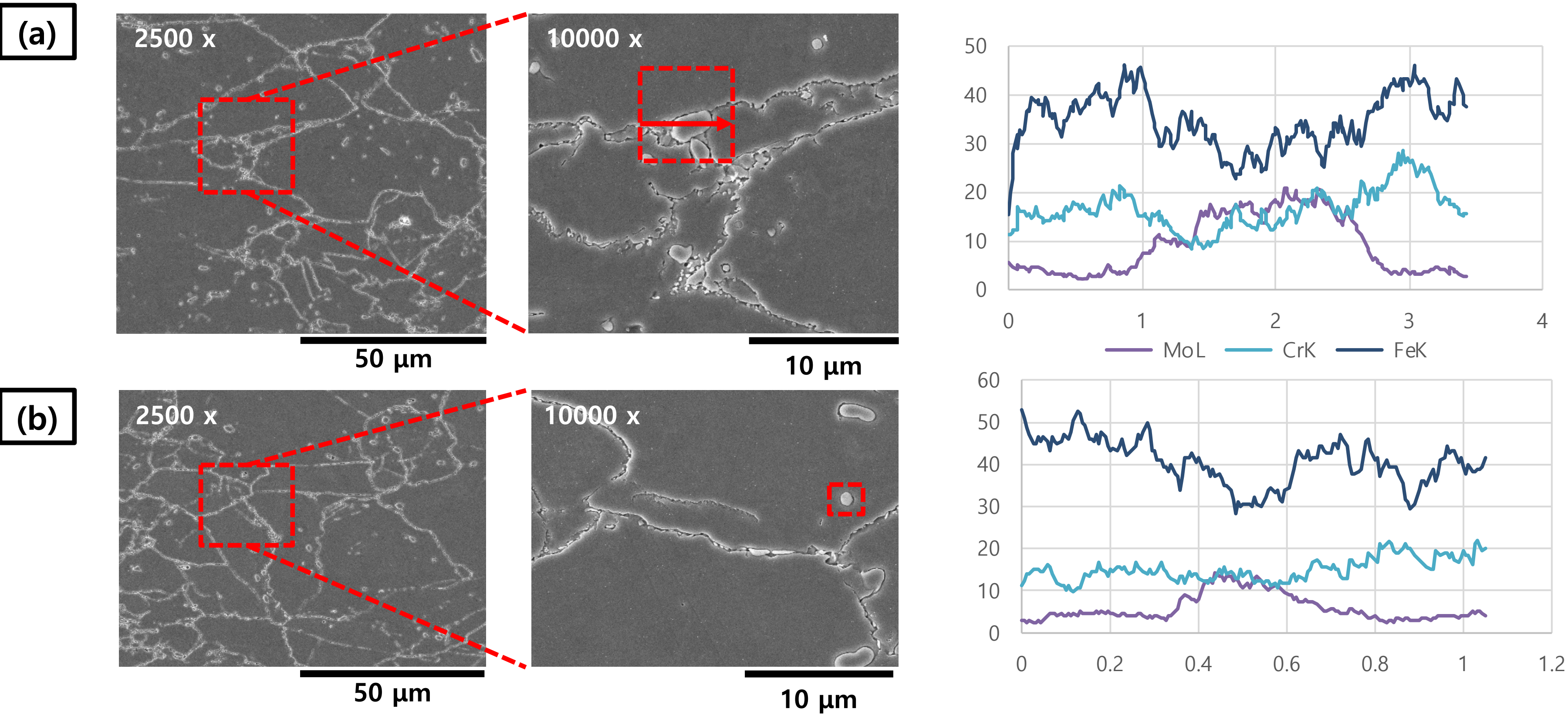



**Fig. SEM image of AFSA steel (a) AFSA #1 (b) AFSA #2**

# Summary and Future Work

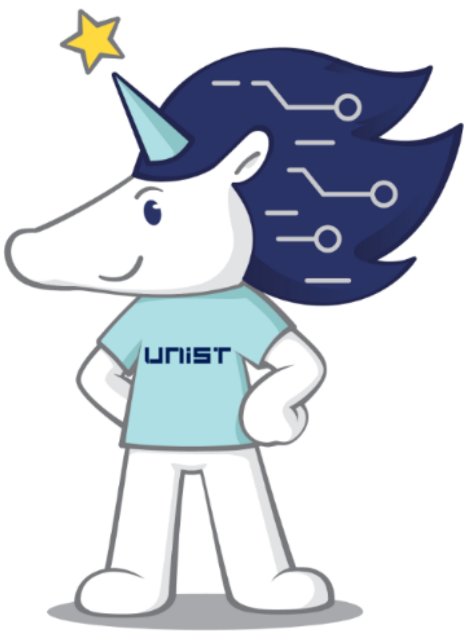
## Summary

- A double-walled once-through steam generator (DWOTSG) design concept is suggested for MicroUranus, a non-refueling and hermetically-sealed 40-year life micro-modular LFR.
- Austenitic stainless steel was selected to be used in LBE side of steam generator tube, considering that the high corrosion resistance of that steel since operating temperature of steam generator might not exceed 350 ℃ during operation of 40 years.
- However, from literature review, we conclude that commercial AFA steels might not suitable for long-term operation. Therefore we tries to develop new alloy called AFAS steel which expected to have higher corrosion resistance to have longer life in LBE environment.

## Future work

- Investigate the material properties of AFSA Steel including basic mechanical properties and corrosion behavior in various environment.
- Leak-Before-Break qualification will be investigated in detail.

# Thank You for Your Attention!

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