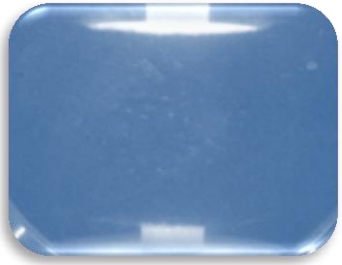
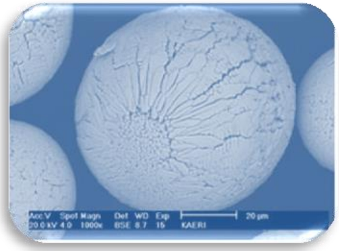
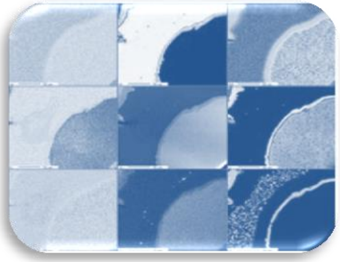
Plasma-Wall Interaction for Irradiated Tungsten and Tungsten Alloys in Fusion Devices
Second Research Coordination Meeting, Seoul National University, Seoul, Republic of Korea, 8-11 September 2015







Tungsten-based High Entropy Alloys and Composites for Plasma Facing Materials

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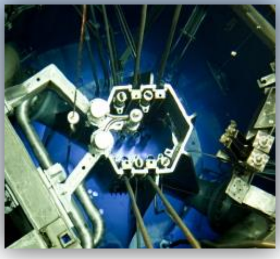
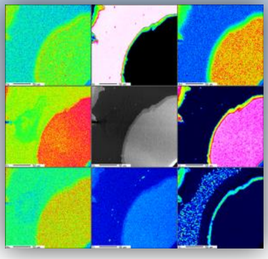
Nuclear Fuel Materials Laboratory

KAIST

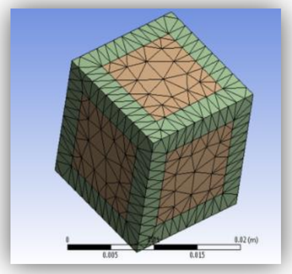
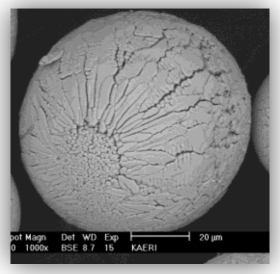
Research Areas

Nuclear Fuel

Irradiation Behavior

Irradiation and Post-irradiation Examination

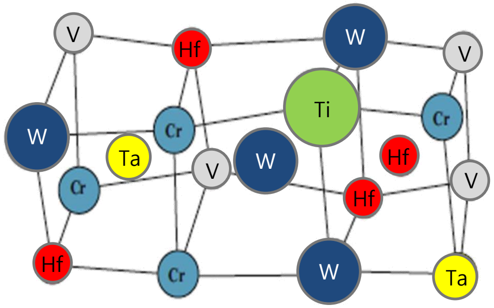



Simulation and Fabrication of Advanced Fuel

Extreme Materials

Alloy Development


Fabrication of Fusion & Aerospace materials



Compositionally Complex Alloys
(High Entropy Alloys)

NQe

Tungsten Alloy Development

High Vacuum Furnace

- Max. 1800°C
- Diffusion pump (10^{-6} Torr)
- Tungsten mesh heater
- Ar, N_2, H_2 atmosphere

Microwave Furnace

- Max. 1600°C
- Ar, N_2 atmosphere

Spark Plasma Sintering

- Max. 1800°C
- Vacuum atmosphere

Cold Isostatic Press

- Powder compaction
- Max. 400 MPa
- ID 50mm X 150 mm (L)
- Air driven water pump

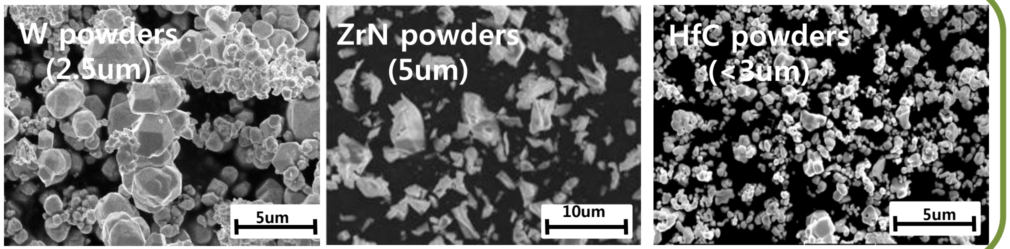
Attritor

- MA ODS alloy fabrication
- Water cooling

Tungsten Alloys/Composites Fabrication

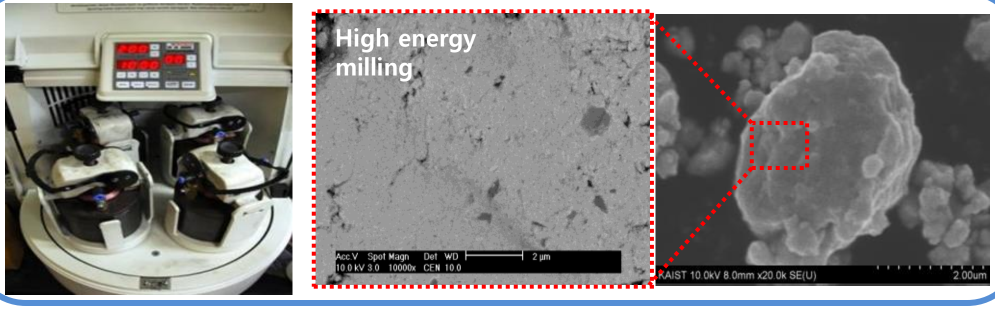
NQe

W and other powders



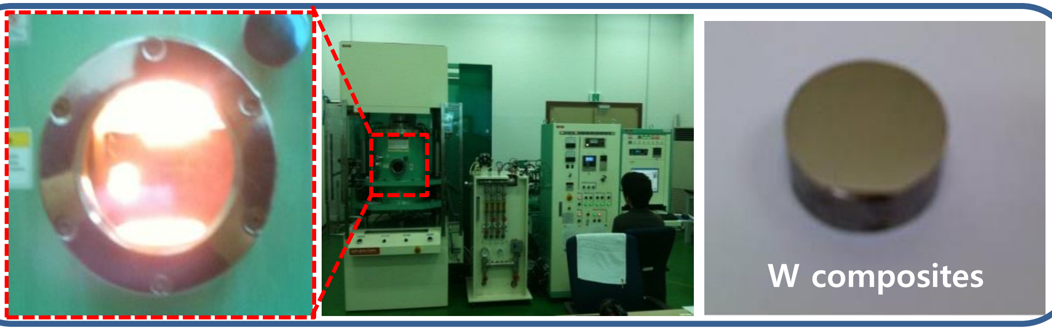
High energy ball milling

W composite powders



Consolidation
(Spark Plasma Sintering)

W composites



Room Temperature Mechanical Properties

High Temperature Mechanical Properties

High Temperature Ablation

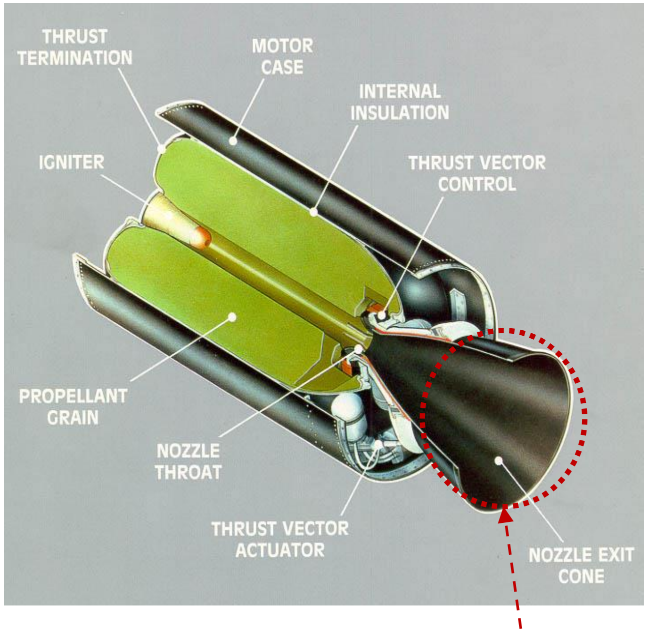
Tungsten Studies of Our Group

NQe

- Ryu, Ho J., Soon H. Hong, and Woon H. Baek. "Mechanical alloying process of 93W-5.6 Ni-1.4 Fe tungsten heavy alloy." *Journal of Materials Processing Technology* 63.1 (1997): 292-297.
- Ryu, Ho J., Soon H. Hong, and Woon H. Baek. "Microstructure and mechanical properties of mechanically alloyed and solid-state sintered tungsten heavy alloys." *Materials Science and Engineering: A* 291.1 (2000): 91-96.
- Park, Sanghyun, et al. "Dynamic deformation behavior of an oxide-dispersed tungsten heavy alloy fabricated by mechanical alloying." *Metallurgical and Materials transactions A* 32.8 (2001): 2011-2020.
- Ryu, Ho J., and Soon H. Hong. "Fabrication and properties of mechanically alloyed oxide-dispersed tungsten heavy alloys." *Materials Science and Engineering: A* 363.1 (2003): 179-184.
- Hong, Soon H., and Ho J. Ryu. "Combination of mechanical alloying and two-stage sintering of a 93W–5.6 Ni–1.4 Fe tungsten heavy alloy." *Materials Science and Engineering: A* 344.1 (2003): 253-260.
- Lee, Kyong H., et al. "Effect of two-stage sintering process on microstructure and mechanical properties of ODS tungsten heavy alloy." *Materials Science and Engineering: A* 458.1 (2007): 323-329.
- Lee, Kyong H., et al. "Effect of mechanical alloying process on microstructure and mechanical properties of ODS tungsten heavy alloys." *Journal of alloys and compounds* 434 (2007): 433-436.
- Lee, Kyong H., et al. "Effect of oxide dispersoids addition on mechanical properties of tungsten heavy alloy fabricated by mechanical alloying process." *Materials Science and Engineering: A* 452 (2007): 55-60.
- Lee, Dongju, et al. "Elevated temperature ablation resistance of HfC particle-reinforced tungsten composites." *International Journal of Refractory Metals and Hard Materials* 43 (2014): 89-93.
- Lee, Dongju, et al. "The effect of HfC content on mechanical properties HfC–W composites." *International Journal of Refractory Metals and Hard Materials* 44 (2014): 49-53.
- Umer, Malik Adeel, et al. "High temperature ablation resistance of ZrNp reinforced W matrix composites." *International Journal of Refractory Metals and Hard Materials* 42 (2014): 17-22.

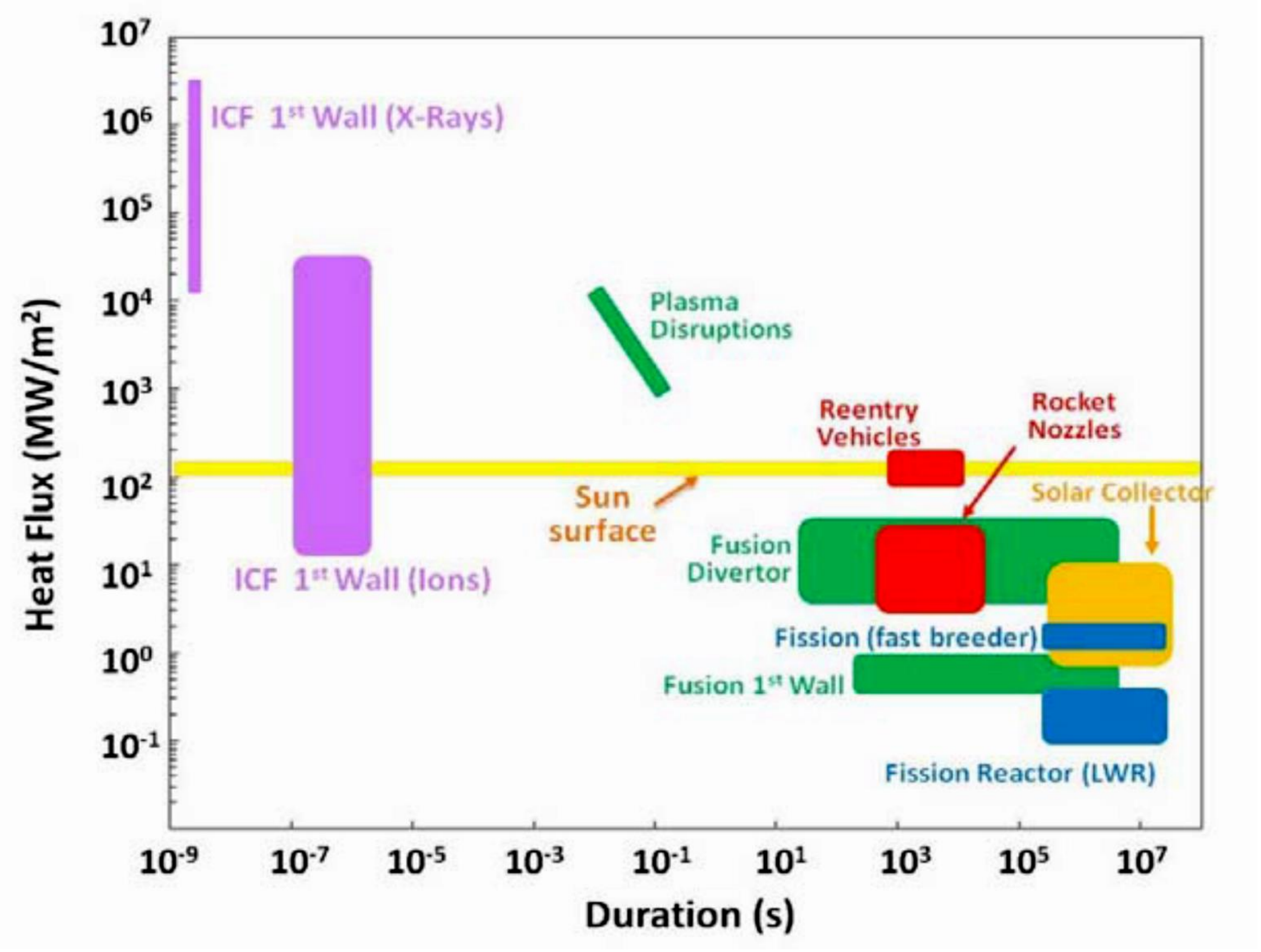
➔ No Fusion Plasma Facing Materials Applications

Aerospace Rocket Nozzle Materials



Our concern

Heat Loads of Space/Fission/Fusion

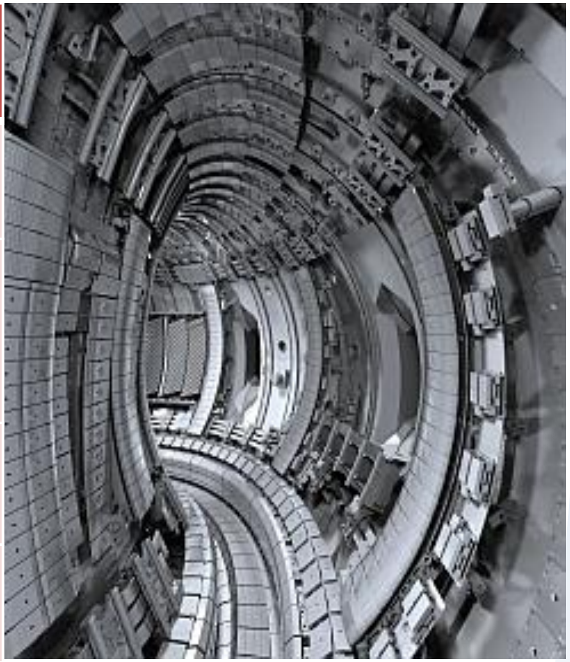


S. J. Zinkle, Workshop on Decadal Challenges for Predicting and Controlling Materials Performance in Extremes
Santa Fe, New Mexico December 6-10, 2009

Tungsten for Plasma Facing Materials

NQe

Advantages	Drawbacks
High Tm: 3410°C	High DBTT (400~800°C)
Low sputtering erosion	Recrystallization (1000~1200°C)
High thermal conductivity	Irradiation Embrittlement
Low tritium retention	Volatile Oxidation, WO_3



Full Tungsten of EFDA-JET

R&D Issues of Tungsten Alloys

D/T Retention in Irradiated Tungsten

Self-Passivation under Loss of Vacuum Accident

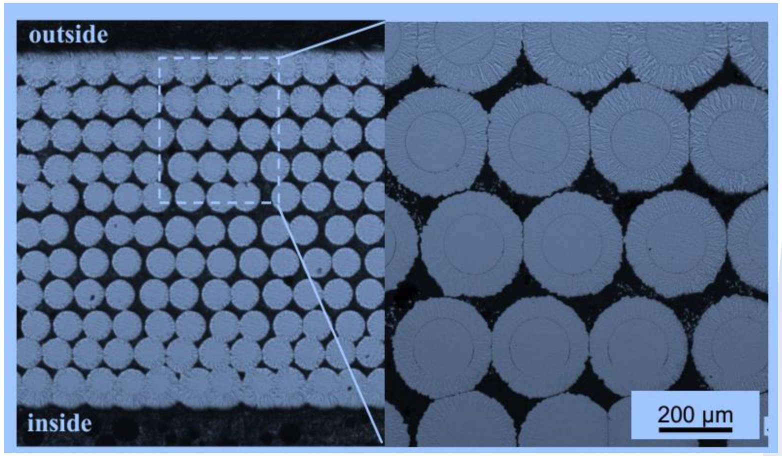
Thermal Fatigue & Thermal Shock Resistance

Variation of Tungsten for PFM

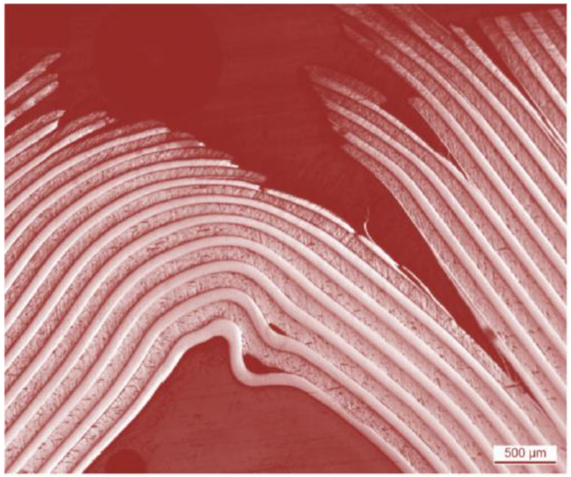
NQe

- **Alloys**
  - W-Re, W-Ta, W-Cr-Ti, W-Cr-Zr-Y
- **Dispersion**
  - W-Y_2O_3, W-La_2O_3, W-TIC
- **Composites**
  - W fiber, W-V laminates

Primarily for mechanical integrity or oxidation resistance



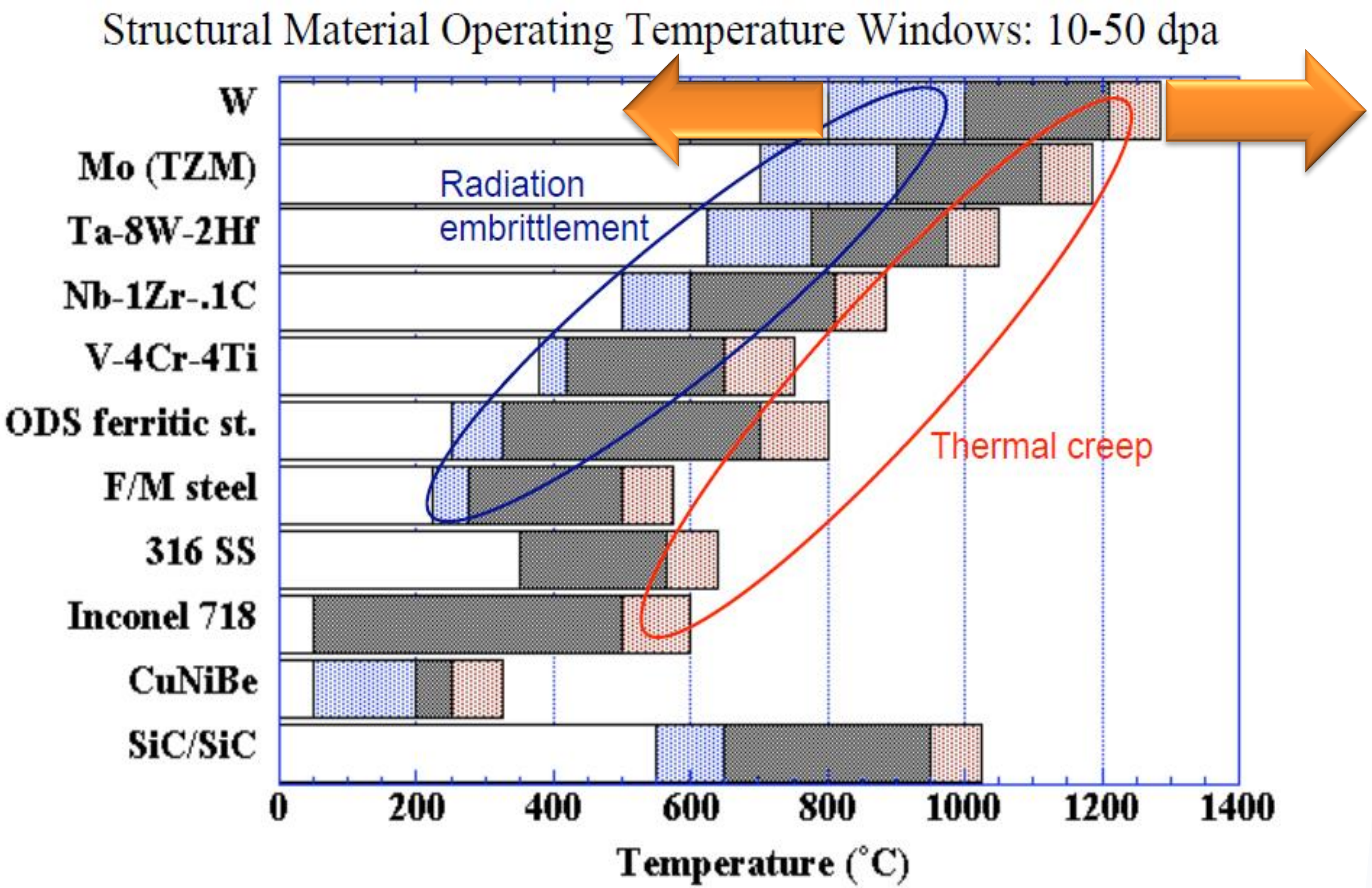
Max-Planck-Institut für Plasmaphysik



Karlsruhe Institute of Technology

Mechanical Properties under Irradiation

NQe

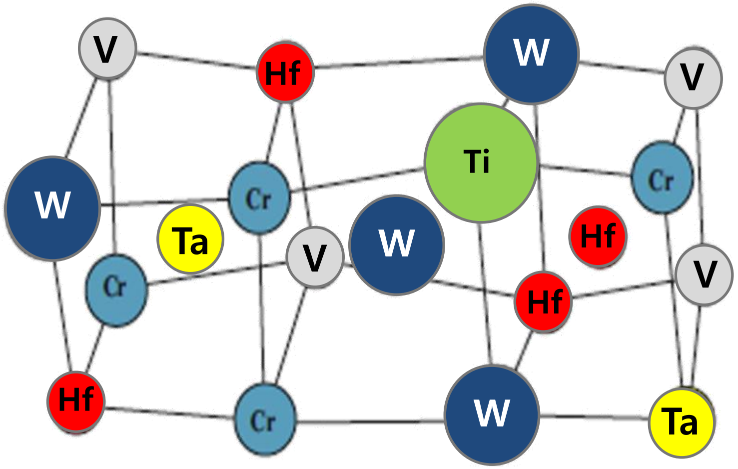


Zinkle, S. J., and Ghoniem, N. M., *Fusion Eng. Des. 49-50 (2000) 709*

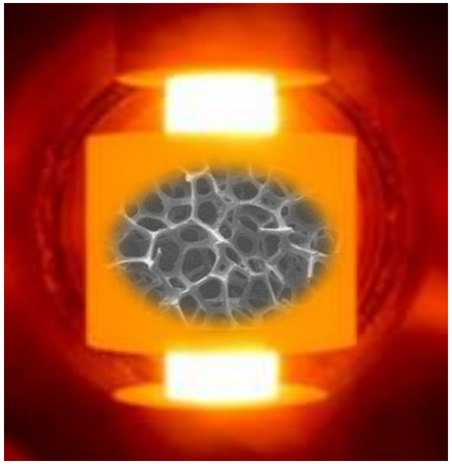
Our Approach – New Alloys/Composites

NQe

- Alloy Design and Fabrication of Tungsten-based Alloys and Composites
- Characterization of Mechanical Properties and Oxidation Resistance
- Radiation Damage and Hydrogen Retention



High Entropy Alloys



Hybrid Composites

Why "High Entropy Alloys"

- **High mixing entropy stabilize a simple phase**

- **Other names**
  - Compositionally Complex Alloys
  - Multi-principal Alloys
  - Equiatomic Alloys (Equimolar Alloys)

- **Definition**
  - Multicomponent alloys with more than 5 components with 5-35 at.% (ΔS_{conf} > 1.6 R)

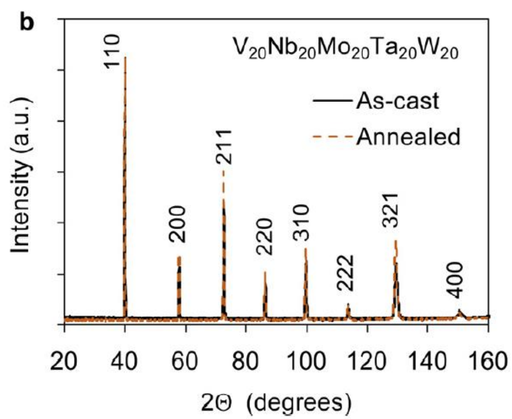
    - *Superalloy with 10+ components:* ΔS_{conf} = *1.3 R*

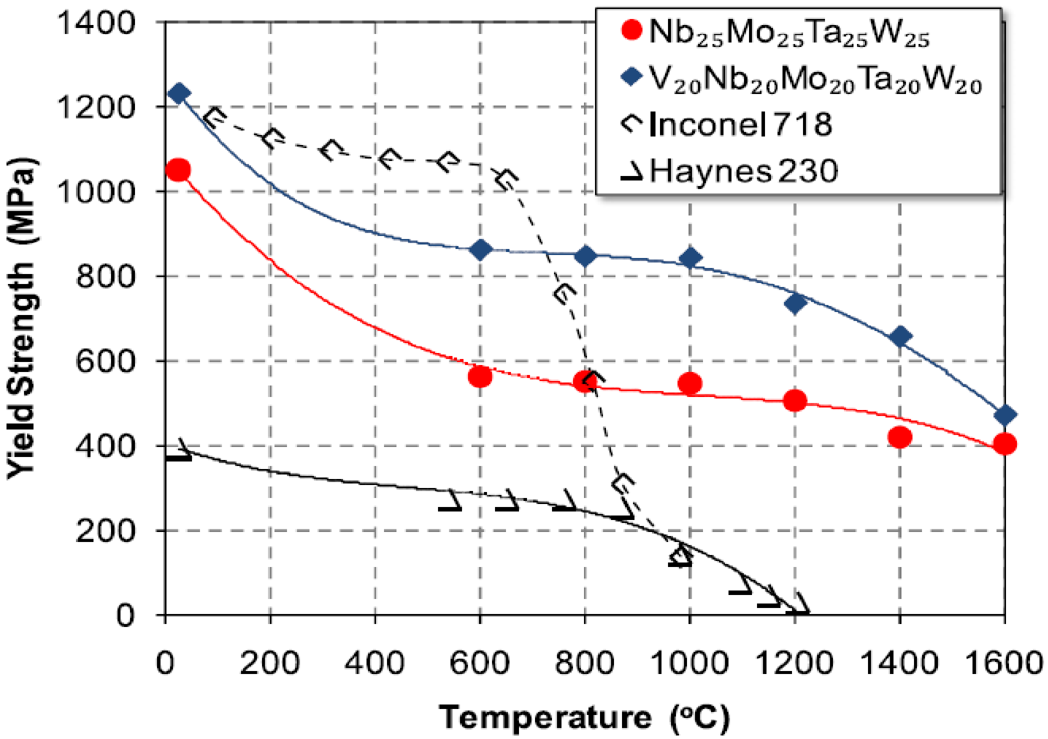
Refractory High Entropy Alloys

NQe

VNbMoTaW by vacuum arc melting (US AFRL)

"to overcome temperature limit of superalloys"





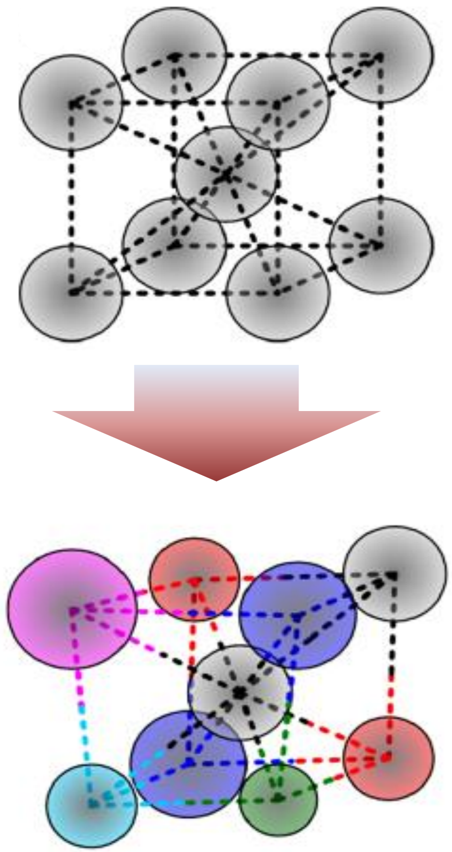
13.8 g/cm^3 for NbMoTaW
12.4 g/cm^3 for VNbMoTaW

O.N. Senkov & D.B.Miracle, Intermetallics 18 (2010) 1758-1765, 19 (2011) 698-706

Four Core Effects of HEAs

NQe

- **Thermodynamics:** High Entropy Effect
  - Enhance the formation of solid solution
- **Structure:** Severe Lattice Distortion Effect
  - Hardness and strength increase
- **Kinetics:** Sluggish Diffusion Effect
  - Slow diffusion and higher activation energy
- **Properties:** Cocktail Effect
  - Composite properties



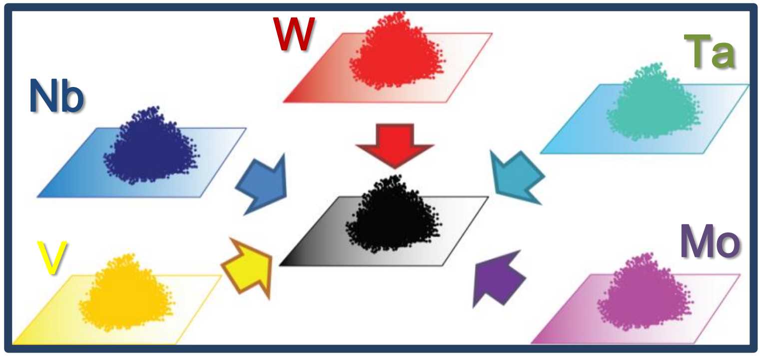
Y. Zhang *et al.* Progress in Materials Science 61 (2014) 1–93

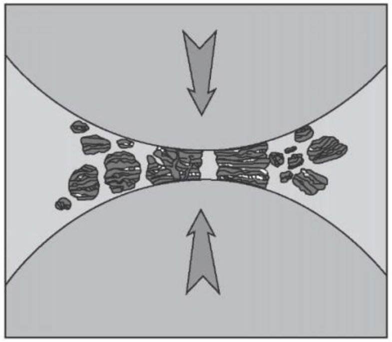
Powder Metallurgy Refractory HEA

Atomic size, density and melting temp. of elements

	Nb	Mo	Ta	V	W
Radius (nm)	0.146	0.139	0.146	0.134	0.139
T_m (ºC)	2750	2896	3290	2183	3695
Density (g/cm^3)	8.6	10.3	16.6	6.1	19.3

Mechanical Alloying



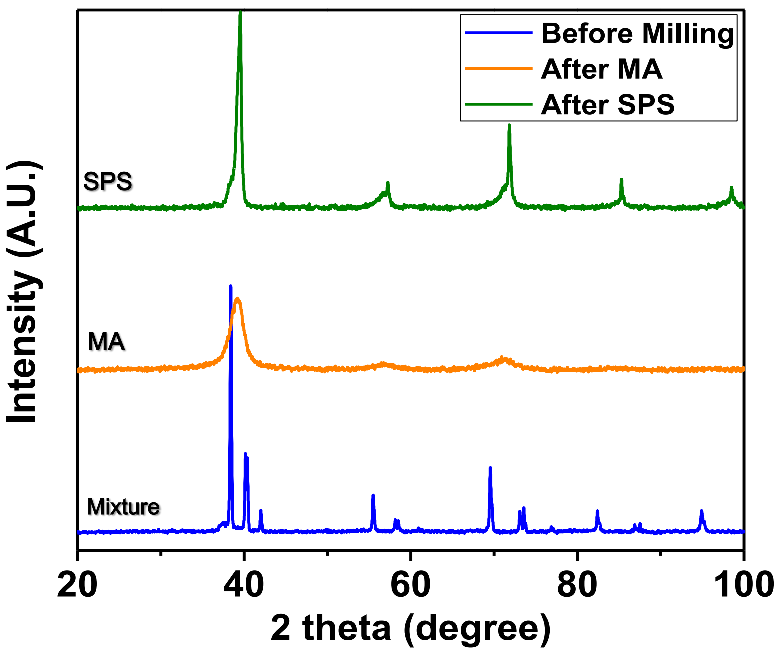


Kuk & Ryu (KAIST, Unpublished Data, 2015)

Microstructures of VNbMoTaW (MA & SPS)

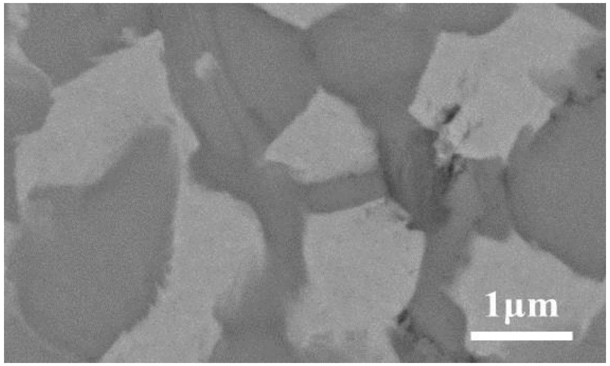
NQe

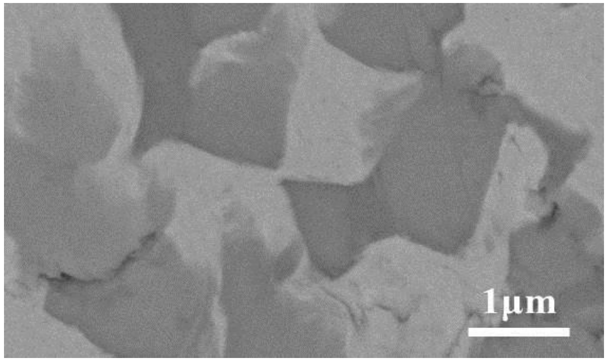
XRD before and after SPS



- $V_{20}Nb_{20}Mo_{20}Ta_{20}W_{20}$
- Multi-phase Microstructure

SEM image of after SPS

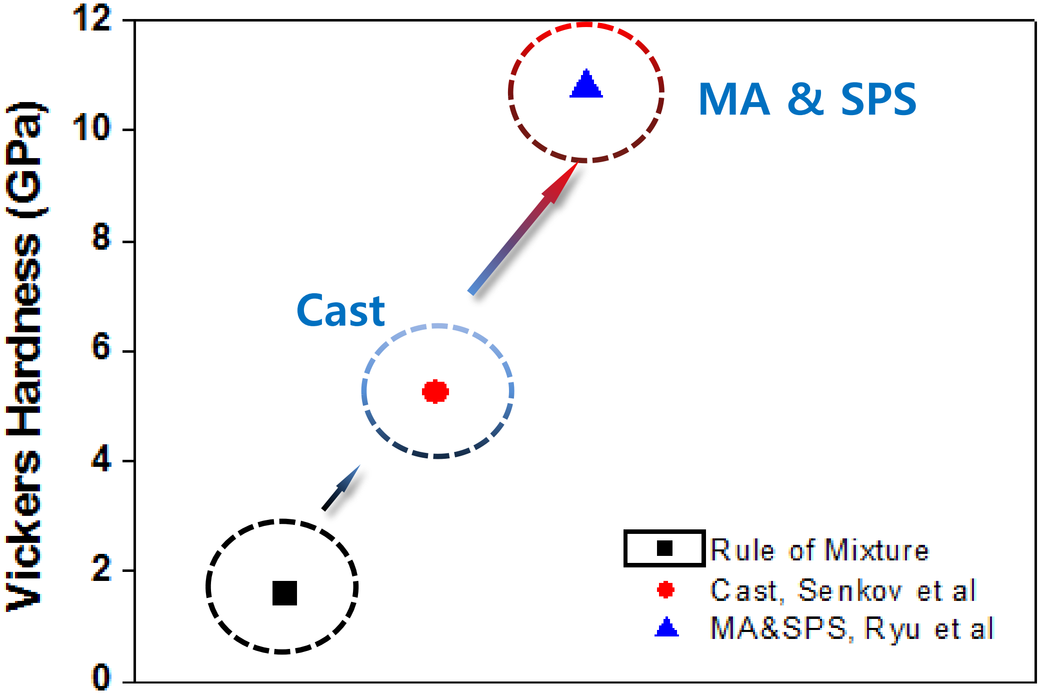




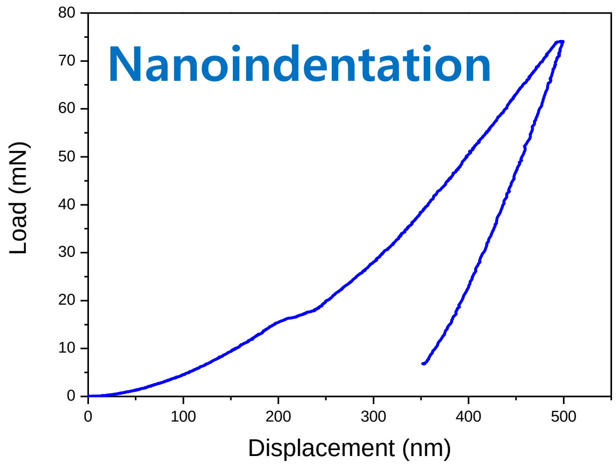
Kuk & Ryu (KAIST, Unpublished Data, 2015)

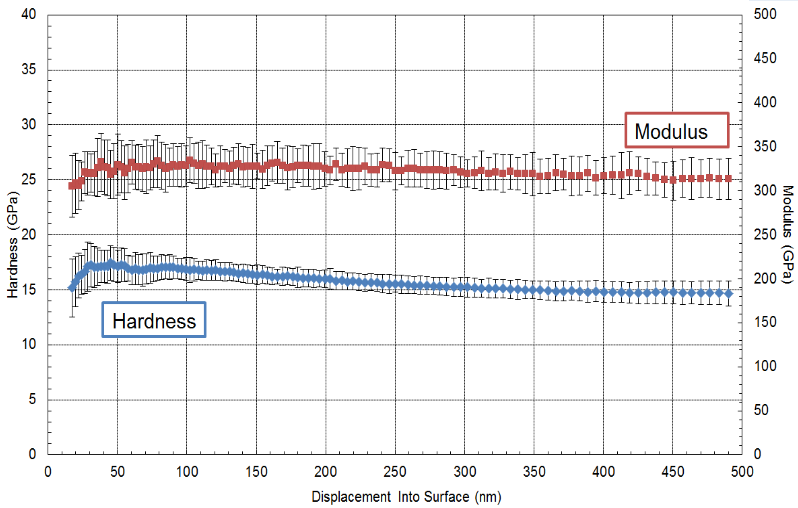
Hardness of VNbMoTaW (MA & SPS)

NQe



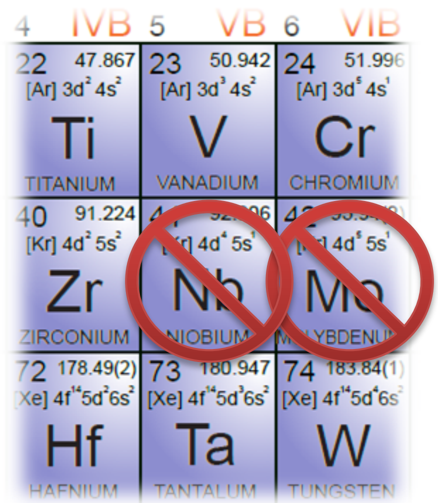
Kuk & Ryu (KAIST, Unpublished Data, 2015)

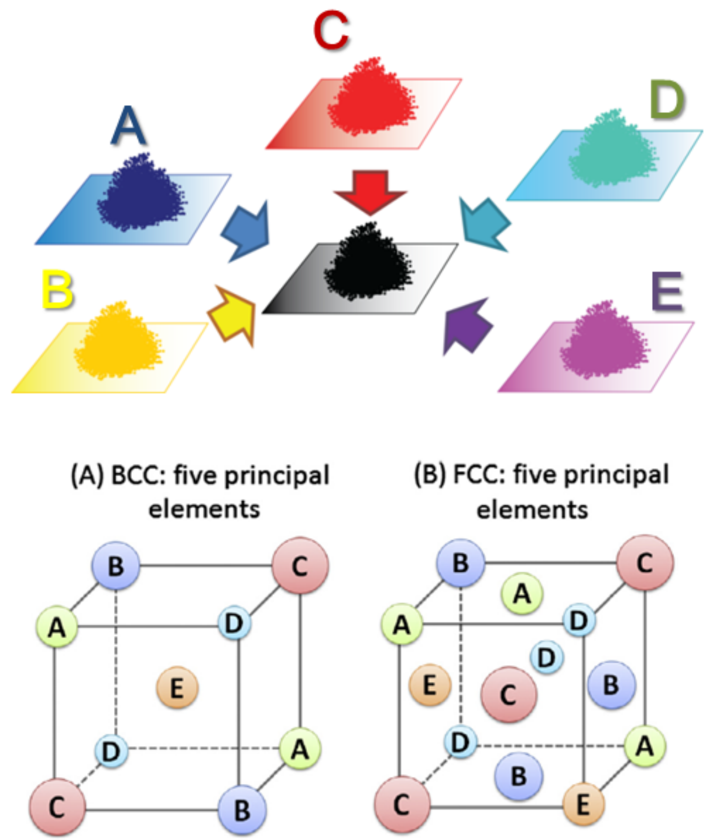




Reduced Activity Alloy Designs

High-Z Multicomponent Alloys





Restricted for low activation
Ni, Cu, Al, Mo, Nb

Phase Selection Rules for HEAs

NQe

The enthalpy of mixing

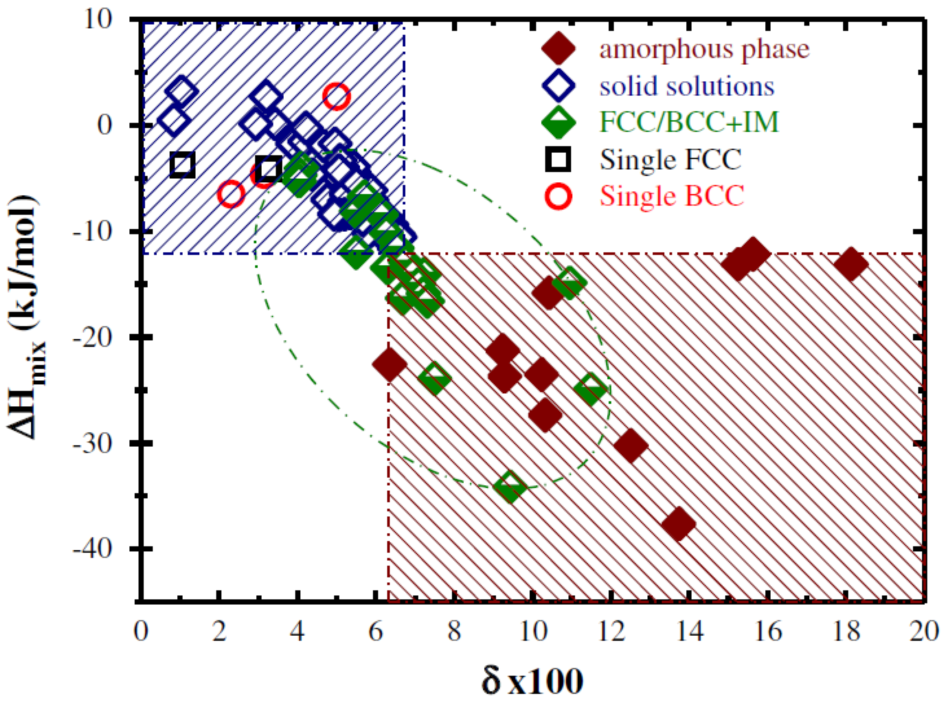
$$\Delta H_{\text{mix}} = \sum_{i,j=1,i\neq j}^{n} \alpha_{ij} c_i c_j$$

Atom size difference

$$\delta = 100\sqrt{\sum_{i=1}^{n} c_i \left(1 - \frac{r_i}{\bar{r}}\right)^2}$$

Valence electron concentration

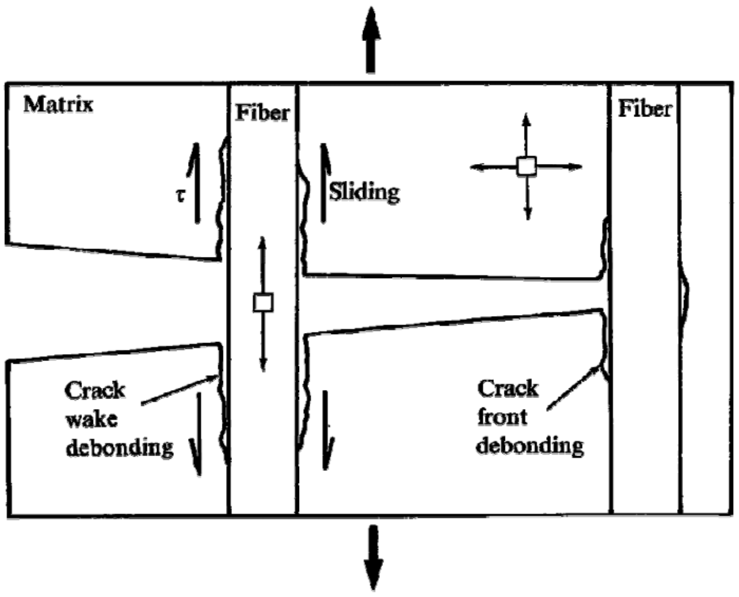
$$\text{VEC} = \sum_{i}^{n} c_i (\text{VEC})_i$$



S. Guo, Q. Hu, C. Ng, and C.T. Liu, Intermetallics 41, 96 (2013).

Why Composites?

- Toughening Mechanisms
  - crack arrest
  - crack deflection
  - crack bridging
- No catastrophic failure



Development Target

- **High Temperature Endurance**

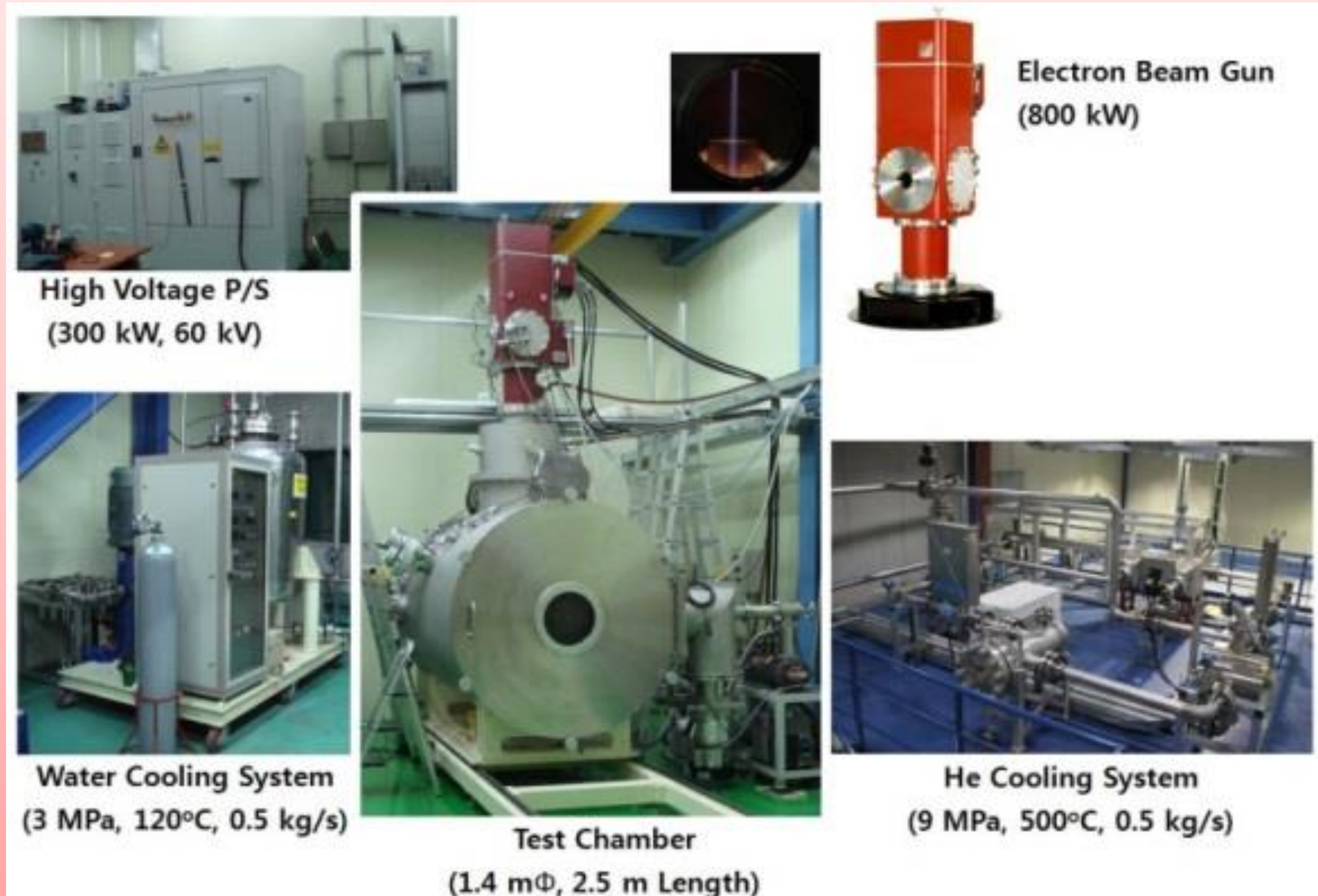
W Properties

- Compressive Strength
  ~330 MPa @ 1200°C
- Rx Temperature
  1000~1200°C
- Fracture Toughness
  5~ 7 MPa-m$^{0.5}$
- Use Temperature
  Δ300~Δ400°C

W-HEA Properties

- Compressive Strength
  500 MPa @ 1200°C
- Rx Temperature >1200°C
- Fracture Toughness
  20 MPa-m$^{0.5}$
- Use Temperature
  Δ600°C

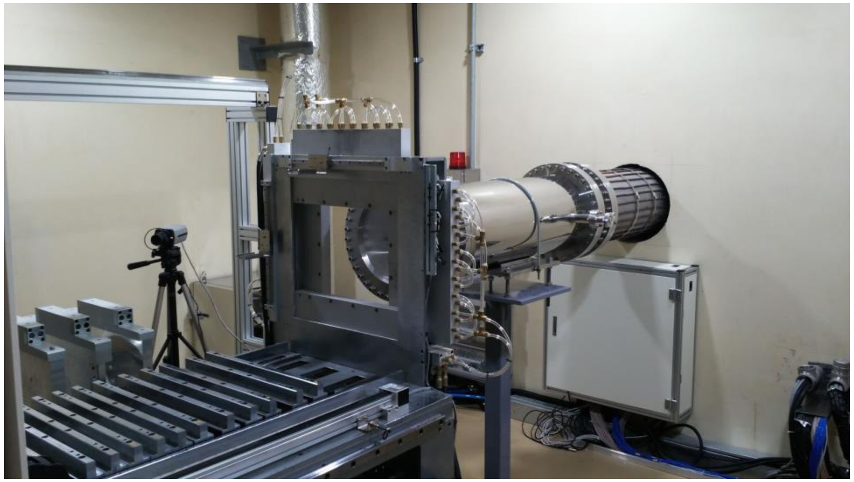
High Heat Flux Test



KoHLT-EB@KAERI

Irradiation Test (Radiation Damage Study)

NQe



KAERI 20 MeV Proton Accelerator
R.T.
1E18 p/cm

Michigan Ion Beam Laboratory
Max 800^{o}C
1E23 p/m^2 (1 dpa/day)

Irradiation Resistance of HEAs ?

- **High atomic level stress ➔ damage healing**

- Free energies of the glass and crystal similar
  - small G.B. energy ➔ grain coarsening is slow ➔ nanocrystalline state can be maintained ➔ effective sink for defects

- 2 MeV High voltage electron irradiation of CoCrCuFeNi
  - stable up to 60 dpa at 298K and 40 dpa at 773K
  - Takeshi Egami (Univ. Tennessee) & Takeshi Nagase (Osaka Univ.)

D/T Retention – Collaboration

NQe

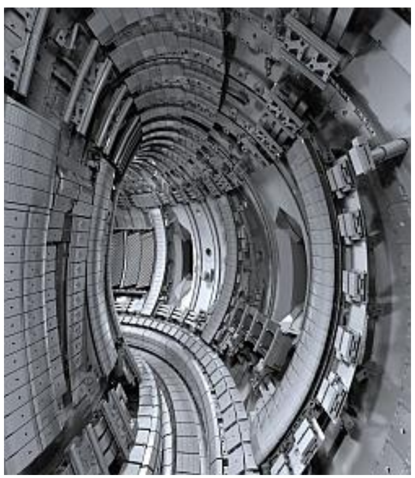
- Hydrogen solubility in irradiated W-HEA
- Vacancy cluster/loop dislocation formation behavior
- He bubble formation behavior
- D/T diffusion in W-HEA

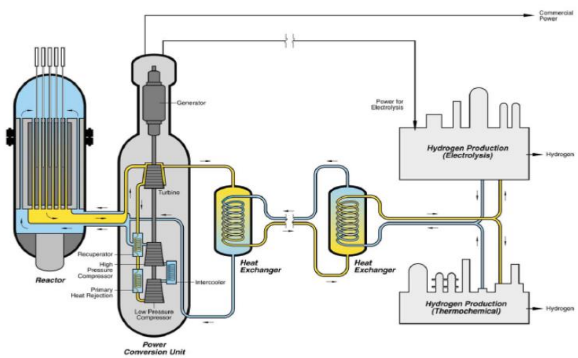
Research and Development Goal

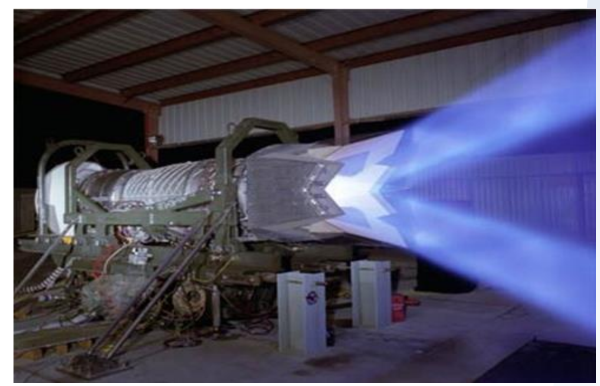
NQe

High Entropy Alloys

Plasma Facing Materials	Advanced Reactors	Aerospace Applications







Thank you