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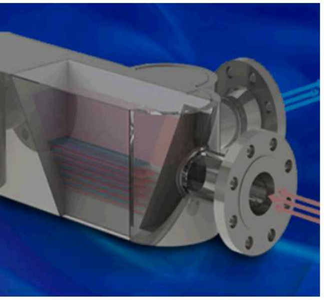

Cost-Competitive Super Alloys for High Radiation, Temperature, Pressure, and Corrosive Environments

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Refractory High Entropy Alloys (RHEAs)

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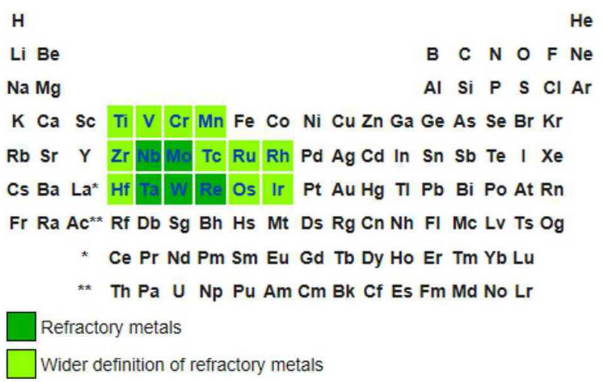
Five Awesome RHEA Properties

- T > 1,600 °C
- P > 300 MPa[1]
- Corrosion Resistance[2]
- Radiation Resistance[3]
- Self-Healing[4]

1. Compressive yield stress is two times larger than Inconel 718 at 1,000 °C; ~10X stronger than SS.
2. Negligible degradation after 240 hours exposure to nitric acid at the boiling point (e.g., HfNbTaTiZr).
3. No issues for proto-RHEA with up to 10 displacements per atom from a high-energy electron beam.
4. Self-healing associated with high entropy and atomic stress.



The 16 refractory elements.

Refractory High Entropy Alloys (RHEAs)

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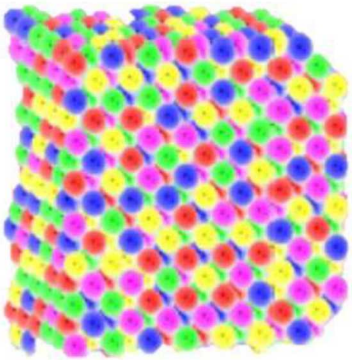
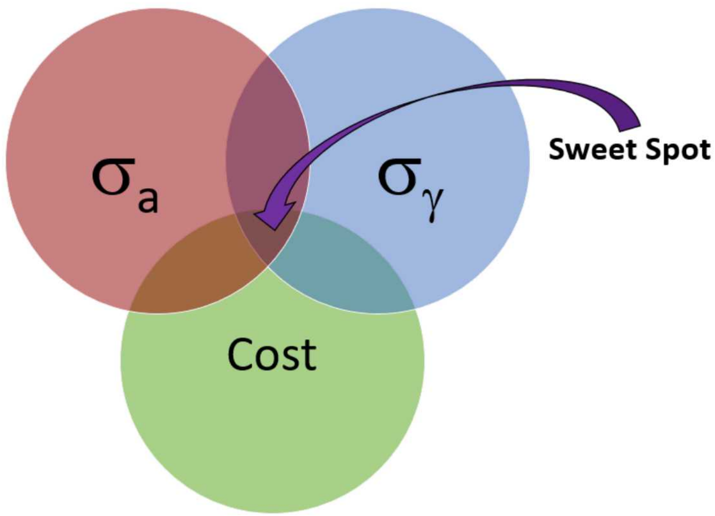
- RHEAs typically consist of five refractory elements that form alloys in near-equiatomic proportions.
- “Refractory” means high-temperature; “entropy” means high mixing tendency—larger entropy lowers Gibbs formation.
- Atomic ordering means the lattice is under larger stress than regular metallic lattice configurations.
  - ✓ This gives RHEAs self-healing properties, meaning that radiative or structural damage is reduced ***automatically*** as the high-stress atoms reorient and repair the damage.
- ***But the number of possible RHEA permutations is 4,368, so it is very expensive to research all RHEAs***.
- *We developed an algorithm to cherry-pick RHEAs with the highest temperature, structural strength, and corrosion/radiation resistance, while remaining cost-competitive.*



The CoCrFeMnNi HEA.

Nuclear RHEA Cherry-Picking

- Thus, our algorithm reduces the number of alloys by choosing elements with properties favorable for use in high radiation fields, at an acceptable cost.
- *Therefore, the initial set of 4,368 RHEA combinations is now reduced to the six most promising RHEAs.*
- *A TA was submitted a month ago, specifying the unique composition of the six RHEAs,* SD# 15012.



Venn Diagram for RHEA Down-Selection.

$$n_{tot} = \frac{n!}{k!(n-k)!} = \frac{16!}{5!(16-5)!} = 4{,}368 \quad \Rightarrow \quad n_{tot} = \frac{n!}{k!(n-k)!} = \frac{6!}{5!(6-5)!} = 6$$

Self-Healing RHEAs

- We recently found that RHEAs can be **self-healing.**
- This means that radiative or structural damage is reduced ***automatically*** **(up to 10 DPA vs. 0.5 DPA for steel)**.
- We did not know this when we submitted our concept LDRD proposal, "Engineering of Refractory High Entropy Alloys for Advanced High Temperature Nuclear Reactors", Idea 20-0214.
- ☹

Refractory High Entropy Alloys (RHEAs)

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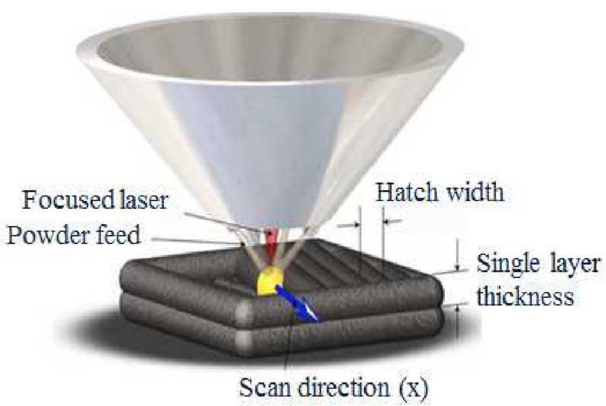
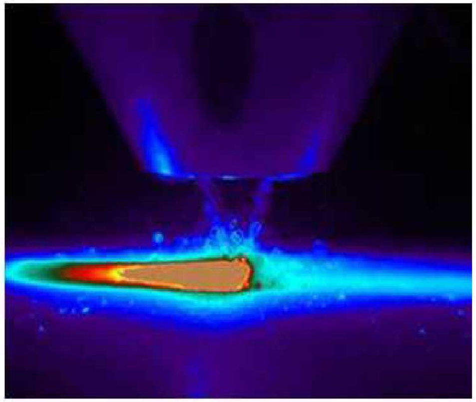
- Furthermore, Advanced Manufacturing of RHEAs can
  - ✓ more than double strength and hardness [Waseem and Ryu, 2017].
  - ✓ SNL showed a 250% increase in strength and order-of-magnitude increase in ductility [Kustas, 2018].
  - ✓ SNL extended structural properties in advanced alloys through rapid cooling rates [Kustas et al., 2018; Agribay, Kustas, et al., 2018].
    - ➢ A patent is currently being sought [Kustas, Rodriguez, *et al*., 2018].
  - ✓ SNL's microstructure control can further increase RHEA high-temperature, corrosion, creep, and thermal-fatigue resistance.





Hybrid laser engineered net shaping (LENS) AM system, where fluidized powder consolidates onto multi-material layers [Smith, 2016].

We See Many Technical & Business Opportunities…

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- Lou Qualls, the national technical director for molten salt reactors at ORNL, is very interested in *pro bono* testing our nuclear RHEAs at his test facility.
  - ✓ *He said that if the RHEAs deliver as anticipated, these are the materials he would use in their next-generation, advanced molten salt reactors.*
- LANL is considering our RHEAs:
  - ✓ High-temperature MegaPower micro reactors applications.
  - ✓ *To meet DoD C17 weight constraints (RHEAs can be 10X stronger than SS, so much less mass is needed).*
  - ✓ *For SNL's sCO2 power conversion units (PCUs) (the higher pressure requires RHEAs to reduce weight, increase safety).*
- Dynetics sees the potential for our RHEAs as higher-temperature replacement for Inconel components in hypersonic vehicles.
- *Our RHEAs are of much interest in these areas:*
  - ✓ Usage in radiation-resistant sensors.
  - ✓ Applications that require self-healing.
  - ✓ Very high temperature systems (VHTRs), concentrated solar power, combustors.
  - ✓ Highly corrosive coolants, e.g., molten salts (MS VHTRs, concentrated solar power).
  - ✓ Aerospace.
  - ✓ Harsh environments (T, P, corrosion, radiation).

We See Many Technical & Business Opportunities…

- Issues RHEAs can resolve **NOW**, thereby extending SNL's sCO2 PCU technology:
  - ✓ The *sCO2 PCU requires high pressure (>7.4 MPa). RHEAs exceed* 300 MPa compressive stress at a reasonable cost.
  - ✓ RHEAs have 10X the toughness of SS, so much less weight is required (e.g., enables C17 transport).
    - ➢ *This permits MICRO reactors to indeed be micro reactor sized!*
  - ✓ With higher RHEA toughness, the pitting of sCO2 turbomachinery will likely be significantly reduced, if not fully eliminated.
  - ✓ sCO2 thermal efficiency is ~45% (vs. ~35% for the Rankine cycle). Using RHEAs, the sCO2 thermal efficiency can increase to 65% or more.
  - ✓ Allow for more durable sCO2 PCUs due to significantly-reduced corrosion.
  - ✓ RHEA bearings and seals will likely have longer and more reliable operation…
- Advanced Reactor Concepts:
  - ✓ RHEA-based fuel/cladding allow for reactor power cycling (load following).
  - ✓ The stress and radiative self-healing, as well as its high temperature range, make the reactor "hot rock" concept closer to reality.
  - ✓ A RHEA-based fuel is more accident-tolerant.

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