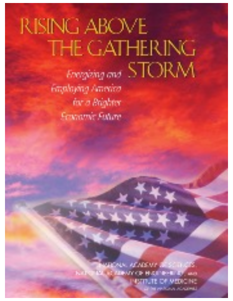
Opportunities with ARPA-E to Advance and Decarbonize Manufacturing and Industrial Processes

Dr. Philseok Kim, ARPA-E Program Director

August 4, 2023

History of ARPA-E (Advanced Research Projects Agency – Energy)

In 2007, The National Academies recommended Congress establish an **Advanced Research Projects Agency for Energy** within the U.S. Department of Energy to fund advanced energy R&D



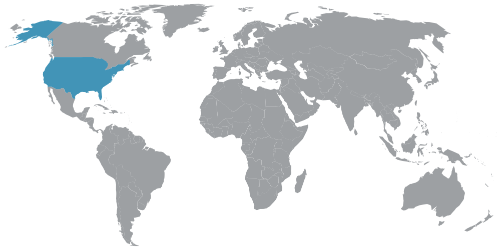
2007

Rising Above the Gathering Storm **Published** - warning policymakers that U.S. advantages in science and technology had begun to erode

America COMPETES Act **Signed** – authorizing the creation of ARPA-E

2009

American Recovery & Reinvestment Act **Signed** – Providing ARPA-E its first appropriations of $400 million, which funded ARPA-E's first projects



2021

1,415+ Awards
69+ Programs

Current Funding:
$470M
(FY23)

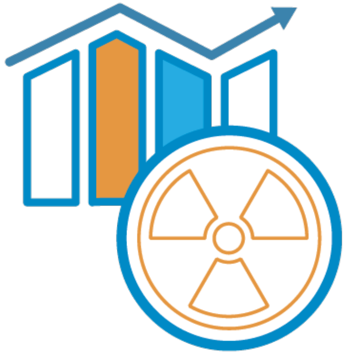
arpa·e
CHANGING WHAT'S POSSIBLE

ARPA-E Mission

REDUCE
imports

REDUCE
emissions

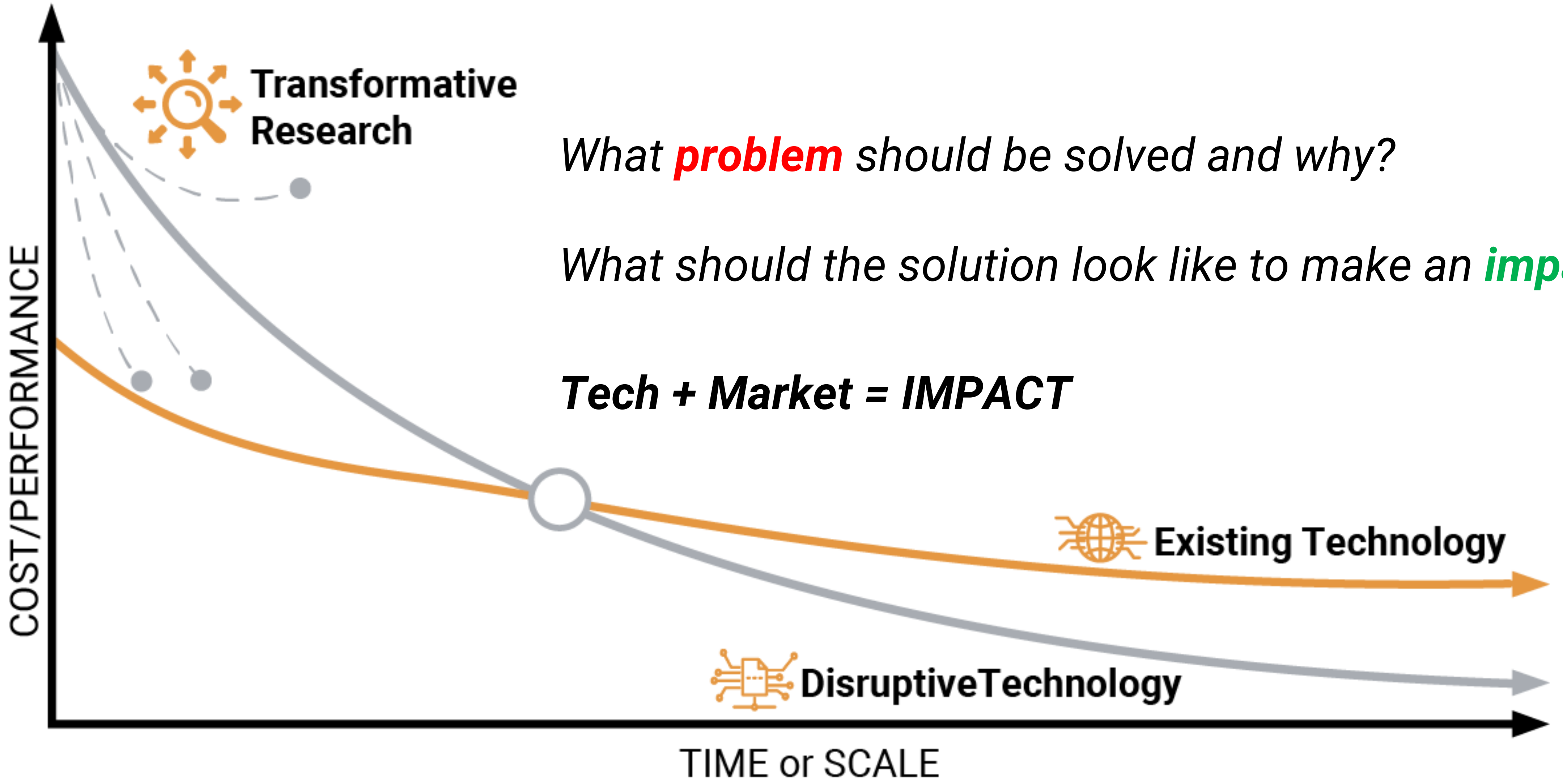
IMPROVE
efficiency



IMPROVE
radioactive waste management

IMPROVE
energy infrastructure resilience

Creating New Learning Curves

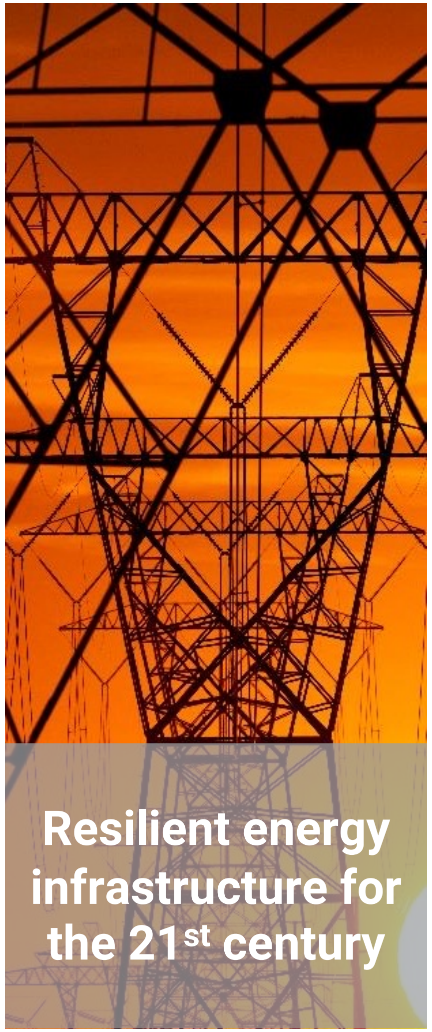


*What **problem** should be solved and why?*

*What should the solution look like to make an **impact**?*

Tech + Market = IMPACT

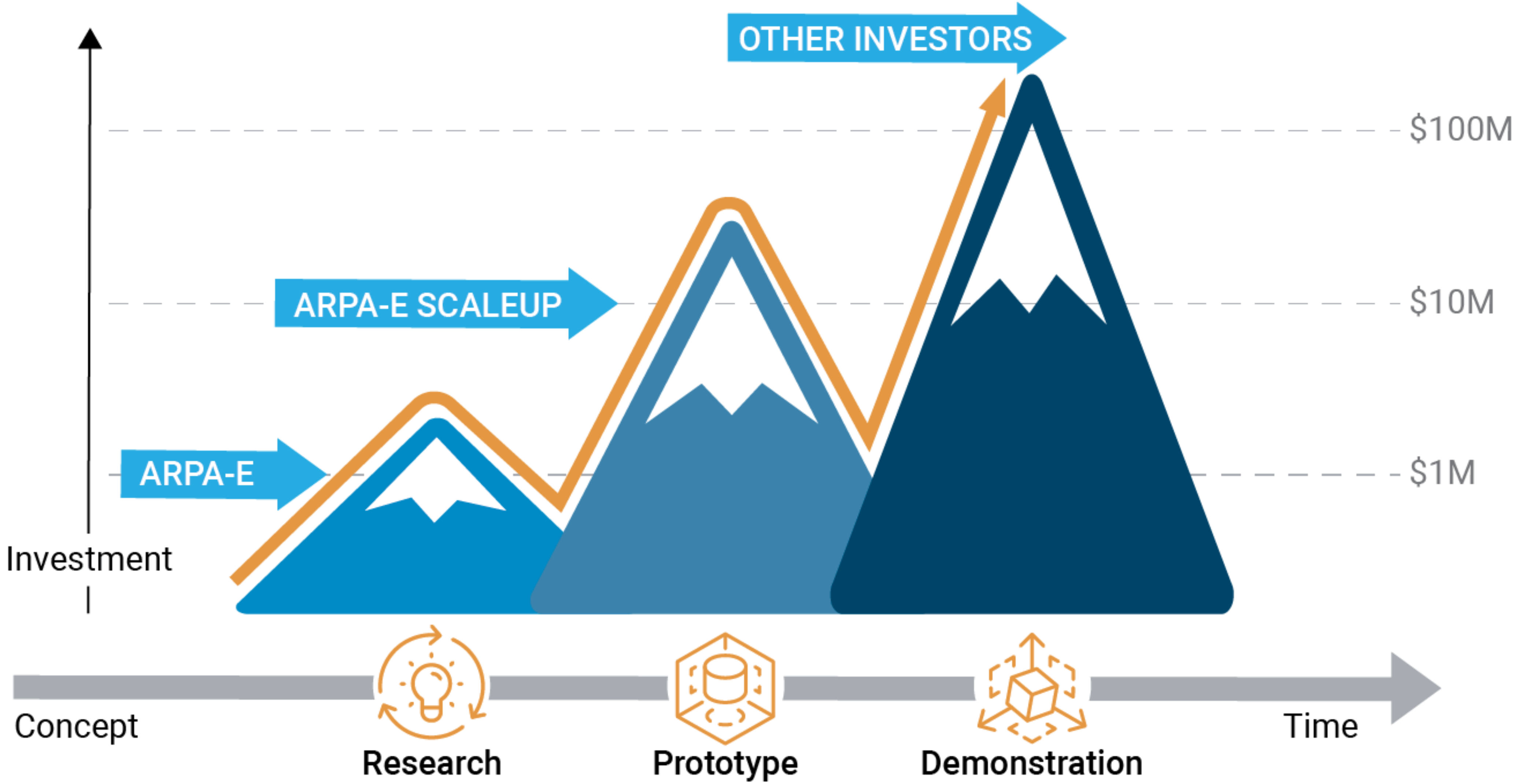
What Problems are We Trying to Solve?



What Makes an ARPA-E Project?

IMPACT	‣ High impact on ARPA-E mission areas ‣ Credible path to market ‣ Large commercial application
TRANSFORM	‣ Challenges what is possible ‣ Disrupts existing learning curves ‣ Leaps beyond today's technologies
BRIDGE	‣ Translates science into breakthrough technology ‣ Not researched or funded elsewhere ‣ Catalyzes new interest and investment
TEAM	‣ Comprises best-in-class people ‣ Cross-disciplinary skill sets ‣ Translation oriented

ARPA-E Creates a "Mountain of Opportunity" for energy technology



Current Funding Vehicles

Focused Program	Exploratory Technologies	CREATE	OPEN	SCALEUP
~$35M/3 yr (CA)	~$10M/2-3 yr (CA)	~$10M, up to $500k/award (Grant)	every 3 years (CA)	since 2021 (CA)
			(next OPEN: 2024)	(alumni project only)

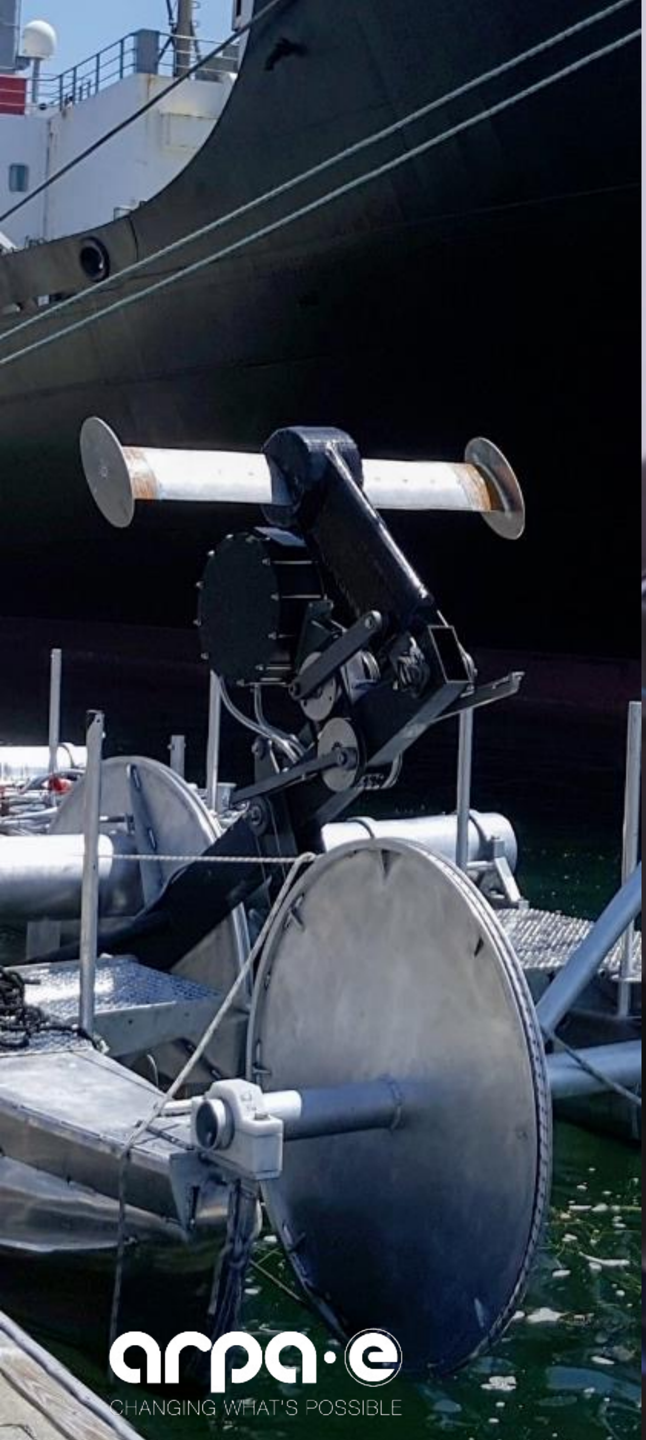
Tech Plus-up
varies (CA)

T2M Plus-up
~$300-500k

*CA = Cooperative Agreement

- ARPA-E will be very much 'hands-on'
- Once selected, we negotiate SOPO (Statement of project objectives), milestones, deliverables as a mutually agreed legal document
- Aims for setting an aggressive goal with SMART
- Each project is reviewed quarterly against this contractual agreement
- Virtual and on-site quarterly reviews vs. project milestones
- Clear Go/NoGo decision points (project terminations do happen)
- Final deliverables as the measure of project success
- Pivot as needed

arpa·e CHANGING WHAT'S POSSIBLE




OPEN Programs

support new technologies across the full spectrum of energy applications

OPEN 2009

41 projects

$176 million investment

10 technical areas

OPEN 2012

66 projects

$130 million investment

11 technical areas

OPEN 2015

41 projects

$125 million investment

10 technical areas

OPEN 2018

77 projects

$199 million investment

13 technical areas

OPEN 2021

68 projects

$175 million investment

13 technical areas

How can I get started?

- Sign up for ARPA-E Newsletter (issued once a month)

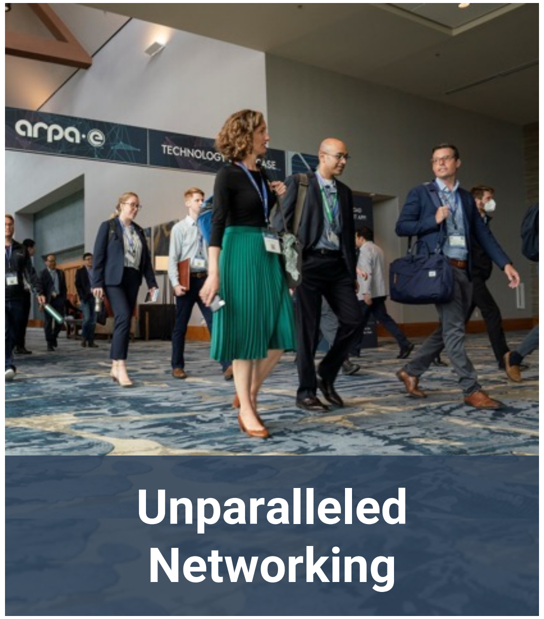
- Google the following...
  - "ARPA-E [Program Name] Workshop"
  - "ARPA-E [Program Name] Kick-off"
  - "ARPA-E [Program Name] Reviews"

- Bookmark
  - https://arpa-e.energy.gov/faqs
  - https://arpa-e.energy.gov/news-and-media

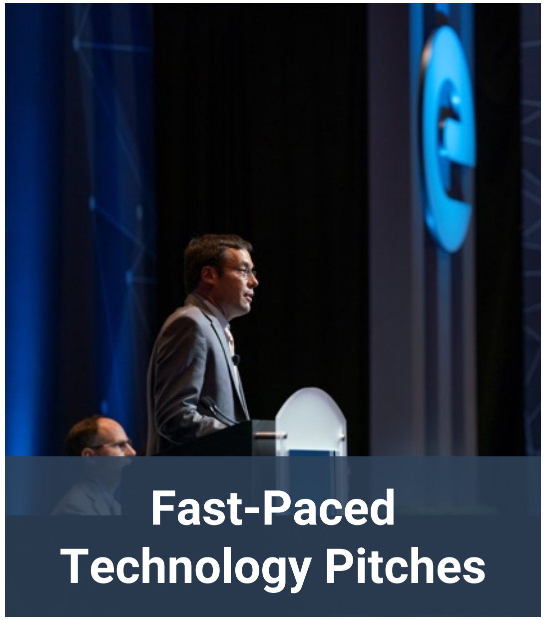
arpa·e energy innovation summit

Highly Selective Technology Showcase

Inspiring Keynotes



Unparalleled Networking



Fast-Paced Technology Pitches

arpae-summit.com

May, 2024 | Dallas, TX

arpa·e
CHANGING WHAT'S POSSIBLE

Join the Team that is Transforming the Energy of Tomorrow

PROGRAM DIRECTOR

- Program development
- Active project management
- Thought leadership
- Explore new technical areas

TECHNOLOGY-TO-MARKET ADVISOR

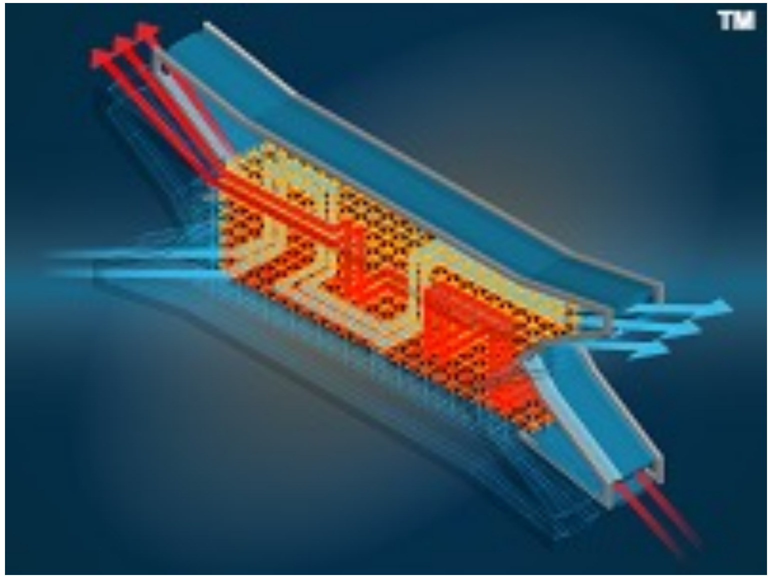
- Business development
- Technical marketing
- Techno-economic analyses
- Stakeholder outreach

FELLOW

- Independent energy technology development
- Program Director support
- Organizational support

arpa·e CHANGING WHAT'S POSSIBLE

Learn more and apply: **www.arpa-e.energy.gov/jobs** or **arpa-e-jobs@hq.doe.gov**.



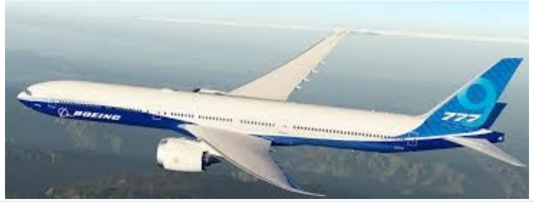
HITEMMP

High Intensity Thermal Exchange through Materials and Manufacturing Processes

arpa·e
CHANGING WHAT'S POSSIBLE

Decarbonization needs high-efficiency heat exchangers operating at extreme conditions

Applications enabled by HITEMMP technologies


Next Generation Aviation


Next Generation Nuclear


Concentrated Solar Power


Advanced Stationary Power


Industrial Process Decarbonization

Kick-off	2019
Total Award	$35M
Projects	15

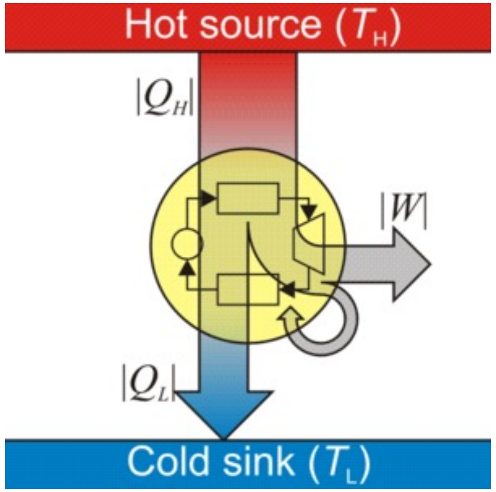
HTHP compact heat exchanger = key missing component

TECHNICAL – Develop innovative metallic-based and ceramics-based **heat exchangers** capable of operating for tens of thousands of hours in **temperatures and pressures exceeding 800°C and 80 bar**, respectively. Demonstrate the developed technology via the testing at the end of the program of a 50-kW lab-scale demonstrator in relevant conditions.

IMPACT – HITEMMP projects will enable a revolutionary new class of heat exchangers and innovative approaches to advanced manufacturing with applications for a wide range of commercial and industrial energy producers and consumers.

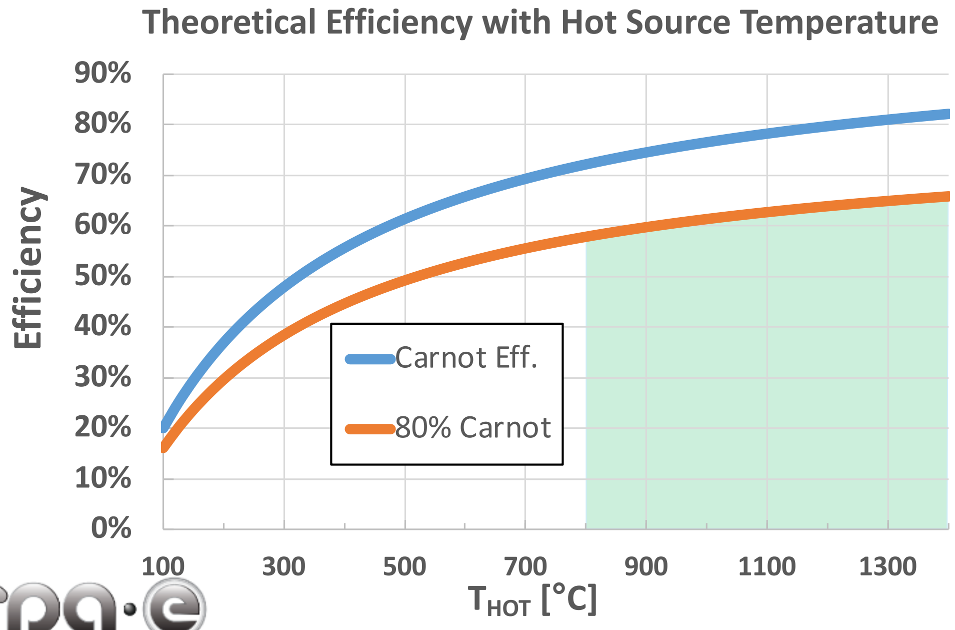
arpa·e CHANGING WHAT'S POSSIBLE

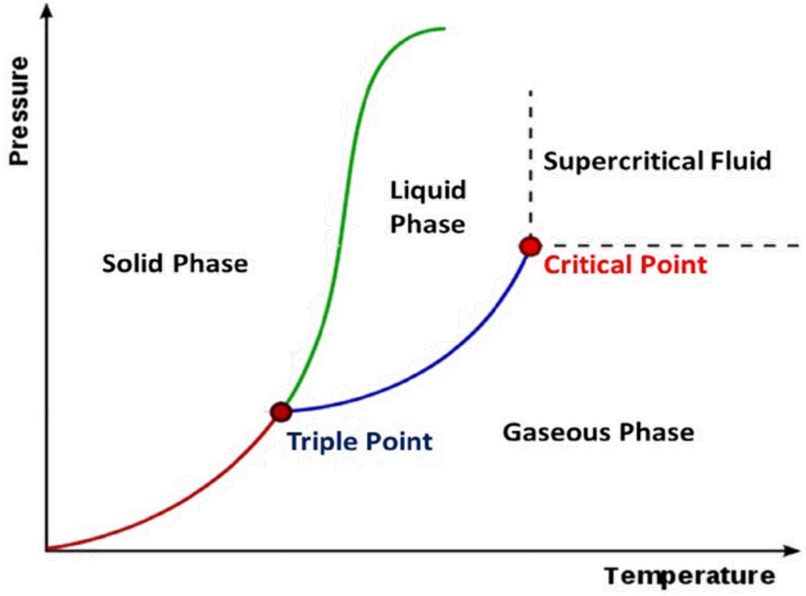
Why high-temperature and high-pressure?

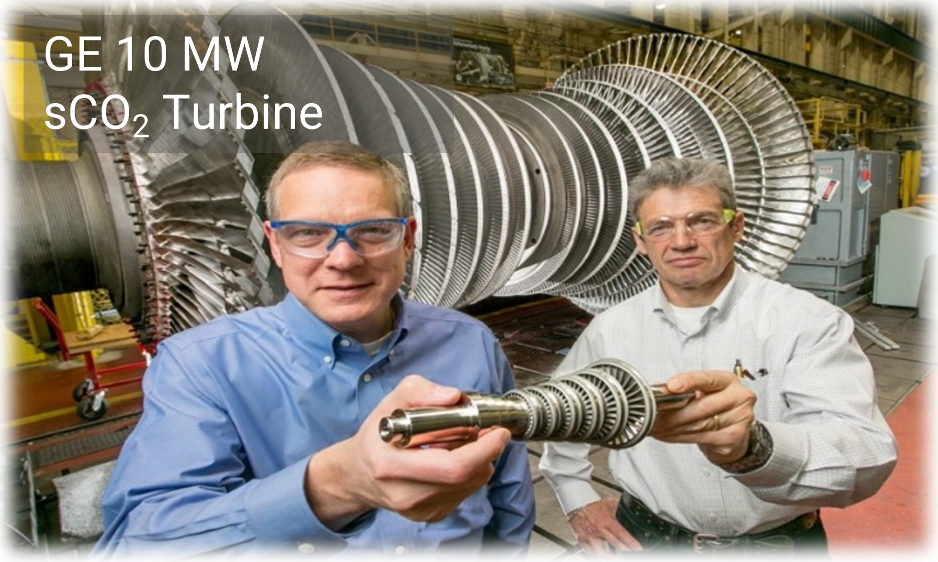


Carnot Efficiency:

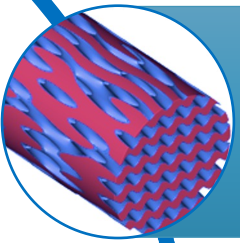
$$\eta = 1 - \frac{T_{cold\ sink}}{T_{hot\ source}}$$



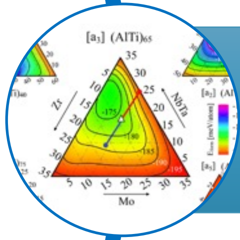




Approaches and targets (HITEMMP)



DESIGN: Novel topology and design for high performance components



MATERIALS: Materials that can withstand the envisioned operating temperatures and pressures

MANUFACTURING: Cost-effective mfg. of fine features and intricate geometries sustaining HTHP conditions at scale

Category A: metallic | Category B: ceramic

- ❑ Hot stream inlet temperature: ≥ **800°C | 1,100°C**
- ❑ Hot stream inlet pressure: ≥ **80 bar**
- ❑ Cold stream inlet temperature: **300°C (fixed)**
- ❑ Cold stream inlet pressure: ≥ **250 bar (fixed)**
- ❑ Pressure Drop: ≤ **2% | 4%** ($\Delta P/P_i$)
- ❑ Effectiveness ε: ≥ **80% | 50%**
- ❑ Demonstration unit: **≥ 50 kW (thermal)**
- ❑ Cost (NOAK): **$5,000°C/kW (aviation) or $2,000°C/kW (stationary power)**
- ❑ Durable: **40,000 hours** (MTBF, mean time between failure)

arpa·e
CHANGING WHAT'S POSSIBLE

Materials and manufacturing processes

Category A: metallic

- Materials
  - Haynes 282, Mar M247, AM303, IN740H, MHA3300, Haynes 214, Cermet
- Manufacturing processes
  - Laser powder bed fusion (LPBF)
  - Directed Energy Deposition (DED)
  - Diffusion Bonding
  - Brazing
  - Powder Metallurgy
  - Laser Welding

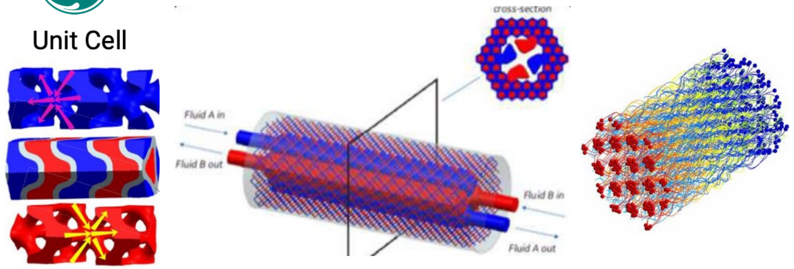
Category B: ceramic

- Materials
  - SiC, ZrB_2, Al_2O_3
- Manufacturing processes
  - Sintering based AM
  - Extrusion based 3D printing
  - Multiple co-Extrusion

Total 14 projects, 10 active

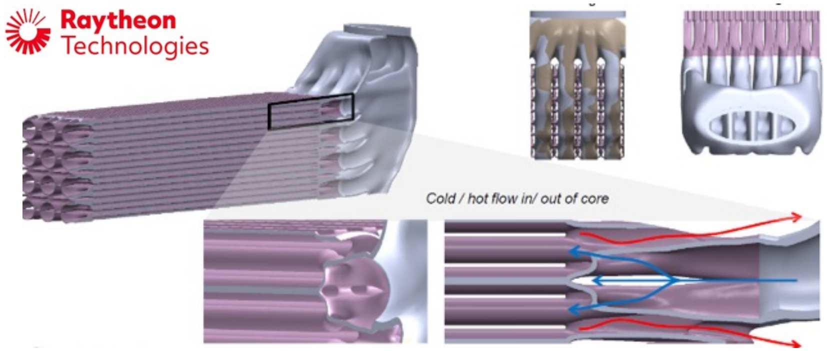
HITEMMP tests various design and manufacturing approaches

GE VERNOVA



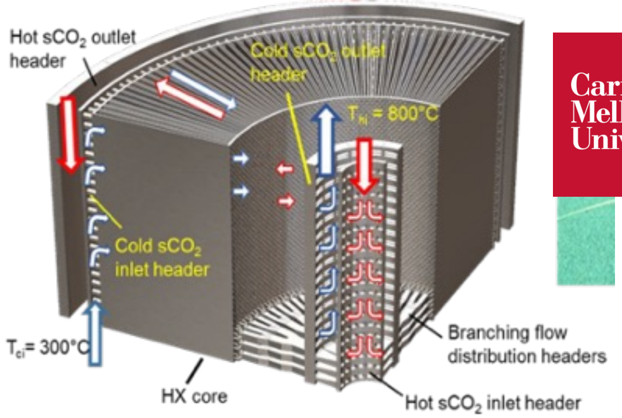
Tri-furcating design | AM303
Direct Metal Laser Melting

Raytheon Technologies



micro-tubes – weak **topology** optimization
H-282 | Laser Powder Bed Fusion

Carnegie Mellon University

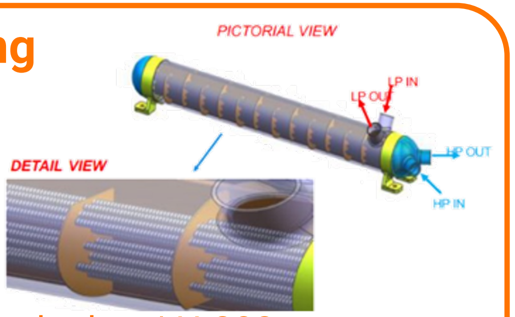


Diverging pin-array | H-282
Laser Powder Bed Fusion

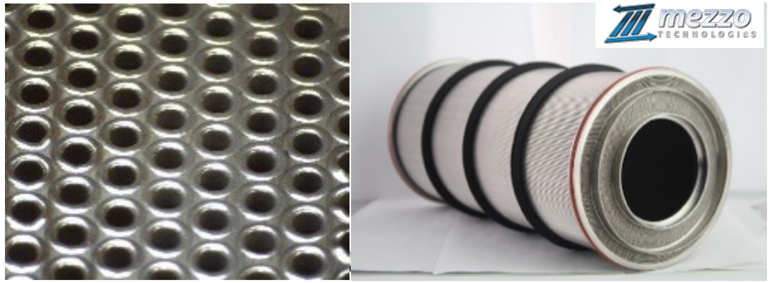
Laser Powder Bed Fusion

Laser Welding

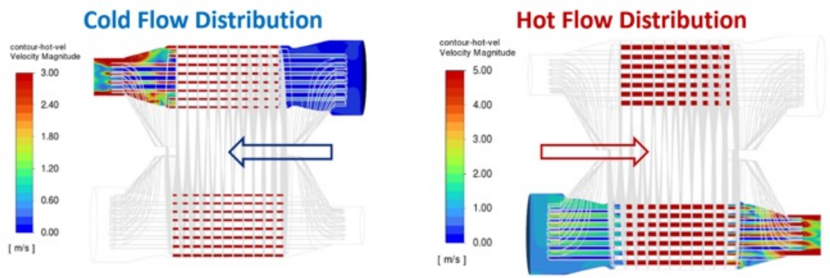
UCLA

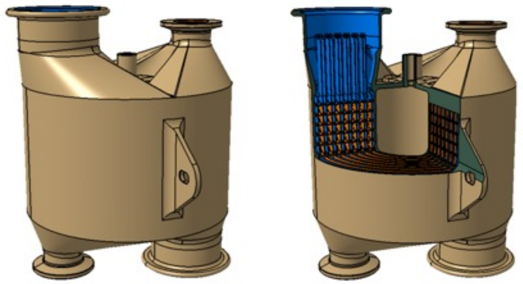


Shell and tubes | H-282
Laser joining, diffusion bonding



Micro-tubes | H-282 | Laser welded



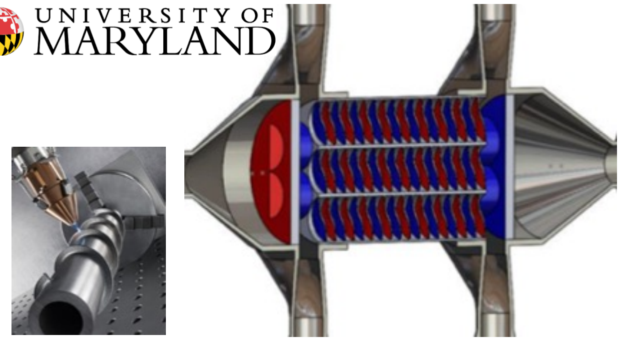


BOEING

ATI1700
ABD-1000AM
BR&T ODS-EECCA
L-PBF

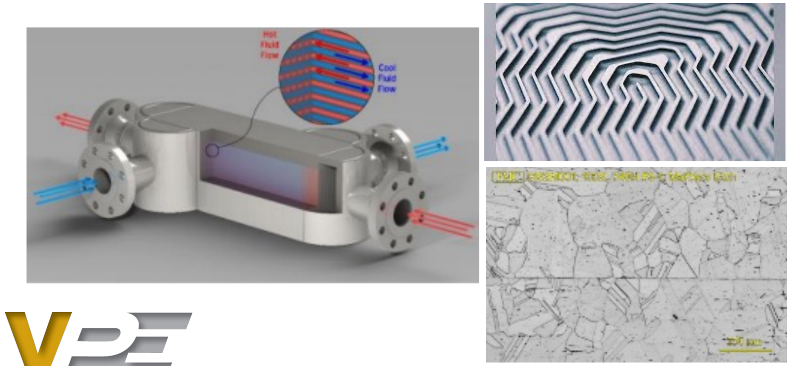
Directed Energy Deposition

UNIVERSITY OF MARYLAND

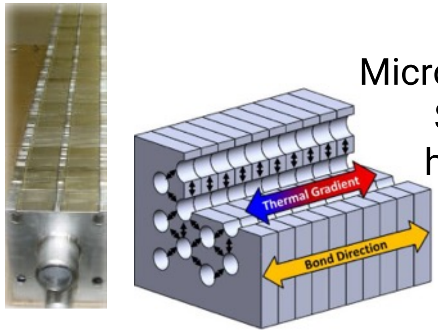


Helical design | Mar-M247
EHLA additive manufacturing

HITEMMP tests various design and manufacturing approaches



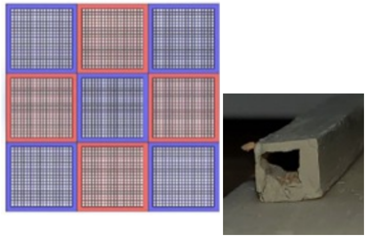
VPE
Vacuum Process Engineering
PCHE | In 740H | Diffusion bonding



Micro-channels | In 625
Stacked-sheet
heat exchanger

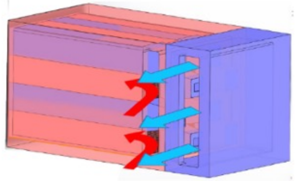
TharEnergy

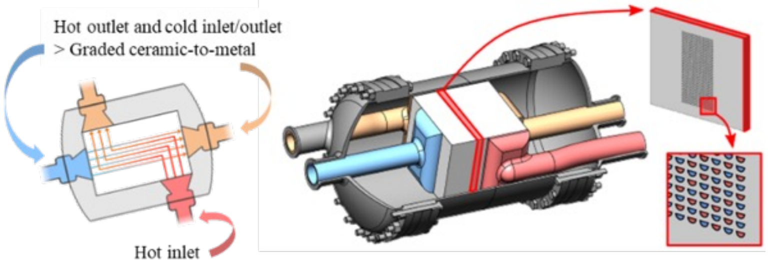
Ceramics



Micro-porous | SiC
Co-Extrusion

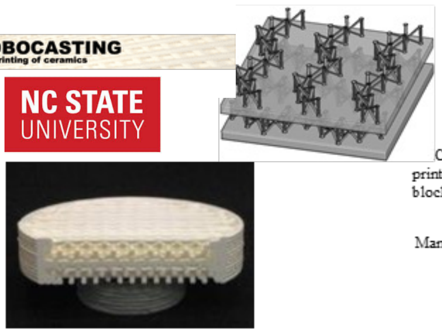
MIT
Massachusetts Institute of Technology

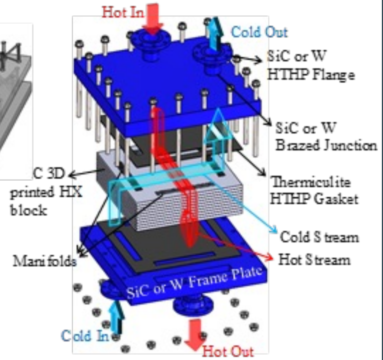




Missouri S&T
Micro-channels | ZrB_2
Ceramic On-Demand Extrusion

ROBOCASTING
3-D printing of ceramics
NC STATE UNIVERSITY





Micro-structured lattices design
SiC | Robocasting

Terminated Projects

MICHIGAN STATE UNIVERSITY

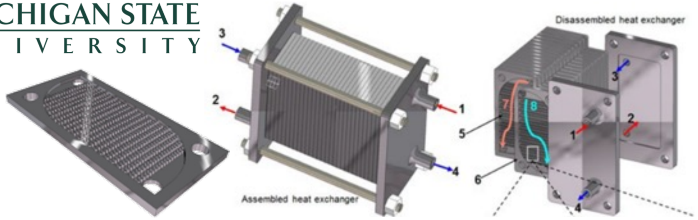
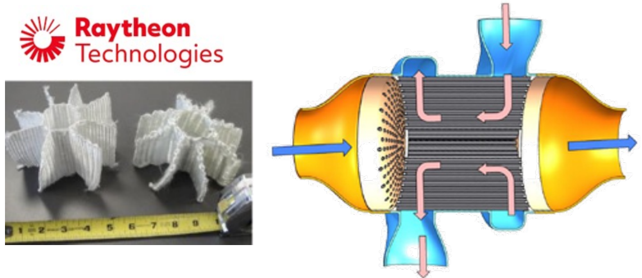


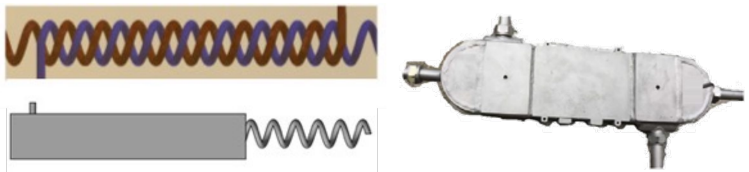
plate-frame | H-214
Hybrid powder manufacturing

Raytheon Technologies



Micro-tubes | Glass Ceramic Matrix Composite
Pin weaving, Transfer molding

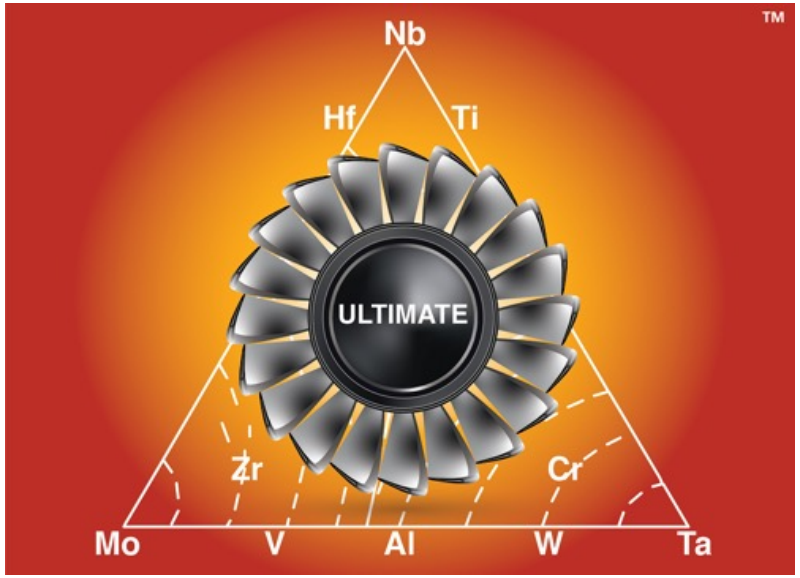
COMPREX



Intertwining helical channels
Cermets (NiTiN and/or NiAlN)
Direct current sintering

Key lessons learned

- **Power density:** Good values obtained for the power density exceeding targets. Most teams stay close to 50% and 80% effectiveness.
- **Pressure drop:** Pressure drops are not an issue giving additional rooms to increase the power density.
- **Modeling:** Full simulations of 50 kW_{th} prototypes remains challenging and requires simplifications or extrapolation of sub-scale models.
- **Manufacturability:** Achievable, but at different degrees of maturity, printing speed critical. Depowdering needs careful consideration. Still less mature for ceramics albeit some progress have been made over the past year. Monolithic 3D printing requires special consideration in the geometry transfer to the printer – very large file
- **Durability:** Application-specific and mostly achievable. *Corrosion with sCO_2 is not a showstopper*. Long-term durability remains to be proven (creep-fatigue test)
- **Cost:** The cost target are hard to meet ($2,000/UA for power generation and $5,000/UA for aviation)

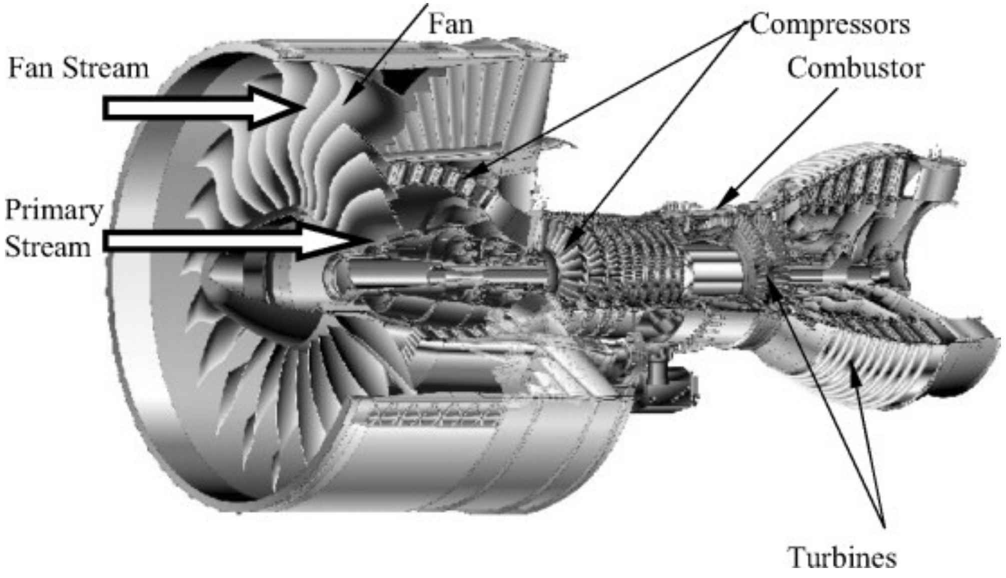


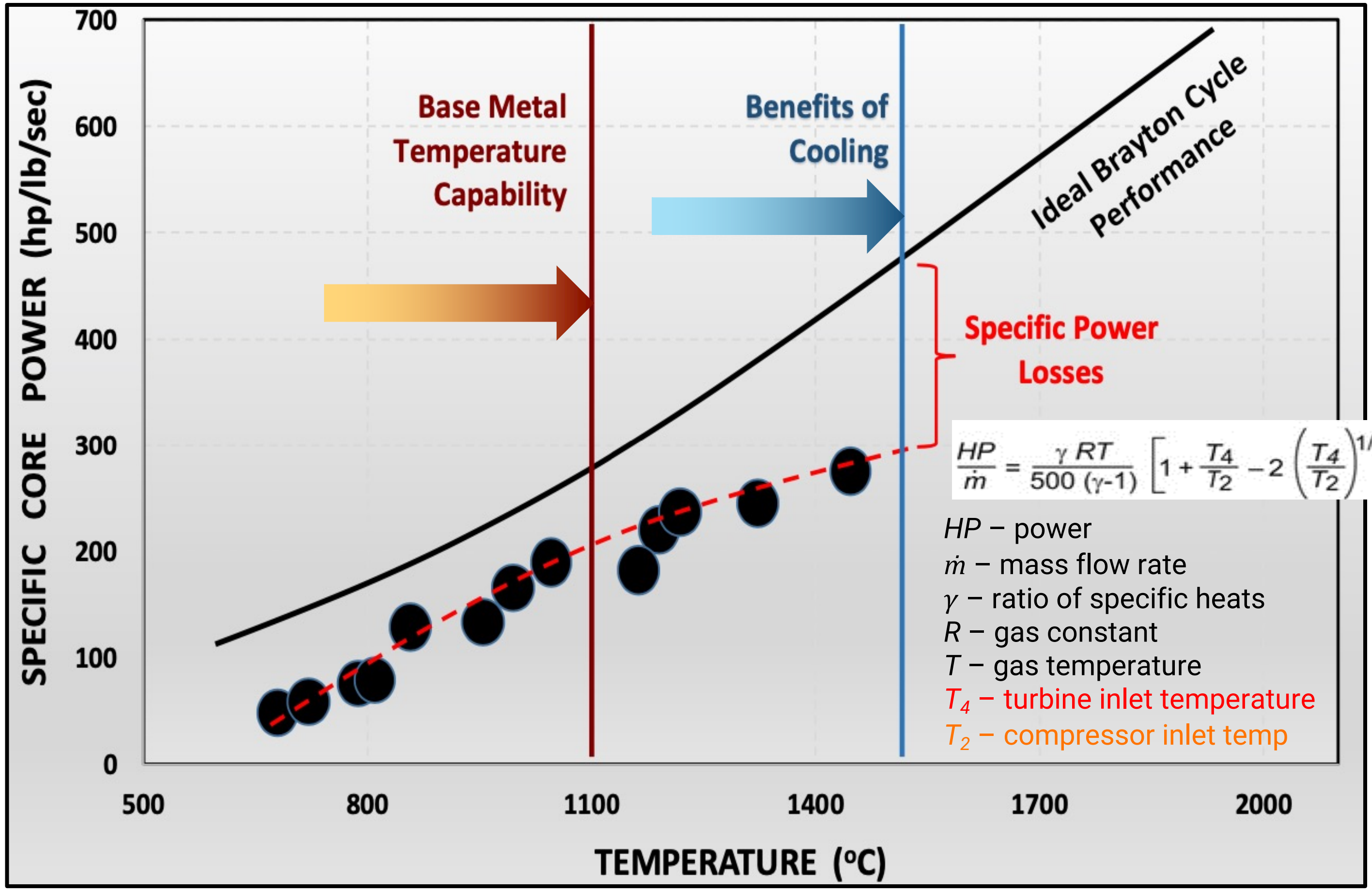
ULTIMATE

Ultrahigh Temperature Impervious Materials Advancing Turbine Efficiency

Hotter engines give more power/mass flow rate

- >34% of NG electricity generation in 2050
- Air travel accounts for 2% of emissions
- Opportunity to improve efficiency up to 7%
- Potential 10-20 Quads saving by 2050





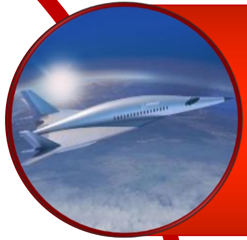
ULTIMATE FOA Figure 1 (recreated from *Science* 326, 1068 (2009))

Kick-off	2021
Total Award	$28M
Projects	17

The hotter the engine, the better, but need

- alloys that can survive
- manufacturing processes that are adaptable to new alloys

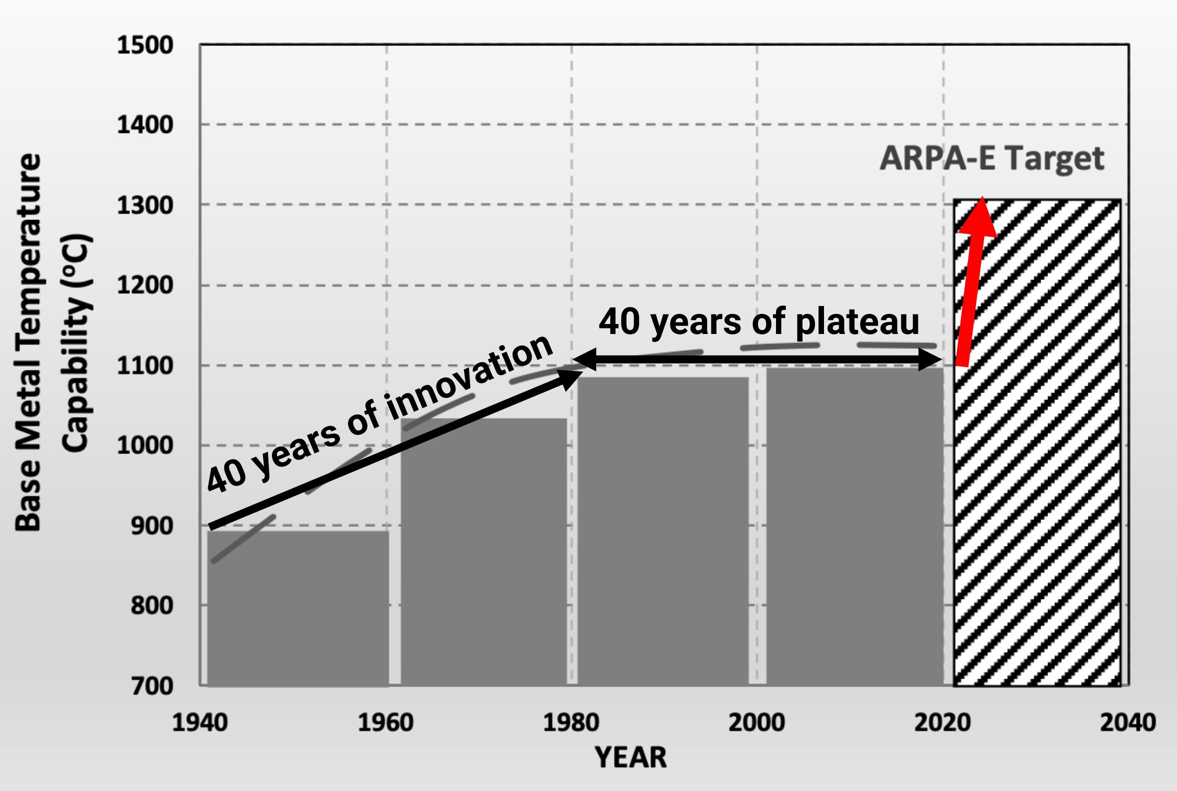
Program targets (ULTIMATE)



Develop ultrahigh temperature materials operating continuously at >1300°C or T4 >1800°C with coatings

Develop concurrent **manufacturing** processes

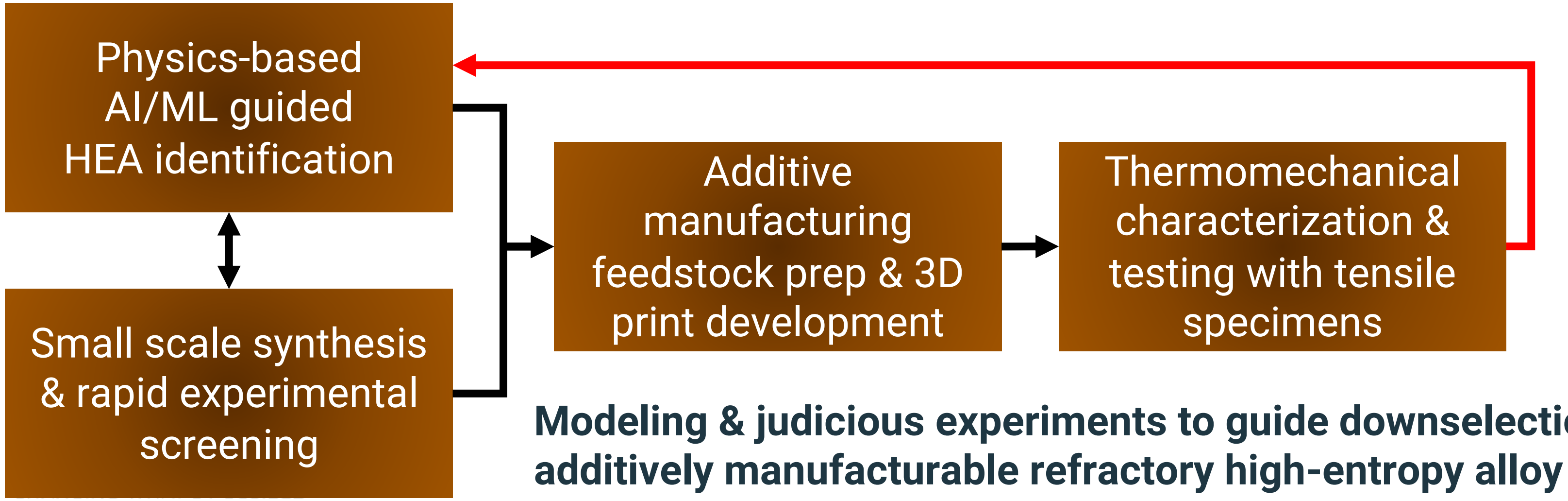
Enable turbine efficiency improvement by 5-7% (SOA NGCC = 64%)

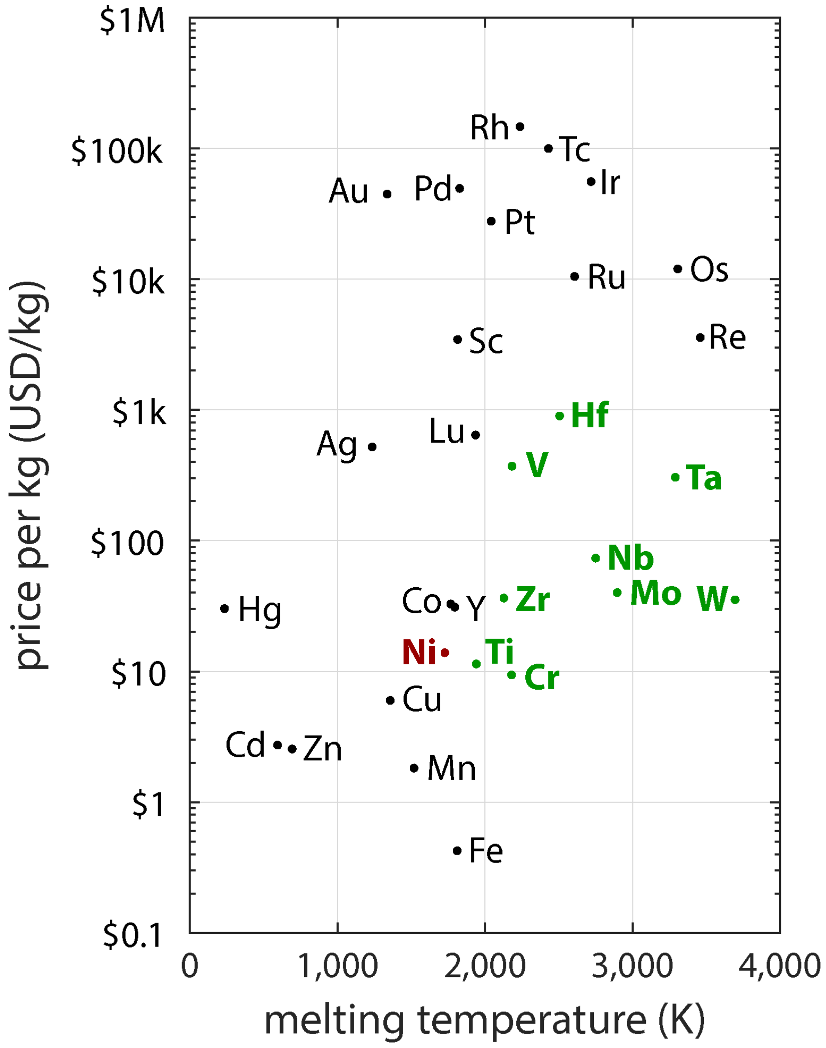


Property	Phase I Goal	Current SOA
Creep strain	<2% at 1300°C 200 MPa, 100 hrs	<2% at 1050°C 190 MPa, 100 hrs
RT tensile ductility	>1.5%	>1.5%
RT fracture toughness	>10 MPa.m$^{1/2}$	>10 MPa.m$^{1/2}$
Coating performance	Retain base alloy ductility after 1700°C air exposure	Temp. capability <1500°C

Navigating 592,000,000,000 possible compositions is not trivial

Sc 1814 K (1541 °C)	Ti 1941 K (1668 °C)	V 2183 K (1910 °C)	Cr 2180 K (1907 °C)	Mn 1519 K (1246 °C)	Fe 1811 K (1538 °C)	Co 1768 K (1495 °C)	Ni 1728 K (1455 °C)	Cu 1357.77 K (1084.62 °C)	Zn 692.68 K (419.53 °C)
Y 1799 K (1526 °C)	Zr 2128 K (1855 °C)	Nb 2750 K (2477 °C)	Mo 2896 K (2623 °C)	Tc 2430 K (2157 °C)	Ru 2607 K (2334 °C)	Rh 2237 K (1964 °C)	Pd 1828.05 K (1554.9 °C)	Ag 1234.93 K (961.78 °C)	Cd 594.22 K (321.07 °C)
Lu 1925 K (1652 °C)	Hf 2506 K (2233 °C)	Ta 3290 K (3017 °C)	W 3695 K (3422 °C)	Re 3459 K (3186 °C)	Os 3306 K (3033 °C)	Ir 2719 K (2446 °C)	Pt 2041.4 K (1768.3 °C)	Au 1337.33 K (1064.18 °C)	Hg 234.3210 K (−38.8290 °C)
Lr 1900 K (1627 °C)	Rf 2400 K (2100 °C)	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn 283±11 K (10±11 °C)





Modeling & judicious experiments to guide downselection of an additively manufacturable refractory high-entropy alloy (HEA)

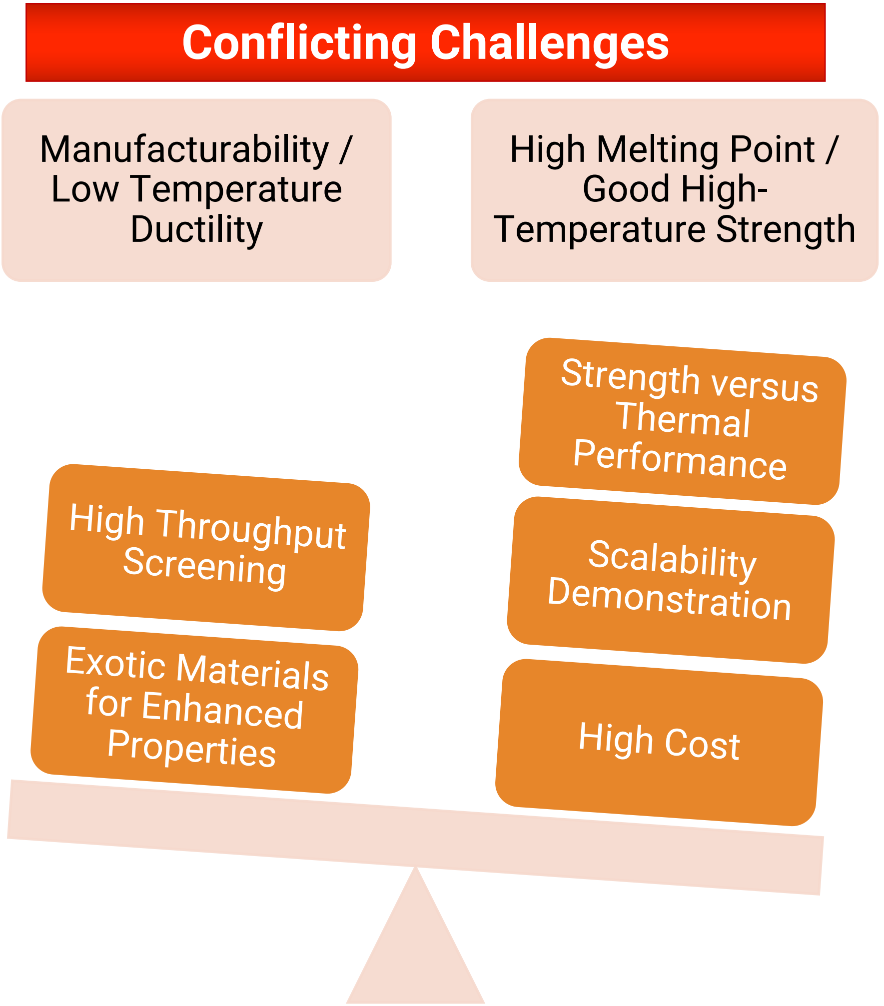
Balancing multiple conflicting properties in a single alloy is hard

Materials Selection

- Lack of thermodynamic database
- Poor oxidation resistance
- High Density
- High Cost

Manufacturability

- High ductile to brittle transition temperature
- Low RT tensile ductility
- High melting point / Incomplete melting
- Difficult post processing
- Sensitive to impurity pick-up



Need to integrate alloy design with manufacturability

ULTIMATE program takes a multi-faceted approach

Alloy Design Tools	Base Alloys	Strengthening	Coatings	Manufacturing Processes
• Physics-based • Machine Learning • CALPHAD • DFT • MC • Inverse Design ...	• Nb-based alloy • Mo-based alloy • RHEA	• Solid solution • Precipitation • Oxide dispersoids • Carbides • Carbonitrides • RHEA	• Silicide/ • Silicates • RE oxides • Multi-layer self-healing EBC • Selective Emissions Coatings	• DED • AM reactive Synthesis • LPBF/Binder-jetting hybrid • Spin casting • SPS

Validation through extensive microstructure characterization and mechanical properties testing

RHEA (refractory high entropy alloy), RCCA (refractory complex concentrated alloy), and MPEA (multi-primary element alloy) describe conceptually similar alloys with minor differences

DED: directed energy deposition, LPBF: laser powder bed fusion (= selective laser melting = direct metal laser melting)
SPS: spark plasma sintering

arpa·e
CHANGING WHAT'S POSSIBLE

Key lessons learned & current status

- **Creep Performance** (Target: 1300°C, 200 MPa, 100 hours, < 2% strain)
  - Likely achievable. Two teams **demonstrated good potential** (no failure at 1300°C, 200 MPa, 100 hours creep life).
  - Development of 1300°C creep test setup at ORNL is a **major accomplishment** and required significant efforts to demonstrate repeatable results.
- **RT Tensile Ductility** (Target: > 1.5%)
  - Many teams struggled with achieving the RT tensile ductility target (>1.5%).
  - **4 teams met the target so far**.
  - **Control of oxygen** was critical to meeting this target.
  - Excellent compression ductility did not necessarily translate to good tensile ductility.
- **Manufacturability** (Target: Test coupons during phase 1)
  - Processing has significant impact on the mechanical properties.
  - Good alloys but compromised processing will fail to deliver required properties.
  - Major concerns: Oxygen Control; Dendritic Microstructure; Porosity;
  - **SPS/FAST (Field-Assisted Sintering Technology) look promising** (no pre-alloyed atomized powder needed and scalable).
  - Arc-melt buttons required hot-working and homogenization to achieve good microstructure.
  - **Powder sourcing is a significant gap** to demonstrate timely success.
- **RT Fracture Toughness** (Target: > 10 $MPa.m^{1/2}$)
  - Definitely achievable. Many teams met the target.
  - **EDM sample preparation required careful attention** (manual polishing to eliminate machining induced defects).
- **Alloy Design**
  - Physical metallurgy approach proven more successful.
  - Purely ML/AI based approaches required physics-based guidance for alloy downselection.
  - **Lack of historical data on refractory alloys is a big gap.**

arpa·e
CHANGING WHAT'S POSSIBLE

ROSIE

Revolutionizing Ore-to-Steel to Impact Emissions

Please contact ARPA-E-CO@hq.doe.gov for questions regarding this and other active Funding Opportunity Announcements

Concept Paper deadline: 9:30 AM ET, 8/8

Cost & Performance Parity Zero-Emission Ironmaking Technologies

1 Mining, Extraction, Sourcing, Beneficiation, other preparation for ironmaking

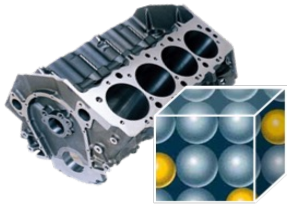
2 **Ironmaking**

3 Steelmaking, Casting, Rolling, Fabrication, other finishing needed for a steel product

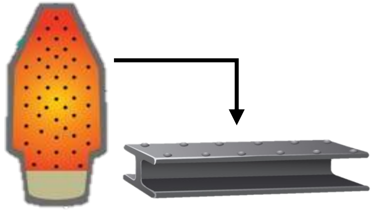
Category A project outcome: Process to make iron product

Category B project outcome: Process to make steel product

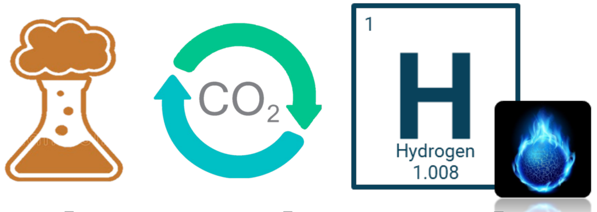
- **Zero non-biogenic process emissions in ironmaking**
- **Comparable product properties**
- **Ultra-low cradle-to-gate GHG emissions**
- **Levelized cost of product at least parity**
- **Scaleup potential to 15 Mt product/year**
- **Lab-scale prototype**
  - **Rate** >= 1 kg product/hour
  - **Reproducibility** 100+ hours
  - **10 kg Fe Product produced**



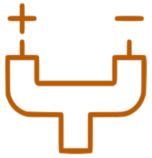
Ore-to-Steel



One-Pot I&S Making



Thermochemical



Electrochemical

$35 M	3 years	2024 start

arpa·e CHANGING WHAT'S POSSIBLE

If it works…

will it matter?