CHANGING WHAT'S POSSIBLE

An ARPA-E Thematic Workshop

Ultrahigh Temperature Materials for Energy Applications

Leveraging Additive and Advanced Manufacturing

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The W Seattle Hotel, Seattle WA

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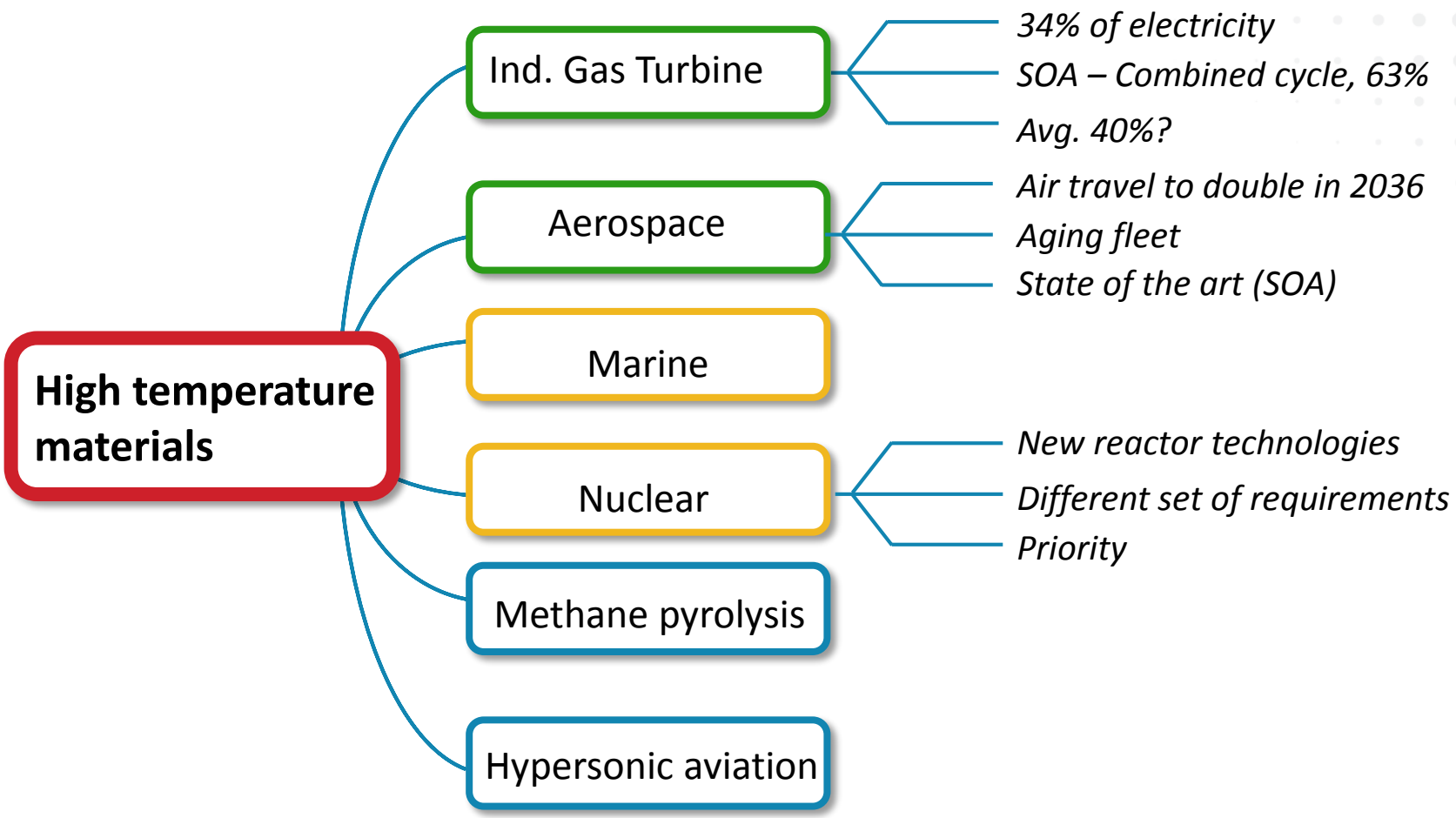
WELCOME

Objectives of the workshop

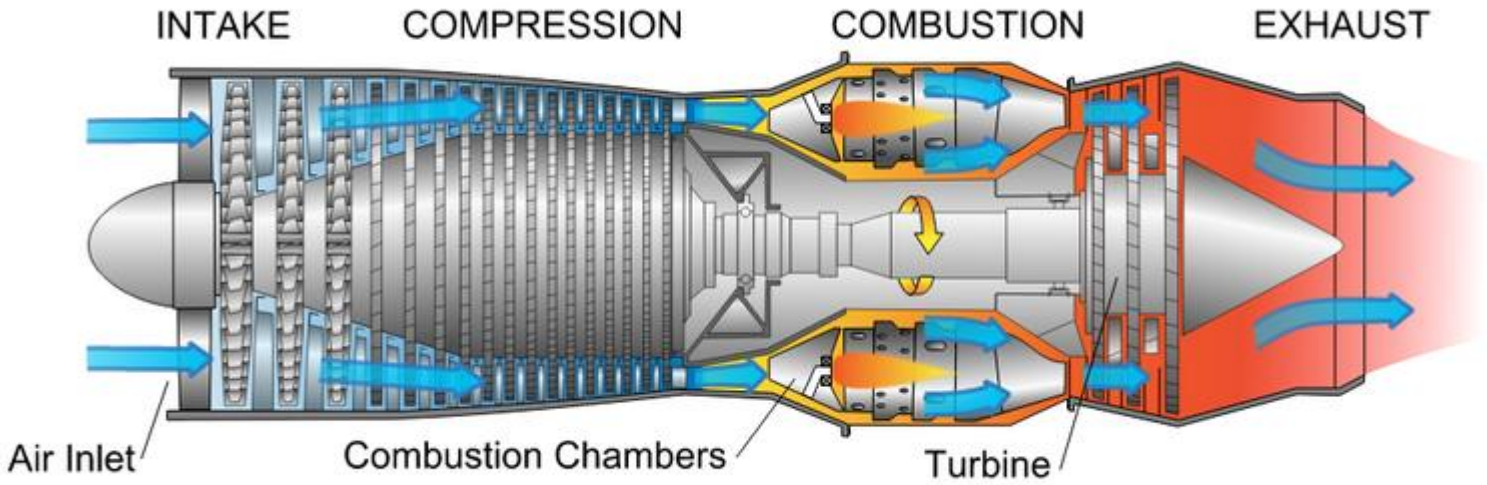
- Explain
- Listen
- Inputs from you
- Metrics
- Better program

High Temperature Materials Markets

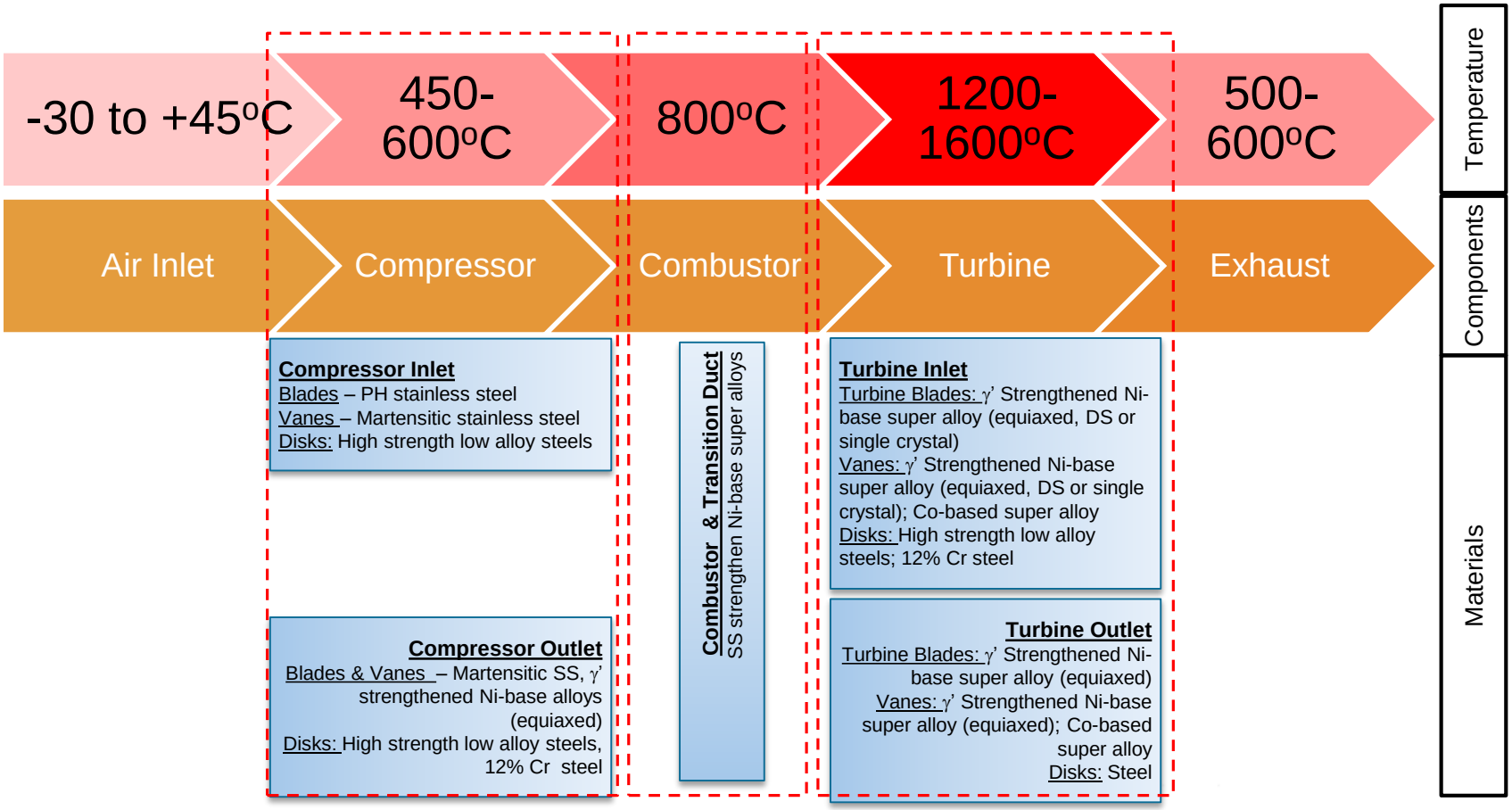


Efficiency of turbines

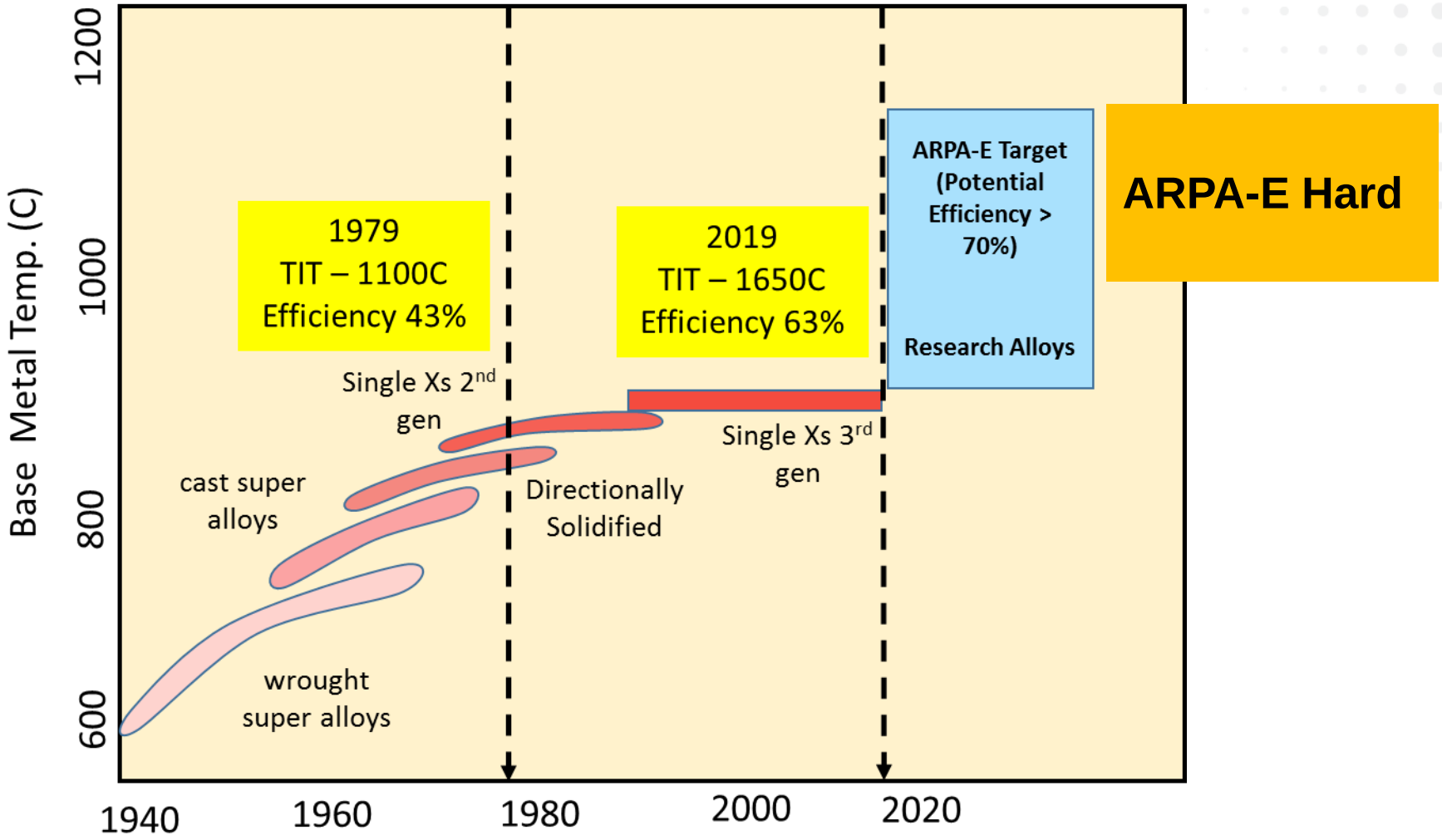
Inlet temperature, limited by material's high temperature capability



Gas Turbine Schematic



High to ultrahigh temperature materials



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

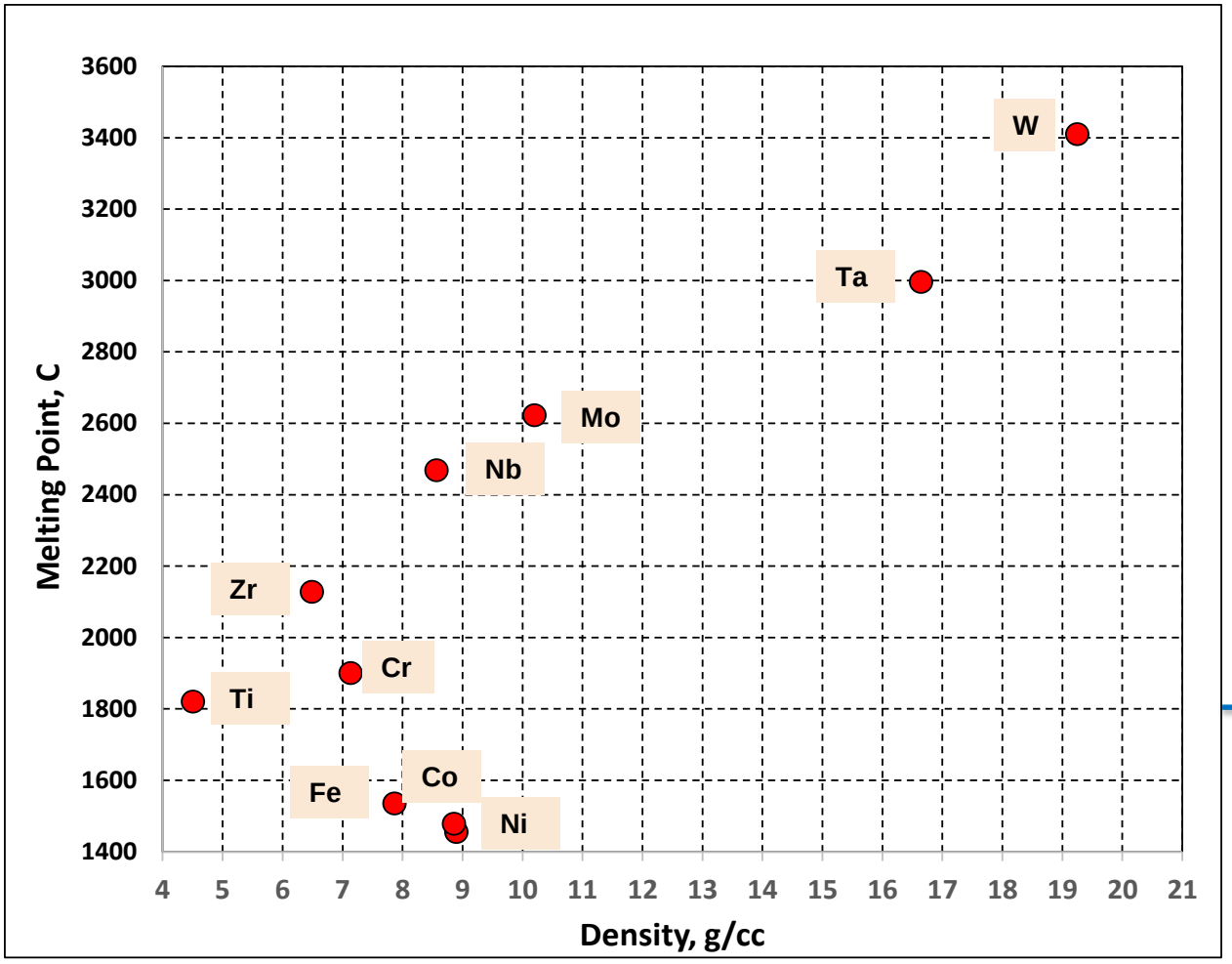
BRIDGE

- Translates science into breakthrough technology
- Not researched or funded elsewhere
- Catalyzes new interest and investment

TEAM

- Comprised of best-in-class people
- Cross-disciplinary skill sets
- Translation oriented

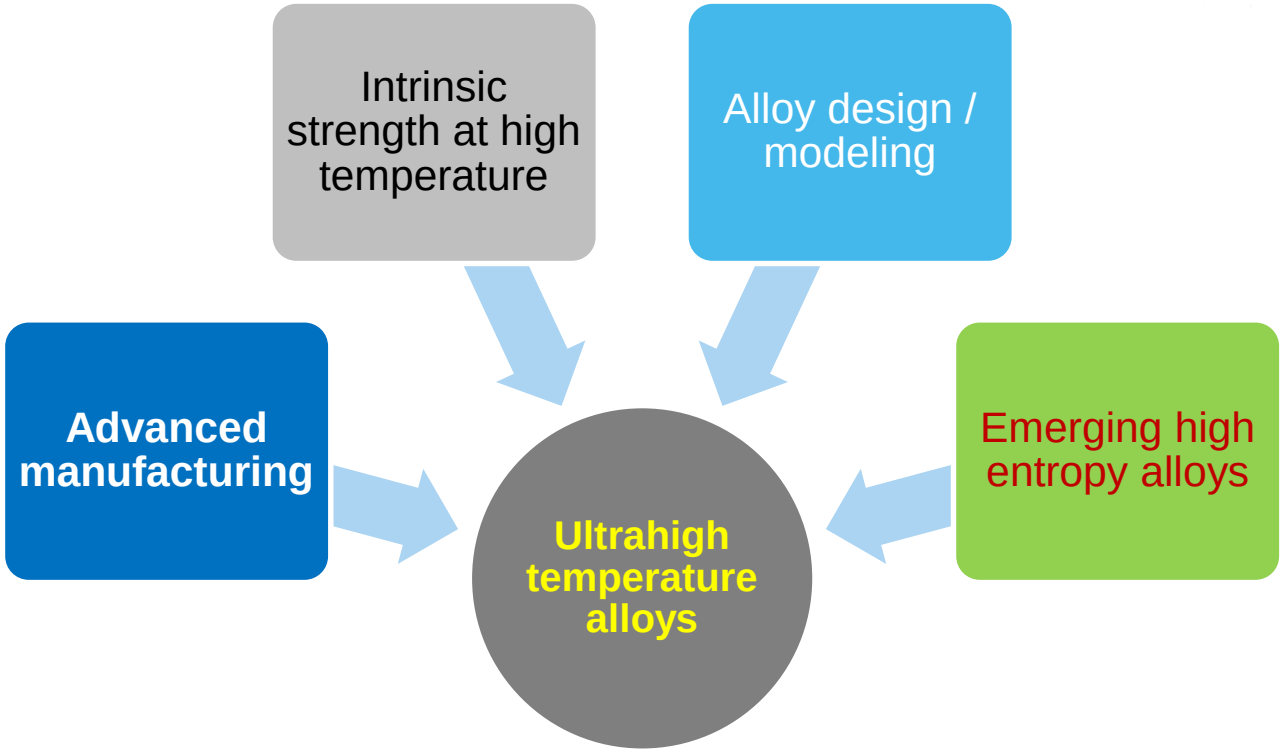
Opportunities for ultrahigh temperature alloys



Un- or less- explored opportunities

State-of-the-art
Historical

A historical opportunity for a step-change



Converging elements of technology innovation

Proposed program – *what are we trying to do*

Develop new **ultrahigh temperature materials** for gas turbine to increase temperature capacity by **>200 C** above SOA**,** potentially enabling an increase of efficiency by 8-10%

Develop new generation **nuclear reactor material** with **high temperature creep, oxidation, corrosion, and radiation** resistance

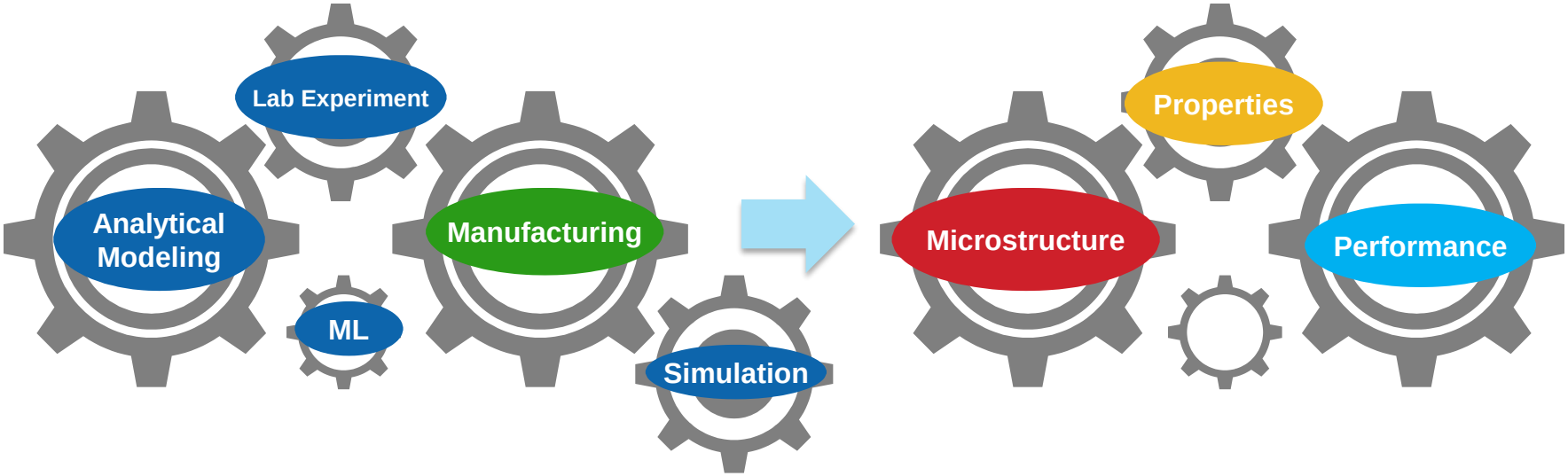
Concurrent development of materials, manufacturing processes, and design

Proposed property targets - draft

Property	Alloys	Current State	FOA Target?
Tensile Yield Strength (MPa)	Udimet 500	730 MPa (760C)	750-1000 MPa (1000°C)
	CMSX-10	994 MPa (760C)	
	Udimet 700	830 MPa (760C)	
	DS Mar M200+Hf	925 MPa (760C)	
Creep Rupture Strength (100 h)	Udimet 500	305 MPa (810C)	300-450 MPa (1000C)
	Udimet 700	400 MPa (810C)	
	DS Mar M200+Hf	465 MPa (810C)	
Fracture Toughness (MPa-$m^{1/2}$)	Ni-based Matls.	90-100	90-100 @T
Liquidus (C)	Ni-based Matls.	1250-1350	>1500
Oxidation Res. (x 10^{-6} mg^2. $cm^{-4}.s^{-1}$)	Inconel 718	40 (1100C)	
Hot Corrosion Resistance	Ni-based Matls.	Good	
Thermal Conductivity			
Thermal Expansion Coefficient (10^{-6} K^{-1})	Udimet 700	16-18 (20-800C)	
	Udimet 500	13.3 (20-100C)	
	Inconel 718	16.0 (20-760C)	

Microstructure driven **Concurrent** development of materials and processes

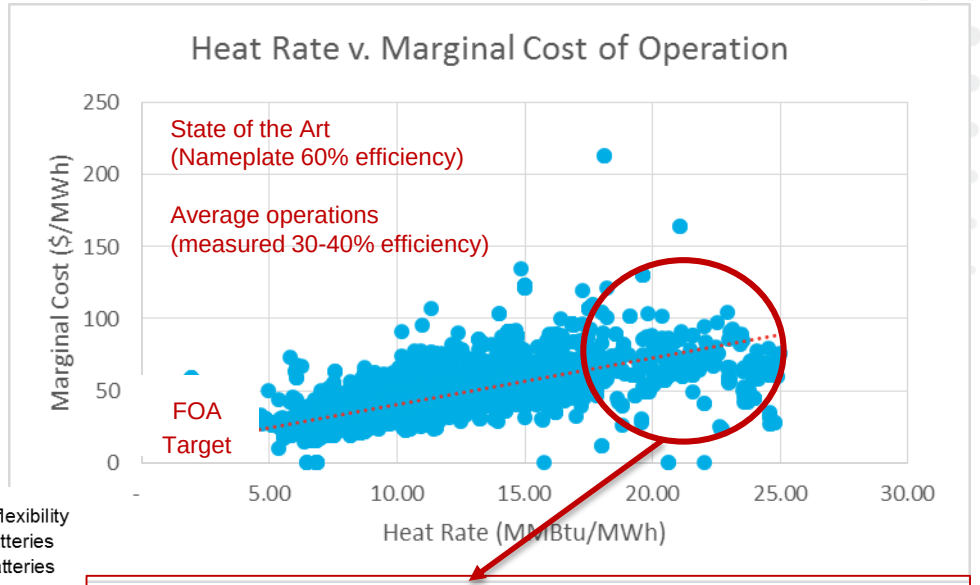
Teaming of different expertise is essential and critical



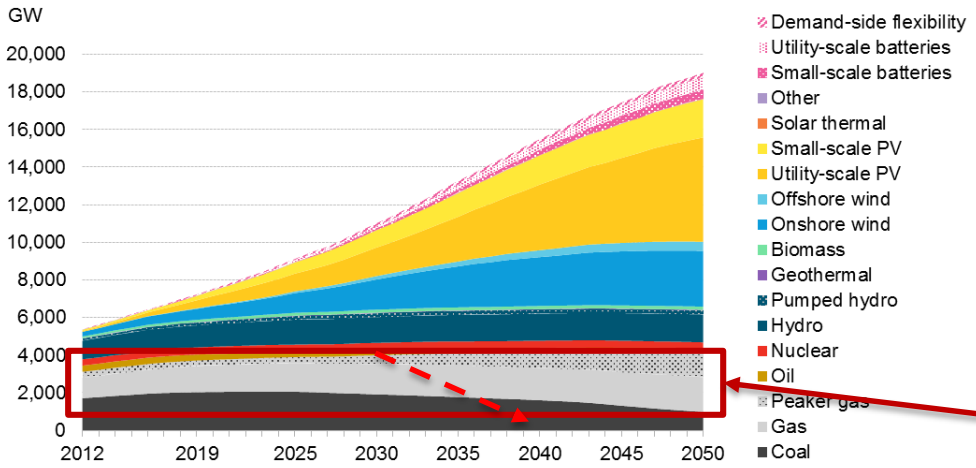
Leveraging advanced manufacturing technologies **(e.g. AM)**

Natural Gas Market Overview

The key to generating efficiency savings in natural gas plants is to force the early retirement of inefficient existing units and replace them with more efficient/economic ones (e.g. H-class case study)



U.S. Installed Capacity (Bloomberg NEF Projections)

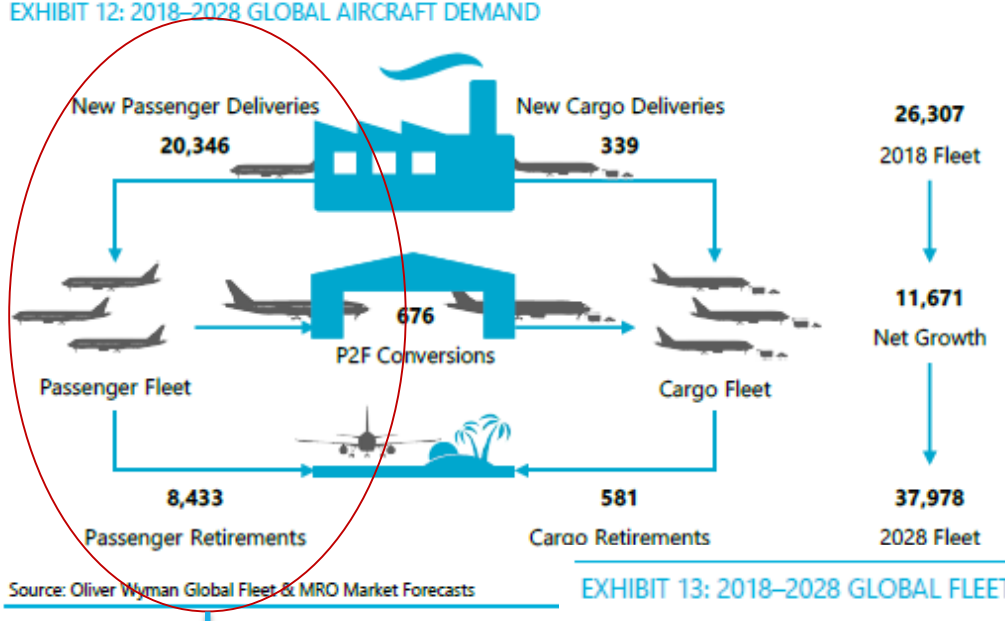


While top line efficiency is estimated to increase 10% of SOA, accelerating the retirement of inefficient units could increase savings significantly

As projected market growth is flat for Nat Gas plants until existing glut is resolved, to see significant savings replacement of inefficient units must start before 2030. Base case would see replacement of an avg. of only 25 GW per year after 2030 otherwise

Aerospace Market Overview

EXHIBIT 12: 2018–2028 GLOBAL AIRCRAFT DEMAND

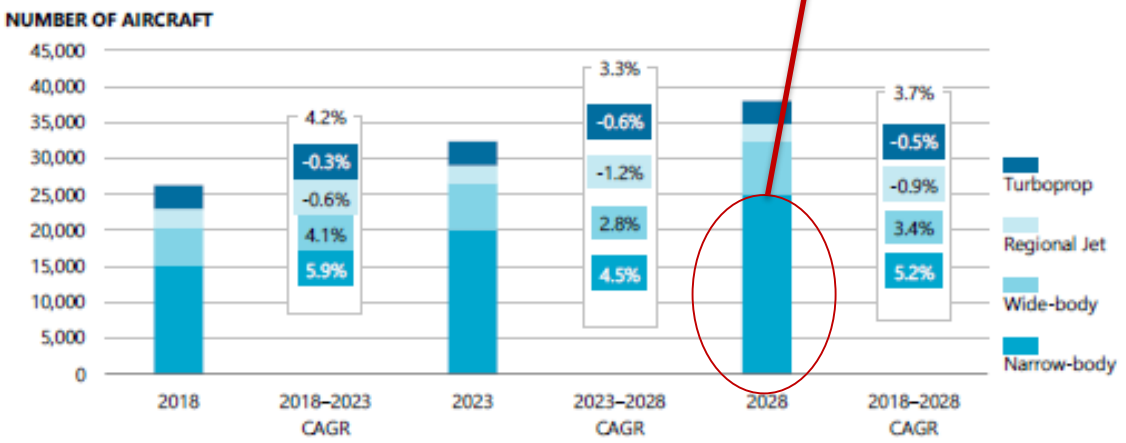


Source: Oliver Wyman Global Fleet & MRO Market Forecasts

Over the past 9 years, the Airbus A320 narrow body planes have been rapidly refurbished into the A320 neo, by replacing the engines with more efficient ones (est. 15% more efficient). This has driven the A320 neo to be the fastest selling plane currently

As in the case of natural gas, accelerating retirement of least efficient planes is critical to achieving impact in Aerospace efficiency

EXHIBIT 13: 2018–2028 GLOBAL FLEET FORECAST BY AIRCRAFT CLASS



Source: Oliver Wyman Global Fleet & MRO Market Forecasts

Impact of 10% improvement in IGT energy efficiency

- Per power plant: $8M - $30 M per year depending on fuel cost*
- Total Impact: $44B per year**

Fuel Cost Savings

- In 2018, 581 million metric tons of CO_2 was produced through gas-fired source***
- In 2015, commercial aviation emitted 120 million metric tons of CO_2 equivalent
- 50 – 100 M metric ton CO_2 reduction possible

Reduce CO_2 Emissions

- In 2018, total US electricity generation is 4178 billion kwh. 21% of this (877 billion kwh) is generated by IGT
- Around 80 billion kwh energy capacity increase is possible

Increase power generation capacity

* Extrapolated from air-cooled J-series gas turbine efficiency improvement by 2% (https://www.forbes.com/sites/mitsubishiheavyindustries/2017/01/05/the-next-generation-of-efficiency-the-race-to-65/#64577c33678)
** Source: GE
*** EIA

Objectives of the workshop

- Explain
- Listen
- Inputs from you
- Metrics
- Better program

Workshop agenda

- Presentations from industry and research community
  - *IGT industry,*
  - *Aerospace,*
  - *Nuclear,*
  - *Alloys by design / modelling,*
  - *High entropy alloys*
  - *Additive manufacturing,*
  - *History of high temperature alloys,*
  - *Refractory metal alloys*
  - *Testing and validation*
- Breakout sessions
- Team building -
- One-to-one meetings with PD

To be continued

Breakout session 1

- Three groups
  - *Industrial gas turbine*
  - *Aerospace*
  - *Nuclear*
- Moderated by ARPA-E PD
- One note taker – ARPA-E Tech SETA
- One breakout session report presenter
- Breakout session report presentations

To be continued

Day 2 Agenda

- Summary of Day 1
- Day 2 objectives
- Breakout session 2
- Breakout session 2 report presentations
- One-to-one meetings

Day 2 Agenda

Summary of Day 1

- *Industry needs*
- *Advances in alloy design by modeling*
- *Advances in manufacturing technologies*
- *Emerging high entropy alloys – a new alloy compositions space*
- *Discussed goals and metrics*
- *Discussed impacts and potential market*

Day 2 Agenda

- Summary of Day 1
- Day 2 objectives
  - *Prior research on ultrahigh temperature materials*
  - *Discuss alloy design by modeling*
  - *Discuss manufacturing challenges and opportunities*
  - *Discuss test and validation issues*

- Breakout session 2
- Breakout session 2 report presentations
- One-to-one meetings

Breakout session 2

- Three groups
  - *Alloy design and modeling*
  - *Advanced manufacturing*
  - *Test and validation*
- Moderated by ARPA-E PD
- One note taker – ARPA-E Tech SETA
- One breakout session summary presenter

Outlines

- Opening remarks
  - *Vision*
  - *Objectives of the workshop*
  - *Agenda*
  - *Breakout sessions*
  - *Team building time*
  - *One-to-one meetings with PD*
- Breakout session 1 remarks
- Day 2 opening remarks
- Breakout session 2 remarks

To be continued