

NUCLEAR THERMAL PROPULSION MATERIAL TRADE FOR ADDITIVELY MANUFACTURED REGENERATIVE CHAMBERS

Space Technology Mission Directorate
Technology Demonstration Mission Program
Space Nuclear Propulsion Project

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- Executive Summary
- Background
- Material Trade
 - Yield Strength
 - Thermal Conductivity
 - Radiation & Hydrogen Embrittlement
 - Manufacturing
- Conclusions

All following slides of this presentation will match content and structure of the paper

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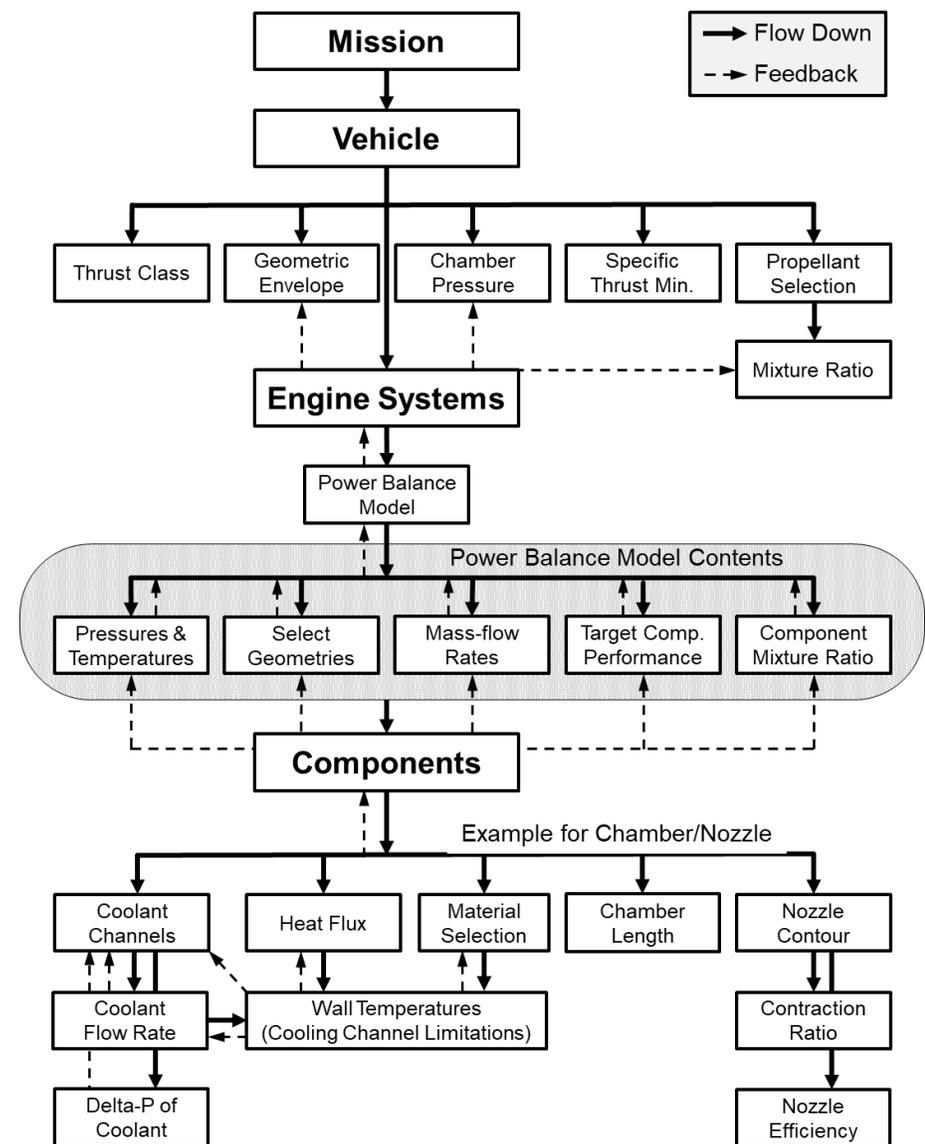


- Performed material trade for regenerative chamber
 - Relevant for both 12.5k and 25k lbf thrust Nuclear Thermal Propulsion engines
- Selection of traditional and advanced materials examined
 - A-286
 - Haynes 230
 - Haynes 282
 - SS 347
 - GRCop-42
 - GRCop-84
 - Inconel 625
 - JBK-75
 - NASA HR-1
- NASA HR-1
 - High strength and conductivity relative to other superalloys
- GRCop-42
 - Substantially higher conductivity than superalloys
 - Higher strength to other copper alloys

Project will move forward concurrently with NASA HR-1 and GRCop-42

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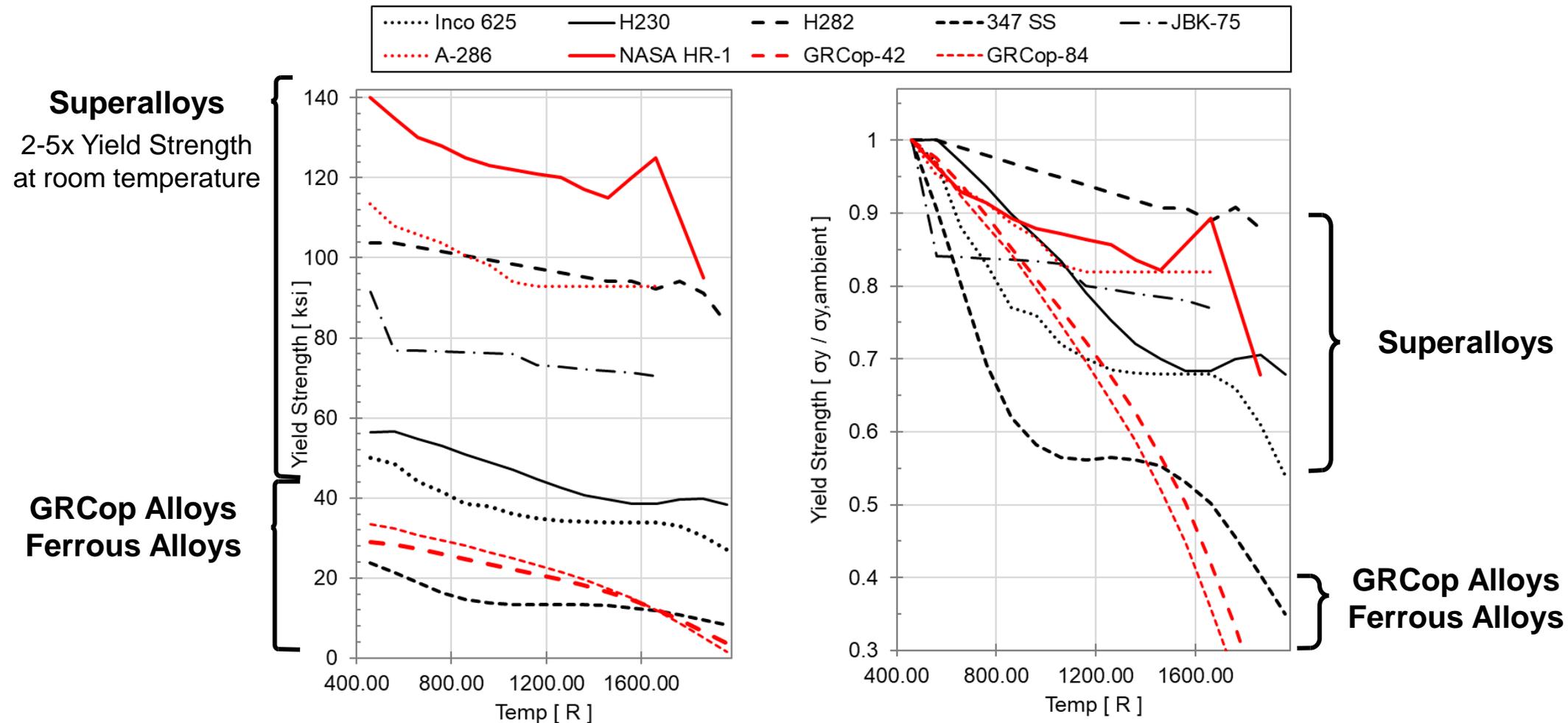
- Constraint flow down and feedback is iterative
 - Inefficient communication may lead to excess iterations
 - Trade study to document material justification
- Chamber material selection
 - One of many decision gates
 - Impacts engine functionality and reliability
- Trade considerations:
 - Chemical & nuclear compatibility
 - Manufacturability
 - Material & mechanical properties
 - System effects
 - i.e., pressure loss, flow rate bypasses, heat regeneration



Goal: Narrow trade space for optimal regenerative chamber material(s) for nuclear thermal engine

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Yield Strengths vs. Temperature

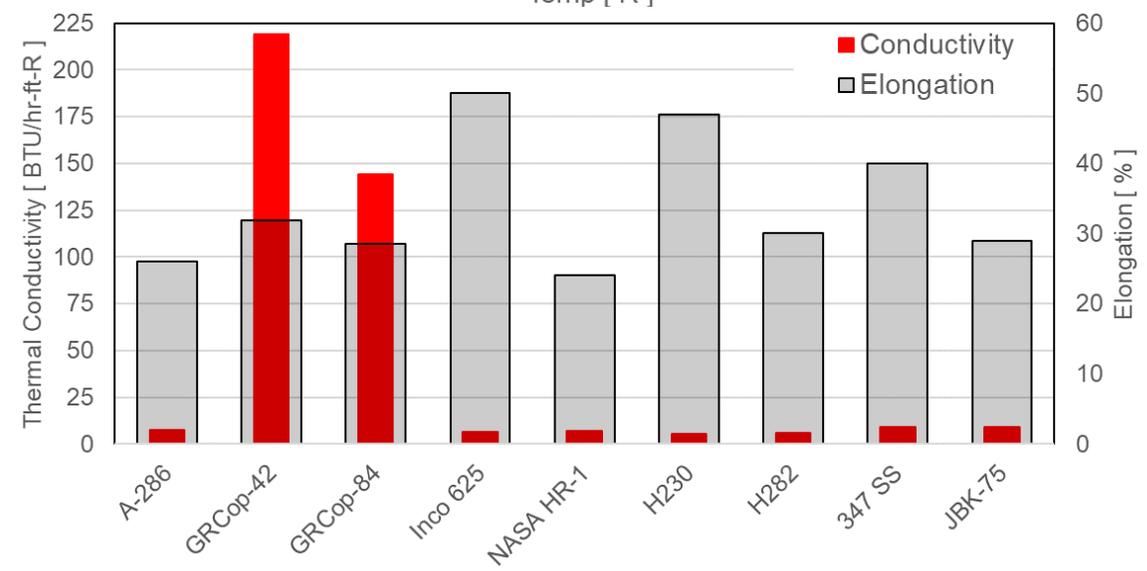
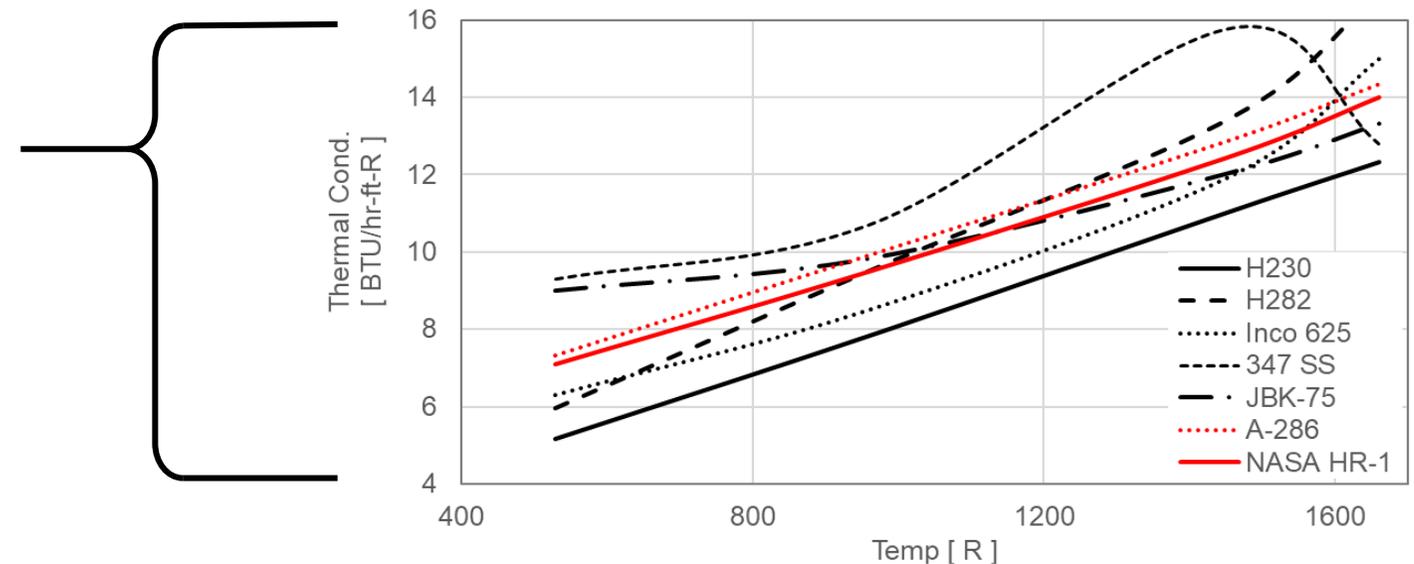


Superalloys (1) have higher strengths and (2) maintain mechanical properties at high fraction of melting point

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- Comparable conductivity
 - Superalloys
 - Ferrous-based alloys
- 15-20x higher conductivity
 - GRCop alloys
- Comparable elongation
 - 25-45%

A balance of relevant material properties is critical



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- Chemical equilibrium calculation for fluid properties
- Convective heat coefficient calculated via Bartz

$$h_g = \left[\frac{0.026}{D_t^{0.2}} \left(\frac{\mu^{0.2} C_p}{P^{0.6}} \right)_{ns} \left(\frac{(PC)_{ns} * g}{c^*} \right)^{0.8} \left(\frac{D_t}{r_c} \right)^{0.1} \right] * \left(\frac{A_t}{A_{local}} \right)^{0.9} * \sigma$$

$$\text{Where } \sigma = \frac{1}{\left[\frac{1}{2} * \frac{T_{wg}}{(TC)_{ns}} * \left(1 + \frac{\gamma-1}{2} M^2 \right) + \frac{1}{2} \right]^{0.68} * \left[1 + \frac{\gamma-1}{2} M^2 \right]^{0.12}}$$

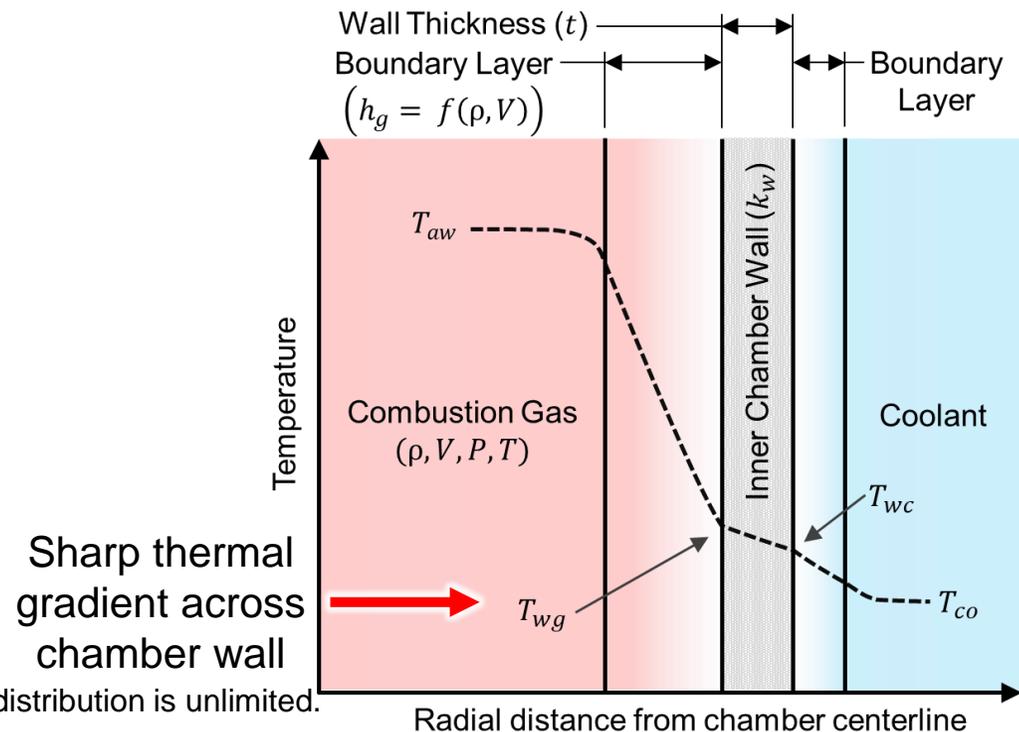
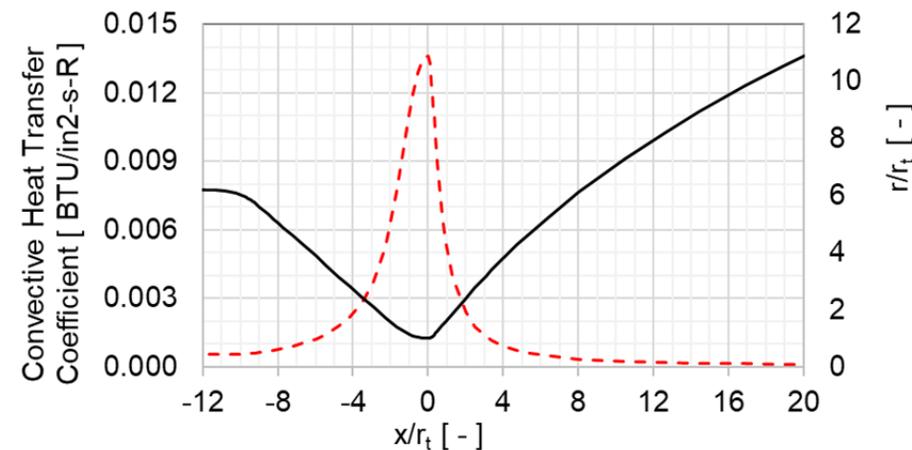
- Balance Heat Flux

- $h_g(T_{aw} - T_{wg}) = q = \frac{k_w}{t} (T_{wg} - T_{wc})$
- Simplifying assumptions of:
 - Maximum coolant convective heat transfer
 - 1D heat transfer

- Margin to 50% of melting temperature

- Copper alloys 37-43%
- Ferrous alloys 36%
- Superalloys 25-37%

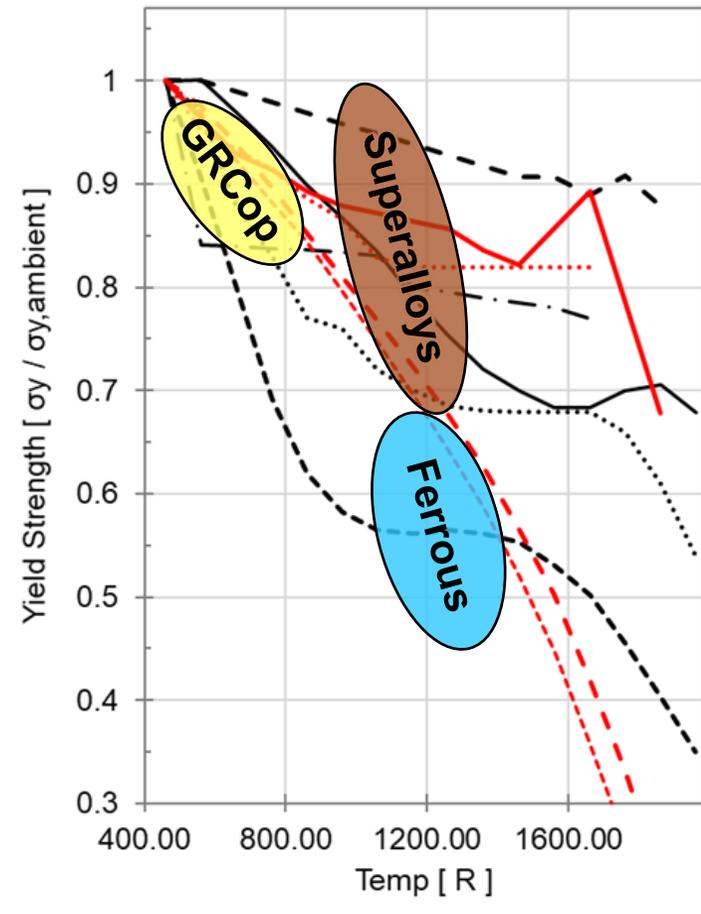
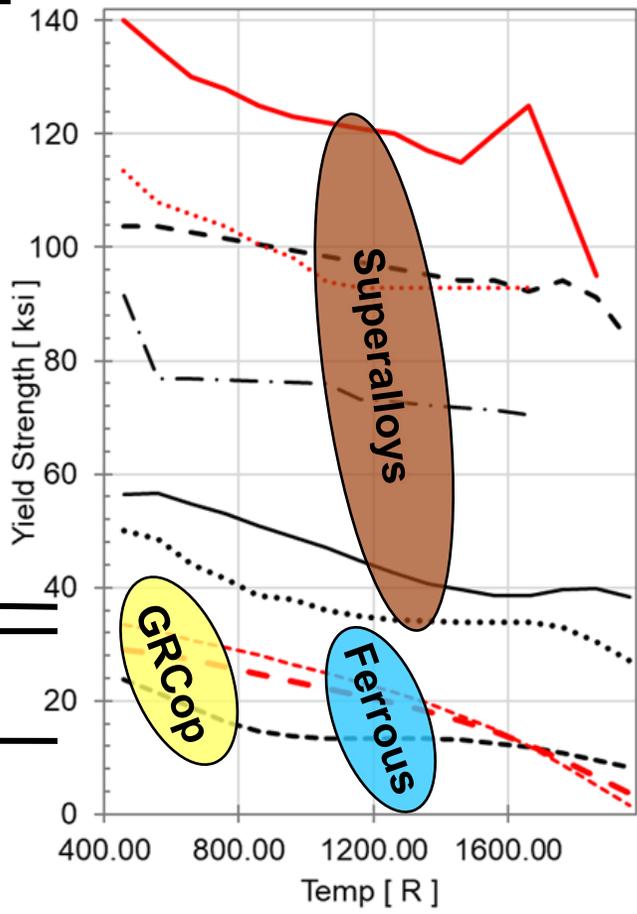
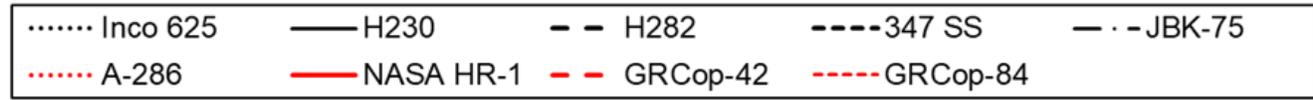
Basic analysis shows reasonable margins



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Superalloys
 2-5x Yield Strength at room temperature
 Creep Resistant
 Corrosion Resistant

GRCop Alloys
Ferrous Alloys



Basic analysis produces reasonable margin
 (order of magnitude estimate)

Advanced analysis will produce lower, but acceptable margin
 (realistic solution)

Operating Ranges

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- Inferred properties from similarly composed materials
 - GRCop-x, Haynes 2xx
- GRCop-x: Concerns of hydrogen isotope absorption by niobium (Nb) leading to embrittlement
 - Occurrence is extremely low with the presence of Cr₂Nb and a slight excess of chromium
- GRCop-x has a ratio of 1.14:1, Cr:Nb.
 - The ratio of copper to Cr:Nb is the key difference
 - Difference not anticipated to cause hydrogen embrittlement issue
 - Pure copper has negligible risk

Material	Qualitative Rating for Hydrogen Environmental Embrittlement
A-286	Negligible, Severe (w/Aging)
GRCop-42	<i>Not Available (Negligible)</i>
GRCop-84	Negligible
H230	High
H282	<i>Not Available (High)</i>
Inco 625	High
JBK-75	Negligible, High (w/ST + Aging)
NASA HR-1	Negligible (Small)
347 SS	Small

Low HEE Risk Materials: GRCop-x, NASA-HR-1, 347 SS

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- Cryogenic hydrogen (between storage tank and chamber inlet) is susceptible to gamma and neutron radiation escaping the moderator block
 - Near-zero para-ortho conversion at liquid hydrogen temperatures
- Conversion from para- to ortho-states (spin isomers) causes significant enthalpy difference
 - Stainless steels act as a catalyst for conversion from parahydrogen to orthohydrogen
 - Long-duration, low-flux radiation has a greater conversion than short-duration, high-flux radiation
 - Catalytic conversion occurs on the order of minutes or hours
 - Residence time (**milliseconds**) in nozzle is insignificant for para-ortho conversion
 - Potential concern for cryogenic fluid management system (residence time ~**minutes**)

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- **Manufacturing method selection reduces risk for both budget and schedule**
- Freeform additive techniques are necessary for nozzle fabrication
 - L-PBF – laser powder bed fusion (small build box, high resolution)
 - LP-DED – laser powder directed energy deposition (large build box, moderate resolution, free form)
 - Laser wire direct closeout – post-processing technique to close channels (not required for fully-integral channels)

Method	A-286	GRCop-42	GRCop-84	Inco 625	HR-1	H230	H282	JBK-75	347 SS
L-PBF		X	X	X	X	X	X	X	X
Laser Wire Direct Closeout				X	X	X		X	X
LP-DED		X	X	X	X	X		X	

- LP-DED applicability limits material trade space
 - **Ineligible materials:** A-286, Haynes 282, 347 SS



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Material	Status
A-286	Ineligible
GRCop-42	Eligible, Selected
GRCop-84	Eligible
Haynes 230	Eligible
Haynes 282	Ineligible
Inconel 625	Eligible
JBK-75	Eligible
NASA HR-1	Eligible, Selected
SS 347	Ineligible

Prop. / Mat.	σ	k	H ₂ Risk	Manufacturability
A-286	6	1	Severe	-
GRCop-42	1	21	Negligible	x
GRCop-84	1	15	Negligible	x
H230	3	1	High	x
H282	5	1	High	-
Inco 625	3	1	High	x
JBK-75	1	1	High	x
NASA HR-1	7	1	Small	x
347 SS	1	1	Small	-

- **NASA HR-1**

- High strength and conductivity relative to other superalloys

- **GRCop-42**

- Substantially higher conductivity than superalloys (lower operating temperature)
- Higher strength to other copper alloys

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