



NETS

2022

**NUCLEAR and
EMERGING
TECHNOLOGIES for
SPACE**



Nuclear Electric Propulsion Brayton Power Conversion Working Fluid Considerations

Rodger Dyson¹, D.V. Rao², Matthew Duchek³, Christopher Harnack³, Robert Scheidegger¹, Lee Mason⁴,
Al Juhasz¹, Luis Rodriguez¹, Ronald Leibach¹, Steven Geng¹ and Daniel Goodell¹

¹NASA Glenn Research Center, Cleveland, , 44135, ²Los Alamos National Laboratory, Santa Fe, New Mexico, 87545

³Analytical Mechanics Associates, Inc., Hampton, Virginia, 23666 ⁴NASA Headquarters, Washington, D.C, 20546



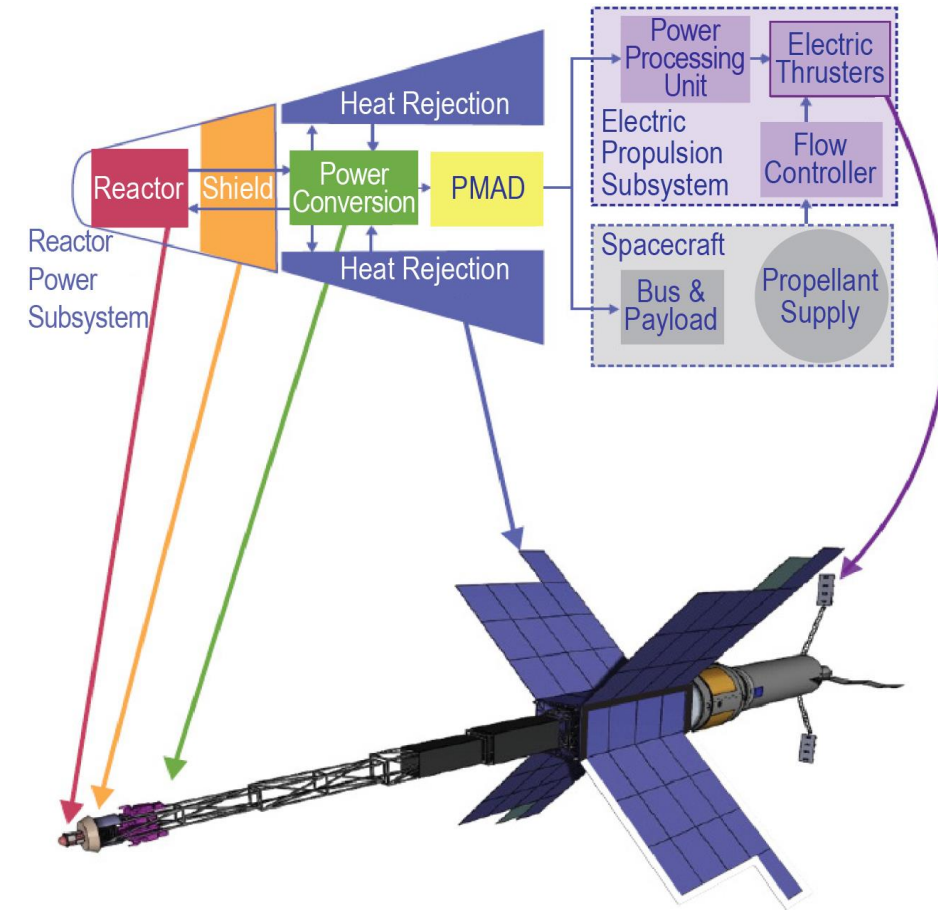
Agenda

- Background
- Closed Brayton Generator Summary and Performance Maps
- Design and Interface Constraints
- Supercritical Brayton Challenges
- Comparisons between He-Xe and s-CO₂ Brayton Cycle Systems
- Concluding Working Fluid Recommendations



Nuclear Electric Propulsion Introduction

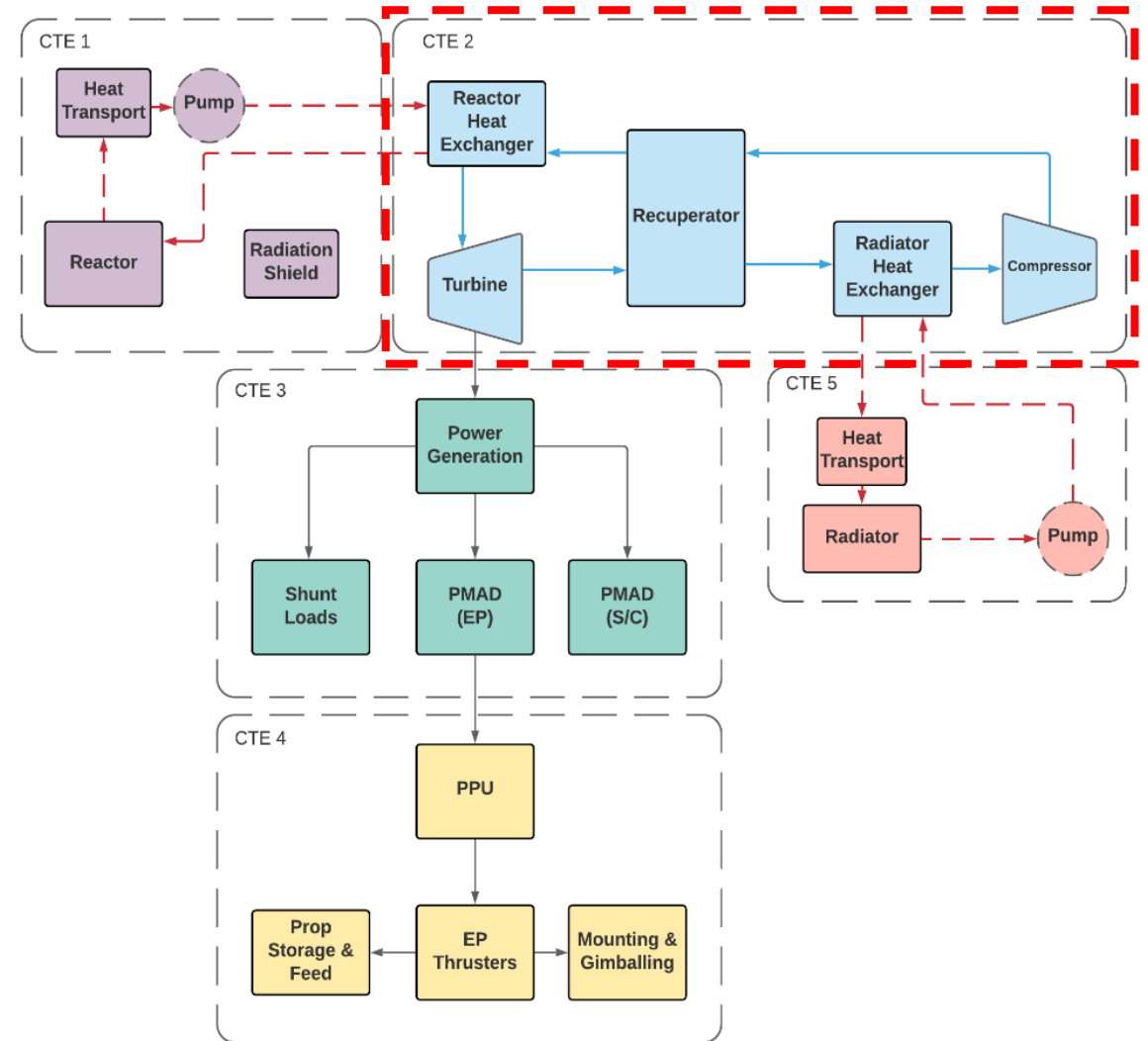
- NASA has considered Nuclear Electric Propulsion (NEP) for high DV missions since the late 1950s, but the current technology readiness level of the requisite powertrain needs to be raised for such a mission.
- The powertrain includes reactor, power conversion, power management, electric propulsion, and thermal management components that must be integrated to minimize system a (kg/kW_e)



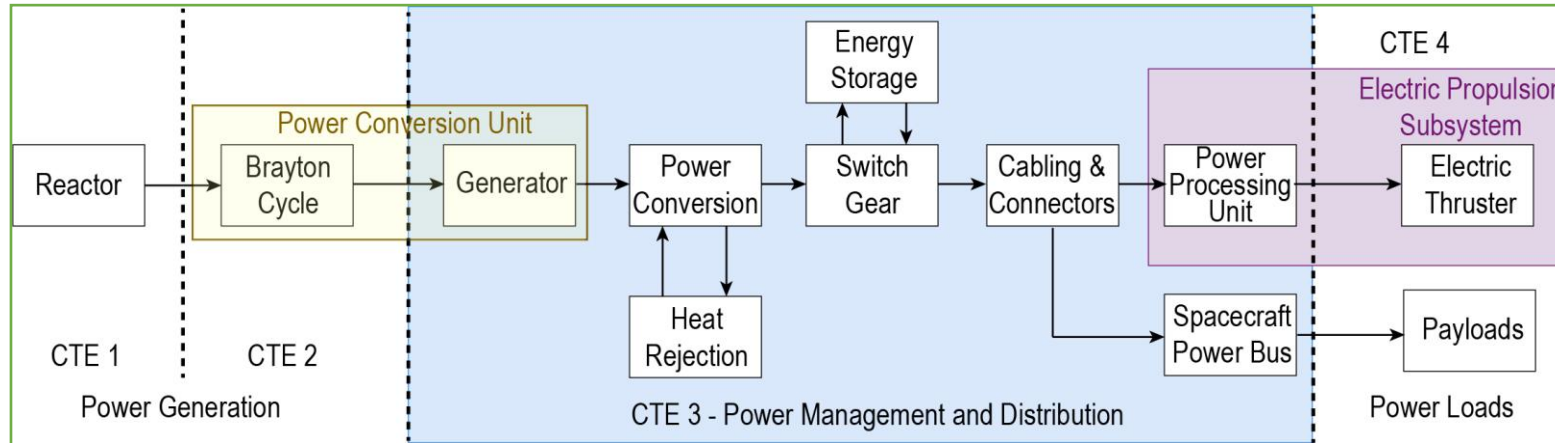
Ref. NASEM

NEP Critical Technology Elements (CTEs)

- In the NEP Power Conversion Subsystem (CTE 2), should SNP invest in the maturation of technologies and systems based on:
- The traditional working fluid of He-Xe?
- A supercritical CO₂ working fluid?
- Both?



Powertrain Architecture

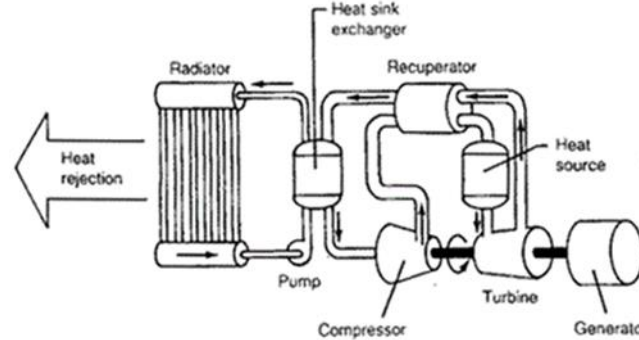


- As part of the development of a technology maturation plan for a potential NEP vehicle, critical technology elements (CTE) have been identified for further development.
- None have been tested to the power levels required for a MWe-class NEP system in an appropriate operating environment

Background

The Brayton power convertor working fluid is an important consideration because it impacts the entire system alpha.

- Multiple independent system studies:
 - NESC, NASEM, MTAS, SNP/AMA, Create, Brayton Engines, COMPASS
- Multiple independent optimizations:
 - Matlab suite, BRMAPS, NPSS, NNEP
- He-Xe, s-CO₂, and s-SO₂ compared:
 - All fluids can be used, but with different risk postures.



Heritage:

Prior closed-cycle space-environment 10 kW_e He-Xe Brayton testing demonstrated 38,000-hour operation

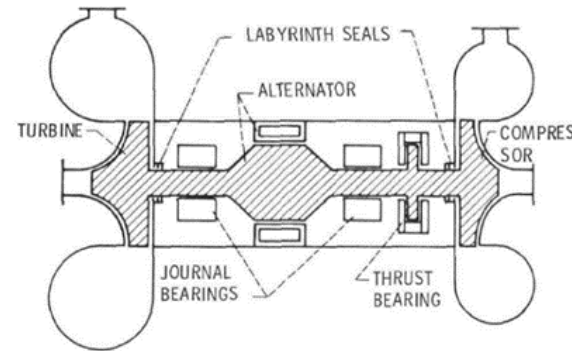
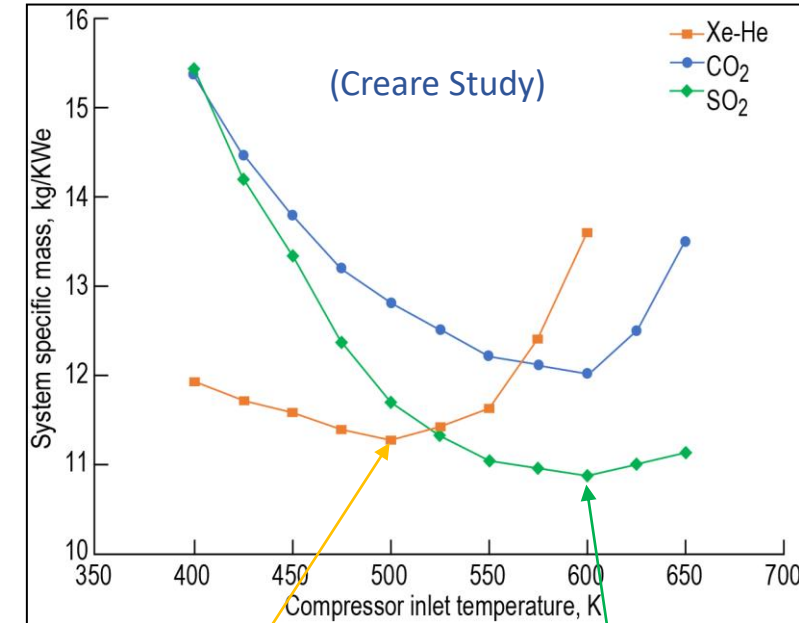
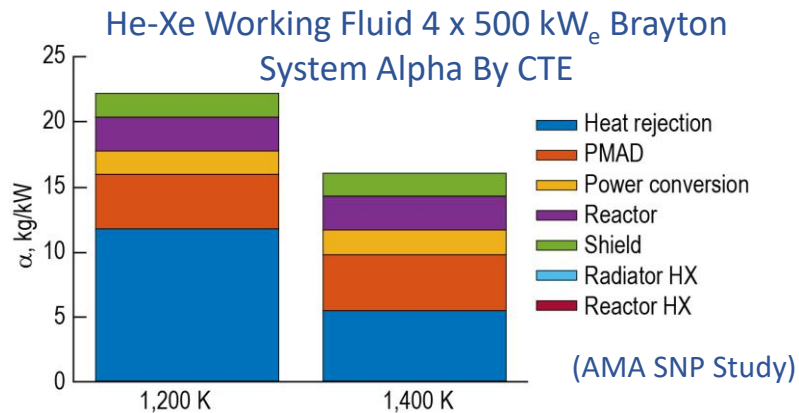


Figure 18. - BRU schematic.



He-Xe working fluid can optimize to a lower system specific mass over a range of compressor inlet temperatures.

s-SO₂ system 'could' optimize to a lower system specific mass than He-Xe, but at a significantly higher development risk

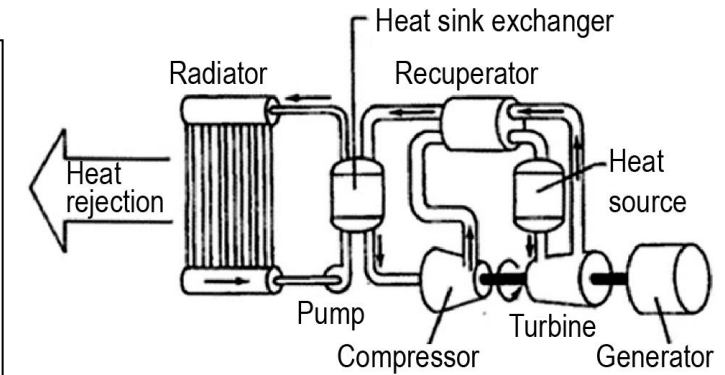
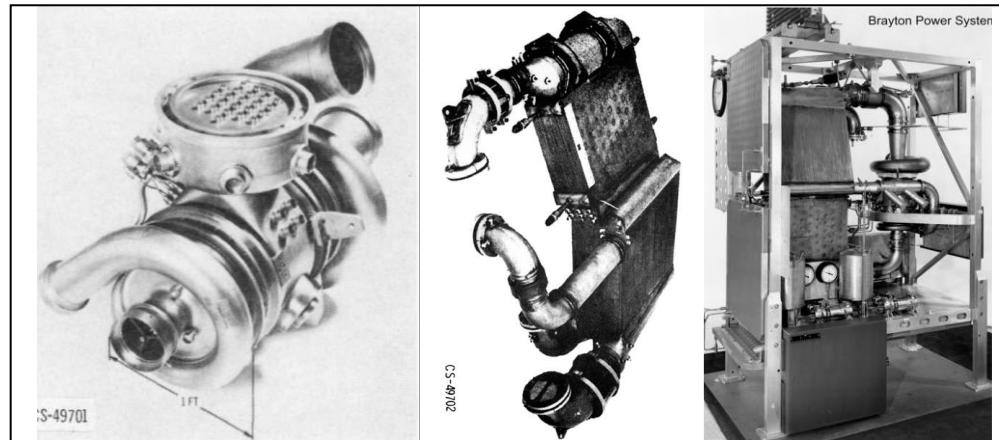
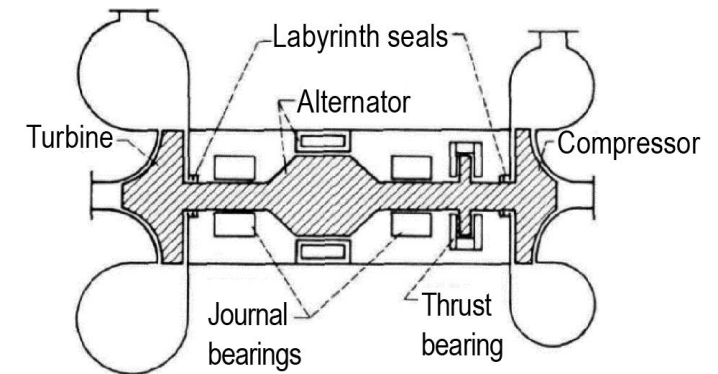


Comparison of He-Xe and supercritical CO₂ indicates better efficiency and system alpha with He-Xe at lower risk 500K inlet.

Closed Brayton Development History

- Original closed Brayton Rotating Unit (BRU) developed over 50 years ago.
- Honeywell purchased AirResearch and continued development until 2005
- DOE sCO₂ only closed Brayton industry today.

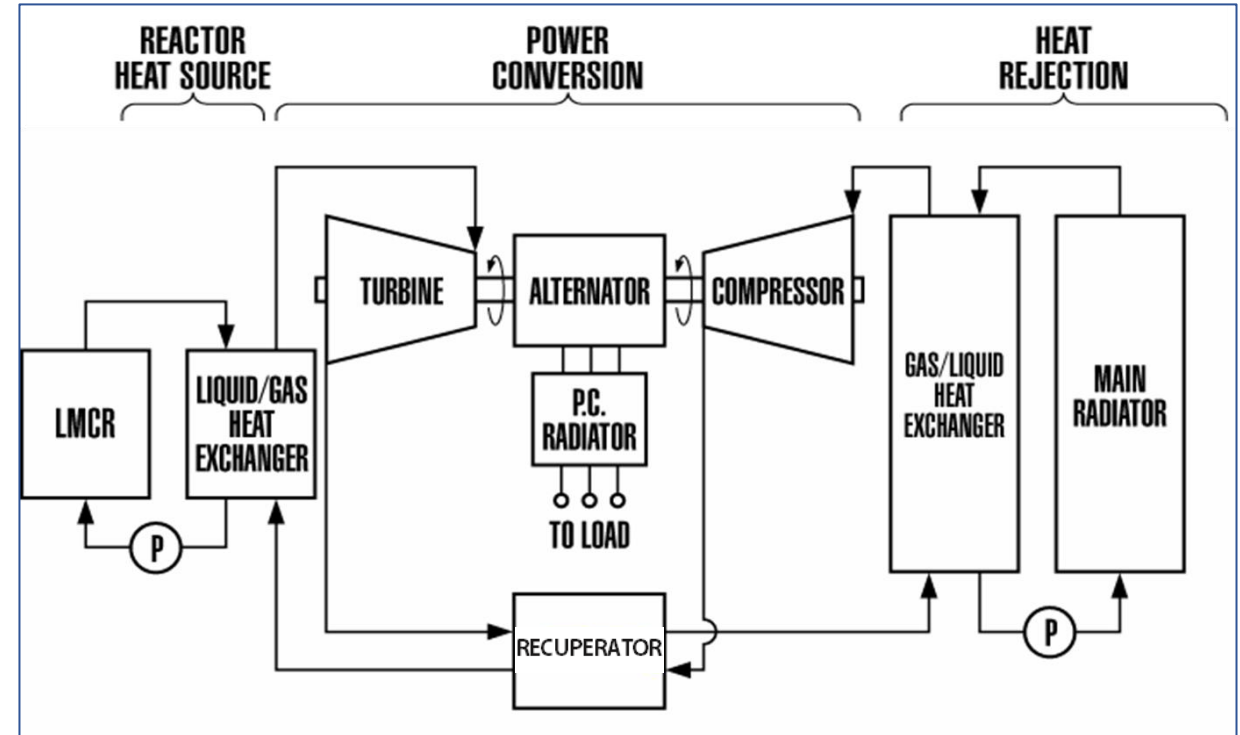
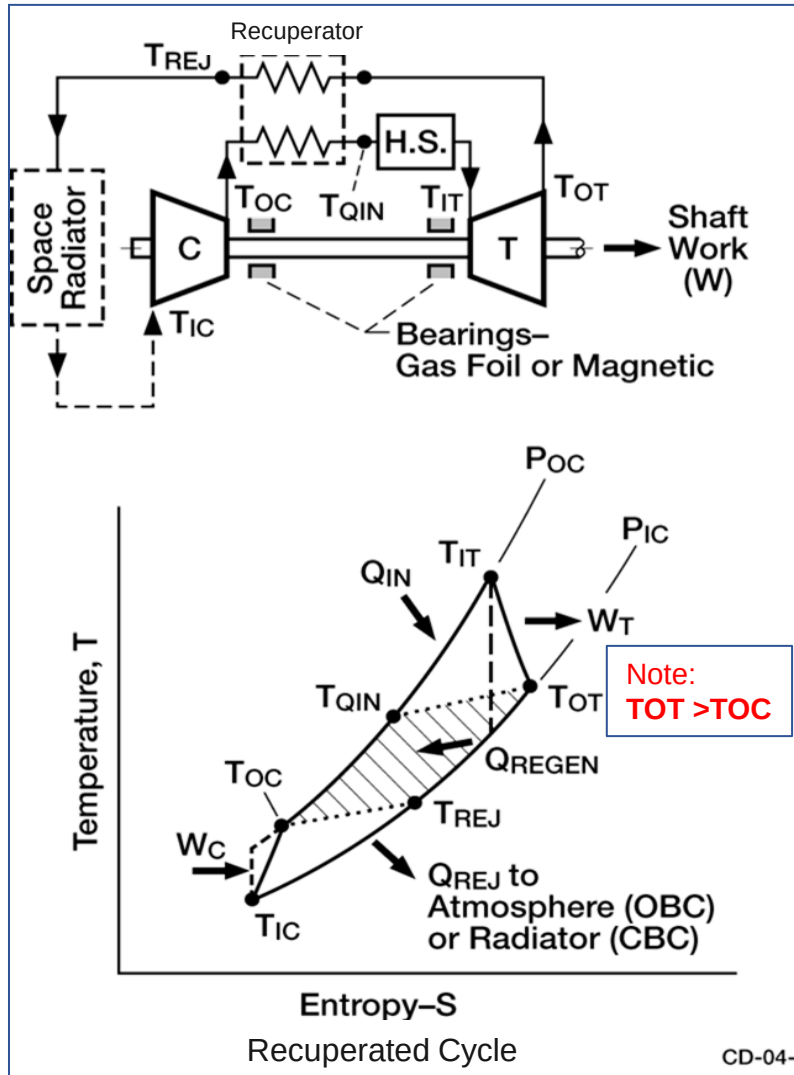
Year (*tested units)	Project Heritage	Power Level (kW _e)
1972 *	BRU	10.5
1978 *	Mini-BRU	1.3
1993	SSF SDPM	36
1997	SD GTD	2
2005	JIMO	100
2005	JIMO ATU	50
2009 *	Dual Capstone	22



BRU, Combined Recuperator/Radiator HX, and Life Testing Assembly

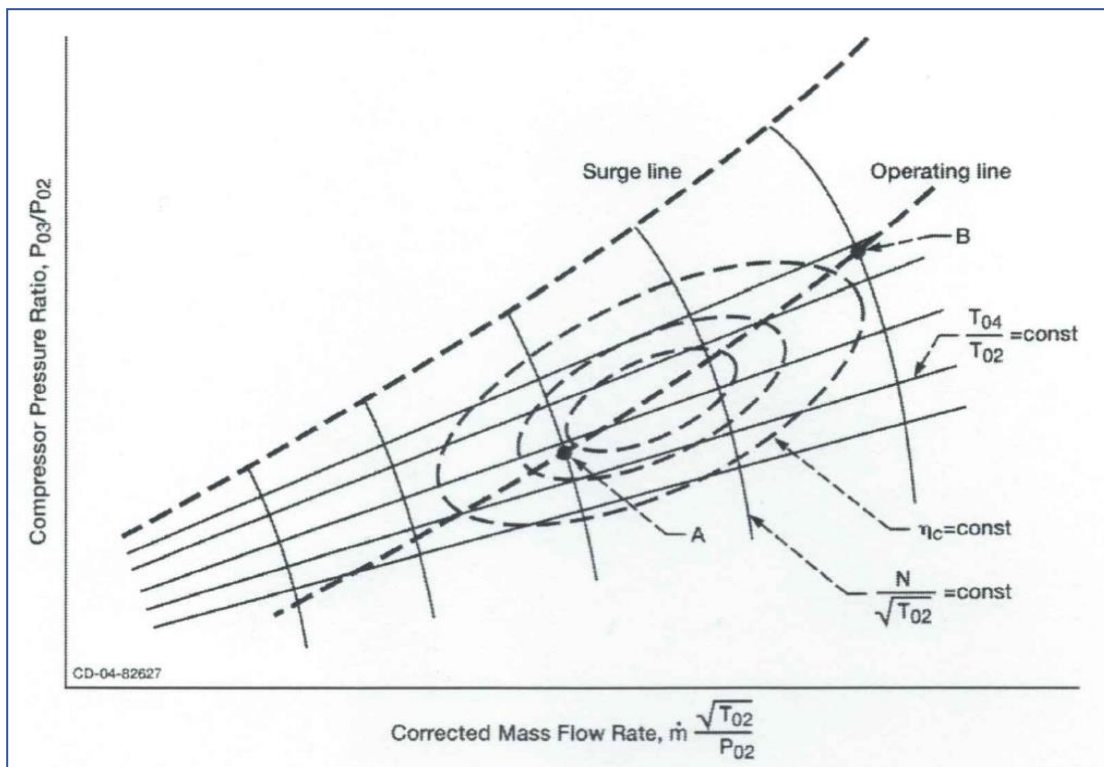
Brayton Cycle Summary

Recuperator Effectiveness
 $Erg = (T_{QIN} - T_{OC}) / (T_{OT} - T_{OC})$

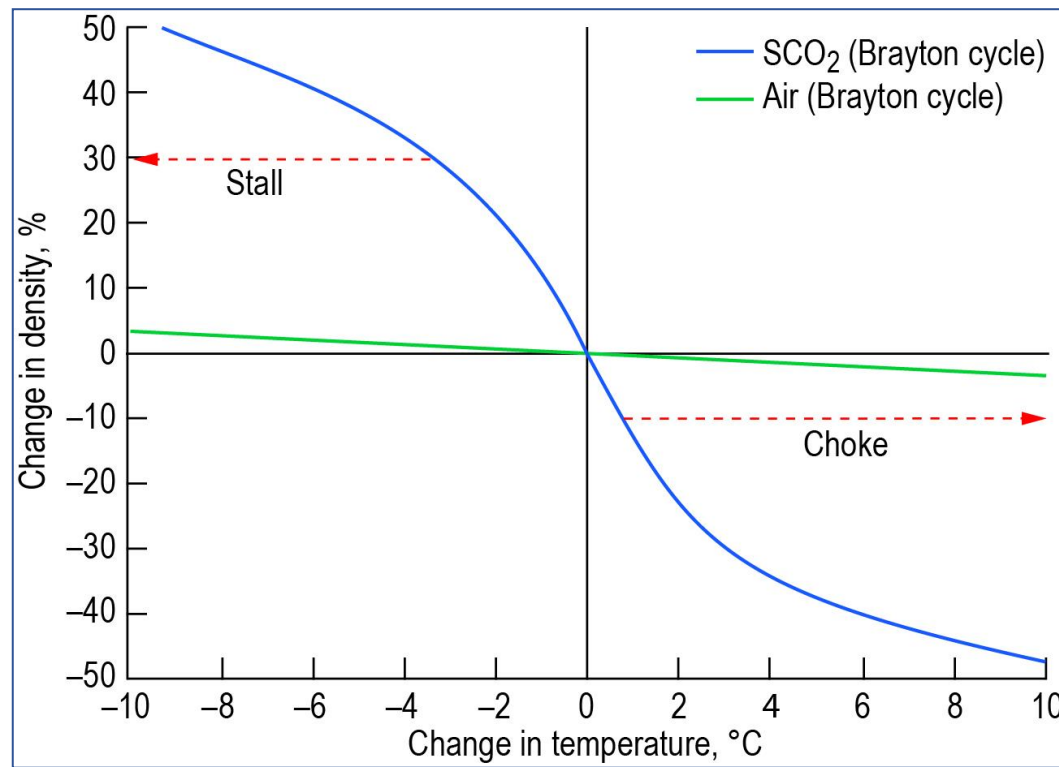


Closed Brayton with Recuperator for High Efficiency

Compressor Performance vs. Working Fluid



Ref. Juhasz



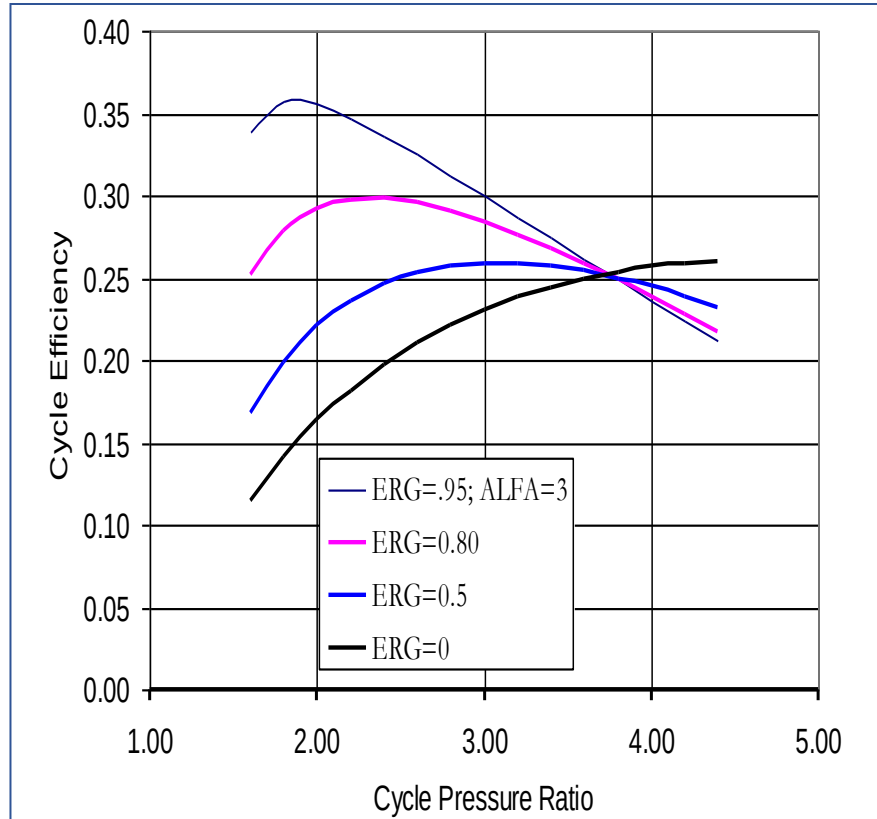
Ref. Wright

Flow properties and speeds impact turbomachinery stability and performance

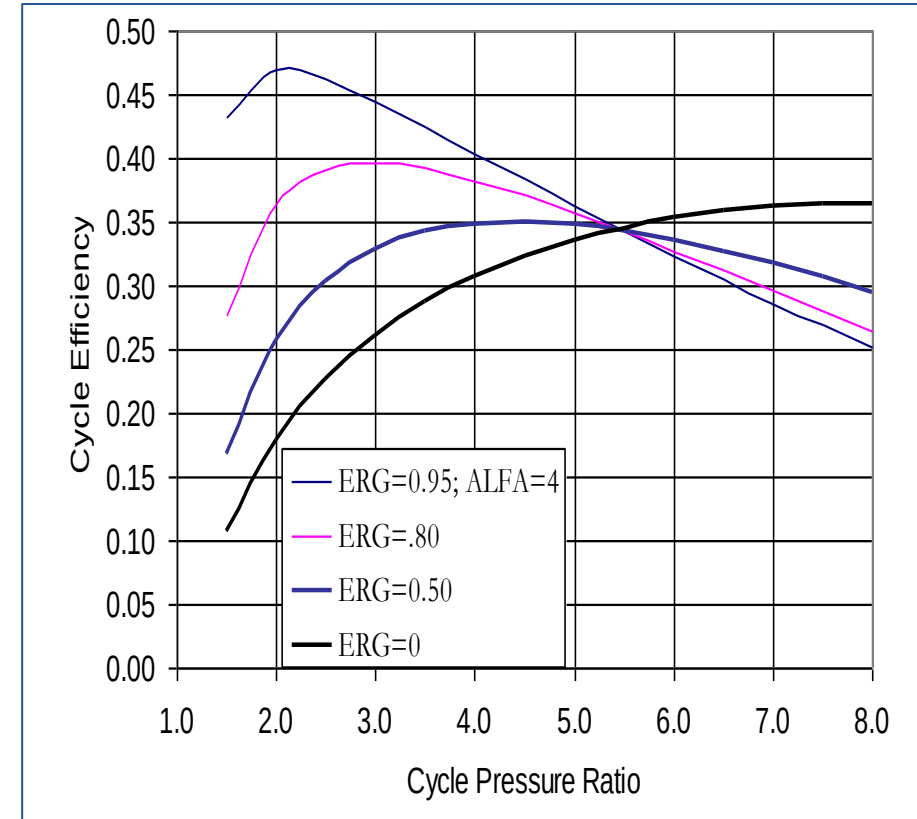


Recuperator Effectiveness Impact on Efficiency

$$\eta_{PC} = \eta_{PT} = 0.9; \quad \gamma = 1.666$$



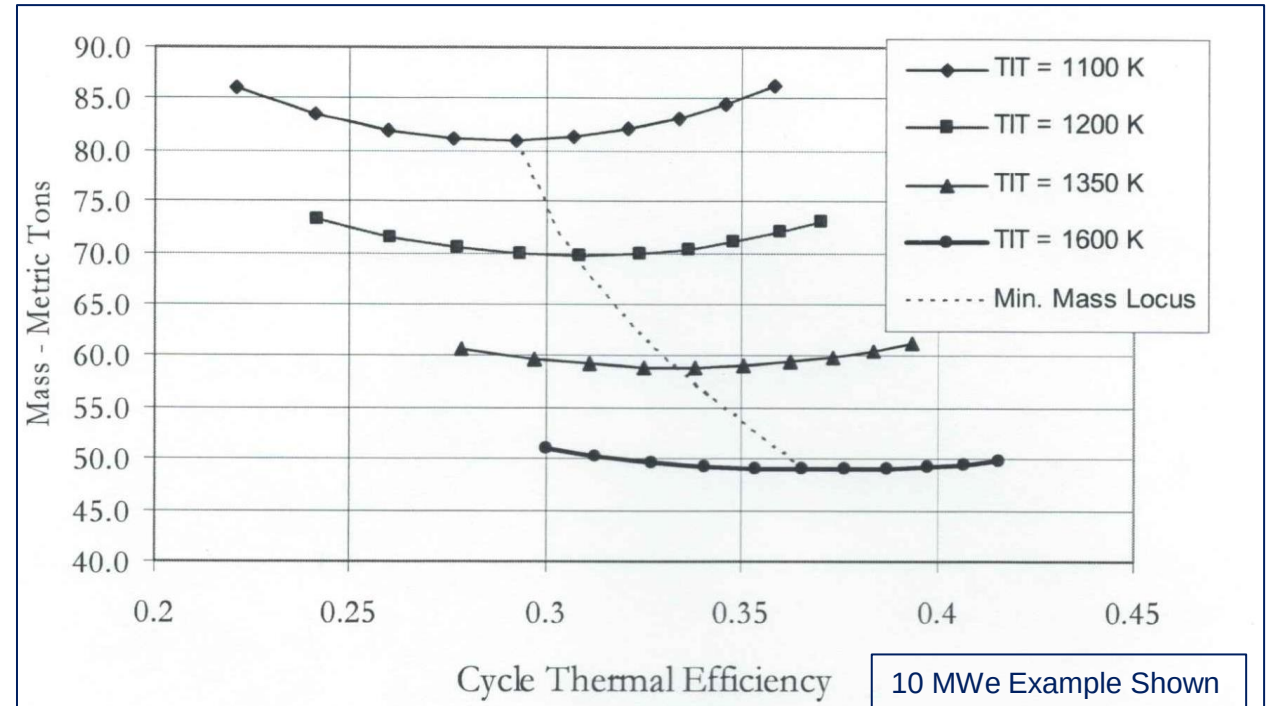
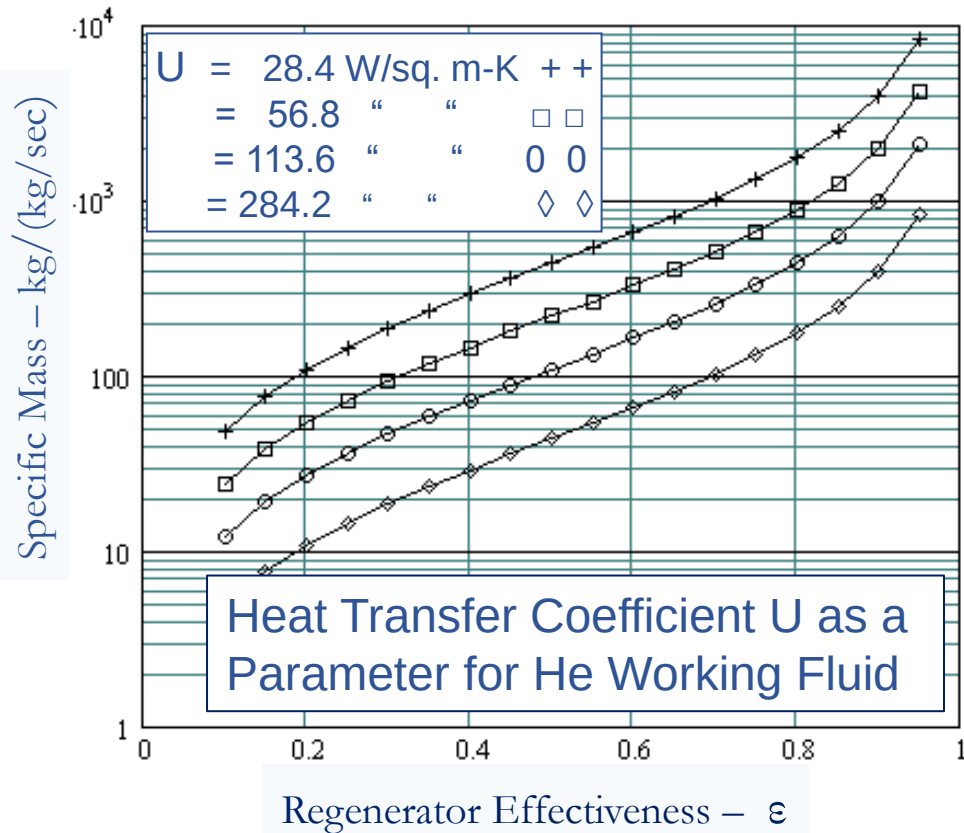
(a) Temp. Ratio = 3.0



(b) Temp. Ratio = 4.0

High efficiency is possible with careful selection of regenerator and compression ratio

Recuperator Specific Mass and System Mass



Higher turbine inlet temperature reduces system mass

M.W. & Pressure impact on size and speed – 500 kWe

He Xe M.W.	Mass Flowrate kg/s	Ratio	Turbine Inlet Temperature
41	14.05	30% Xe 70% He	1200

He Xe M.W.	Mass Flowrate kg/s	Ratio	Turbine Inlet Temperature
112	32.53	85% Xe 15% He	1200

	Pressure Level		Speed rpm	Disk Diameter	
	MPa	Psia		m	in
2		290	32,360	0.244	9.6
4		580	45,800	0.173	6.8
6		870	56,000	0.141	5.55
8		1160	64,600	0.122	4.8
10		1450	72,400	0.109	4.3

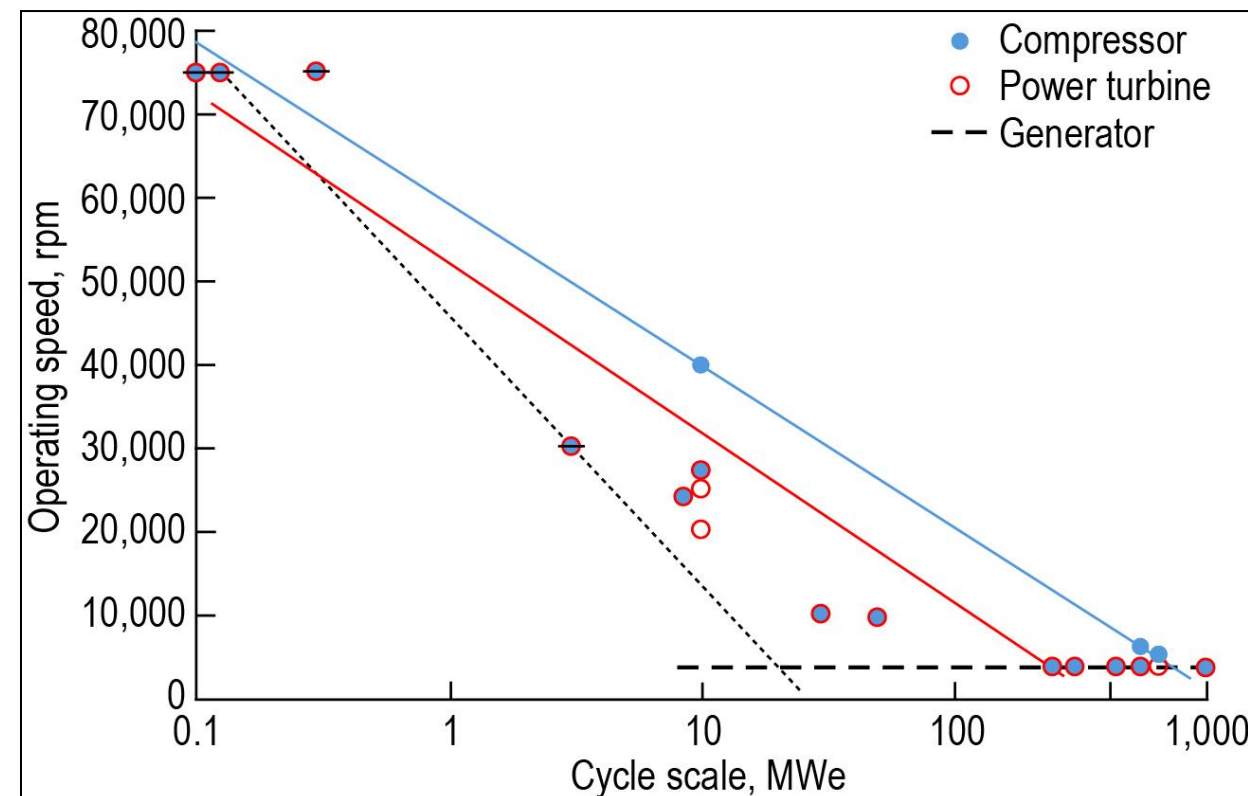
	Pressure Level		Speed rpm	Disk Diameter	
	MPa	Psia		m	in
2		290	16,400	0.29	11.42
4		580	23,200	0.205	8.08
6		870	28,400	0.168	6.62
8		1160	32,700	0.146	5.73
10		1450	36,700	0.13	5.11

Must match generator speed with turbine speed



Brayton Architecture Scaling

TM Feature	Power, MWe						
	0.3	1.0	3.0	10	30	100	300
TM Speed/Size	75,000/5 cm		30,000/14 cm		10,000/40 cm		3,600/1.2 m
Turbine Type	Single stage			Radial	Multistage		
	Single stage			Radial	Multistage		Axial Multistage
	Single stage			Radial	Multistage		Single stage Axial Multistage
Bearings	Gas foil		Hydrodynamic oil				
				Magnetic	Hydrostatic		
Seals	Adv. labyrinth			Dry lift off			
Freq/alternator	Permanent Magnet			Wound, Synchronous			
				Gearbox, Synchronous			
Shaft Configuration	Dual/Multiple			Single shaft			



Eliminate gearbox with proper working fluid operating conditions



Corrosion/Material Constraints

- s-CO₂ limited to 923K
- He-Xe limited to 1200K with superalloy
- He-Xe limited to 1400K with refractory
- Hipercor radiation susceptibility

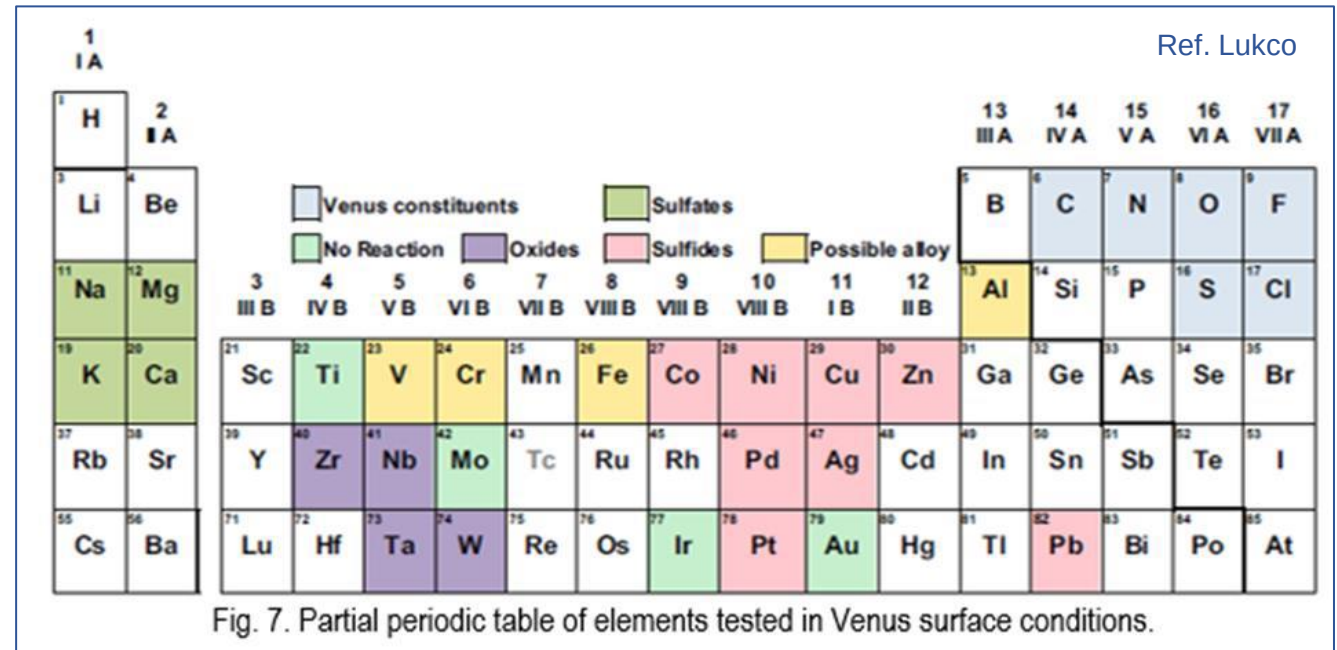


Table 5. High-Temperature Soft Magnetic Properties of Hipercor-50-HS

Property	Temperature, °C								
	21	100	200	300	400	500	550	600	Return to 21
Coercivity, Oe	1.137	1.113	1.114	1.063	0.970	0.781	0.616	0.567	0.567
Max relative permeability	14,553	13,361	12,998	12,271	13,589	17,715	19,845	22,051	30,513
Retentivity, G	12,400	11,400	11,700	11,000	11,300	11,000	11,500	12,600	12,300
B at H = 0.1 kA/m (1.25 Oe), G	10,650	10,500	10,700	10,000	10,700	11,100	12,100	12,000	12,600
B at 0.5 kA/m, G	17,300	16,500	16,800	16,100	16,600	16,800	17,200	16,800	18,600

Ref. Geng

Partial Discharge Voltage Limits

- sCO_2 is a better dielectric above 1 torr-cm than He-Xe
- 1kV is supported in pressure vessel due to $>2\text{MPa}$ working fluid pressure
- Near vacuum environment at feed-throughs due to outgassing needs high voltage protections from creepage, arcing, and partial discharge events

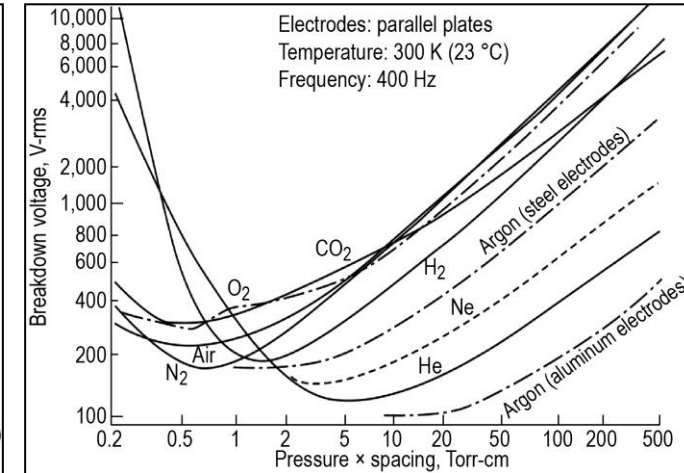
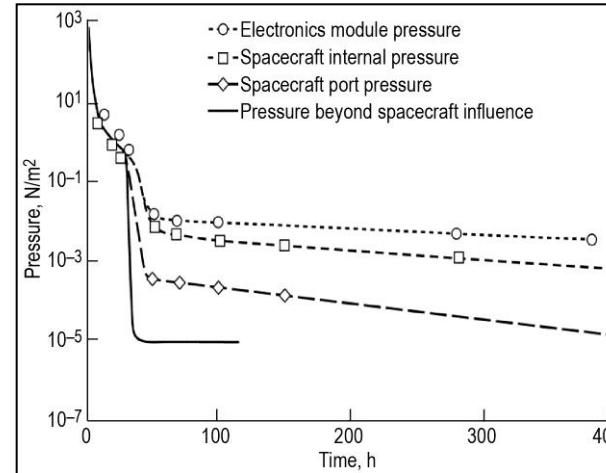
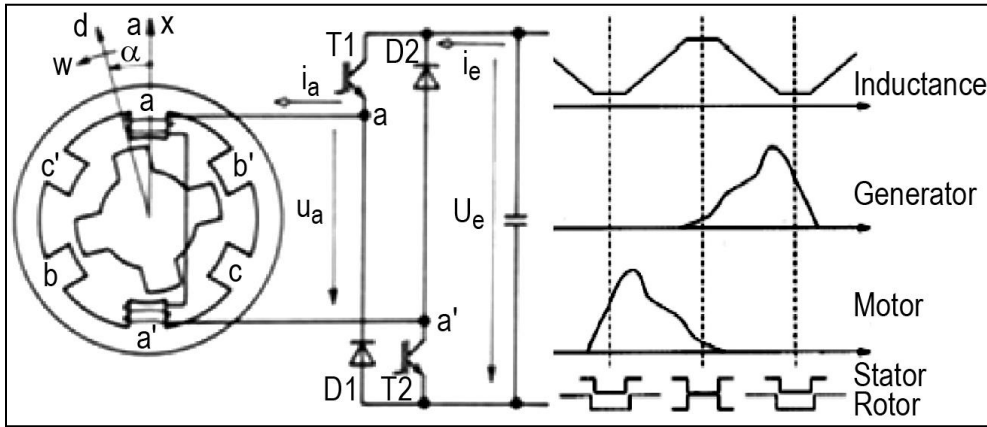


Table 1—Paschen's Law Breakdown Voltages at the Critical Pressure-Spacing Dimension for Select Gases at dc and 400 Hz

GAS	BREAKDOWN VOLTAGE	
	dc (V)	ac (V)
Air	327	230
Helium	189	132
Hydrogen	292	205
Nitrogen	265	187

Ref. NASA HNBK-4007

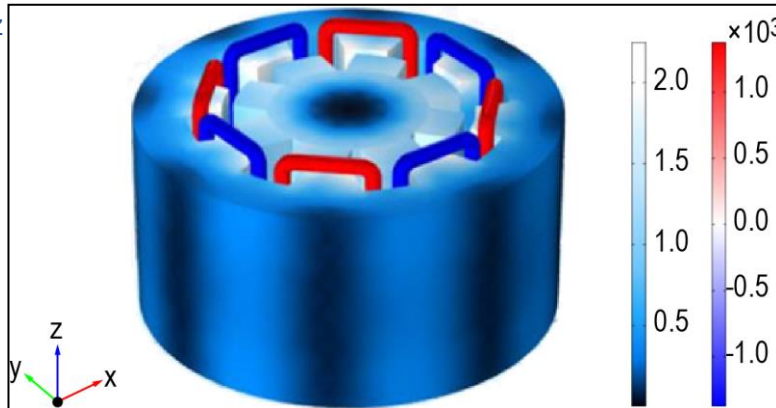
Generator Interface Matching



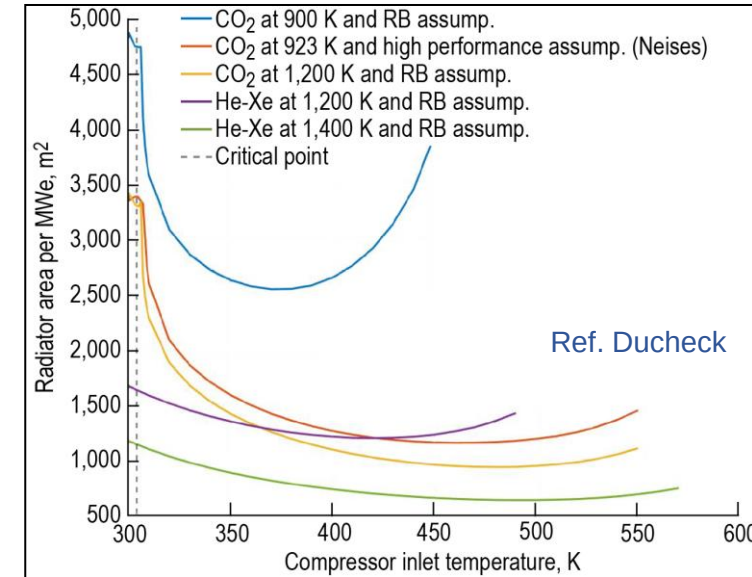
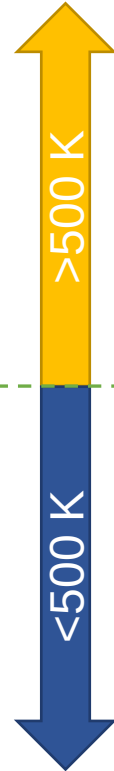
Ref. Torrey

Switched Reluctance Generator

Ref. Rodriguez



Permanent Magnet Generator



Component	Location	Limit (K)
Hysol	Coil Potting	503
Polyamide	Coil Insulation	513
Magnet	Rotor Shaft	523
Turbine-CO ₂	Rotor Shaft	923 ^a
Turbine-He/Xe	Rotor Shaft	1150 ^b
Turbine-He/Xe	Rotor Shaft	1350 ^c

^a Corrosion Limit (Ref. 15)

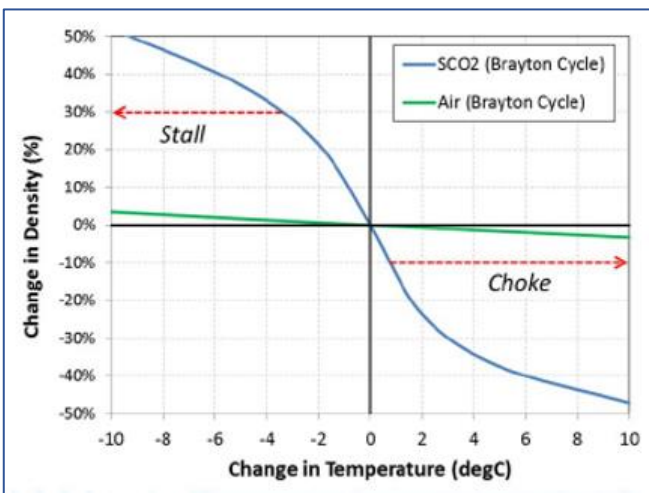
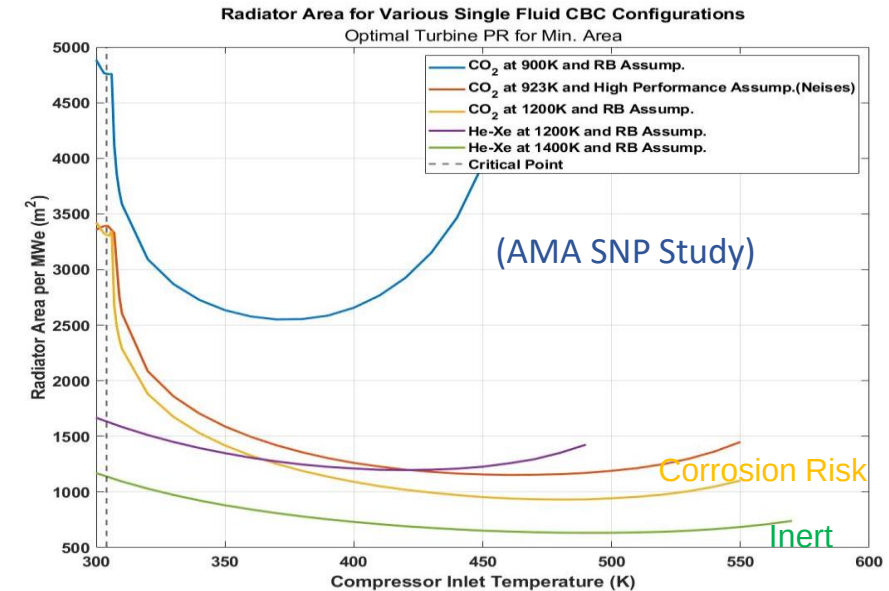
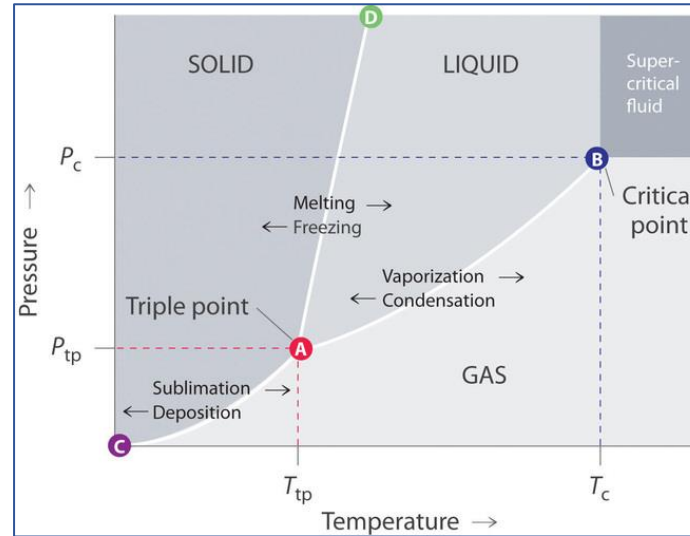
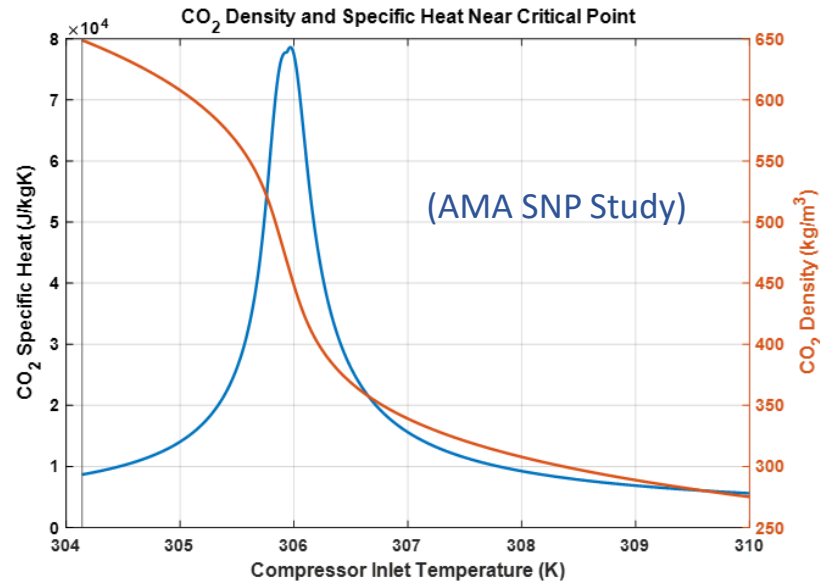
^b Superalloy Creepage Limit

^c Refractory Creepage Limit

Generator type selection depends on required operating temperature

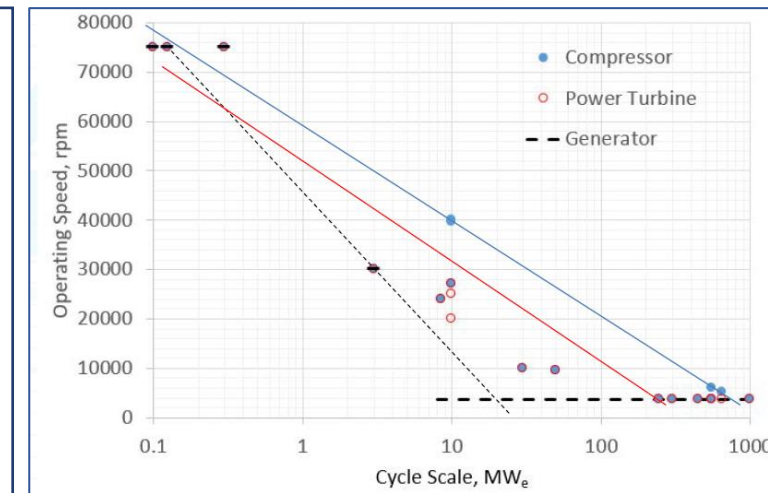
Supercritical Brayton Challenges

Brayton power convertor efficiency is optimized when the compressor fluid (e.g., CO₂) operates near the critical point...



... But it is challenging to achieve in a NEP System:

- Highly nonlinear fluid properties impact stall margins, recuperator pinch, and heat transfer
- High operating pressures impact material creep, seals, bearings and limit operating temperatures
- Potential for corrosion, fouling, and degradation
- Sensitivity of radiator size to low inlet temperature
- Higher shaft speed not compatible with generator



He-Xe vs s-CO₂ Summary

It is recommended that NASA focus near-term development on a TRL 5 He-Xe Brayton to reduce overall project risks

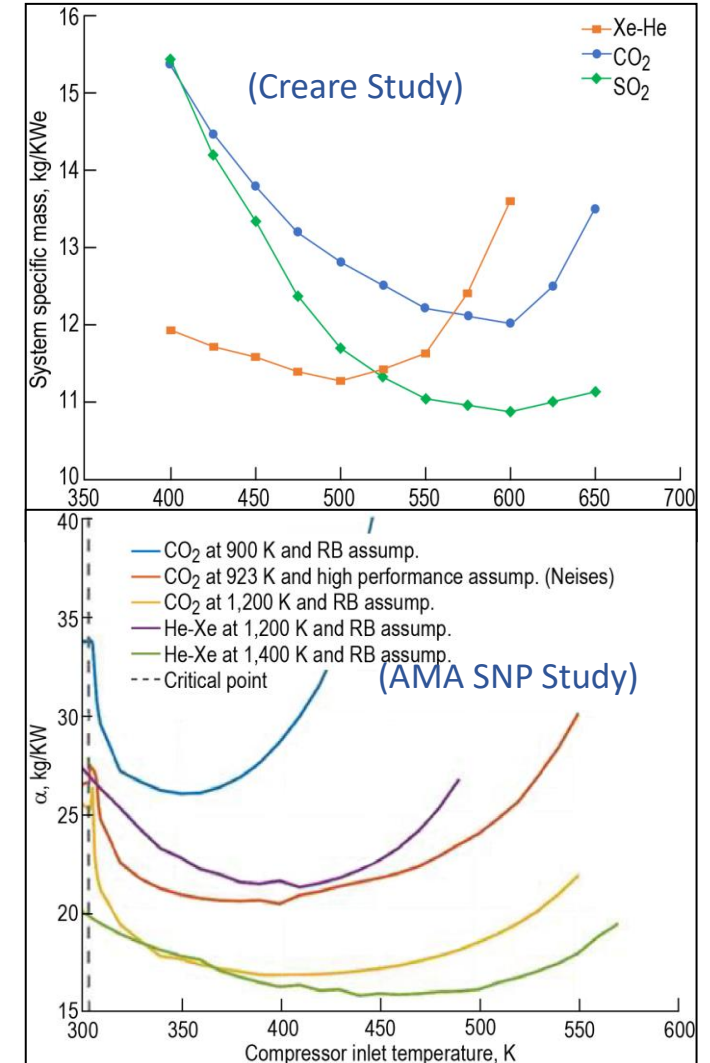
	He-Xe	s-CO ₂
Efficiency (%)	33	23
Rejection Temperature (K)	500	600
Heat Input/Output (MW)	6.2/4.2	9.1/7.1
Recuperator Power (MW)	2.5	8
Radiator Mass (kg)	7831	8316
Shaft Speed (krpm)	35	54
Corrosion	No	Potential
System Alpha (kg/kW _e)	11.3	12



Ref. English

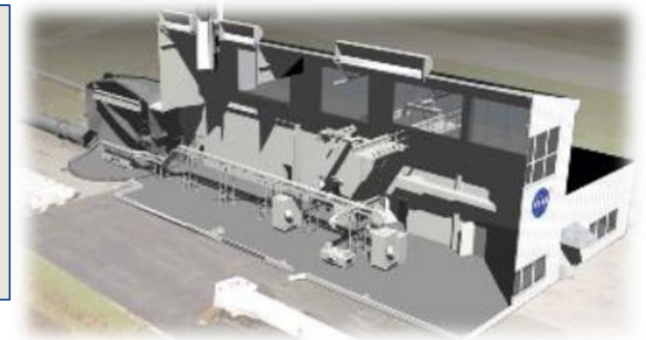
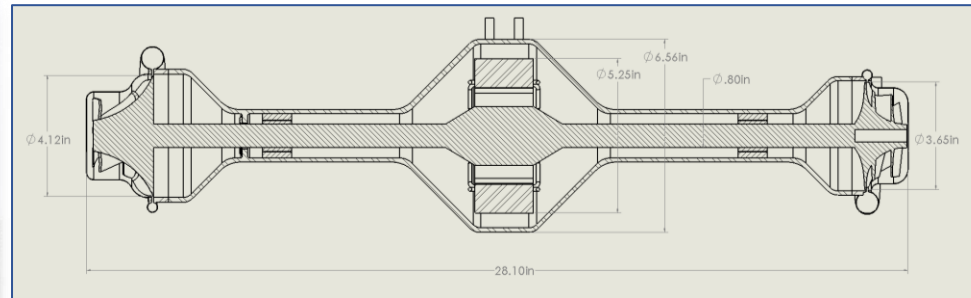
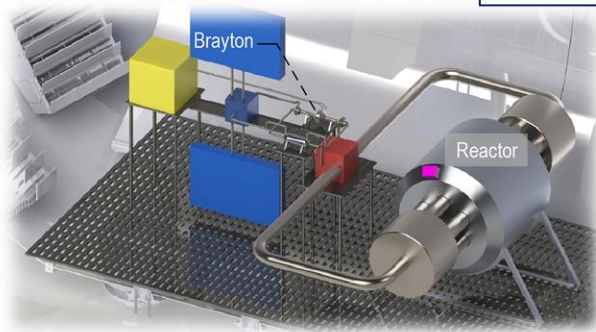
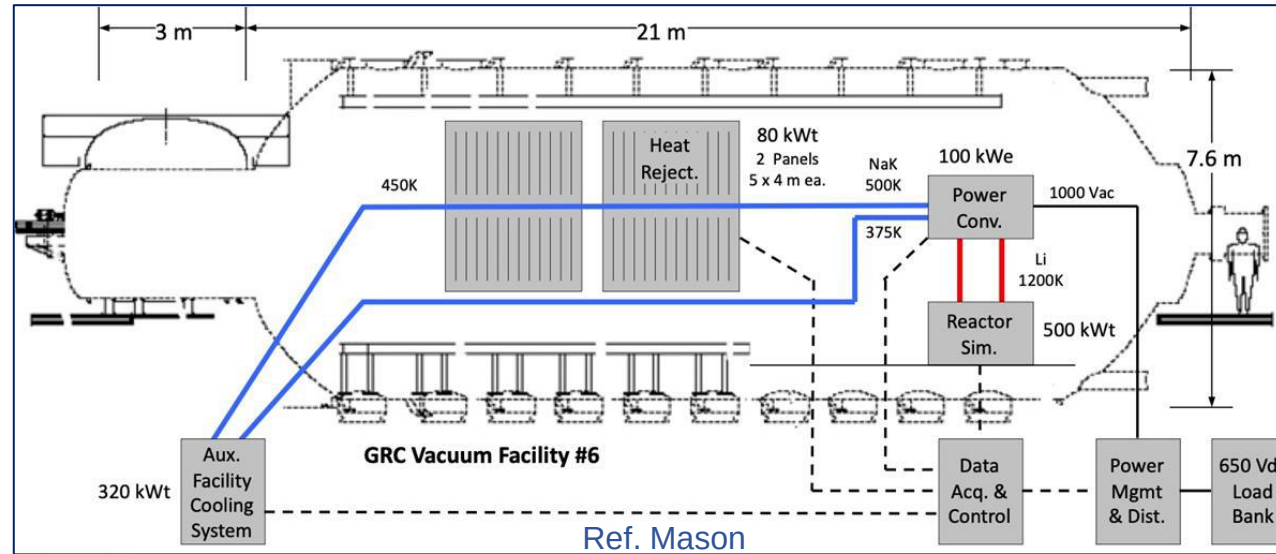
He-Xe working fluid reduces risk since it has:

1. a generally higher efficiency than s-CO₂ in a NEP system (when not at critical point)
2. a lower rejection temperature that increases the generator life and is compatible with light-weight Ti-H₂O radiators
3. less heat input/output resulting in a smaller recuperator and radiator
4. a lower rotor speed compatible with generator
5. no susceptibility to corrosion or fluid degradation
6. a lower operating pressure that reduces creepage, bearing loads, and seal leakage
7. no risk of neutronic interactions enabling a potential design option of a direct gas cooled reactor
8. demonstrated 38,000-hour TVAC operation at 10kW_e power level



Multiple independent studies indicate sufficient NEP system alpha margin is achieved with He-Xe Brayton.
Increasing the turbine inlet temperature with He-Xe fluid is a potential path to reduce overall system mass

TRL 5 Technology Demonstration



High power TVAC 2500-hour life testing options are available at sub-scale and full-scale

Conclusions

- **Supercritical SO₂** can provide the lowest specific mass but is at low maturity and likely corrosive
- **Supercritical Xe-He** is only slightly higher (3% greater than SO₂) and is at a higher maturity and inert
- **Supercritical CO₂** has the highest specific mass (11% greater than SO₂) and is corrosive above 923K

Working Fluid	Optimal Compressor Temp. (K)	Specific System Mass (kg/kW)	Risk
SO ₂	600	10.9	Corrosion
He-Xe	500	11.2	Minimal
CO ₂	600	12.3	Corrosion

Ref. Breedlove

A primary conclusion of this work is that a single-shaft Xe-He radial compressor/turbine closed Brayton power conversion unit with an embedded permanent magnet rotating alternator can be developed with the least technical risk to meet both the technology readiness schedule and the required system performance metrics.

However, it is acknowledged that there are no existing closed Brayton Xe-He industrial efforts aside from the small studies supported by NASA and this will require additional government investment to develop it to TRL 5.



Acknowledgments

- This work was supported by NASA's Space Technology Mission Directorate (STMD) through the Space Nuclear Propulsion (SNP) project. We also acknowledge Creare, Brayton Engines, Raytheon, Kurt Polzin, Marc Gibson, Max Chaiken, Wayne Wong, Scott Wilson, Sal Oriti, Max Yang and Paul Schmitz for their many helpful discussions and insights.

