



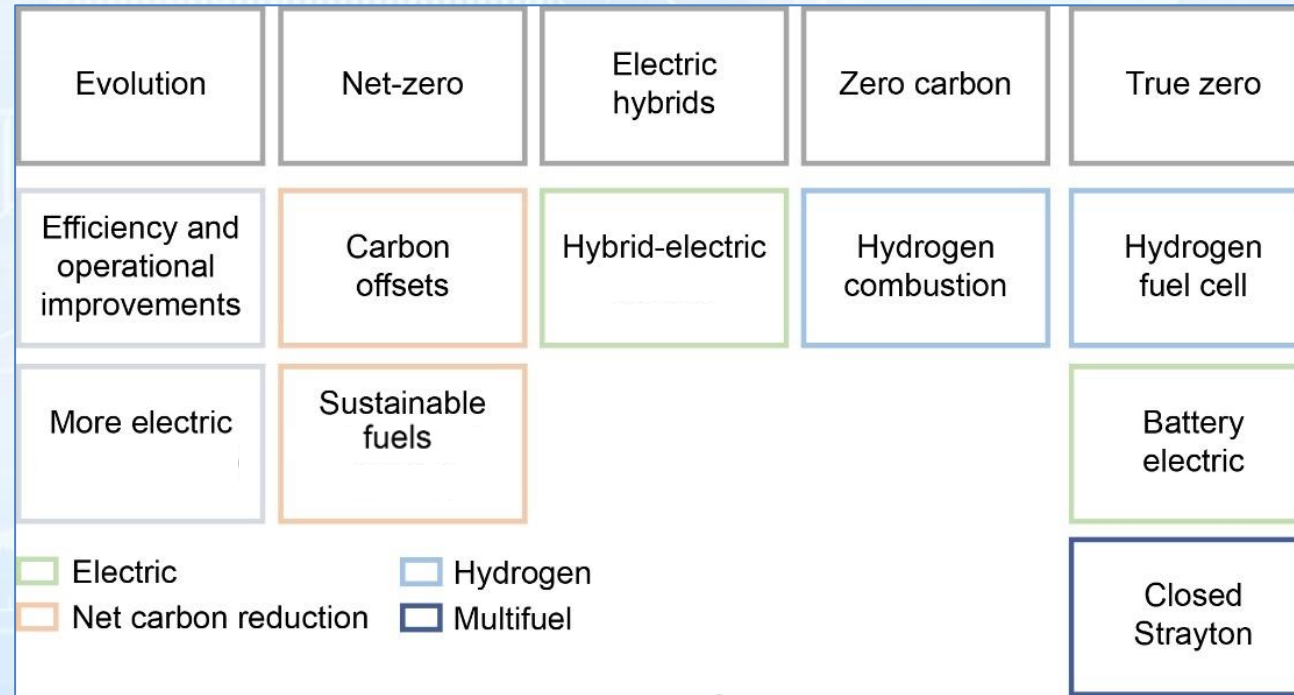
Zero-Emission Multi-Fuel Strayton Powered Off-Road Machinery

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3rd Design and Development of Zero-Emission Off-Highway Hybrid Summit
Innovatrix International, Chicago, Ill., Dec. 7-8



True Zero Greenhouse Gas Technology



Propulsion power sources	(Emission reduction) × Scalability × Specific power = Net impact					
	CO ₂	NO _x	Contrail	Scalability	Specific power	Net impact
H ₂ fuel cell						
H ₂ combustion						
Sustainable fuel						
Battery electric						
Hybrid electric						
		Good		Moderate		Limited

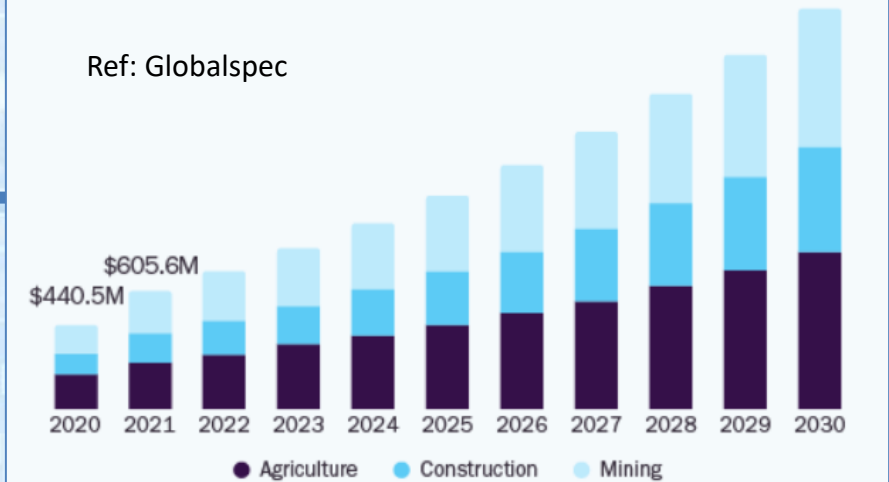


Electrification Path

- **Off-Highway Machinery Accounts for about 10% total U.S. Greenhouse Gas Emissions (5% globally)**
 - Diesel and Diesel electric are the two most used technologies due to their efficiency, reliability, compactness, and low cost. But they are difficult to manage emissions.
- The only true zero emission technologies are battery and low temperature fuel cells.
 - The battery option is only practical in very small vessels
 - The fuel cell option suffers from lack of tolerance to salt air, shock resistance, size, sulfur intolerance, limited life, and not multifuel.
- The next cleanest technology options include gas turbines, but they produce NOx even when used with hydrogen fuel.

North America Off-highway Electric Vehicle Market
size, by application, 2020 - 2030 (USD Million)

Ref: Globalspec



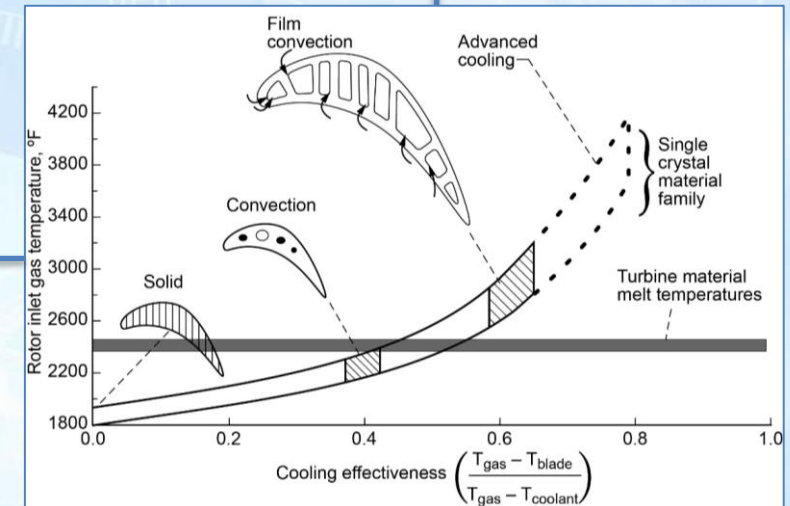
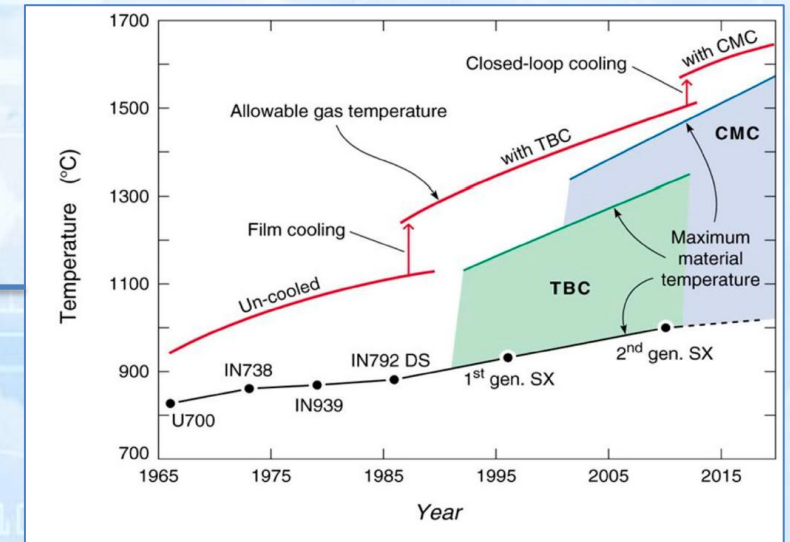
Technology	Power Level	Application
Battery	<125 kW	Compact Tractors
Diesel/Battery	125 kW-250 kW	Mid-size Machines
Strayton/Fuel Cell	>250 kW	Earthmovers

<https://www.powersystemsdesign.com/articles/bevs-have-a-weight-problem-that-cant-be-solved-with-traditional-approaches/22/20794>

Internal Combustion Turbine Challenges

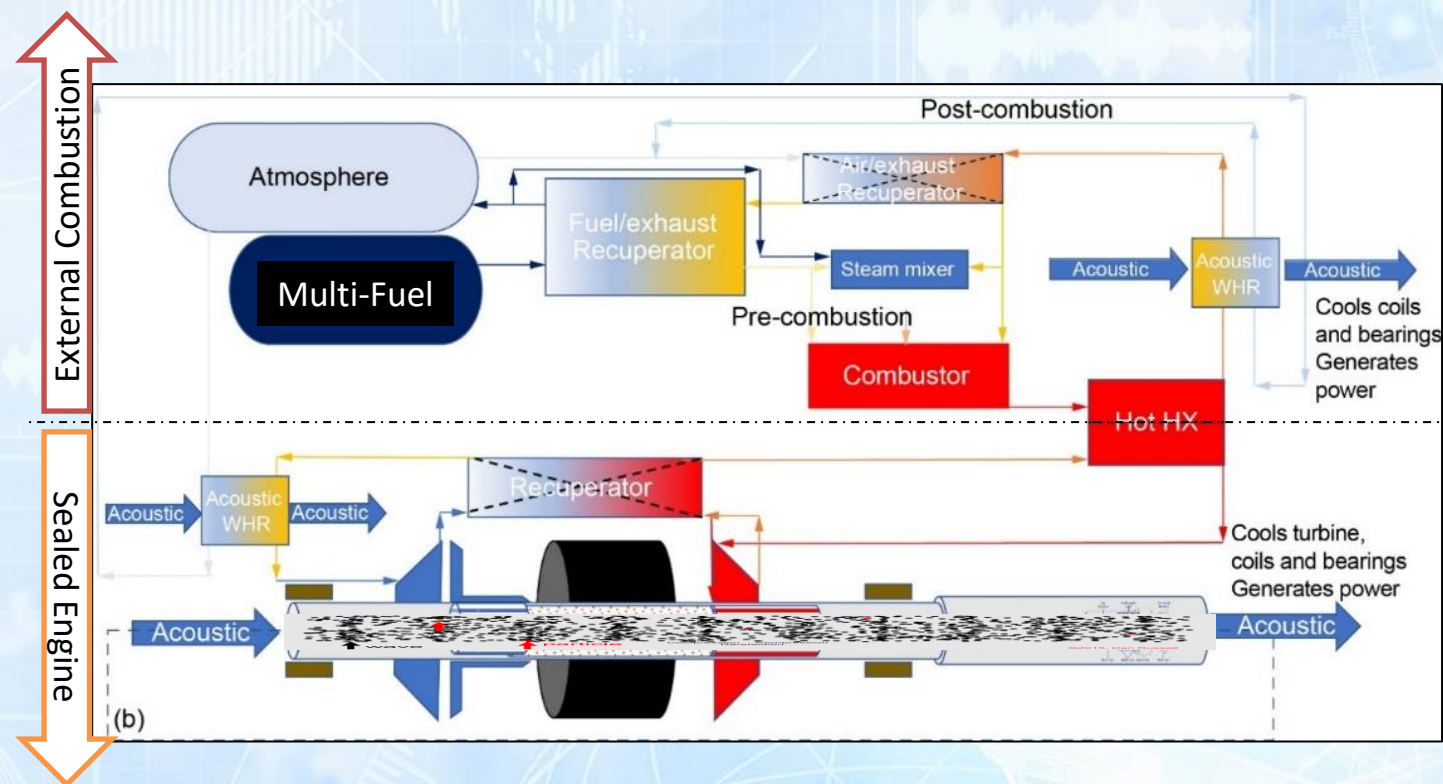


- Originally demonstrated in 1937
 - Gas turbine complimentary to other hydrogen-conversion technologies such as fuel cells: cost-efficient at large scale and can utilize lower-purity hydrogen, 43% eff. in open cycle, 63% combined
- H₂ combustion:
 - Wet Low Emission (add treated water or N₂) reduce flame temp.
 - Dry Low Emission (fuel lean conditions) difficult with 100% H₂, turbulent (flashback), still fuel-rich early combustion-Nox and melting
 - Quenching distance ½, Higher steam concentration, higher HTC
 - Combustor 1600C or higher, creep rupture, oxidation, cycle endurance, formability, and weldability
- Turbine impacts:
 - High temperature oxidation of materials exposed to H₂+steam
 - Larger temperature gradients that emerge across air-cooled components from smaller flame-wall quenching distance, higher flame temperature, high HTC
 - TBC need lower conductivities, fracture toughness from thermal stress, increased steam content impacts barrier coatings
 - Dual atmosphere effect (air + H₂)
 - Hydrogen embrittlement H-diffusion
 - AM control of microstructure in Ni-based
 - Turbine inlet, 1300-1600C, axial loading, thermal, vibrational, centrifugal stress. Tensile strength, creep, fatigue, oxidation, corrosion, Ni-based SA, elevated temperatures, stress, creep, tensile, and toughness.
 - Hot corrosion from Sulphur and alkali metal impurities, higher fuel/air ratio, lower impurity tolerance





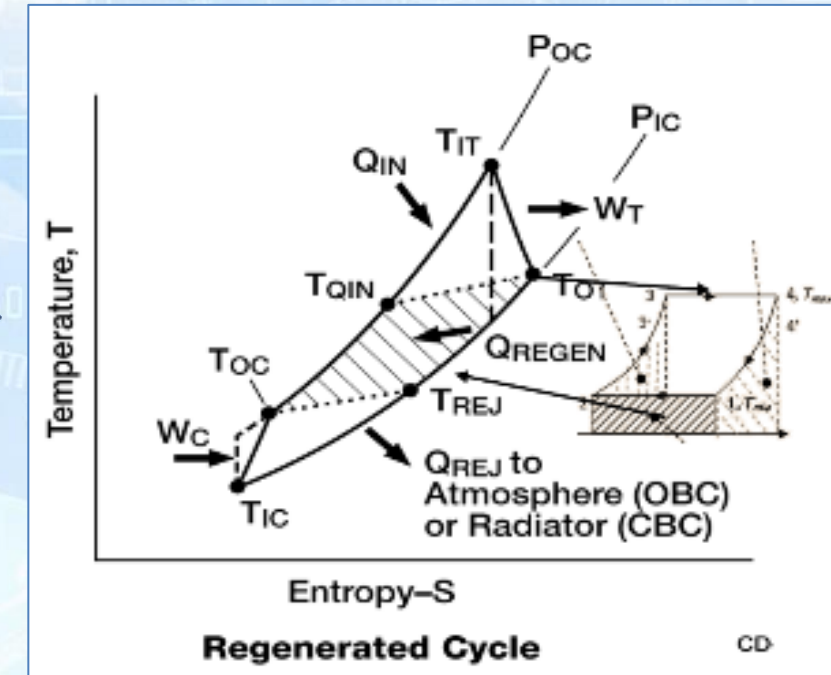
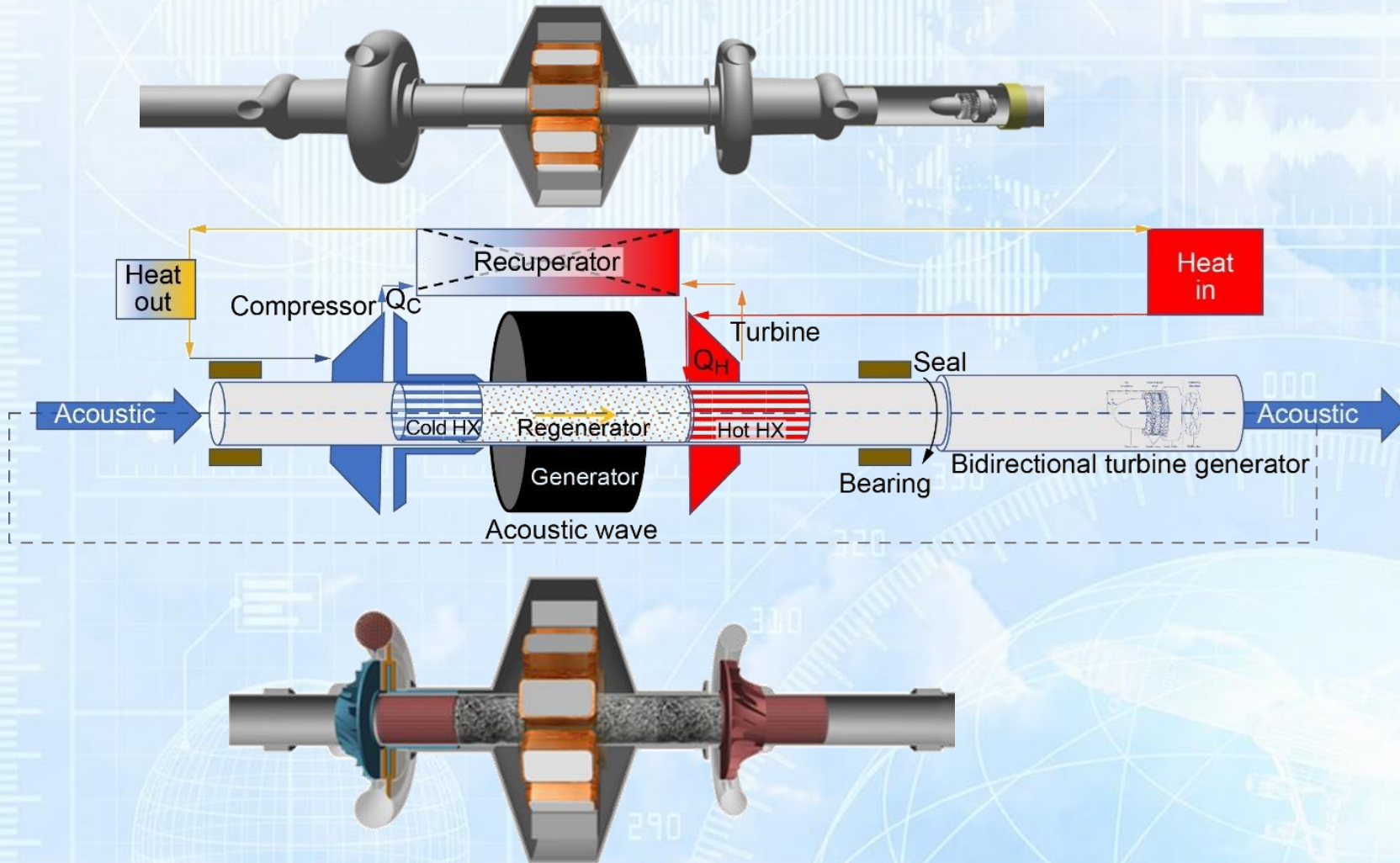
Closed Strayton Basic Concept



Combine Compact Closed Brayton with acoustic Stirling Turbine Cooling and External Multifuel Flameless Combustion

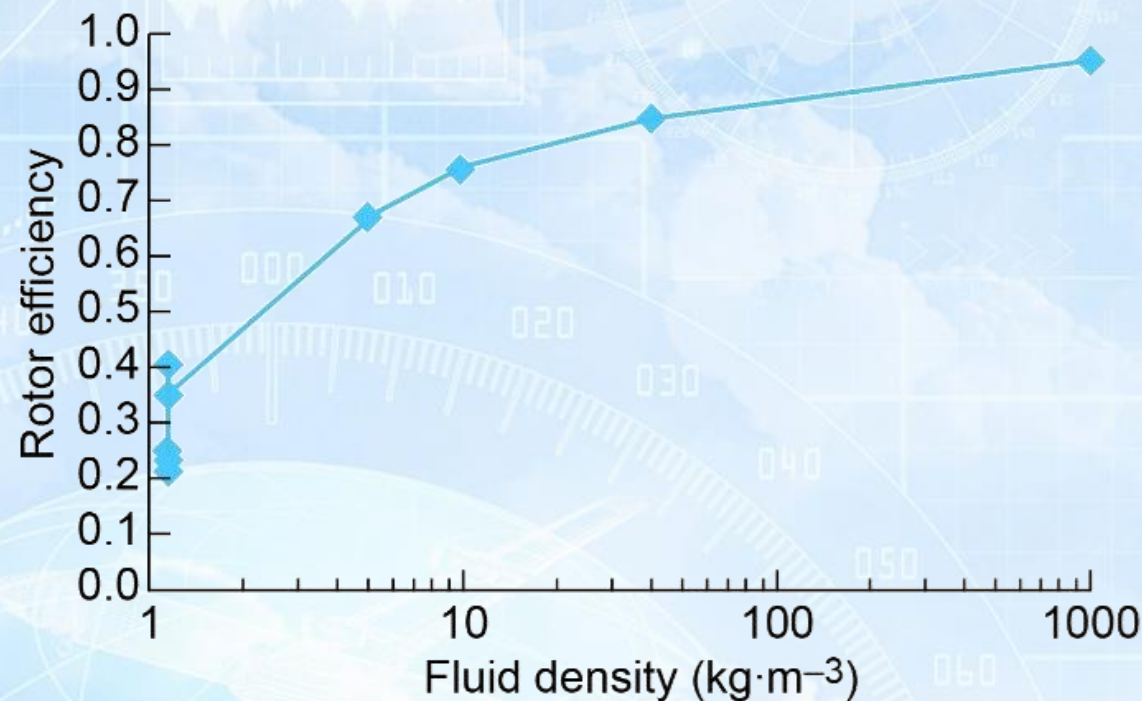
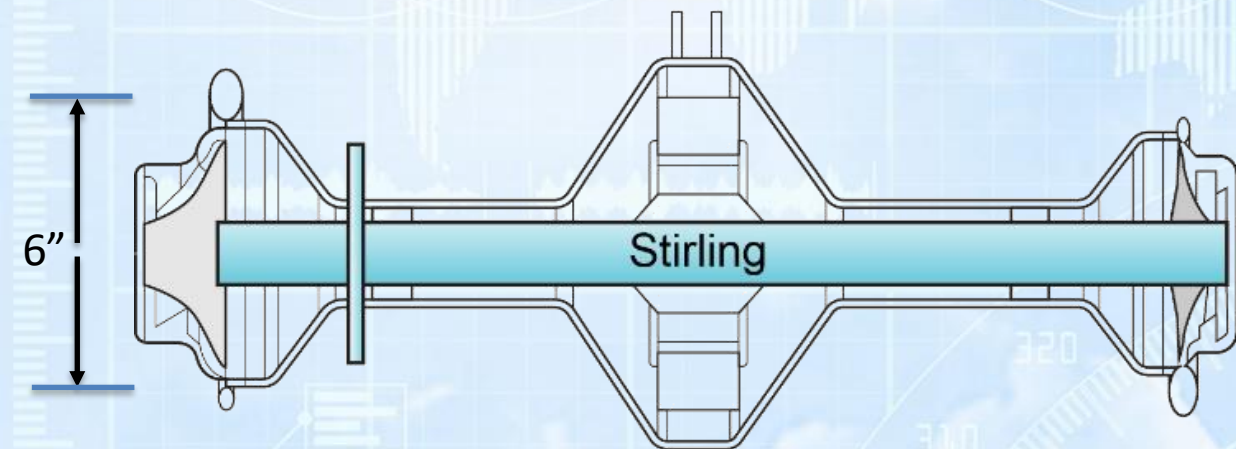


Strayton Fundamentals





Inert High Molecular Weight Pressurized Fluid Reduces Size and Increases Efficiency

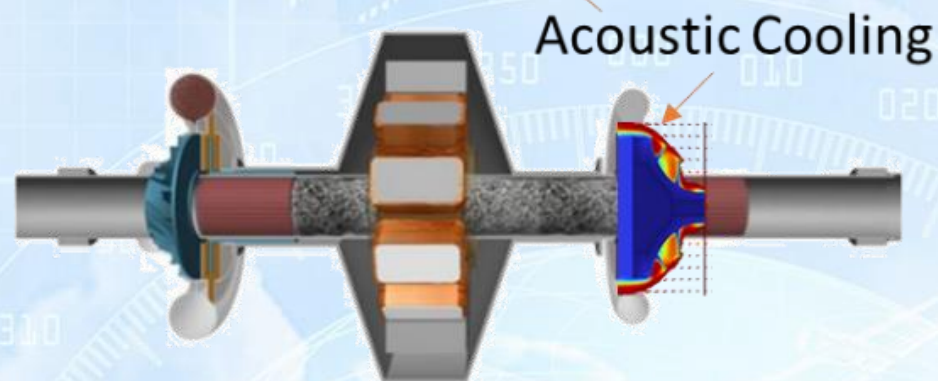
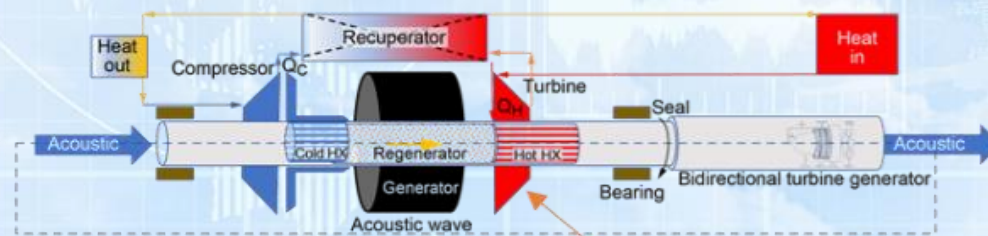
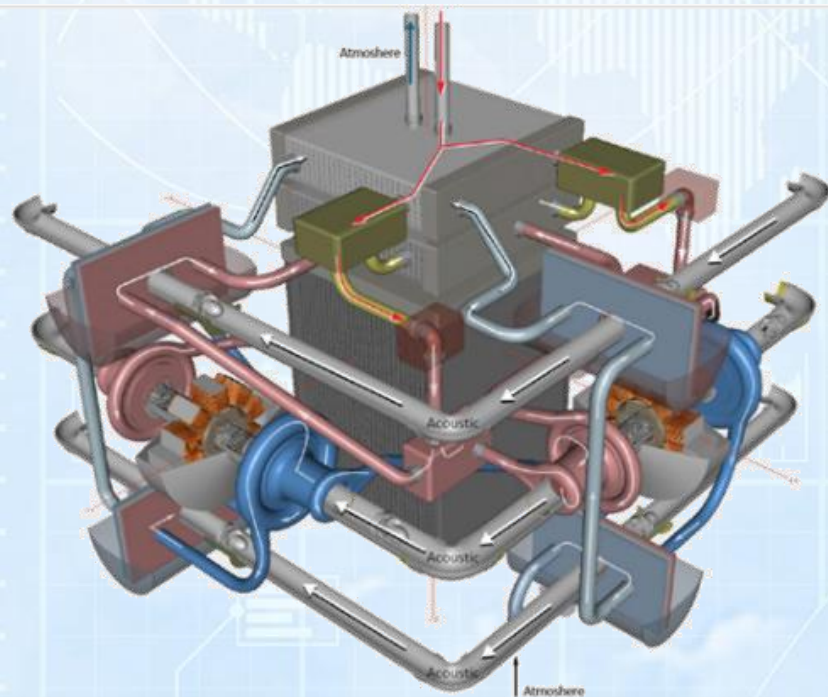


Brayton and Stirling cycles share same working fluid

Bi-directional Turbine Efficiency



How it works

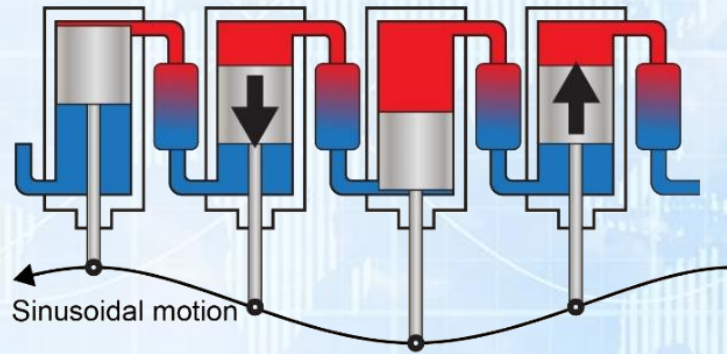


[Flameless Combustion Video](#)

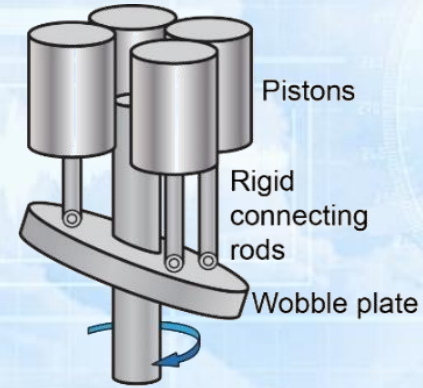
[Multi-Fuel Closed Strayton Quad Generator Video](#)



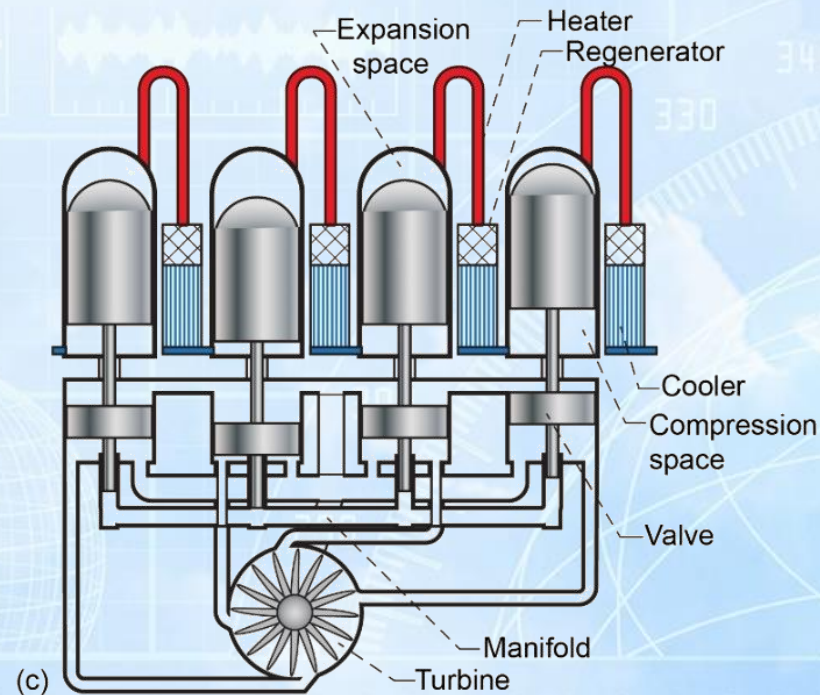
Multistage Stirling Engines



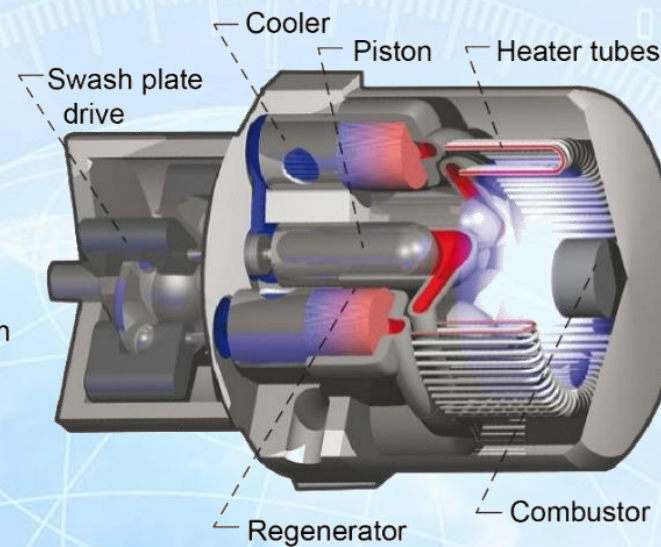
(a) Double-acting Stirling engine



(b) Swash plate drive



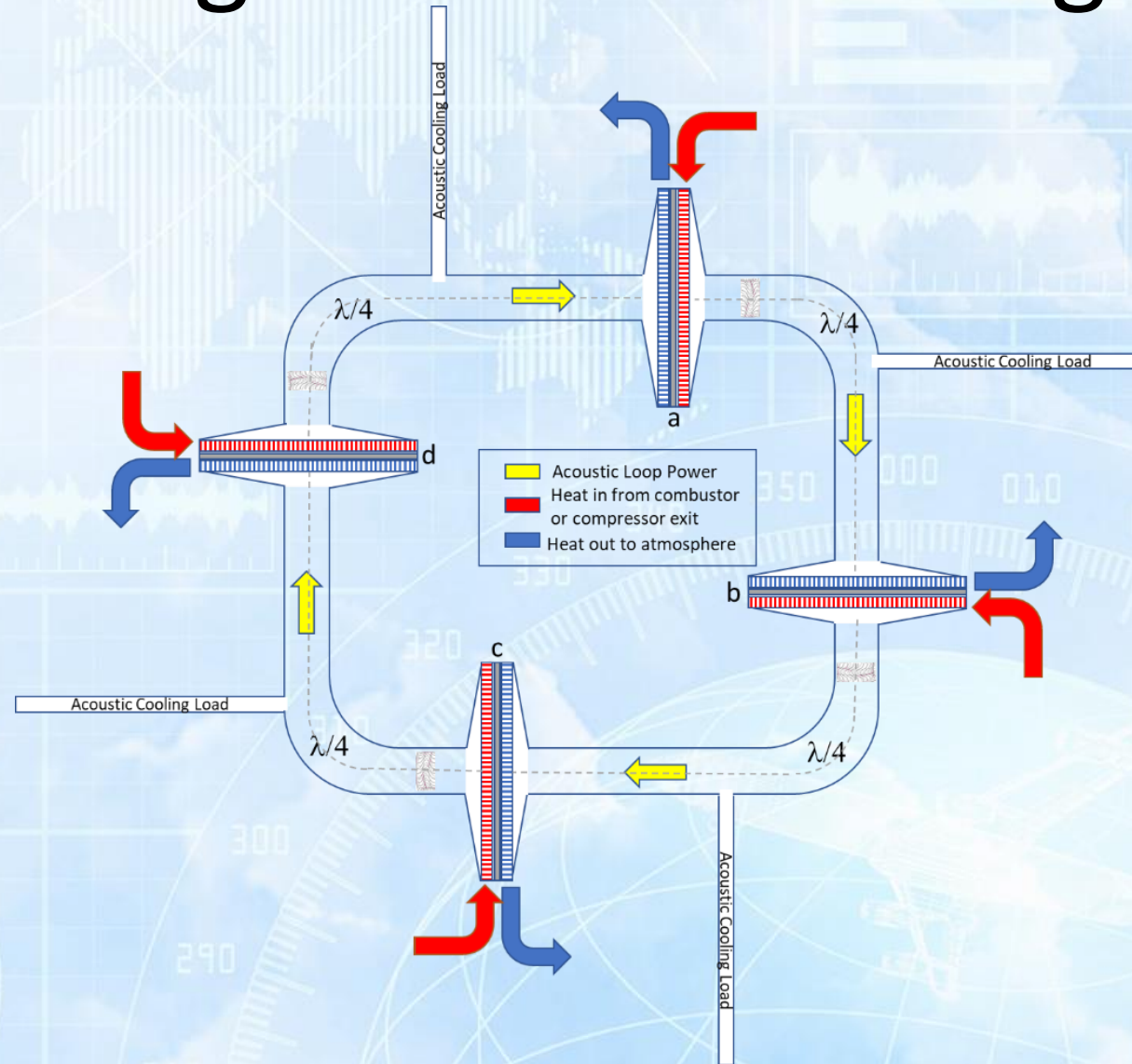
(c)



(d)

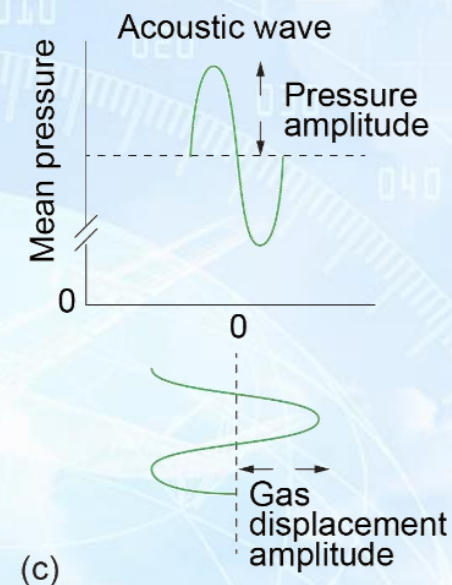
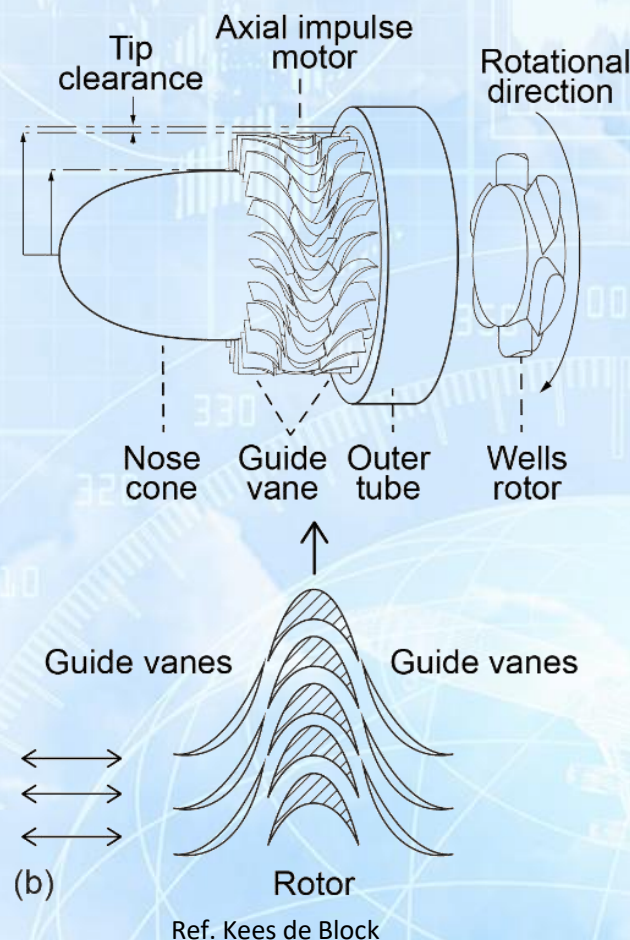
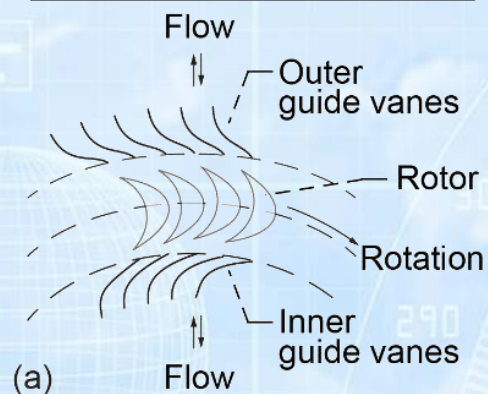
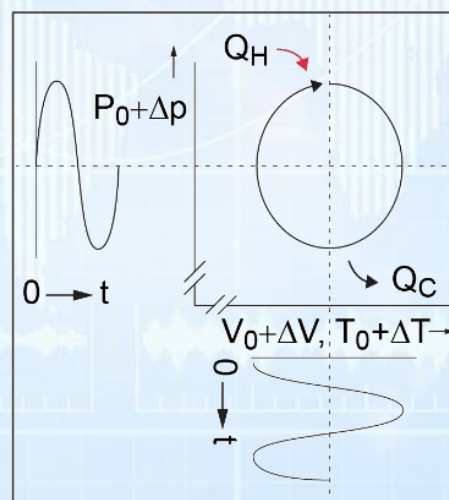


Multistage Acoustic Stirling Engines



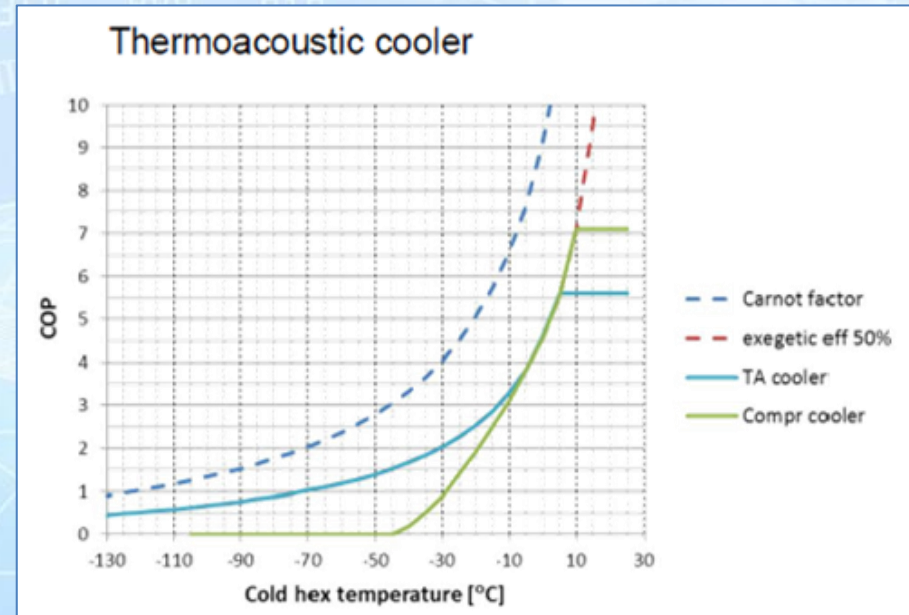
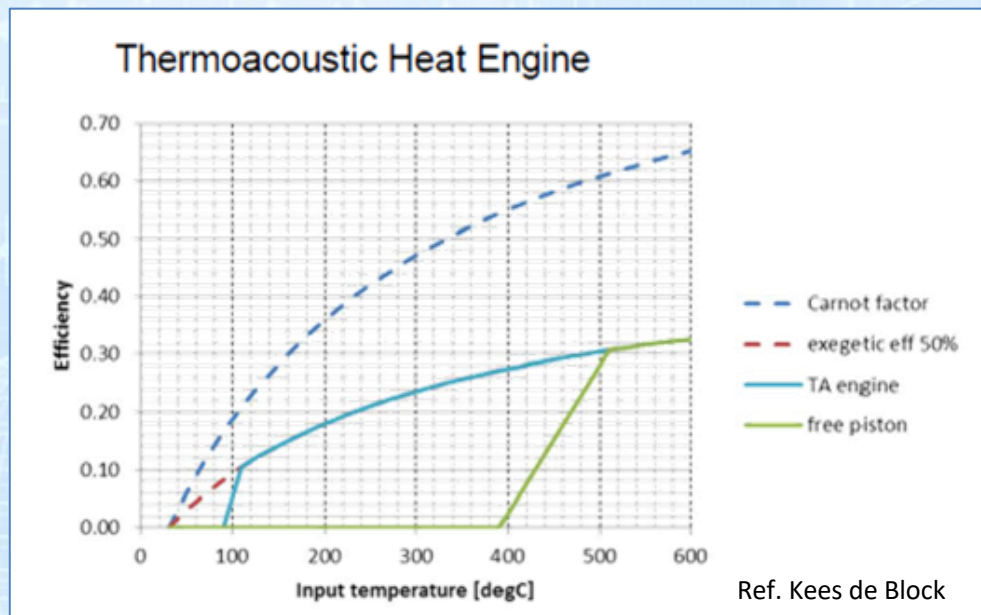
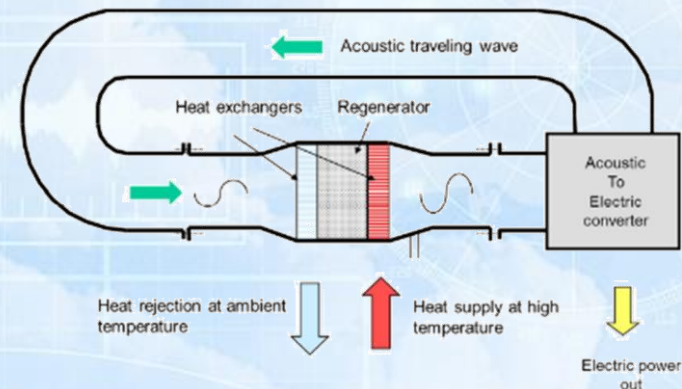


Bi-directional Turbine Oscillating Velocity Wave Power Extraction



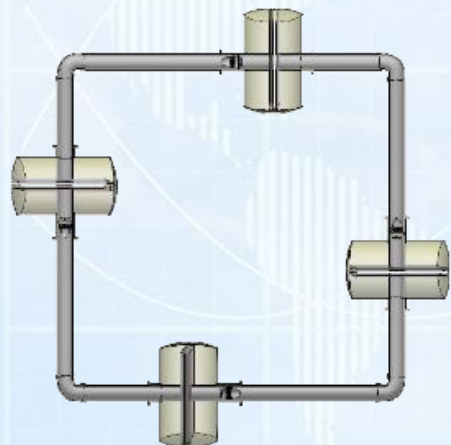


Acoustic Stirling Fundamentals

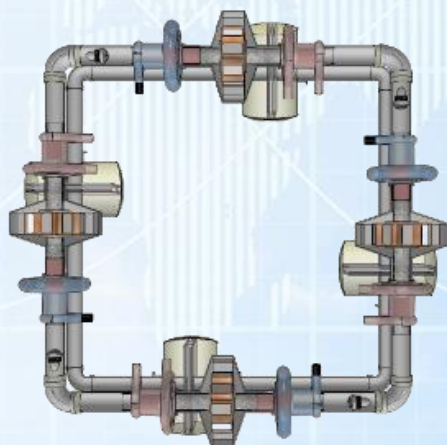




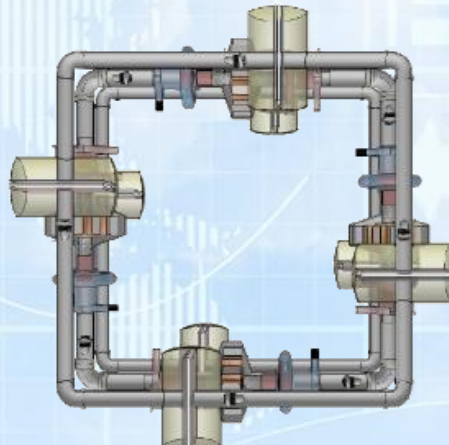
Three Quad Layers



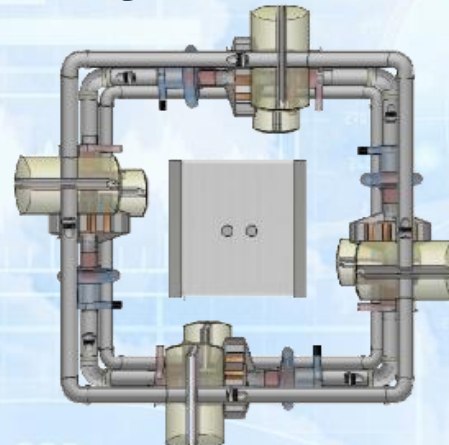
Acoustic interstage cooling quad



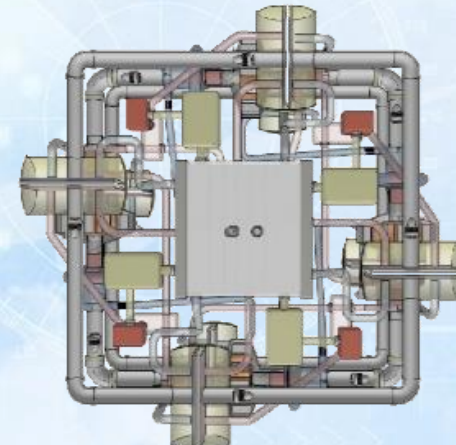
Closed Strayton quad



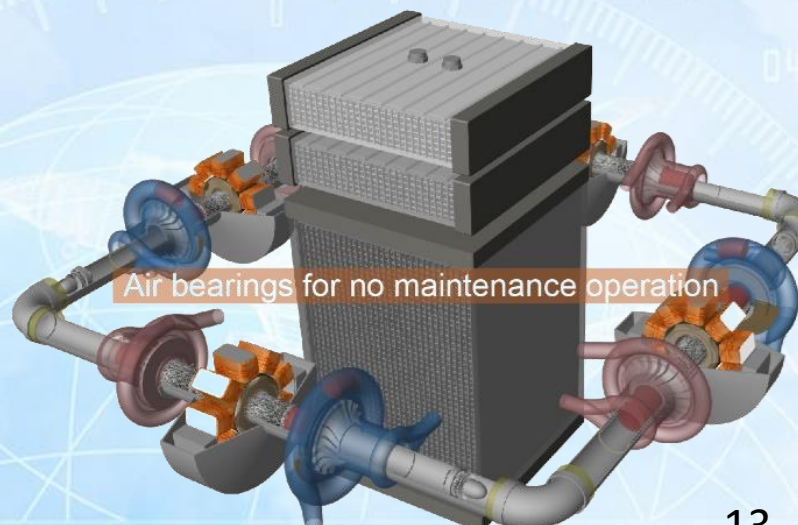
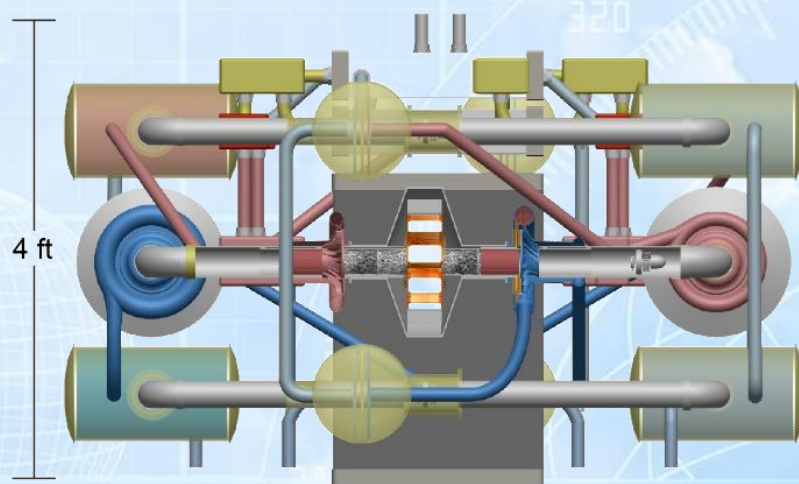
Acoustic interstage heating quad



Central recuperator

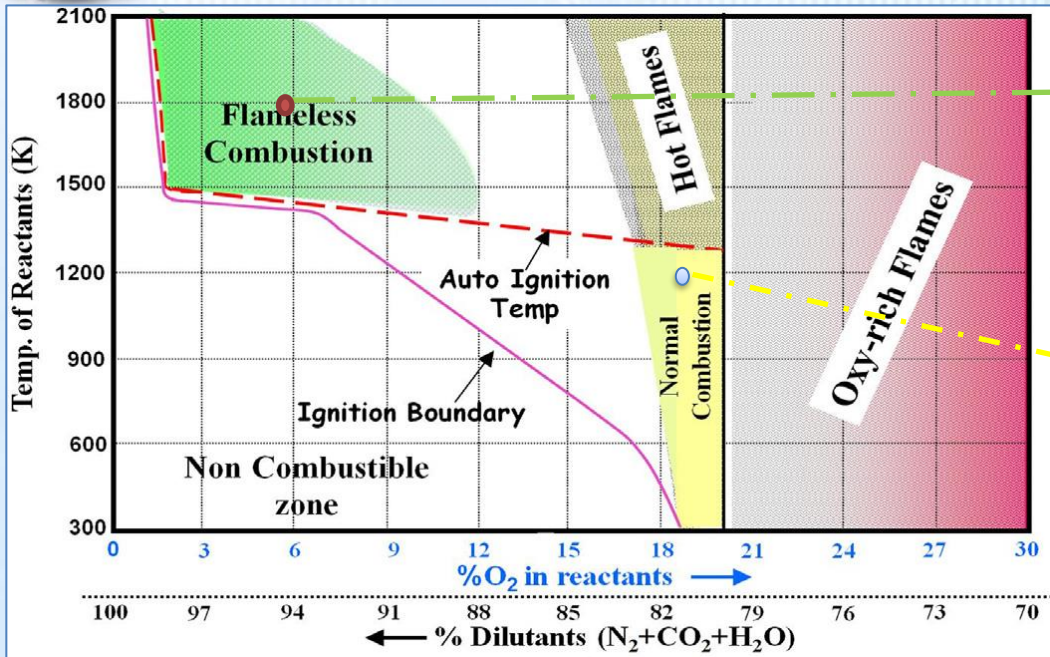


Connected system





Multifuel Flameless Combustion Enabled



Multi-Fuel

Single-Fuel

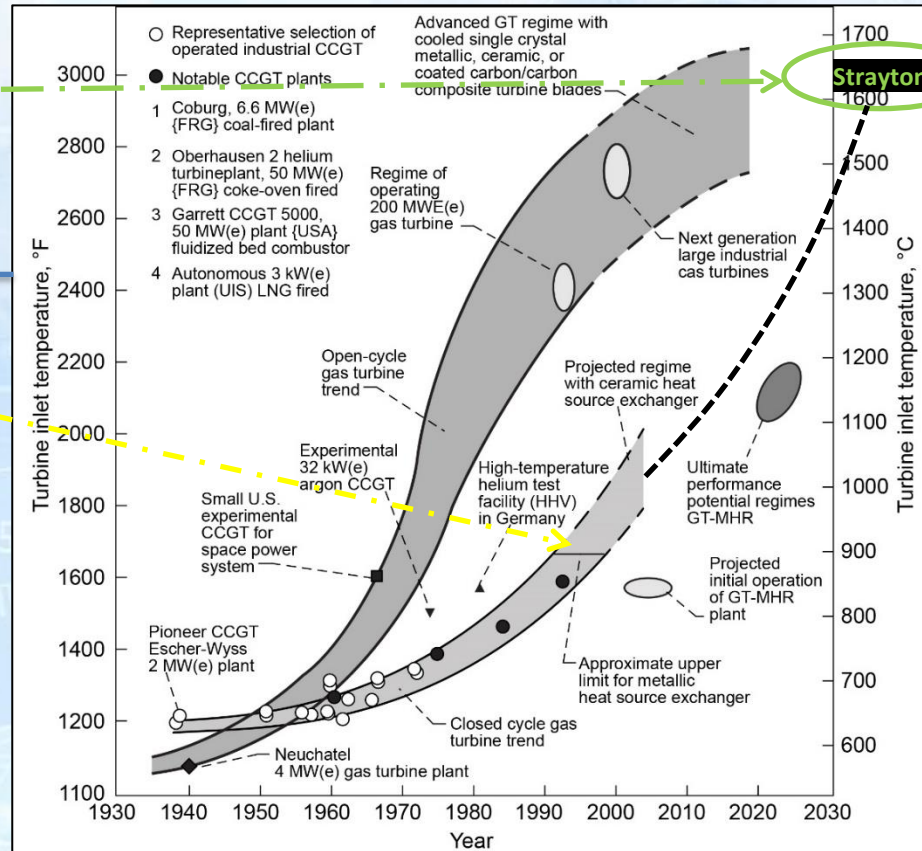
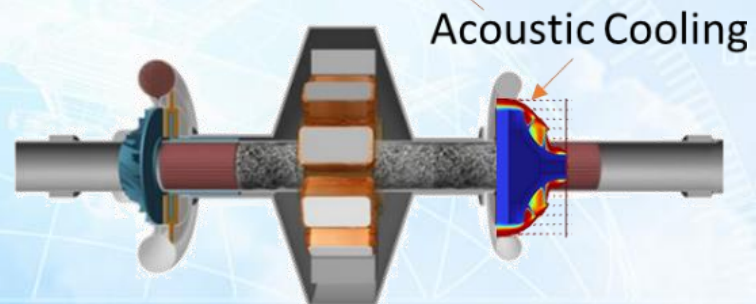


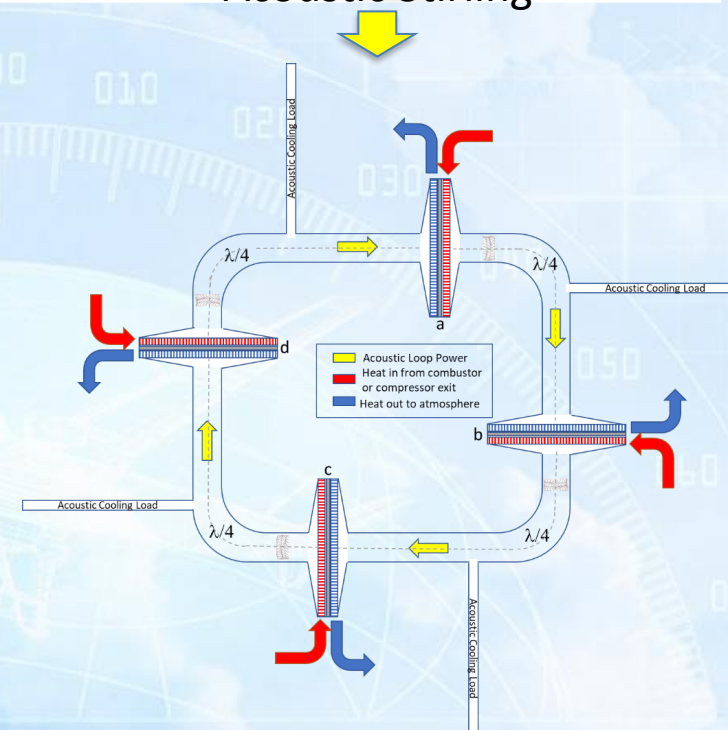
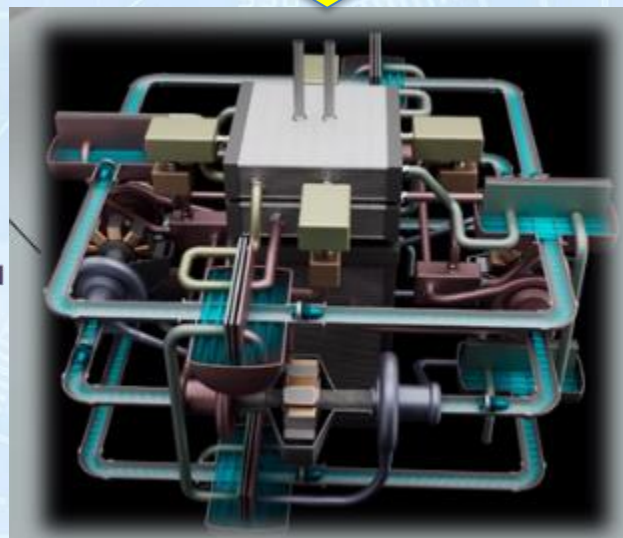
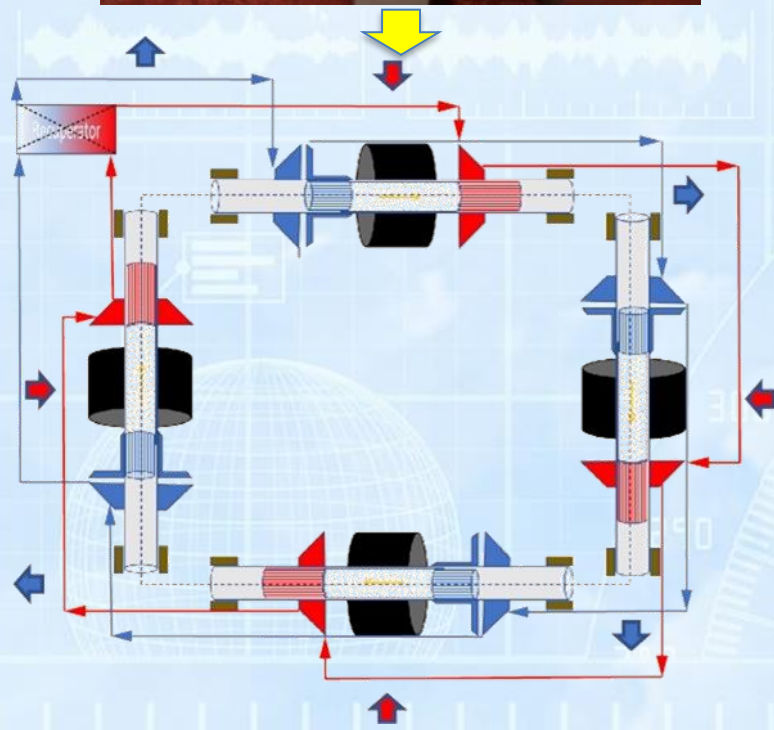
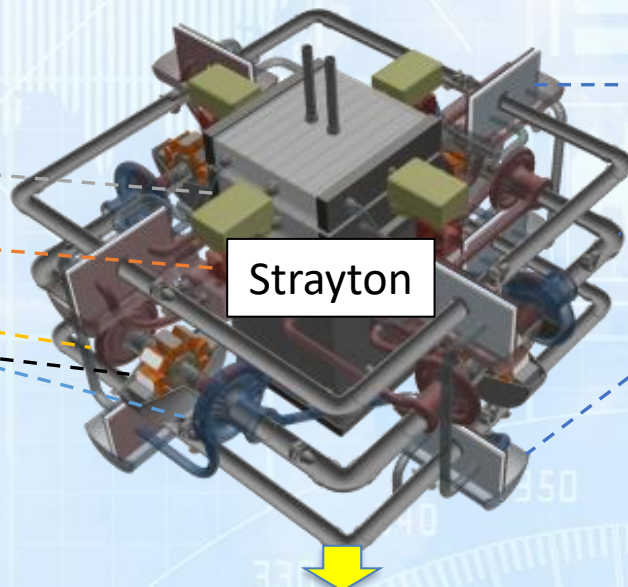
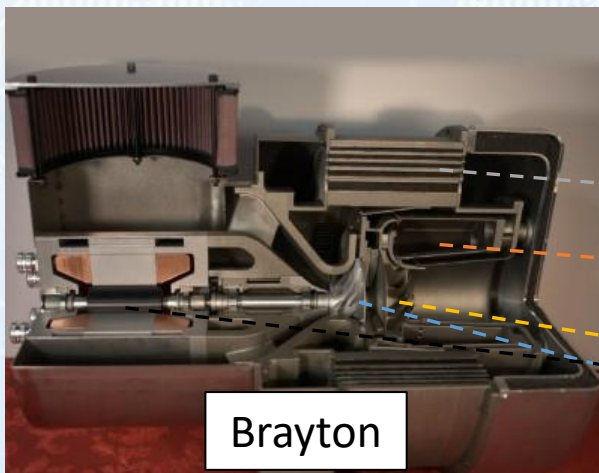
Table 1
Qualitative comparison of different combustor types.

	Combustor type			
	Lean premixed	Lean direct injection	RQL	Flameless-based
Combustion efficiency	High	High	High	High
Combustion instability	High	Low	Low	Low
Fuel flexibility	Moderate	High	High	Moderate
Integration into engine	Moderate	Moderate	Easy	Difficult
Mechanical complexity	Moderate	High	Moderate	Moderate
NOx emission	Low	Low	Moderate	Ultra-low
Operating range	Moderate	High	High	Low
Soot emission	Very Low	Low	Moderate	Low
Volume requirement	Moderate	Low	Low	High





Compact Closed Quad Configuration

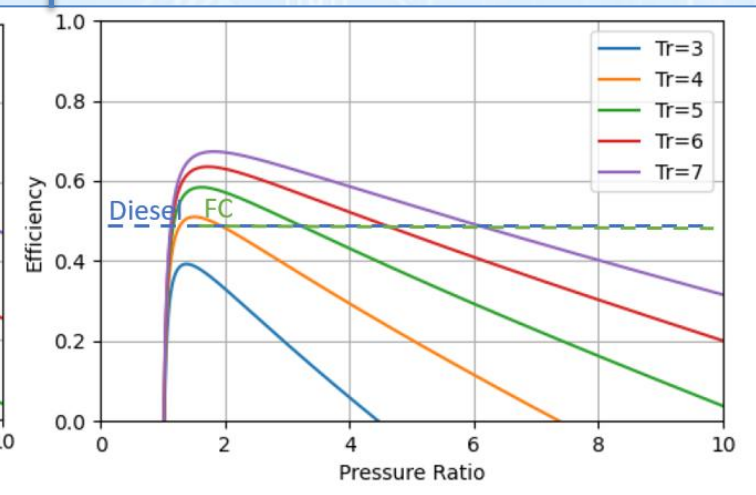
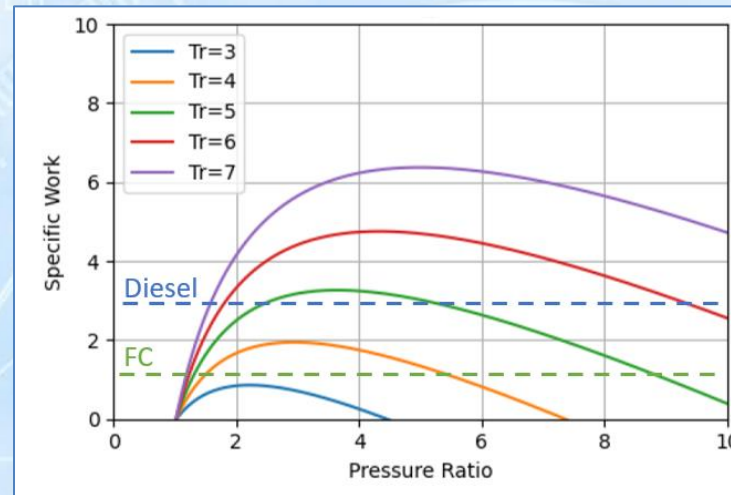




Off-Highway Vehicle Power Benefits

- Multifuel Flameless External Combustion
- Low or Zero GHG Emissions
- Quiet
- No Maintenance Long-Life
- Very High Efficiency
- Very Compact
- Modular and Scalable 0.5 MW to 50 MW
- Sealed from brackish environment
- Synergy with other markets

Criterion	MCFC	PEM	Diesel	Gas Turbine	Stirling	CSQG
Efficiency over a wide range of loads	Flat	Flat	Best at >75% load, poor at partial load	Best at >80% load, very poor at partial load	Best at >40%, reasonable at part load	Flat
Response to load changes	Slow at startup	Fuel/reformer dominated	Good	Fast	Fast	Very Fast
Life	1,000 hrs	10,000 hrs	20+ years	20+ years	30+ years	30+ years
Noise, vibration	Low	Low	High	Medium	Low	Low
Power range	500-2500 kW, modular	20-2500 kW, modular	Up to 68 MW	Up to 50 MW	Up to 25kW, modular	Up to 10MW, modular
NOx, CO, HC emissions, CO2	Very low, reduced CO2	Very low, reduced CO2	Medium	Medium, no CO2 benefit	Very low or zero	Very low or zero

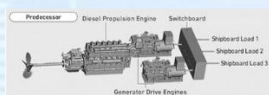




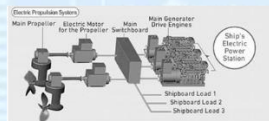
Marine and Aircraft ePropulsion Synergy

Current Maritime Propulsion

- Not Scalable- ICE, Diesel, and/or Turbine required
- **Internal Combustion**
- Single-Fuel
- Maintenance
- Noise
- GHG Emissions
- <50% Efficient

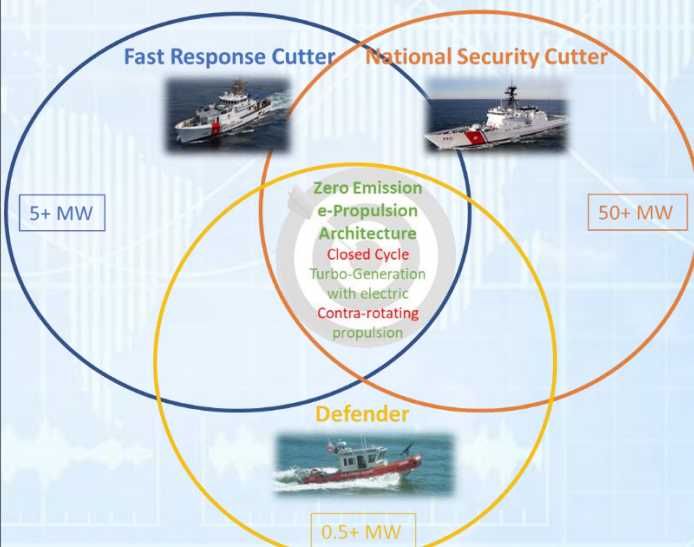


Open Cycle Diesel



Open Cycle Diesel and Gas Electric

Zero Emission Energy-Efficient Maritime e-Propulsion



Proposed Maritime Electric Propulsion

- Scalable 0.1-100 MW
- **External Combustion**
- Modular supports fossil fuel and alternative energy
- Sealed from brackish air
- Silent with energy storage
- Low and Zero Emissions
- >50% Efficient



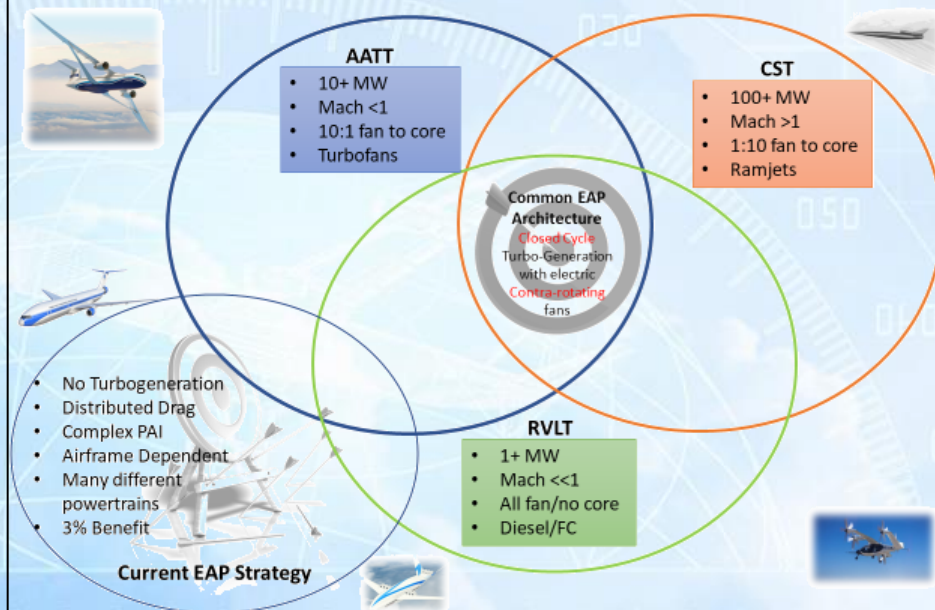
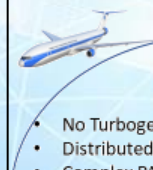
Scalable Closed Cycle Turbogeneration



Scalable Contra-rotating Propulsor

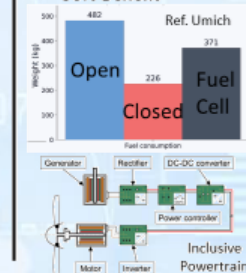


Aligning our EAP Strategy for Maximum Impact Across Vehicle Classes



Common EAP Architecture Benefits

- Scalable 1-100 MW
- High thrust/drag
- Airframe Neutral
 - TTBW Compatible
- Supports Multi-Fuels
 - ZEROe Capable
- Single Simple Inclusive Architecture
- Asymmetric Engagement with Airbus FC and H2 TF
- >30% Benefit





Summary and Conclusions

1. **Multifuel**
 - MFC enables the use of any fuel which is key to transitioning from fossil fuel to new fuel sources
2. **Emissions**
 - External combustion and MFC significantly reduces emissions even with fossil fuels and enables zero GHG emission with hydrogen
3. **Quiet**
 - MFC and Closed cycle reduce noise significantly
4. **Efficiency**
 - MFC is high temperature leading to 70% efficient systems with closed cycles that have acoustic turbine cooling
5. **Compact**
 - Sealed high-speed gas bearing systems provide MW-scale with 6" diameter turbines
6. **Low cost**
 - Does not require rare earth or exotic materials
7. **Low maintenance**
 - Sealed system uses gas bearings instead of oil lubrication
8. **Lifetime**
 - Never have combustion gases inside the engine and it doesn't degrade like a chemically reacting fuel cell or battery
9. **Scalable 1 MW to 100 MW**
 - Modular compact solution 4' X 4' X 4' cube supports **10 MW** and can be stacked

Technology can be exclusively licensed for specific markets from NASA.

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