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Decarbonization of Transport: Synergies between Hydrogen and Alternative Engine Concepts

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With grateful acknowledgement to:
Dr Giovanni Vorraro, Matthew Turner, and Adamos Adamou (University of Bath)
Professor Peter Edwards (University of Oxford)
Robert Head (Saudi Aramco)
Nick Carpenter (Delta Motorsport)

West of England LOCAL ENTERPRISE PARTNERSHIP | HM Government | Research England

Automotive Propulsion Research at Bath

- One of the largest engine/hybrid powertrain research groups in the UK
  - *~ 70 staff, including four professors and 12 academics*
- > 40 year track record of successful partnership with industry
- IC Engine Systems Efficiency Spoke of the APC
  - *A government / industry partnership in the UK*

ADVANCED PROPULSION CENTRE UK

- Current facilities include five engine test cells, 4WD chassis dyno, turbocharger gas stand, engine and vehicle workshops…
- Capability in:
  - *Laboratory-based testing and simulation of powertrain systems*
    - Engines, hybrids, boosting systems, and transmissions
  - *On-road emissions measurement (PEMS)*
  - *Driver behaviour and psychology (linked to consumption and emissions)*
- New facility being built to increase capability and capacity – the ***IAAPS laboratory***

University of Bath: The IAAPS Laboratory

- **The Institute for Advanced Automotive Propulsion Systems** will be a world-leading centre of excellence for research, innovation, enterprise, and education supporting the automotive industry
- £70 mio. capital investment:
  - University of Bath ~£30 mio.
  - Research England ~£29 mio.
  - West of England Local Enterprise Partnership ~£10 mio.
- Delivering 11,300 m^2 of collaborative space and research test cells
  - First test cells operational Q1 2021

Some of Our Project Partners

ADVANCED PROPULSION CENTRE UK

AVL

RICARDO

JAGUAR LAND ROVER

Ford

Shell

TATA

CURTIS

GE PRECISION ENGINEERING

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LOTUS ENGINEERING

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DRIVE SYSTEM DESIGN

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BorgWarner Turbo Systems

CRF CENTRO RICERCHE FIAT

HiETA technologies

Advanced Design Technology

Continental

JM Johnson Matthey

KISTLER measure. analyze. innovate.

CNH

MAHLE Powertrain

SIERRA CP ENGINEERING

TOROTRAK Driving Change

ORBITAL TRACTION

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MIRA A HORIBA COMPANY

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Garrett by Honeywell

AshWoods THE HYBRID PEOPLE

CAMBUSTION

ADVANCED PROPULSION CENTRE UK

EPSRC Engineering and Physical Sciences Research Council

Innovate UK

aeristech

CATERPILLAR

lightfoot Rewarding better drivers

أرامكو السعودية saudi aramco

mazda

INTRODUCTORY THOUGHTS

Decarbonization of (Heavy-Duty) Transport

- The complete decarbonization of transport requires a portfolio approach
- There is no single solution to replace **transport's historical silver bullet** of **the internal combustion engine operating on fossil fuels**
- The heavy duty sector is one which will likely need to adopt hydrogen as an energy carrier
  - *Because the energy storage and recharge time requirements for HD vehicles preclude the use of batteries*
- Here it would be pragmatic to start with hydrogen engines (H_2 ICEs)
  - *In order to limit vehicle costs during a deployment ramp-up phase…*
  - *…While providing a draw for fuel infrastructure investment*
- Since the ICE will therefore pull the infrastructure forward, fuel cells can be adopted at a later date
- To an extent this approach **decouples the prime mover problem from the infrastructure one**

HYDROGEN

"Hydrogen is a great fuel for the future… and it always will be."

Is this really the case?

Is its time about to come for some applications?

Hydrogen Characteristics

- Using molecular hydrogen (H_2), a useful amount of energy can be stored on a vehicle, and recharging times will be much lower than batteries
  - *Cryo-compressed hydrogen: 2 kg/min / 4 MW rate / 67 kWh/min (BMW, 2012)*
- H_2 has some useful and some challenging attributes for use as a fuel
- **Benefits** include:
  - *Very high LHV and HHVs (the highest of all chemical fuels)*
  - *Very wide ignition limits (~ 4-75% v/v, enabling lean operation at $\geq \lambda=4$)*
  - *Very fast flame speed (6x hydrocarbons, enabling significant dilution of the charge)*
- **Challenges** include:
  - *Very low ignition energy (it is "an **angry gas**")*
  - *Very short quenching distance (increasing heat transfer losses)*
  - *High adiabatic flame temperature (promoting the formation of NOx)*

There is limited understanding of H_2 autoignition behaviour: research opportunity!

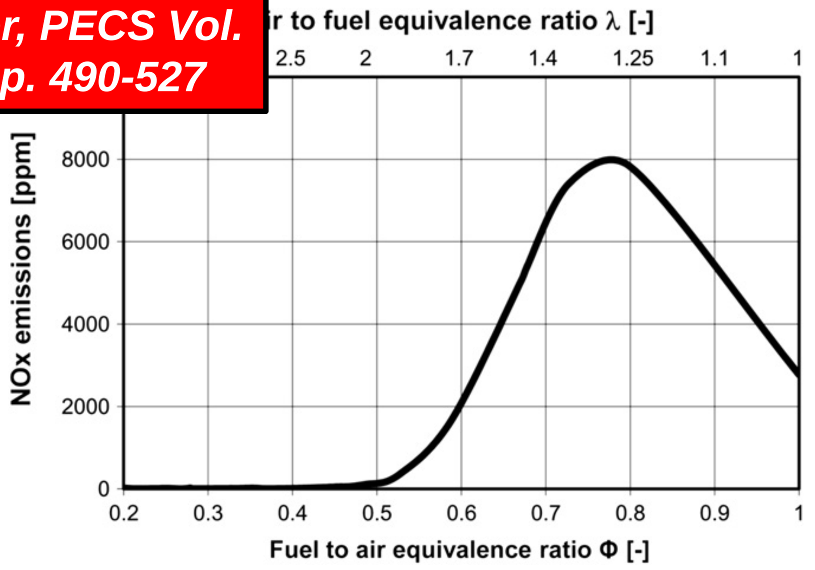
As a result of these, I would suggest that the classical poppet-valve 4-stroke engine is arguably the worst of all available options to combust hydrogen efficiently…

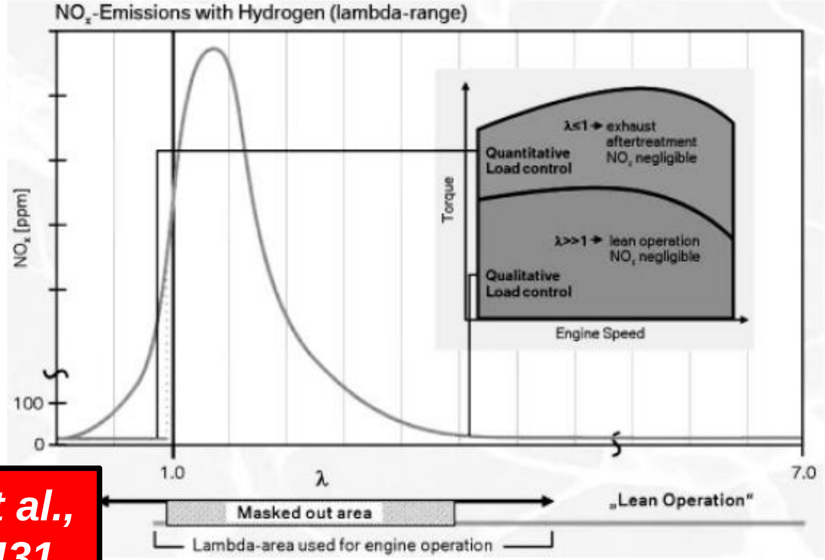
4-Stroke Engines and Hydrogen

Why is a classical 4-stroke engine (arguably) sub-optimal for hydrogen operation?

- Hot exhaust valves can lead to preignition
- In PFI engines, backfiring provides a limit to injection timing
- Catalyst over-temperature protection strategies cannot include enrichment
  - *Fewer cylinders can make this more challenging*
- The low density of hydrogen displaces air and significantly reduces power output
  - *External mixture preparation has a theoretical maximum power of approximately 80% that of stoichiometric gasoline*
- The “lambda leap” to avoid high NOx (from λ=1 to 2) is problematic

From Verhelst and Wallner, PECS Vol. 35, pp. 490-527





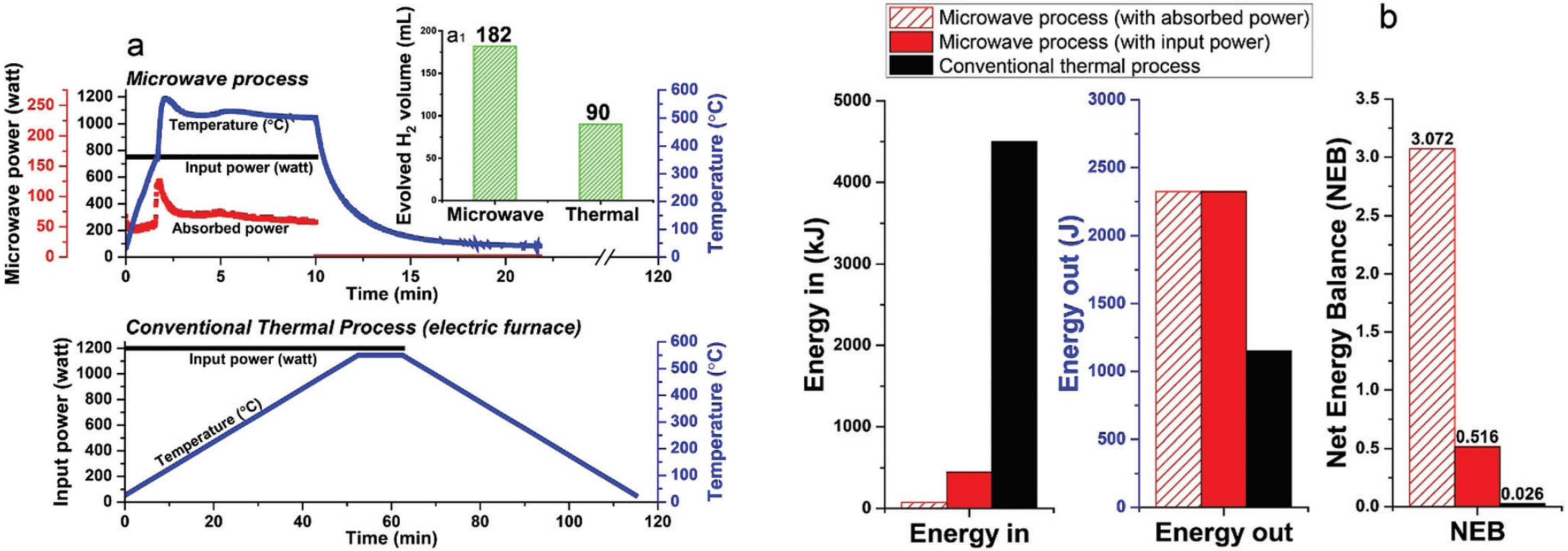
From Kiesgen et al., SAE 2006-01-0431

Hydrogen to Mitigate Fossil CO_2 Release

- It is well known that hydrogen could be used as a fully-renewable fuel
  - *If the storage problems can be overcome*
- "Green" hydrogen can be obtained by electrolysis of water
  - *Obviously, if the electricity (and in some cases heat) used to do this is carbon-free, a zero-fossil-carbon energy vector is created ("green hydrogen")*
  - *However, the amount of energy required for electrolysis is very high, and electrolyzers have efficiencies of 77-83%*
- However, clean hydrogen can also be obtained from oil
- KACST and the University of Oxford are developing new processes to dehydrogenate oil using catalysts
  - *In the KACST–Oxford Petrochemical Research Centre (KOPRC)*
- This gives **green hydrogen** and a **solid black carbon residue**
  - *Can then safely be buried or used in other industrial processes requiring carbon*
- The atmospheric release of fossil CO_2 can therefore be completely avoided

KOPRC Process

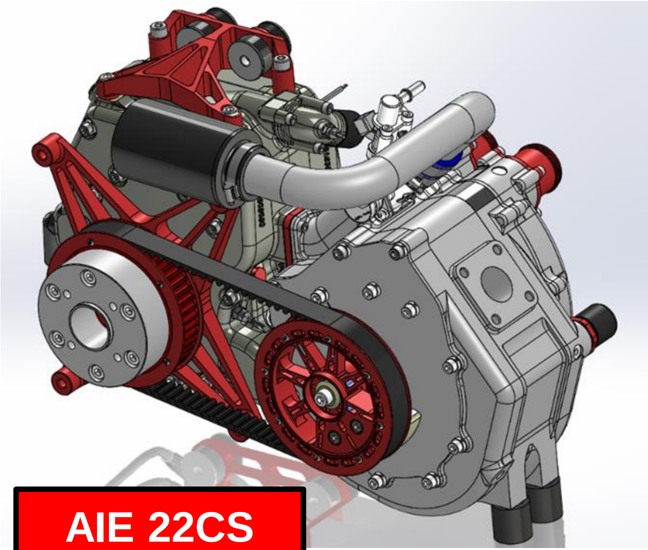
- Such a process allows the continued use of fossil oil **without climate impact**
- One form of the process uses microwave power
  - *If this power is renewably produced it will further improve the situation*

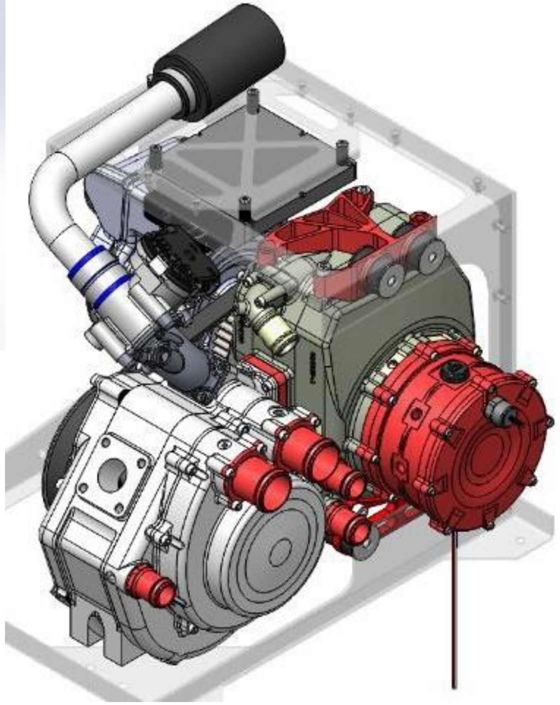


Jie et al., "The decarbonisation of petroleum and other fossil hydrocarbon fuels for the facile production and safe storage of hydrogen", Energy Environ. Sci., Vol. 12, pp. 238-249. 2019

FAVOURABLE ENGINE OPTIONS FOR USE WITH HYDROGEN

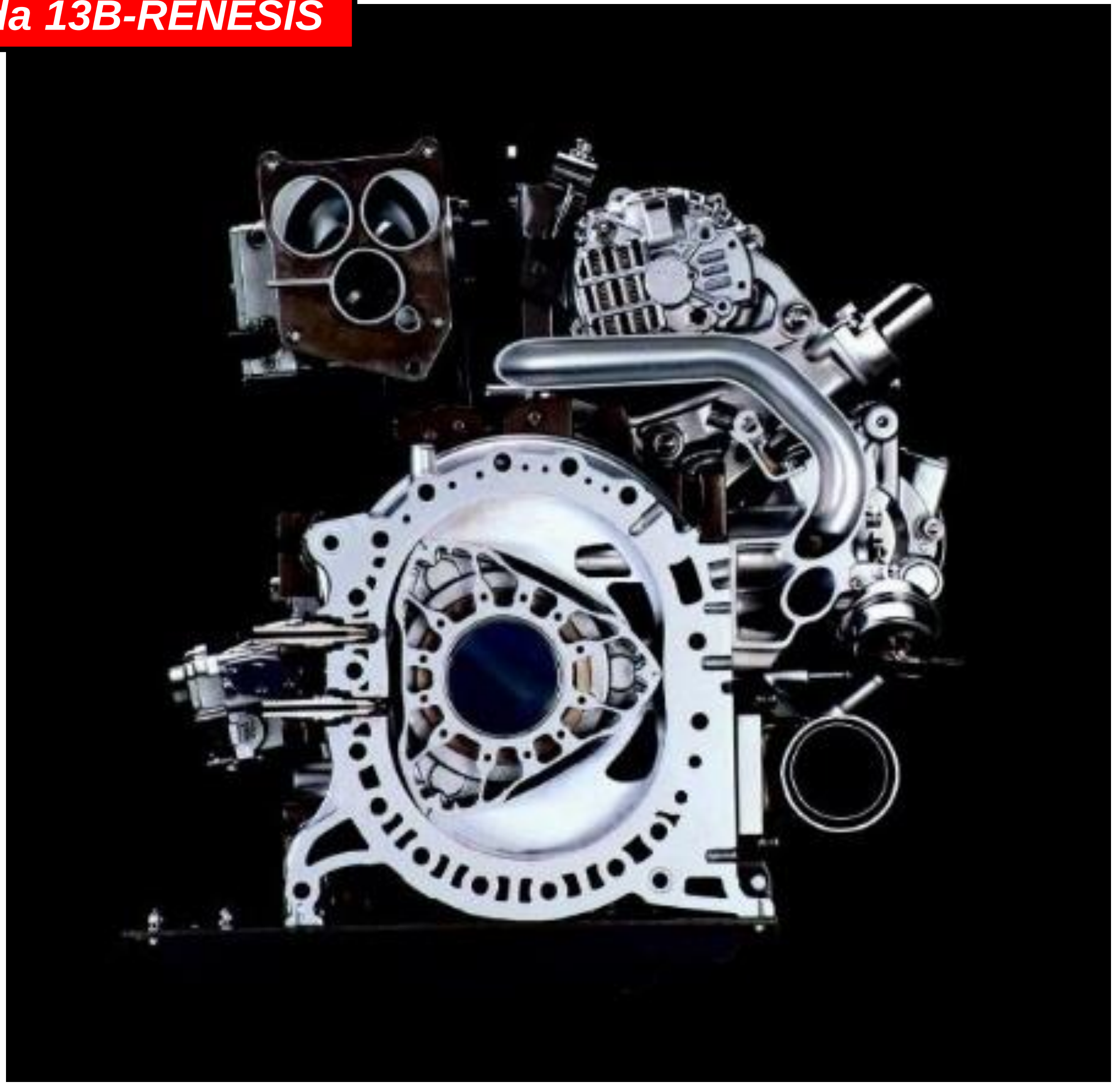
THE WANKEL ENGINE





AIE 22CS with Wankel expander (tested at UoBath)

Mazda 13B-RENESIS

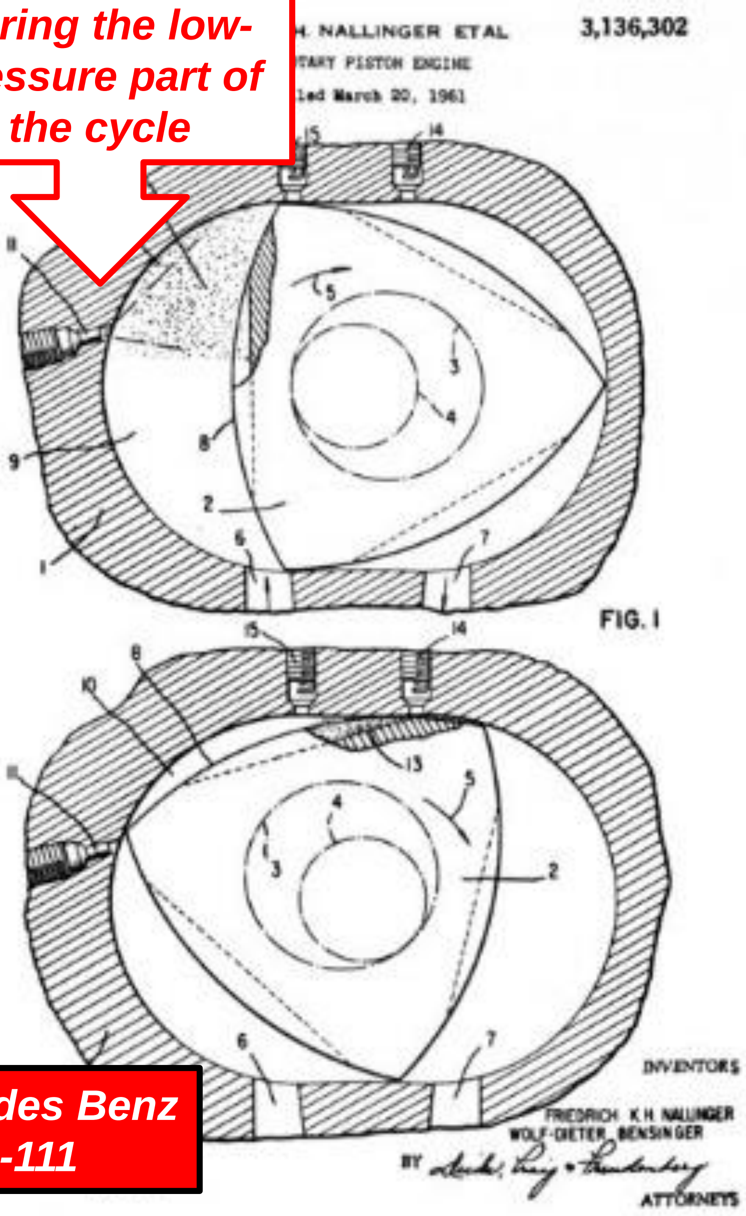


The Wankel Engine and Hydrogen (1)

Advantages:

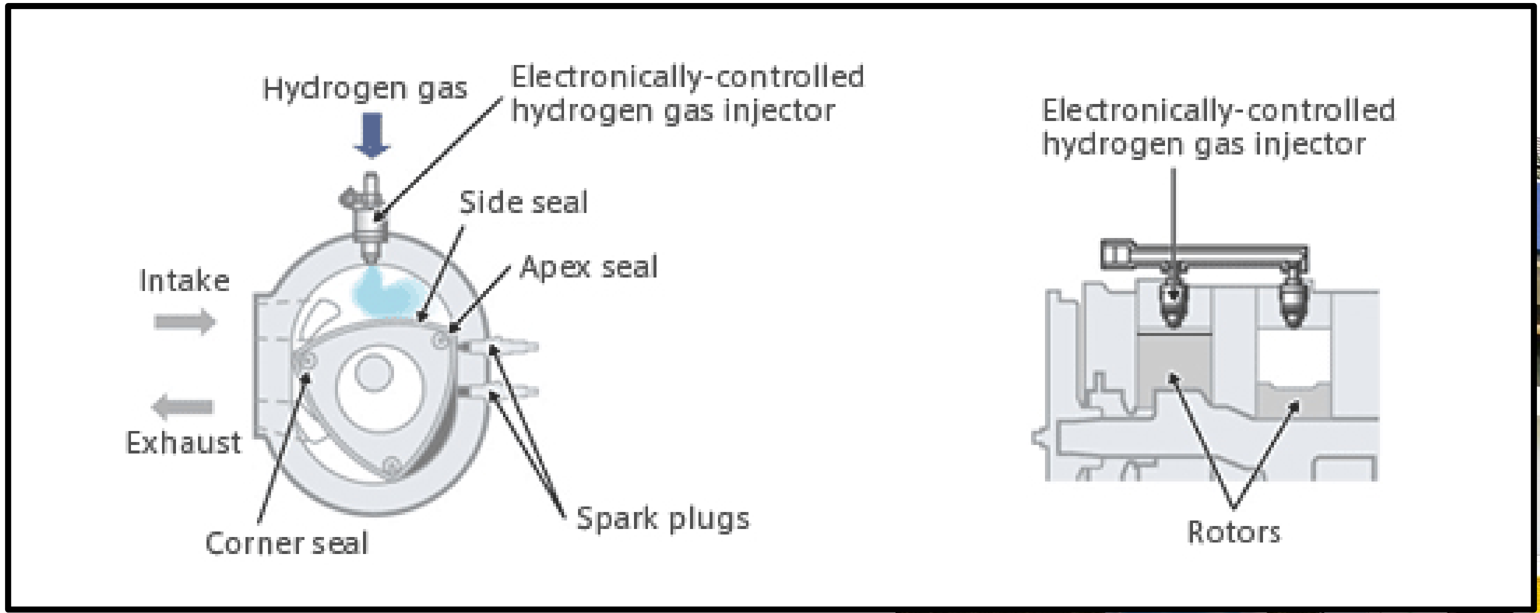
- The poor combustion chamber shape is mitigated by H_2's short quenching distance
- The fact that the leading apex seal "runs away" from the flame front is mitigated by the high flame speed
- The hydrocarbon problem caused by port overlap is eliminated
  - *Especially if lean operation is used at low loads*
- The absence of hot spots reduces the preignition problem
- The long period of the intake stroke means that low-pressure direct injection can be used
  - *Mitigating the dethrottling/power compromise*

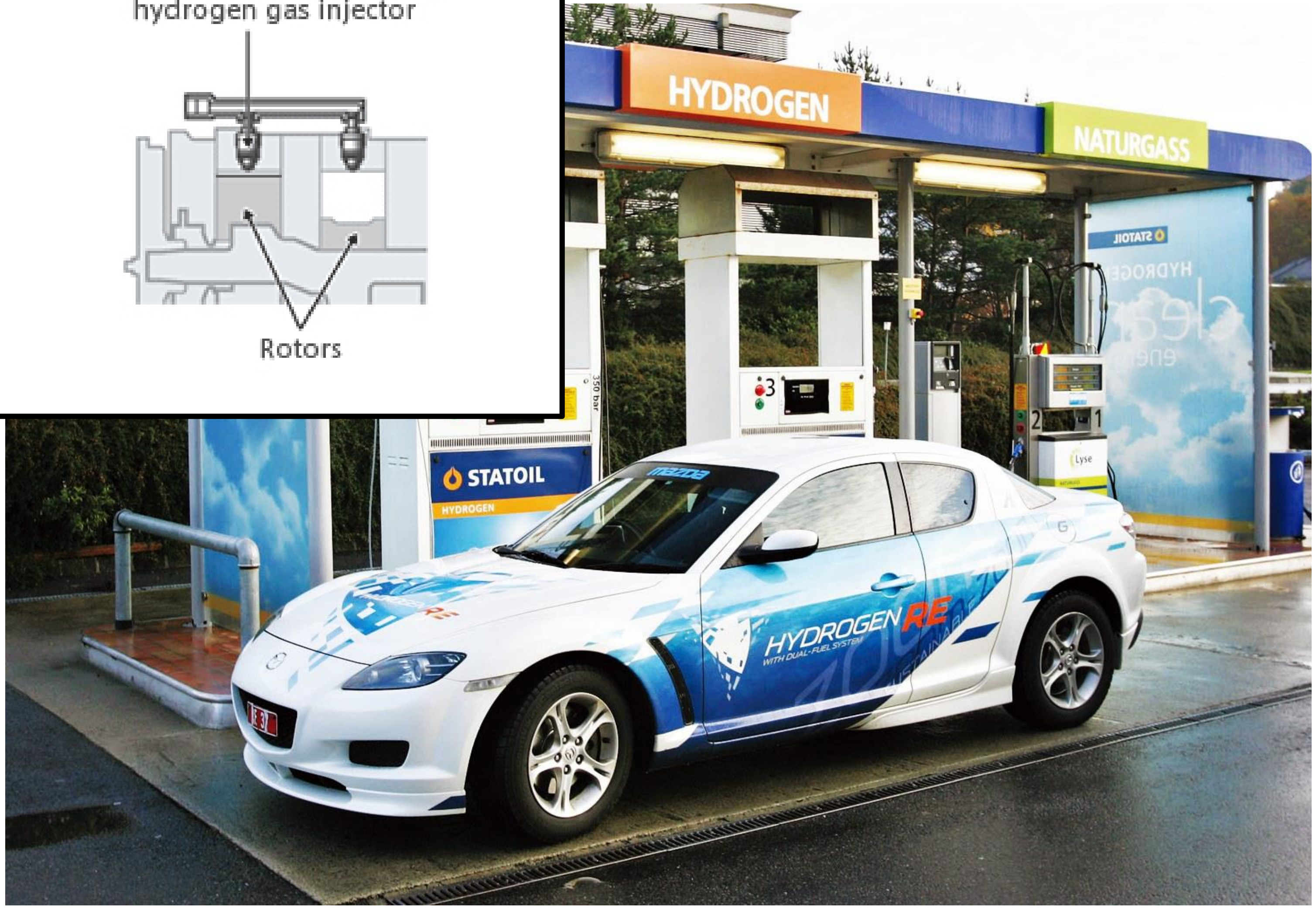
Direct injection during the low-pressure part of the cycle



Mercedes Benz C-111

Mazda Hydrogen RX-8

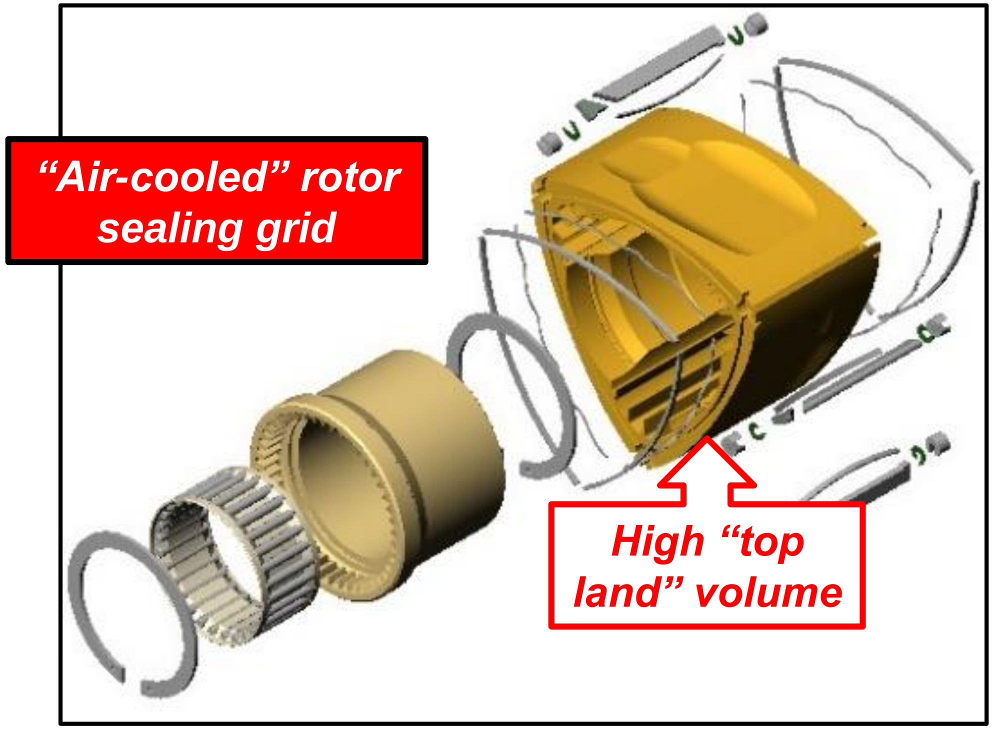


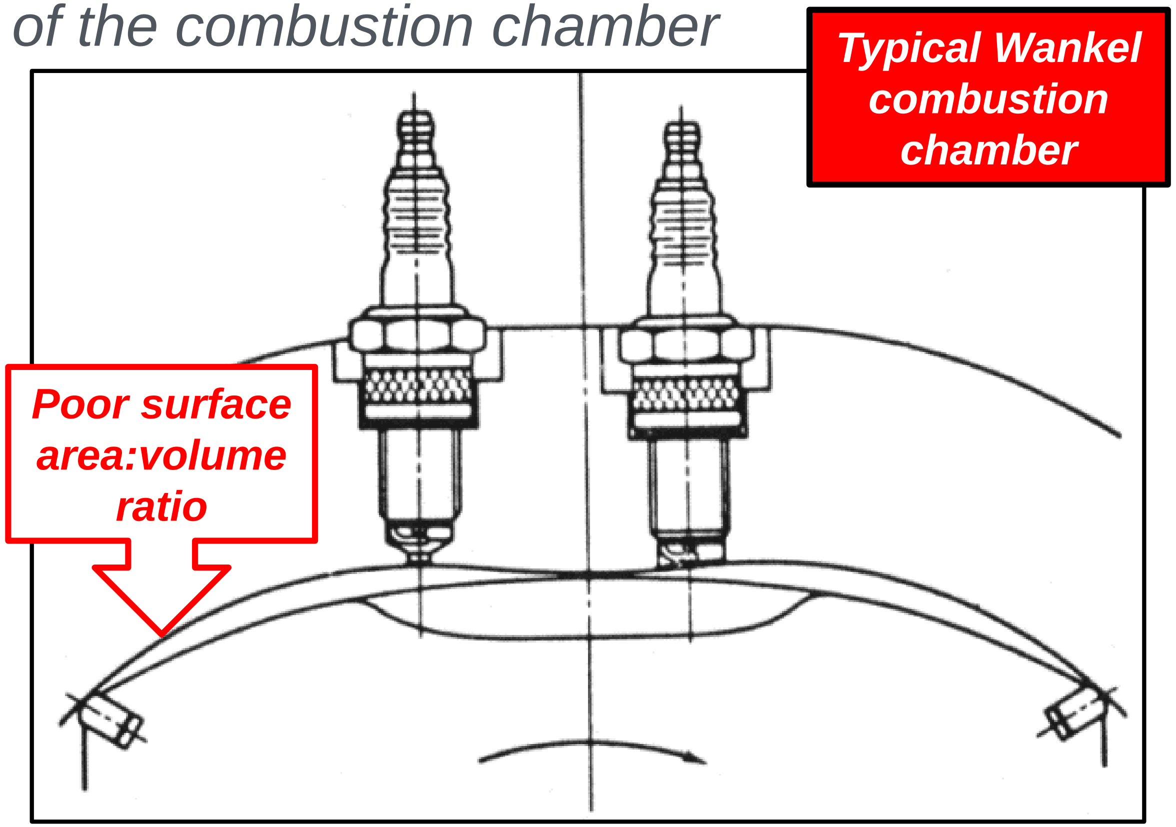


The Wankel Engine and Hydrogen (2)

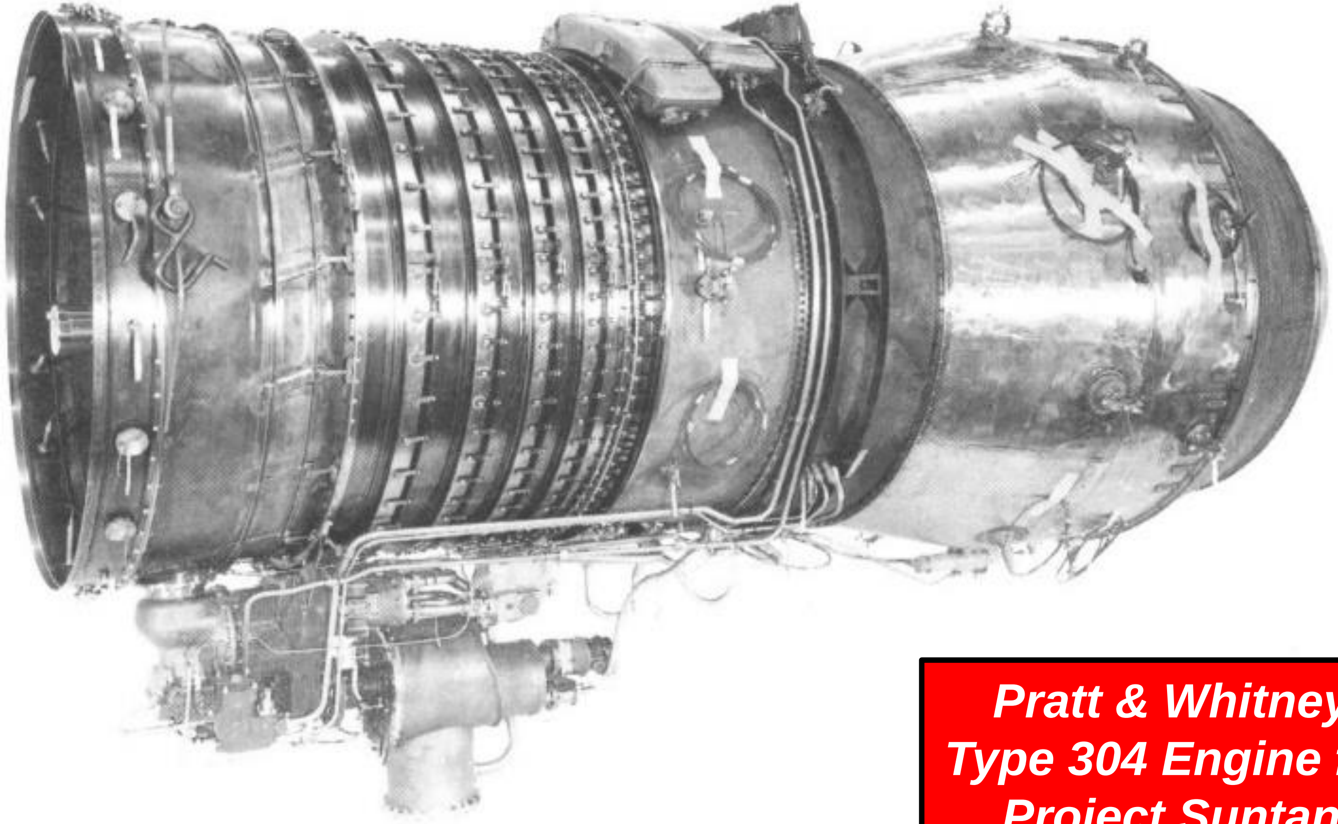
Disadvantages:

- Preignition caused by "top land" ignition is likely to be more problematic
  - *Because of increased "top land" volume due to the Wankel engine's geometry*
- Heat losses will be very high
  - *Due to the poor surface area:volume ratio of the combustion chamber*





THE GAS TURBINE



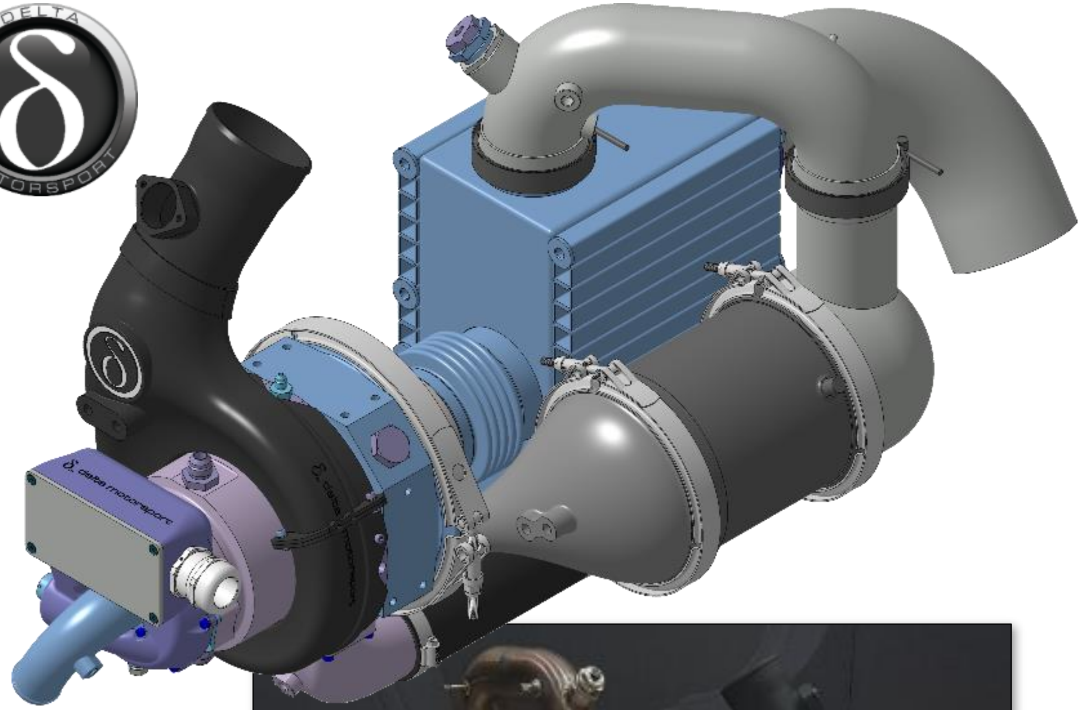
Pratt & Whitney Type 304 Engine for Project Suntan

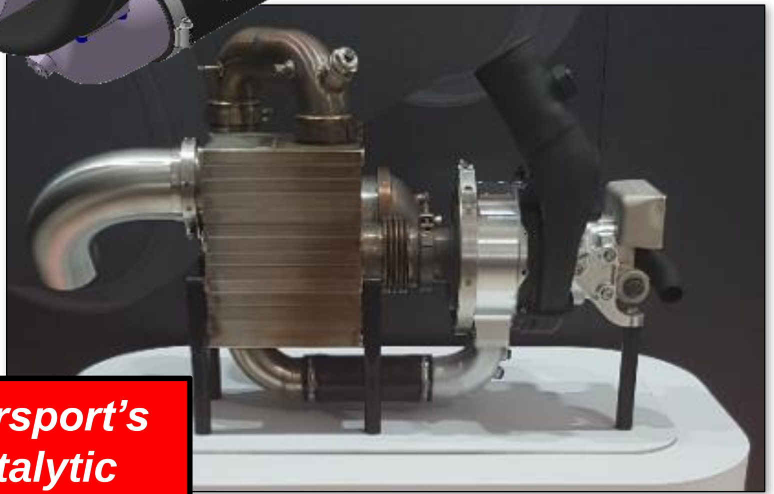
The Gas Turbine and Hydrogen

Advantages:

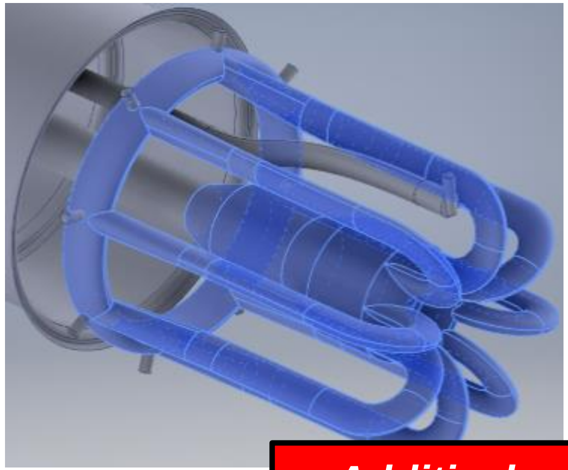
- Improved startability on hydrogen
- Wider combustion limits
- The start-up hydrocarbon problem is completely avoided
- If using catalytic combustion start-up should be straightforward
  - *Sufficient heat could be provided by an electric heater or compression heat*
- Due to the ready catalysis of hydrogen there would be minimal catalyst heating requirement
  - *Catalyst heating might be unnecessary due to compression heating of intake air*
- When using catalytic combustion the NOx emissions problems are eliminated

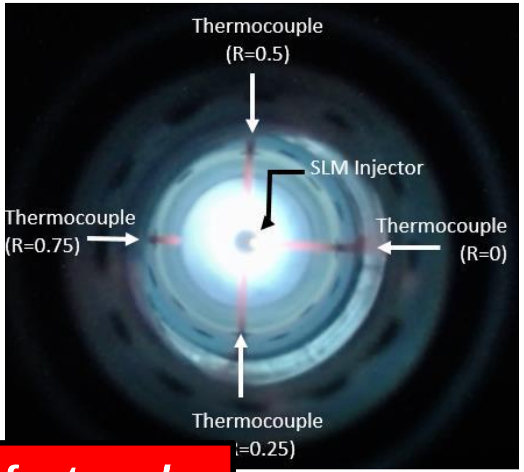
Modern Micro Gas Turbine Research (1)



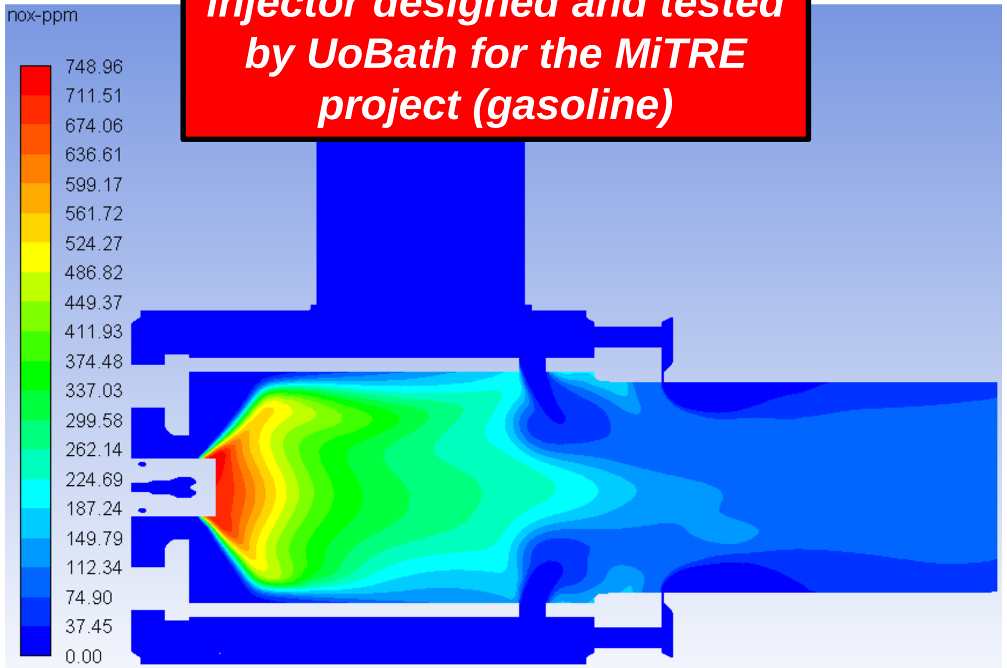


Delta Motorsport's 35 kW Catalytic Generator (gasoline)

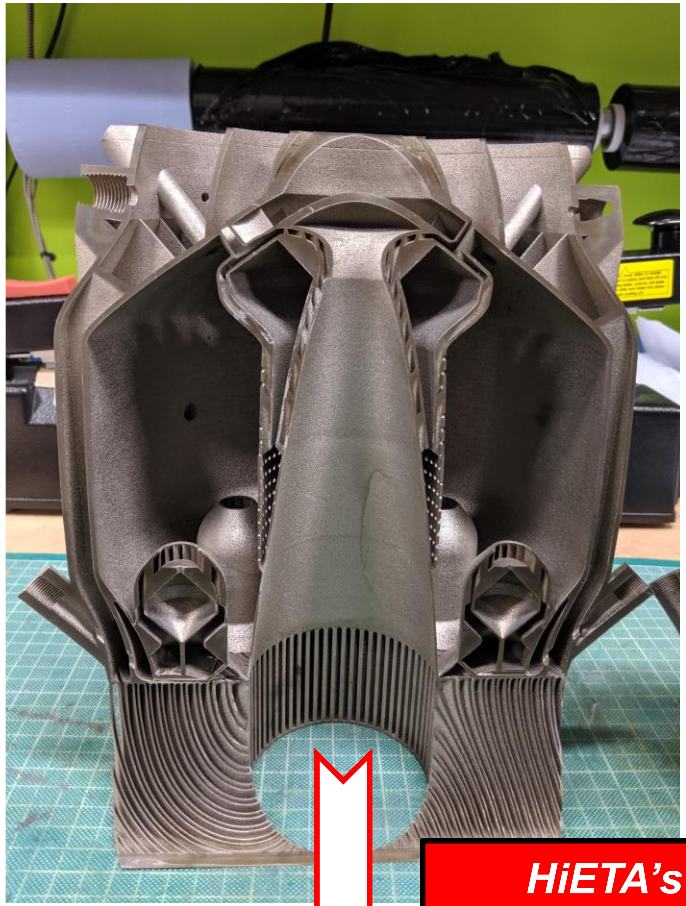


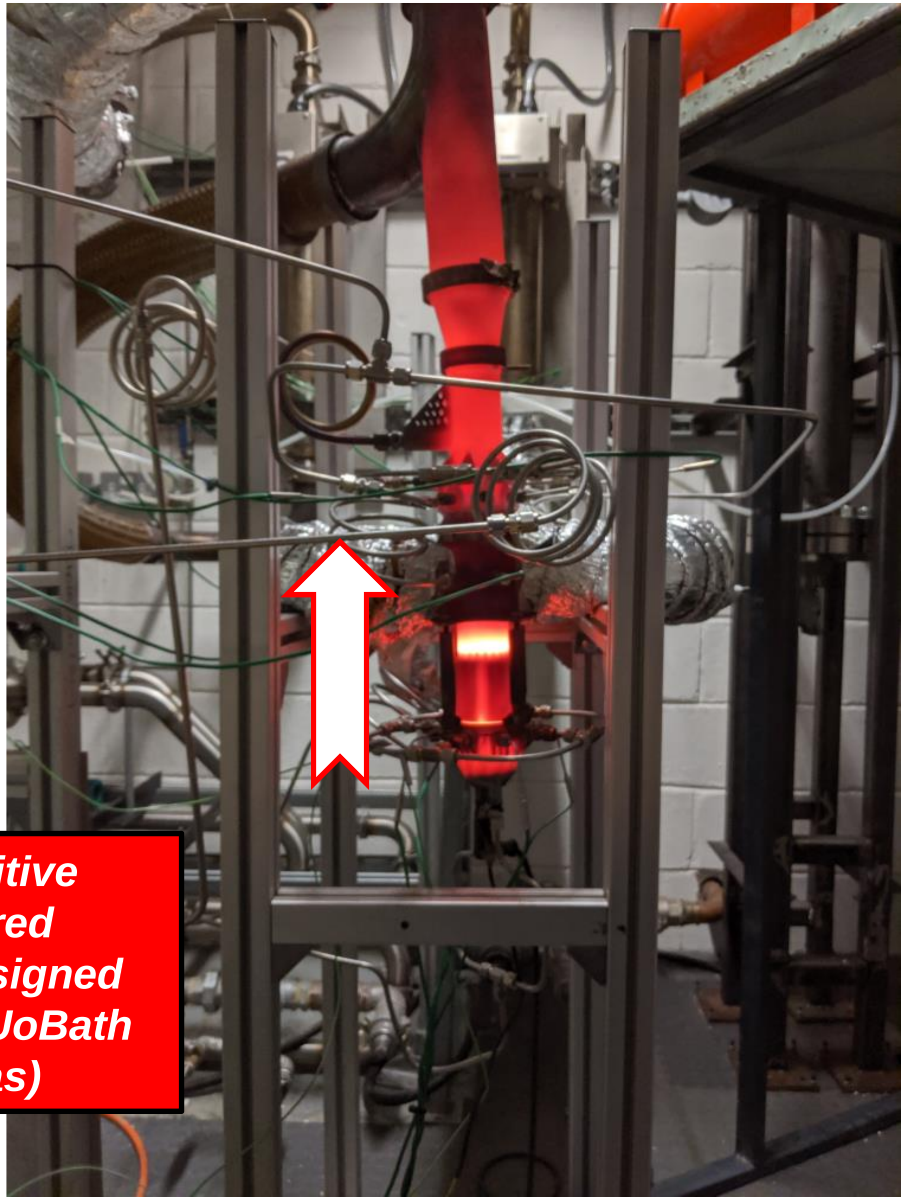


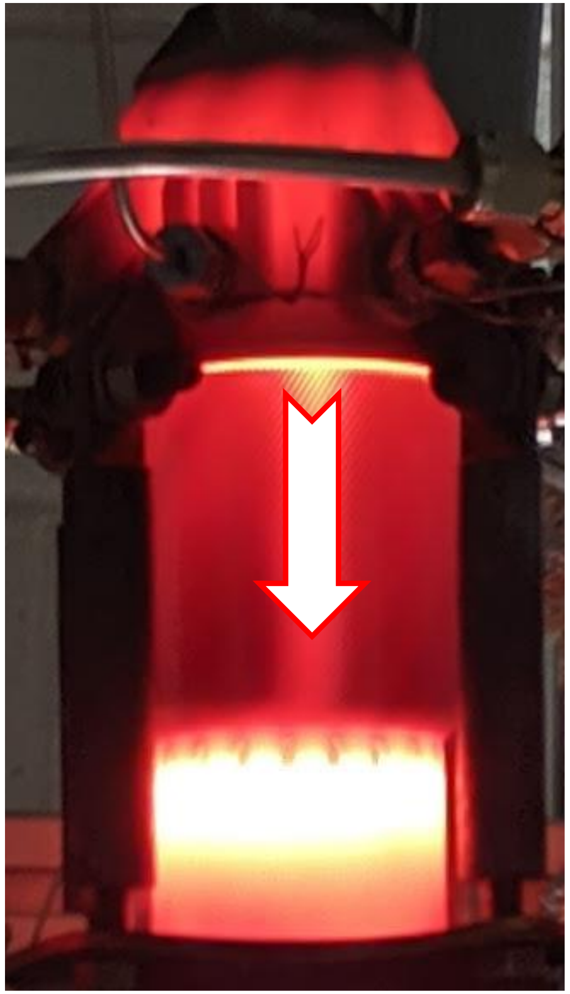
Additively-manufactured injector designed and tested by UoBath for the MiTRE project (gasoline)



Modern Micro Gas Turbine Research (2)

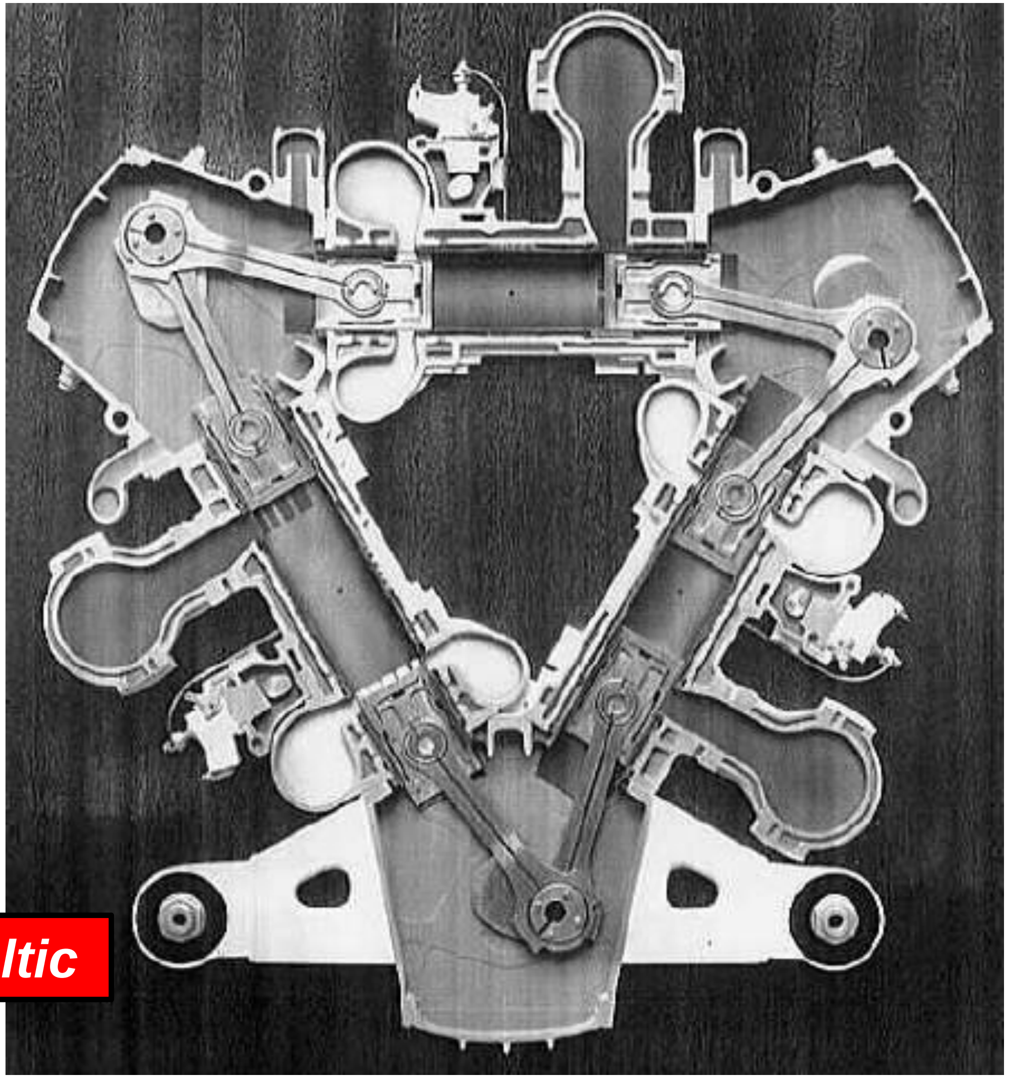






HiETA's additive manufactured combustor designed and tested by UoBath (natural gas)

THE 2-STROKE ENGINE



Napier Deltic

The 2-Stroke Engine and Hydrogen (1)

Advantages:

- Since they effectively *have* to operate lean due to scavenging loss, hydrogen suits 2-stroke engines due to its very wide flammability limits
- Hydrocarbon carryover emissions are eliminated
- Fuel/air mixing will be extremely rapid, overcoming reduced time windows
- HCCI-type combustion is most easily arranged in a 2-stroke
  - *Mitigating NOx emissions and increasing efficiency*
  - *Variable compression ratio is most easily provided by the 2-stroke*
- <u>For non-poppet valve engines</u>, the elimination of exhaust valves mitigates preignition
- <u>For the opposed-piston engine</u>: gaseous injection eliminates wall wetting, enabling smaller engine frame sizes
- <u>For the opposed-piston engine</u>: the very good surface area-to-volume ratio means less heat loss due to the small quenching distance

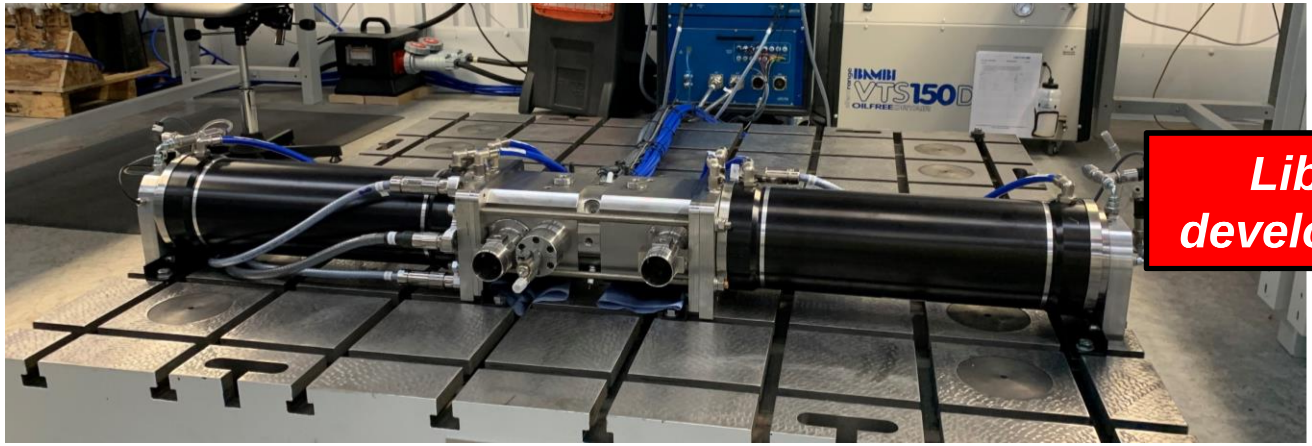
The 2-Stroke Engine and Hydrogen (2)

Disadvantages:

- The 2-stroke piston is already thermally highly loaded
  - *However, for a given capacity, the OP engine will have more piston ring circumference than other types to reject heat via*
- Direct injection is required
  - *Due to preignition and to avoid fuel loss in short-circuiting*
  - *Injector development will be necessary*

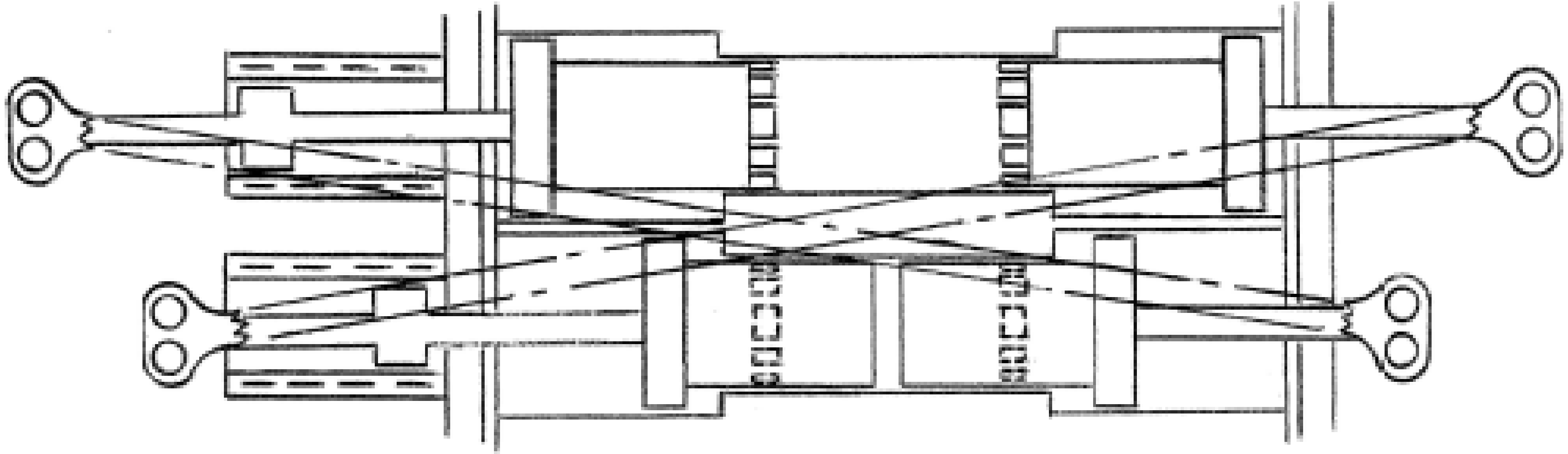
2-Stroke Free-Piston Engines and Hydrogen

- The 2-stroke free-piston engine operating on compression-ignited hydrogen has the potential to provide a very efficient CO_2-free EV range extender
  - *Van Blarigan et al. showed the potential of this (during 1998-2000)*



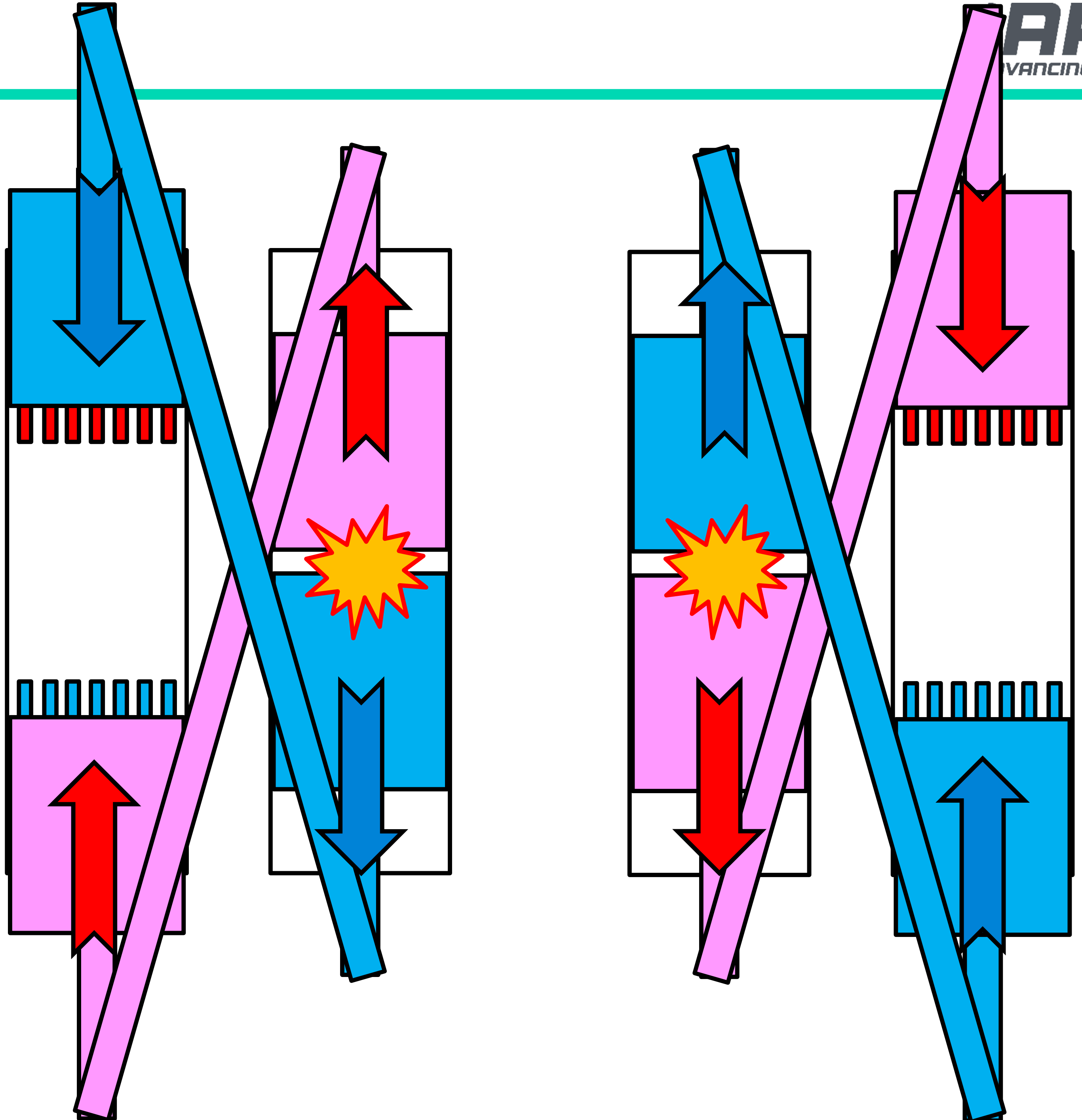
Libertine intelliGEN 20kWe development OP engine platform

UoBath's "ISOTOPE-X" opposed-free-piston engine



The system alternates between two states

Colours of the arrows relate to the direction of motion of each twin-piston and mover assembly (movers/ motors not shown)



Combustion in one cylinder directly compresses the charge in the other, removing the absolute requirement for a bounce chamber

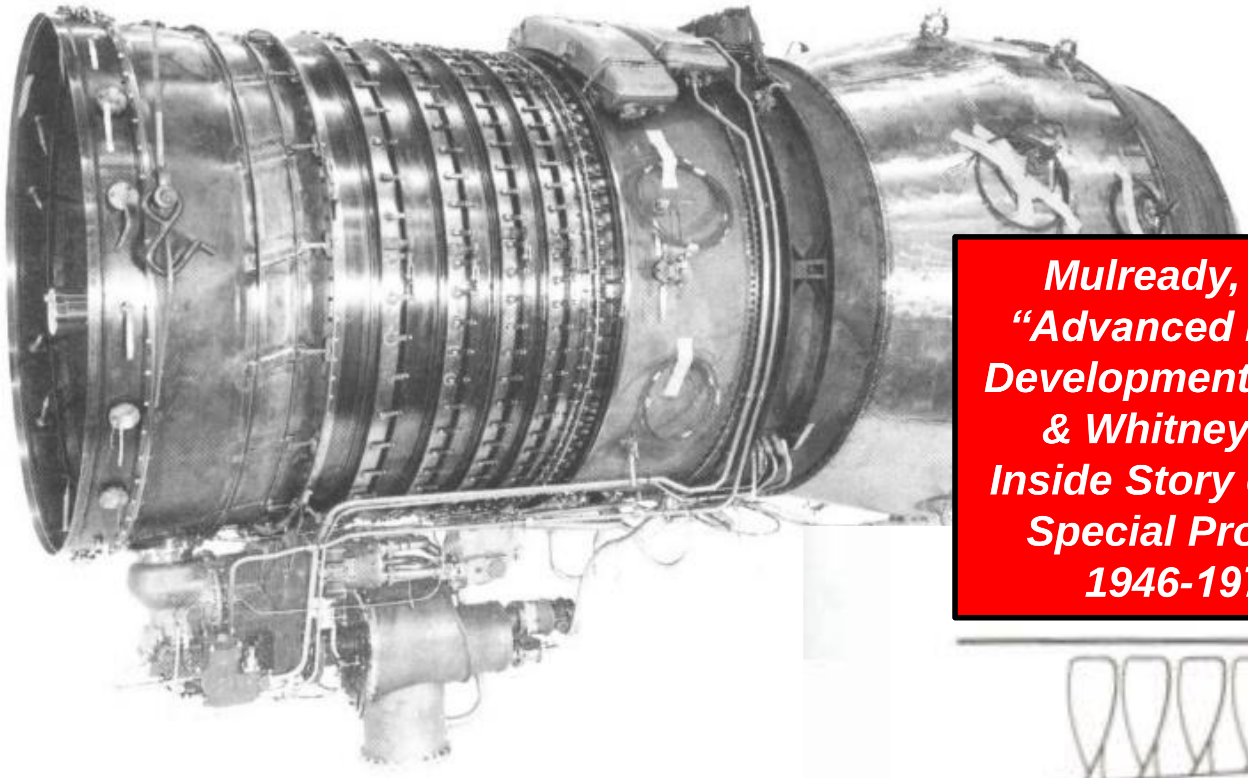
Variable Compression Ratio for HCCI control is afforded by varying TDC

OTHER CONSIDERATIONS

Hydrogen Storage Energy

- A considerable amount of energy has to be invested in hydrogen to make it storable either by pressurization or liquefaction
  - *This can be up to 20% as a proportion of its lower heating value depending on the scale of the plant*
  - *This is a function of hydrogen's very high C_P*
- Pressurization storage pressures are commonly assumed to be 700 bar (light duty) or 350 bar (heavy duty)
  - *Density is then ~46 kg/m^3 and ~23 kg/m^3 respectively*
- Liquefaction requires cooling to 20 K (the second lowest boiling point of all elements after helium)
  - *Density is then 70.8 kg/m^3*
- Cryo-compressed H_2 would appear to be most promising for the future (BMW)
- For maximum system efficiency, especially with liquid hydrogen, we should also consider a hydrogen expansion as a topping cycle
  - *This would work extremely well as a form of waste heat recovery*

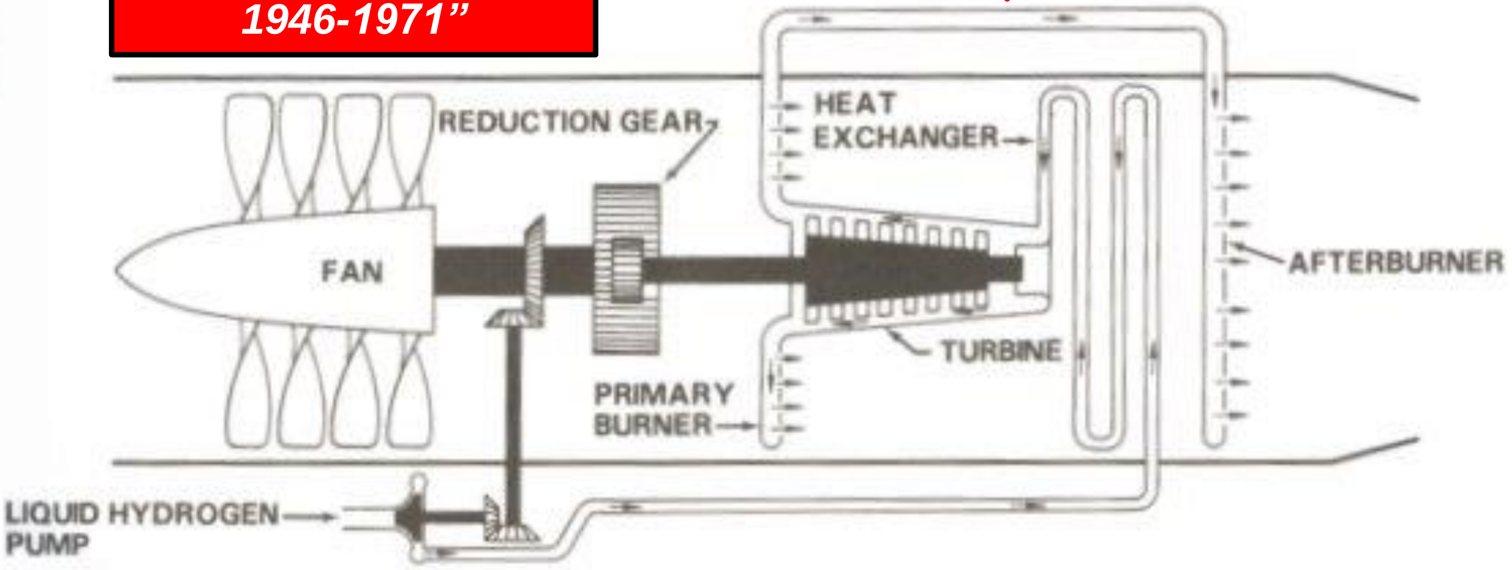
Other Opportunities



Also used in rocket engines (RL-10)

Rae hydrogen expander cycle with hydrogen turbine

Mulready, R.C., "Advanced Engine Development at Pratt & Whitney: The Inside Story of Eight Special Projects, 1946-1971"



Pratt & Whitney Type 304 Hydrogen Expander Engine

CONCLUDING REMARKS

Concluding Remarks

- Hydrogen has some appealing and some less appealing attributes as a fuel
- It can be manufactured with zero fossil carbon footprint either renewably or by stripping it from oil
- Using it in combustion engines for HD applications would allow the infra-structure problem to be solved before attempting to change the prime mover
- Dedicated H_2 engines may approach the in-vehicle efficiency of PEM FCs
  - *Especially when the series hybrid requirement of a FC is considered*
  - *More research is required to judge the gap*
- There are some interesting waste heat recovery possibilities due to hydrogen
- Some “alternative” solutions appear to offer increased benefits over the 4-stroke reciprocating engine
- The gas turbine (with series or parallel hybrid transmission), or the opposed-piston 2-stroke engine operating on compression ignition of hydrogen offer some significant potential

Thank You for Listening

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Grateful acknowledgement:

Saudi Aramco: Funding our 2-stroke collaborative scavenging system study, significant contribution to literature searching and results interpretation within it, and comments on the ISOTOPE-X concept