The Opposed-Piston Engine:

Studies on Efficiency and Geometry and Some New Concepts to Further Improve Its Thermodynamics in Concert with Increased Powertrain Electrification

Prof. James Turner and Dr Giovanni Vorraro

Institute of Advanced Automotive Propulsion Systems
University of Bath, UK

With acknowledgement to:

Robert Head, Saudi Aramco

West of England LOCAL ENTERPRISE PARTNERSHIP | HM Government

Research England

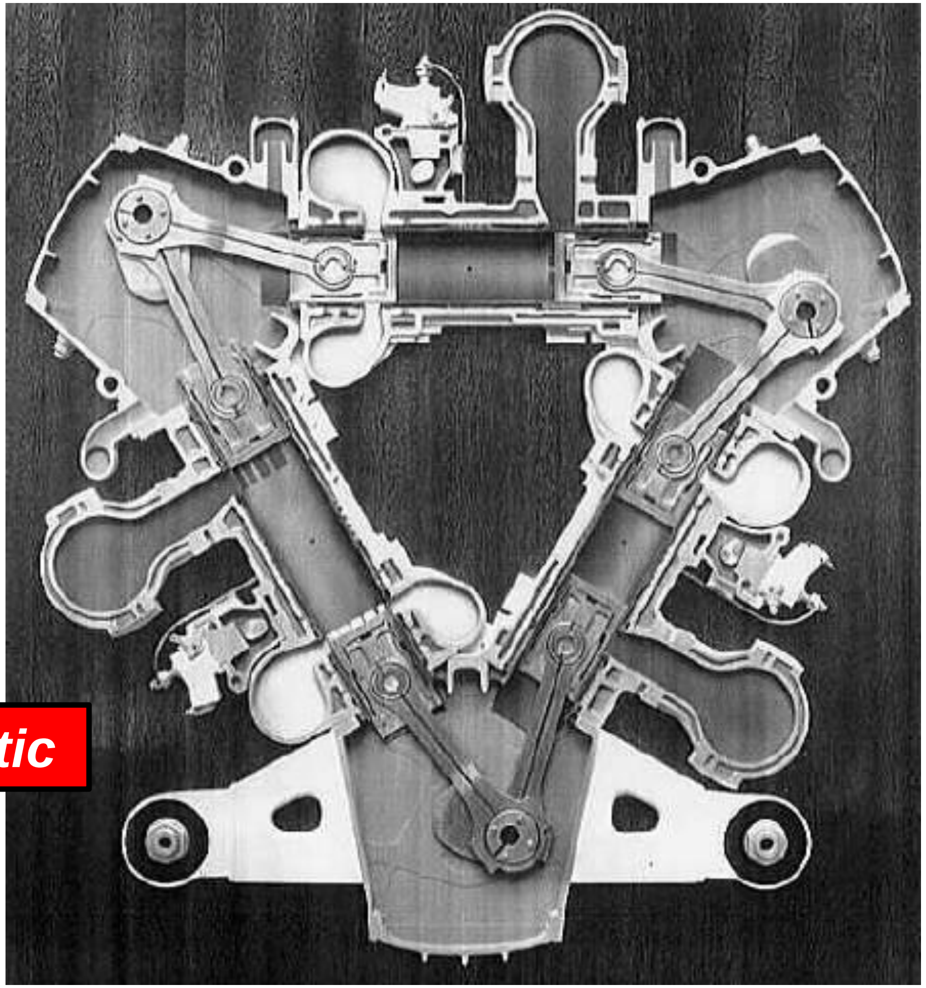
Bath, IAAPS, and the APC TPS Efficiency Spoke

IAAPS

ADVANCED PROPULSION CENTRE UK
TPS SYSTEM EFFICIENCY SPOKE

Contents

1. **OP2S efficiency** versus other 2-stroke scavenging systems
2. **Geometry studies:** using crankshaft offset to realize piston phasing and simultaneously facilitate reduced side thrust
3. **Variable compression ratio** via crankshaft phasing
4. **The value of turbocompounding** the OP2S
5. **Powertrain electrification:** OP2S opportunities
6. **A new concept** for a high efficiency, increased cost-effectiveness free-piston OP engine
7. **Conclusions**



Napier Deltic

The Opposed-Piston Engine: Background

- The opposed-piston 2-stroke engine (OP2S) has been shown to have advantages over other 2- and 4-stroke engines due to:
  - *Reduced heat rejection*
  - *Potentially improved mechanical efficiency*
  - *A good ratio of expansion ratio to compression ratio (can be "nearly Miller")*
- Its ratio of exhaust power to total fuel input power is high
  - *Meaning that turbocompounding would theoretically be very beneficial*
- Full-range HCCI has also been found to be possible in 2-stroke engines
  - *With full-range sparkless operation on a wide range of fuels*
    - On diesel, E85, or gasoline, including crank-starting without a spark *(by Lotus)*
  - *This extensive operating window was <u>enabled by wide-range VCR</u>*
- In the OP2S, GCI has been shown to be possible across the full operating map

OP2S EFFICIENCY VERSUS OTHER 2-STROKE SCAVENGING SYSTEMS

University of Bath and Saudi Aramco scavenging systems paper: SAE 2019-01-0071, "2-Stroke Engine Options for Automotive Use: A Fundamental Comparison of Different Potential Scavenging Arrangements for Medium-Duty Truck Applications"

Scavenging Systems Study (1)

- Six different scavenging systems were studied using GT-Power
  - *Opposed-piston (OP2S) – Port-poppet – Forward-uniflow sleeve valve – Reverse-uniflow sleeve valve – Reverse-loop scavenged – Loop scavenged*
- All of the systems studied provided **asymmetric port timing**
  - *The loop-scavenged architecture used Lotus's Charge Trapping Valvesystem*
- Key dimensions were kept fixed throughout the study *(see later)*
- Three operating points – "A": 1500 rpm, 3 bar IMEP (part load), "B": 1500 rpm, 14 bar IMEP (peak torque, 225 Nm/l), and "C": 3000 rpm, 12 bar IMEP (peak power, 60 kW/l)
  - *The heat release profile was taken from previous Saudi Aramco GCI work*
  - *GCI used to theoretically enable high efficiency and low engine-out NOx and PM*
- Exhaust pressures were chosen to ensure availability of energy to drive a turbocharger, and to provide allowance for full system back pressure

Scavenging Systems Study (2)

- Because of the different nature of the scavenging systems, different stroke-to-bore ratios were adopted
  - *e.g. OP2S stroke/bore ratio was taken from Achates Power publications, and both of the loop-scavenged arrangements used square arrangements*
- Otherwise, key dimensions were kept constant
  - *Capacity (751 cc), conrod length/crank radius (4.0), geometric CR (15:1)*
- However, the stroke:bore ratio was varied to give a fairer comparison
  - *For the sleeve valve configurations, the sleeve stroke:piston stroke ratio was kept as per the Rolls-Royce Crecy (45%)*
- The combustion chamber surface area changed with the geometry
  - *At TDC, OP2S had the lowest surface area-to-volume, as often reported…*
  - *…But the total cylinder surface area at BDC was highest for OP2S*

Results

Engine Type	Effective Compression Ratio [:1]	Effective Expansion Ratio [:1]	Ratio of Expansion to Compression Ratios [-]
	Volume at start of compression / clearance volume	*Volume at end of expansion / clearance volume*	*Expansion ratio / compression ratio*
OP2S	13.68	13.67	1.00
Port-Poppet	13.79	11.18	0.81
Forward-Uniflow Sleeve	13.85	11.49	0.83
Reverse-Uniflow Sleeve	10.97	13.53	1.23
Piston-Ported Loop	13.73	11.49	0.84

"Nearly" Miller cycle

Actual Miller Cycle

The possibility of achieving operation on the Miller Cycle with the 2-stroke engine with heavy mechanical constraints has not been shown before

?

Final Ranking (1)

- The final ranking was based on averaging the results for each operating point for NSFC and estimated supercharger power requirement
- In terms of NSFC, the OP2S has a significant advantage over the others
  - *Approximately 8.3% over the others and 9.6% over the loop-scavenged*
- This stems from reduced heat transfer, increased expansion work, and reduced supercharger power requirement
- The latter two points are linked and relate to its ability to use approaching the **whole cylinder bore circumference for its ports**
  - *Yielding the related maximum expansion work*
  - *Suggests OP2S would be very good for turbocompounding*
- The reverse-uniflow sleeve valve is considered to be worthy of further investigation

Final Ranking (2)

Engine Type	NSFC		Estimated Supercharger Power Requirement		
	Average of three operating points [g/kWh]	Change relative to Loop-Scavenged Piston-Ported [%]	Average of three operating points [kW]	Change relative to Loop-Scavenged Piston-Ported [%]	
OP2S	188	-9.6	0.79	-45.9	1st
Port-Poppet	204	-1.9	1.51	+3.4	3rd =
Forward-Uniflow Sleeve	206	-1.0	1.50	+2.7	3rd =
Reverse-Uniflow Sleeve	201	-3.4	1.63	+11.6	2nd
Piston-Ported Loop	208	-	1.46	-	3rd =

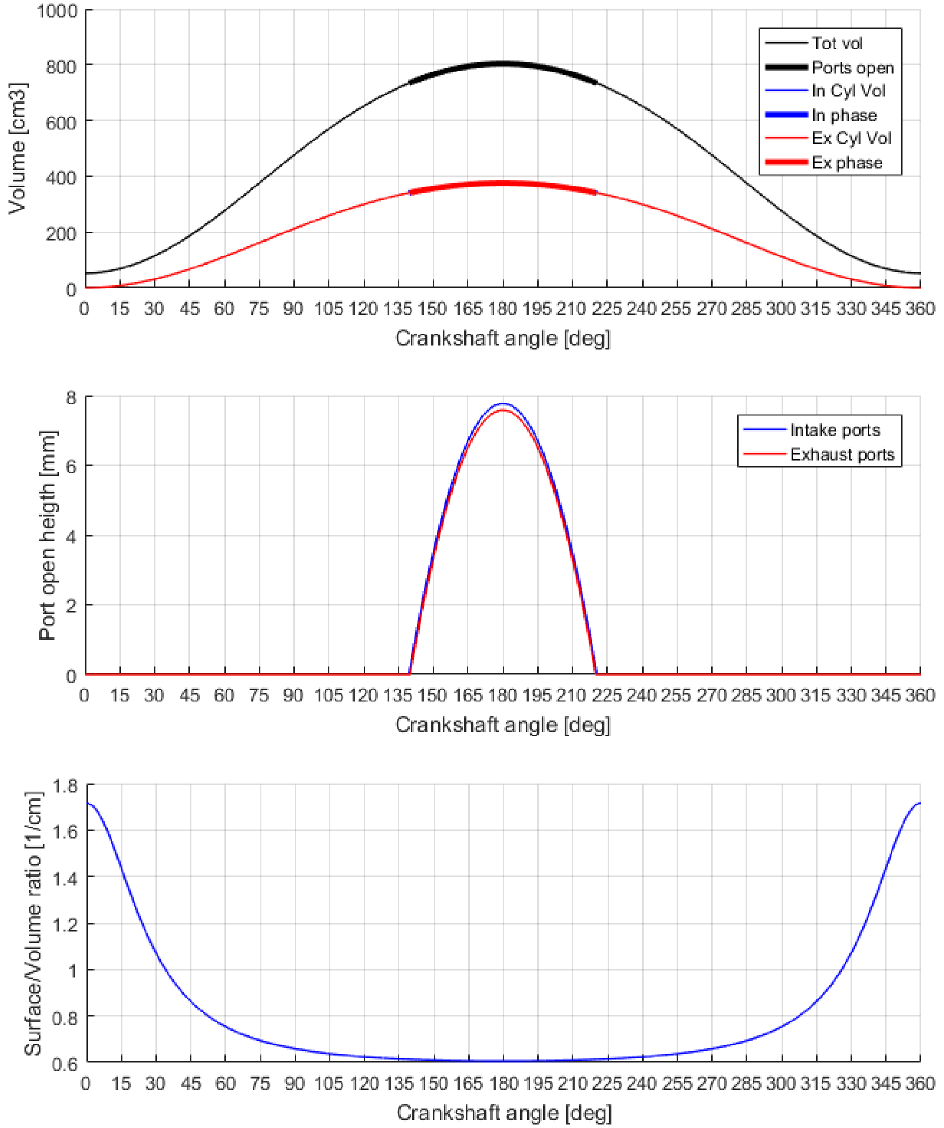
***Very** close – average is 205 g/kWh with a span of ~3.5%*

The reverse-loop scavenged poppet-valve engine was considered to be in a definite 6th place

GEOMETRY STUDIES:
Using crankshaft offset to realize piston phasing

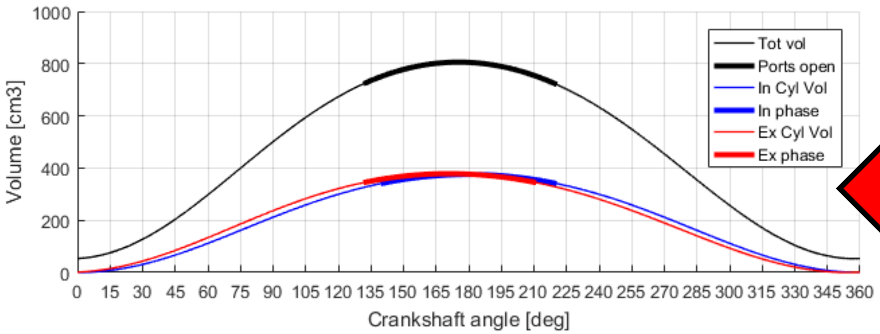
Crankshaft Phasing versus "Désaxé" (1)

- The same OP2S geometry as was used in SAE 2019-01-0071 was used for some geometry studies into crankshaft offset
  - *Aim was to formalize the conjecture made by Morton et al. in SAE 2017-01-1076, where it was noted that crank offset (versus phasing) could help to eliminate torque reversal due to the exhaust producing more power than the inlet*
- In theory, this can give <u>additional</u> advantages to the OP2S
  - *It could also reduce friction due to reduction in piston side thrust*
  - *Possibly improve durability in the process*
- We believe these advantages have not yet been fully exploited in an OP2S

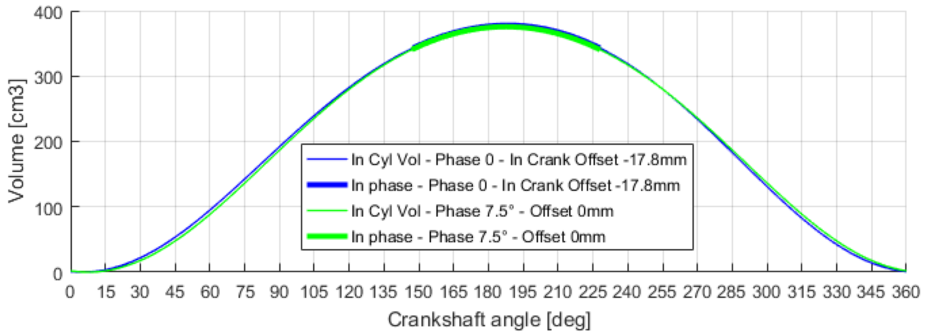


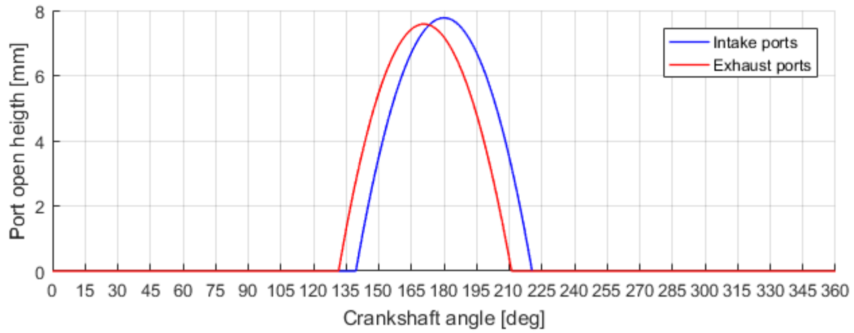
No crank offset or piston phasing – symmetrical timing

Crankshaft Phasing versus "Désaxé" (2)

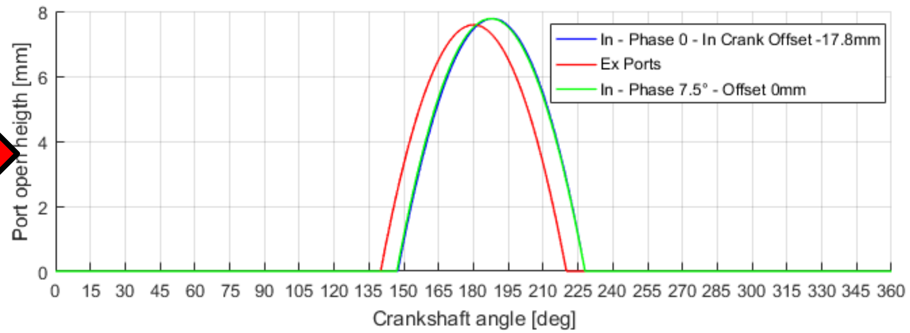


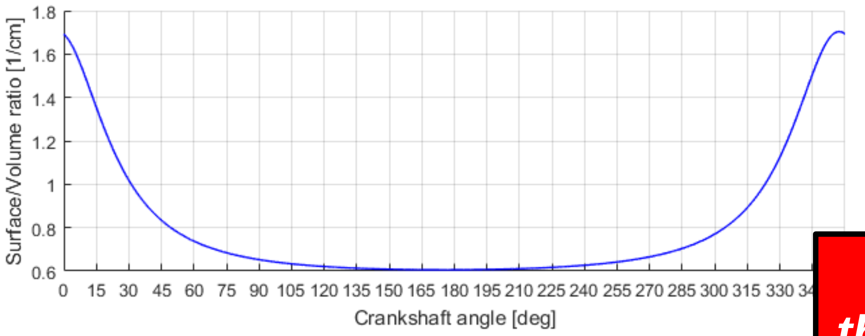
Effect of crank offset only

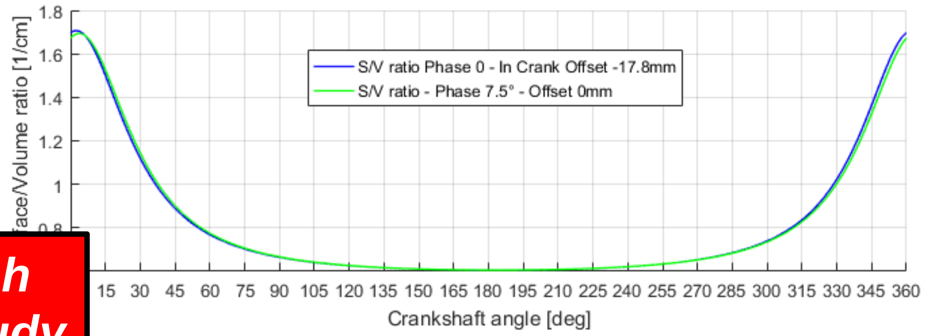




Effect of crank offset and crank phasing compared







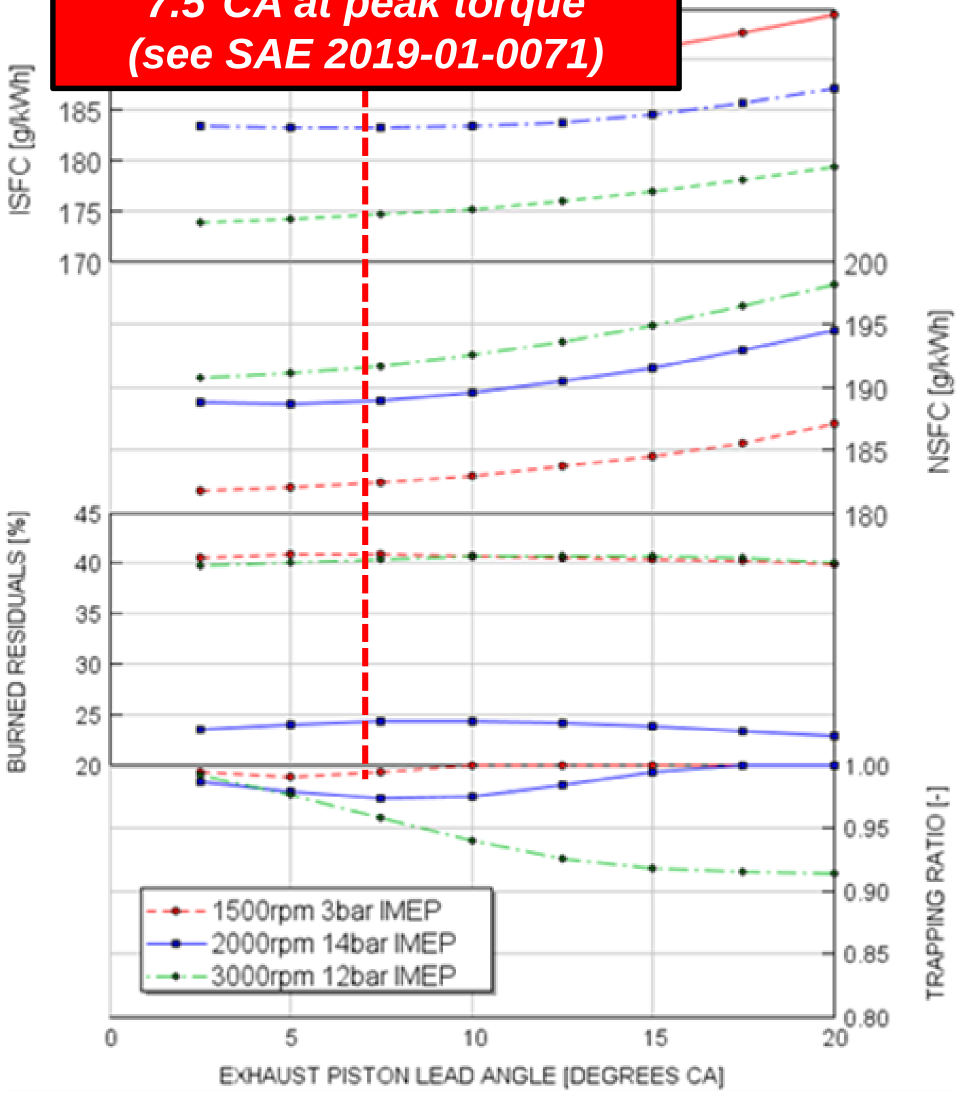
We intend to publish the results of this study in more detail shortly

CRANKSHAFT PHASING TO PROVIDE VARIABLE COMPRESSION RATIO

Variable Compression Ratio for OP2S

- *In theory*, the OP2S can be given VCR relatively easily by varying the exhaust lead
  - *VCR has been shown to be a very strong lever on combustion phasing with advanced compression ignition combustion systems in 2-stroke engines*
- This possibility was investigated in SAE 2019-01-0071 while keeping the ports and the rest of the geometry and operating points constant
- This showed very little change in ISFC as the lead was varied across quite a wide range
  - *Worthy of further investigation w.r.t. HCCI/GCI combustion control*

Originally-optimized lead: 7.5°CA at peak torque (see SAE 2019-01-0071)



THE OPPOSED-PISTON ENGINE AND TURBOCOMPOUNDING

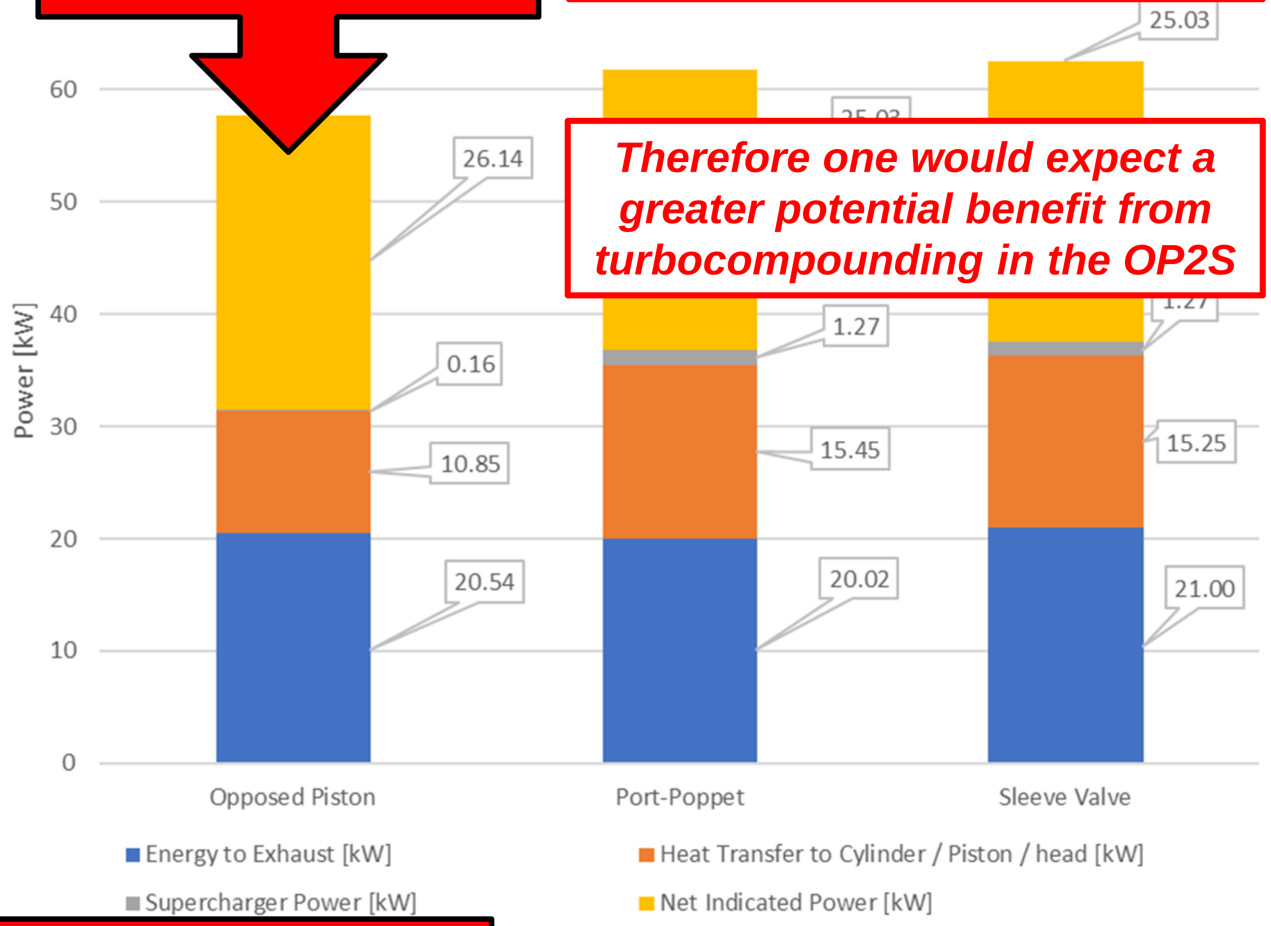
OP2S: Value of Turbocompounding

- Research published by Bath and Aramco shows that for the OP2S engine over 35% of the fuel energy is rejected to the exhaust
  - *i.e. if 20% of this could be recovered then this would improve ITE by 7% points*
- The low scavenging work requirement of the OP2S means that the work ratio of a turbocompounder will be high
  - *Because $P_{turbine} >> P_{compressor}$*
- ***Further improving the situation***

OP2S requires lowest indicated power and thus has the lowest fuel flow requirement

The ratio of power to exhaust to total fuel power is significantly higher for the OP2S than the others

Therefore one would expect a greater potential benefit from turbocompounding in the OP2S



Breakdown of indicated power flow at peak torque – <u>not an efficiency comparison</u>

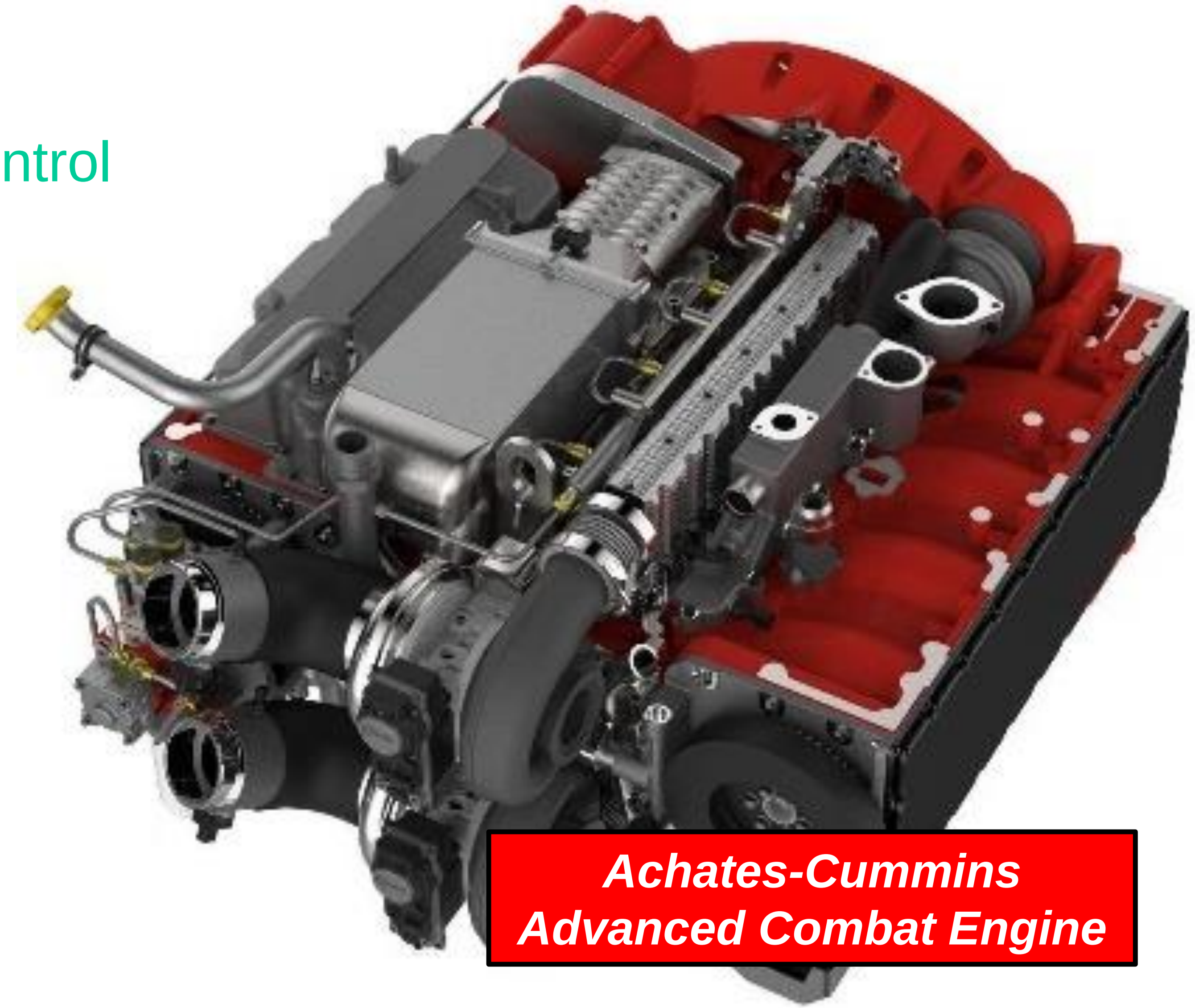
From ASME ICEF2018-9766

OPPORTUNITIES AFFORDED BY INCREASED POWERTRAIN ELECTRIFICATION

OP2S: Potential Areas for Improvements

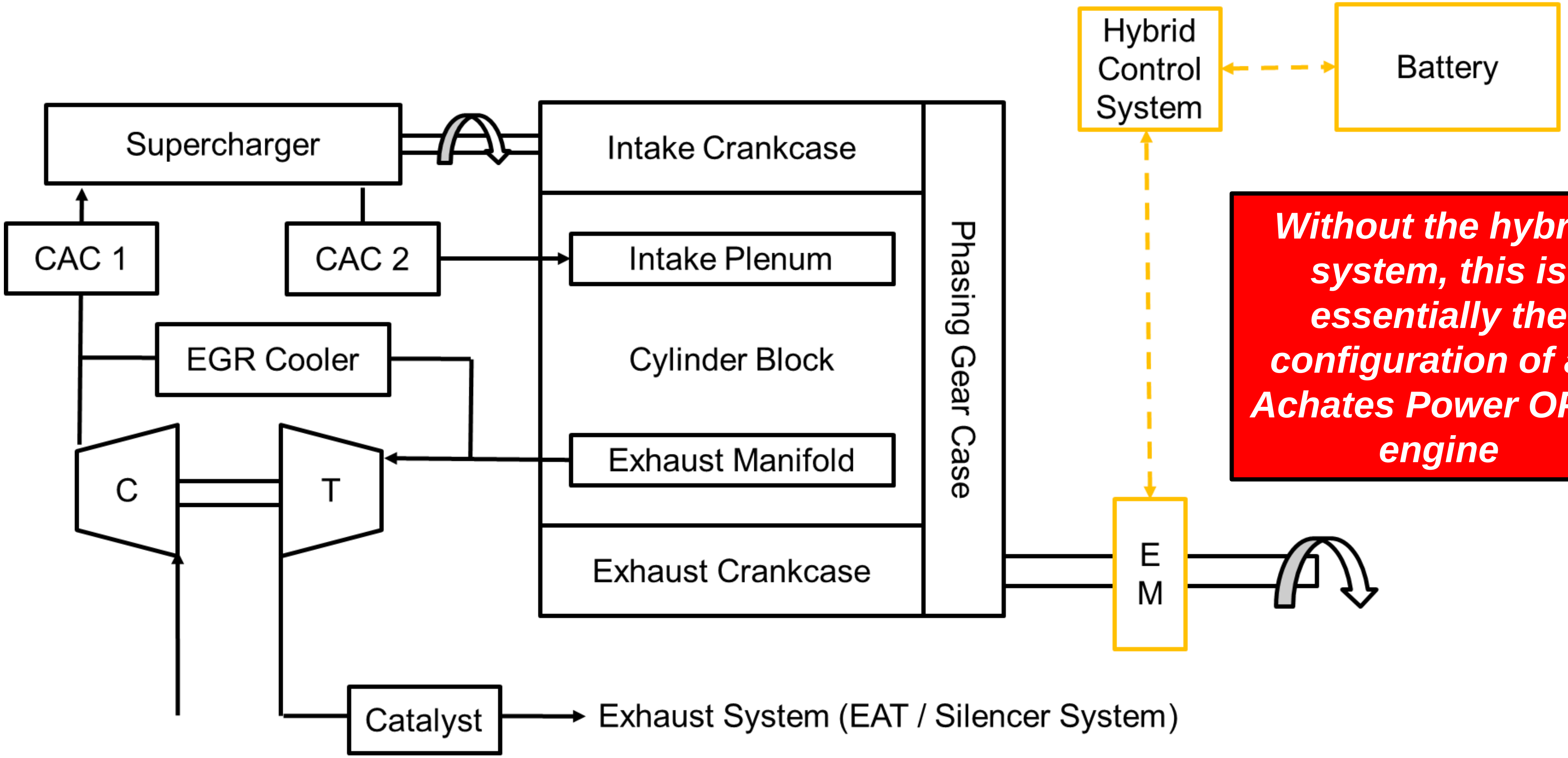
- Potential areas to improve the OP2S would appear to be:

1. Maximized use of hybridization
2. Combustion and combustion control
   - *Via wide-range VCR*
3. Improved mechanical efficiency
4. Improved waste heat recovery



Achates-Cummins Advanced Combat Engine

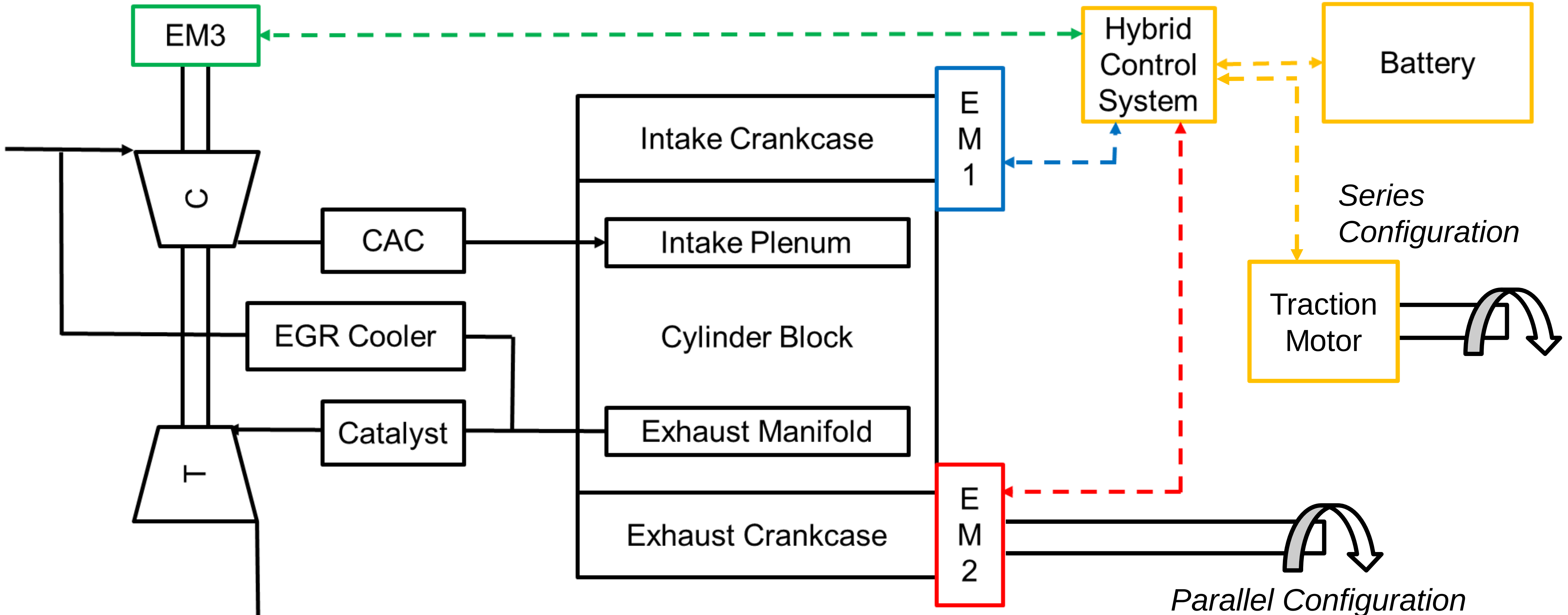
OP2S: “Conventional” Hybridization



Without the hybrid system, this is essentially the configuration of an Achates Power OP2S engine

OP2S: "ISOTOPE" Concept

"Integrated System to Optimize the Thermodynamics of Opposed-Piston Engines"

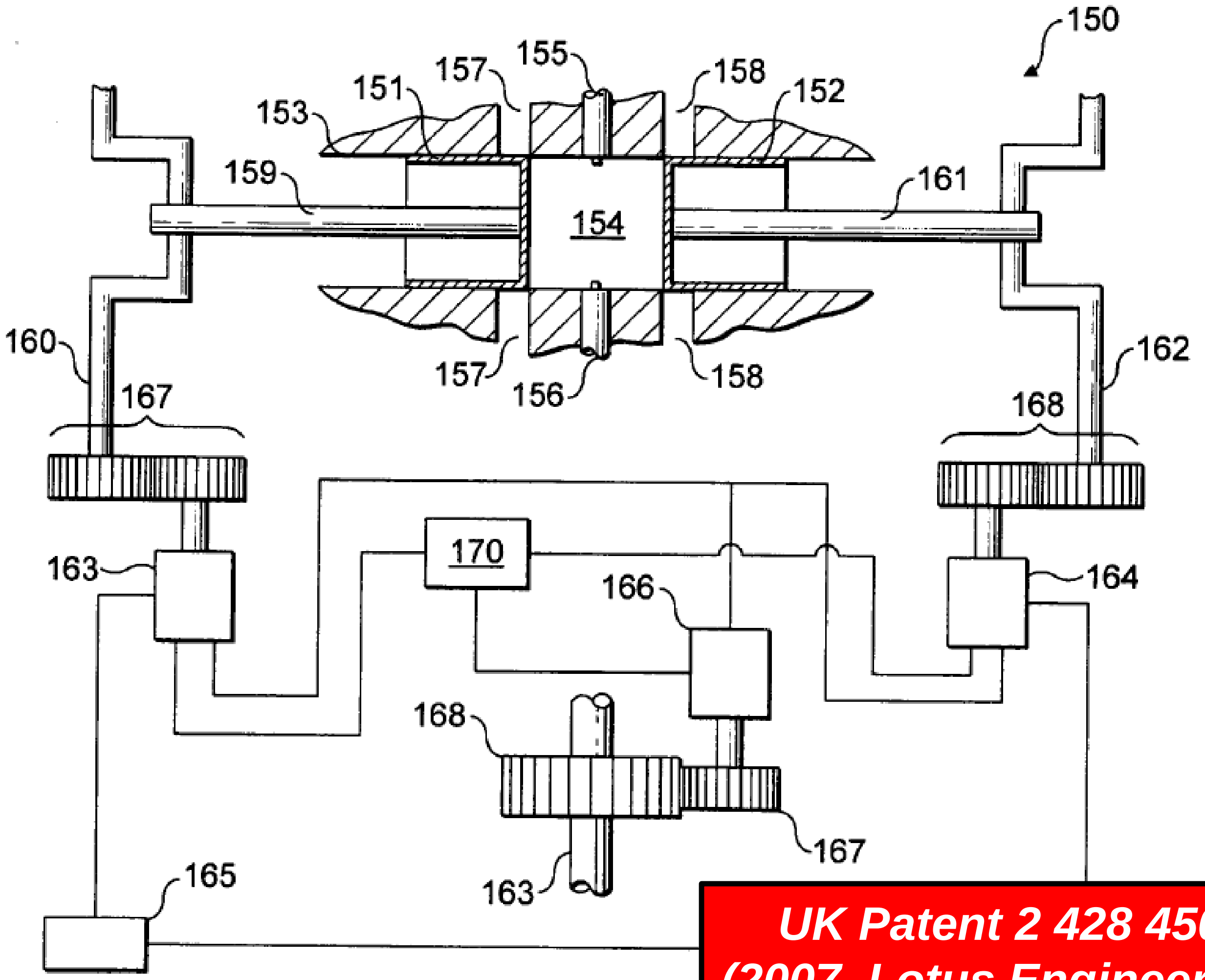


Piston-to-piston clash is eliminated at the design level

Maximum CR is not limited by valve cut-outs (as in a 4-stroke)

OP2S: Electrifying the Crankshaft Linkage

- Removal of the phasing gears and replacing them with electric machines brings myriad advantages:
  - *Variable compression ratio*
  - *Lower friction*
  - *Lower engine cost*
  - *Improved assembly*
  - *Reduced machining tolerances*
  - *Improved NVH*
  - *Reduced engine mass*
- ***But it's not a new idea…***



UK Patent 2 428 450 (2007, Lotus Engineering – now lapsed)

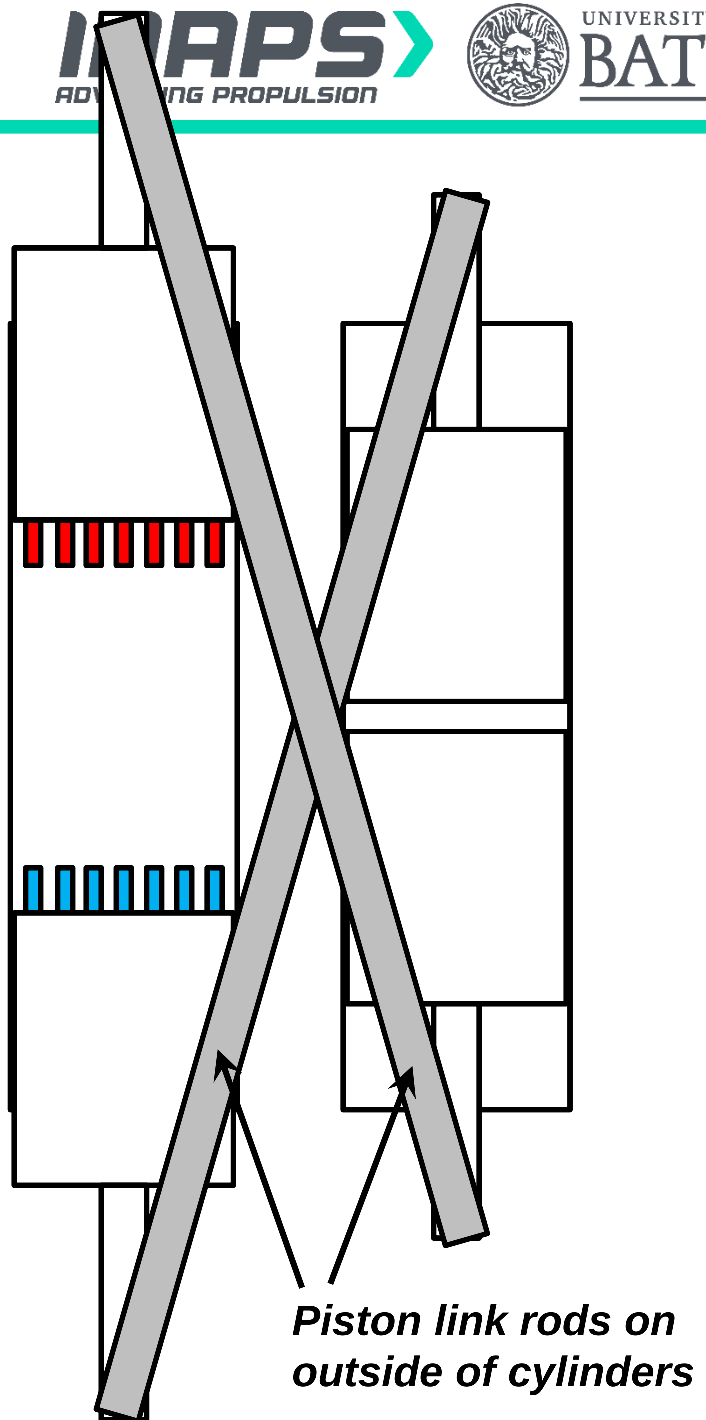
ISOTOPE-X:
A new concept for a high efficiency, increased cost-effectiveness free-piston engine

Opposed Free-Piston Engines

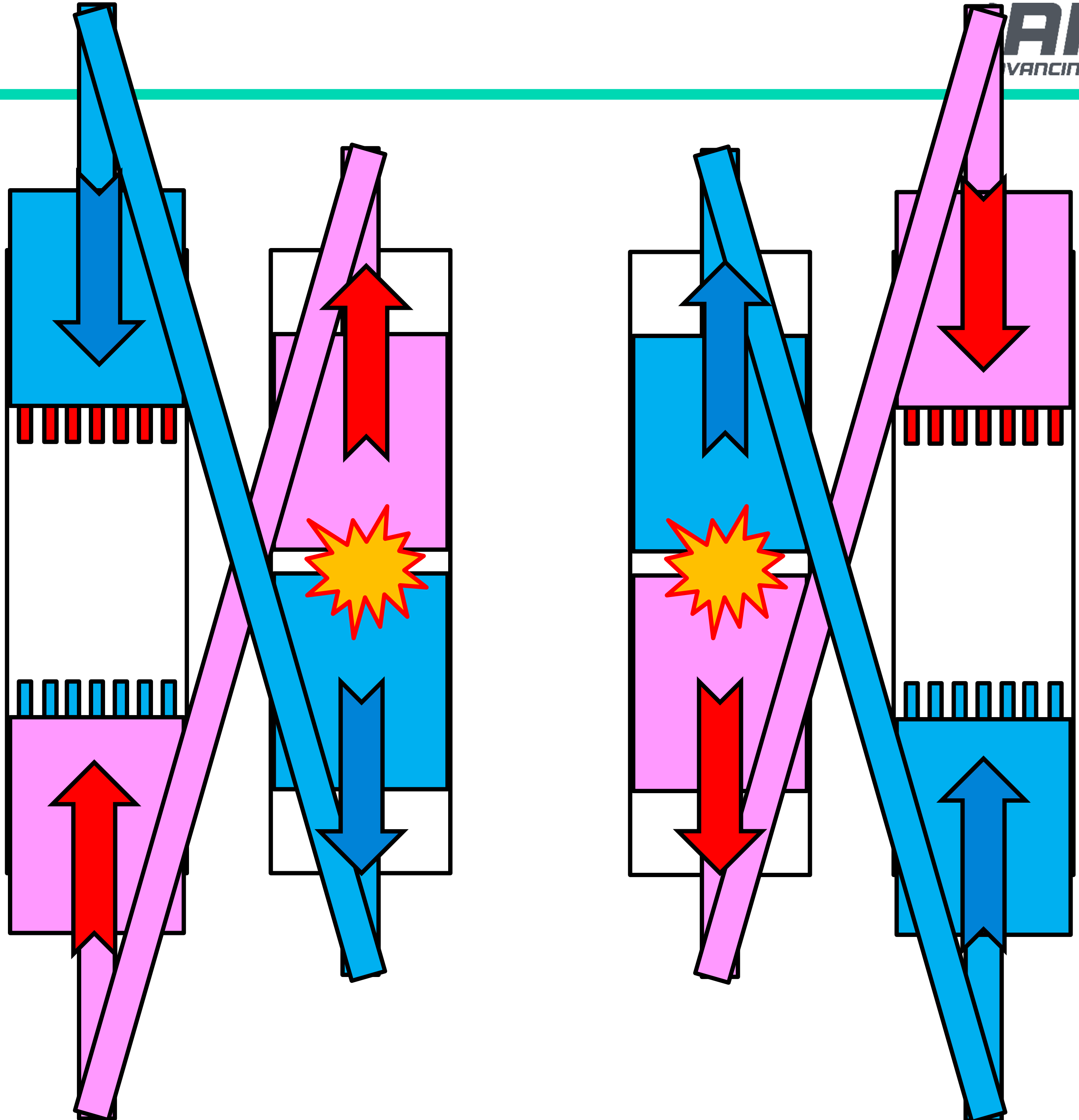
- One type of engine which may be extremely beneficial as a series hybrid engine or range extender (REx) is the free-piston engine (FPE)
- The OP FPE might be the thermodynamic ideal, but conventionally it requires two power take-offs (PTOs) per cylinder
  - *These are linear electric machines for an electric REx*
  - *So this is an expensive solution*
- Bath has created a new concept for larger power REx requirements – "**ISOTOPE-X**"
- It combines benefits of OP construction with a reduction in the **average** number of electric machines per cylinder to one
  - *Note: in an OPE, "electric machines" could be replaced by hydraulic or pneumatic PTO*

ISOTOPE-X: Concept

- Power for compression is taken directly from the expansion process
  - "180 degree" firing interval
  - Minimizes power requirement for electric machines
  - Reduces/eliminates bounce chamber requirement
- PTOs only have to deal with the net power output
- Variable top and bottom dead centres would still control gas exchange and compression ratio
- Excellent balance
- Except for starting, the piston cross link rods are only ever in tension
  - Opportunity for light weight construction?



Operation



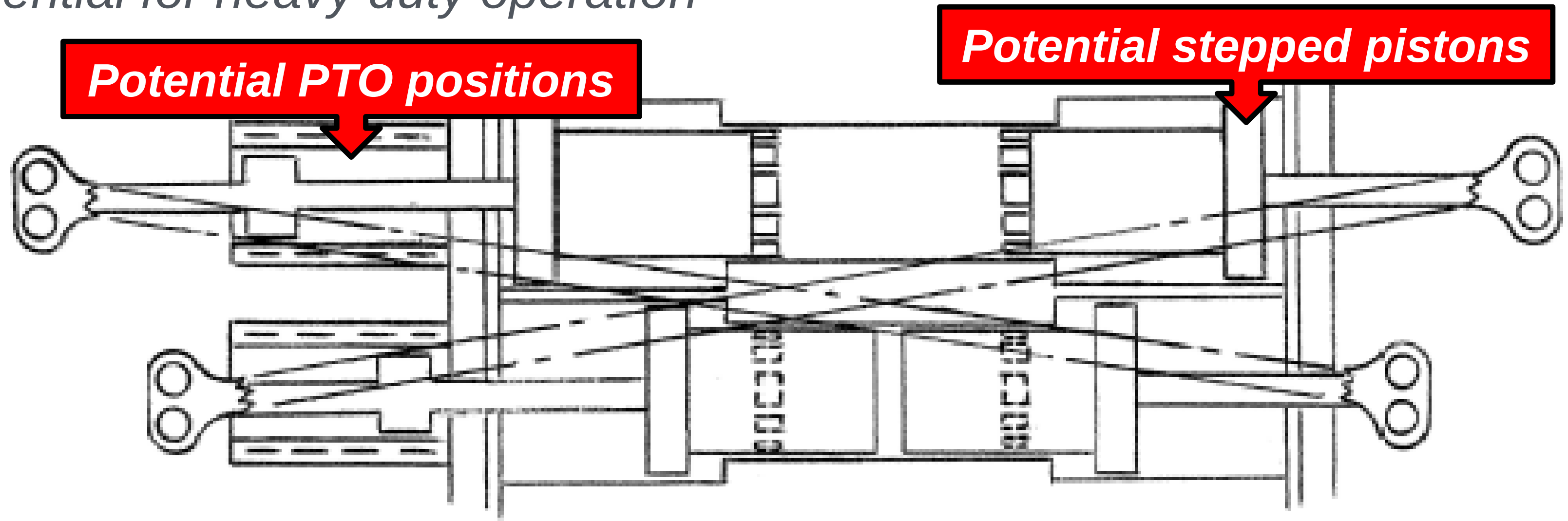
The system alternates between two states

Colours 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

Further Observations

- The PTOs can attach directly to a piston or anywhere along the cross links
  - *Can then optimize form factor and balance*
- Pumping and bounce chambers can be incorporated on one or either end
- Stepped pistons offer possibility of further system integration
  - *Incorporating the scavenging system*
- Like all OP engines, the concept has synergies with hydrogen fuelling
  - *Clear potential for heavy duty operation*



A Ph.D. study will start on this concept this year

CONCLUSIONS

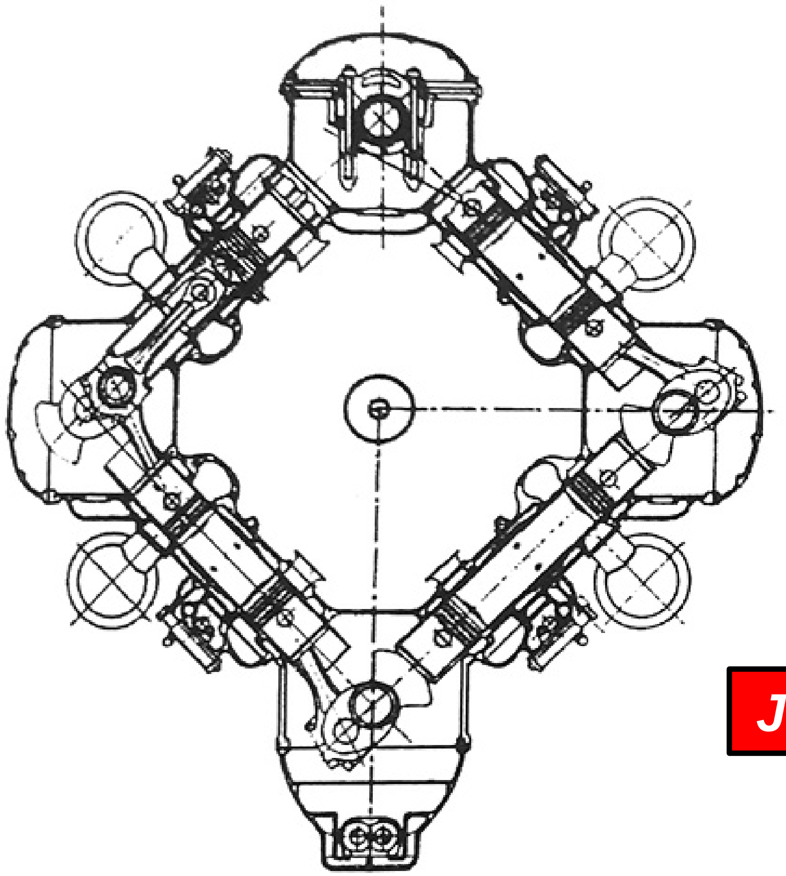
intelliGEN 20kWe development OP engine platform

Image courtesy Libertine

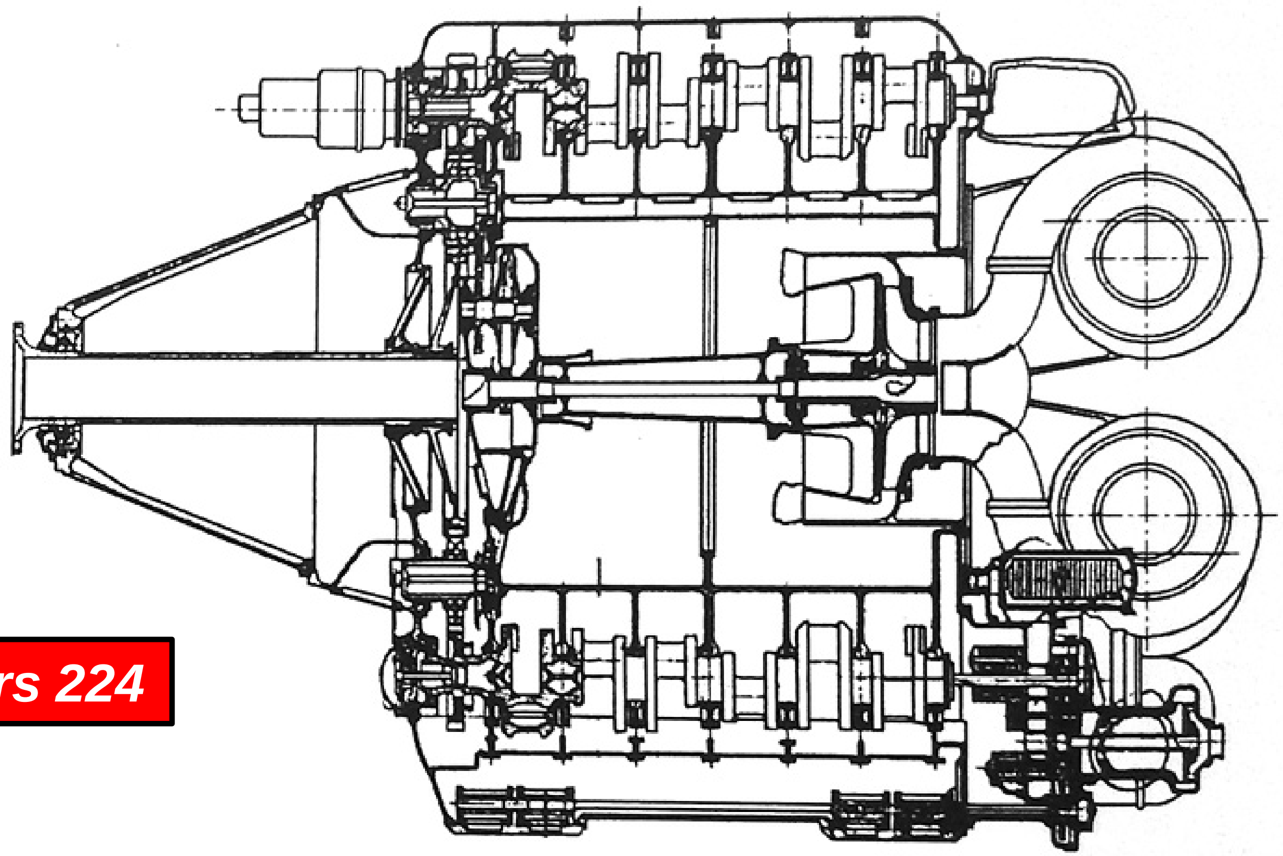
The Potential of the Opposed Piston Concept…

- The OP2S has significant potential to maximize thermal efficiency versus other positive-displacement engines
- Crankshaft offset can be used instead of phasing
  - *Giving the potential to reduce friction*
- VCR can be incorporated relatively simply by phasing the pistons
  - *High CRs can be reached because of the elimination of valve cutouts*
  - *Piston-to-piston clash can be eliminated at the design level*
- There are significant opportunities with hybridization
  - *VCR, improved machining, assembly, and NVH, and reduced friction and engine mass*
- A new scheme has been introduced to permit an optimized free-piston OP2S
  - *Using cross-linked pistons*
  - *Reduces the number of electric machines with the potential to improve their control*
- There are synergies between the OP2S and hydrogen
  - *To be discussed at the KAUST Low Carbon Mobility Conference*

THANK YOU FOR LISTENING



Junkers 224



Grateful acknowledgement:

Saudi Aramco: Funding the collaborative scavenging system study, and significant contribution to literature searching and results interpretation within it