The Recuperated Split Cycle Engine:
A practical Hydrogen solution for Heavy Duty?

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Dolphin N2: Established to commercialise the game-changing Recuperated Split Cycle Engine

DOLPHIN N2

Dolphin N2 Limited

- Established in 2017 to commercialise IP originating in the UK engineering company, Ricardo
- Acquired by FPT Industrial, part of the Iveco Group, in 2019
- Based UK, ~35 staff
- Multi-cylinder prototype running since December 2020

Why?

- High thermal efficiency – 55-60% BTE
- Low emissions – NOx at SULEV or below with standard SCR
- Fuel compatible – Diesel, Methane, Hydrogen
- *Targeting heavy duty, long-haul sectors where most commercial vehicle CO_2 originates, and alternatives are most challenging…*

Collaborative Projects & Partnerships

Innovate UK

ADVANCED PROPULSION CENTRE UK

Step CO_2

RE-ARMD

HIFLUX

The University Of Sheffield. Advanced Manufacturing Research Centre BOEING

University of Brighton

zircotec

FPT POWERTRAIN TECHNOLOGIES

IVECO • GROUP

How it works: Recuperated Split Cycle Engine
Re-thinking ICE thermodynamics for cleanliness and efficiency

The Basic Cycle

- **Dedicated Cold & Hot** cylinders of unequal size
- **Insulation** of hot cylinder
- **Recuperation** of exhaust energy
- **Low-NOx Cool Combustion** enabled by dense sonic intake air
- **Cooled Compression**

ThermoPower:

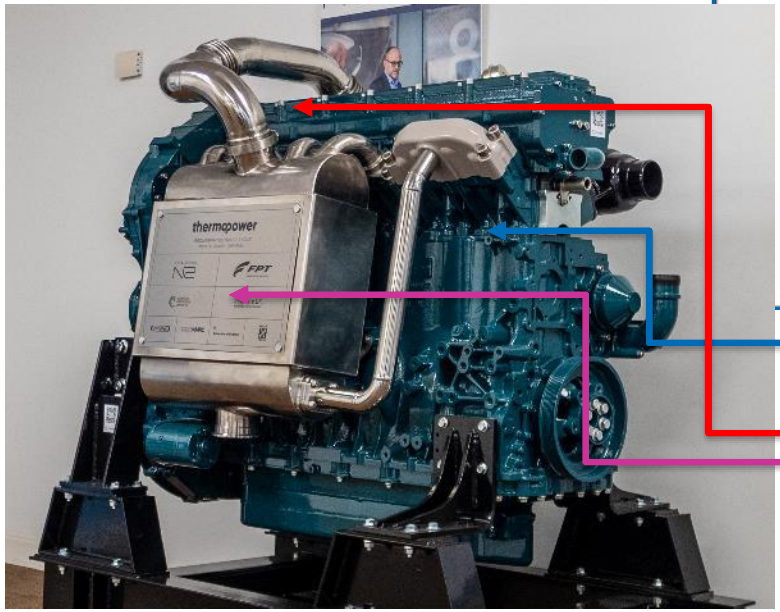
Trucks, NRMM, Shipping

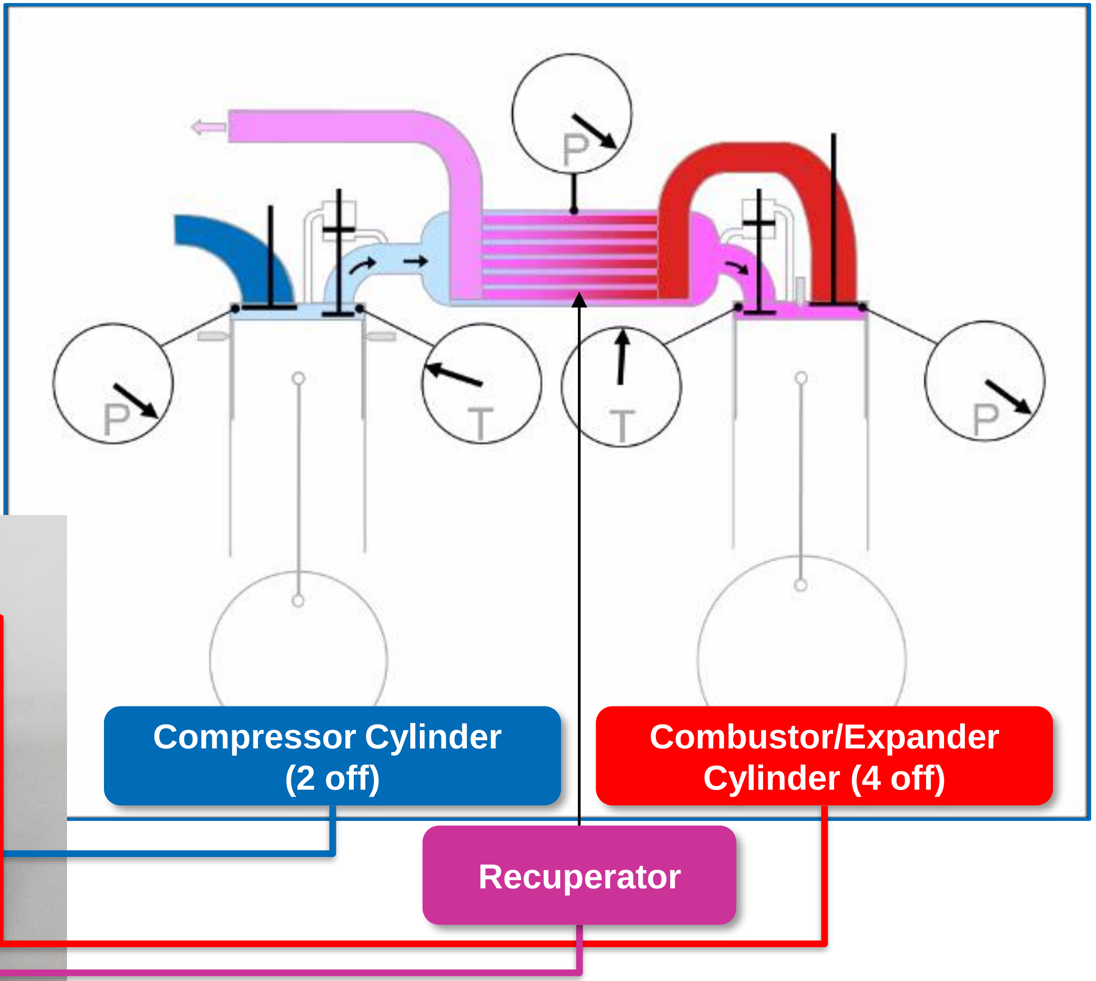
- **Water** injected at ~33% fuel by mass
- *Up to 55%BTE, SULEV*

CryoPower:

Stationary Generation

- **Liquid Nitrogen** injected, 3x fuel by mass
- *Near ~ZEV, ~60%BTE*
- *LiN made using wrong-time renewables*

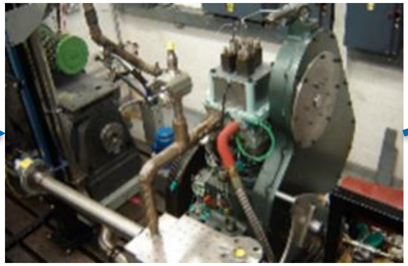




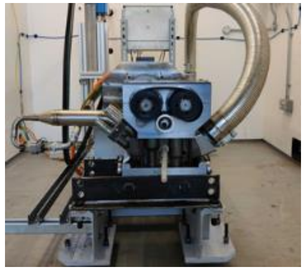
Running hardware (Diesel): “Mule” multi-cylinder engines were used to develop challenging mechanical systems – now validating thermodynamics

2017-20 Singles & Rigs | 2021-22 Mule Engine | 2022-3 Integration

Titan: Single cylinder Expander (Brighton Uni), exploring combustion and thermodynamics

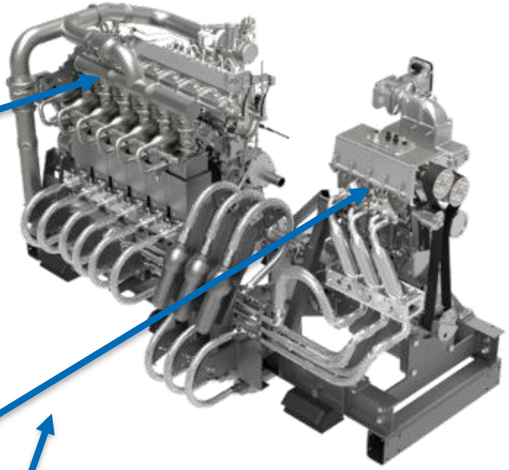


Hydra: Single cylinder Compressor (Brighton Uni), compression cooling



Breathing rig: Dynamic high pressure rig, exploring valvetrain and port performance

(Sheffield Uni AMRC)



Mule Engine: Multi cylinder 267kW unit, built on base hardware of two FPT engines

Development challenges overcome

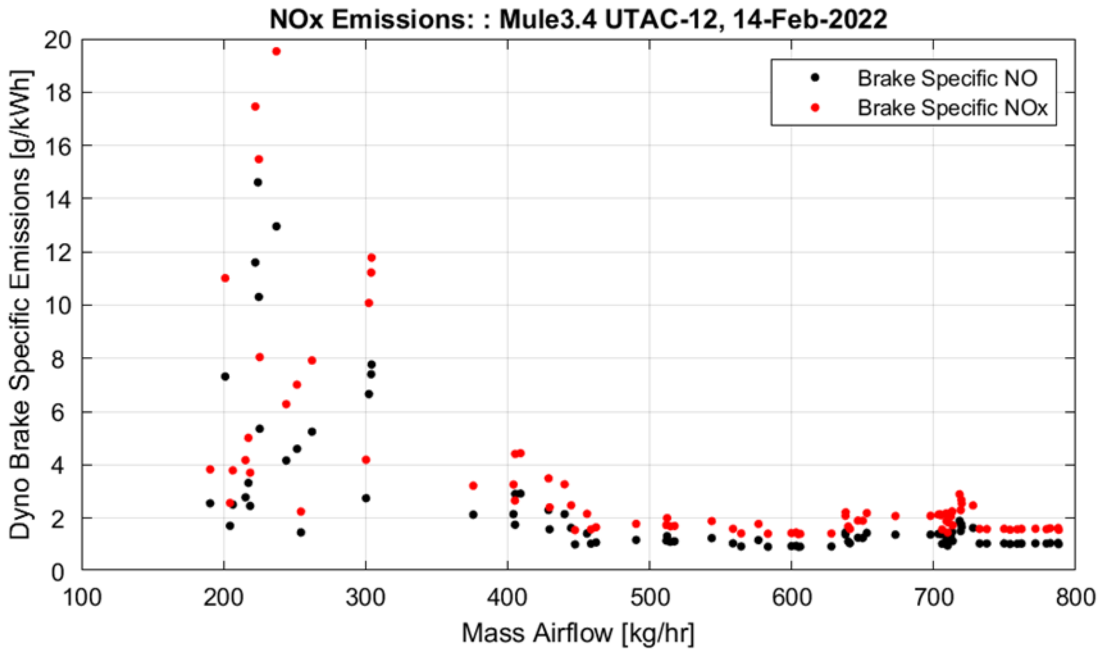
- *Startability & warm-up transition*
- *Ceramic insulation durability*
- *Recuperator life at 70 bar 800°C*
- *Extreme thermal loads, piston & ring durability*
- *Valvetrain at 70 bar, <30deg open, 180deg VVT*
- *Boosting & airpath control*

Integrated Engine

Package compatible with 4-stroke

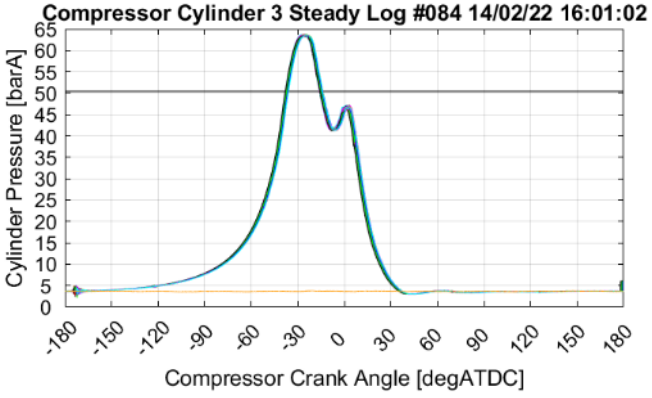
Truck, off-highway, marine and power-gen application

Results so far: Base engine delivers low NOx readily; development toward efficiency targets advancing



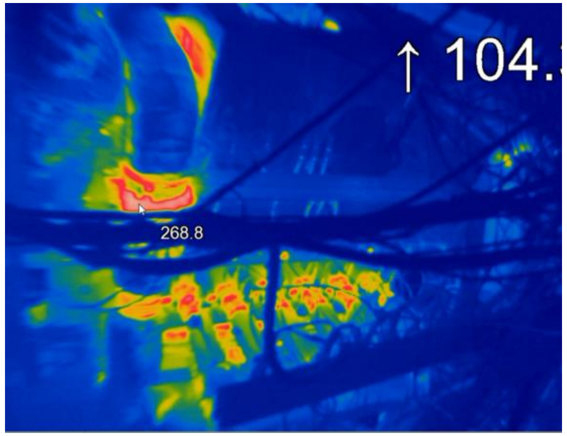
- Low NOx <2g/kWh achieved at a range of ratings up to high load (torque curve target ~1000kg/hr)
- Trigger for clean combustion found to be a function of high air density, high air temperature, and the right small quantity of trapped residuals
- Light load values represent running out of proper split cycle mode; development ongoing

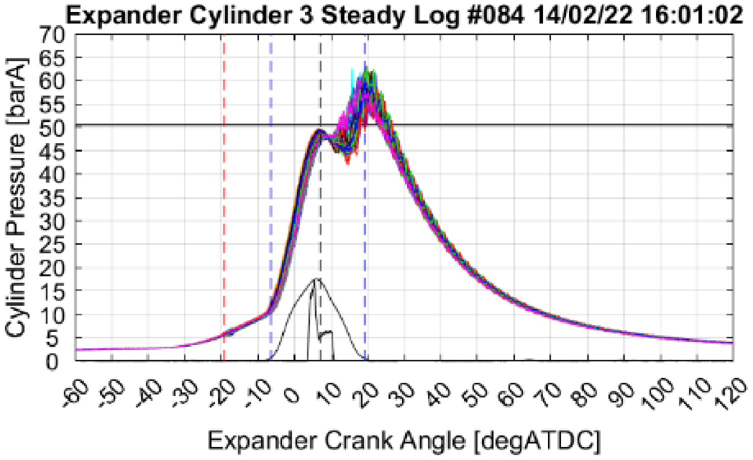
- Indicated efficiency development is ongoing and on track to target; illustration of some key "levers" is below:



Compressor efficiency can be optimized via valve timings – in this case discharge opens too late, leading to pressure peak and negative work

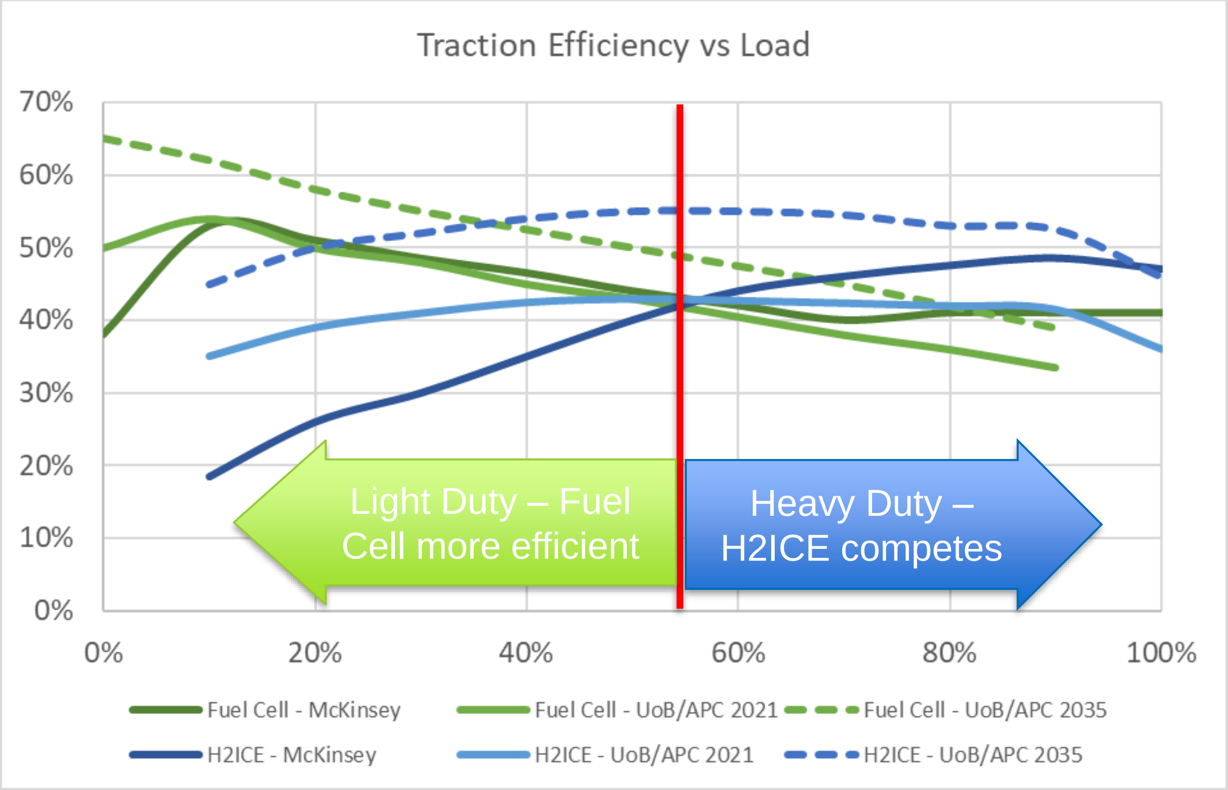
Expander efficiency is driven by reducing recuperator heat loss, minimizing pre-TDC pressure, and developing faster burn





What about Hydrogen?
Favoured on-highway fuel; RSCE is fairly fuel-agnostic

- **Hydrogen is politically favoured as "alternative to electricity" for on-highway application**
  - Readily produced from renewables, zero "source to tank" & net GHG (which matters)
  - Zero GHG at tailpipe (politically popular)
  - Fairly quick refuelling
  - Energy density acceptable with compromise
  - Suits both Fuel Cell and ICE – creating critical mass of demand
- **Hydrogen ICE works and is fast to adopt**
  - Same supply chain, familiar servicing
  - NOx entirely manageable via lean burn
- **And it suits Recuperated Split Cycle well…**
  - In principle, "fast oxidation" combustion is fuel agnostic – violent mixing with red-hot sonic and supercritical air will burn many things
  - If Hydrogen can maintain BOTH high efficiency and low NOx, advantage is clear…



Fuel Cell vs Hydrogen ICE: *Reports from McKinsey (2021) and APC / University of Brighton (2021) highlight how the higher loads of Heavy Duty might favour an efficient Hydrogen ICE*

Chemical kinetics modelling suggested that Hydrogen combustion was feasible – though (unlike Diesel) an ignition source is needed

- 0-d, fixed volume Chemkin model used as an approximation to RSCE combustion
  - There are compromises in the simplifying assumptions, but the same approach had been found to correlate indicatively with Diesel test data
- Analysis performed for Hydrogen, Methane and blends
  - Bio-methane is another future fuel of interest, already growing in popularity in agricultural propulsion
- The model looked at HCCI auto-ignition, and spark ignited
  - **Spark Ignited** showed lower ignition temperatures and NOx formation
  - **Pure HCCI** impractical – marginal ignition, and no possibility of a cold start
  - **Dual fuel** likely to lie between the two cases, some potential to minimise or turn off pilot fuelling at load

Results from compression (HCCI) strategy
– high pre combustion temperatures required

HCCI nH 0.1 mole fraction Fuelφ0.4 60 atm	Minimum ignition temperature (K)	NOppm at peak temperature	NOppm at 5ms
CH4	1125	8.16	172.22
H2575	1100	7.28	137.50
H5050	1050	6.27	124.09
H7525	940	1.88	29.37
H2	1000	4.81	133.19

Results from Spark Ignition strategy
– Lower initial temperature required and lower overall NOx emissions

SI Fuel φ0.4 60 atm	Minimum igntion temperature (K)	NOppm at peak temperature	NOppm at 5ms
CH4	775	1.10	1.72
H2575	750	1.01	1.59
H5050	720	1.01	1.59
H7525	700	1.58	2.48
H2	600	3.08	4.84

A single-cylinder experiment was devised to validate Hydrogen combustion – practicalities of FIE and ignition dominate

Aims

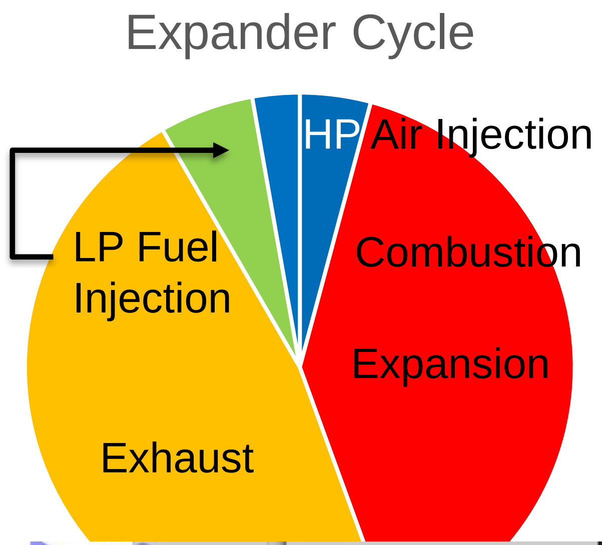
- Can stable RSCE combustion be achieved? (misfire, knock)
- Can the same efficiency and low NOx as Diesel be achieved?

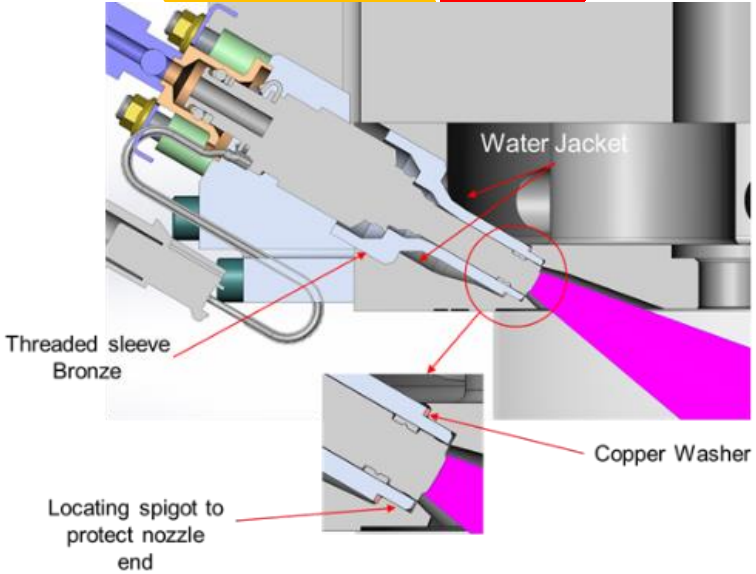
Approach – Single Cylinder Engine

- Dual Fuel (Pilot ignition) was selected as the most robust approach, as the engine was known to start and run on Diesel
  - Allowed progressive introduction of Hydrogen
- The original, central Diesel injector was retained
- And a new, Hydrogen injector added from the side of the chamber
  - Driven by package constraint; not ideal location but suitable for a basic validation experiment

Hydrogen injection

- Must be Direct Injection
- HPDI is ideal, but only one supplier, unit would not package
- LPDI (35 bar) injector used, with injection starting before the high-pressure air
- This approach limits us to ~25% load





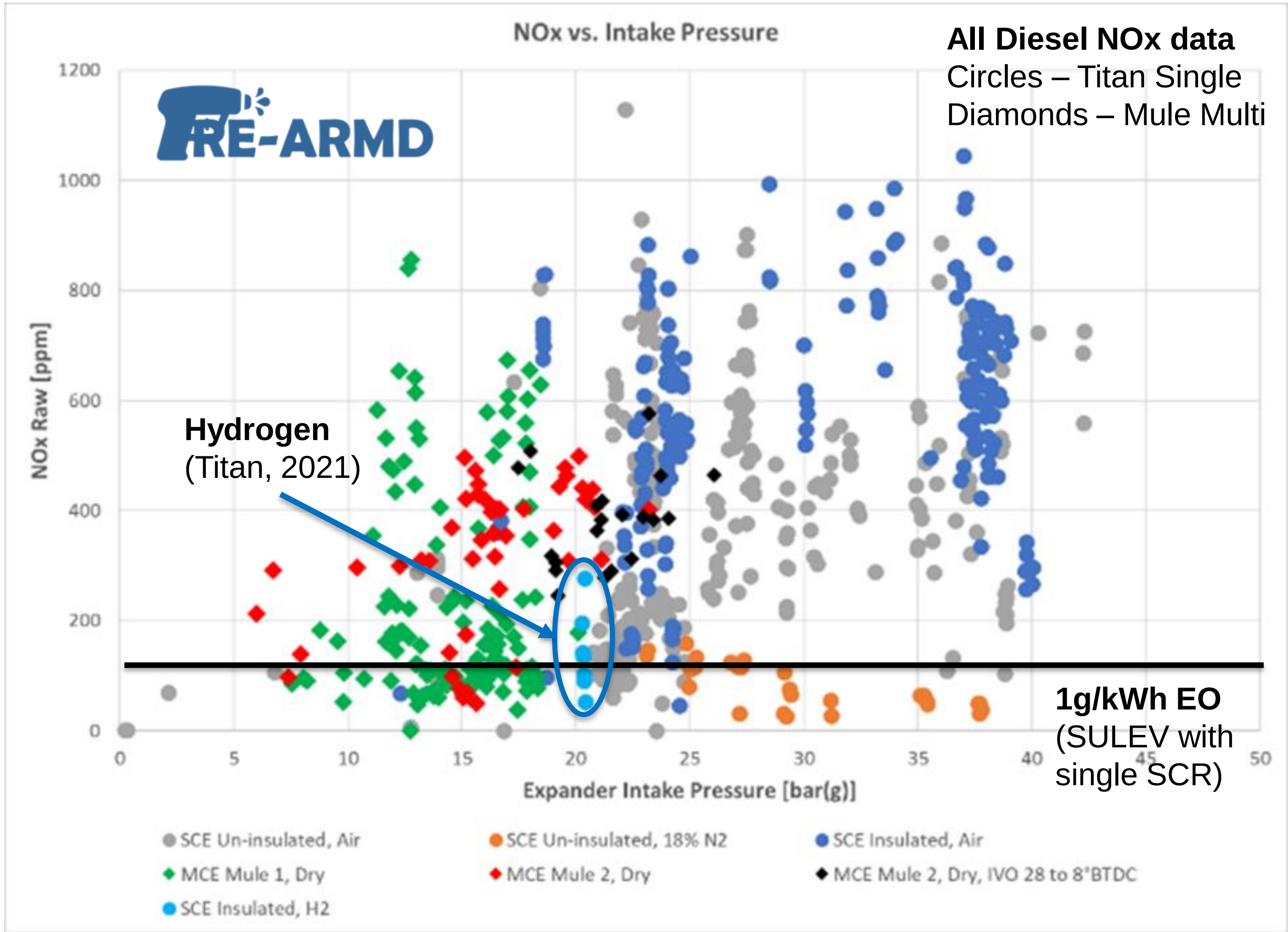
Low NOx emissions were validated by test results – equal to best Diesel calibrations from Single & Multi cylinder testing

Split Cycle on Diesel

- These are engine-out emissions (no catalytic after-treatment)
- A typical modern Diesel truck engine produces 7-10g/kWh Engine Out (above the data band here)
- Best Split Cycle results on Diesel were **below 1g/kWh EO – SULEV with SCR**

How does Hydrogen compare?

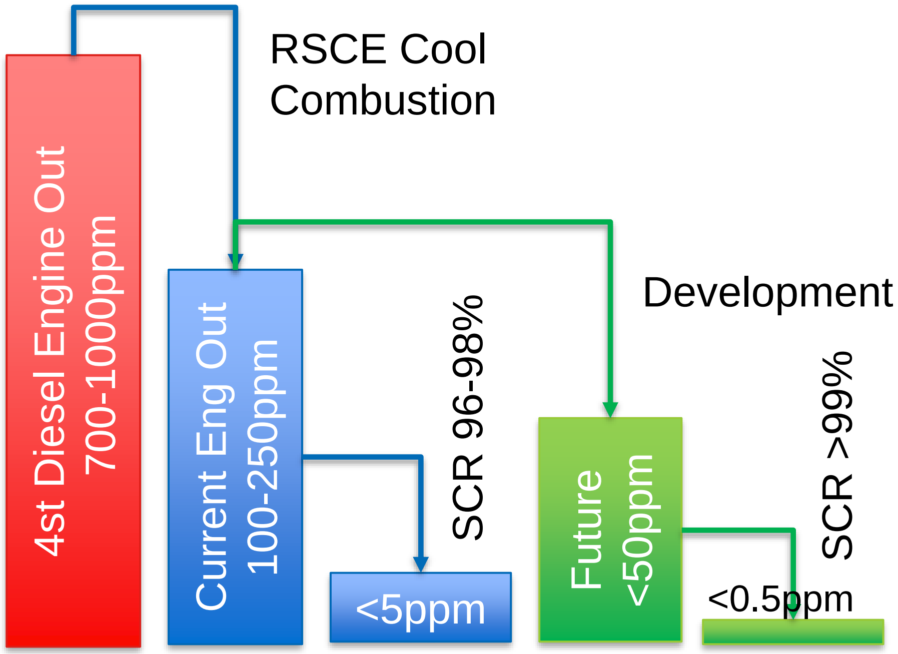
- Operation limited to 20 bar air pressure, to get enough hydrogen in
- Energy input limited to 55% hydrogen to keep heat in the process
- But, **same low NOx readily achieved**, and no detonation or misfire seen



What this means – possible to get to SULEV NOx or below
At this level, impact on human health is well below other threats

Aftertreatment – modelled performance (on Diesel)

- Chemical-kinetics model: Cu-SCR catalyst
- 97% without NH_3 surplus, 98-100% conversion at 1.1
- 5ppm is equivalent to **SULEV (27mg/kWh)**
  - **Readily done**
- 0.5ppm is attainable, this is ~1000µg/m^3 –
  - **Same as poor UK city ambient – air cleaner!**



Emissions in Context

A study was performed for Dolphin by Ricardo Energy & Environment, using DEFRA factors to estimate human health impacts.

SULEV NOx vs EuVI: Converting the whole UK truck fleet would save **~4000 life-years** per annum

SULEV NOx vs absolute ZEV: Cost is **253 life years**, equivalent to 3.5 hours of the average life.

In context:

- UK Covid-19 so far*: ~350,000 life-years
- Pandemic every 100yrs 3,500 life-years
- Road traffic fatalities 76,000 life-years
- SULEV HD NOx vs ZEV 253 life-years (~3.5h average)
- 10% SULEV future 25 life-years

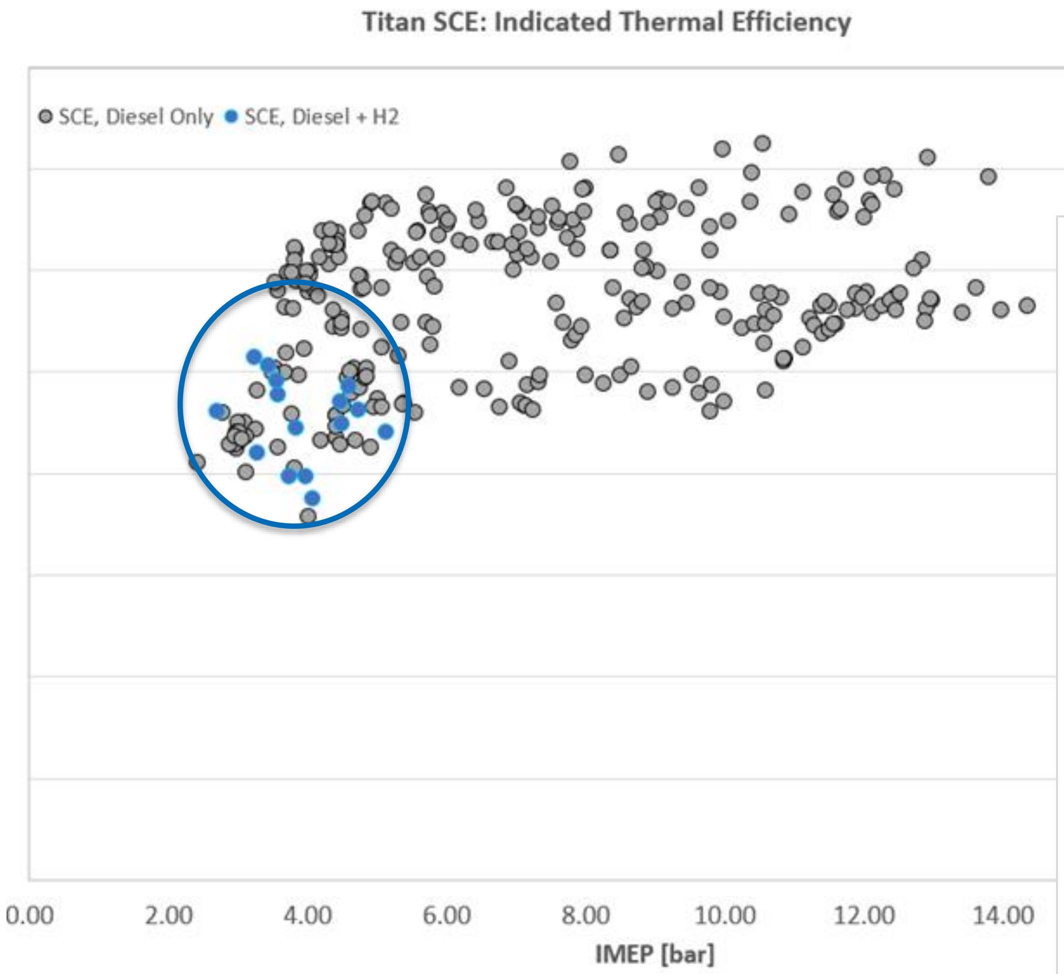
Perhaps we should focus on things that save most lives?

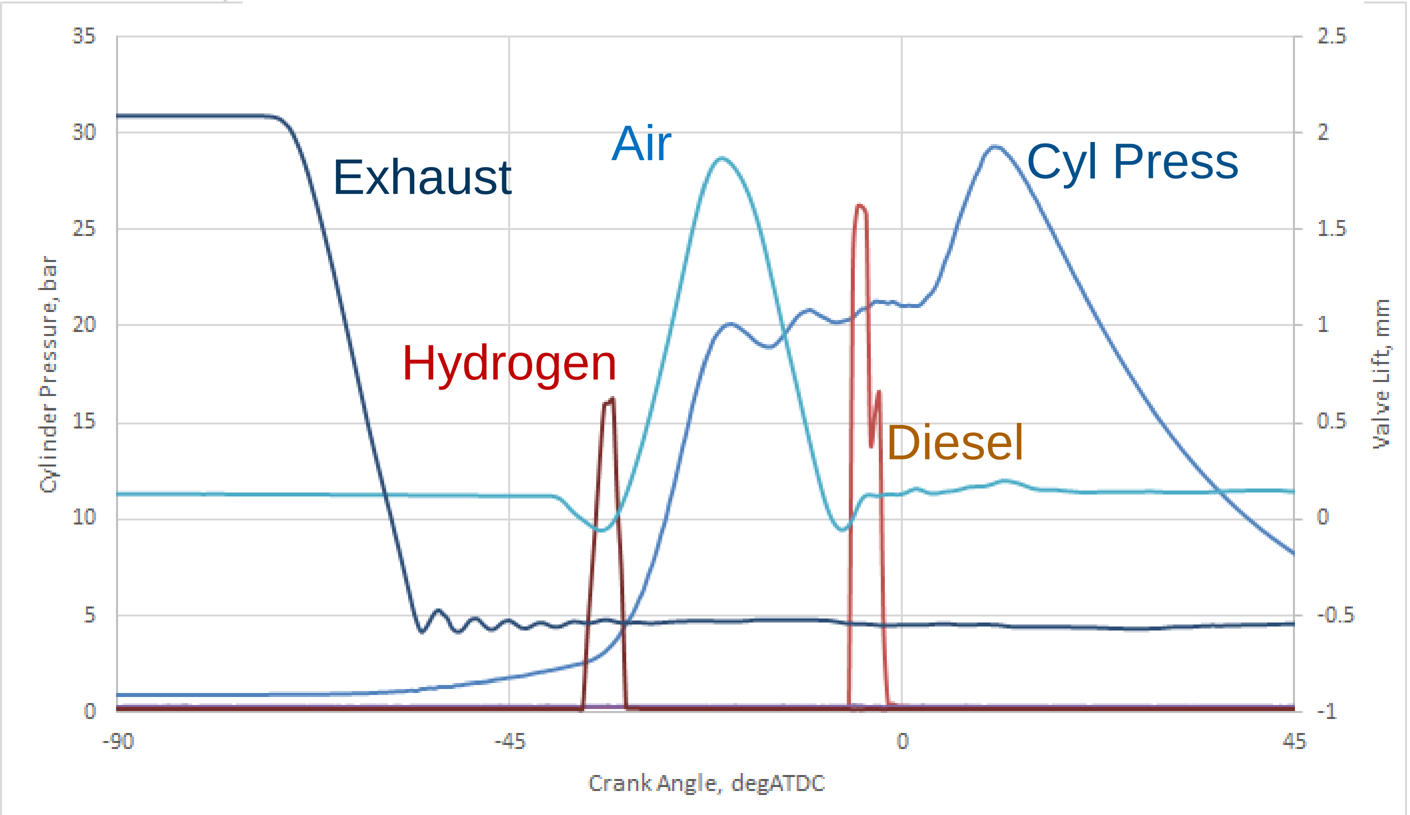
Sources: Analysis by Ricardo E&E and Dolphin N2
Please note that estimates are subject to assumptions made. COVID data is from a year ago, Feb'21

Indicated efficiency – similar to Diesel RSCE at light load, even though in-cylinder events are compromised by equipment limitations

Scope for optimization

- Shorter, later intake valve (air injection) event removes negative work on piston
- Later, HPDI Hydrogen does same, allows later EVC, improves mixing, and reduces risk of detonation
- Faster burn and higher load improve ITE





Conclusion: The Hydrogen ICE is a key enabler for Net Zero; Recuperated Split Cycle Engine offers a step ahead in efficiency

Hydrogen ICE as an enabler

- Capable of being clean (local air quality) – including NOx
- Cheap, impurity tolerant, easy to make, integrate to vehicle, and service

Recuperated Split Cycle Engine as a step ahead

- Significant mechanical challenges of the base concept now being overcome
- Low NOx and efficient thermodynamics increasingly demonstrated
- Hypothesis that these can be achieved on any fuel validated with Hydrogen
- Potential to take on the Fuel Cell – or simply help it into the market by justifying fuel infrastructure

Next Steps

- 2022: Single cylinder testing of a spark-ignited system (limited load)
  Testing of HPDI dual fuel (full load range)
- 2023: Demonstration in vehicle