Following TRL to Enable the H2 Value Chain

Dr Mark Eldridge
Director of Hydrogen Nov 2023

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THE JOURNEY SO FAR

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275+ LOCATIONS

9,500+ PEOPLE

30+ COUNTRIES

ENERGY & ENERGY TRANSITION

TESTING, INSPECTION AND CERTIFICATION FOR

55,000+ CUSTOMERS

- CONNECTED TECHNOLOGIES
- MOBILITY
- LIFE SCIENCES
- BUILT ENVIRONMENT
- AEROSPACE

OUR PURPOSE

MAKING TOMORROW SAFER THAN TODAY

60%+ REVENUE HELPING CUSTOMER SUSTAINABILITY JOURNEYS

#1 ESG RANKING IN INDUSTRY VIA SUSTAINALYTICS

10x REVENUE GROWTH TO OVER $1.5B

50 ACQUISITIONS

Following TRL & TIC Services

Time, Hydrogen ,Other Options – Systems Thinking

The importance of TRL and H2 Value Chain

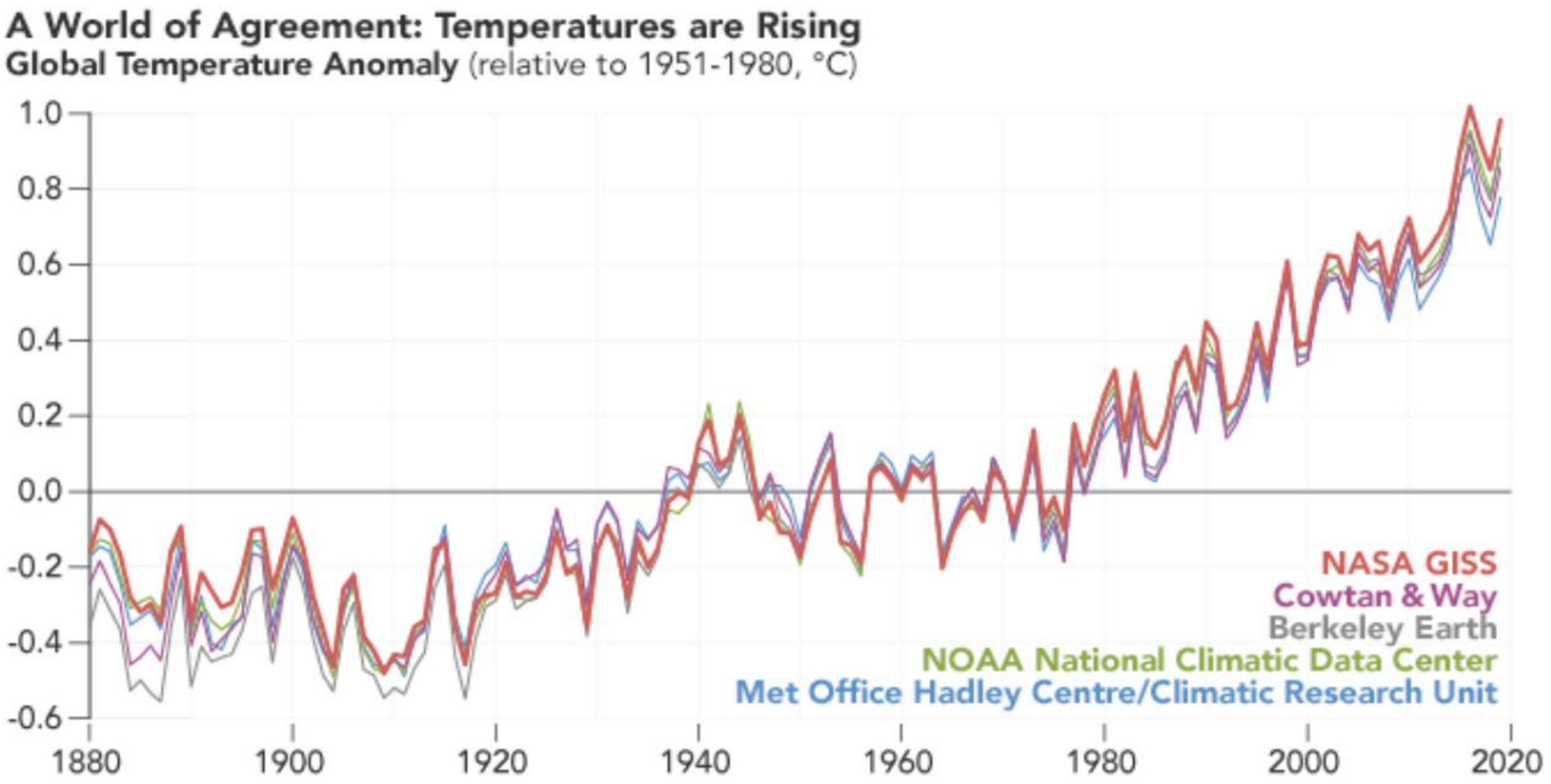
Some Characteristics of Hydrogen

Some Elements of Element

From testing, to following TRL

How we are looking to help?

The Rapid Need to Decarbonise



Global temperature anomaly (relative to 1951-1980) Image: NASA: Earth Observatory

TIME ?

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ITS NOT JUST HYDROGEN

Hydrogen Must Always be Considered as Complimentary in the Energy System based on Sound:

Economic
Thermodynamics and Metallurgy
Environmental
Alternatives
Specific Contexts
AND/OR – to Both?
Where is the system boundary

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System, Context, End Use, Properties

H2 We need to look at the whole system

NEW

EXISTING

Resources

Coal | Natural Gas | Biomass/Waste | Nuclear | Solar & Wind

Production

Gasification | Reforming | Pyrolysis

Carbon Capture Use and Storage (CCUS)

BLUE HYDROGEN

WATER

Electrolysis | Photo and Bio Catalysis | Thermochemical Cycles

GREEN HYDROGEN

Storage & Transport

Compressed Gaseous H2 | Liquid H2 | Ammonia | Liquid Organic Carriers | Hydrides and Solids

Pipelines | Road | Rail | Shipping

Utilisation (End Use)

Chemical Feedstock | Aerospace | Mobility | Energy Plants & Storage | Combined Heat and Power

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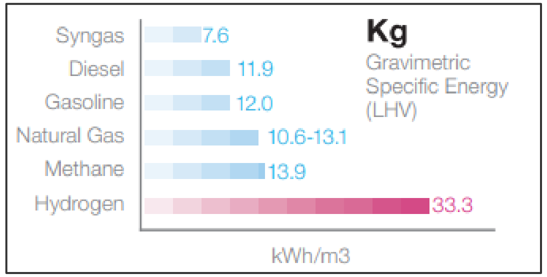
Fundamentals also drive TRL..

90% of our Universe atoms are H2
10% of our Body
Common Water reference
Only element that can exist without neutrons



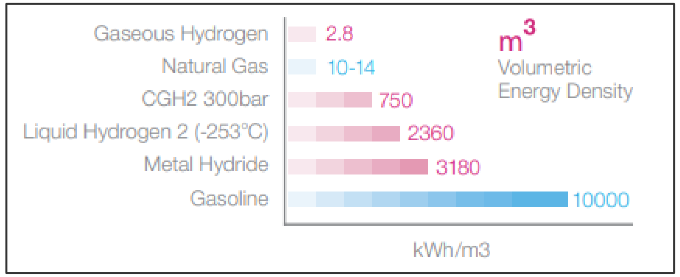


Table 1 - Characteristics of hydrogen, dry natural gas and gaseous propane

Property	Dry natural gas (methane)	LPG (propane)	Hydrogen
Density (Kg/m^3) *	0.65	1.88	0.090
Diffusion coefficient in air (cm^2/s) *	0.16	0.12	0.61
Viscosity (g/cm-s x 10^{-5}) *	0.651	0.819	0.083
Ignition energy in air (mJ)	0.29	0.26	0.02
Ignition limits in air (vol %)	5.3 – 15.0	2.1 – 9.5	4.0 – 75.0
Auto ignition temperature (C)	540	487	585
Specific heat at constant pressure (J/gK)	2.22	1.56	14.89
Flame temperature in air (C)	1875	1925	2045
Quenching gap (mm) *	2	2	0.6
Thermal energy radiated from flame to surroundings (%)	10-33	10 - 50	5-10
Detonability limits (vol % in air)	6.3-13.5	3.1 – 7.0	13-65
Maximum burning velocity (m/s)	0.43	0.47	2.6

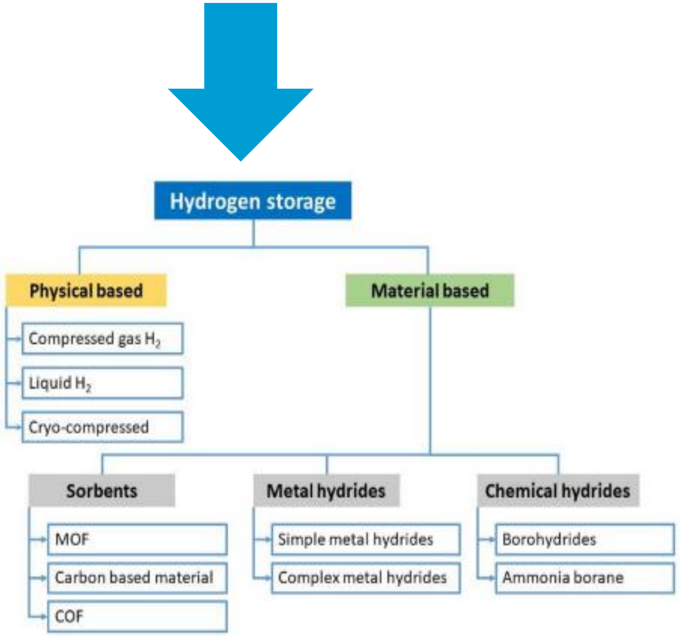
* at normal temperature and pressure – 1 atmosphere and 20°C

Propensity to leak
- Low Viscosity
- Very high diffusivity
- Likelihood of Embrittlement

Storage Volume
- Transportation
- Weight
- Technical Challenges

Propensity to Ignite
- Wide flammability range
- Very low ignition energy
- Spontaneous Ignition

Consequences of Fire and Explosion
- Invisible Flame
- Rapid Burning Rate
- Possibility of detonation



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Go to Market Strategy

Market Maturity

Where are you with H2 TRL?

CHANGE REQUIRMENTS
Element Offering: Full Life Cycle Service

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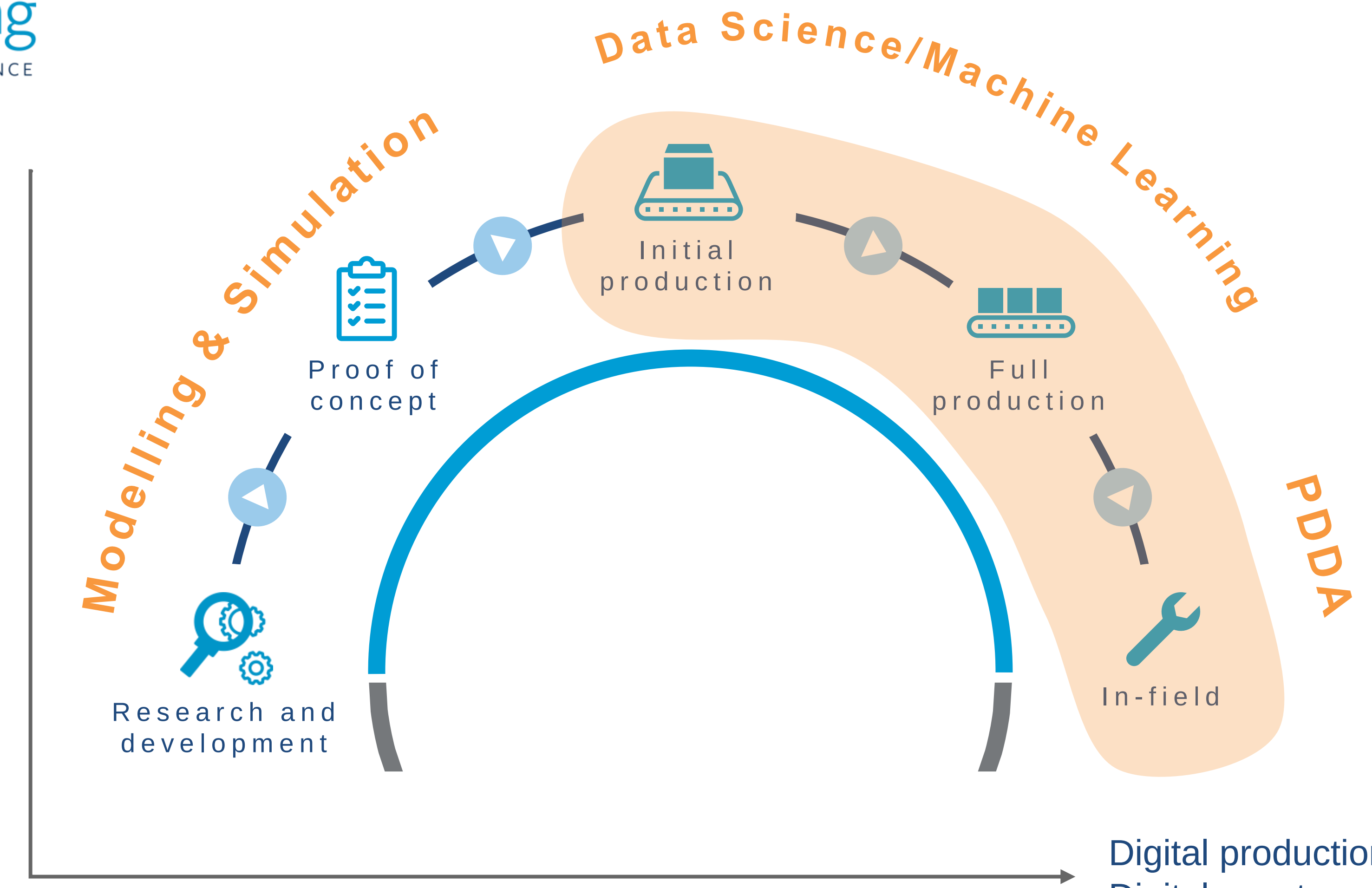
Digital Engineering
MODELLING | SIMULATION | DATA SCIENCE

Extension to core services

One stop shop for product development

Faster and cleverer R&D iterations



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Core Services
Production
Test & Validation
Inspection
Low Digital
Late TRL R&D

Digital production support
Digital asset management

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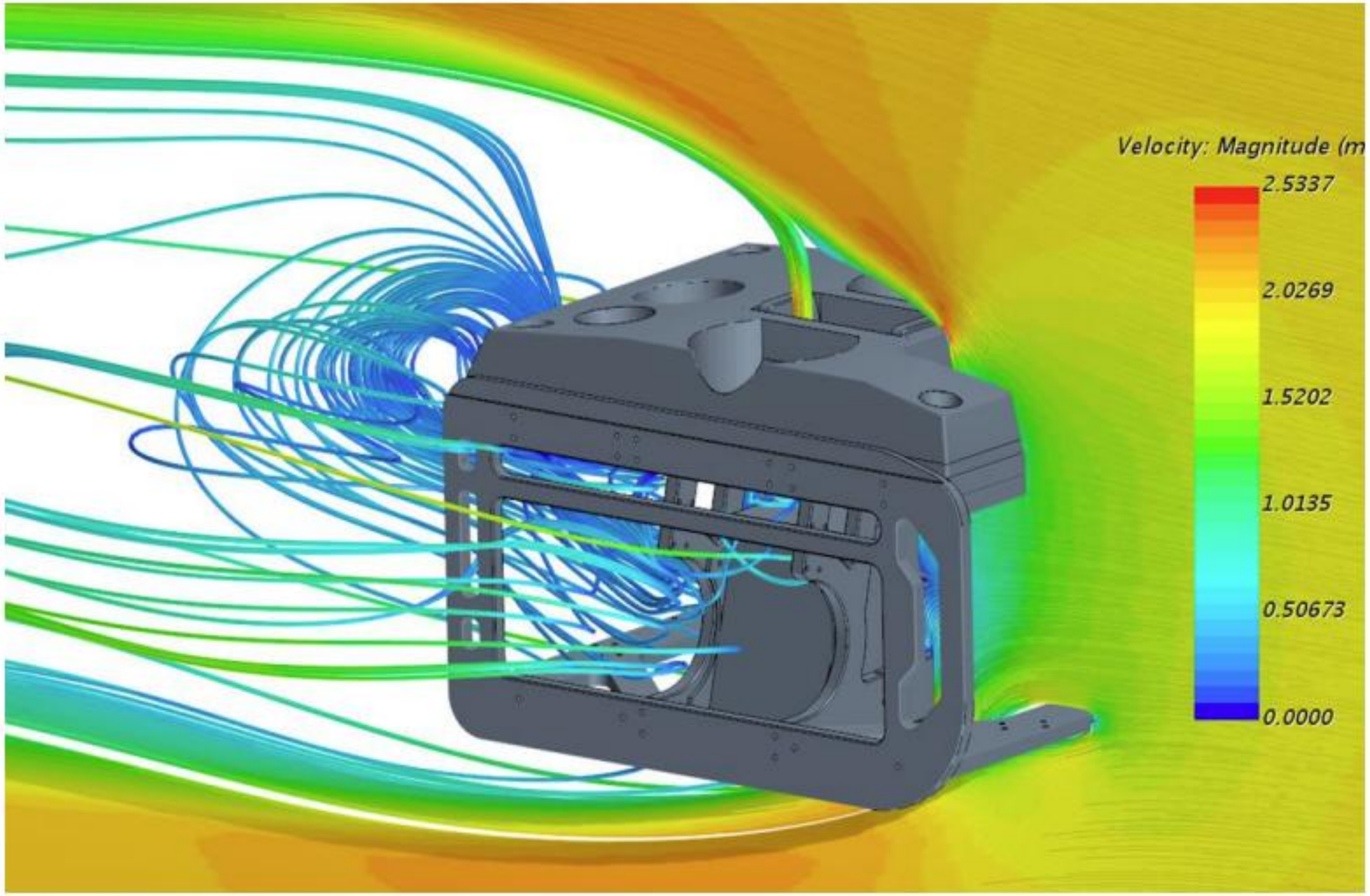
Digital Engineering

Broad Expertise

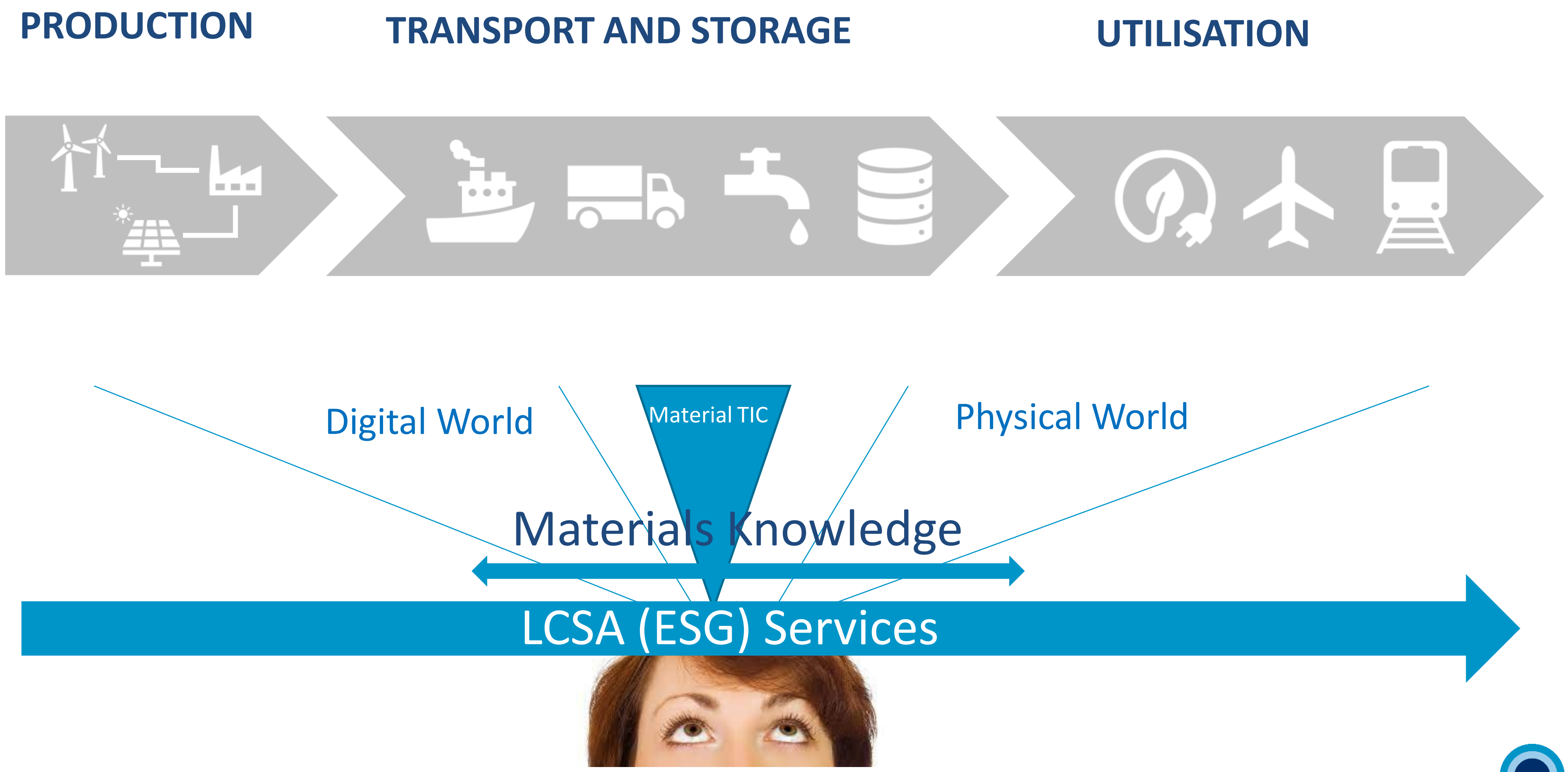
Numerical analysis
- Fluid dynamics
- Structural dynamics
- Process simulation
- Safety analysis
- Acoustics
- Electromagnetics

Digital and Data
- Reduced order modelling
- Data analysis
- Software Development
- Uncertainty quantification

Management support
- Techno-economic analysis
- Real Options Valuation
- Business planning support



Element – Assuring Your Energy Transition



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TRL Service Examples from Aerospace

Element in Aerospace

Materials and Product Qualification Testing

Aerostructures

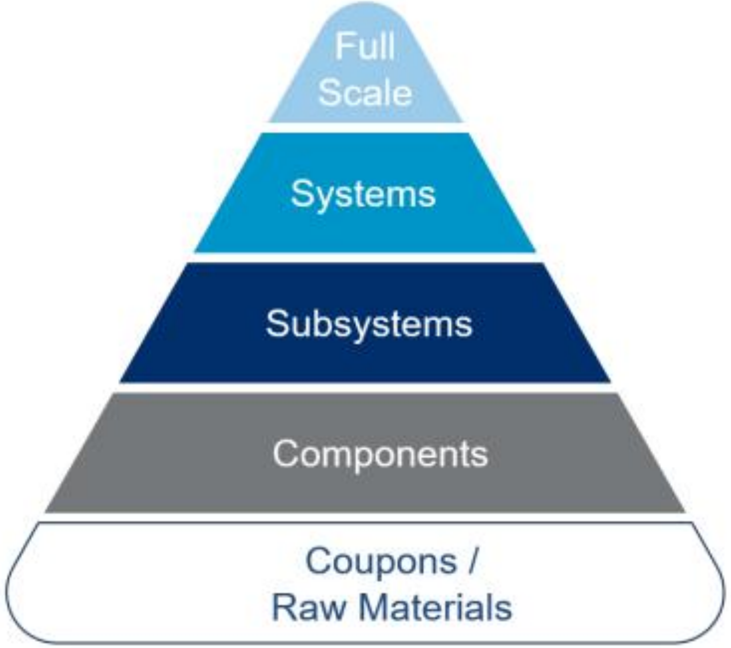
- Air fuselage
- Center fuselage
- Nose section
- Fasteners
- Fittings
- Seals
- Wing leading & trailing edge
- Slats and flaps

Airframe Systems

- Sensing Systems
- Actuators, Shock struts
- Landing Gear
- Wheel & Brakes
- ECS System
- Pumps & Valves
- Avionics
- Refuelling Systems

Engines

- Fuel systems
- Fan blades
- Compressor blades
- Turbine blades
- Vanes
- Cases
- Combustors
- Sensors



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System Scalability and Time

- Global H2 ~ 75 million tonnes per year - demand > projected to 621 million tonnes 2050.
- 75 Million Tonnes is Grey – without little or no CCUS infrastructure.

- e.g.Paris Orly Airport - filling up 30 percent of flights H2 - 270 tons of 'liquid' hydrogen pe
- Largest single liquefier - 32 tonnes per day (TPD), global capacity is 350 tonnes per day.
- Liquifaction – energy losses (~40%), Safety, Scale….

- Hydrogen from Electrolysis - 18 gigawatt-hours every day - one typical nuclear plant 900
- The electricity is produced through solar power, 44 square kilometers of solar panels would be needed—a footprint representing three times the entire surface area of the airport.

- Largest hydrogen-electrolysis plants today ~20 megawatts of capacity - maximum production of just 0.5 gigawatt-hours a day—A growth factor of 50x.

Hydrogen Liquifaction (Review Article) *Energy Environ. Sci.*, 2022, **15**, 2690-2731

International Energy Agency (IEA), Energy Technology Perspectives 2020, Paris, France, 2020.

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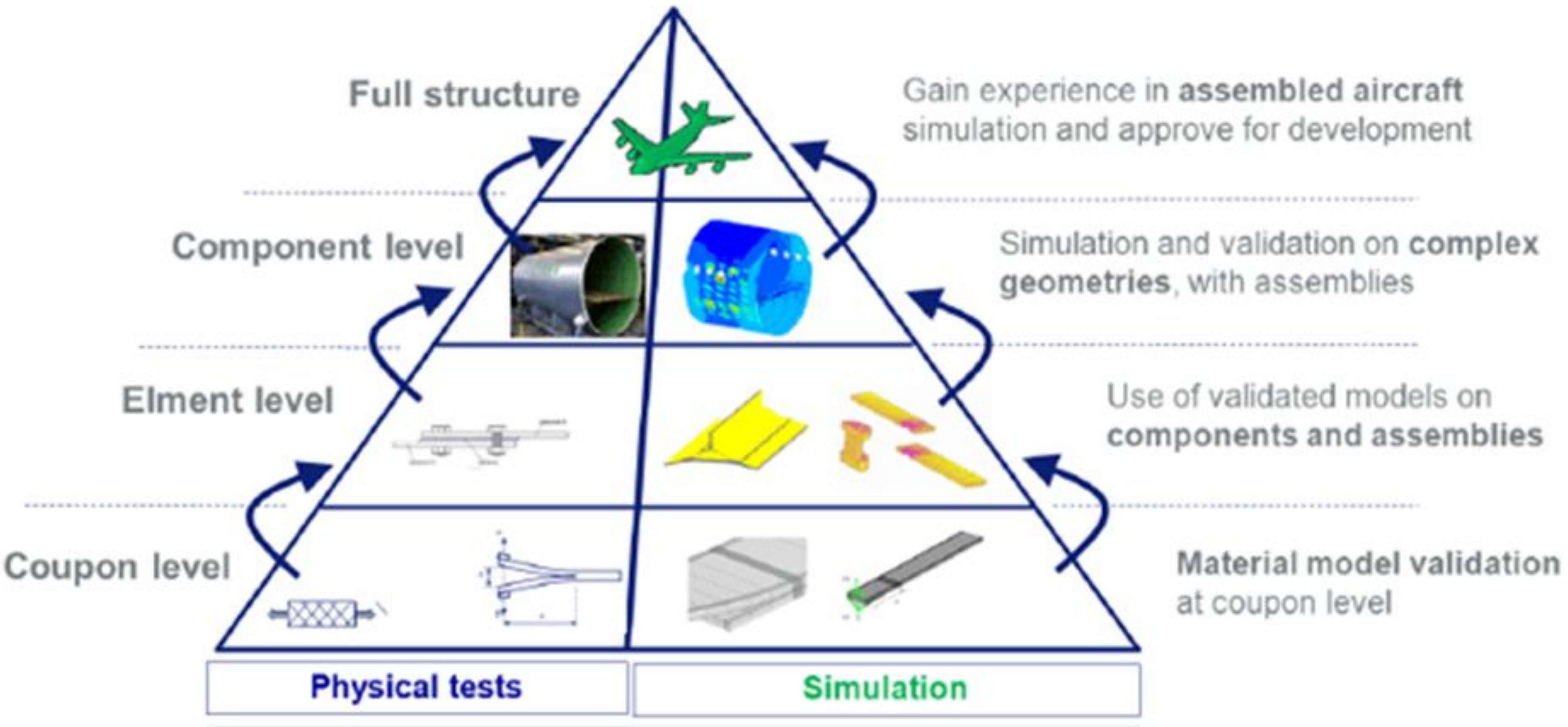
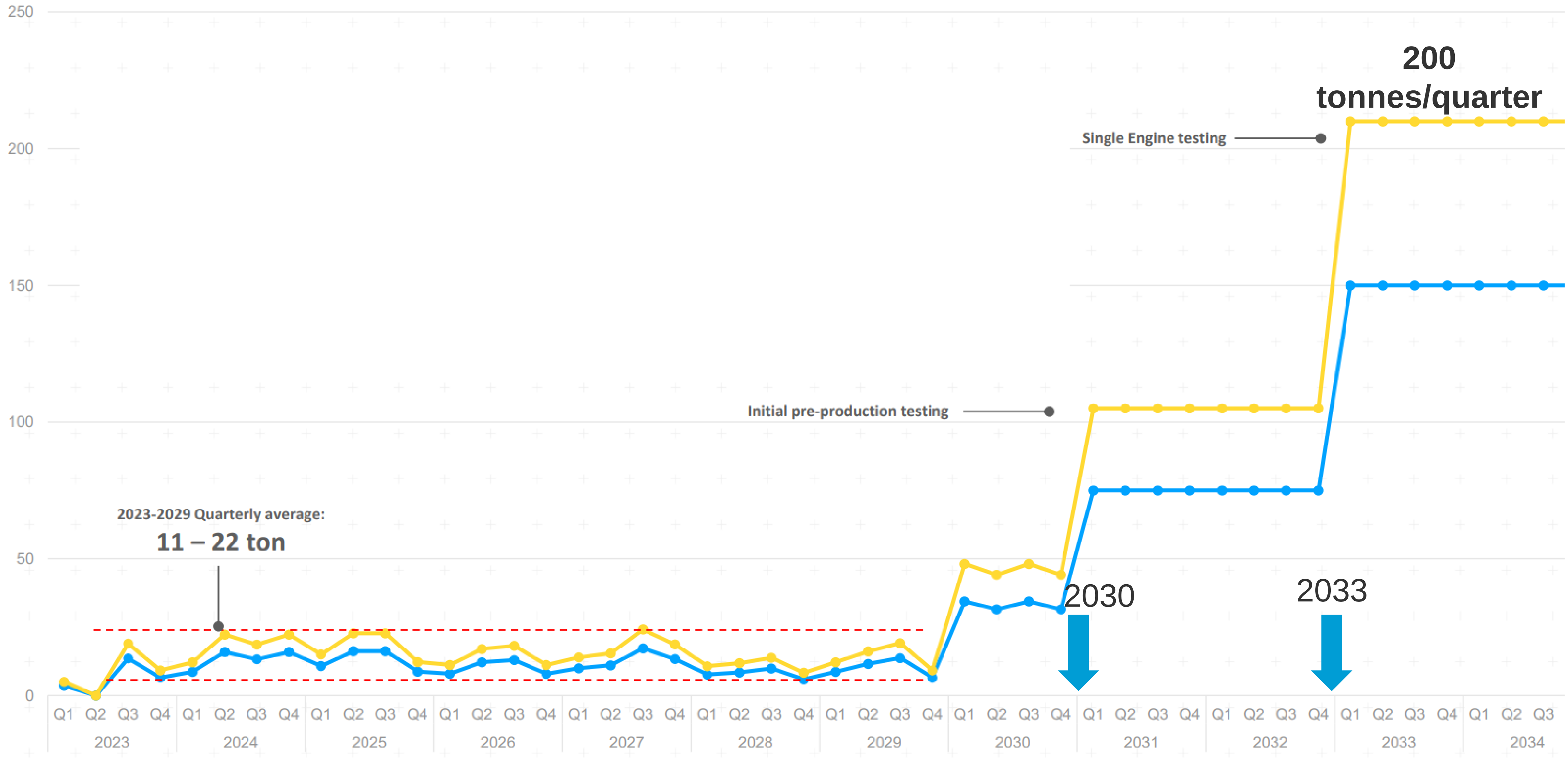
How do you get a H2 Aircraft in the Sky (at scale)?



‘UK’ Aero Anticipated LH2 (Development) Demand



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Hydrogen Fuel Test Facility

Located at our Kemble test facility we have recently upgrading the infrastructure to include both gaseous and liquid hydrogen testing, this is possible by our in-house designed and built liquefaction plant

Completely designed, developed, built, and operated by FSE

- Temp range: 18k to 800k
- Liquid H2 production rate 8kg/day
- Liquid H2 storage 16kg
- ATEX compliant

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Bloodhound – Iterative stress/design for optimised structural components.

- **Background**

- FSE worked with Bloodhound SSC to provide design and stress analysis for a critical structural component.
- The design was optimised through iterative stress analysis to minimise weight and maximise strength for sudden loading.

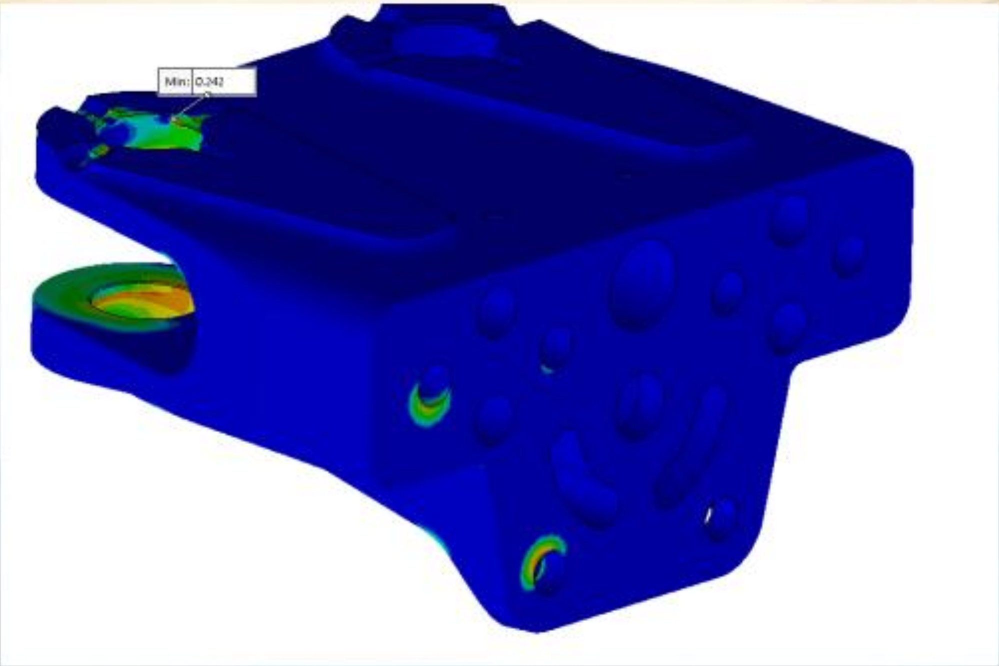
- **Capabilities**

- Mechanical design
- Stress Analysis

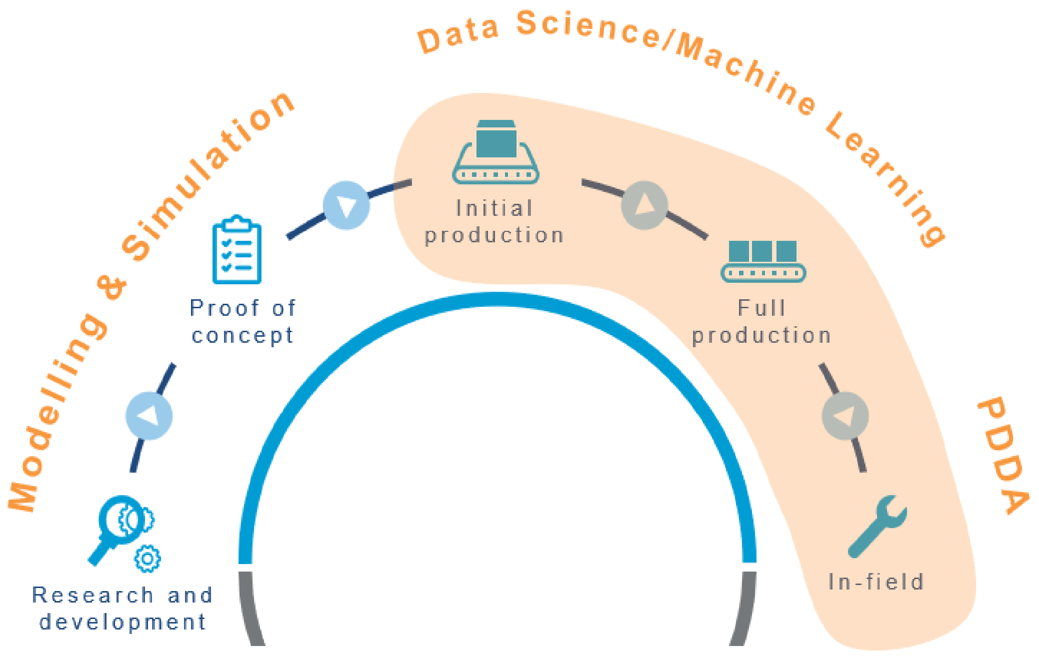
- **Outcomes**

- The project was a success, weight was able to be minimised which is critical for this type of vehicle.
- Bloodhound performed multiple test runs testing the use of this component and was a full success.

BLOODHOUND
LAND SPEED RECORD
PRODUCT SUPPLIER



Definition of Testing?



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Addressing TRL enables the H2 Value Chain.....

Wind Offshore

Wind On-shore

Electrical Pipelines

Electrolyser

Duty Cycle

Reliability

Scale

Efficiency

Storage

System

Efficiency

Technology

A to B

Storage

Form

Liquefaction Gas

Demand

Duty Cycle

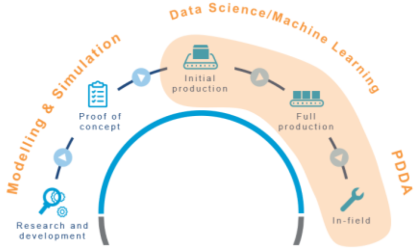
Reliability

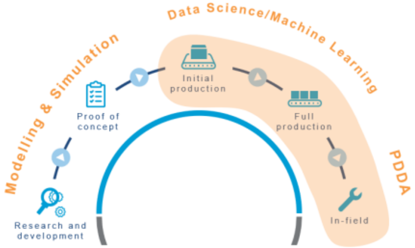
Technology

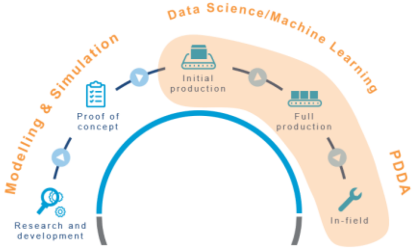
Efficiency

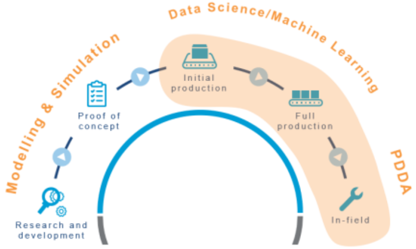
System

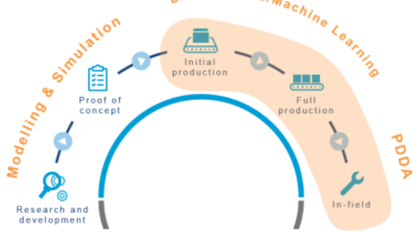
Scale







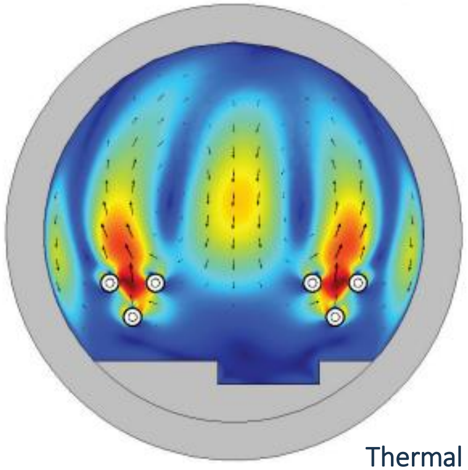




TRL services along the H2 Value Chain

High-Voltage Cable Modelling

element Digital Engineering



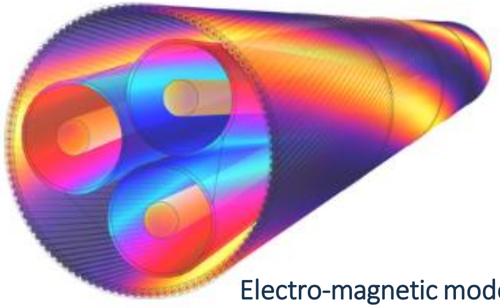
Thermal modelling

Challenges

Designing and managing the electrical grid to ensure it is capable of sustaining the demand, are fundamental for its reliability and minimising CAPEX. This becomes more complex as wind generation is highly variable which results in further challenges when predicting thermal ratings for different environments.

Our capability

To assist, we can simulate the cable performance using COMSOL Multiphysics software and IEC60287, which can include complex thermal environments and non-standard installations. Our consultancy team has conducted previous work in this area including cycling ratings which can be further explored in references provided.



Electro-magnetic modelling

1. R.D. Chippendale et al., Cyclic Load Profiles for Offshore Wind Farm Cable Rating, *IEEE Transactions on Power Delivery*, 2015.
2. R.D. Chippendale et al., Analytical Thermal Rating Method for Cables Installed in J-tubes, *IEEE Transactions on Power Delivery*, 2016.
3. R.D. Chippendale, Offshore Wind Cable Catalogue*, ORE Catapult*, 2016.

Outcome

Testing cables is not a trivial task and is expensive to conduct, as they are buried deep underground and do not exist as an isolated component but are part of a larger system.

The use of simulation to accurately predict the thermal ratings of cables within clear safety margins maximises throughput, ensures reliability and keeps costs as low as possible.

Safety:

Explosion modelling and structural response

Outcome

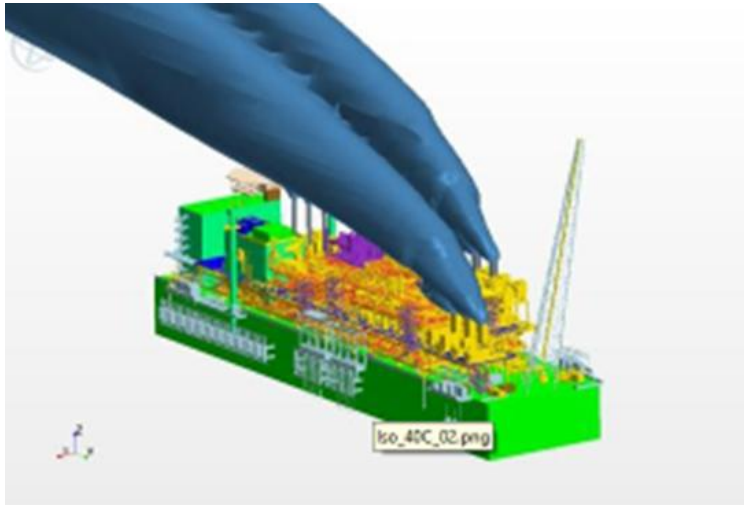
Explosion risk assessment generated, submitted and accepted by the safety authorities. The vessel is now in service.

Challenge

- Safety studies for FPSO
- Dispersion, helideck safety & blast response
- Simulation used to support FPSO design

Our work

- Simulation used to assess consequences of accidental gas releases and quantify blast over-pressures along with assessment of helideck safety and structural response



Safety & Reliability Engineering

As part of our complete offering to the system or equipment lifecycle we have experienced safety and reliability engineers capable of taking full ownership of the product safety and reliability documentation & strategy.

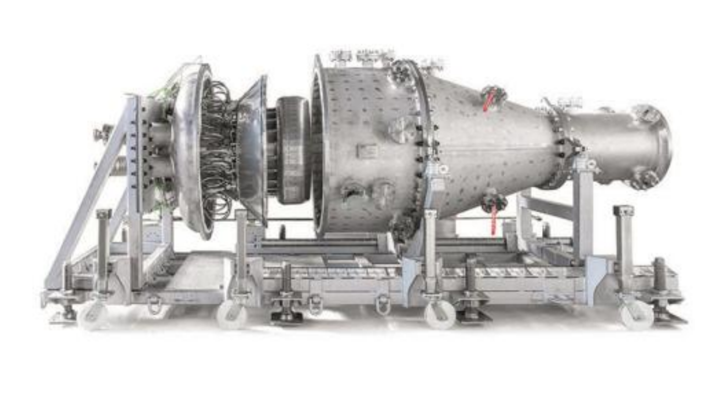
Capabilities in this team include (but not limited to):

Safety

Fault Tree analysis
Process Hazard Analysis
Functional Hazard Analysis
Safety Strategy Documentation
Safety Assessments

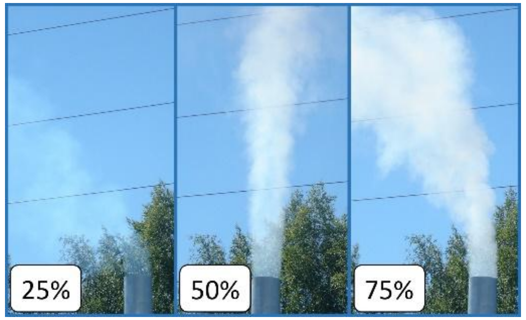
Reliability

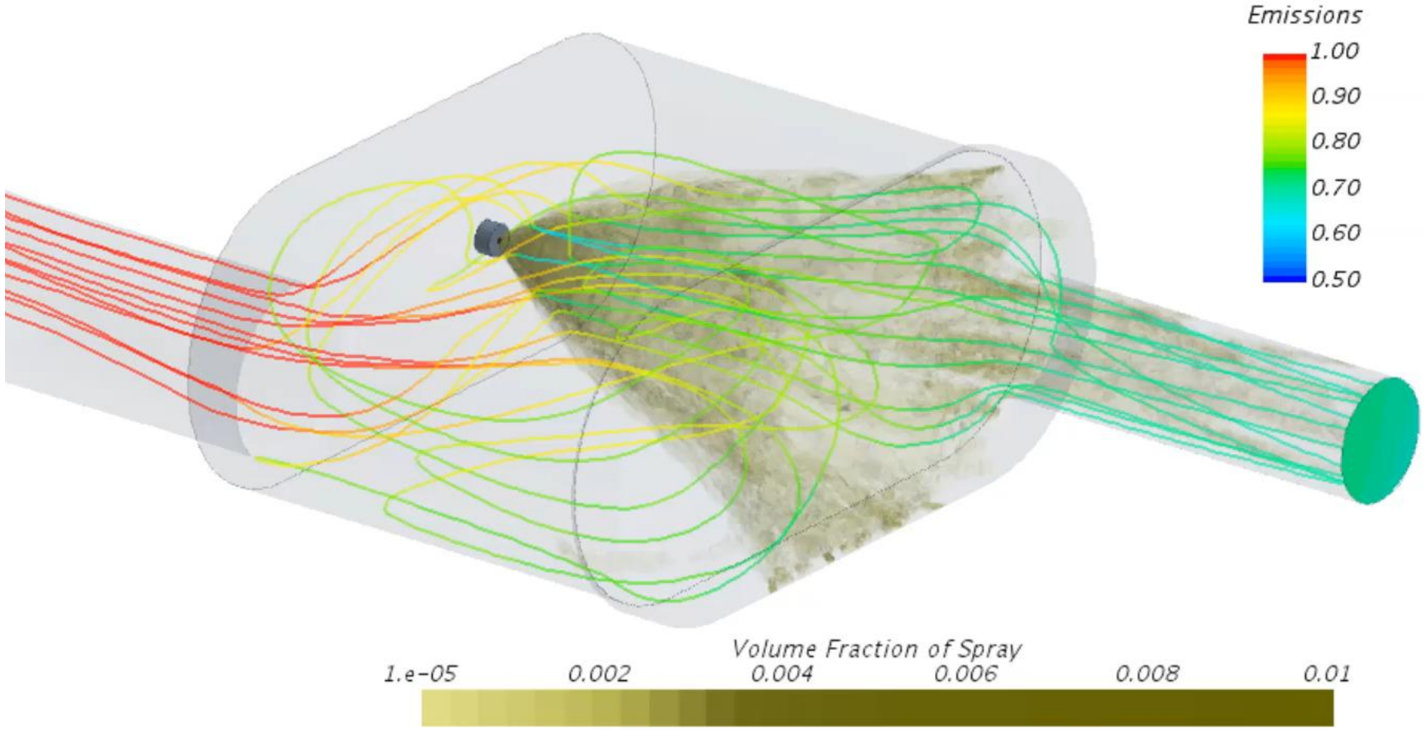
Reliability modelling
FMEA (Failure Modes & Effects Analysis)
PFMEA (Process FMEA)
MTBF, MTBUR, calculations from analytical means (Mil-HBK)



Emissions control technology development

Controlling the environmental emissions of industrial plants is critical in the fight against the climate crisis. However, it is oftentimes difficult to find alternative designs to reduce emissions using physical testing and experimentation alone. The use of **automated design-space exploration** together with **computational fluid dynamics simulations** can enable the discovery of solution options in a much shorter timeframe.





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Physical Experience

PRODUCTION | **TRANSPORT AND STORAGE** | **UTILISATION**

Fracture mechanics & ECA

Corrosion

Coatings

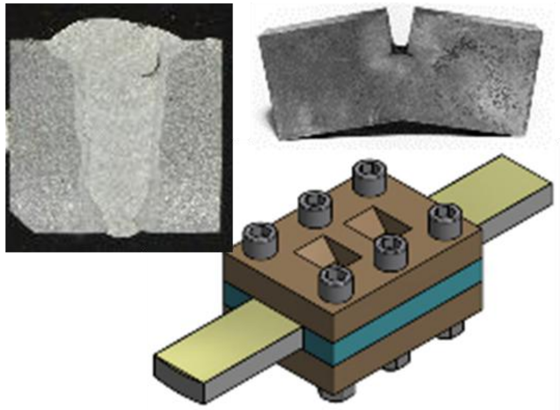
Polymers/Composites

Pipeline installation & operation, input data, ECA analysis, In-situ fracture testing, Riser fatigue testing, Reeling, AUT validation

Weld & material integrity HPHT, Sweet & Sour operations, Full Ring Testing, Inhibitor Testing, Failure Analysis

FJC, Chemical resistance, CD testing, Subsea insulation, HPHT testing, CUI, Electrochemical, Inspections, Failure Analysis

Flexible pipes, Umbilicals, Elastomer seal testing, Composite ageing, HPHT: H_2S, CO_2, Hydrocarbon compatibility



Gas Turbine Technologies

Hydrogen Storage

Prod, Transport, Refueling Infrastructure

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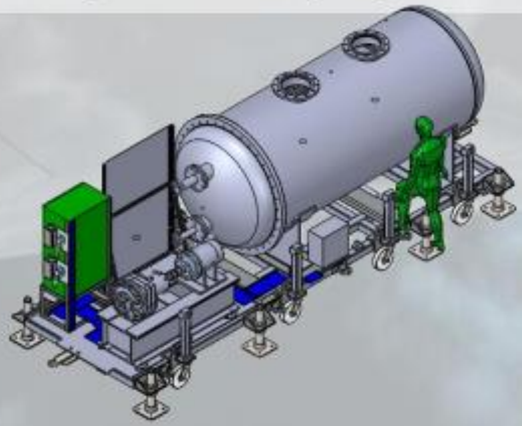
Test Management and Rig Design

All aspects of fluid systems and equipment test programmes:

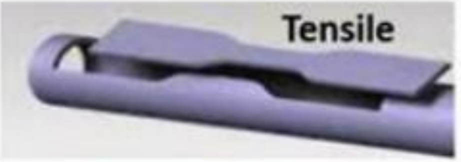
- Delivering entire test programmes to cost and time-scale
- Defining product test requirements for development, qualification and robustness testing
- Defining test rig/tooling requirements
- Designing and building test rigs
- Rig test, Ground test, Flight test preparation
- Performing testing
- Analysis and investigation into test data
- Trouble shooting and failure investigation
- Writing formal test data reports
- Writing test campaign summary and certification reports

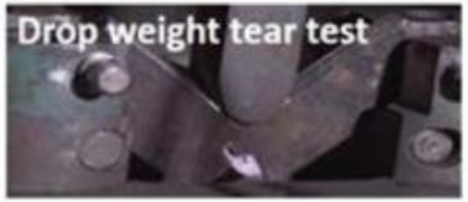


Test Facility Rationalisation

Examples for Metallics

MECHANICAL PROPERTIES - HYDROGEN EFFECT





Limited or no effect	Some effect	Significant effect	Unknown/ High strain rate

Generic property	Pipeline Steel Parameters	Effect of Hydrogen
Strength	Yield (0.2% or 0.5% proof stress)	Limited effect
	Ultimate tensile strength (UTS)	Limited effect
	YS/UTS ratio (Y/T)	Limited effect
	Young's Modulus (E)	No effect
	Poisson's ratio (ν)	No effect
Ductility	Elongation (Total)	Significant reduction
	Elongation (Uniform)	Limited effect
Charpy impact	Charpy impact energy	Limited data found, High strain rate
Crack propagation resistance	Drop weight tear test (DWTT)	No data found on DWTT, but possibly limited effect due to high strain rate
Fracture toughness	K/J/CTOD initiation fracture toughness	Some reduction
	J/CTOD ductile tearing resistance	Significant reduction
Fatigue	Fatigue threshold stress intensity factor range (ΔKth)	slight reduction in some cases
	Fatigue Crack growth rate	Significant increase: many variables
	S-N fatigue line	Effect observed more strongly in high stress LCF region

Source - UK HSE

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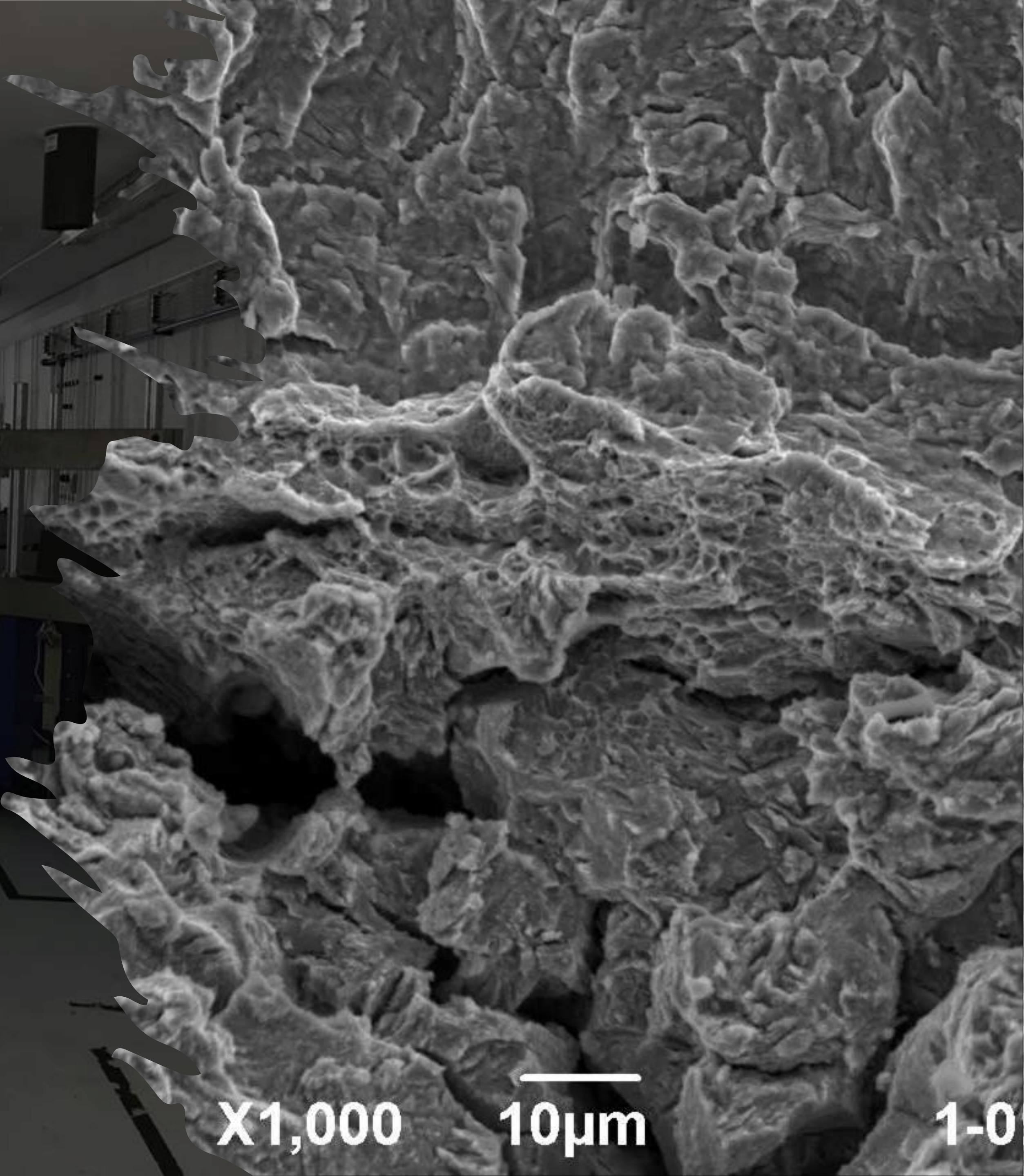
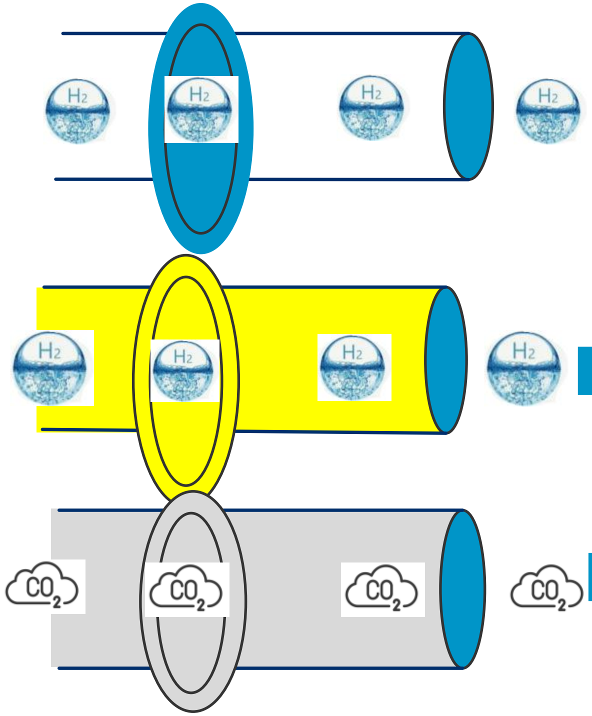
Like sand on the beach H2 – it gets everywhere!!
HE Cracking Mechanisms



H2 Piping – Evolving Infrastructures



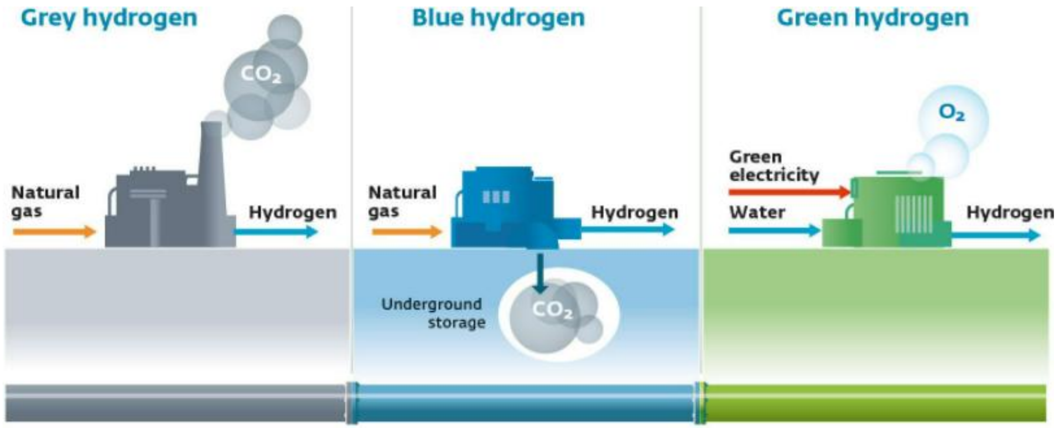
Metallic Pipe / Welds / Fittings / Jointing / Coatings / Seals

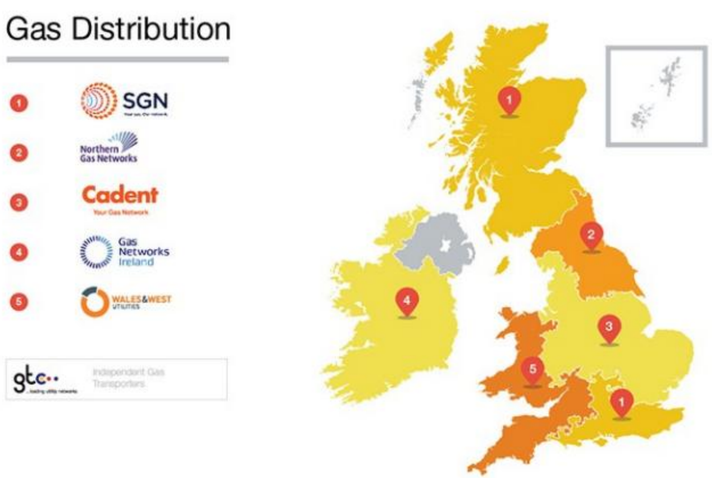
Non Metallic Polymer/composite Pipe / Joints / Fittings / Coatings / Seals / Permeation

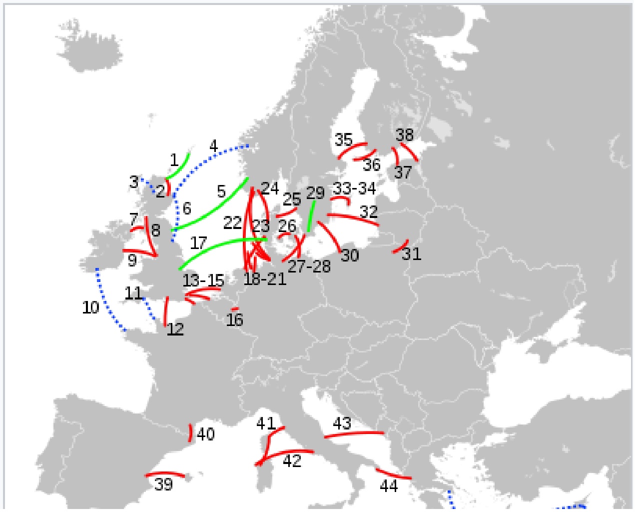
CO2 Pipelines

New / Old?

- H2 Blends
- Impurities
- 100% Hydrogen
- Cryogenics



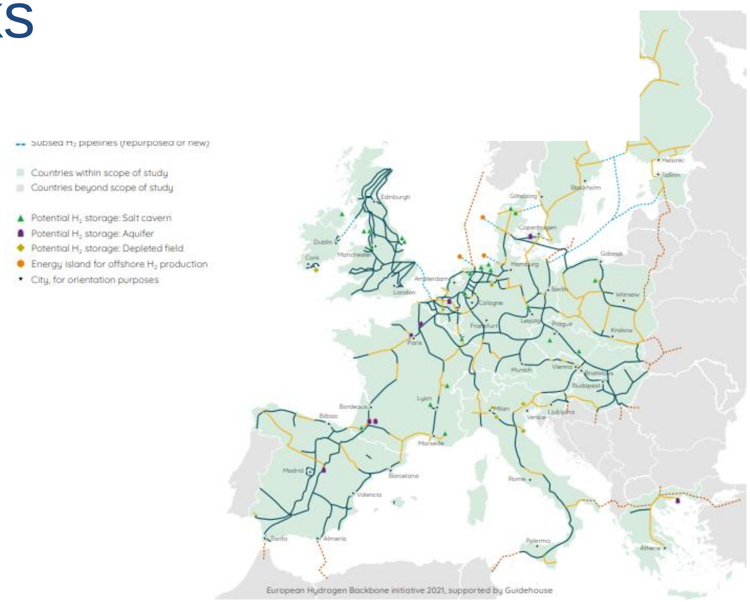




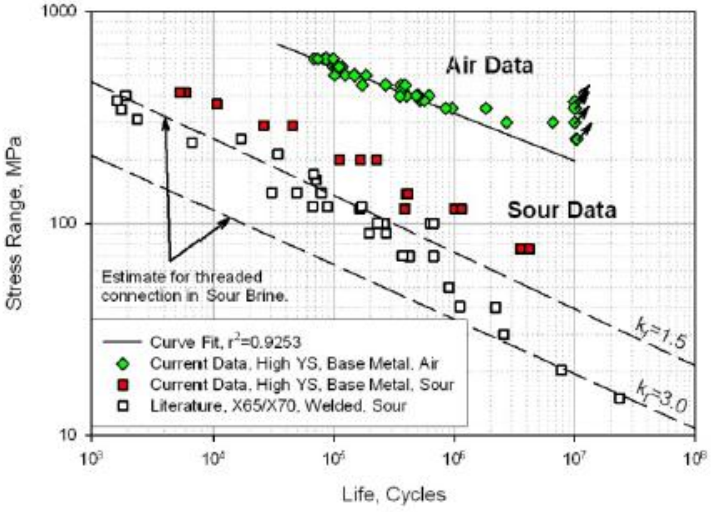
(H2 AND CO2) For just H2: 39,700 km across 21 European countries

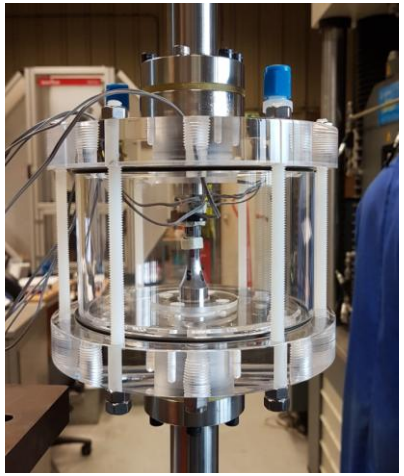
69% Repurposed pipe networks

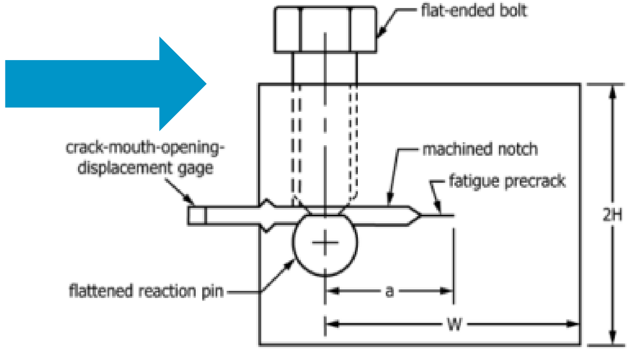
31% New build

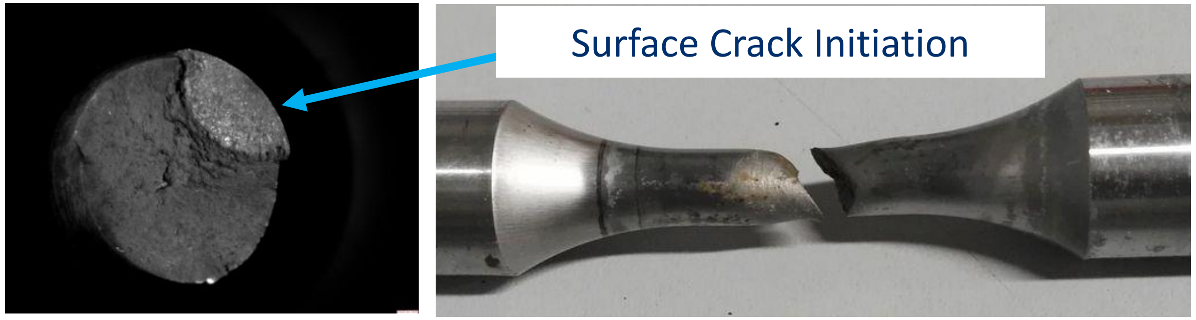


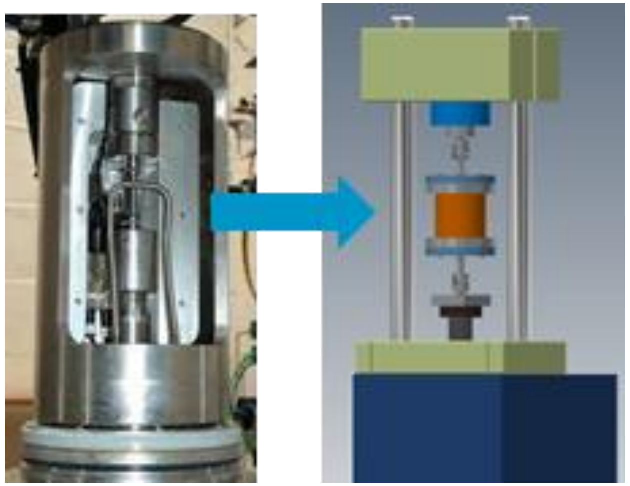
Fatigue Endurance - in-situ









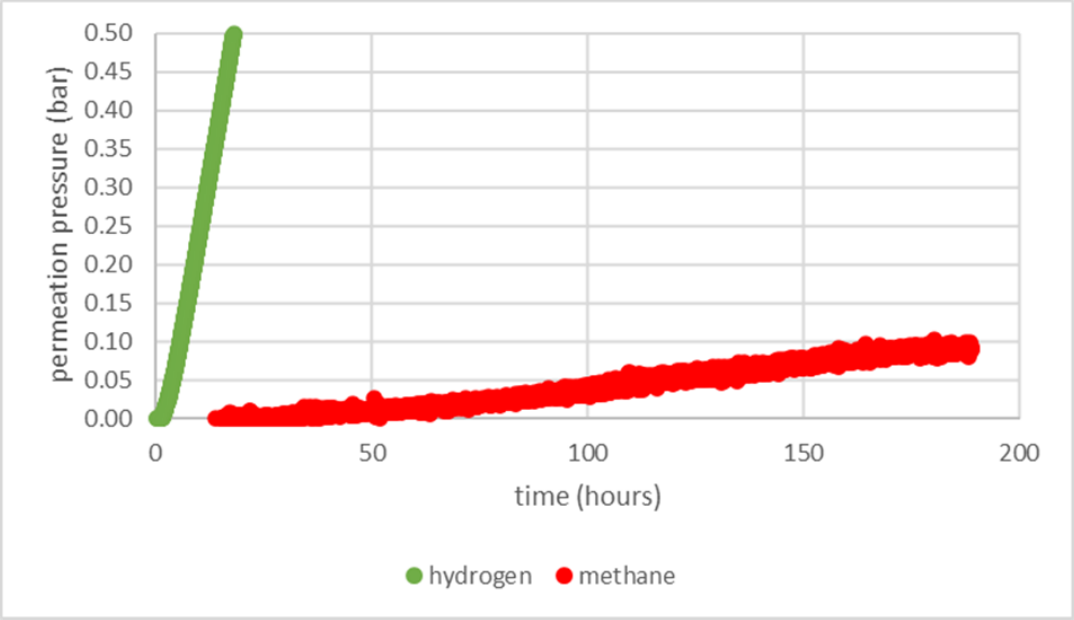


ASME B31.12 Standard on Hydrogen Piping and Pipelines contains requirements for piping in gaseous and liquid hydrogen service and pipelines in gaseous hydrogen service.

Non-Metallic Effects of H2

Permeation

Thermoplastic hydrogen 40 bar 40 °C:



Rapid Gas Decompression with H2

❑ Carbon dioxide has for years caused RGD damage:

H2: Context is Key, System and TRL

Pulling it all together – SystemsThinking

Model the dynamics of complex stochastic systems

Challenge

Model the behavior of an *entire* mining fleet powered mostly by hydrogen in a way that can inform business strategic decisions.

But how can one deal with the interaction of thousands of subsystems full of uncertainty?

Our work

We used a combination of discrete event simulation (DES), deterministic and probabilistic analysis, and Monte Carlo simulation along with Python to pressure-test the system (scheduling, routing, supply, failure, cost, …).

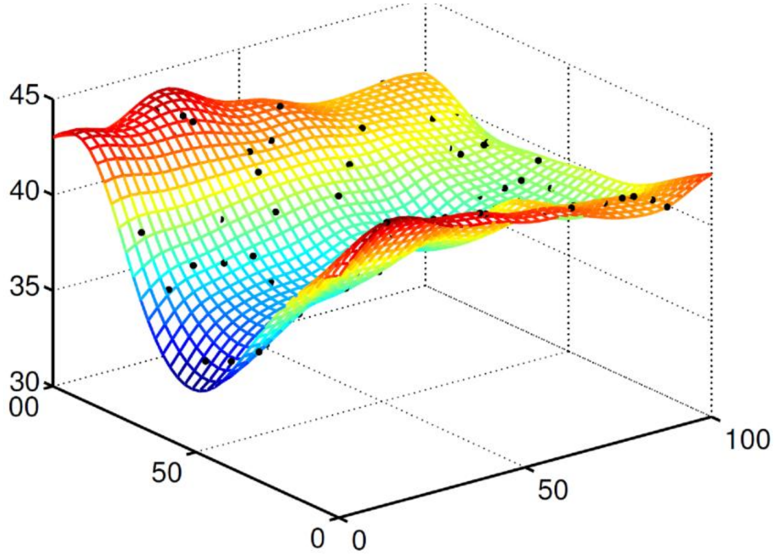
Our client brought the domain-specific knowledge to build the models.

Outcome

Our contribution has helped enable scenario playing and (in)validate assumptions, both of which have facilitated risk analysis and probabilistic design of the full system. The beginnings of a digital twin.

Client is well equipped to make a next generation energy efficient mining system a reality and at scale.

Condition Monitoring and Digital Twins

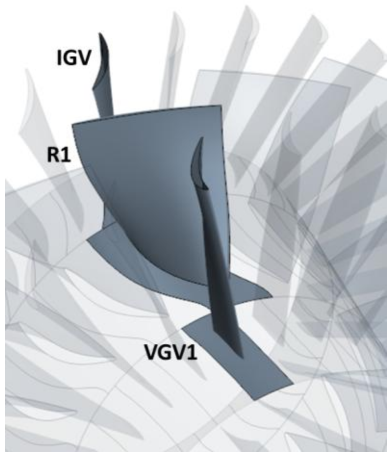


Challenge

An industrial turbine manufacturer wished to develop a predictive tool to determine how real-life variation of operating conditions affects component fatigue life which relates to maintenance schedules.

Our work

A limited number of high-fidelity simulations have been computed to determine component response surface. Using this data, a reduced-order model was calibrated. Component stress and fatigue damage could then be estimated by feeding the reduced-order model with real-life operating data.

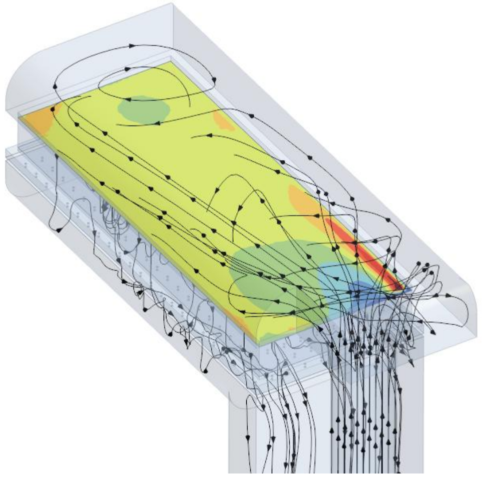


Outcome

The resulting approach is a simplified analysis process that allows for fatigue damage to be rapidly estimated based on real-life operating data. This allows damage and failure to be tracked in close to real time based on actual operating history. In turn, this allows for service intervals to be extended.

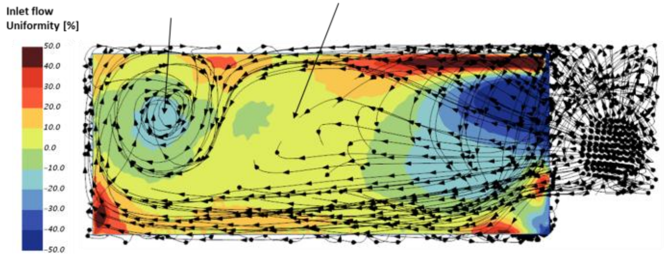
Hydrogen fuel cell performance optimisation

Digital Engineering



Challenge

We have been approached by a fuel cell manufacturer to support the troubleshooting of in-service operation of their fuel cell.



Our work

Computational Fluid Dynamics models were built and used to predict flow distribution and characterize non-uniformity in the catalyst and the cell itself.

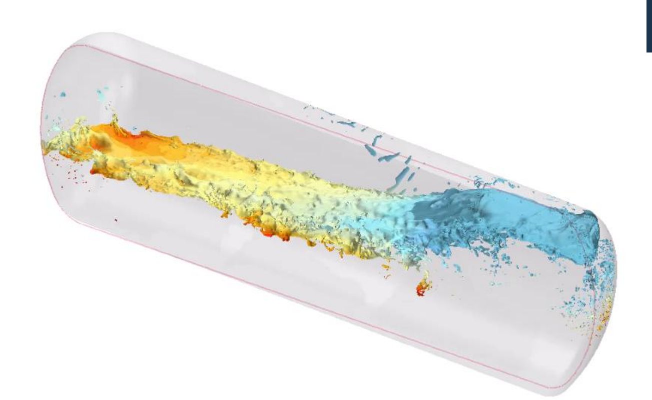
The team proposed a design modification consisting of porous strips used to improve flow uniformity within the fuel cell.

Outcome

The client received a solution which helped reduce wear of fuel cell whilst in operation saving costs of maintenance over time.

Sloshing of cryogenic hydrogen tanks

element
Digital Engineering

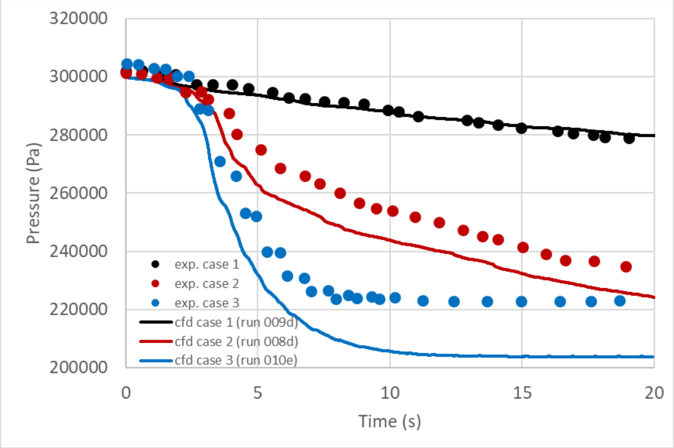


Challenge

In applications where cryogenic hydrogen storage is considered, the risk of sloshing-induced hydrogen boil-off must be assessed to determine overpresurization rates

Outcome

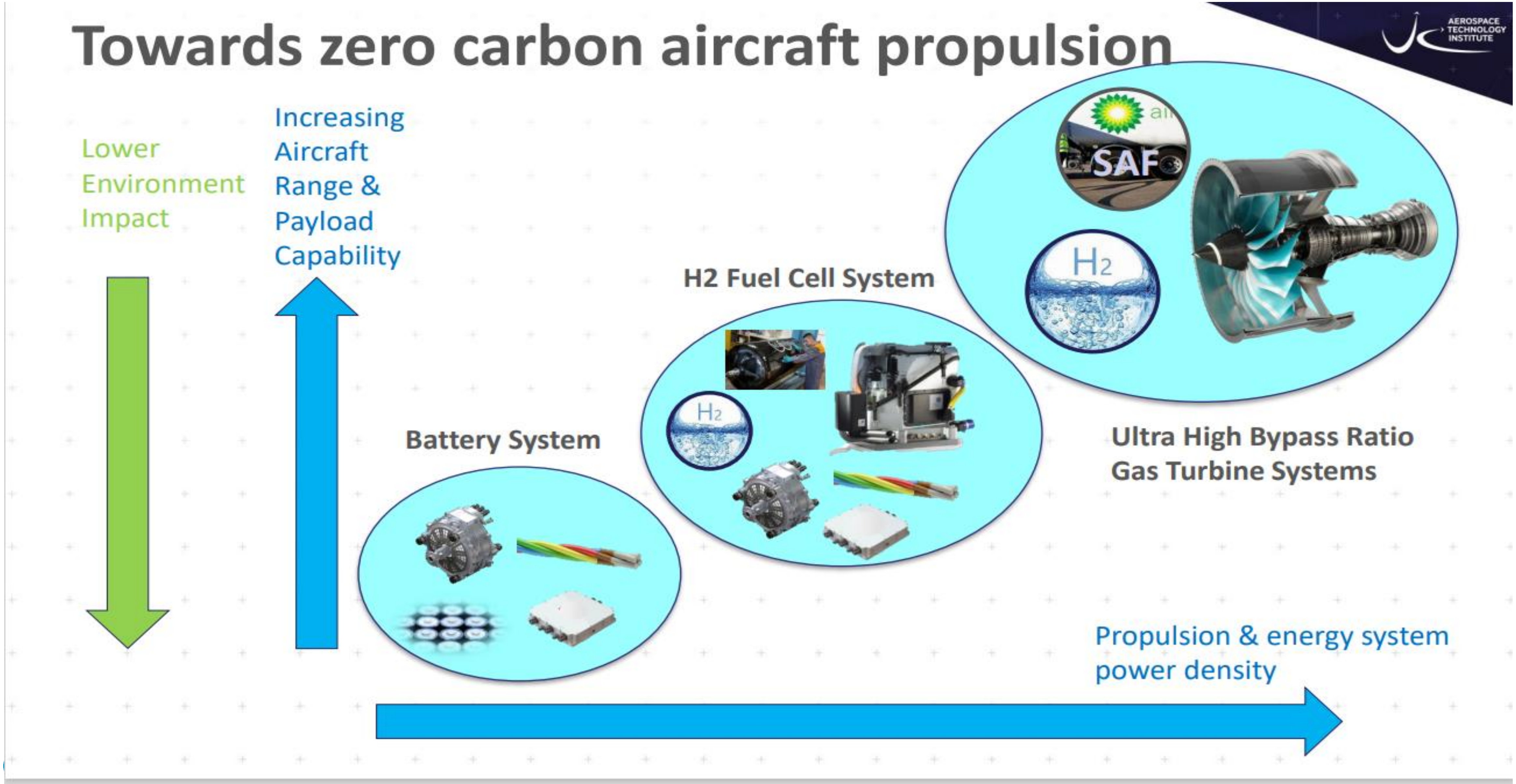
We have assisted a UK government-funded Aerospace programme by delivering new insights regarding the behaviour of the liquid hydrogen undergoing sloshing



Our Capabilities

Norton Straw have implemented a calibrated boiling model in the commercial CFD tool StarCCM+. This model has then been validated against experimental data and used to produce insights regarding sloshing-induced hydrogen boil-off.

Cross over to other Technologies



Connected Technologies

Internet of Things

Radio Frequency Identification (RFID)

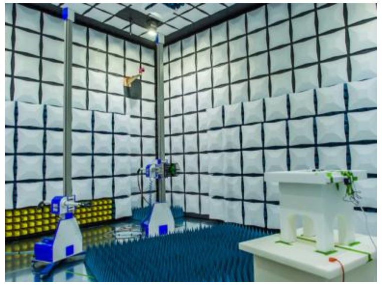
International Certifications, CE Marking and Approvals

Lithium Battery Testing and Certification

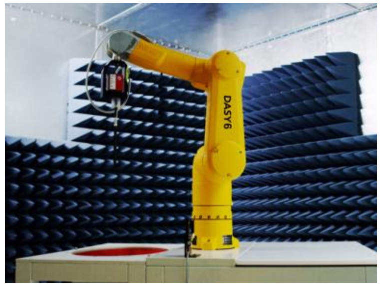
5G Test and Certification

Field Interoperability Testing (FIT)

Long Term Evolution LTE Conformance Testing

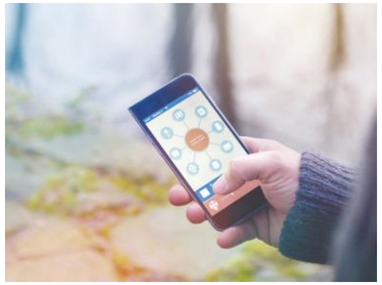


RF Parametric & Protocol Testing

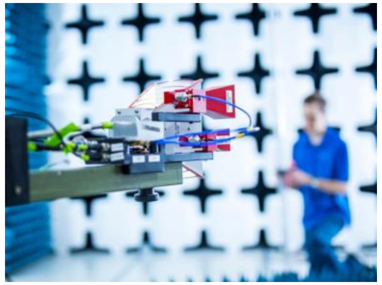


Specific Absorption Rate (SAR)

Over-the-Air (OTA) Testing



Zigbee Certification Testing



Radio Certifications and Testing

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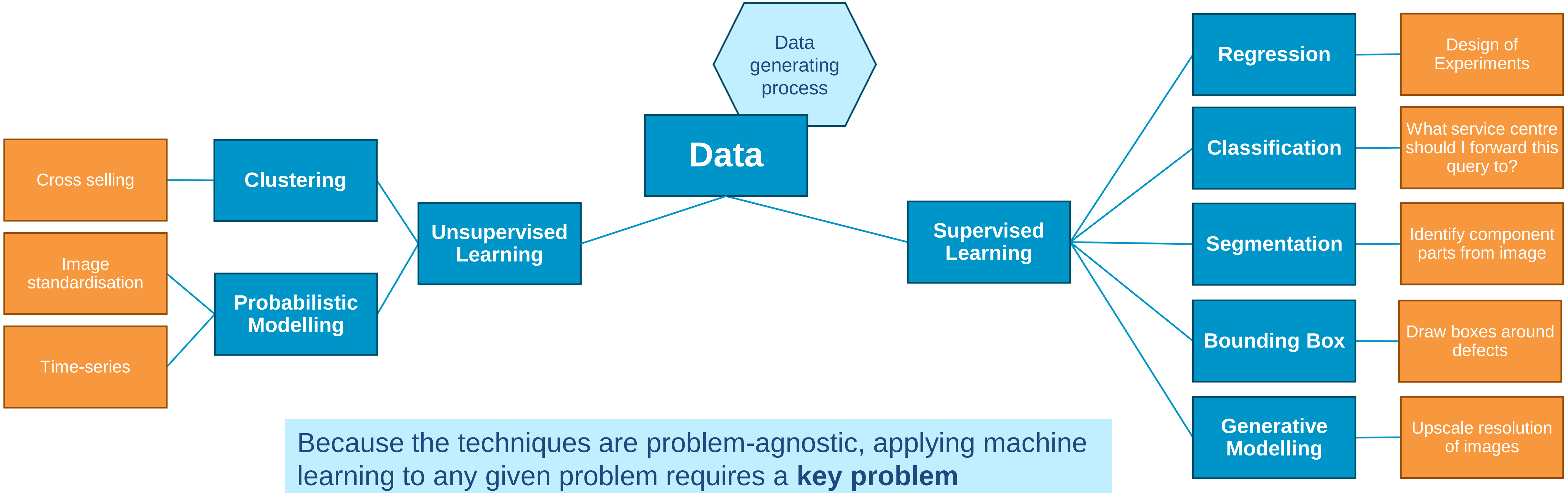
Further services – Analytics and Data Science

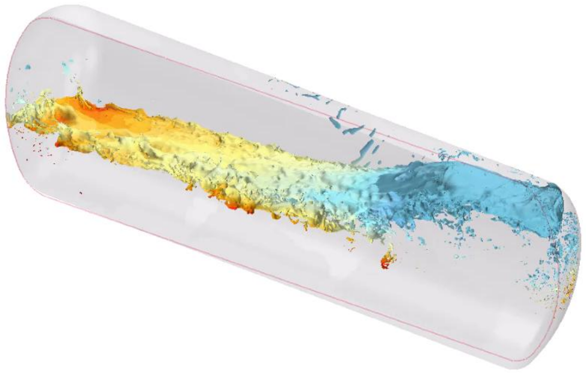
The unifying concept in **machine learning** is that algorithms are set up to perform a task whose outcome improves with experience.
Supervised and unsupervised learning algorithms can offer solutions to a wide variety of problems.



Because the techniques are problem-agnostic, applying machine learning to any given problem requires a **key problem conceptualisation** step in which includes data preparation and heavy engagement with the DE experts.

element

Sloshing of cryogenic hydrogen tanks



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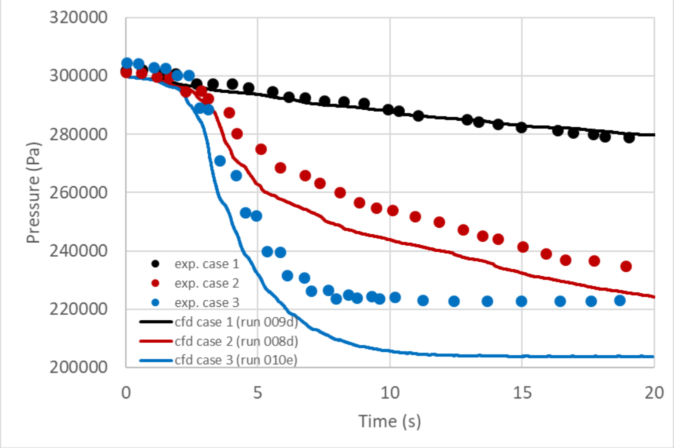

Pioneers in Space Testing

EXPERIENCE WITH EVERY MAJOR SPACE PROGRAM SINCE THE INCEPTION OF MANNED SPACE EXPLORATION

- Astronautics and Propulsion Testing
- Rocket Thrust Stand and Exhaust Duct Testing
- Space Simulation/Thermal Vacuum Cycling
- Extreme Environmental Testing, Including Pyroshock, High Intensity Vibration, and Launch Level Acoustics
- Cryogenic Component Tests, LH2, LO2, LN2, LNG
- High Pressure, High Flow Pneumatic Tests at Temperature, GHe, GN2, GH2, GO2, and GNG
- Precision Cleaning
- Advanced EMI/EMC Testing

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Access to Test Gases and Liquid Hydrogen & Helium

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Hydrogen

Flow: 7 lbs/sec Gas
700 gpm Liquid
Temp: Ambient to -253 degC
Pressure: 350bar

Nitrogen

Flow: 60 lbs/sec
Temp: Ambient
Pressure: 5000 PSI

Hydrogen Fuel Test Facility

Located at our Kemble test facility we have recently upgrading the infrastructure to include both gaseous and liquid hydrogen testing, this is possible by our in-house designed and built liquefaction plant

Completely designed, developed, built, and operated by FSE

- Temp range: 18k to 800k
- Liquid H2 production rate 8kg/day
- Liquid H2 storage 16kg
- ATEX compliant

H_2, FC & ICE Market Landscape

- ❑ H_2 is highly flexible and can be used as a alternative for storage, transportation and low carbon high-grade heat
- ❑ Market by 2050 is projected to be worth $2.5tn (Comparing to a $2-3Trn Automotive market today!)

Fuel Generation

- Bio-mass
- Electrolysers
- SMR
- CCUS
- Purification



Fuel Distribution

- Blending / Splitting
- Low/High Pressure Storage
- Infrastructure
- Transportation
- Fuel Stations

Motive Applications

- Buses
- Cars
- Motorbikes
- Forklifts
- Trucks
- Trains
- Off highway





Power & Heat

- Ceramics/Glass/Cement/Steel
- Telecom/Data Centre
- Back-up
- Residential
- Commercial
- Micro Grid


Portable

- Mobile
- Laptop
- Generators
- Drones
- Military

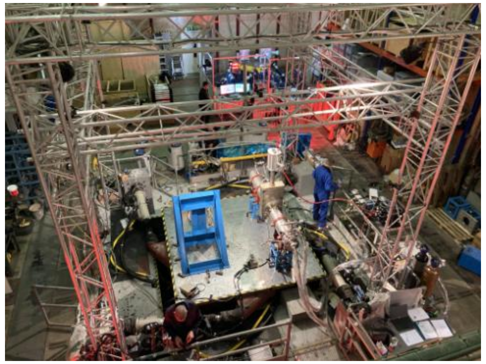



PQT Capabilities Overview

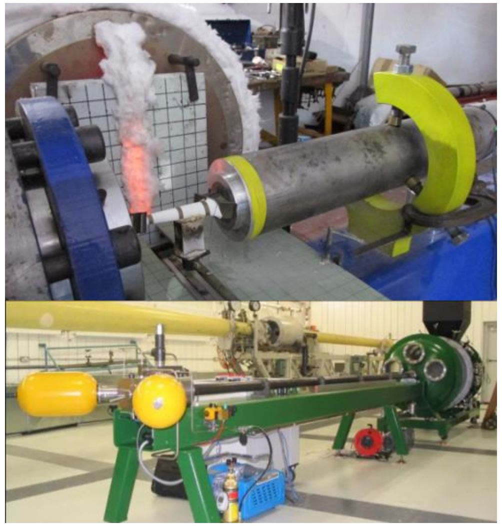
- Vibration
- Seismic/ Ballistic
- Temperature
- Bespoke Testing
- I.P.
- Sand & Dust
- Shock
- HCF
- HALT
- Salt Mist
- Advisory Services
- Spin (development)

Spin

Vibration

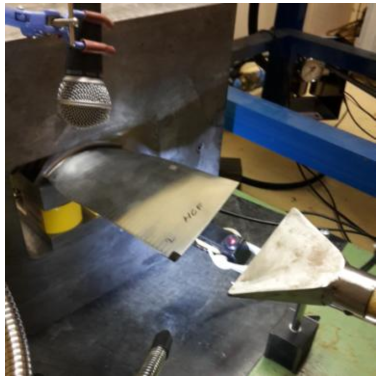


Seismic



Ballistic

Bespoke Testing

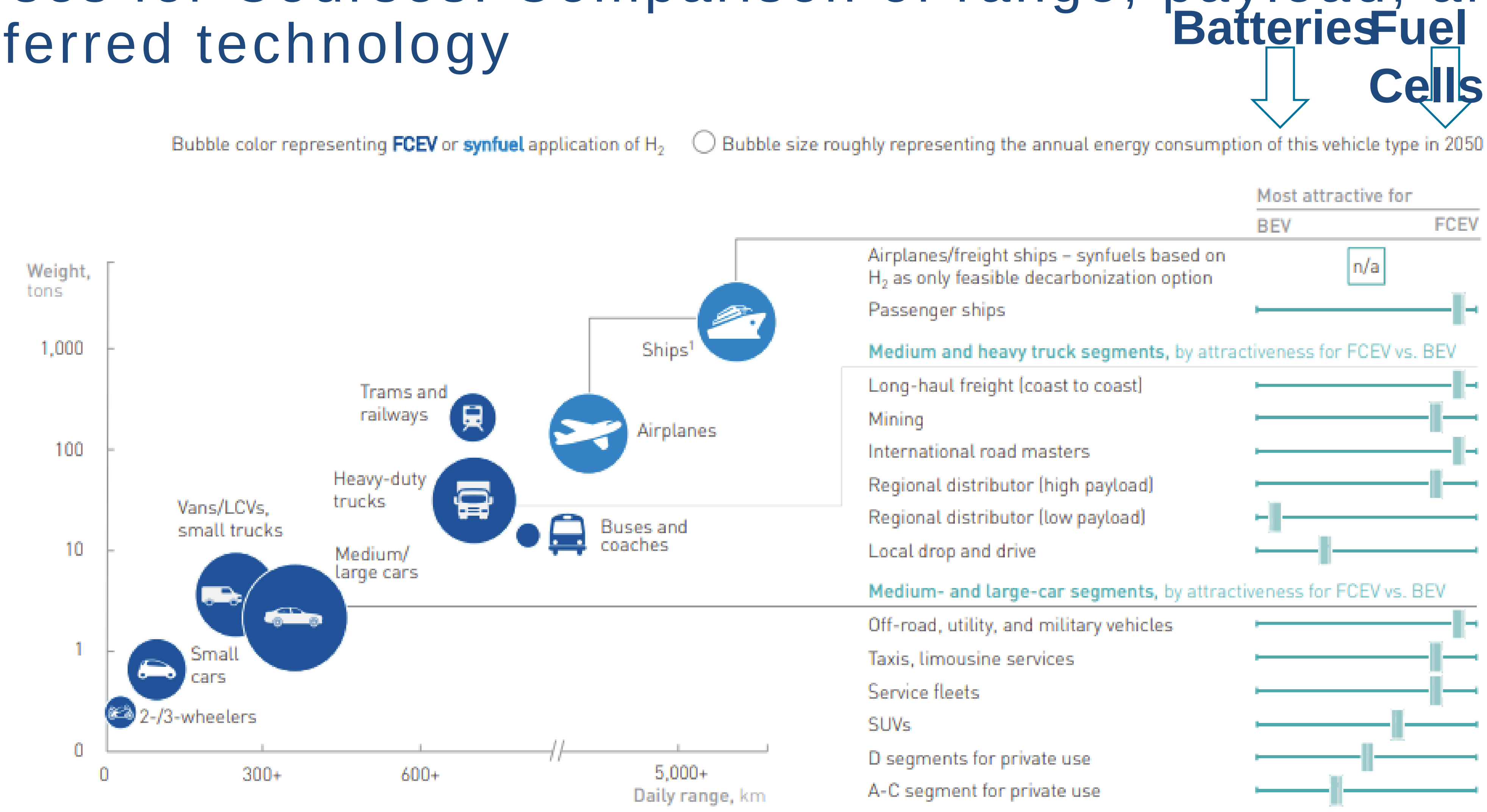


High Cycle Fatigue

Salt, Water, Sand & Dust Ingress

Temperature

Horses for Courses: Comparison of range, payload, and preferred technology



1 H_2-based fuels or fuel cells

Ref: Hydrogen Roadmap Europe 2019

TRL and Product Lifecycle

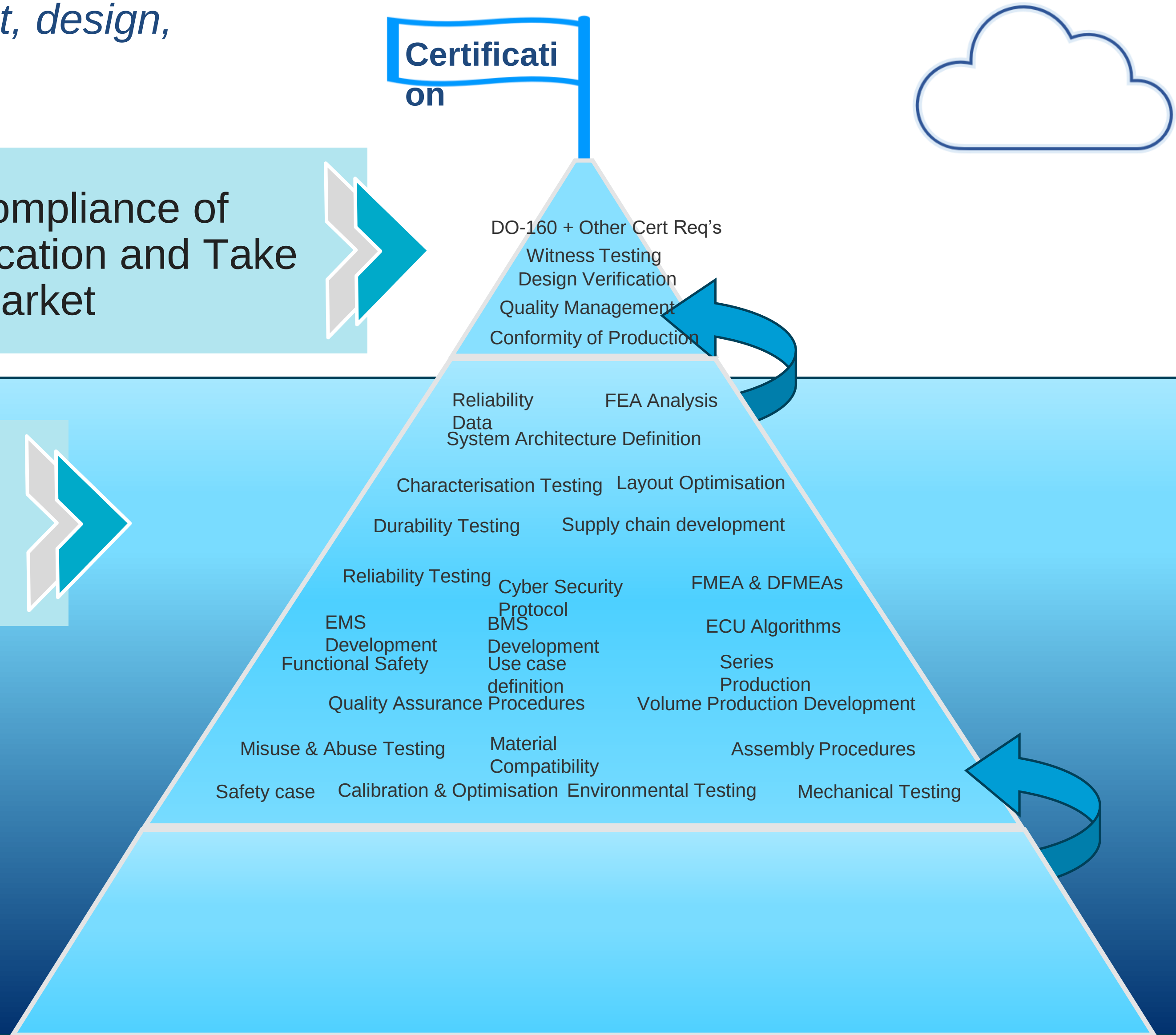
DO-160 is the tip of the Iceberg!

*- The **Majority** effort is taken up in development, design, testing, production and conformity at **TRL5-8***

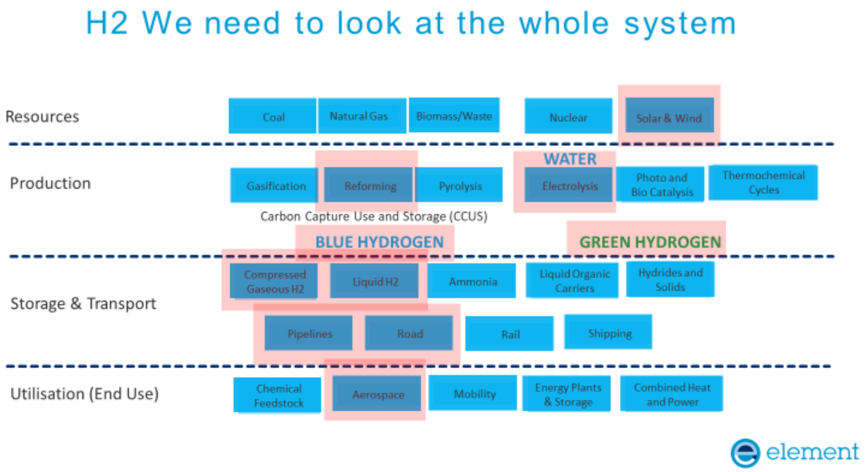
TRL9 – Show compliance of design for certification and Take the product to market

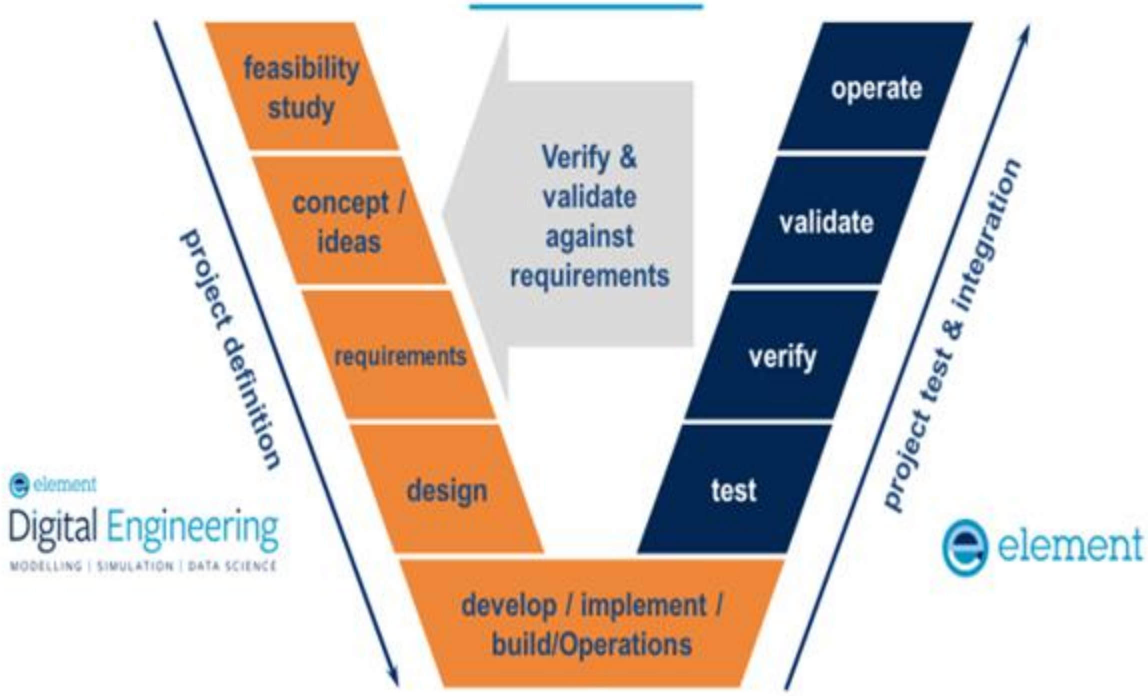
TRL5-8 - Develop & Test in a simulated environment and optimise design for production

TRL1-4 - Showcase the idea, leading to a Prototype demonstrator at ambient conditions in application



Following TRL: Systems, Context, Component Level





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Following TRL to enable the H2 Value Chain

Come and talk to us to accelerate your H2 Energy transition

Making tomorrow safer than today

Thank you for Listening ☺

Dr Mark Eldridge
Director of Hydrogen
07827926757
Mark.Eldridge@Element.com / www.element.com