PROTECTING PEOPLE AND PLACES FOR 50 YEARS HSE

Net Zero Science at HSE

Simon Gant, Strategic Science Adviser for Net Zero

Arup, London, 14 October 2024

Outline

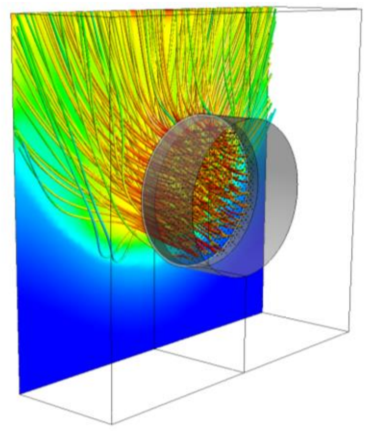
- Introduction to HSE
- Context of Net Zero developments in Great Britain
- Recent and ongoing HSE Net Zero research
  - Hydrogen
  - Carbon Capture Utilisation and Storage (CCUS)
  - Ammonia
- Joint industry projects
- Remaining technical issues and possible future work

Introduction to HSE

- HSE is the UK regulator for workplace health and safety
- Includes onshore/offshore pipelines, chemical/oil/gas infrastructure, offshore platforms etc.
- Activities: evidence gathering, policy development, consultation, regulation, incident investigation, enforcement
- In 2022-23, HSE investigated over 230 fatal and 5,500 non-fatal incidents
- 2,700 total staff (FTE): £262M annual budget, 66% from Government



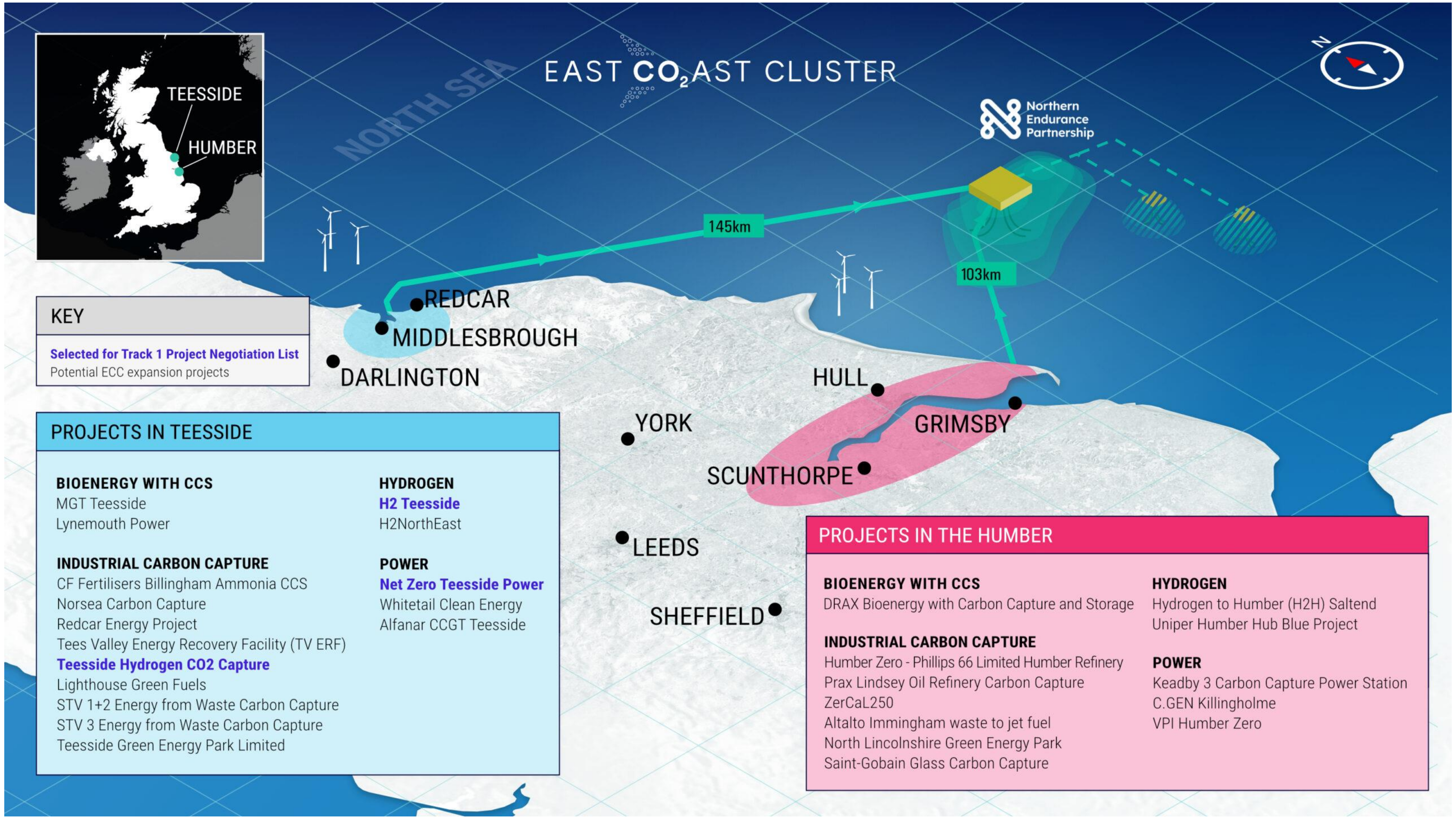
- HSE Science and Research Centre, Buxton, UK
- 400 staff, 550-acre test site
- Scientific support to HSE and other Government departments
- “Shared research” or joint-industry projects co-funded by HSE
- Bespoke consultancy on a commercial basis

UK Government’s Net Zero ambitions (October 2024)

- Quadruple offshore wind with an ambition of 55 GW by 2030
- Pioneer floating offshore wind, by fast-tracking at least 5 GW of capacity
- More than triple solar power to 50 GW
- More than double our onshore wind capacity to 35 GW
- Get new nuclear projects at Hinkley and Sizewell over the line, extending the lifetime of existing plants, and backing new nuclear including Small Modular Reactors
- Invest in carbon capture and storage, hydrogen, and long-term energy storage to ensure that there is sufficient zero mission back-up power and storage for extended periods without wind or sun, while maintaining a strategic reserve of backup gas power stations to guarantee security of supply
- Double the government's target on green hydrogen, with 10 GW of production for use particularly in flexible power generation, storage, and industry like green steel
- Unleash marine and tidal power

East Coast Cluster



NEP Partners: BP, Equinor and TotalEnergies

Onshore gas and dense-phase CO_2 pipelines

Two new offshore dense-phase CO_2 pipelines: 16-24 inch diameter

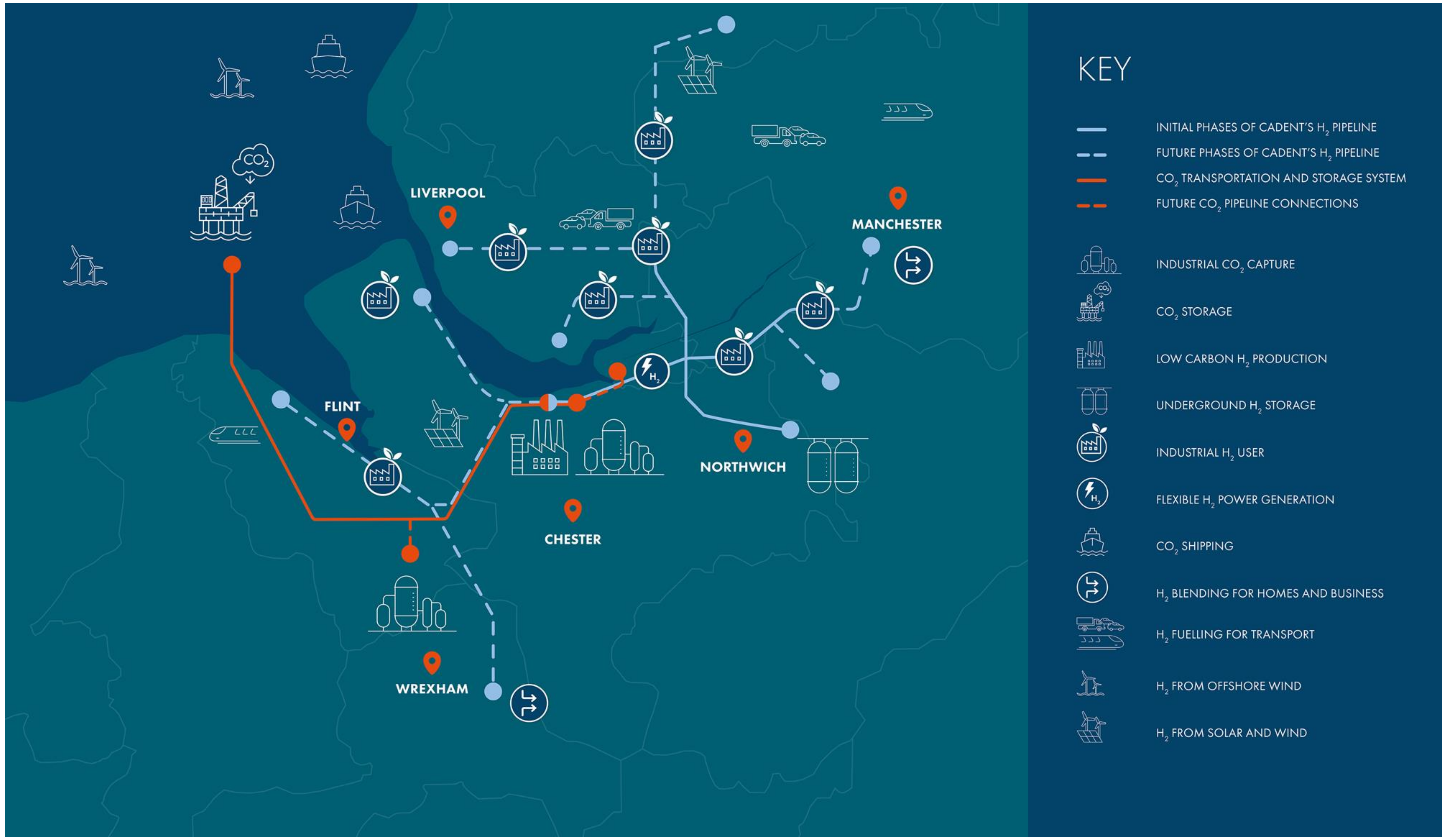
March 2023: Funding awarded for three Track 1 capture plants

Sept 2023: NSTA awarded further licenses to BP and Equinor for 1 GTe CO_2 storage

Due to be operational by 2027

https://eastcoastcluster.co.uk

HyNet



https://hynet.co.uk

Initially, gas-phase onshore/offshore CO_2 pipelines with sequestration in depleted natural gas field

40 miles of onshore pipeline, MAOP approximately 42 bar

Later, transition to dense-phase CO_2 pipelines offshore – compression at the coast

Pipelines: 20”, 24” and 36” diameter, mixture of repurposed and new

New ENI offshore platform connected to several repurposed normally unmanned installations

Capture plants: cement, refinery, blue hydrogen

Planned to store 10 $MtCO_2$/yr by 2030

Energy Transition context in Great Britain

- Other developing CCS and CO_2 pipeline projects
  - Acorn https://www.theacornproject.uk/
  - Viking CCS https://www.vikingccs.co.uk/
  - Morecambe Net Zero cluster https://www.mnzcluster.com/
  - Bacton Thames Net Zero https://www.eni.com/static/bactonthamesnetzero/
  - Poseidon https://perenco-ccs.com/the-poseidon-project/
  - Orion https://perenco-ccs.com/the-orion-project/
  - South Wales industrial cluster https://www.rwe.com/en/research-and-development/hydrogen-projects/south-wales-industrial-cluster/
  - Solent CO_2 Pipeline Project https://www.solentco2pipeline.co.uk/

Energy Transition context in Great Britain

- Hydrogen pipeline projects
  - Transmission
    - FutureGrid research https://www.nationalgas.com/future-energy/futuregrid
    - Project Union https://www.nationalgas.com/future-energy/hydrogen/project-union
    - European Hydrogen Backbone initiative https://www.ehb.eu/
    - SGN LTS Futures https://www.sgn.co.uk/about-us/future-of-gas/lts-futures-0
  - Distribution
    - H100 neighbourhood trial https://www.h100fife.co.uk/
    - H21 https://www.northerngasnetworks.co.uk/wp-content/uploads/2024/03/H21-Phase-2-Technical-Summary_V4-compressed-compressed-2.pdf

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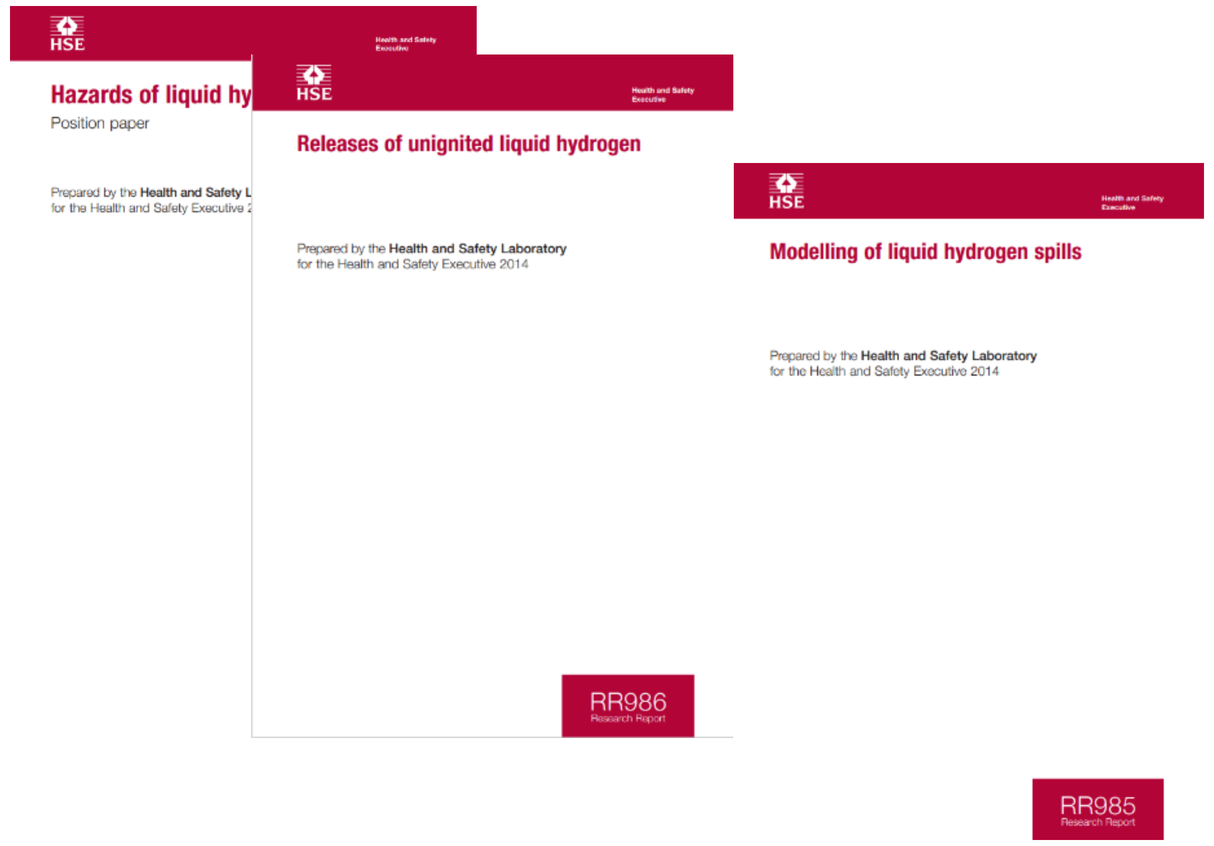
HSE publications on hydrogen

- RR1133 – Maintaining the integrity of process plant susceptible to high temperature hydrogen attack. Part 1: analysis of non-destructive testing techniques
- RR1134 – Maintaining the integrity of process plant susceptible to high temperature hydrogen attack. Part 2: factors affecting carbon steels
- RR1169 – Hydrogen in the natural gas distribution network: Preliminary analysis of gas release and dispersion behaviour
- RR715 – Installation permitting guidance for hydrogen and fuel cell stationary applications: UK version
- RR1047 – Injecting hydrogen into the gas network – a literature search
- RR769 – Hazards of liquid hydrogen: position paper
- RR985 – Modelling of liquid hydrogen spills
- RR986 – Releases of unignited liquid hydrogen
- RR987 – Ignited releases of liquid hydrogen
- RR1159 – Hydrogen research priorities workshop
- RR615 – Spontaneous ignition of hydrogen: Literature review



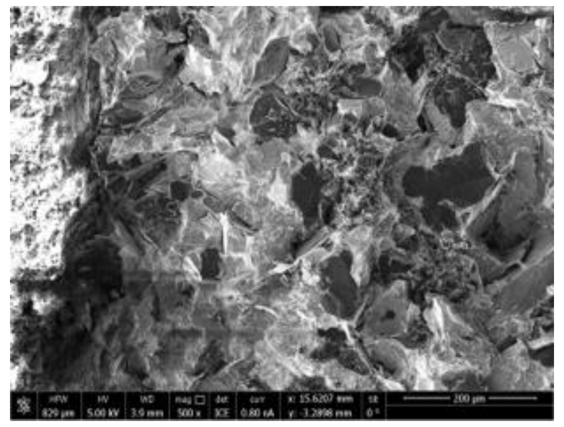
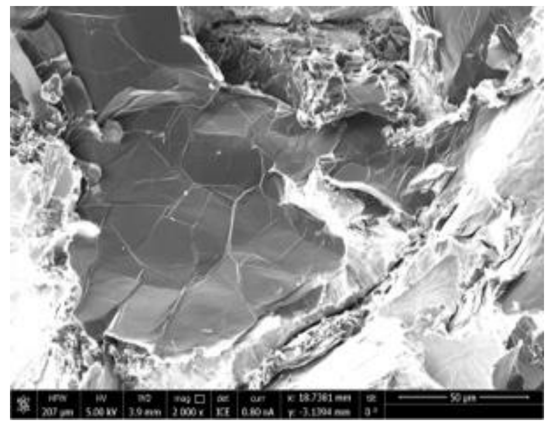
https://www.hse.gov.uk/research/rrhtm/index.htm

Hydrogen research

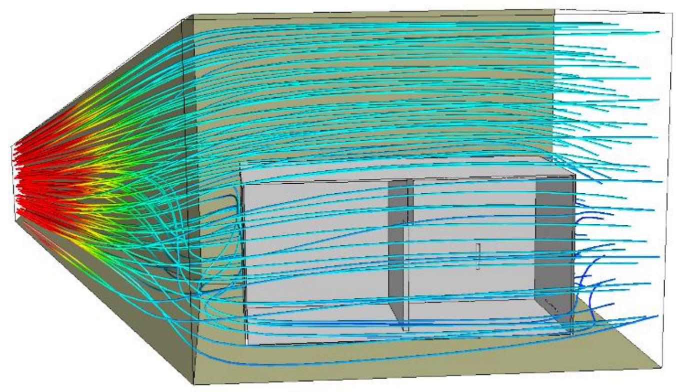
HyDeploy

https://hydeploy.co.uk/

- **Blend of 20% hydrogen in natural gas**
- Scientific analysis and experiments to support QRA for 20% blend
- Community trials at Keele University and Winlaton village (668 homes)





h21

https://h21.green/

- **Repurposing of existing natural gas distribution network for 100% hydrogen**
- Leakage tests on recovered assets, gas migration through soil, dispersion, accumulation, ignition, fires, explosion severity, QRA, operational procedures



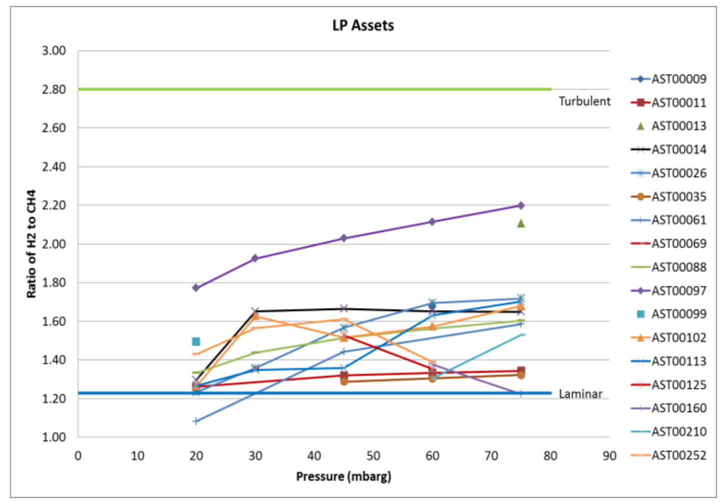
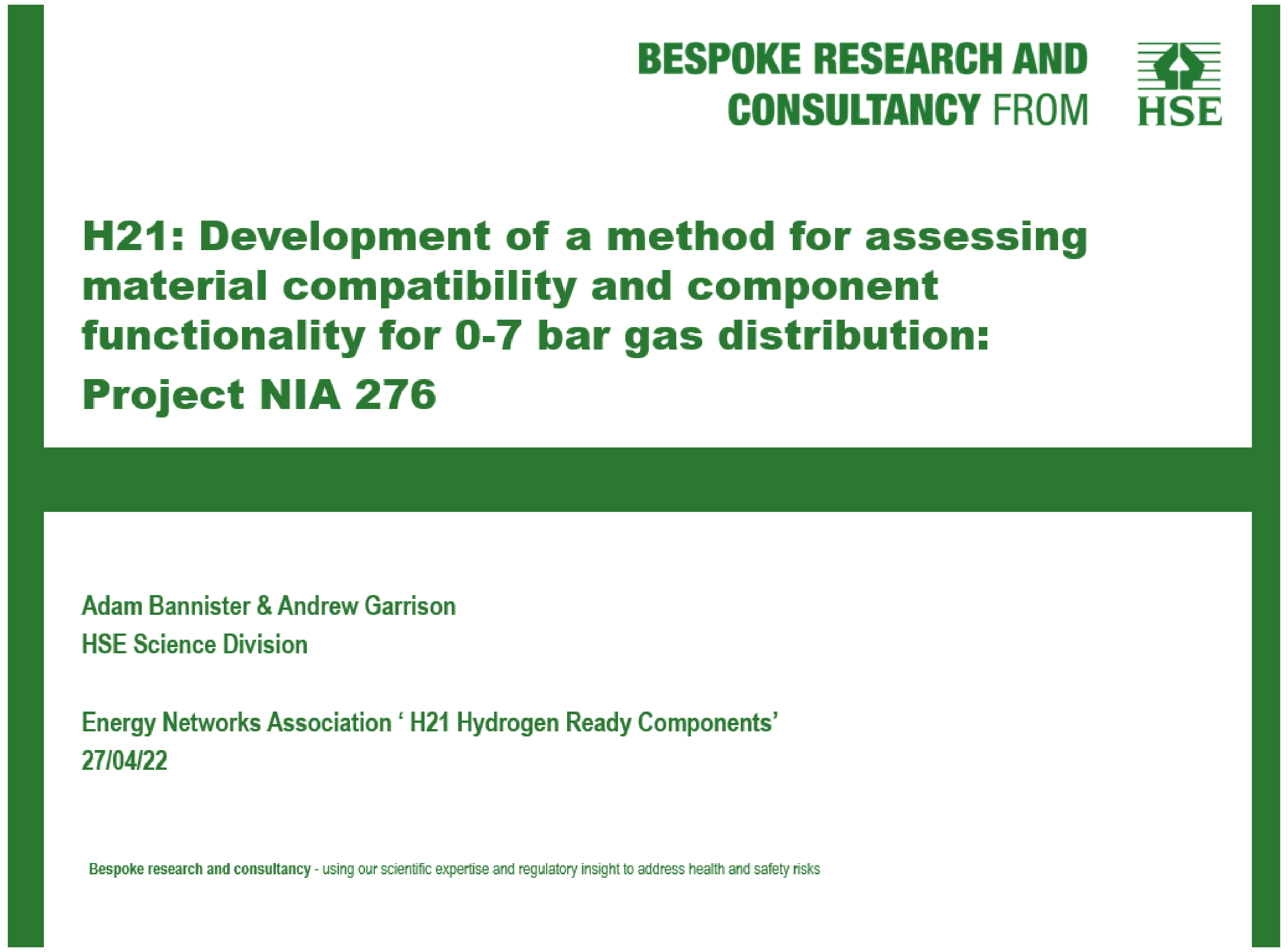


Image of H21 test site at Spadeadam courtesy of DNV (© DNV, 2021)

Hydrogen research


BESPOKE RESEARCH AND CONSULTANCY FROM HSE

H21: Development of a method for assessing material compatibility and component functionality for 0-7 bar gas distribution: Project NIA 276

Adam Bannister & Andrew Garrison
HSE Science Division

Energy Networks Association ' H21 Hydrogen Ready Components'
27/04/22

Bespoke research and consultancy - using our scientific expertise and regulatory insight to address health and safety risks

Slides available on request, presented by Adam Bannister (HSE) to ENA in April 2022

Aims

- Develop a methodology for assessing materials and component suitability (gas facing) for hydrogen service at 100% hydrogen at up to 7 bar
  - Applicable to fixed gas-facing assets
  - Excludes temporary assets
- Demonstration of the methodology through a series of case studies
- Allow individual manufacturers currently unfamiliar with hydrogen to make their own assessments and to understand the role of materials

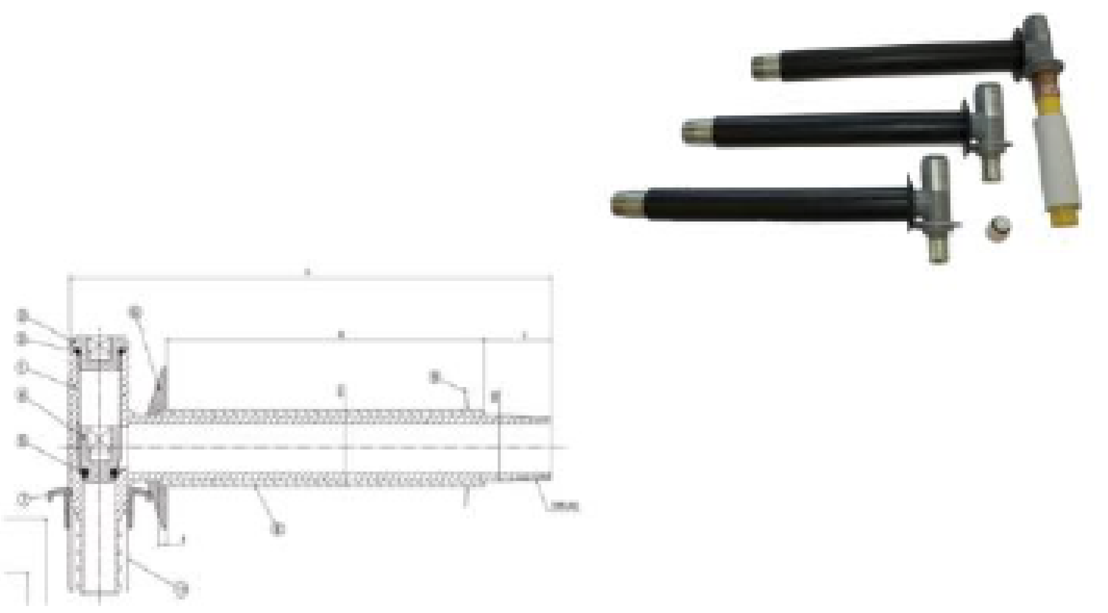
Hydrogen research

- Utilise existing network information (assets, materials, standards)
- Overall net risk level concept: Existing risk (NG) + New risk (Hydrogen)
  - Existing risk evaluated at 'asset assembly' level
  - New risk evaluated at 'component' level
  - Definition of a threshold
- Quantitative method based on combination of:
  - Sensitivity of a material to hydrogen degradation
  - How it is loaded
  - Potential consequences of failure
- Mitigation options for cases not achieving 'pass' on first assessment
  - 1: Improve data quality on material, operation or loading
  - 2: Testing of material or additional analyses
  - 3: Asset protection, monitoring or secondary controls
- Provide a spreadsheet tool for carrying out the assessments in a consistent manner

Hydrogen research

Version: 4.0

Natural Gas Asset Assessment			Score	Comments
Age and model number and relevant GIS year	A	Known or assumed for a family of locations	3	
Operating Pressure Tier	P	Low Pressure (19-75 mbar)	0	
Function (Consequence of loss of)	F	Emergency isolation	10	
Location	L	R, S and T locations and within property (use for all internal assets)	15	
Failure History	FH	Failures known to occur and/or occur at a frequency high enough to be recorded	5	
Inspection and Maintenance	IM	Usually fit-and-forget with no inspection required due to asset reliability	0	
Sum of individual score ratings in NG		High	33	



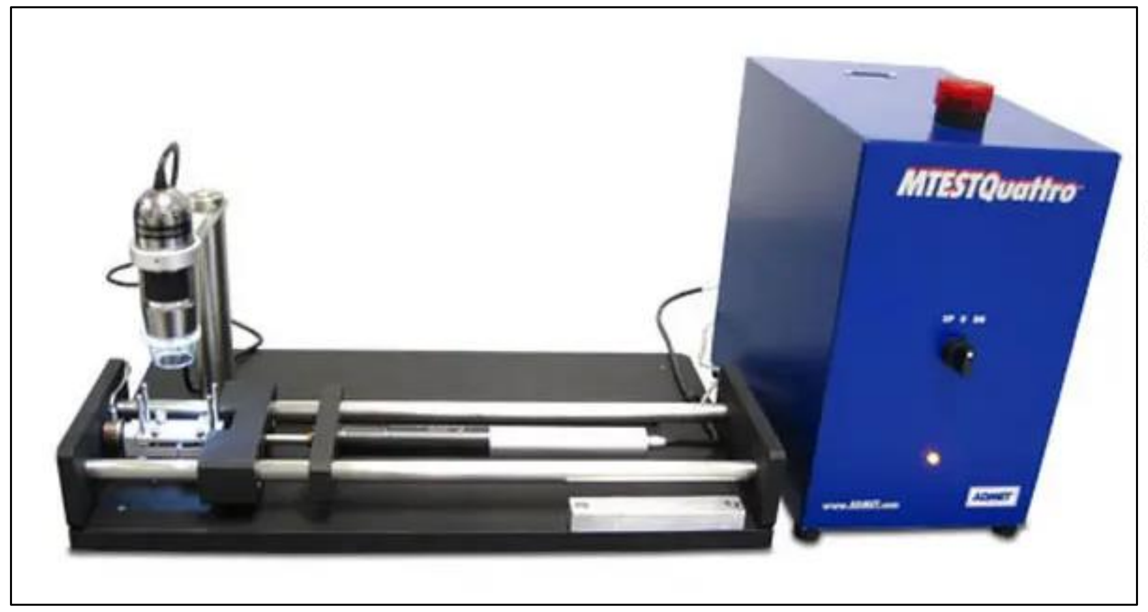
Hydrogen Component Assessment

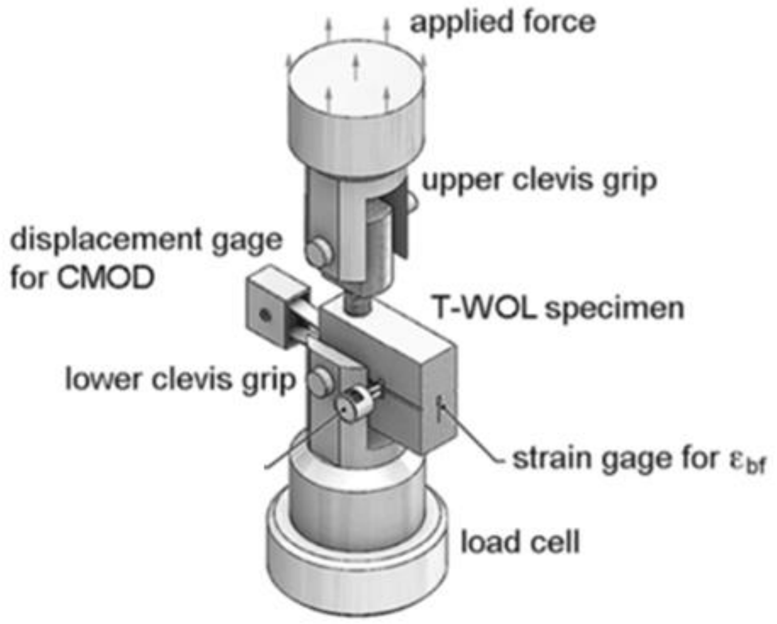
Component No.		1y Gas facing Y/N	Material	DL score	CL: consequence level	CL score	LL score	Total H2 score	Pass/ Fail in H2 (1y)	2y gas facing Y/N (If Y, complete DL & CL)	Red list material and High CL score Y/N (If Y, complete LL Score)	Pass/ Fail in H2 (2y)
1	Body	Y	Carbon steels, Pipeline and generic steel, A106 B and generic low strength	10.4	Loss of asset integrity and control function	10	8	28	Fail		-	-
2	Anti Tamper Top Cap	Y	Carbon steels, Pipeline and generic steel, A106 B and generic low strength	10.4	Loss of asset integrity and control function	10	0	20	Pass		-	-
3	O-ring	Y	Rubbers/ Elastomers, Nitrile (NBR) rubber (or N Buna),	2.8	Loss of asset integrity only	6	4	13	Pass		-	-
4	Internal Plug	Y	Nylons, Glass-filled nylon,	5.6	Loss of control function only	4	0	10	Pass		-	-
5	O-ring	Y	Rubbers/ Elastomers, Nitrile (NBR) rubber (or N Buna),	2.8	Loss of asset integrity only	6	4	13	Pass		-	-
6	Wall Plate	N	Rubbers/ Elastomers, Viton Fluorocarbon rubber,	13.9			0	14	-	N	-	Pass
7	GRP Retention Washer	N	Miscell. Polymers, Polycarbonate,	18.1			0	18	-	N	-	Pass
8	Through Wall Sleeve	N	Polyethylene, PE80, PE80	6.0			0	6	-	Y	N	Pass
9	Spring Washer	N	Carbon steels, Spring steels, SL, SM, SH, DM, DH	20.1			4	24	-	N	-	Pass
10	Crimp Sleeve < 63mm	N	Copper, Castings, Grade CR004, 99.90 % pure Cu	9.7			0	10	-	N	-	Pass
11	PE Pipe	Y	Polyethylene, PE80, PE80	6.0	Loss of asset integrity only	6	4	16	Pass		-	-
12	Sleeve	N	Carbon steels, Threaded pipe fittings, BS EN 10241 ; BS 3799	13.6			0	14	-	N	-	Pass
13	GRP Pipe	N					0	0	-	N	-	Pass
14							0	0	-		-	-

Overall rating of asset assembly for service in hydrogen: Fail

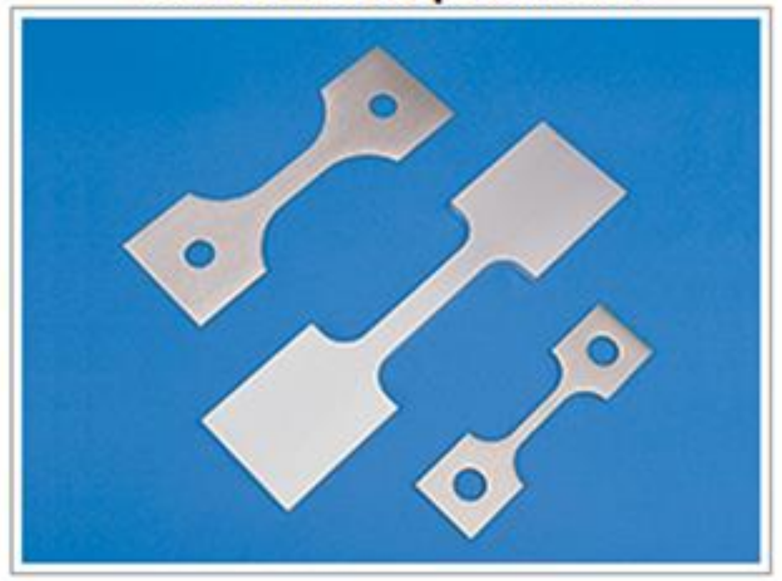
HSE hydrogen materials testing facility

- HSE is investing in a new hydrogen materials testing facility at its Science and Research Centre in Buxton
- Aim to conduct long-term exposure tests of materials (~years) in gaseous hydrogen up to 10 bar
- Testing methods:
  - In-situ micro tensile testing
  - Ex-situ tensile testing
  - Ex-situ impact testing
- Testing of metals, polymers and elastomers
- Four vessels acquired, setup ongoing
- Due to be operational in 2025





Flat Tensile Specimens



Round Tensile Specimens

HSE pipeline regulation

- Pipeline Safety Regulations, 1996 (PSR) provides a risk-based goal-setting approach to regulating pipelines in Great Britain
- PSR covers: requirements (design, construction, operation etc.), measures to prevent damage to pipelines, requirements for co-operation amongst pipeline operators
- Major Accident Hazard (MAH) pipelines convey a dangerous fluid
- Dangerous fluid classification includes hydrogen > 7 barg, CO_2 under review
- Additional requirements for MAH pipelines: emergency shut-down valves, notifications, major accident prevention document, emergency procedures, emergency plan
- HSE has a duty to provide land-use planning advice around MAH pipelines
  - HSE uses the pipeline risk assessment model (MISHAP) and creates risk-based LUP zones around the pipeline
  - HSE advice is provided to planning authorities when they are considering new developments near pipelines (e.g., new housing, hospitals, schools etc.)

HSE pipeline risk modelling work (ongoing)

- Objectives: Review HSE's pipeline risk assessment methodology to determine its suitability for hydrogen and CO_2, and update it if needed, considering:
  - Failure rate model, pipeline release rate model, event trees, ignition model, fire and explosion model, dispersion model for CO_2, including consideration of crater source model
- Motivation: Need to update HSE pipeline risk assessment methodology for hydrogen and CO_2 pipelines, for application to provision of HSE's statutory land-use planning advice to local planning authorities
- Related projects and information
  - SAFEN Joint Industry Project https://www.safetec.no/en/news/safen-jip-ready-to-meet-new-challenges
  - FutureGrid https://www.nationalgas.com/insight-and-innovation/transmission-innovation/futuregrid
  - Energy Institute guidance https://publishing.energyinst.org/topics/hydrogen
  - IGEM standards development https://www.igem.org.uk/technical/buy-technical-standards/transmission-and-distribution.html

Skylark CO_2 dispersion joint industry project

- Aims
  - To undertake dispersion experiments on CO_2 pipeline releases and venting, including releases from craters and dispersion in sloping/complex terrain
  - To run joint collaborative model validation exercises
  - To improve emergency preparedness and support first responders
- Work Packages
  1. CO_2 pipeline craters and source terms – DNV
  2. Wind-tunnel experiments – University of Arkansas
  3. Simple terrain dispersion experiments – DNV
  4. Complex terrain dispersion experiments – DNV
  5. Model inter-comparison and validation – HSE
  6. Emergency response – NCEC
  7. Venting – DNV

Total cost: £13.5 m
(support of £5m from DESNZ)
Timeline: start in late 2024 for 3 years

https://www.dnv.com/article/skylark-pioneering-excellence-in-co2-pipeline-safety-250648/

Ammonia research

- Jack Rabbit III ammonia release experiments (2021-ongoing)
  - Led by US Departments of Homeland Security and Defense
  - Aims:
    - Conduct large-scale releases of ammonia, similar to Jack Rabbit II chlorine trials
    - Validate dispersion models
    - Improve preparedness of emergency responders
  - HSE co-chairs the Jack Rabbit III Modelling Working Group and has coordinated international dispersion model inter-comparison exercises

Images of previous series of Jack Rabbit II chlorine trials conducted in 2015-2016

Images © DHS S&T CSAC and Utah Valley University
https://www.uvu.edu/es/jack-rabbit/

RAND CORPORATION

RESEARCH AND GUIDANCE FROM HSE

Summary of results from the Jack Rabbit III international model inter-comparison exercise on Desert Tortoise and FLADIS

Simon Gant[1] , Joseph Chang[2], Sun McMasters[3], Ray Jablonski[3], Helen Mearns[3], Shannon Fox[3], Ron Meris[4], Scott Bradley[4], Sean Miner[4], Matthew King[4], Steven Hanna[5], Thomas Mazzola[6], Tom Spicer[7], Rory Hetherington[1], Alison McGillivray[1], Adrian Kelsey[1], Harvey Tucker[1], Graham Tickle[8], Oscar Björnham[9], Bertrand Carissimo[10], Luciano Fabbri[11], Maureen Wood[11], Karim Habib[12], Mike Harper[13], Frank Hart[13], Thomas Vik[14], Anders Helgeland[14], Joel Howard[15], Veronica Bowman[15], Daniel Silk[15], Lorenzo Mauri[16], Shona Mackie[16], Andreas Mack[16], Jean-Marc Lacome[17], Stephen Puttick[18], Adeel Ibrahim[18], Derek Miller[19], Seshu Dharmavaram[19], Amy Shen[19], Alyssa Cunningham[20], Desiree Beverley[20], Matthew O’Neal[20], Laurent Verdier[21], Stéphane Burkhart[21], Chris Dixon[22]

[1]Health and Safety Executive (HSE), [2]RAND Corporation, [3]Chemical Security Analysis Center (CSAC), Department of Homeland Security (DHS), [4]Defense Threat Reduction Agency (DTRA), [5]Hanna Consultants, Inc., [6]Systems Planning and Analysis, Inc. (SPA), [7]University of Arkansas, [8]GT Science and Software, [9]Swedish Defence Research Agency (FOI), [10]EDF/Ecole des Ponts, [11]European Joint Research Centre (JRC), [12]Bundesanstalt für Materialforschung und -prüfung (BAM), [13]DNV, Stockport, [14]Norwegian Defence Research Establishment (FFI), [15]Defence Science and Technology Laboratory (DSTL), [16]Gexcon, [17]Institut National de l'Environnement Industriel et des Risques (INERIS), [18]Syngenta, [19]Air Products, [20]Naval Surface Warfare Center (NSWC), [21]Direction Générale de l'Armement (DGA), [22]Shell

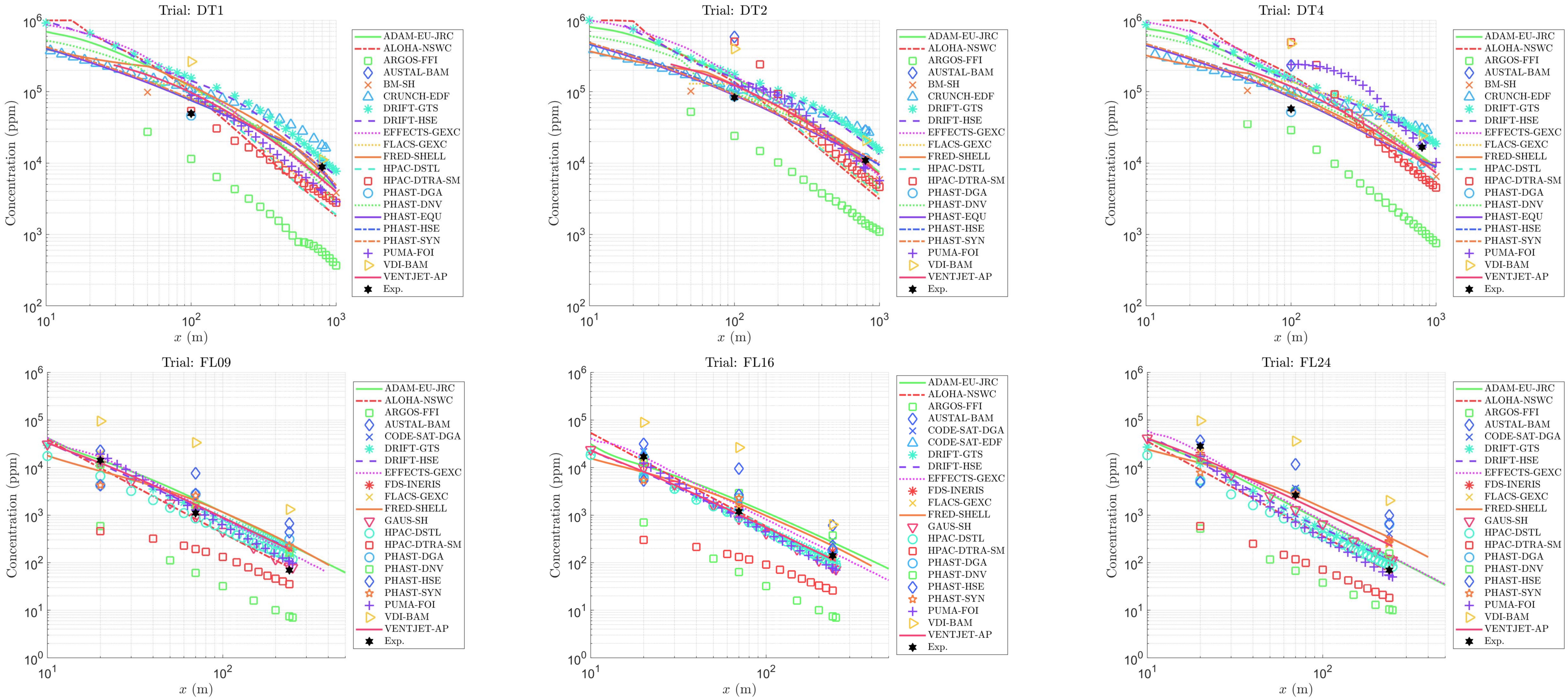
21st International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes

27-30 September 2022

Participants in the JRIII Initial Modeling Exercise

#	Organization	Model	Model Type				Desert Tortoise			FLADIS		
			Empirical nomogram/ Gaussian plume	Integral	Gaussian Puff/ Lagrangian	CFD	1	2	4	9	16	24
1	Air Products, USA	VentJet		■			■	■	■	■	■	■
2	BAM, Germany	AUSTAL			■		■	■	■	■	■	■
3		VDI	■				■	■	■	■	■	■
4	DGA, France	PHAST v8.6		■			■	■	■	■	■	■
5		Code-Saturne v6.0				■				■	■	■
6	DNV, UK	PHAST v8.61		■			■	■	■	■	■	■
7	DSTL, UK	HPAC v6.5			■		■	■	■	■	■	■
8	DTRA, ABQ, USA	HPAC v6.7			■		■	■	■	■	■	■
9	DTRA, Fort Belvoir, USA	HPAC			■		■	■	■	■	■	■
10	EDF/Ecole des Ponts, France	Code-Saturne v7.0				■					■	
11		Crunch v3.1		■			■	■	■			
12	Equinor, Norway	PHAST v8.6		■			■	■	■	■	■	■
13	FFI, Norway	ARGOS v9.10			■		■	■	■	■	■	■
14	FOI, Sweden	PUMA			■		■	■	■	■	■	■
15	Gexcon, Netherlands	EFFECTS v11.4		■			■	■	■	■	■	■
16	Gexcon, Norway	FLACS				■	■	■	■	■	■	■
17	GT Science & Software	DRIFT v3.7.19		■			■	■	■	■	■	■
18	Hanna Consultants, USA	Britter & McQuaid WB	■				■	■	■			
19		Gaussian plume model	■							■	■	■
20	HSE, UK	DRIFT v3.7.12		■			■	■	■	■	■	■
21		PHAST v8.4		■			■	■	■	■	■	■
22	INERIS, France	FDS v6.7				■				■	■	■
23	JRC, Italy	ADAM v3.0		■			■	■	■	■	■	■
24	NSWC, USA	RAILCAR-ALOHA		■			■	■	■	■	■	■
25	Shell, UK	FRED 2022		■			■	■	■	■	■	■
26	Syngenta, UK	PHAST v8.61		■			■	■	■	■	■	■

All Model Results

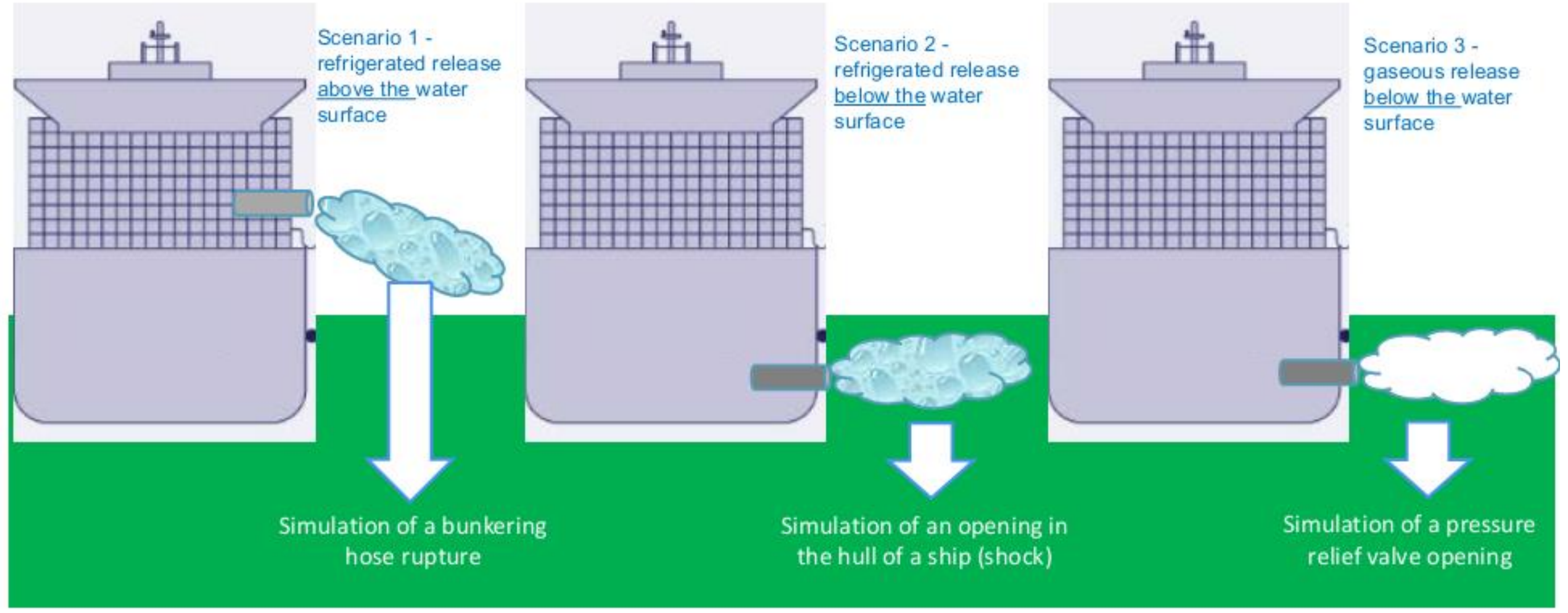


Ammonia research

- HSE is partner in the ARISE Joint Industry Project led by INERIS, CEDRE and Yara Clean Ammonia
- Aims:
  - Conduct multi-tonne spills of ammonia at sea
  - Improve understanding of dispersion in water and air
  - Provide dataset for validation of models
  - Develop methodology for risk assessment for marine applications
- Experiments planned for 2025
- Contact: Laurent.Ruhlmann@yara.com

ARISE
Ammonia Response In Sea Emergencies

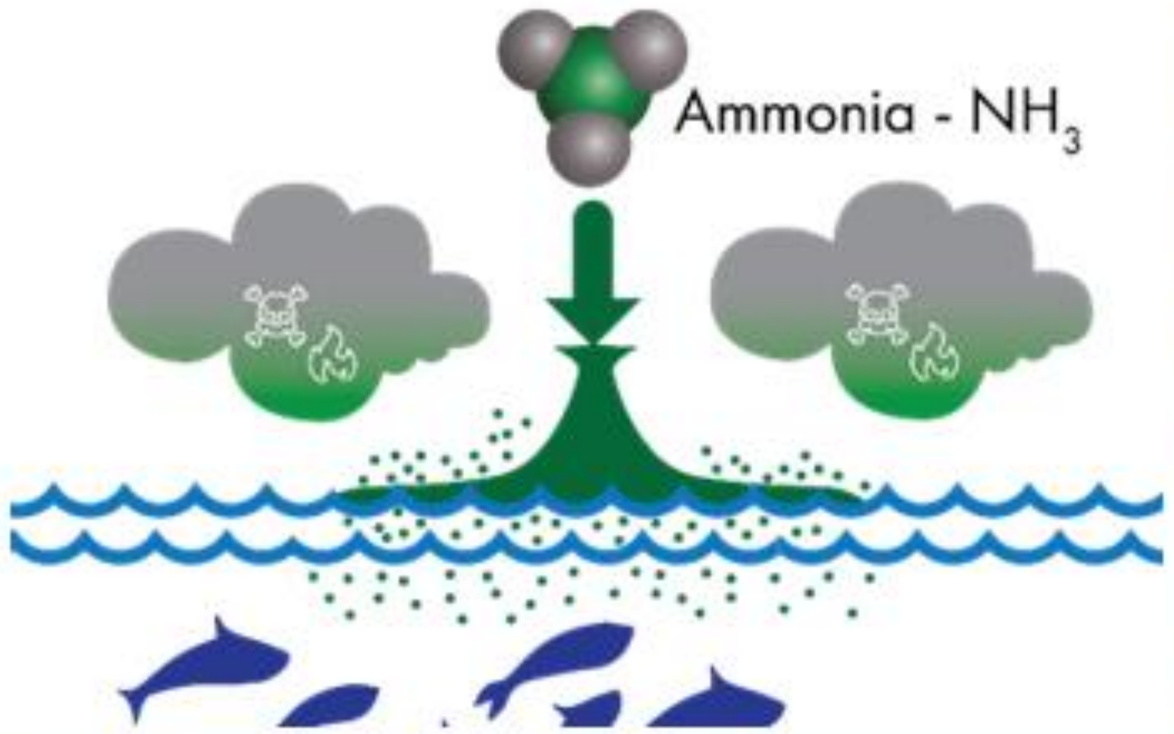
www.arise-partnership.org



SafeAm

Increased Safety of Ammonia Handling for Maritime Operations

SafeAm



Consortium of 21 partners led by SINTEF

LOWEMISSION, Sjøfartsdirektoratet Norwegian Maritime Authority, Havtil, KYSTVERKET, HSE Health & Safety Executive, DNV, TotalEnergies, WÄRTSILÄ, amon MARITIME, YARA, NTNU, USN University of South-Eastern Norway, equinor, ConocoPhillips

BACKGROUND

- Ammonia (NH_3) is deemed by many as a promising energy carrier to reduce carbon dioxide (CO_2) emissions from transport and a viable solution for global H_2 transport
- Although NH_3 has been safely transported as a chemical in dedicated carriers for decades, the potential large-scale implementation and handling by different users, introduces emerging risks and a potential need for stricter requirements

OBJECTIVE Accelerate the implementation of new value chains for NH_3 as a zero-emission fuel and energy carrier by improving safety systems design and procedures for handling of LNH_3 spills on and into water.

APPROACH AND EXPECTED OUTCOMES

- Experiments on NH_3 spills on and into water (evaporation, dissolution, mixing dynamics)
- Thermophysical modelling of NH_3_water interface, Rapid Phase Transition model, partition ratio model (PIRATE)
- Safety and environmental risk analysis (trade-offs, case studies, input to standards and regulations)

Total budget ca. 18 MNOK
For info: marta.bucelli@sintef.no (project manager)

https://www.sintef.no/en/projects/2023/safeam__increased_safety_of_ammonia_handling_for_maritime_operations

SH_2IFT II

- Safe hydrogen fuel handling and use for efficient implementation 2
- Project funded by Research Council of Norway and industry sponsors, 2021 – 2025
- Aim: study explosive and toxic atmospheres of hydrogen and ammonia, respectively, in ventilated enclosed spaces (includes dispersion, fire and explosion tests and modelling)
- Partners: SINTEF, RISE Fire Research, Gexcon, Universities of Southeast Norway, NTNU, Stavanger, Bergen, Demokritos and Karlsruhe Institute of Technology
- Two blind modelling exercises announced in late 2023 on dispersion of hydrogen and ammonia in a confined geometry with active ventilation, with or without congestion
  - Hydrogen results deadline 4 March 2024
  - Ammonia results deadline 11 March 2024
- https://sh2ift-2.com/blind-prediction-study
- Exercises coordinated by Trygve Skjold (University of Bergen) Trygve.Skjold@uib.no
- HSE participated in providing results for the ammonia study using the CFD model Fluent

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Joint Industry Projects

CO2SafePipe (DNV)	To close knowledge gaps identified in the transportation of CO_2 in pipelines covering CO_2 in both gas phase and dense phase, including: 1. CO_2 stream composition and its effect on corrosion and materials 2. the risk of running ductile fracture The project will update Recommended Practice DNV-RP-104	https://www.dnv.com/article/design-and-operation-of-co2-pipelines-co2safepipe-240345/	2023-2024
Materials in CCS Wells (DNV)	1. Identifying the role of key environmental factors on damage modes in Corrosion Resistant Alloys (CRAs) based on preliminary thermodynamic calculations. 2. Characterizing the performance of CRAs and establishing environmental limits for localized corrosion and SCC in CCS storage wells. 3. Creating a framework to translate qualification test observations into long-term performance predictions in service.	https://www.dnv.com/article/materials-performance-in-ccs-wells/	2023-2025
CO-CO_2 cracking in pipelines (DNV)	1. Define limits on CO and oxidizers (O_2, NO_2) to prevent CO/CO_2 cracking 2. Identify metallurgical limits (yield strength/hardness) to mitigate CO/CO_2 cracking 3. Develop a qualification test methodology to screen line pipe steels and welds for susceptibility to CO/CO_2 cracking.	https://www.dnv.com/article/establishing-guidelines-to-avoid-co-co2-cracking-in-co2-pipelines-251263/	?
CO_2 CFD simulation software (DNV)	Model development and validation of KFX including complex thermodynamics and heat transfer processes for release of liquid CO_2, including: dry ice formation, deposition of dry ice on the ground and in complex geometries, sublimation of dry ice, condensation of moisture in the surrounding air	https://www.dnv.com/article/co2-cfd-simulation-software-232808/	-2024
Offshore CO_2 good practice (Energy Institute)	Good Practice Guide for working on offshore oil and gas structures repurposed for CO_2 streams, including consideration of what action to be taken in the event that an evacuation proves necessary	Andy Brown proposed to EI in 2024	2024-

Joint Industry Projects

SAFEN (Safetec)	Develop risk models for hydrogen, ammonia and CCS Share knowledge for development of best practices for safe design of technologies	https://www.safetec.no/en/innovation/safen	Phase 2 2024-
Offshore Monitoring of Large-Scale Subsea Releases of CO_2 (SINTEF)	The project will collect observations from four releases from 300 meters depth, each lasting approximately 30 minutes Aim is to create an open curated dataset for public utilization	contact: Paal.Skjetne@sintef.no	2024-2025
CO_2 EPOC (SINTEF)	Characterization and prediction of the CO_2 effect on polymeric materials within the CO2 transport chain (pipelines and ships) in order to avoid leakage and failure	https://www.sintef.no/en/projects/2020/co2-epoc/	2020-2025
MASCO2T II (TWI)	Materials Assessment for Supercritical CO_2 Transport 1.Generate corrosion data for candidate metallic materials in high pressure/supercritical CO_2, with varying types and concentrations of impurities 2.Establish a thorough knowledge of the impact of a range of environmental factors (such as pressure, temperature, fluid composition etc.) on (i) the corrosion behaviour of candidate metallic materials including welds, and (ii) the effect of stress on the environmental performance of candidate metallic materials and welds.	https://www.twi-global.com/media-and-events/press-releases/2023/join-our-new-supercritical-co2-transport-project	2023-2026
Permeation of CO_2 through thermosets (TWI)	Combined Permeation of Pressurised CO_2 and Impurities through Thermosets 1. To establish the barrier performance of thermoset materials to CO_2 with associated impurities. 2. To establish if any transport of these impurity species causes ageing in the thermoset matrix.	https://www.twi-global.com/what-we-do/research-and-technology/research-programmes/joint-industry-projects#/	?
Industry Guidelines for Setting the CO_2 Specification for CCS Chains (Wood)	to define an industry accepted set of guidelines to set the CO_2 specification for effective and economic CCS chains • The guidelines shall cover the full CCUS chain, considering different CO_2 sources and transport options. • The JIP will collaborate with research and industry experts to provide a holistic understanding of the impact of impurities.	https://www.woodplc.com/insights/blogs/leading-the-way-with-carbon-capture-and-storage-ccs	2022-2024

Outline

- Introduction to HSE
- Context of Net Zero developments in Great Britain
- Recent and ongoing HSE Net Zero research
  - Hydrogen
  - Carbon Capture Utilisation and Storage (CCUS)
  - Ammonia
- Joint industry projects
- Remaining technical issues and possible future work

Technical issues: hydrogen

- Uncertainties in pipeline risk assessment
  - Failure rates
  - Potential for delayed ignition
  - Consequences of delayed ignition
- Some uncertainty in material response to long-term hydrogen exposure
  - Findings so far suggest:
    - Steel strength not significantly affected but effect on elongation to failure is significant
    - Fracture toughness reduced for most steel grades
    - Some studies indicate that theoretical net fatigue life in the presence of hydrogen is 10-100 times less than in natural gas. Greatest effect is on crack growth rate
- Pipeline inspection: techniques for monitoring defect size?

Technical issues: hydrogen

- Increased size of hazardous areas: encroachment into public spaces
- Relative impacts of different %blends of hydrogen
- Repurposing of low-pressure iron mains
- Evaluation of measures to mitigate risk to domestic consumers: excess flow valves, hydrogen detection and automatic isolation valves
- Leakage
  - Pipelines and all associated assets, e.g., valves, joints etc.,
  - Potential ingress of air over prolonged period of time into isolated sections of pipework
  - Inspection and testing of domestic pipework
- Risk assessment of liquid hydrogen bulk storage facilities

Technical issues: CO_2

- Pipeline risk assessment and emergency planning and response
  - Terrain effects: heavier-than-air CO_2 cloud flowing downhill, collecting in low areas
  - Issues with dispersion models
    - Crater source: uncertainty (correlations based on just two experiments)
    - Need to develop fast-running dispersion models that can simulate terrain effects
  - Need experimental data to develop, test and validate these models
- Venting
  - Some dispersion models used for venting studies lack validation: need experimental data to assess accuracy of models

Skylark project aims to tackle these issues

http://dx.doi.org/10.1016/j.ijggc.2015.04.001

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Technical Issues: CO_2

- Offshore sequestration of CO_2
  - Planned and accidental releases of CO_2 offshore
    - Venting strategies: from the underside of platforms?
    - Detection and emergency control systems on platforms handling both hydrocarbons and CO_2
    - Potential impact of dense CO_2 clouds on floating support vessels, ingress of CO_2 into lifeboats
  - Consequences of subsea CO_2 pipeline release or well blowout
    - How much CO_2 is absorbed into the water column?
    - Characteristics of rising plume and zone affected on sea surface

https://www.equinor.com/energy/sleipner

Technical issues: CO_2

- Fracture propagation
  - Brittle fracture due to cooling of CO_2 release: growth of small punctures to ruptures?
    - Mitigated by warm prestressing?
  - Running ductile fractures in dense-phase CO_2 pipelines due to net decompression speed of the fluid < fracture propagation speed along the pipe
    - Effect of CO_2 impurities on decompression behaviour
  - Recent publications on running ductile fractures:
    - Skarsvåg *et al*. (2023) "Towards an engineering tool for the prediction of running ductile fractures in CO_2 pipelines" Process Safety and Environmental Protection 171 (2023) 667–679. https://doi.org/10.1016/j.psep.2023.01.054
    - Cosham *et al*. (2022) "The decompressed stress level in dense phase carbon dioxide full-scale fracture propagation tests". Proceedings of the 14th International Pipeline Conference IPC2022, 26-30 Sept 2022, Calgary, Canada
  - Revision of guidance in DNV-RP-F104 and ISO 27913 (TC/265)?
  - Further CO_2 pipeline rupture experiments to inform guidance?
  - More work done on dense-phase than gaseous; therefore, less certainty in fracture arrest requirements for gaseous CO_2

Technical Issues: CO_2

- Fracture tests
  - Suitability of Charpy impact test and Drop-Weight Tear Test (DWTT) to predict fracture resistance in CO_2
- Corrosion
  - If water present, other impurities (NOx, SOx) can increase likelihood of corrosion
  - CO_2 specification is project-specific?
    - Refrigerated storage for rail/ship transport requires very low water content (< 30ppm)?
  - What to do in case of process upset (e.g., CO_2 composition outside specification)?
  - Inspection and maintenance regimes?
- Measurement of CO_2 composition
  - Wood JIP findings? Energy Institute work proposed by Andy Brown (Progressive Energy)
- Risk assessment
  - What failure rates probabilities should be used for CO_2 pipelines and vessels?
  - Need to modify fracture-mechanics model used in pipeline risk assessment code?

Technical Issues: learning lessons from CO_2 incidents

- Valves
  - Reports from Satartia incident: previously experienced problems with dry-ice blocking pipeline valves in their open position
    - What valves and/or operating procedures should be used?

- Existing CCUS plant operations (onshore and offshore)
  - E.g. Sleipner, Snøhvit, Shell Quest, In Salah, Gorgon
  - Has there been a review of safety-related operational practice?
    - Gas detection, corrosion, dry-ice plugging, maintenance issues, near-misses, emergencies

Thank you

Any questions?

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- Disclaimer: the contents of this presentation, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy
- To review HSE areas of research interest, search here: https://ari.org.uk/

Extra slides

Energy Transition: Pipeline Regulation in Great Britain

- Pipeline Safety Regulations, 1996 (PSR) provides a risk-based goal-setting approach to regulating pipelines in Great Britain
- The regulations cover:
  - Definition of a pipeline
  - General requirements for all pipelines (design, construction, operation etc.)
  - Requirement for co-operation amongst pipeline operators
  - Measures to prevent damage to pipelines

Energy Transition: Pipeline Regulation in Great Britain

- Major Accident Hazard (MAH) pipeline is one which conveys a dangerous fluid
- Classification of dangerous fluid given in Schedule 2 of PSR (see next slide)
- PSR sets out requirements for MAH pipelines:
  - Emergency shut-down valves
  - Notifications
  - Major accident prevention document
  - Emergency procedures
  - Emergency plan
- HSE has a duty to provide land-use planning advice around MAH pipelines
  - HSE uses the pipeline risk assessment model (MISHAP) and creates risk-based LUP zones around the pipeline
  - HSE advice is provided to planning authorities when they are considering new developments near pipelines (e.g., new housing, hospitals, schools etc.)

Definition of Dangerous Fluid (PSR Schedule 2)

1. Flammable, boiling point < 5°C at 1 bar(a) and conveyed in the pipeline as a liquid.
2. Flammable, conveyed in the pipeline as a gas at above 8 bar(a) ← Hydrogen at > 7 barg, 100 psig
3. Liquid with vapour pressure > 1.5 bar(a) at temperature of pipeline or 20°C
4. Toxic/very toxic fluid which is gas at 20°C and 1 bar(a) and is conveyed as a liquid or a gas
5. Toxic with vapour pressure > 0.4 bar at 20°C h and is conveyed in the pipeline as a liquid
6. Acrylonitrile
7. Very toxic with saturated vapour pressure > 0.001 bar(a) at 20°C or is conveyed in the pipeline as a liquid at a pressure > 4.5 bar(a)
8. Oxidising fluid conveyed as a liquid
9. Fluid which reacts violently with water
10. Oxidising liquid and toxic or very toxic fluid, or reacts violently with water if it has been, or is liable to be classified, pursuant to regulation 5 of the Chemicals (Hazard Information and Packaging for Supply) Regulations 1994, as the case may be, oxidising, toxic, very toxic or reacts violently with water.

CO_2 is not currently classified as a dangerous fluid

Natural gas pipelines and hydrogen blends

- Onshore natural gas pipeline network operators are also regulated under the Gas Safety (Management) Regulations, 1996 (also offshore gas export by pipeline)
- High-hazard permissioning regime
- Applies to networks transporting “gas”: any substance in a gaseous state which consists wholly or mainly of methane
- However, specification of GB natural gas currently has a hydrogen limit of ≤0.1% (molar)
- Transportation of blends in the gas network outside of this limit requires an HSE exemption
- Work has been ongoing in the GB gas industry since 2017 to assess the implications of blends up to 20% hydrogen https://hydeploy.co.uk/
- March 2023: Government took strategic policy decision to support blending of up to 20% hydrogen by volume into GB gas distribution networks
- Plans in Europe to increase hydrogen content in natural gas has implications for GB, due to pipeline interconnectors between EU and GB

CO_2 pipeline regulation

- CO_2 pipelines are not currently classified as Major Accident Hazard (MAH) pipelines
  - Classification is irrespective of the operating pressure (gaseous or dense-phase)
  - Therefore, no legal requirement to notify HSE of plans for new CO_2 pipelines
  - Not subject to controls under land-use planning regulations
- However, HSE inspects and regulates non-MAH pipelines, prioritisation based upon risk
- Potential hazards of CO_2 pipelines reviewed by HSE in the period 2007-2017
  - https://www.hse.gov.uk/research/rrhtm/rr1121.htm
- Guidance published on HSE website: https://www.hse.gov.uk/pipelines/co2conveying-full.htm
- Existing major hazards regulatory framework not drafted with CCUS in mind
- There are provisions in existing regulations relevant to CO_2 pipelines (see next slide)
- Consideration of whether any regulatory amendments required

CO_2 pipeline regulation

- Health & Safety at Work etc. Act 1974 - Sections 2 and 3
- General health and safety legislation, e.g.
  - Management of Health and Safety at Work Regulations – Risk assessment requirement
- Specific health and safety legislation, e.g.
  - PSR Part 2 applies to all pipelines (design/ materials/ examination/ maintenance/ construction/ installation/ emergency arrangements/ decommissioning)
- Standards and relevant good practice