Non-Destructive Testing Challenges in the Net Zero World

Dr Patricia Conder

ESR Technology

ESR Technology
Maximising Inspection Value

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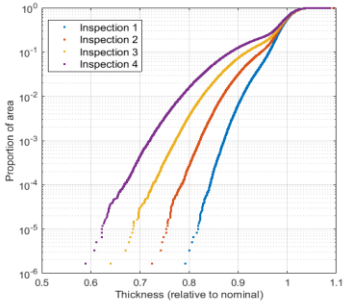
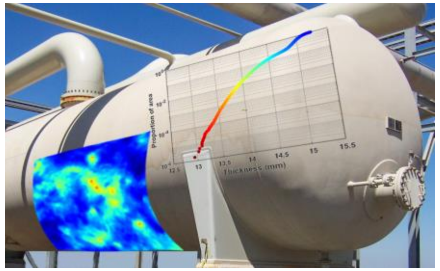
Inspection & Integrity Consultancy





HOIS
Advancing NDT

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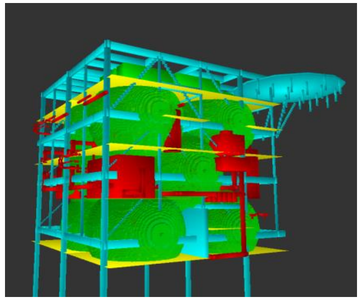
Safety & Risk Management



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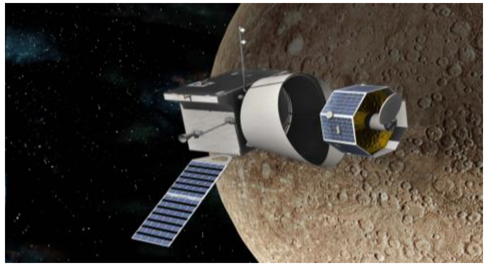
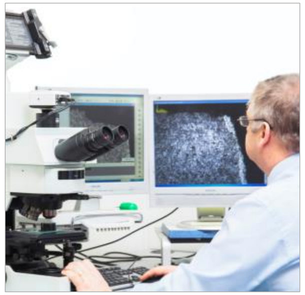
Quantifying Risk, Delivering Safety

Space and Vacuum Tribology



ESR Space
Insight into Motion

Industrial Tribology and Materials Engineering



NCT
Engineering in Motion

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What is HOIS?

- Joint industry project established in 1982
- Good practice for in-service non-destructive testing (NDT) in the energy industry, managed by ESR Technology
- Annual budget ~ £800k
- Members include:
  - Asset owner/operators;
  - NDT service providers;
  - NDT equipment vendors and technology developers;
  - Notified/appointed bodies;
  - The Net Zero Technology Centre.

What do HOIS do?

HOIS mission: independent guidance for asset integrity management to the energy industry on the capabilities and effectiveness of different non-destructive testing (NDT) methods.

Developing good practice documents for specific inspection applications.

Rigorously controlled blind trials: Independent assessment of the performance of current and developing inspection techniques.

Industry forum for latest developments: what's new and what works.

HOIS
Advancing NDT

Net Zero – Where does NDT fit?

The road to Net Zero is paved with engineering and materials advances.

Multiple sectors all accelerating – wind, hydrogen, carbon capture and storage, wave, solar….

The role of inspection is to predict maintenance requirements and reduce the risk of failure.

Will the equipment and materials give rise to new inspection challenges?

Can existing non-destructive testing techniques and equipment evaluate all the predicted degradation mechanisms? Or is innovation required here too?


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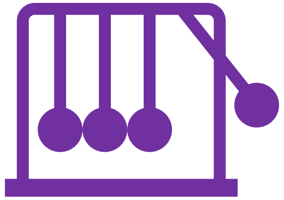
In-Service Inspection

What needs to be considered?

Degradation
- What are you actually looking for?

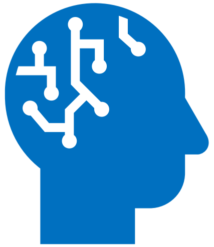
Physics of Inspection
- How can you find it?



Inspection Deployment
- How to access chosen locations?

Planning
- Where, how much and when?

Data Analytics
- What does it all mean?



Degradation

What to look for?

Degradation

What forms of in-service degradation are predicted?

Each NDT technique, including visual inspection, is limited to a range of different degradation morphologies

- e.g. Near/far surface wall loss, near/far surface cracking, delamination etc.

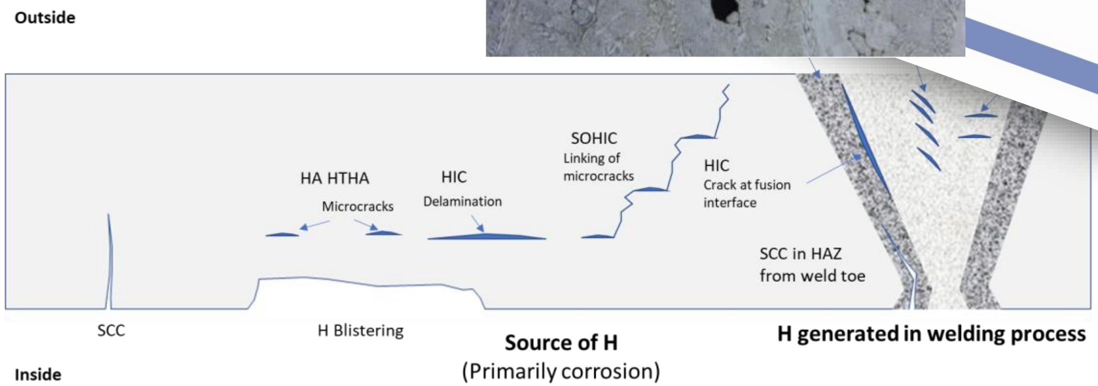
Limited by current knowledge

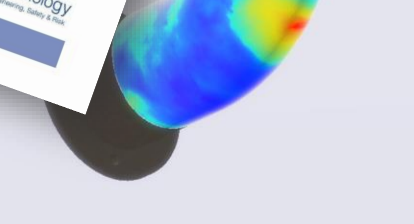
- Always potential for new failure mechanisms using new materials or new applications

Lagging indicator

Need to consider the implications of change

- Different materials
  - Composites
    - E.g. Delamination
- Different manufacturing route
  - Additive Manufacture
    - E.g. Porosity
- Different applications
  - Repurposing pipelines
    - E.g. hydrogen embrittlement





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Offshore Wind Turbines

Failure and damage mechanisms

Some mechanisms unique to or more predominant in offshore wind generation

- Erosion e.g. Leading edge erosion
- Lightning strikes
- Impact damage
- Overload
- Corrosion fatigue
- Fatigue cracking
- Scouring

Other mechanism common to marine structures

- Microbiologically influenced corrosion (MIC)
- Hydrogen induced cracking (HIC)
- Stress corrosion cracking (SCC)
- Corrosion

Blade Damage

Leading Edge Erosion leads to

- Coating loss on leading edge
- Reduction in aerodynamic performance
- Loss of structural integrity

Different categories of damage

- Repair not cost effective
- Cost effective planned repair
- Urgent expensive repair

Cost implications if categorisation is incorrect

Table 2-5 – Erosion class related to coating and laminate mass loss from IEA Wind Task 46.

Erosion Class	Description	Coating Mass Loss	Laminate Mass Loss	Turbine Power Loss
1	Light pitting of coating	<10%	0%	-
2	Small patches of missing coating	10% - 50%	0%	-
3	Large patches of missing coating	50% - 100%	<10%	1%
4	Erosion of laminate	100%	10% - 100%	3%
5	Complete loss of laminate	100%	100%	5%

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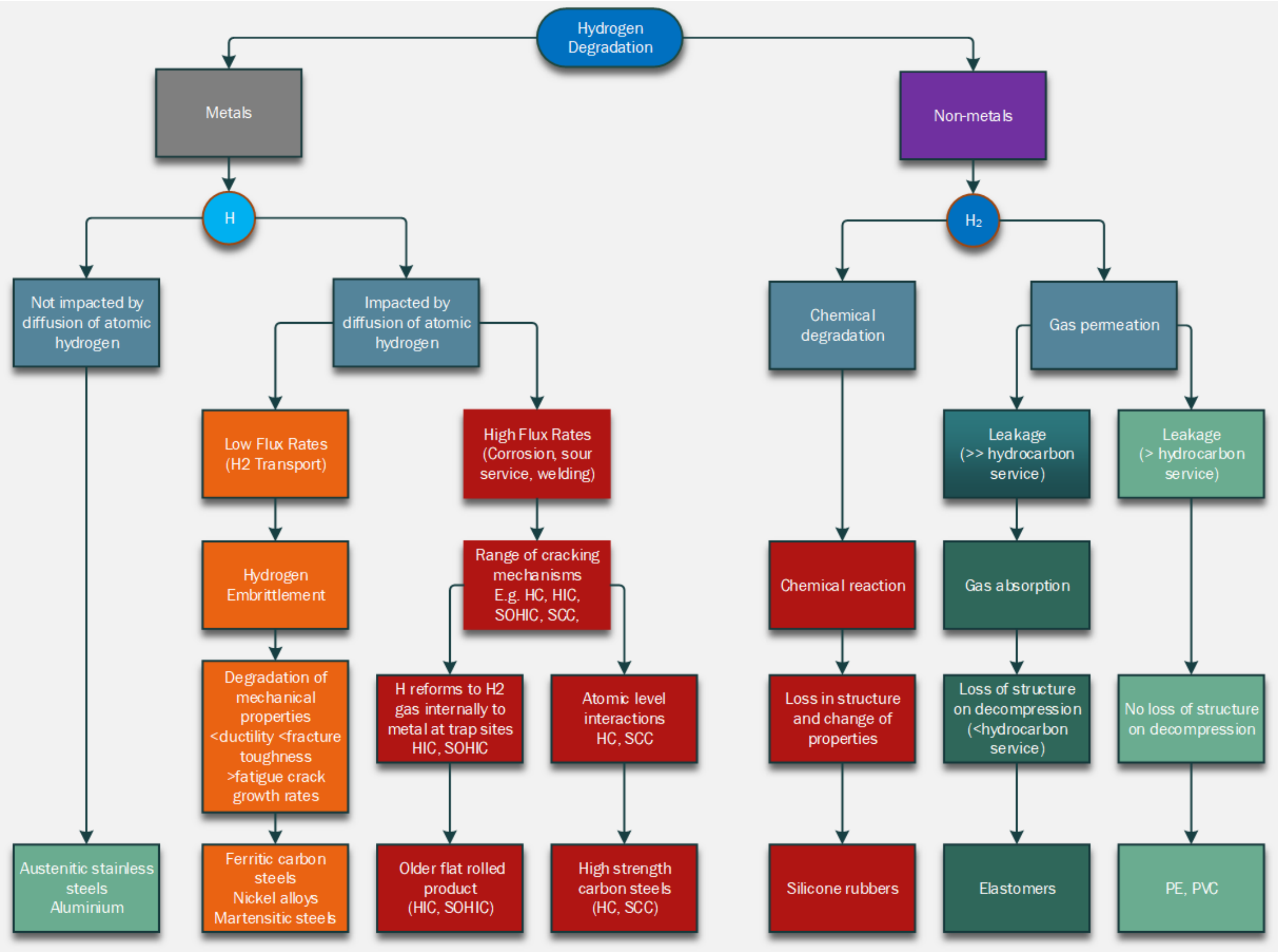
Hydrogen Degradation

- Some metals not impacted by hydrogen
  - e.g. Austenitic stainless steel
- Hydrogen can lead to range of degradation in different types of materials
- Hydrogen embrittlement
  - e.g. Ferritic carbon steel
  - Propagation of crack like features
- Hydrogen related cracking e.g. HIC, SOHIC, SCC



Repurposing of Gas Pipelines for Hydrogen

Hydrogen gas can disassociated at the metal surface and H atoms can diffuse into the body of the metal where embrittlement can arise.

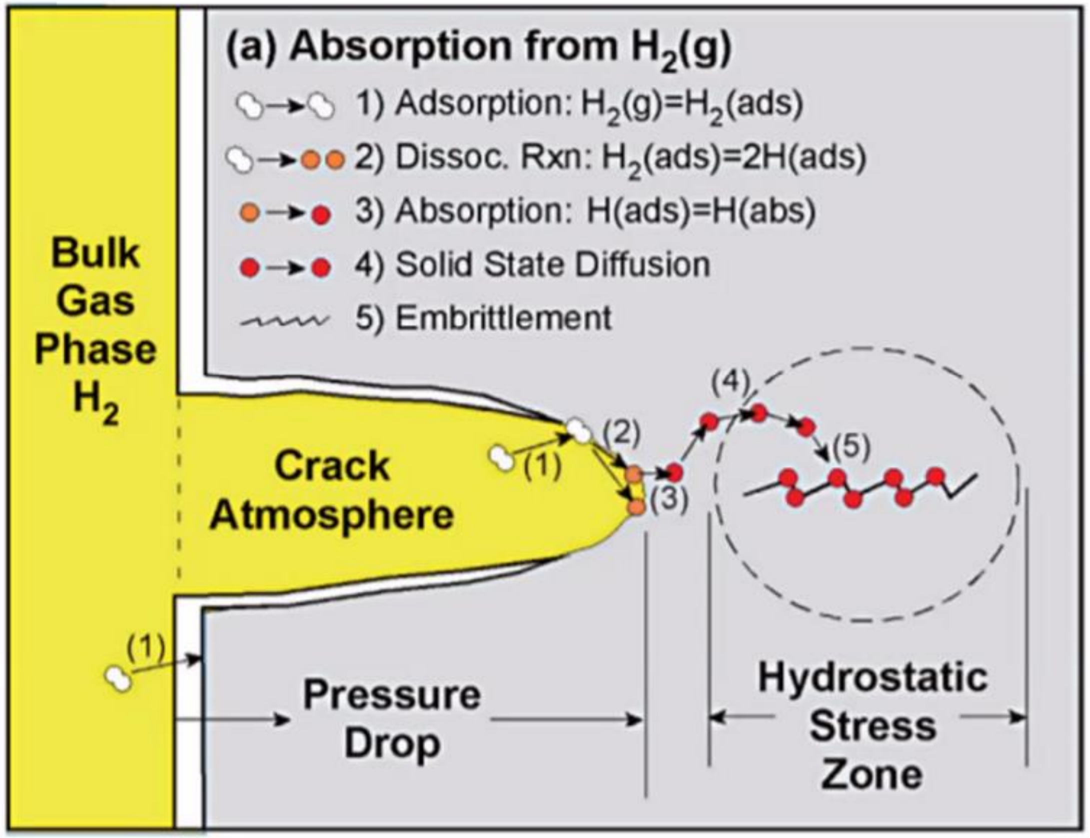
- Reduce ductility
- Reduced fracture toughness
- Increase fatigue crack growth rates

Quantifying impact - major area of current research

Concern for repurposing is existing crack like features

- Each pipeline will have differing critical flaw size specifications
- Could be smaller than original design specification

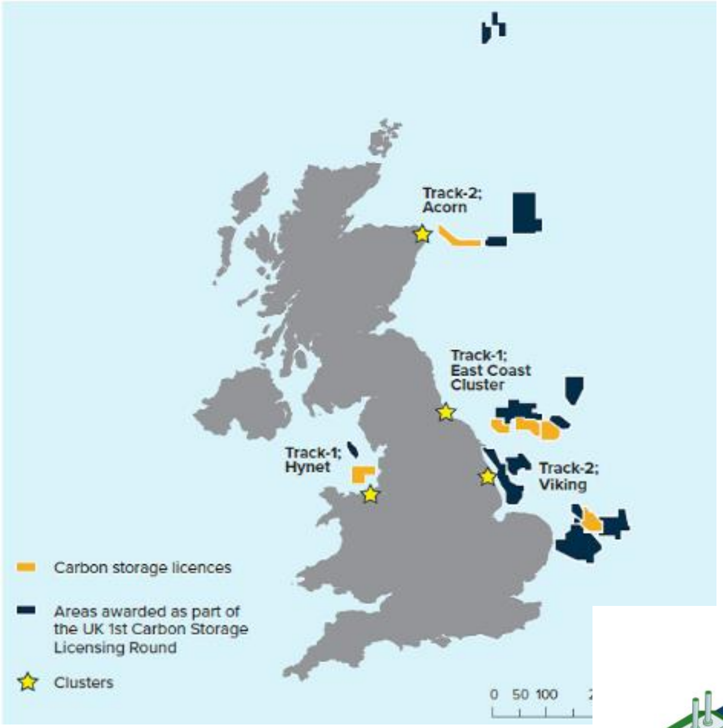
NDT challenge is identifying crack like features at minimum critical size



Lee, J.G. (2016) "Computational materials science." Available at: https://doi.org/10.1201/9781315368429

Actual embrittlement mechanism unknown

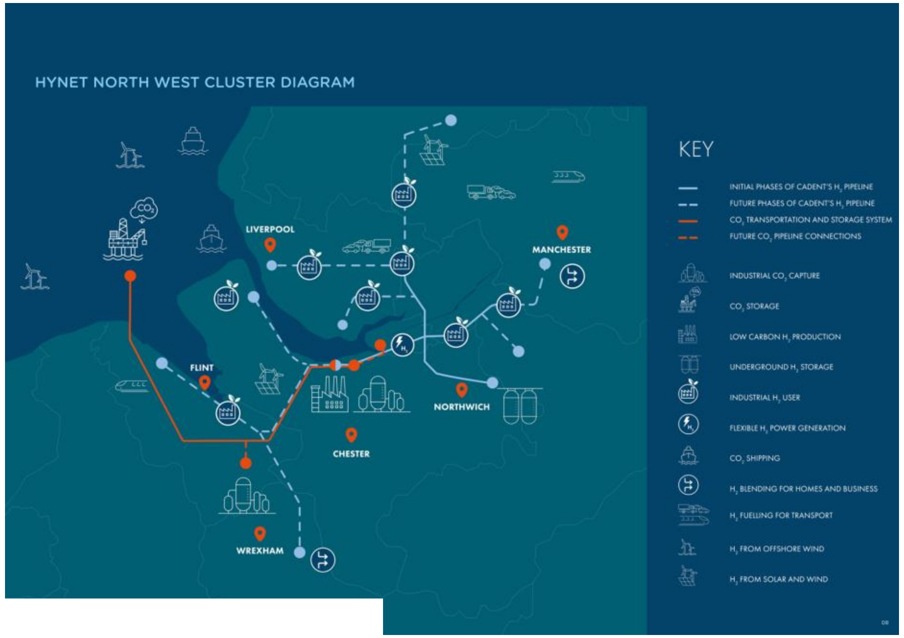
Carbon Capture and Storage



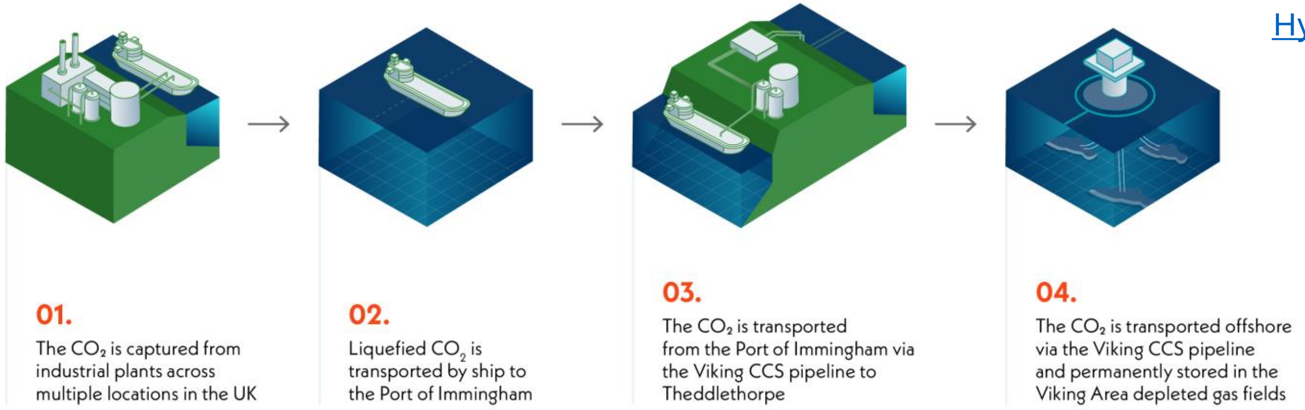
www.gov.uk

UK CCS

- Plans to capture CO_2 from industrial hubs
- Gathered via new pipeline
- Transport CO_2 via shipping and/or repurposed pipelines
- Sequestrate into used oil and gas reservoirs.



HyNet North West



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CO_2 Production and Capture

- Pure dry CO_2 is a non-corrosive fluid
- Impurities and water can cause corrosion
- Impurities dependent on source of CO_2 and capture process
- Production
  - Enhanced Oil Recovery (EOR) – CO_2 gas among others injected into reservoir to maximise oil production – either industrially produced (pure) or a closed loop recovery system (existing contaminants e.g. H_2O, H_2S)
  - Anthropogenic CO_2 – “man-made” CO_2, which contains range of impurities that are problematic e.g. NOx, SOx
- Capture
  - Pre-combustion, post-combustion, oxy-fuel combustion, chemical looping combustion and direct air capture

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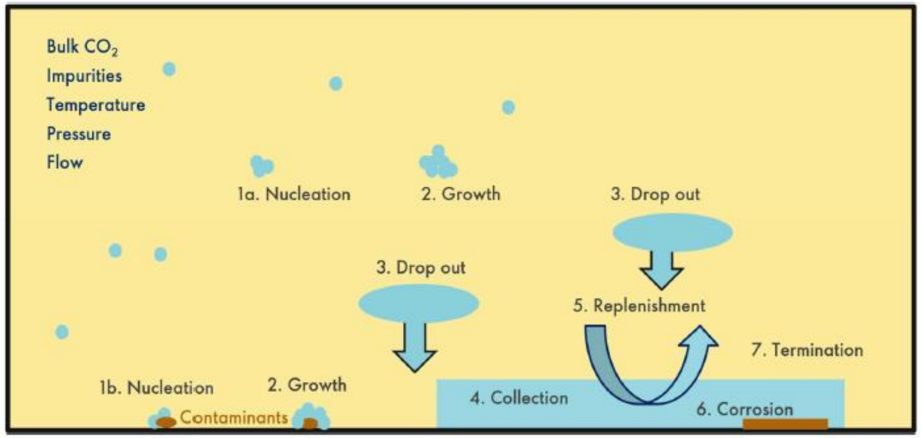
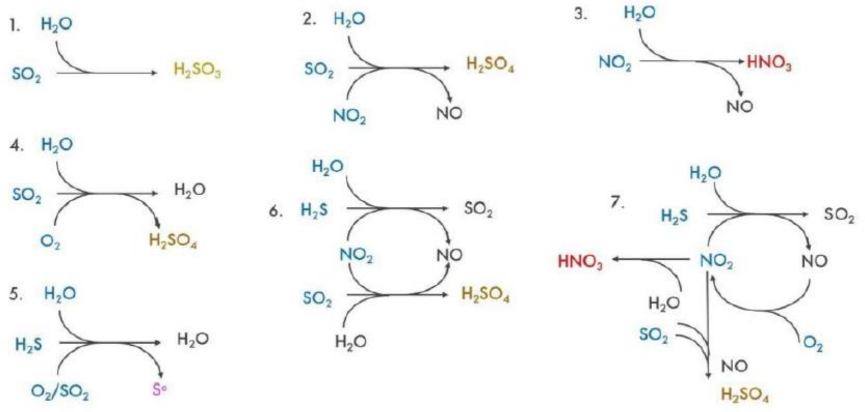
Degradation Mechanisms

- Carbonic acid corrosion (free water)
  - Free water will absorb CO_2 creating carbonic acid
- Strong acid corrosion
  - Complex interaction of impurities generates HNO_3 and H_2SO_4
  - H_2O required to disassociate acid but can be generated as bi-product
  - Can result in very high corrosion rate
  - Humectants e.g. MEG and TEG could promote droplet formation
  - IFE, Norway, is managing a joint industry project, Kjeller Dense-Phase CO_2 Corrosion Project (KDC)
- CO-CO2 SCC
  - Unlikely to occur in dense and supercritical CO_2 transportation conditions
  - More work required to relax CO specification
- Sulphide Stress cracking (SSC)
  - Presence of strong acids would promote cracking, but high corrosion rates could blunt initiated cracks reducing stress
  - DNV CO_2 Safe and Sour Joint Industry Project aim to set H_2S limits





J.Sonke et al, Corrosion and chemical reactions in impure CO_2 (2024)

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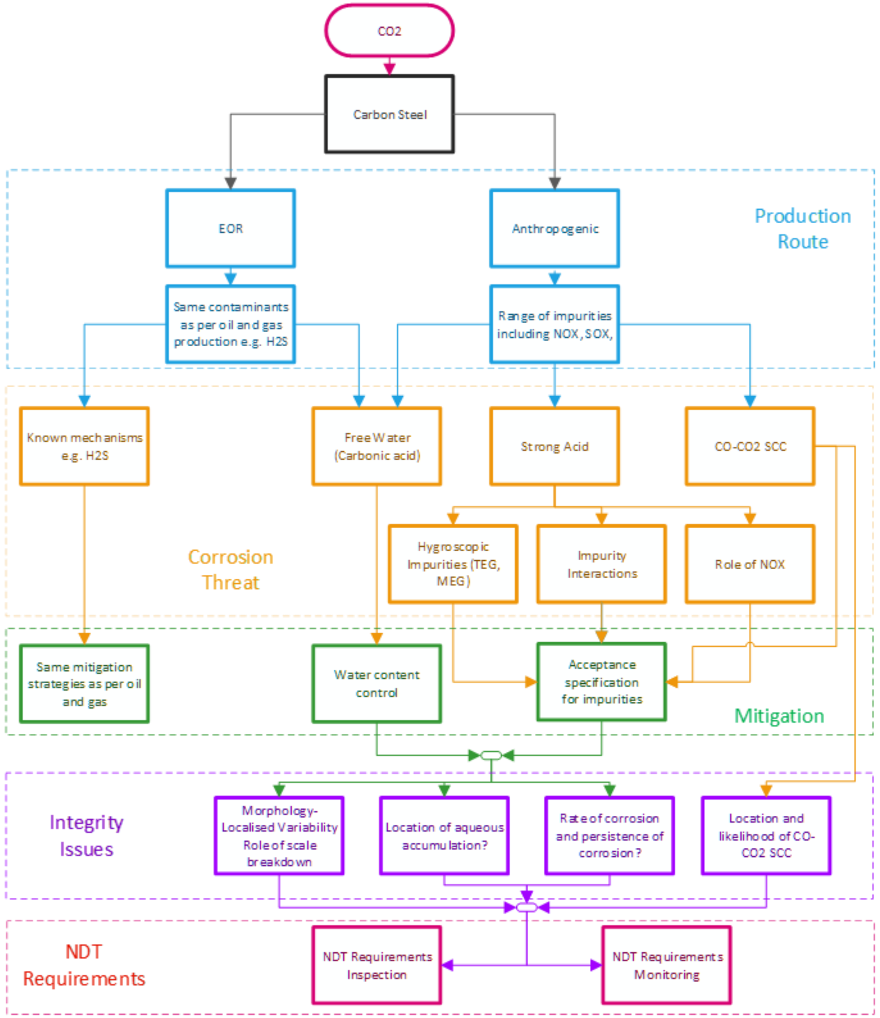
Corrosion Morphology

- What will NDT inspection or monitoring be looking for?
- Free water
  - Change in physical conditions, (pressure, temperature)
  - Drop out will occur throughout region of change
  - Corrosion will be extensive wherever free water is in contact with carbon steel pipe wall
- Strong acid
  - Change in chemical conditions
  - Corrosion will be extensive if free water occurs
  - Lab scale morphologies described as general and pitting
  - Lab scale morphologies would be detectable, but would the morphology and density be the same on large scale?
- Cracking
  - Critical crack dimensions same as hydrocarbon pipeline
  - Regions of highest stress, e.g. inlets, most susceptible



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Physics of Inspection

How can it be found?

Physics of Inspection

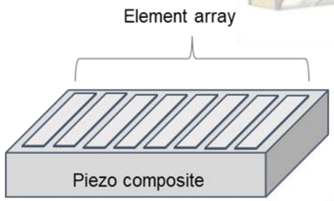
How can the degradation be found?

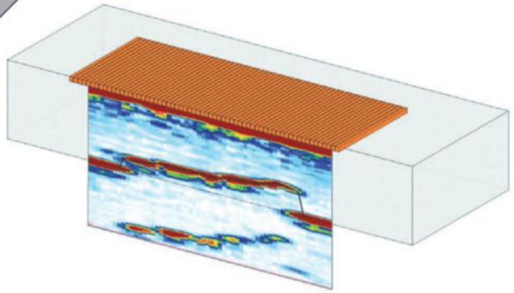
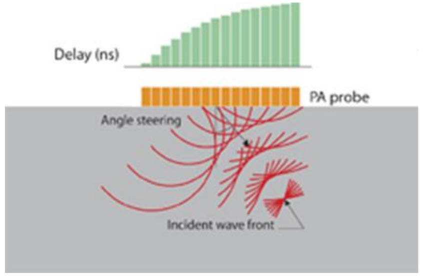
Range of different techniques all have limitations

- Ultrasonics, eddy current, electromagnetic, visual, etc.
- One technique **cannot** find all degradation types in all materials

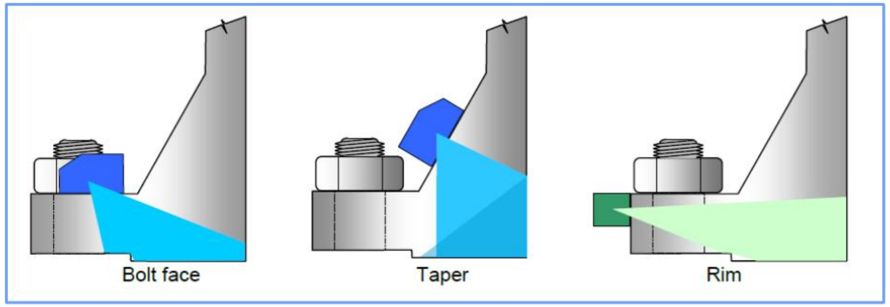
Key factors include

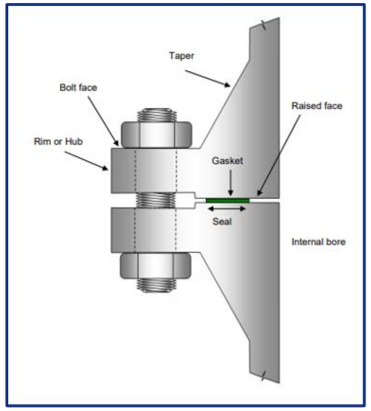
- Material
- Geometry
- Coating
- Coupling

Evident





Developments can pose new challenges (and some old ones)

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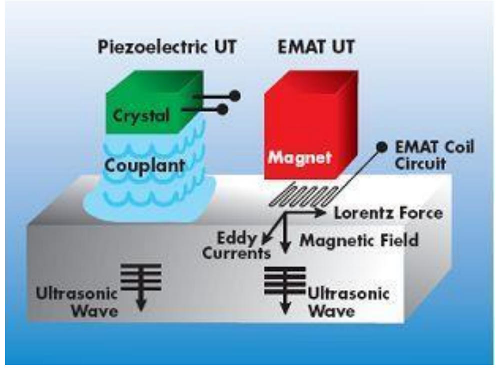
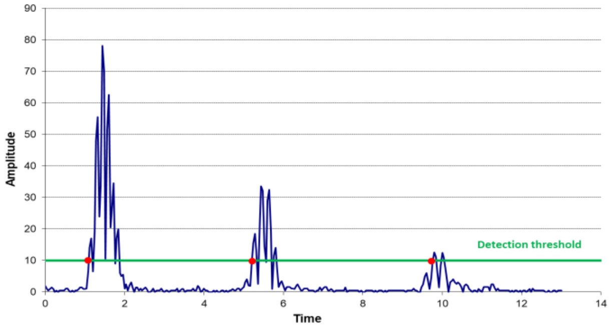
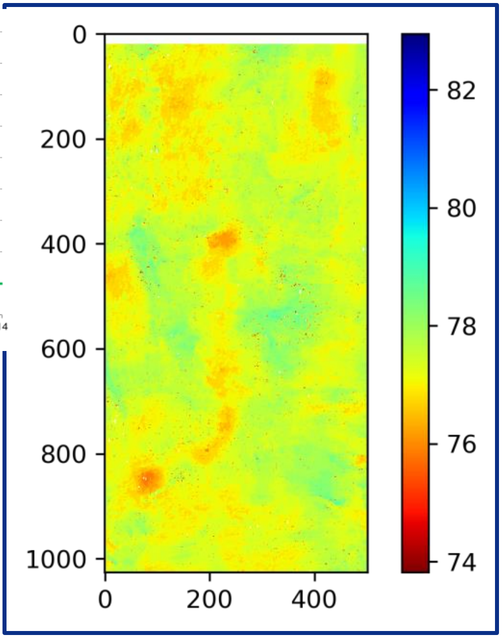
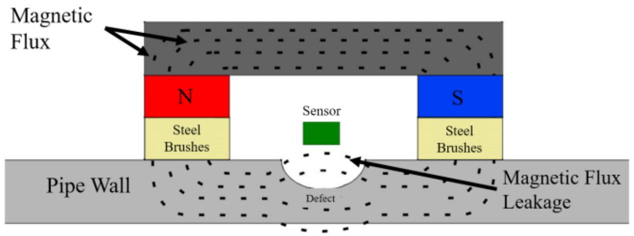
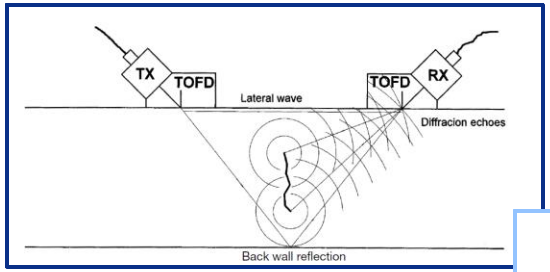
Case Studies

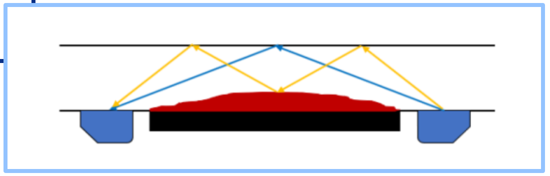


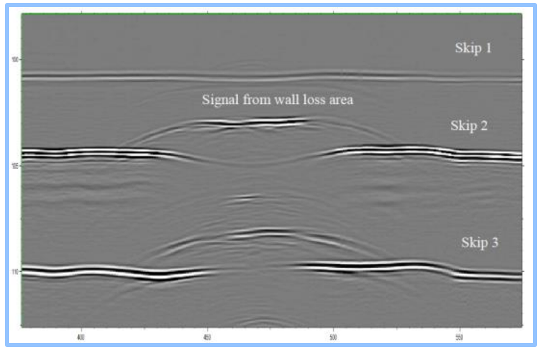












- Multiple inspection options
- Leading edge corrosion
  - Visual
- Internal pipeline wall loss
  - Ultrasonic Zero degree pulse echo
  - MFL (magnetic flux leakage)
- Internal pipeline cracking
  - EMAT (electromagnetic acoustic transducer)
  - Angled UT

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Inspection Deployment

How to get there?

Inspection Deployment

How to access chosen locations?

Rate and extent of coverage?

Deployment (largely) controls rate of data acquisition and therefore costs

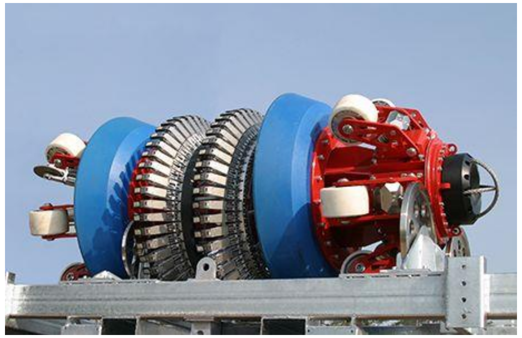
Fixed monitor

Robotics

- Autonomous
    - Unmanned Aerial Vehicles
    - Stand-off robots
    - Contact robots
    - In-line inspection tools (intelligent pigs)
- Non-autonomous
    - Scanners
    - Unmanned Aerial Vehicles
    - Contact robots

Manual

Stock



ROSEN

Trials of inspection of offshore wind foundations using mini-ROV at ORE Catapult

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Visual Inspection of Wind Turbine Blades

Visual inspection is impacted by deployment method

- In-person or by camera

Easy of access drives choice of deployment method

- No access issues – in person
- At height – camera from ground, rope access
- Remote options - UAV (drones), inspection robots delivered by drone

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Engineering, Safety & Risk

Inspection Performance - Visual

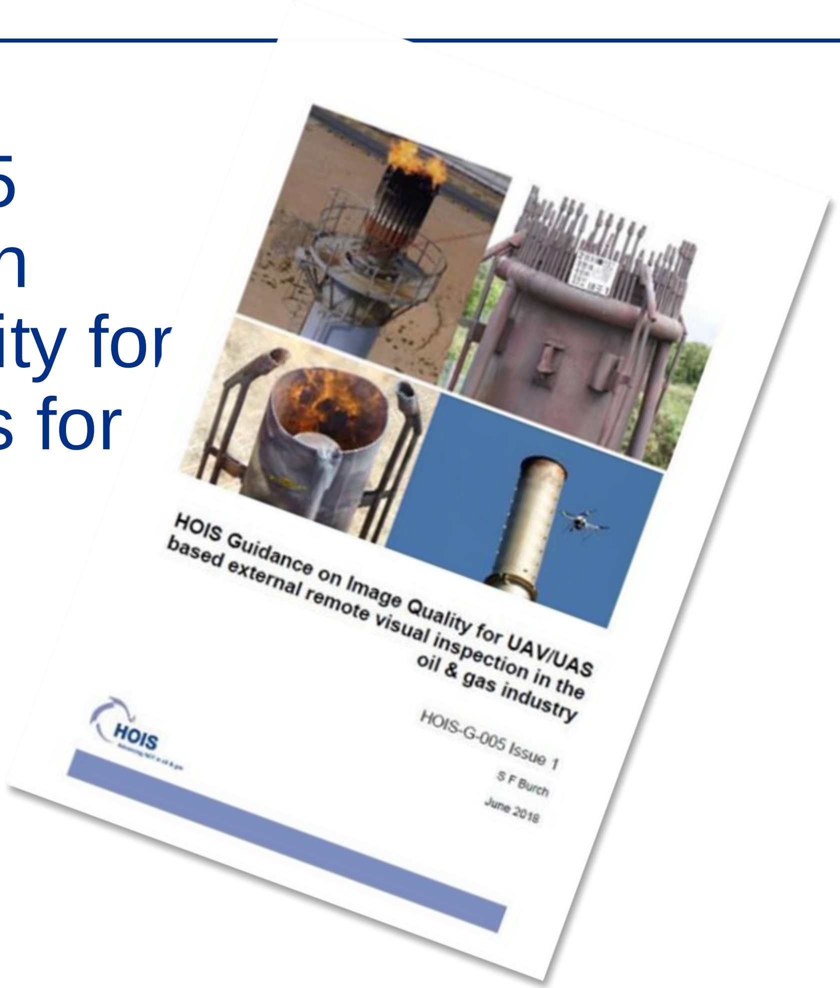
Inspection method has required capability but is it impacted by deployment?

Requirement to understand whether inspection performance is acceptable for chosen method of deployment.

Can you see the defects of interest?

- Correct sizing / classification
- Acceptable probability of detection

HOIS G-005 Guidance on Image Quality for use of UAVs for RVI



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Angle of Inspection

UAV

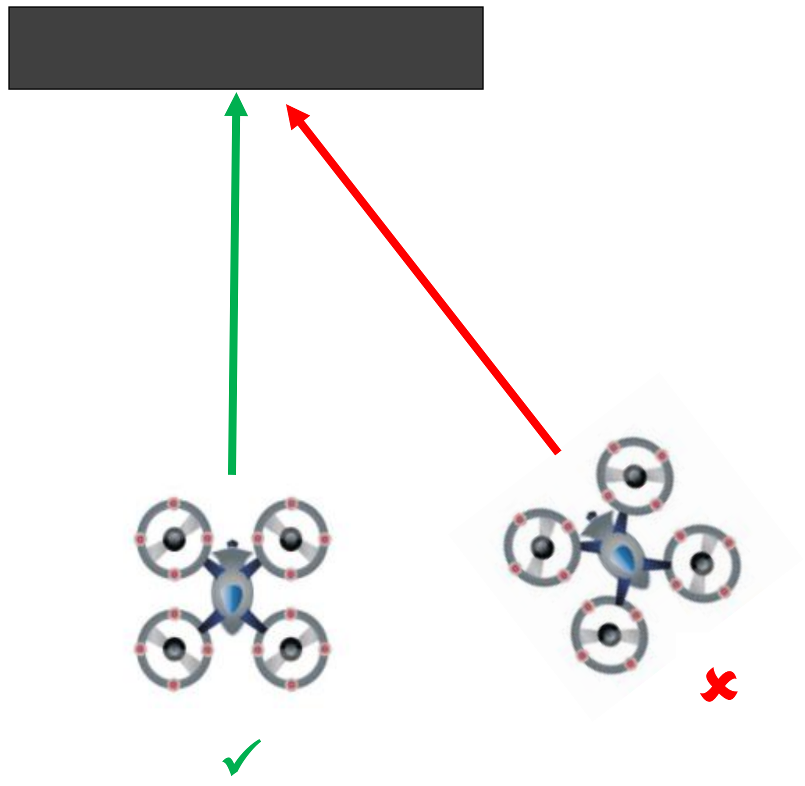
- For many UAV RVI applications the component should be viewed square on to the UAV. This will maximise the area of the surface under inspection that is in sharp focus.

In person

- For CVI inspection, standards (e.g. ASME V Article 9) state that the viewing direction should not less than 30° to the surface (i.e. within ±60° of the surface normal).

In practice

- For some applications there may be advantages to viewing a surface obliquely as irregularities or undulations then show up more clearly.



Lighting

Lighting can affect the ability to defect some defects.

Ideally lit from behind

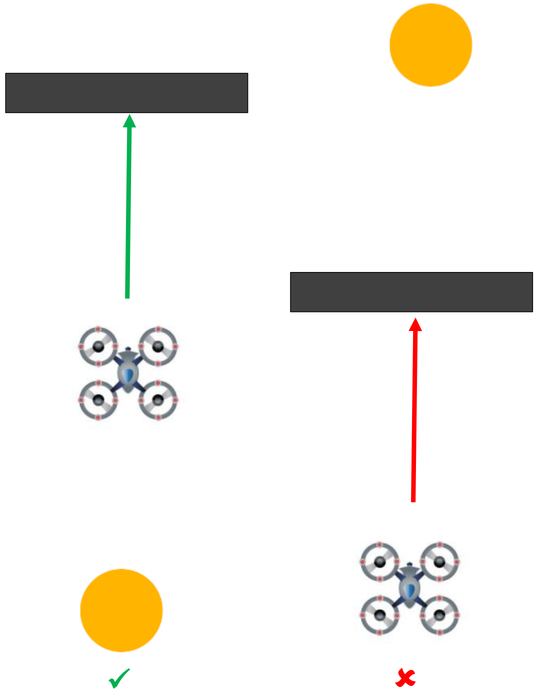
Does this mean

- East facing in the morning,
- South facing at noon,
- West facing in the afternoon
- And don’t bother with North facing?

Not always practical to wait for ideal lighting conditions

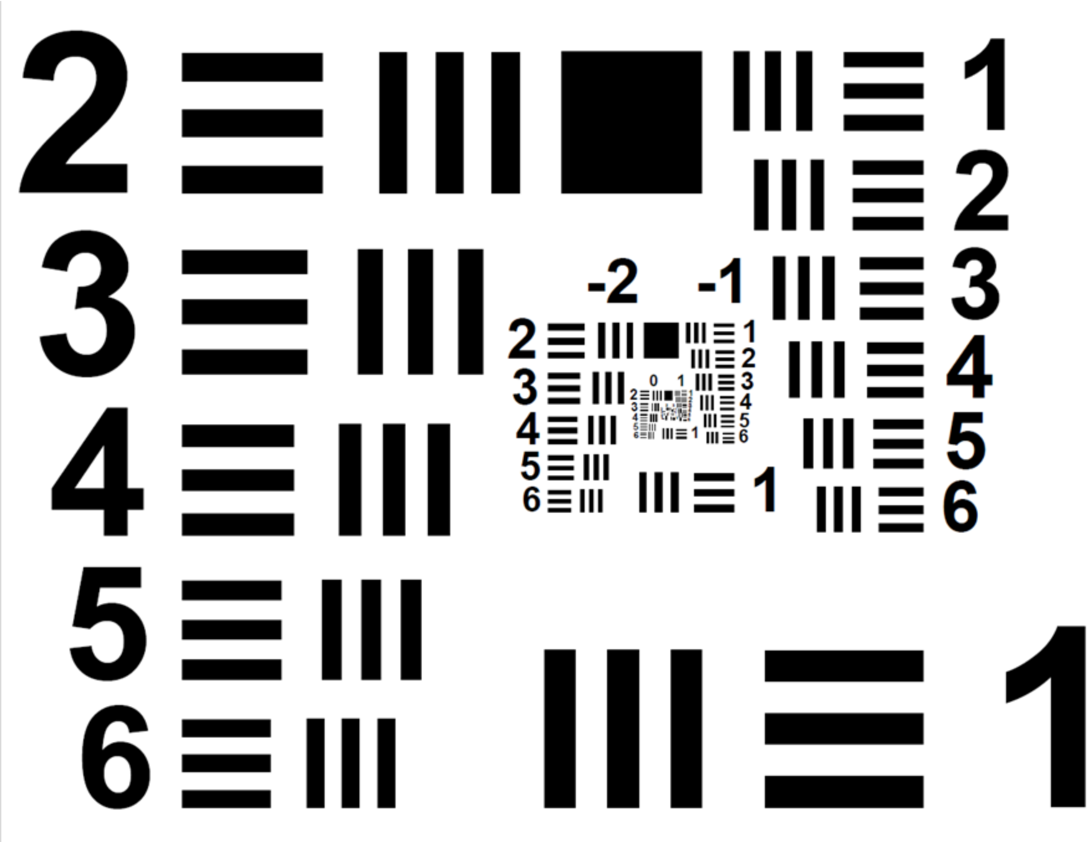
But wait for daylight or use additional lighting

Need to assess performance

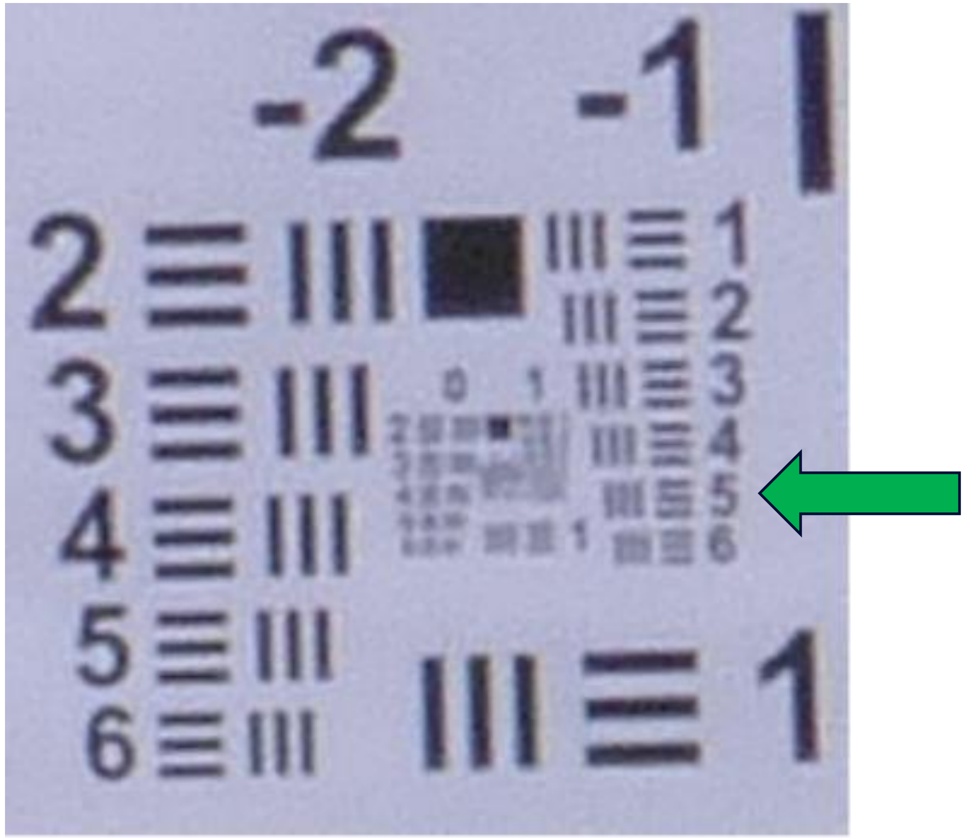


Resolution

How good is your eyesight?



How well did the camera do?



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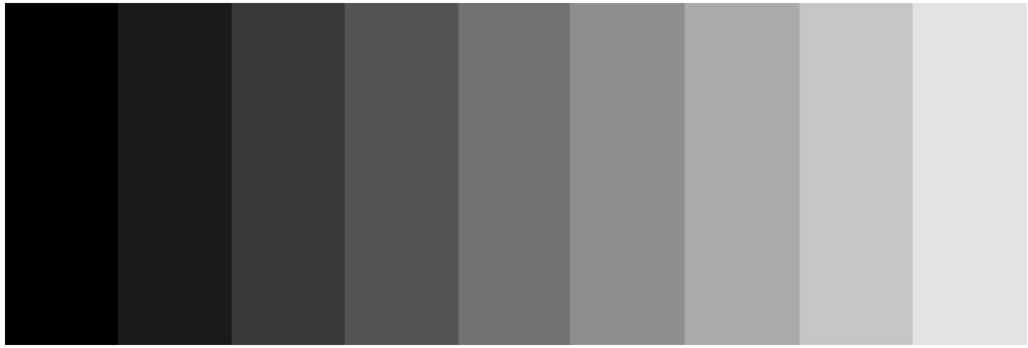
Other factors

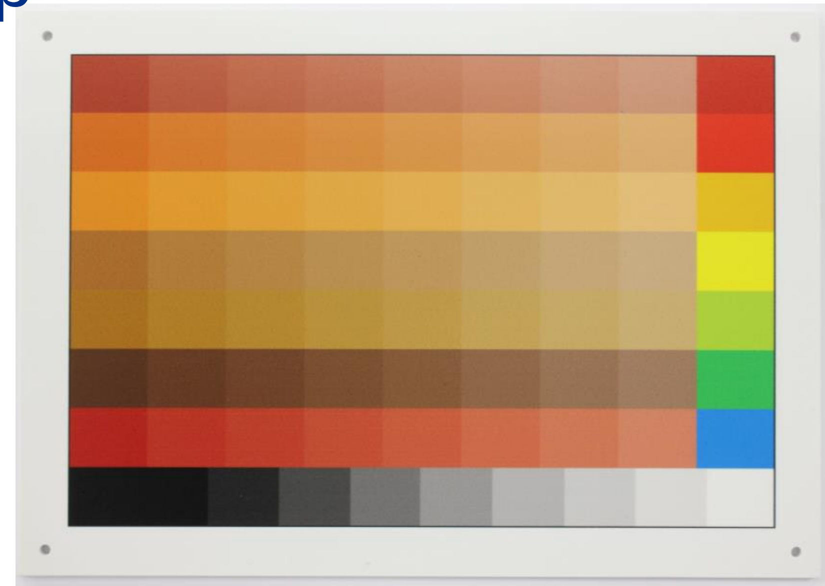
Signal to noise

- To measure noise levels, it is necessary to find the standard deviation of the image grey levels in small areas in each grey-level step in the image.
- Similar to radiographic image assessment.

Degradation not always just shades of grey



Test chart for measurement of image noise levels



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Placing Resolution Targets

Ideally the resolution target would be on the equipment to be inspected

- Not always practical
- Or safe
- Can still examine test chart under similar lighting and distance conditions

Alternatively mock-up or sample test pieces can be used.

Courtesy of Lloyd's Register

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HOIS G-005 Guidance on Image Quality for use of UAVs for RVI

Use of Unmanned Aerial Vehicles (UAV) for remote visual inspection (RVI).

Aim to develop guidance on minimum quality of UAV imagery needed for different applications to equate to close visual inspection (CVI).

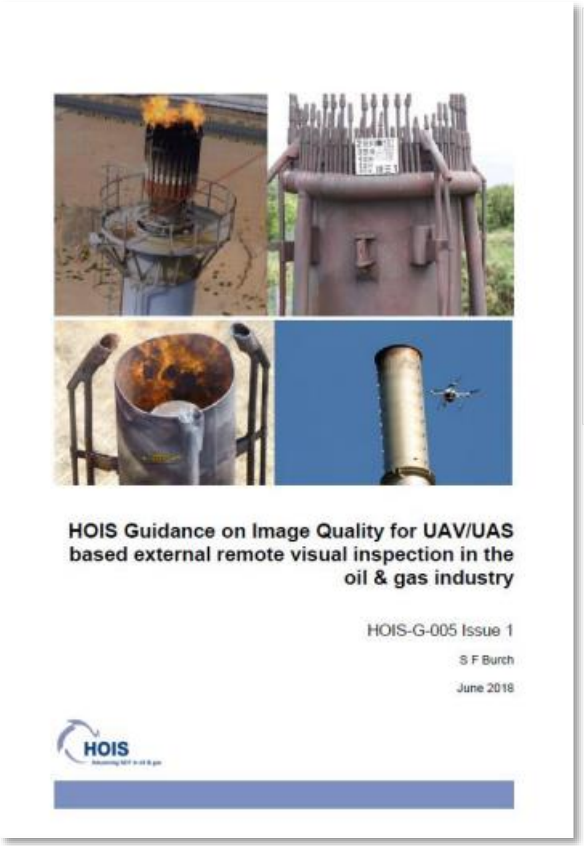
- *Can a camera deliver the same or better than on-site in-person inspection?*

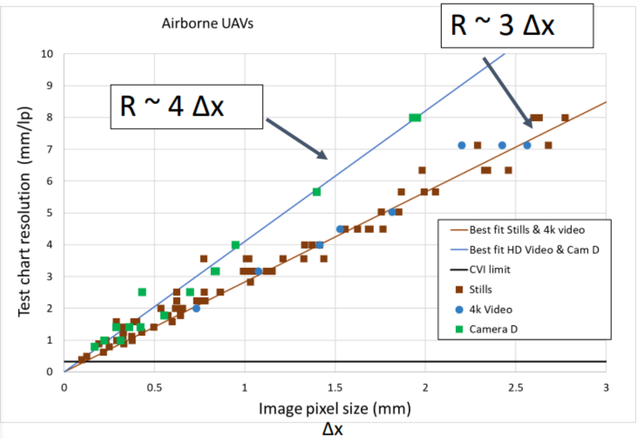
Key aspects

- Camera specification i.e. lens and pixel size
- In field application i.e. lighting, distance, demonstrable resolution
- Validated by HOIS member trials using airborne UAVs to image USAF 1951 charts at different distances.

Since 2018 publication:

- ASME V Article 9 revised to include reference to resolution charts (e.g. USAF 1951).
- HOIS guidance being referenced in industry tenders
- Publicly available
- https://www.bindt.org/shopbindt/hois-documents/
- HSE publication due soon





HOIS Advancing NDT

Hydrogen ILI

For immersion in H_2 environments (e.g. in-line inspection (ILI) tools) hydrogen can pose specific challenges. These include:-

- Rare earth magnets for MFL can disintegrate – require sealing
- Higher ATEX ratings are required to avoid ignition in hydrogen/air mixes e.g. in pig traps
- “Dry” pigging medium may lead to increased cup wear
- Ingress of hydrogen into electronics pressure vessels may reduce time to failure

Instrument performance may vary due to changes in pipeline geometries, conditions and run speeds.

- Lower energy density of H_2 required higher gas velocities which can impact on ILI run speeds

Rare earth magnets, like those used in ILI tools, before and after exposure to hydrogen environment.

T.D. Williamson - Making Way for Hydrogen

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CO_2 Pipelines

- In-line inspection
  - Successful ILI runs in dense phase CO_2
    - Non-lubricating fluid – increased wear
    - Damage to polymeric materials due to rapid gas decompression
    - Frequency of runs unclear at present
- Monitoring
  - Corrosivity state - internal applied small area
    - Would depend on location confidence and fluid homogeneity
  - NDT Externally applied small area
    - Would depend on location and density confidence
  - NDT Externally applied larger area
    - Location confidence still required but density confidence relaxed

Potential in-line inspection techniques that can be used for CO_2 pipelines. (Van de Camp, 2023).

NDT techniques	Metal loss	Crack detection
Magnetic flux leakage (MFL) - ILI	Not affected by medium, upper wall thickness limit, options to use Ultra High Resolution (UHR) tools for the detection of pitting/pinholes	
Liquid coupled ultrasonic technique - ILI	Single phase liquid, no knowledge if it works in dense phase CO_2	Has been used in oil and gas pipeline for crack detection but has not been applied to CO_2 pipeline yet
Acoustic resonance - ILI	Potential for heavy walled, dense CO_2 phase lines, under NDT Global investigation	
Electromagnetic acoustic transducer approach (EMAT) - ILI		Narrow wall thickness range (~9-15 mm) likely not suitable for CO_2 lines

Examples

- Corrosivity state
  - Weight loss coupon, Linear polarized resistance, Electrical resistance, High sensitivity electrical resistance, Ring pair corrosion monitor, electrochemical noise
- Small Area
  - Pulse Echo UT, pulse echo array of sensors, EMAT, Field signature method, Lamb wave tomography,
- Large Area
  - Guided wave

Planning

Where and when?

Planning

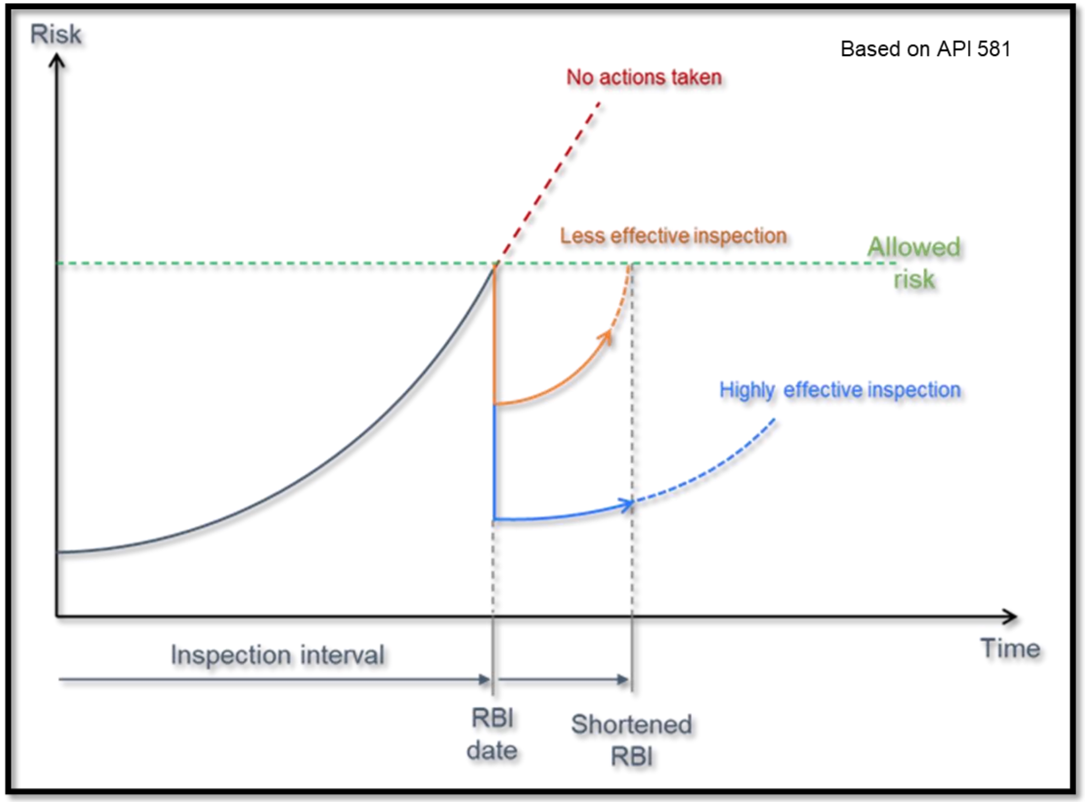
Where, when and how much inspection?

Is monitoring an option?

Aim of inspection is to reduce risk of failure

Need to understand

- Likelihood of degradation mechanism(s) occurring
- Progression of degradation mechanism(s)
- Spatial distribution of degradation mechanism(s)



Turbine Blade Inspection

What is the degradation of concern?

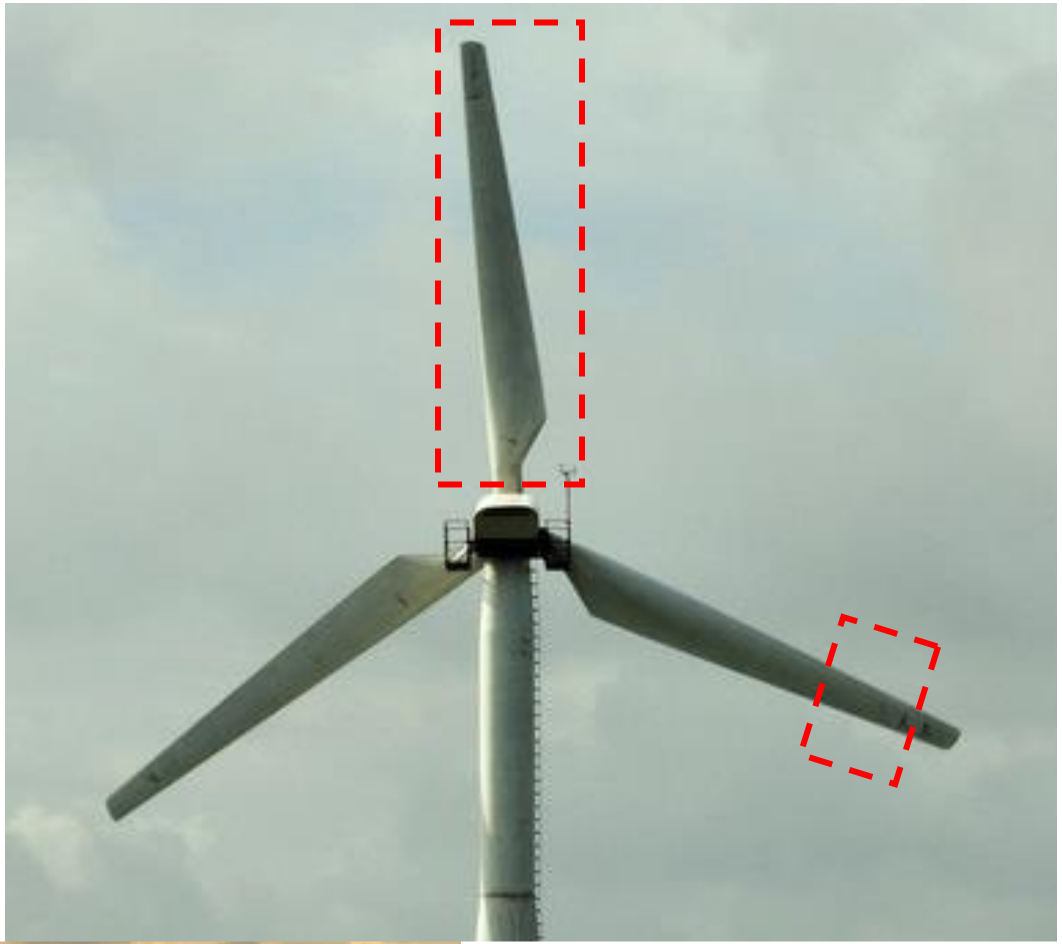
- Leading edge corrosion

Is the degradation across all blades?

- Homogeneity and high density of degradation can justify sampling.
- Sampling can significantly reduce inspection load.

Or is isolated degradation of concern?

- Lightening strikes
- Drives towards full inspection



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CO_2 Planning

Hydrocarbons

- Hydrocarbon pipelines experience gradual progressive corrosion
    - Can change over time with fluid composition but rate of change slow compared with fluid sampling.
- Periodic inspection using ILI tools
- Calculate an averaged corrosion rate for the time period between inspections.

CO_2

- CO_2 threat is potentially severe but short lived
- Just inspect for current integrity state?
- When to inspect?
- In response to impurity variations?
- Currently no in-line continuous monitoring of impurities

Inspection Strategy - When and where to inspect?

- Consecutive drivers
    - Onshore - Typically the onshore hazard ranges for gaseous CO_2 are less than natural gas equivalents, but for dense CO_2 (liquid/critical phase) the hazard ranges to toxic levels can be significant
    - Offshore - mitigation of CO_2 dissolving into the water column likely to be significant but subject to modelling and experimental research
- Time-based progression
    - Under normal operation, acceptance specifications should prevent high corrosion rates, and these may only occur under transient conditions
    - Corrosion is a cumulative process so it would be difficult to predict a longer-term corrosion rate without modelling based on continuous fluid composition and operational condition monitoring
    - Chosen ILI inspection interval based on risk and predicted corrosion rate
    - In the case of anthropogenic CO_2 pipelines the inspection interval would have to be purely time based until sufficient confidence was built up around the prevention or prediction of corrosion events
- Location
    - NDT monitoring would depend on predicting the areas of greatest risk

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Data Analytics

What does it all mean?

Data Analytics

What does it all mean?

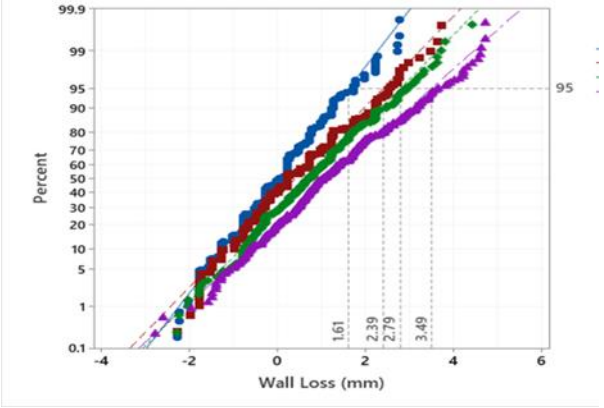
Historically NDT has been focussed on reporting on the area of inspection,

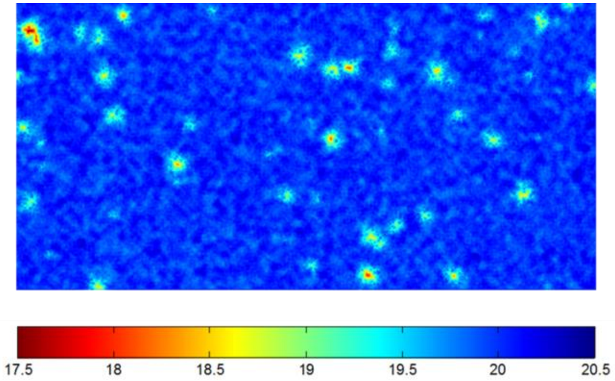
- e.g. minimum overall wall thickness, highest category of scab, anomaly exceeding defined threshold

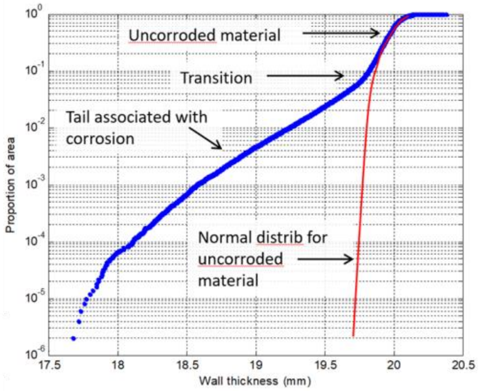
Focus now on looking at the bigger picture and combining results or results from different techniques to better understand and predict degradation behaviour

Building on

- Data science and statistics
- Machine learning and AI







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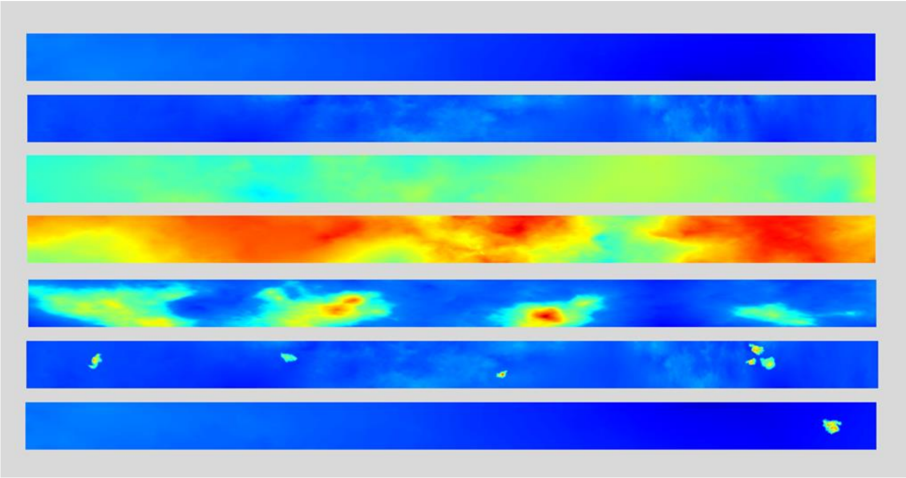
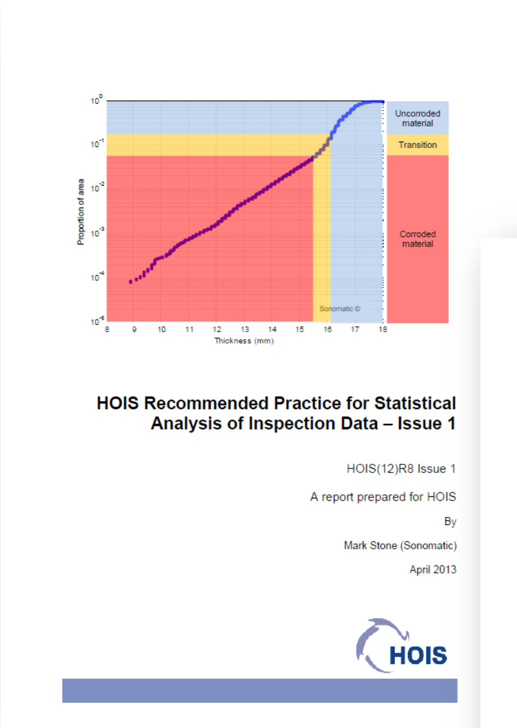
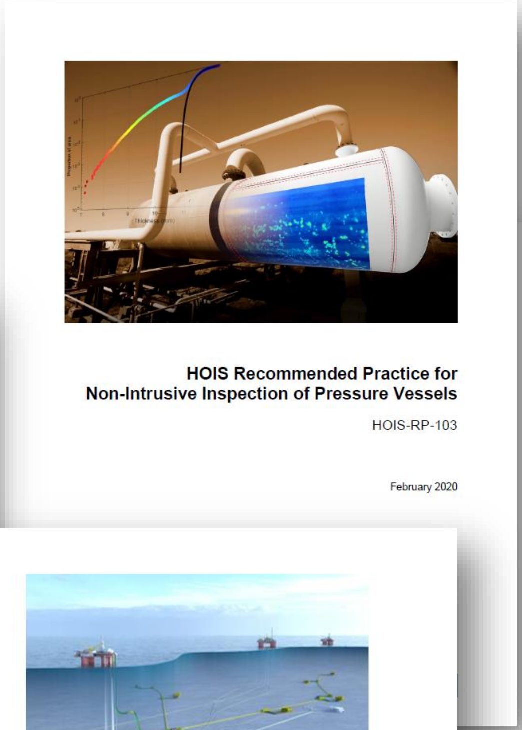
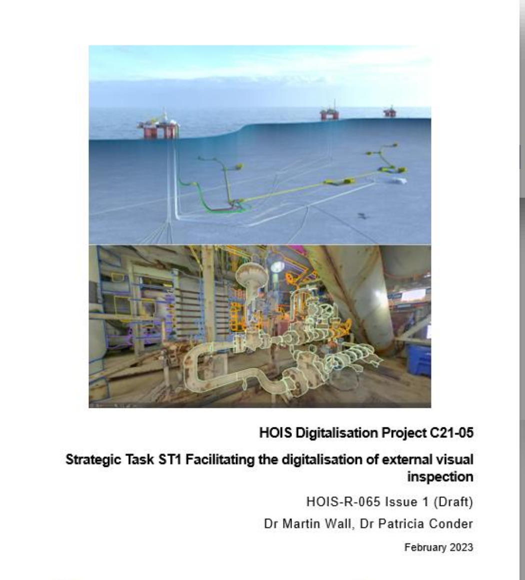
Applying Data Science

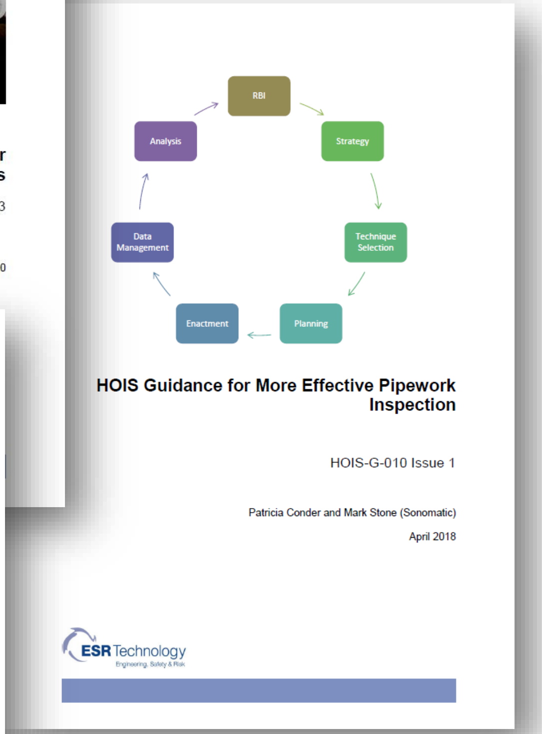
- Developing an understanding of the likelihood, progression and spatial distribution of degradation can better inform planning
- Approach can be applied to different applications
- Matching inspection to degradation
- Digitalising workflow











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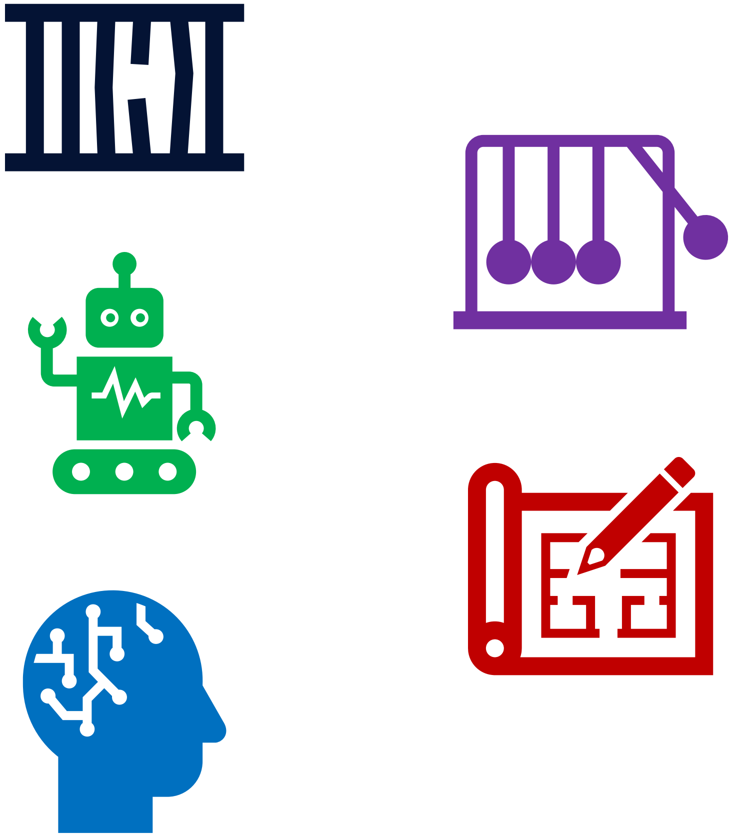
Inspection for Net Zero

New Applications, New Challenges - Same Basic Approach

- What are you actually looking for?
  - Degradation
- How can you find it?
  - Physics of Inspection
- How to access chosen locations?
  - Inspection Deployment
- Where, how much and when?
  - Planning
- How can you maximise the value of your inspection?
  - Data Analytics



NDT inspection solutions can only meet defined challenges. The better the definition of degradation challenges the better the inspection solutions.

HOIS Digitalisation Forum HDF

www.abysssolutions.com.au

Want to know more?

Join us at HOIS Digitalisation Forums

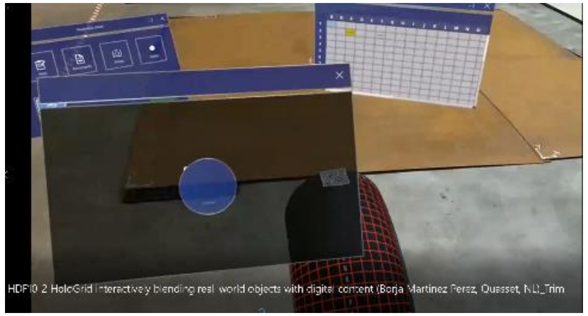
- Open event – not limited to HOIS members
- Covers all aspects of digitalisation of NDT throughout the workflow in the Energy sector

“To promote engagement with NDE 4.0 and digitalisation stakeholders worldwide and across industry sectors.”

Registration info@hois.co.uk

Catch-up

https://www.youtube.com/@HOIS-JIP



https://quasset.com/hologrid/

www.bam.de Courtesy Marija Bertovic

www.guided-ultrasonics.com

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Non-Destructive Testing Challenges in the Net Zero World

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