VISUAL ASSESSMENT OF PIPELINE CLEANLINESS FOR CCUS CONVERSION: A NEW DIAGNOSTIC APPROACH: LIVERPOOL BAY CASE STUDY

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Abstract:

Objective, Scope; The repurposing of existing hydrocarbon pipelines for carbon dioxide (CO_2) transportation in Carbon Capture, Utilization, and Storage (CCUS) projects presents both an opportunity and a technical challenge. Ensuring internal cleanliness is critical to safe and efficient CO_2 transport, particularly given the corrosive potential of impurities and residual hydrocarbons. Traditional cleaning and verification methods offer indirect assurance of cleanliness. However, they often lack the ability to confirm uniform cleanliness along the entire pipeline length.

Methods, Process; This paper presents a novel, high-resolution, free-swimming video assessment tool that enables direct visual assessment of pipeline interior conditions. Believed to be the first field deployment of its kind globally, the system captures continuous 360-degree footage of the internal pipe wall over long distances without tethering or real-time data transmission. Prior to launch, the device is pre-programmed with pipeline requirements, enabling autonomous navigation and data logging.

Results, Observations, Conclusions; The technology was successfully applied to a 27-kilometer, 24-inch carbon steel pipeline originally designed for gas service and undergoing conversion for CO_2 transportation. Following a bespoke cleaning programme of brush pigs, foam pigs and batch cleaning fluids to ensure the removal of any pipeline debris the video assessment tool was deployed to verify the pipeline's readiness. The captured footage provided operators and regulatory stakeholders with unequivocal, quantifiable visual evidence of internal cleanliness, supporting pipeline integrity certification and reducing uncertainty around repurposing decisions.

This paper details the inspection methodology, operational setup, and findings from the case study. It also explores broader implications for CCUS infrastructure readiness and risk management. The technology represents a significant step forward in pipeline verification, offering a scalable, non-invasive, and data-rich approach to ensuring CO_2 pipeline integrity.

Novel/additive information; The technique described in this paper involves the application of the world's first multi sideview array camera, providing complete pipeline

visual coverage. This was combined with a bespoke data analysis and visualisation suite, intuitive and interactive log, creating 2D and 3D models. Critically, it provides all stakeholders with indisputable evidence to allow them to plan and execute pipeline conversion from oil & gas service to transport Co2 without the need for constructing new pipelines.

Introduction

Net-zero pathways increasingly rely on CCUS to decarbonize hard-to-abate sectors. In the UK, HyNet North West and the Liverpool Bay CCS development (operator: Eni UK via LBCCS) illustrate how legacy infrastructure can accelerate deployment timelines and reduce capital intensity. Yet converting dry-gas pipelines for dense-phase CO_2 introduces safety and integrity constraints that hinge on verified internal cleanliness and stringent dehydration.

Conventional practice—cleaning metrics, pressure trends, debris volume, and ILI readiness—offers indirect assurance. By contrast, direct visual confirmation along the full bore provides clarity on residuals, localized deposits, coating remnants, and surface condition relative to ISO 8501-1 Sa 2.5 targets. This paper describes a purpose-built, free-swimming camera system and analytics stack designed to deliver that evidence at scale.

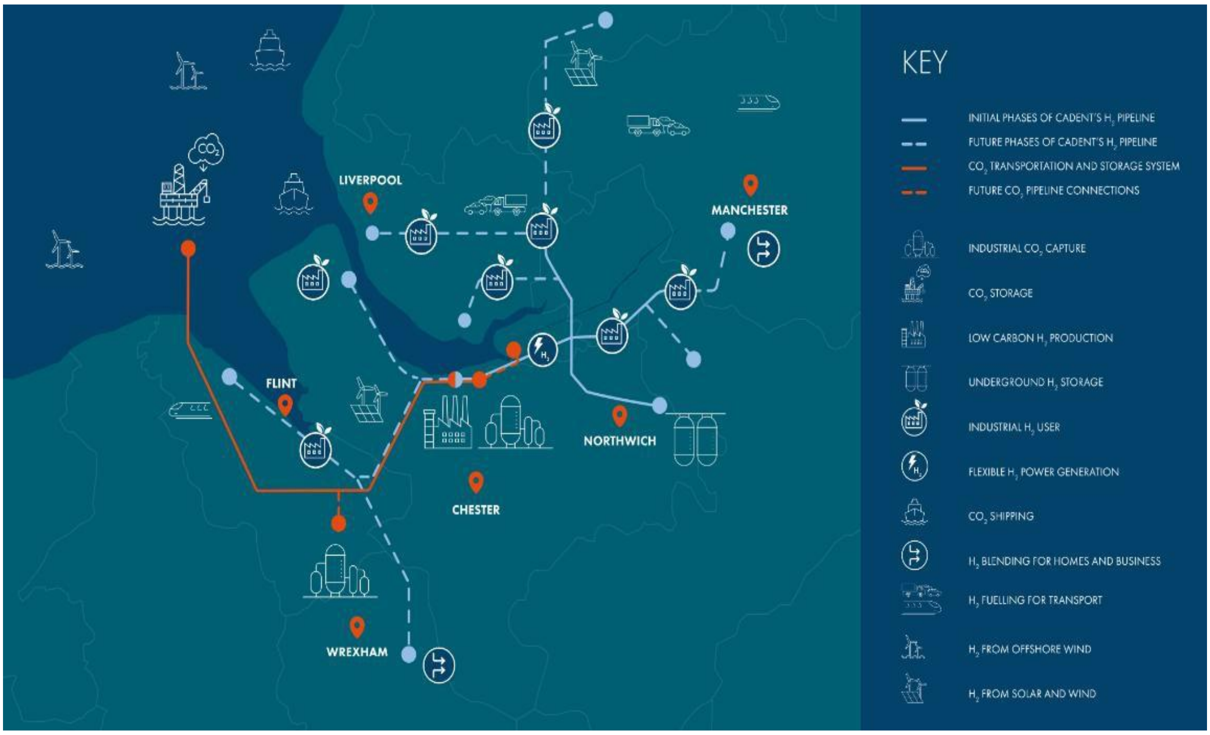


Fig 1: Repurposing of pipelines for CO_2 transportation

CCUS Context and Liverpool Bay Overview

Liverpool Bay's existing offshore network (Douglas/Lennox/Hamilton complexes) and shore-tie assets provide a platform for a regional CO_2 transport and storage system. The project plan combines new and repurposed pipelines (~145 km on-/offshore), routing captured CO_2 from the Point of Ayr terminal to depleted reservoirs with proven seals and capacity. The development aligns with UK policy targets for large-scale CO_2 storage and staged expansion beyond 2030.

Operational implication: Repurposed carbon steel lines must be proven clean, dry, and compatible with dense-phase CO_2, minimizing corrosive pathways from H_2O/impurity interactions and preventing hydrate or multiphase instabilities.

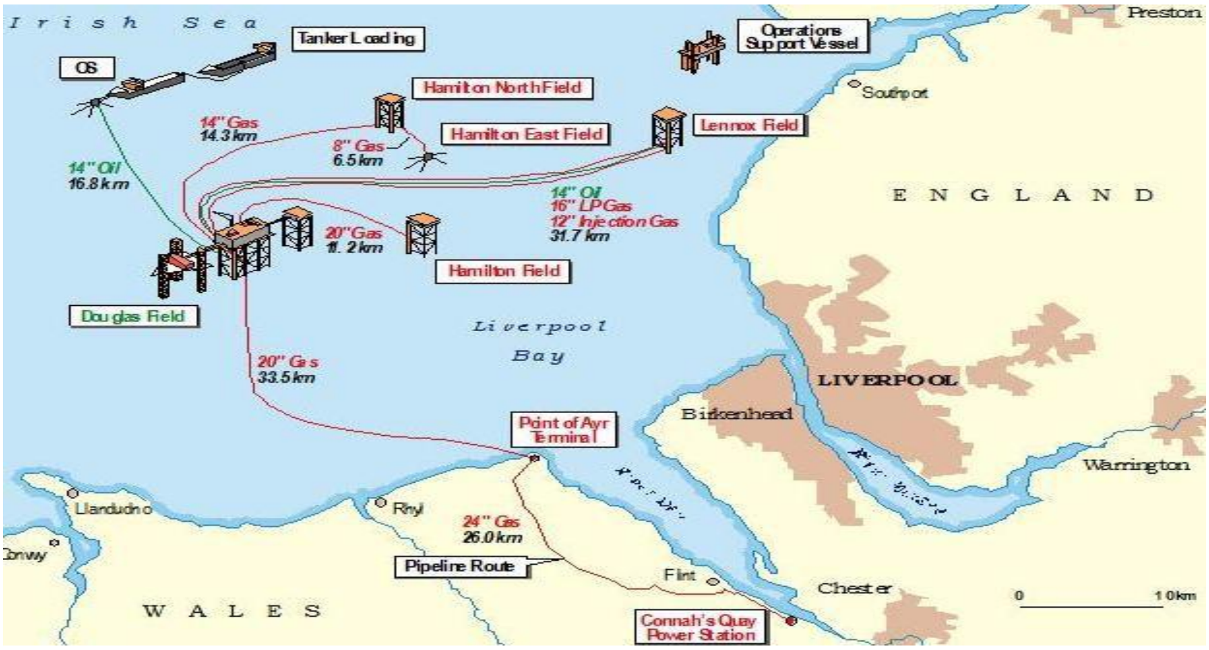


Fig 2: HyNet/Liverpool Bay CO_2 transport and storage network overview.

Requirements for Pipeline Repurposing to CO_2 Service

To safely transition existing assets, operators typically demonstrate:

- Decommissioning & isolation: Complete removal of legacy contents per regulation.
- Mechanical & chemical cleaning: Multi-stage campaigns to remove deposits and residues.
- Surface condition: Visual confirmation to ISO 8501-1 Sa 2.5 (or better) along the full length *(Fig. 6)*.
- Drying: Dew point ≤ −45 °C prior to introduction of CO_2.

- Structural integrity: NDT/ILI (e.g., MFL/UT/EMAT) to screen for corrosion, cracks, and geometric anomalies.
- Pressure envelope: Verified capacity to maintain dense-phase conditions (>~85 bar depending on spec).
- In-service monitoring: Corrosion growth, dew point, pressure/temperature, and flow surveillance.

Inspection Challenge: Why Videography Needed to Evolve

Traditional tubular videography struggles with speed variation, long ranges, and sidewall resolution. For CCUS repurposing, the Liverpool Bay application required:

1. Untethered, free-swimming operation over 5–40 km per run with GN_2 propulsion.
2. Stable, high-resolution sidewall imagery despite non-uniform velocity, frequent stops/starts, and excursions >6× typical camera regimes.
3. Efficient data handling: robust onboard storage, rapid retrieval at PLR, and cloud workflows for QC → prelim → final reporting without delays.

Side-view advantage: Down/forward-view (DV/FV) cameras waste pixel density on the dark central bore and suffer from wide-angle dilution. Side-view arrays concentrate the sensor's most accurate pixels exactly where it matters—the pipe wall—achieving much higher effective pixel density (up to ~8× versus 720p DV/FV in 24" ID) and enabling reliable stitching and AI screening.

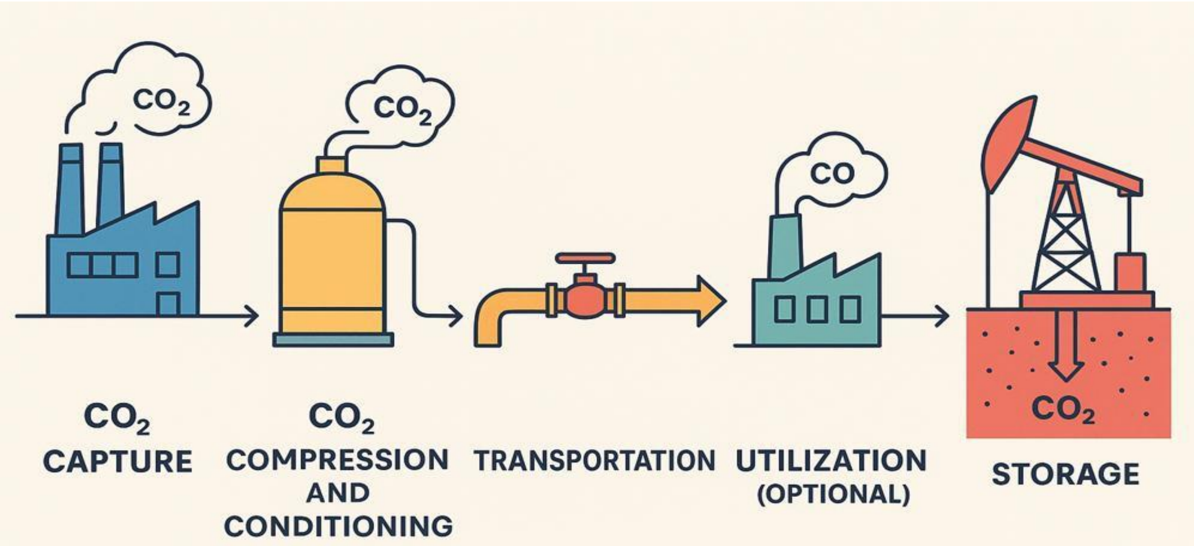


Fig 3: **CCUS lifecycle stages and pipeline-transport focus.**

System Description and Innovations

The inspection system PigCAM® comprises:

- Multi-side-view camera array providing full 360° circumferential coverage.

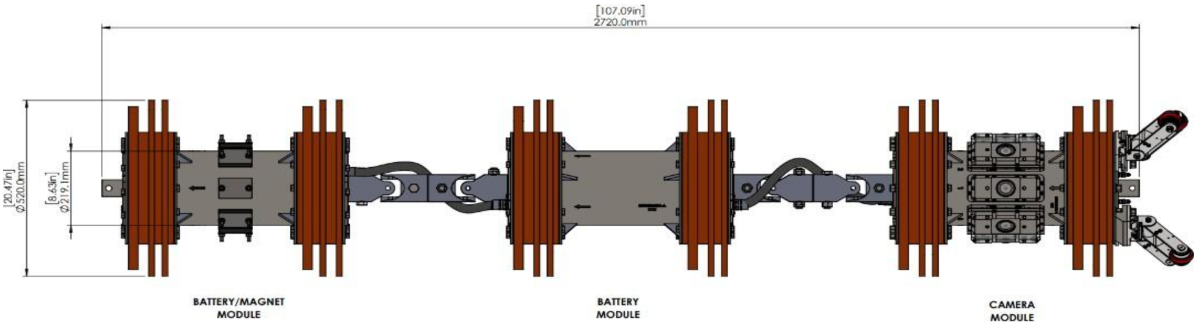


Fig 4: Camera/Video Pig 18-36" capable, 1.5D bend radius, 8side array cameras

- Adaptive optics & lighting tuned for high-speed motion to mitigate blur and improve contrast.
- Onboard computer & storage for autonomous logging; no live telemetry required.
- Propulsion & navigation: GN_2/air drive; autonomous mission execution pre-programmed to pipeline constraints.
- Data products: 2D/3D stitched mosaics, synchronized with geometry/caliper/ILI where available (Fig 5)

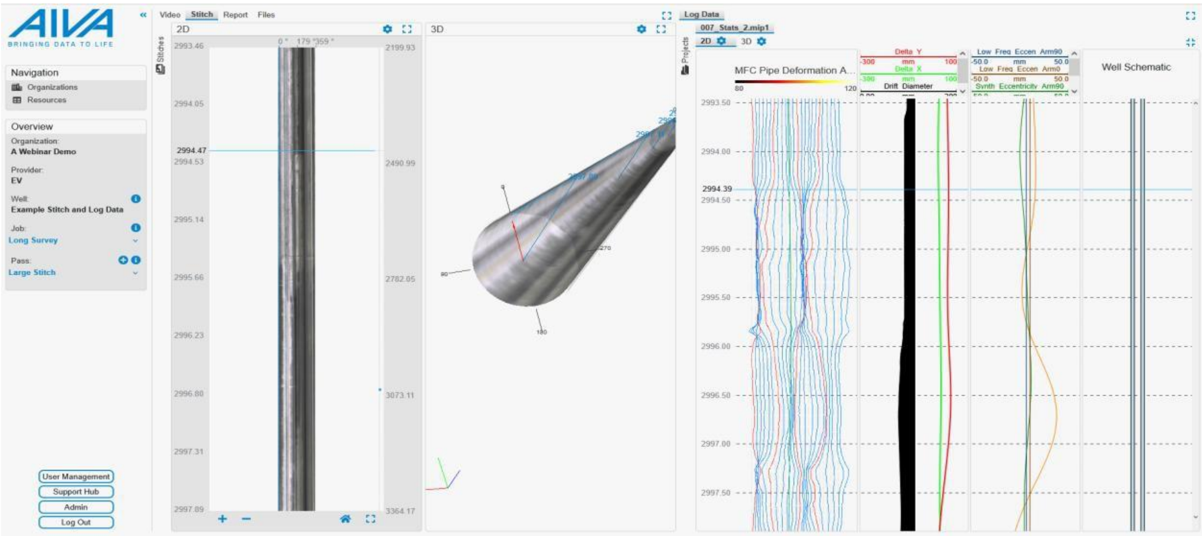
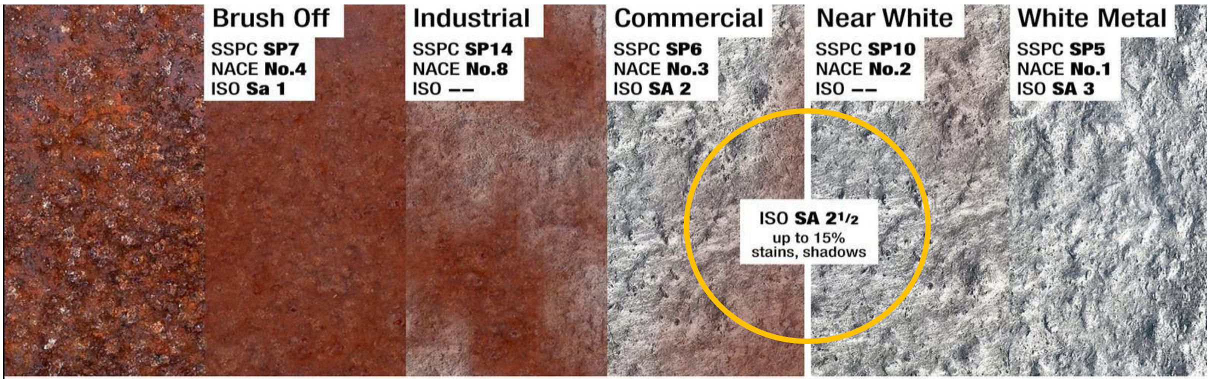


Fig 5: Stitched mosaic aligned with ILI/Caliper.

- AI-enabled analytics (AIVA™ class): Screening models calibrated to ISO 8501-1 for cleanliness quantification; interactive, cloud-hosted review (Fig 6)



Loose Material	None	None	None	None	None
Tight Material	100%	up to 10%	None	None	None
Stains, Shadows	100%	100%	up to 33%	up to 5%	None

Fig 6: ISO 8501-1 Sa 2.5 visual reference.

Scalability & compatibility: Tool families cover ~10″–36″ IDs, negotiate common 1.5D bends, operate for long endurance (up to ~96 h / ~176 km), and can be integrated with IMU/odometry for speed–distance–position traceability essential to dataset fusion, active speed control for speed up to 4.47m/s (10mph), 16”-48” along with other caliper & ILI tools as needed for the application.

Case Study: 24”, 27 km Line in Liverpool Bay

Objective. Verify internal cleanliness relative to ISO 8501-1 Sa 2.5 post cleaning (brush pigs, foam pigs, batch fluids) and inform readiness for CO_2 conversion.

Operation. Launch: 17 May 2025, 15:00; receive: 18 May 2025, 19:00 (≈28 h total). The eight-camera array traversed 27 km from Connah’s Quay to Point of Ayr under GN_2. Early video near the launcher showed clear, high-fidelity imagery (e.g., gated tee) indicating low debris at the upstream end *(Fig. 7)*.

Observations.

- Progressive lens fouling was detected across several cameras, attributed to residual fluid bypass and entrained fines from low-lying sections. Overlap between camera FOVs and persistent wall-motion parallax confirmed debris on lenses rather than features on the wall.
- Despite intermittent blur during higher-velocity segments, clean wall condition was visible in multiple sections, enabling assessment continuity.

- No major obstructions, severe corrosion, or gross geometric anomalies were apparent in the footage.
- A feature of special interest (circumferential, >400 mm length; sub-millimetre height) was noted across multiple views at 16:55:33, referenced to the long seam weld at ~90° position *(Fig 8)*

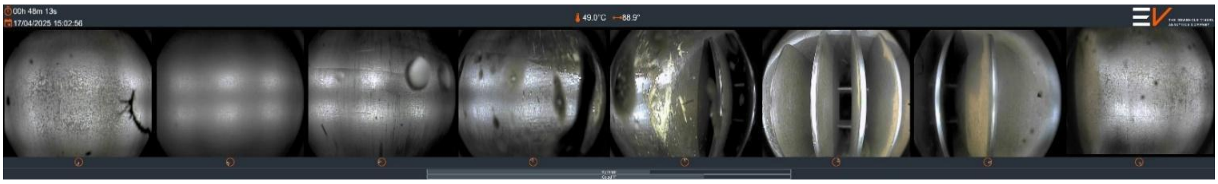
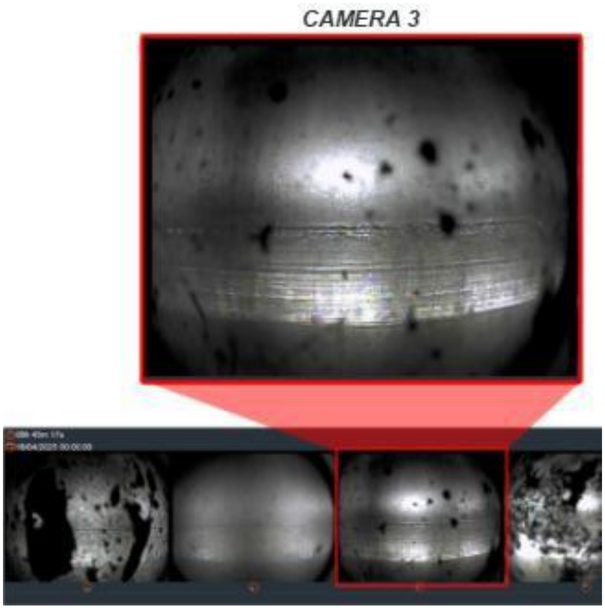


Fig 7: Gated Tee & clear footage



Camera 3

Footage taken ~10hrs into the operation clearly depicting the girth weld of the pipeline. Showing good root weld of the pipeline which has been in service since ~1990.

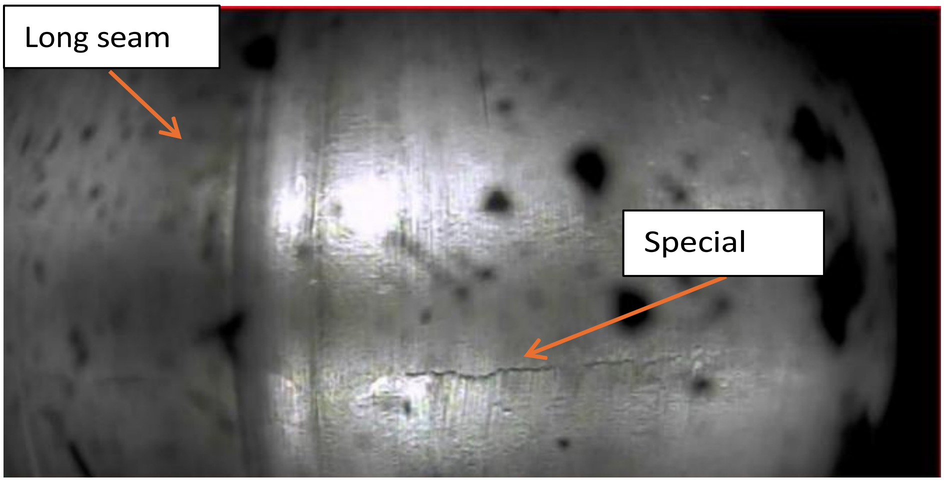


Fig 8: Feature with special interest, circumferential

Preliminary conclusion. The pipeline exhibited generally good internal condition but required additional cleaning/drying to remove residual liquids/particulates before re-inspection and certification for CO_2 service.

Results: Cleanliness & Condition Summary

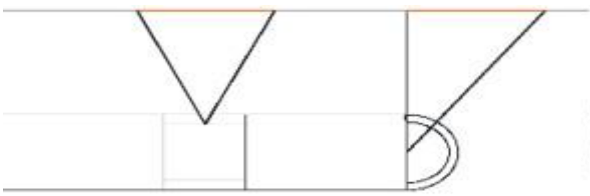
Line-wide visual evidence provided operators and regulators with quantified cleanliness indicators aligned to ISO benchmarks, plus stitched artifacts for intuitive review and cross-reference with other logs. Table 1 consolidates key outcomes.

Table 1 — Post-Run Visual Assessment Summary

Parameter	Observation
Surface Cleanliness	Generally clean; minor surface marks similar to mild pitting observed.
Deposits	Light, non-obstructive particulate accumulation in some locations.
Liquid Presence	Notable in low-lying areas toward the pipeline's downstream end.
Geometry/Ovality	No evidence of ovality, buckles, deep scratches, or girth weld damage (based on footage).
Foreign Objects	No intrusive debris found; small foam pig fragments retrieved post-inspection.
Corrosion	No significant internal corrosion or pitting observed.
Obstructions	No flow-restricting obstructions noted; pipe bore remained open throughout.

Discussion

Value of side-view arrays. Concentrating pixels on the sidewall improves defect visibility, enables robust frame-to-frame feature matching, and supports high-quality stitching—vital for analyst throughput and AI training. DV/FV optics, by comparison, suffer from pixel wastage and weak parallax, challenging both human review and automation.



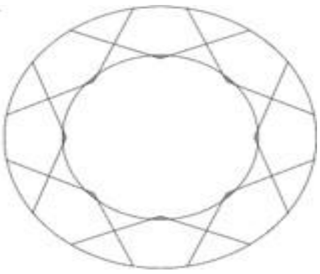


Fig 9: SV vs. FV field alignment

Fig 10: Cross-section, 8 SV cameras for full coverage

AI readiness. Clean, well-lit, high-contrast inputs reduce false positives/negatives and accelerate throughput from first look to formal reporting. Model outputs in this deployment served as screening aids, with engineers retaining adjudication authority.

Operational lessons.

- Cleanliness campaigns materially influence video outcomes—analogous to ILI preparation.
- Speed discipline and odometry are essential for dataset fusion across suppliers.
- Residual liquids can foul optics; future runs may benefit from post-clean drying extensions, improved lens shielding, and dynamic wiper/anti-fouling options where feasible.

Recommendations for CO_2 Conversion Workflows

1. Pair cleaning with visual verification to anchor ISO Sa 2.5 claims in direct evidence.
2. Enforce dryness targets (≤ −45 °C dew point) pre-inspection to minimize lens fouling and maximize wall SNR.
3. Integrate odometry/IMU to align video with ILI/caliper and streamline AOI call-outs.

4. Adopt stitched 2D/3D artifacts as the default deliverable for stakeholders, with cloud review to accelerate concurrence.
5. Schedule a verification re-run post final clean/dry to lock in CO_2 readiness and satisfy regulatory expectations.

Conclusions

A free-swimming, multi-side-view HD videography system coupled with calibrated, AI-enabled analytics provided line-wide, quantified, and defensible evidence of internal cleanliness in a 27 km, 24″ pipeline slated for CO_2 service. The deployment demonstrated:

- Practical 360° sidewall coverage over long distance without tethering.
- Actionable insights for cleaning efficiency, residual fluid management, and rework scope.
- A clear, evidence-based bridge between cleaning campaigns, ILI readiness, and CO_2 qualification against ISO 8501-1 benchmarks.

This approach reduces uncertainty in repurposing decisions, enhances regulator confidence, and complements conventional ILI/NDT by addressing the persistent gap: direct visual proof of cleanliness at scale.