Fracture Propagation in a CO_2 Pipeline – An Operator's Perspective

Russell Cooper, National Grid

The Don Valley CCS Project is co-financed by the European Union's European Energy Programme for Recovery. The sole responsibility for this publication lies with the authors. The European Union is not responsible for any use that may be made of the information contained therein.

Overview

- National Grid has completed a major research programme on the transportation of dense phase CO_2 by pipeline - called '*COOLTRANS*'
- CO_2 is a hazardous substance, so a CO_2 pipeline must comply with UK safety legislation and be design in accordance with recognised standards
- Hazards posed by CO_2 include:
  - To people - CO_2 is toxic and an asphyxiant
  - To integrity - is corrosive in the presence of free-water, there can be low temperatures during decompression, etc. and is susceptible to long running fractures in the (unlikely) event of a failure resulting in a rupture
- Key design requirements are summarised as:
  - Routeing to minimise risk posed to people
  - Fracture control to avoid propagating fractures
- This presentation outlines the research undertaken to ensure suitable fracture control measures are in place

The Project

- National Grid's interest in CO_2 pipelines is in the development of a network to support the implementation of Carbon Capture and Storage (CCS)
- Currently finalising the Front End Engineering Design (FEED) study for a cross country pipeline system in the Yorkshire and Humber region to transport dense phase anthropogenic CO_2 from emitters to storage

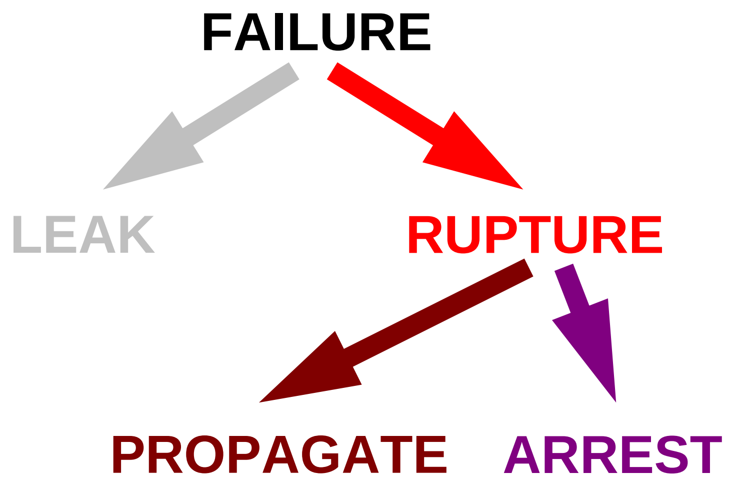
National Grid research – fracture control

Research	Purpose	Experimental	Analytical
Decompression behaviour	Investigate and measure the decompression behaviour	Shock tube tests	Analytical and Computational Fluid Dynamics (CFD) decompression studies
Behaviour of defects subject to decompression	Will a rupture propagate?	West Jefferson (instrumented burst) tests	Analytical studies on critical defect length
Fracture propagation	Can a propagating fracture be arrested?	Full-scale fracture propagation tests	Application of the Battelle Two Curve Model and correction factors

nationalgrid

Fracture control requirements

- Pipelines transporting gaseous fluids or fluids with a high vapour pressure are susceptible to fracture propagation
- Efficient transportation of CO_2 requires that it is in the dense phase
- In the dense phase, CO_2 has a high vapour pressure, so CO_2 pipelines are susceptible to fracture propagation
- Standards and codes require that fracture control is considered in material selection and design



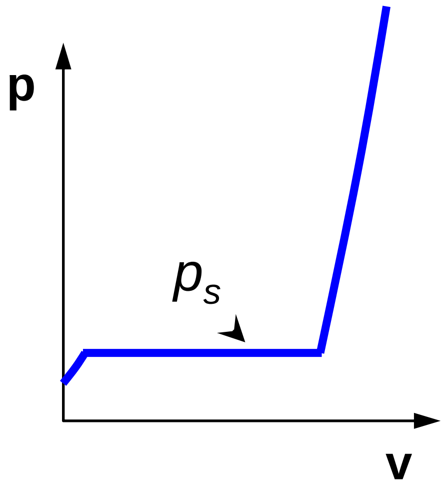
Fracture control requirements (Cont.)

- Brittle fracture is prevented by specifying a minimum shear area of 85% as measured in a drop weight tear test carried out at the minimum design temperature (e.g. 0 ºC)
- Ductile fracture propagation is prevented by specifying a line pipe toughness sufficiently high to arrest a ductile fracture
- If it is not possible to obtain the toughness required for arrest, mechanical crack arrestors must be installed at an appropriate spacing along the pipeline

nationalgrid

Design to avoid ductile fracture propagation

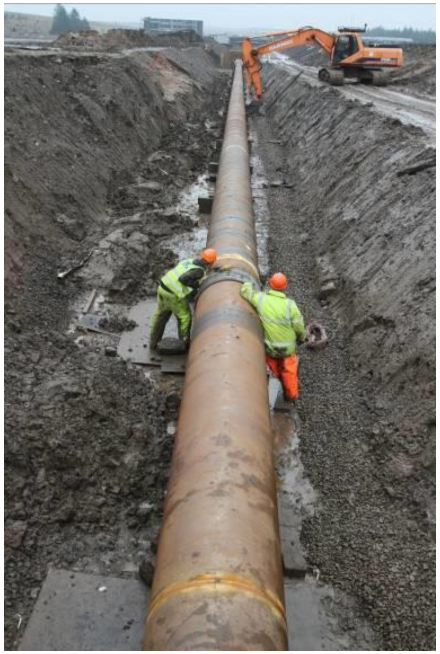
- The Battelle Two Curve Model (TCM) is used to estimate the toughness required for arrest when transporting lean or rich gases
- The TCM is semi-empirical; it has not been validated for application to pipelines transporting dense phase CO_2 (or CO_2 rich mixtures)
- CO_2 exhibits a ‘long’ plateau during decompression
- National Grid has investigated the application of the TCM to dense phase CO_2 pipelines
- This required full-scale fracture propagation tests
- Full-scale tests are expensive, time consuming and there are difficulties procuring the pipe needed



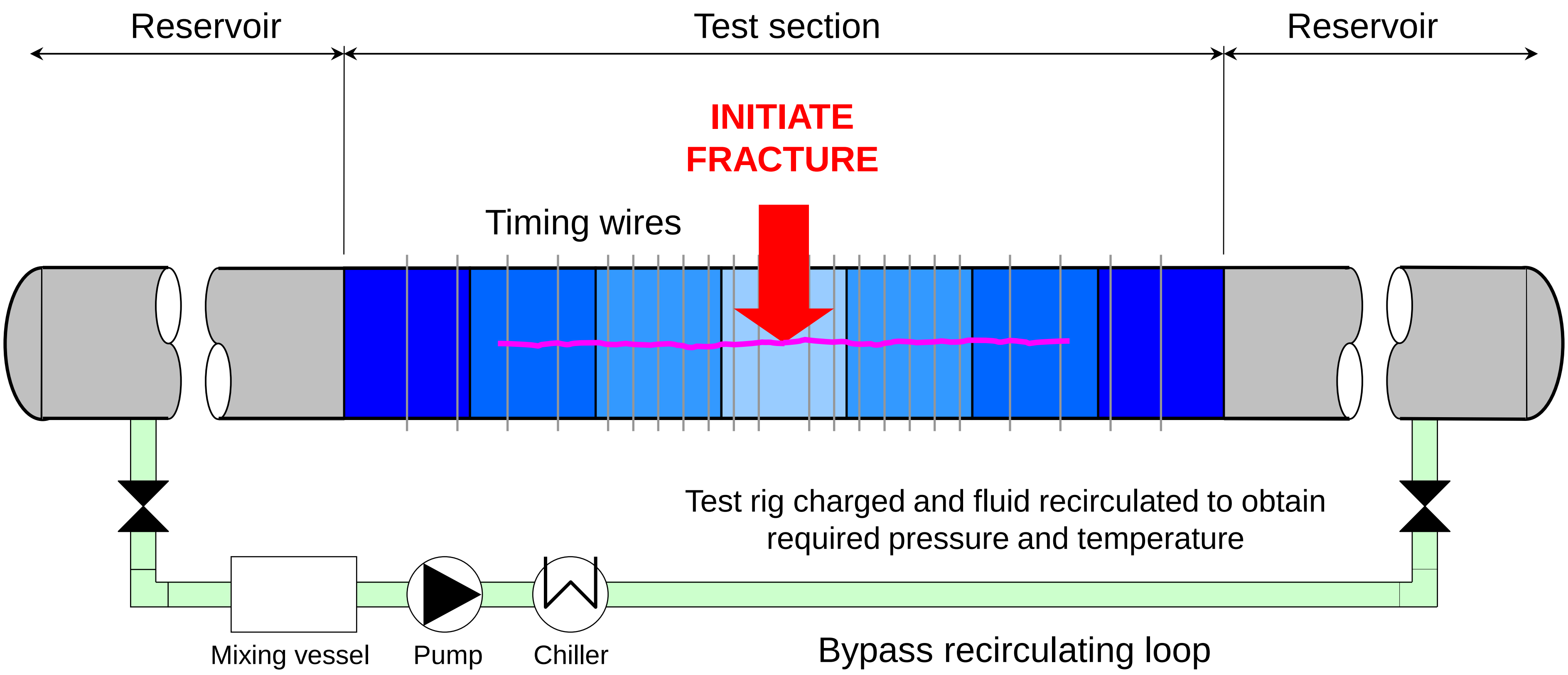
What is a full-scale fracture propagation test?

- A ‘telescopic’ test section with a long reservoir at each end (to simulate a section of pipeline), a circulating loop, and associated ancillary pipework and fittings
- The test section is instrumented with pressure transducers, thermocouples and timing wires
- The reservoirs are anchored with concrete anchor blocks
- The long reservoirs and anchors provide a stress state similar to that of a long, buried transportation pipeline
- The long reservoirs simulate the decompression in a long pipeline

Constructing the test arrangement



Full-scale test arrangement



National Grid's three full-scale tests

Test No.	Date	Pipe geometry & material grade	Saturation pressure (p_s) in barg
1	21 April 2012	914 mm OD x 25.4 mm WT, L450	80.6
2	13 October 2012	914 mm OD x 25.4 mm WT, L450	73.8
3	25 July 2015	610 mm OD x 19.1 mm WT, L450	89.0

Key
OD = Outside Diameter
WT = Wall Thickness

Spadeadam test site

The first and second tests

- To investigate the most severe CO_2 rich mixture that can be transported in commercially available 914 mm (36”) outside diameter, 25.4 mm wall thickness, grade L450 line pipe

What happened in the first and second tests?

- The fracture arrested in both tests, but it propagated further than predicted using the TCM and the (notionally conservative) Wilkowski et al. correction factor
- The predicted toughness would need to be increased by a factor of at least 1.2 and 1.8 to conservatively predict the two tests

Test 1

Test 2

Issues for the operator

- The two tests showed that the TCM with a correction factor for high toughness under estimates the toughness required to arrest a propagating fracture
- It is essential that it can be demonstrated that a fracture can be arrested, but the semi-empirical model is non-conservative
- Project requirements:
  - Specification of a line pipe toughness that will arrest ductile fractures with a safety factor is required, or
  - Mechanical crack arrestors must be specified

Assessment of the options

	Specification of arrest toughness	Mechanical crack arrestors
Advantages	• Maximum confidence in pipeline integrity • Minimum impact on integrity management and maintenance • Once specified, this is the minimum life time cost option	• Existing designs are available
Disadvantages	• TCM is semi-empirical and non-conservative • Project specific full-scale test is needed to validate the predictions	• Designs are difficult to evaluate • Impact on integrity management and maintenance • Higher cost life time option

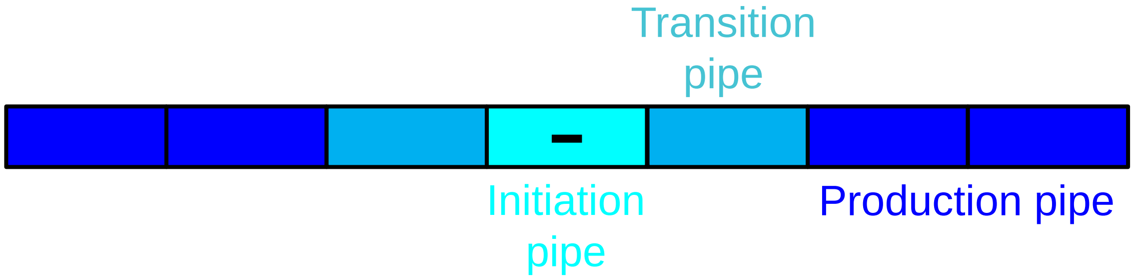
Following a detailed assessment of the options, a third, project specific, full-scale test was actioned

The third test

- The objective of the test was to determine whether or not a fracture will arrest in 610mm outside diameter x 19.1 mm wall thickness, grade L450 line pipe with a toughness of 250 J, given a dense phase CO_2 rich mixture with a saturation pressure not exceeding 80 barg
- The third test was designed to be representative of the proposed Yorkshire and Humber CCS pipeline
- The results of the first and second tests were used to estimate the conditions that might be required for arrest
- The third test was designed to provide confirmation (or otherwise) of this empirical prediction

The design of the third test

- An initiation pipe with a toughness of approximately 100 J
- Two transition pipes with a toughness of 152 J and 173 J, either side of the initiation pipe
- Four production pipes with a toughness higher than 325 J
- The production pipes were intended to be representative of the type of line pipe that would be used in the Yorkshire and Humber CCS pipeline
- The higher toughness of the production pipe was addressed by increasing the saturation pressure



The third test (before)

The third test (after)

Results of the third test

- A running fracture was successfully started in the initiation pipe
- The fracture propagated through the transition pipes on either side of the initiation pipe at a speed of approximately 100 m/s before it arrested on entering the production pipes
- The rapid arrest in the production pipes suggests that the toughness of the production pipes was significantly higher than that required to arrest a propagating ductile fracture
- The third full-scale test confirmed that a running ductile fracture will arrest in the proposed Yorkshire and Humber CCS pipeline

What about different geometries or grades?

- National Grid have done three tests on two different geometries (24 & 36"), but only one grade (L450)
- The SARCO2B Project will do two tests on one geometry (24") and one grade (L450)
- The results of the National Grid tests suggest that the driving force for CO_2 is higher than for a lean or rich gas, possibly associated with the long plateau in the decompression curve
- The TCM with a correction factor for high toughness (e.g. Wilkowski et al., 1977) is non-conservative, but it can be used to ***estimate*** the required toughness and wall thickness for arrest
- The additional corrections are empirical and require experimental validation, as here in the third test, if the geometry or grade differs significantly from the existing small data set

Conclusions

- The TCM with the Wilkowski et al. (1977) correction factor requires an additional correction on the measured Charpy V-notch impact energy and on the saturation pressure
- The additional corrections are empirical and (currently) based on only three tests, and so require experimental validation through additional full-scale testing
- A full-scale test can be used to successfully validate a proposed design, as was done here, but such a test requires careful design and planning in order to fit in with project schedules
- The research work and three full scale fracture propagation tests have (i) confirmed that fracture arrest will occur in the proposed CCS pipeline, and (ii) justifies the optimum cost pipeline in terms of design, construction and operation
- The research work conducted by National Grid allows appropriate project specific full scale fracture propagation tests to be designed

Any questions?