FRACTURE PROPAGATION PREVENTION ON CO_2 PIPELINES: FULL SCALE EXPERIMENTAL TESTING AND VERIFICATION APPROACH

Massimo Di Biagio*, Antonio Lucci, Elisabetta Mecozzi
Centro Sviluppo Materiali S.p.A., Roma, Italy

Carlo M. Spinelli
Eni S.p.A., Milano, Italy

ABSTRACT

CO2 pipeline transportation is becoming increasingly important as the following schemes worldwide are moving from pilot to demonstration phases:

- Enhanced Hydrocarbon Recovery (EHR),
- Carbon Capture and Storage (CCS),
- Exploitation of Natural Gas Fields rich in CO2

In particular the important safety and risk discriminators emerging in pipelines transporting anthropogenic CO2 service are:

- effect of contaminants & impurities,
- volume transported that forces the use of larger diameter pipelines,
- longer distances with several crossings of high-hazardous areas.

All these factors have a dramatic impact on fracture propagation arrest in case of pipeline failure caused by any kind of large enough defect (corrosion, third part damage, construction defect, etc.).

The most catastrophic type of pipeline failure is running fractures, potentially involving rapid “unzip” of the pipeline up to several hundred meters length, causing the release of large fluid amount in a short time span. For natural gas there’s a long lasting experience and consolidated Know How; the method named “Battelle Two Curve” (BTC) was the first developed to express the criterion for predicting the minimum toughness required for having an arrest in case of long shear running fracture propagation by comparing the fluid decompression wave velocity and crack propagation velocity.
It’s well known the susceptibility to long running shear fracture of any pipeline transportation system involving high pressure gases, dense phase fluids, two phase fluids or high vapor pressure liquids as Carbon Dioxide.
In this context SARCO2 “Requirements for Safe and Reliable CO2 Transportation Pipeline”, was lunched, an RFCS project with the support of EPRG and DNV GL. The project was aimed at contributing to the pipeline design in order to assure the long-term integrity and included a full scale testing campaign on CO2 pipeline as part of the fracture propagation prevention programme. This paper presents such activity which involved EN 10208-2 L450 24” outside diameter, 12.5-13.7 mm wall thickness pipes, with upper shelf Charpy V-notch impact energy (toughness) up to a maximum of 320 J coming from different metallurgic routes and the use of composite crack arrestors.

1. CARBON CAPTURE TRANSPORTATION AND STORAGE OUTLINE

Among the several options to permit fossil fuels consumption and global warming reduction methods, Carbon Capture Transportation and Sequestration (CCTS) solution appears now, after more than ten years of R&D and pilot plant the one more technically viable as it uses established technologies to capture, transport and store carbon dioxide emissions from large point sources, such as power stations. It also has an important role to play to ensure manufacturing industries, such as steel and cement, can continue to operate, without the associated emissions.

In a relatively short time span of 10 years the industry sector has got experience in capturing, transporting and piping carbon dioxide (CO_2) deep underground, as well as experience in understanding and monitoring the behaviour of stored carbon dioxide. Specifically the underground sequestration sites may be very carefully selected in areas where the rock formations will safely absorb carbon dioxide deep below the ground/seabed.

In 2016 have been identified 38 large-scale CCS projects around the world, and 20 of them will be operational by the end of 2017, so these projects are a clear evidence of the level of the safety, reliability, adaptability, and cost-efficiency of CCS got in the recent years; and three of them are in US as:

a) The world's largest post-combustion capture project linked to a power station (the Petra Nova Carbon Capture Project in Texas);
b) The world's first large-scale bio-CCS project (the Illinois Industrial Carbon Capture and Storage Project);
c) The world's first CCS project at a commercial-scale coal gasification power facility (the Kemper County Energy Facility in Mississippi).

In the U.S.A. several decades experience of transporting, pumping down carbon dioxide for enhanced oil recovery EOR as the first CO_2 pipeline was installed in 1972, and there are now over 7000 km of carbon dioxide pipelines in North America.

The cost balance and Energy Penalties associated to all the three CCTS streams are fundamental to keep low to permit a CCTS diffusion.

The **Capture** in a CCS process accounts for the 70-90 per cent of the overall cost of a large-scale CCS project and are driven by expenses related to the capture and compression process. More cost-effective capture technologies may be developed through utilisation of R&D technologies for gas separation, hybrid approached. These benefits may be applied not only to power generation but also for other industrial stream as cement, natural gas processing, fertilisers' production, H_2 manufacturing, steel making and petrochemical making potentially enlarging the applications of CCTS.

The **Geological** storage of CO_2 has been applied at a number of pilot and large-scale sites over the last 15 years in both onshore and offshore environments. This has resulted in established practices and techniques required to select, safely operate and close (secure) CO_2 storage sites, even though the long lasting experience through more than 50 years is still missing.

The **Pipeline Transportation** is gaining confidence through the existing network of CO_2 pipelines and because of the regulations and industry-recognised standards than in the last years have been issued. As a supplement to these existing national and international pipeline standards and codes, an International Standard for CO_2 transportation systems was finalised this year (ISO Standard 27913:2016), However there are still current research programs focused on further improving in terms of safety by developing and validating new predictive models for CO_2 pipeline design and behaviour in case of pipeline failure. To complete the transportation several engineering efforts also target large-scale shipment of CO_2, as several recent studies show that CO_2 transportation by ship can be a flexible and cost-effective alternative to CO_2 pipelines, especially where onshore and close-to-shore storage locations are not available.

2. CO_2 PIPELINE PECULIARITIES AND REASONS FOR SARCO2 PROJECT

Pipeline fluid transportation, especially for hydrocarbons pipelines, is a proven technology as there is a high degree of experience and know-how which can be transferred to CO_2 transport. The approach for a carbon dioxide pipeline design is similar to the one applied for Oil&Gas pipeline system; it should be defined by describing functional requirements including the expected design life and operational conditions.

A fundamental prerequisite for CO_2 pipeline transport is the achievement of suitable safety levels, so the possibility to anticipate/reduce major accident scenarios. While natural gas pipeline transportation industry makes use of an extensive experience, CO_2 pipelines (and in particular those gathering anthropogenic CO_2) show significantly different physical behaviour for the transportation process. Compared to natural gas, the most relevant differences for structural integrity issues are:

- Higher susceptibility to long-running ductile fracture propagation than natural gas pipeline operating at comparable material usage factor; as a matter of fact the CO_2 is transported in dense phase and its decompression curve is more severe. As a consequence, the resulting driving force is stronger and the crack arrest conditions can be reached only using steel pipes with very high toughness and/or by external mechanical devices (crack arrestors).

- The likelihood to reach lower temperatures during service operation, as during line venting (temperature down to -20 °C) or in the case of unlikely event such as a leakage (temperature down to -80 °C), due to the significant Joule Thomson cooling effect [4]. This results in lowering pipe material toughness so that steel may exhibit local brittle behaviour. The potential risk that a leak may evolve into a break for CO_2 pipeline has to be investigated. This forces the definition of more stringent requirements in terms of minimum service temperature for both base material and welded joints in anthropogenic CO_2 pipeline, compared to that in natural gas pipeline: -5°C ÷ -10°C are typical values of onshore natural gas European pipelines grid, while -25°C ÷ -30°C are the values adopted for the minimum service temperature in the CO_2 “Cortez” pipeline made recently in USA. Such lower design service temperature reflects in more demanding requirements for welding consumables and in the need for specifically developed Welding Procedure Specification (WPS) which should guarantee girth welded joints with good toughness also at such low service temperature.

- Increased pipe wall corrosion and/or stress corrosion susceptibility when free water phase is present within the CO_2 mixture. About this issue, laboratory studies using CO_2 at high pressure and corresponding field experiences suggest that corrosion on carbon steel in pure and dry CO2 is negligible. But it is well known that at low to medium carbon dioxide partial pressures severe corrosion damage will occur if a water-enriched phase is present. Economic considerations in the power plant sequestration process require a minimum degree of humidity. Moreover, stress corrosion cracking and corrosion fatigue issues can arise due to the presence of gases like H_2S, CO, SO_x, NO_x and probably even hydrogen assisted cracking due to H_2 could occur. In addition, a possibility exists to have a spec-off period at the capture unit when CO_2 purity can be allowed to be outside limits over a limited time span (that needs to be studied and quantified). The likelihood and severity of these different corrosion mechanisms depend on several parameters. Data concerning these effects are not available.

All these topics are part of the SARCO2 RFCS funded project jointly sponsored by EPRG companies, furthermore as concern the fracture propagation, DNV GL acts as a co-sponsor of this task. The paper here presented reports on the results of the two CO_2 Full Scale Tests carried out in of this project.

3. FULL SCALE PROPAGATION TESTS

Two full scale propagation tests have been carried out by CSM in the Military Shooting Range of Nettuno, located 60km south of Rome, Italy. Both tests have been executed using CO_2 mixture in dense phase with different amount of N_2 in order to explore different levels of driving force applied in terms of decompression behaviour.

Main tests parameters are summarized in Table 1.

FULL SCALE FRACTURE PROPAGATION TESTS PARAMETERS		
	First test	**Second test**
pipe nominal diameter	24in	24in
pipe nominal wall thickness and producer	12.7mm SAWL (SAWL12.7) 13.7mm HFI (HFI13.7)	12.5mm HFI (HFI12.5) 12.7mm SAWL (SAWL12.7) 13.7mm HFI (HFI13.7)
test section length*	48m	48m
API 5L steel grade	X65	X65
pressurizing medium	CO_2 mixture (3.8% N_2)	CO_2 mixture (6% N_2)
test pressure	129.5barg	127.0barg
test hoop stress*	304MPa (12.7mm SAWL) 282MPa (13.7mm HFI)	300MPa (12.5mm HFI) 304MPa (12.7mm SAWL) 282MPa (13.7mm HFI)

Table 1: Full scale fracture propagation tests general design parameters

Note to Table 1

* Total test line was about 400m long in order to assure regular decompression behaviour in the central test section for the whole test duration

** Different hoop stress values are due to different wall thicknesses of the pipes involved in the test

The objective of the two full scale fracture propagation tests was to evaluate the effectiveness of 24" outer diameter ISO3183 L450M (API 5L X65) grade steel pipes designed and produced for natural gas pipeline transmission system in arresting a running ductile fracture when CO2 mixture in dense phase is conveyed. From a design point of view a specific aim was to verify the capability of existing model like Battelle Two Curve method to correctly predict the minimum toughness requirements to arrest a ductile fracture propagation for CO2 pipeline.

In order to allow the decompression of the gas as in a real pipeline, two reservoirs of 24in diameter were placed at both ends of the test section. Both the South and the North reservoirs are 86m long. Between the test section and each reservoir a composite crack arrestor was designed and installed as a second line of defence against unexpected long fracture propagation during the test (that is in case tested pipe would not be able to arrest the fracture).

3.1 First full scale propagation test

Test section was made of 5 pipes (1 initiation pipe and 4 test pipes) for a total length of about 48m; 2 HFW pipes were placed at the North side and 2 SAWL pipes at South side.

CO_2 based mixture (3.8% N2 plus CO2) was used as pressurizing medium at a pressure of 129.5barg this resulting in a different hoop stress depending on the local pipe wall thickness, that is:

- 304MPa (0.68 SMYS) for the SAWL pipes and
- 282MPa (0.63 SMYS) for the HFI pipes.

Main test design parameters are summarized in Table 1.

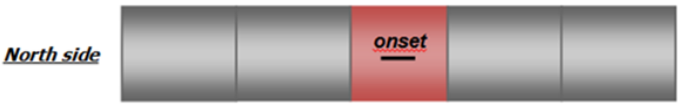
Given the line geographical orientation and the position of the onset charge, the two branches of the lines are identified as *North-side* and *South-side*. The two sections mainly differ in the typology of pipes installed, that is:

- 10m long, 24in OD x 12.7mm thick longitudinal welded pipes are located along the North side;
- 10m long, 24inOD x 13.7mm thick HFI pipes are located along the South side.

3.1.1 Test conditions

The layout of the test is reported in Table 2 which also provides the following information:

- the pipeline arrangement
- the geometrical properties.
- tensile properties (room temperature test data, round bar specimen).
- toughness properties. Data refer to Charpy V-notch (10mmx10mm) and DWTT (5mm pressed notch type) energy tests were performed at +20°C.



		TEST ID	N2	N1	I	S1	S2
		PRODUCER ID	125740	125728	125734	LYO 973/1	LYO 970/7
		type	LSAW	LSAW	LSAW	HFI	HFI
GEOMETRICAL PROPERTIES							
outer diameter	[in]		24	24	24	24	24
nominal wall thickness	[mm]		12.7	12.7	12.7	13.7	13.7
actual wall thickness	[mm]		13.0	12.9	12.8	13.7	13.8
actual pipe length	[mm]		10500	10500	6000	10500	10500
TENSILE TEST (TRANSVERSE)		ROUND-BAR SPECIMEN TEST @ ROOM TEMPERATURE					
$R_{p0.2}$	[MPa]		500	543	549	462	496
R_m	[MPa]		596	624	629	580	592
$R_{p0.2}/R_m$	[%]		84	87	87	80	83
CHARPY V-NOTCH		10X10 CV SPECIMEN @ +20°C					
absorbed energy	[J]		258	173	135	321	320
DWTT PRESSED NOTCH		DWTT energy @ +20°C					
total energy	[J/cm²]		942	681	622	1381	1390
propagation energy	[J/cm²]		647	450	443	977	971

Table 2 – 1st SARCO2 X65 full scale fracture propagation test - Pipes geometrical and mechanical properties.

Pipes along the North side were disposed according to the traditional "*telescopic layout*" (see Table 2): pipes with higher toughness were placed at increasing distance from initiation, so that crack faced pipes of increasing fracture resistance while propagating along the line. Pipe on South side were disposed according to the "*even toughness*" configuration. The whole line was buried with 1.4m compacted local soil to reproduce real in-field conditions.

The fracture propagation in a dense phase CO_2 transporting pipeline is strongly affected by the CO_2 mixture saturation pressure which depends upon CO2 chemical composition and initial pressure value. Therefore, the test gas mixture composition, the initial pressure and temperature were established to assure a saturation pressure of at least 59 barg. This value of saturation pressure was evaluated considering the experience of available tests carried out with CO_2 before that moment and using the Battelle two curve model.

Such target value of saturation pressure was achieved using a CO_2 mixture in the following conditions:

- Gas composition: 96.2 mol% CO_2 and 3.8 mol% N_2
- Initial test pressure of 129.5barg
- Initial test temperature of +13°C
-

3.1.2 Instrumentation

The following instrumentation was used for both tests:

- timing wires (TW) to measure the fracture speed;
- pressure transducers (TP), to measure the initial test pressure and monitor the pressure decay during the fracture propagation event;
- thermocouples (TG and T), to measure both gas and pipe wall temperature respectively.

In order to increase the reliability of the measurements, each transducer was monitored and sampled by two independent Data Acquisition Systems (DAS).
Consequences of the line rupture and the subsequent gas dispersion in the environment were also evaluated. This was achieved by means of dedicated sets of transducers:

- CO_2 sensors to directly measure the CO_2 concentration in atmosphere;
- Oxygen cells in order to estimate the CO_2 levels in atmosphere by measuring the variations of O_2 concentration in air;
- a set of temperature sensors, to measure the CO_2 cloud temperature.

Atmospheric conditions before and during the test have been measured by means of the following instrumentation:

- ultrasonic anemometers to measure the wind speed and direction;
- pyranometers for the measurements of the solar irradiance;
- barometric pressure sensors for the atmospheric pressure.

3.1.3 First fracture propagation test results

The fracture was successfully initiated by means of the explosive charge and propagated on the upper pipe generatrix along both longitudinal directions. On site measurements after the test revealed that fracture deviated from the straight trajectory after 0.8m of propagation along the North side and after 0.4m along the South side.
Few seconds after initiation, CO_2 cloud dispersed as shown in Figure 1.

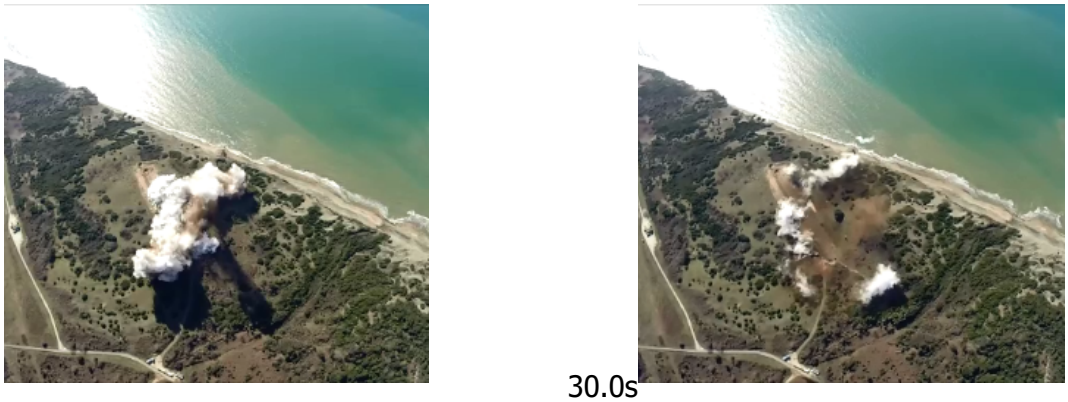


Figure 1: CO2 dispersion pictures sequence

Gas decompression

Time evolution of the pressure decay has been correctly acquired and the pressure versus decompression velocity curve has been calculated and compared to GASMISC model predictions. The code, developed by CSM, is able to calculate the one-dimensional decompression behaviour of mixture basing upon its initial chemical composition, pressure and temperature.

The experimental-to-numerical comparison has been performed for TP2 that was located along pipe S2. Results are given in Figure 2, which allows making some considerations:

- The measured values exhibit a good agreement with GASMISC prediction, thus revealing that during the decompression phase no unexpected factors regarding the gas affected the regular pressure vs. decompression speed and further confirming that the CO_2 mixture was well mixed inside the line.
- The signal is reliable since consistent with the typical decompression trend in a gas transmission line during ductile fracture propagation test.
- The decompression code underestimated the initial value of the waves speed (about 30m/s slower than the experimental velocity, corresponding to 513m/s) and predicted a saturation pressure which is slightly lower (~2bar) than the observed value (i.e. 61barg).
- The plateau of the decompression curve predicted by GASMISC develops at constant pressure of 59barg, while the experimental plateau decreases with the wave speed. This behaviour has been experimentally observed in decompression curves measured in other experimental tests involving CO_2 mixtures [5].
- The experimental decompression curve interrupts at 51barg (for a velocity of 34m/s). This pressure level was detected by TP2 after about 750ms, corresponding to the time at which the first expansion wave to return at the TP2 position after being reflected by the reservoir end cap.

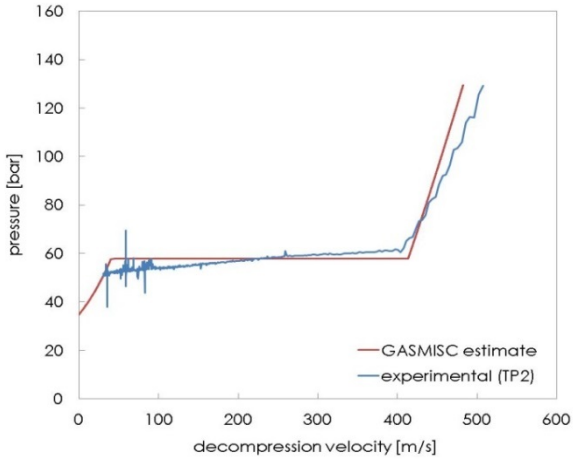


Figure 2: Decompression velocity curve, experimental to numerical comparison.

Crack speed and fracture path

A general overview of the test result is given in Figure 3, where both ends of the fracture propagation are shown and the deformed shape of the initiation pipe is clearly depicted. The detailed analysis of the appearance of fracture surface revealed that crack propagated in fully ductile manner with presence of separations “arrowhead type” as typical of this kind of pipe products (see Figure 4).

Figure 3: Test result - overview.

Figure 4: Fracture surface appearance along the axial propagation.

By basing upon the pipe appearance after the test execution, the fracture path was inferred as in Figure 5. The plot shows that after a short axial propagation, fracture was redirected and arrested within the initiation pipe.

However, it is anticipated that the fracture redirection and arrest are driven by the inherent fracture resistance property of the initiation pipe. This was evidently sufficient to contrast the crack driving force generated by the gas escaping. In other words, the observed arrest, though very short, is a “good” arrest and provides reliable indications about the material effectiveness in arresting a running ductile fracture.

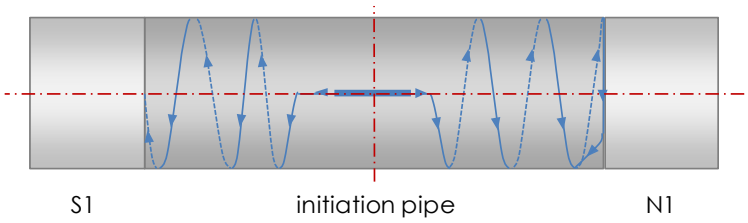


Figure 5: Fracture path.

This is well in accordance with the fact that toughness property of the initiation pipe (Charpy-V abs.en.: 135J) is higher with respect to the BTC minimum energy requirement for assuring a safe arrest, as estimated through the Battelle Two Curve Method using the actual tensile properties for the evaluation of the flow stress has shown in Figure 6 (i.e. 85J). The actual tensile properties were considered due to the fact the tensile properties of some pipes in the layout presented very high values in particular for the imitation and north section.

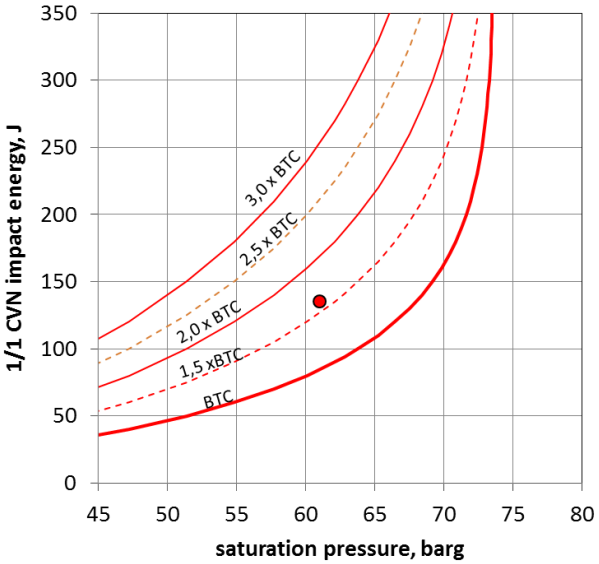


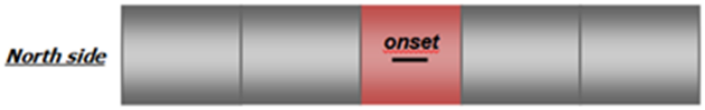
Figure 6: BTC prediction considering actual tensile properties for the evaluation of the flow stress.

3.2 Second full scale propagation tests

The second full scale propagation test has been carried out on the same pipe geometry 24in outer diameter and X65 grade steel pipes. Main test design parameters are summarized in Table 1.

3.2.1 Test conditions

The layout picture of the second full scale test is reported in Table 3. The test layout present some small differences in the pipe wall thickness moreover it is clearly even toughness is Charpy-V is considered but is telescopic toughness is the DWTT total and/or propagation energy is considered.



	TEST ID	N2	N1	I	S1	S2
	PRODUCER ID	125740	7950 17/4	7953 17/7	7960 18/4	LYO 970/7
	type	LSAW	HFI	HFI	HFI	HFI
GEOMETRICAL PROPERTIES						
outer diameter [in]		24	24	24	24	24
nominal wall thickness [mm]		12.7	12.5	12.5	12.5	13.7
actual wall thickness [mm]		13.0	12.5	12.5	12.6	13.8
actual pipe length [mm]		10000	10000	8000	10000	10000
TENSILE TEST (TRANSVERSE)	ROUND-BAR SPECIMEN TEST @ ROOM TEMPERATURE					
$R_{p0.2}$ [MPa]		500	465	468	441	496
R_m [MPa]		596	591	605	578	592
$R_{p0.2}/R_m$ [%]		84	79	77	76	83
CHARPY V-NOTCH	10X10 CV SPECIMEN @ +20°C					
absorbed energy [J]		258	260	296	271	320
DWTT PRESSED NOTCH	DWTT energy @ +20°C					
total energy [J/cm²]		942	810	702	729	1390
propagation energy [J/cm²]		647	501	415	467	971

Table 3: 2nd SARCO2 X65 full scale fracture propagation test - Pipes geometrical and mechanical properties.

The line instrumentation layout was the same of the first test (see chapter 3.1.2).

3.2.2 First fracture propagation test results

The test line was pressurized with CO_2 based mixture (94.0% CO_2) up to a pressure of 127.0barg. The test initial temperature was of about +17.8°C. The fracture was successfully initiated by means of the explosive charge and propagated on the upper pipe generatrix along both longitudinal directions. Few seconds after initiation, CO_2 cloud dispersed as shown in Figure 7.

Figure 7: CO_2 dispersion pictures sequence

Crack speed and fracture path

A general overview of the test result is given in Figure 8, where it is clear the ejection of line after the test ends. The detailed analysis of the appearance of fracture surface revealed that crack propagated in fully ductile manner (see Figure 9) with, as observed in the first test, some presence of separations on pipes fracture surface.

Figure 8: Test result: overview.

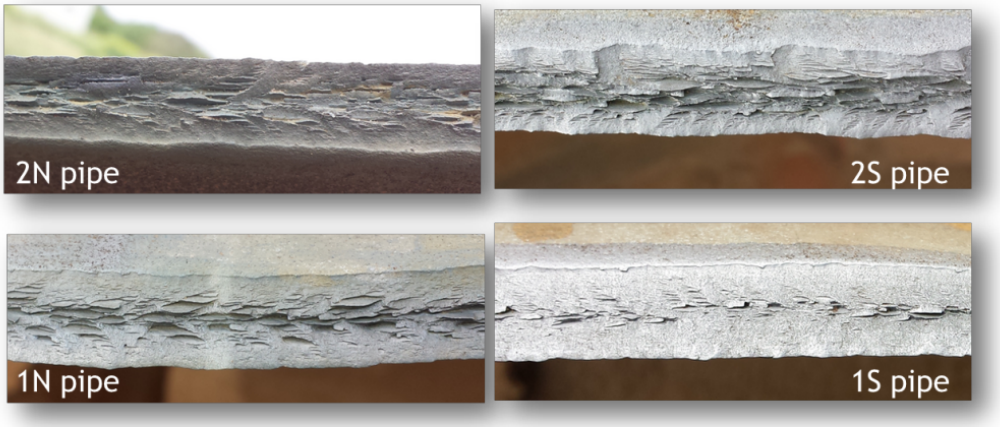


Figure 9: Fracture surface appearance along the axial propagation.

By basing upon the pipe appearance after the test execution, the fracture path was inferred as in Figure 10. The fracture, initiated straight on top generatrix, run for the whole initiation pipe in both directions.

In North side the fracture run in the top generatrix in fully ductile manner in the first pipe after initiation pipe and also in the second pipe at constant speed (~110m/s) arresting in the composite Crack Arrestor (CA). The arrest in the CA was clear and quite rapid (10-15cm) without generating severance on the line demonstrating the good design of the CA.

In South side the fracture run in the top generatrix in fully ductile manner in the first pipe after initiation pipe at constant speed (~120m/s) and arrested in the second pipe after 4,3m. The arrest in this pipe was clear and with a classical spiral path before arrest, also in this case without generating severance on the line.

The ejection of line occurred after the test was concluded, due to the strong driving force and the pour resistance of trench (sand soil), not affecting the results. The demonstration of the good execution of the test and of the fact that the test line was ejected after that the fracture stopped on both sides is due to the analysis of timing wires that was acquired up to the fracture arrest on both sides. In fact even only a small line movement, before the fracture arrest, would produce a anticipation of the timing wire rupture that is not present on the crack speed diagram (Figure 13). On the contrary the crack speed diagram is clean and sensors ruptures are clearly correlated with the crack speed and positions.

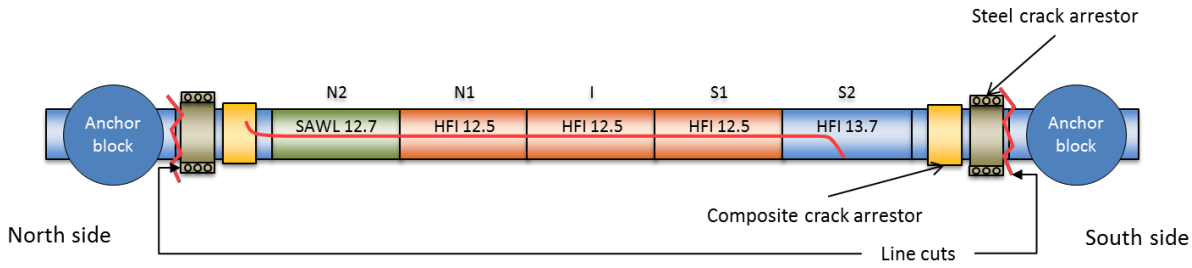


Figure 10: Second test - Fracture path.

Gas decompression

In order to provide a check about the reliability of the sampled data, the pressure versus decompression velocity curve has been compared to that predicted by using GASMISC

The experimental-to-numerical comparison has been performed for TP3 and TP6 that was located respectively on pipe S1 and N1. Results are given in Figure 11 and Figure 12, which allow making some considerations:

- The measured values exhibit a good agreement with GASMISC prediction, thus revealing that during the decompression phase no unexpected factors regarding the gas affected the regular pressure vs. decompression speed and further confirming that the CO_2 mixture was well mixed inside the line.
- The signal is reliable since consistent with the typical decompression trend in a gas transmission line during ductile fracture propagation.
- The plateau of the decompression curve predicted by GASMISC develops at constant pressure of ~72barg, while the experimental plateau decreases with the wave speed.

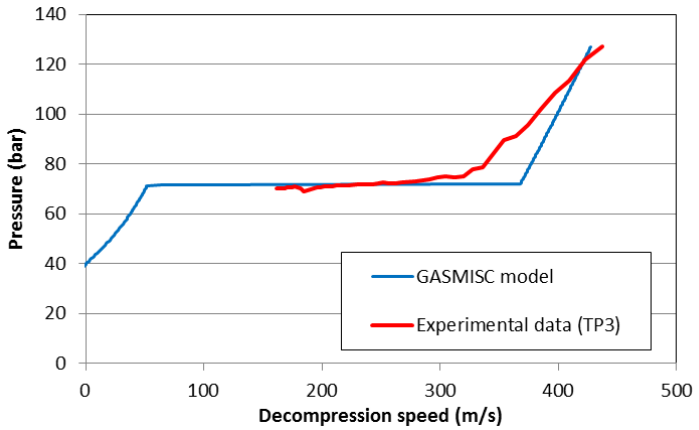


Figure 11: Decompression velocity curve, experimental to numerical comparison.

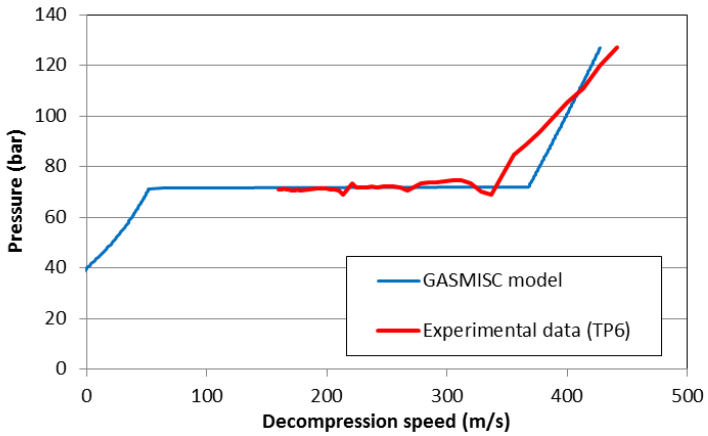


Figure 12: Decompression velocity curve, experimental to numerical comparison.

At the burst onset the gas and pipe wall temperatures were as follows:

- Gas temperature on the test line (average): +17.8 °C.

Timing wires positioned along the line permitted to evaluate the fracture speed during the test, the results is reported in Figure 13 on which it is clear a stable crack propagation on both sides up to the entrance in pipe S2.

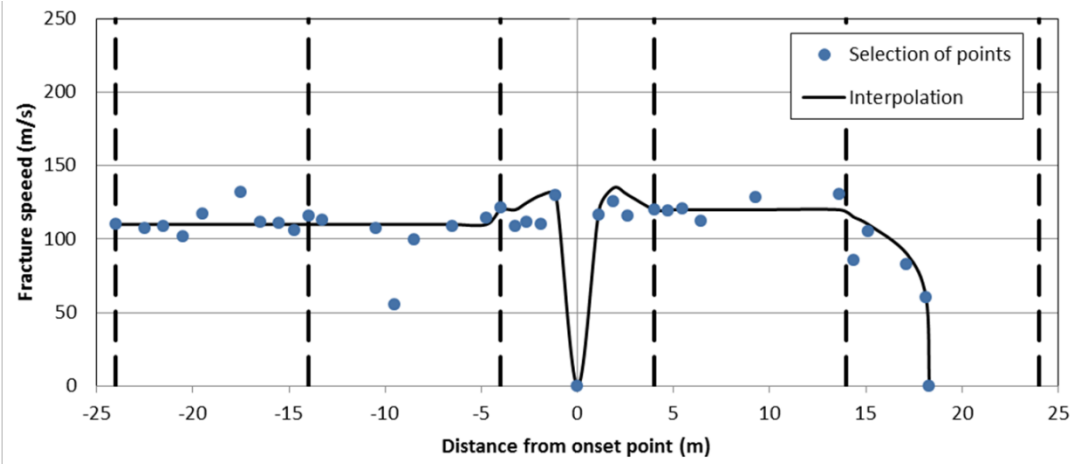


Figure 13: Crack speed diagram.

The constancy of the crack speed is due to the large plateau in the decompression curve (see Figures 10 and 11) which forces the crack tip to maintain a minimum level of speed even if material properties change a little from pipe to pipe.

The image of the arrest on the composite crack arrestor is reports Figure 14 a) where is clear that the running fracture stop shortly but without producing severance. On the other side of the line the fracture arrest was due to pipe body material toughness.

a) Arrest on composite CA

b) Natural arrest

Figure 14: Arrest on composite crack arrestor and natural arrest.

3.3 Measurement of the CO2 release in the surrounding environments

In both tests after the rupture the CO_2 escaped from the pipeline and was subjected to a rapid expansion, from chocked to atmospheric pressure, thus leading to a sudden temperature decrease. Phase changes can take place during the expansion with the possible formation of solid and/or liquid CO_2. The consequent dispersion is guided mainly by the atmospheric conditions and takes place along a prevalent direction determined by the wind blowing, but also it diffuses in all the other directions because of the atmospheric turbulence contribution.

In order to evaluate the evolution of the CO_2 concentration in atmosphere a number of transducers have been placed in the surroundings of the line. They consist of:

- 2 CO_2 sensors (CO_2) to directly measure the CO_2 concentration in atmosphere;
- Oxygen cells (OC) in order to estimate the CO_2 levels in atmosphere from the variations of O_2 concentration in air:
  - 31 oxygen cells at 1m height;
  - 5 oxygen cells at 2m height;
- a set of temperature sensors (TS), to measure the CO_2 cloud temperature in correspondence to each oxygen cell.

Signal from all the sensors (oxygen cells and CO_2 sensors) were properly sampled and stored, thus allowing the CO_2 dispersion in environment to be reconstructed. As an example of the CO_2 dispersion, the time evolution of the CO_2 concentration in atmosphere detected by the oxygen cells at the height of 1m above the ground during the second full scale test is shown in Figure 15. On the basis of those data, it is observed that:

- the maximum CO_2 concentration value is 8% and it is detected by one transducer that was located almost close to the fracture onset section (see Figure 15).
- the remaining transducers detect maximum CO_2 concentration vales not exceeding 5%;

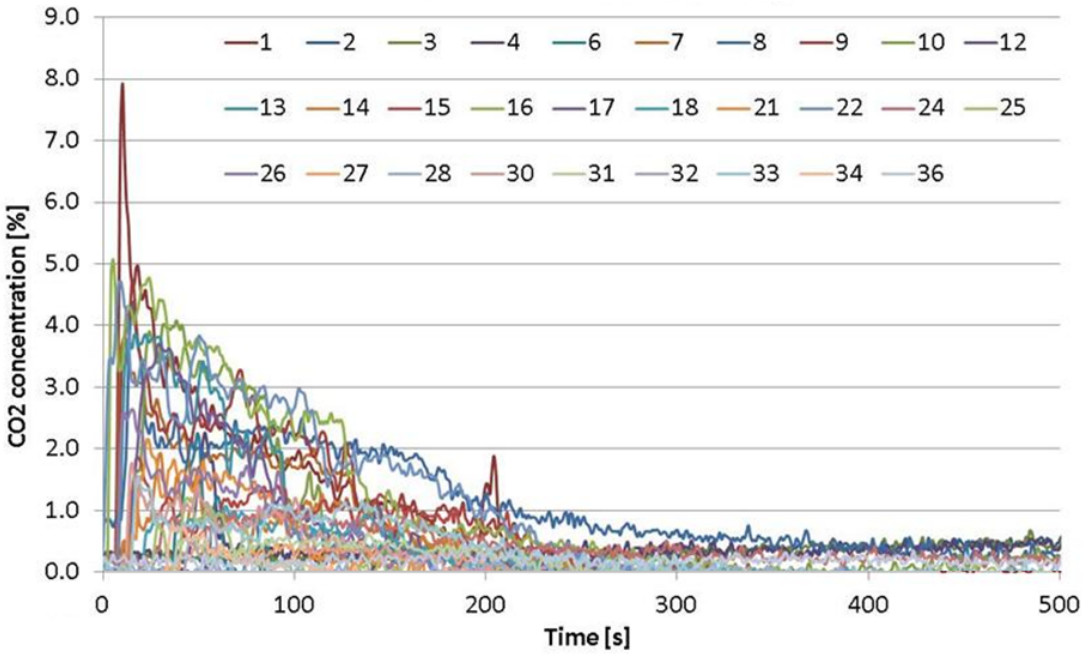


Figure 15: CO2 concentration measured by oxygen cells at 1m height above the ground

3.4 Final consideration on ductile fracture propagation models for CO_2 pipeline

With the aim make an interpretation of the results obtained for the two full scale propagation tests carried out inside the SARCO2 project a comparison with other three tests publically available [6], [7] and carried out in similar conditions was made. This permits to have a set of four tests to be used for assessing the predictive capability of the existing design approaches.

In Table 4 is reported a summary of test conditions for all the considered tests.

	Test				
	1	2	3	4	5
Test name	SARCO2 #1	SARCO2 #2	NG #1	NG #2	NG #3
Diameter (in)	24	24	36	36	24
Wall thickness (mm)	12,7-13,7	12,5-13,7	25,4	25,4	19,1
Test pressure (bar)	129,5	127,7	148,3	150,6	150,2
Test Temperature (°C)	13	17	13,1	10,5	15,0
Gas composition	CO_2: 96.2% N_2: 3.8%	CO_2: 94.0% N_2: 6.0%	CO_2: 90.9% H_2: 1.0% N_2: 4.0% O_2: 1.8% CH_4: 2.2%	CO_2: 93.7% H_2: 1.1% N_2: 3.4% O_2: 0.0% CH_4: 1.8%	CO_2: 90.3% H_2: 1.1% N_2: 6.6% O_2: 0.0% CH_4: 2.0%
Saturation pressure (bar)	58	72	80,6	73,8	73,8

Table 4 – CO2 full scale tests results available.

Tests reported in the Table 4 have been analysed in the light of the Battelle Two Curve Model (BTCM) predictions.. BTCM is the most acknowledged and used method for predicting the minimum Charpy-V energy value for having an arrest of a shear running facture (Maxey [9]). It was developed for natural gas pipeline and its straightforward use for CO2 mixture transmission pipeline must be verified.

Due to its formulation, based upon the comparison between driving and resistance forces taking part to the propagation, it is able to take consider the particular decompression behaviour of CO_2 mixture during the fracture propagation event. For this reason it is used and suggested in the DNV-RP-J202 [8].

It is important to highlight that the BTCM is a semi-empirical predictive method based on a set of tests data that not include test performed using CO_2 mixture neither new modern steels with toughness greater than 100-150J. This is the reason why also for the application to natural gas pipelines it require correction factors for higher grade, very rich gases and high operating pressure.

With the aim to verify the prediction behaviour of the BTCM for case of interest, the results of the tests reported in Table 4 have been compared with the BTCM predictions.

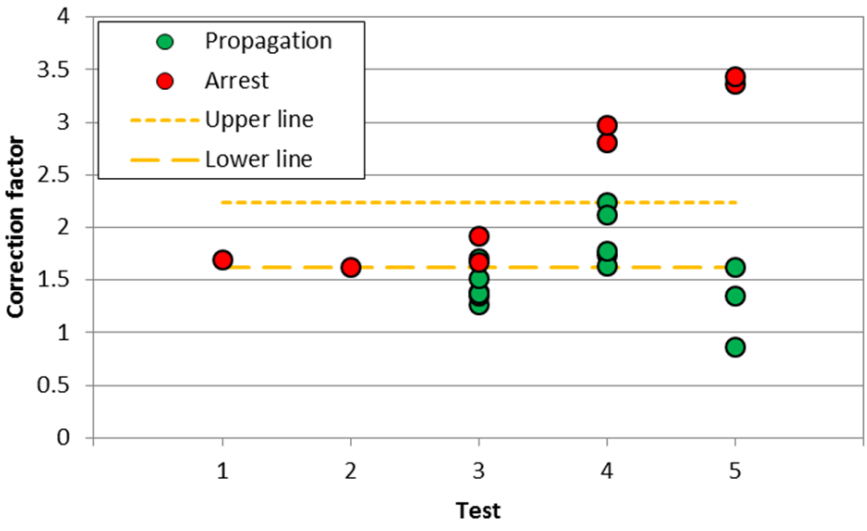


Figure 16 – Evaluation of correction factor for BTC model in the CO2 mixture transportation

More in detail the decompression curves have been calculated using the GERG-2008 equation of state and the resistance curves have been calculated using the nominal valued of Diameter and wall thickness and actual values of yield and tensile material propertied for the calculation of flow stress.

Plotting the arrest/propagation results for all the tests here considered, , it is evident that it is not possible to obtain a unique correction factor (that is the ratio between the toughness value of the pipe which actually arrested the fracture in the test and the toughness value predicted for having an arrest by BTCM); looking at Figure 16 a range can be however identified, that is between 1,6 and 2,2. This range is bounded by an upper and lower line, the first one is the conservative limit on which all the obtained propagations are avoided.

Due to the small number of tests available, further investigations and tests are necessary before to considered as reliable the previous correction factors, in particular because just some testing conditions have been taken into account and also because these results exhibit a not negligible level of inherent scatter.

4. CONCLUSIONS

Two full scale propagation tests have been carried out in the SARCO2 project with the aim to understand whether modern API grade steel pipes produced for natural gas transmission pipeline can be also safely used for conveying CO2 mixtures as far as the arrest of a running shear fracture is concerned. . The test were successfully executed at two different levels of saturation pressure that correspond to different levels of test severity.

The tests have demonstrated that:

1. the pipes produced for natural gas transportation pipeline can arrest, for the conditions considered in the project, the running fracture on pipeline conveying CO_2 mixtures
2. Crack arrestor, if properly designed, can arrest the running shear fracture when the pipe inherent toughness can not
3. The Battelle Two Curve model, used for predicting the minimum toughness requirement to arrest the fracture, cannot be used “as is” for the application to CO_2 pipeline but a correction factor is mandatory.
4. The whole set of available full scale tests performed with dense CO2 is not enough to identify a reliable correction factor for the BTCM due to the fact the number of tests is low and the scatter on the results is not negligible.

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