Technical challenges facing the transport of anthropogenic CO₂ by pipeline for carbon capture and storage purposes

G.Demofonti (Centro Sviluppo Materiali) and C.M. Spinelli (eni .)
Presenter C.M.Spinelli (eni)

With the support of
Corinth Pipeworks, Europipe, Salzgitter Mannesmann Line Pipe, V&M.
GdF Suez, National Grid, Salzgitter Mannesmann Forschungsinstitut
and the European Pipeline Research Group (EPRG)

Abstract
The massive effort required to reduce emissions of CO₂ to atmosphere will inevitably require the roll out of Carbon Capture and Storage (CCS) at many existing and new power stations. Considerable effort has been focused on capture or storage, while only little effort has been directed towards filling the existing gaps of knowledge in CO₂ handling and transportation in a safe, efficient and convenient manner. CO₂ pipelines have been in operation in USA, Europe and North Africa since the 1980’s; however anthropogenic carbon dioxide transport by pipeline brings with it new challenges due to the effects of different impurities coming from flue gases. It cannot be assumed that knowledge regarding the transportation of pure CO₂ for Enhanced Hydrocarbon Recovery (EHR) can be transferred to the design challenges presented by the transportation of anthropogenic carbon dioxide mixtures through densely populated regions of Europe.

This paper will address the Scope of Work of SARCO2 Project “Requirements for Safe and Reliable CO₂ Transportation Pipeline”, presented as a research proposal from an integrated team of pipe producers (Europipe, Salzgitter Mannesmann Line Pipe, V&M Deutschland, Corinth Pipeworks), energy companies (eni, GdF Suez, National Grid) and research centres (Centro Sviluppo Materiali, Salzgitter Mannesmann Forschungsinstitut) with the support of EPRG. The aim is to develop specific design requirements and steel pipe performance criteria for anthropogenic carbon dioxide transportation pipeline systems, as a first step towards creating European Guidelines for the safe design and operation of anthropogenic CO₂ pipeline networks. The most relevant technical topic is the improvement of know-how and experimental data on fracture control initiation (the strong cooling effect due to a leaking defect can cause a brittle/ductile transition) to prevent an unstable long running shear propagation event by developing crack arrest design tools (also including composite reinforced pipes). Furthermore, information and data on anthropogenic carbon dioxide dispersion from a suddenly-fractured pipeline and from leaking vessels will be collected. This last “by product” result will increase the available public data for validating existing models for assessing carbon dioxide release (the size of the affected area and the consequences) in the unlikely event of a leak or rupture. This breakthrough approach will add to the knowledge base through extensive and expensive full scale testing in a manner that has never been performed before.
1. Introduction

*Carbon Capture Transportation and Sequestration (CCTS)* is a mandatory approach for reducing fossil fuel power plant emissions down to acceptable levels, and technical solutions for capture and sequestration of anthropogenic CO₂ have to be found urgently. This is in accordance with the European Union Renewable Energy Directive that aims to pave the way for a 20% cut in greenhouse gas emissions by 2020, the so-called “20:20:20 Plan”. For example, Figure 1 shows that the use of CCTS technology could allow a reduction in the CO₂ emission to atmosphere from 0.4-0.8 ton/MWh to 0.05-0.12 ton/MWh /1//2//3/. However, the issue of anthropogenic carbon dioxide transportation from the energy plant to the remote sequestration area represents a fundamental concern regarding the feasibility of applying CCTS technologies. /4//5/.

*Figure 1 Ranges for the COE and CO₂ emissions factor for different power plant technologies with and without capture based on current technologies./3*/

In this scenario pipelines (both onshore and offshore) can represent a very promising solution, as they can efficiently transport supercritical or dense phase CO₂ (see Fig 2) and most of the know-how already available from natural gas transportation system could be used. As it can be noted from Figure 3 below, the power requirement of compressors is much greater than the power requirement of pumps. So, if carbon dioxide were transported in the gas phase, a huge amount of power would be required. Furthermore considering the low viscosity of the supercritical phase, it is easy to understand why carbon dioxide is transported in this way. This means that pure CO₂ has to be transported at a pressure above 8 MPa (at room temperature) to avoid phase changing due to temperature fluctuations (which, of course, cannot be
controlled quantitatively and depend on the seasons and the region in which the pipeline is operating).

**Figure 2. Pure Carbon dioxide phase diagram**

Large diameter pipelines have already been used in USA, Canada, Algeria and Norway, mainly for pure CO$_2$ in EHR (Enhanced Hydrocarbons Recovery) applications. One example is the *Cortez Pipeline* for the transportation of CO$_2$; this pipeline, which has a total length of 800 km, a diameter of 30” and a maximum service pressure of 17.8 MPa, has been operated since 1984 in the USA by Kinder Morgan, with a capacity of transport of about 20 Mton/year.

**Figure .3 Power requirement for compression or pumping.**
Nevertheless, even if CO\textsubscript{2} transportation by pipeline could be regarded as mature (above 7000 km of pipelines have already been laid or are planned worldwide), the accumulated operating experience and guidelines are absent or inadequate for European scenarios. The existing CO\textsubscript{2} pipelines are largely located in remote areas (in particular in the South-West of USA, Texas and New Mexico) where the population density is very low and at the same time the probability of external mechanical interference (one of the most frequent causes of failure in buried pipelines) is lower than the average value recorded in Europe over the last five years (about 0.2 leak events for 1000 km of line per year according to EGIG). Moreover a significant amount of this know-how has been developed on the transportation of pure CO\textsubscript{2}, and it cannot be directly applied to anthropogenic CO\textsubscript{2} transportation. The presence of impurities (such as H\textsubscript{2}S, SO\textsubscript{2}, CH\textsubscript{4}, H\textsubscript{2},) and water has a significant impact on the physical properties of the CO\textsubscript{2}, particularly those affecting transportation (recompression distances), operation & maintenance (corrosion and stress corrosion control) and design (fracture control and corrosion/stress corrosion prevention), /6/ /7// /8/.

Furthermore networks connecting multiple anthropogenic carbon dioxide capture and sequestration areas need proper specification. The major challenges for these infrastructures can be summarized in the following four key issues:

- engineering design of pipelines from the integrity long term point of view,
- supply and demand balance,
- overall cycle cost and capacity,
- regulatory, financing, legal issues, codes/standards.

Regarding this last point, the review of existing codes and standards dedicated to the transport of fluids in pipelines has revealed that suitable guidelines for anthropogenic CO\textsubscript{2} transportation are not available. Codes as IP6, BS EN 14161, BS PD 8010, DNV OS-F101 and ASME B31.8 may be applicable to pipelines transporting CO\textsubscript{2}, while ASME B31.4 is applicable to liquid hydrocarbons, but none of these explicitly include transportation of anthropogenic CO\textsubscript{2} in the supercritical/dense phase. Up to now a specific design or fitness-for-service procedure for CO\textsubscript{2} pipelines within the international regulatory frameworks does not exist. DNV has recently proposed a new Recommended Practice (DNV-RP J 202 “Design and Operation of CO\textsubscript{2}
Pipelines”) as conclusion of the first phase of a Joint Industry Project (“CO\textsubscript{2} PipeTrans-phase 1”) aimed at assessing the possibilities of updating the DNV-OS-F101 code for offshore transportation of CO\textsubscript{2}.

All these key issues will impact on the general development and in-field application of anthropogenic CO\textsubscript{2} capture and storage technologies, particularly in Europe. The lack of CCTS operational know-how, combined with the uncertain long-term financial environment, the regulatory constraints and the acceptability and capacity of selected locations, affect the commercial development of large-scale CCTS pipeline infrastructures/17/. Efforts to increase the know-how on the integrity of anthropogenic carbon dioxide pipelines and their management will help to reduce these barriers and allow initiation of significant investment in pipeline networks.

To address this lack of know-how, many research initiatives have been launched in Europe in recent years, without and with the contribution of European Community (E.C.).

Outside the E.C., but closely connected with several European energy industry companies, one project about to be launched is DNV - JIP proposal (“CO\textsubscript{2} PIPETRANS – Phase 2”). This project is specifically aimed at defining the toughness requirements, material compatibility and corrosion behaviour of steel pipes, as well as providing data enabling the management of dense phase CO\textsubscript{2} releases. Results from this JIP will be used to update the existing DNV Recommended Practice DNV-RP-J202 “Design and Operation of CO\textsubscript{2} Pipelines”, April 2010. Moreover a European consortium involving the electricity and gas supplier National Grid, the energy providers E-On Ruhrgas, GDF Suez and eni S.p.A. and the three pipe manufactures Europipe GmbH, V&M Deutschland GmbH and Salzgitter Mannesmann Line Pipe GmbH has been formed with the aim of launching a JIP to define the requirements for avoiding corrosion and stress corrosion issues in anthropogenic CO\textsubscript{2} transportation pipeline systems. Other initiatives in progress or about to be launched have the following aims:

- to study the release of large quantity of pure and/or anthropogenic CO\textsubscript{2} from a small-medium diameter pipeline.
- to collect and produce experimental data about the decompression of CO\textsubscript{2} mixtures starting from supercritical conditions, to provide a better definition of the driving force during a running ductile fracture propagation event.

In parallel, but under the umbrella of European Community, in response to the FP7-ENERGY-Call at the end of 2008 three proposals focusing on specific aspects of transportation of CO\textsubscript{2}, including ship transportation, have been accepted and are ongoing. The objectives of these projects are the following:

- Quantitative analysis of failure hazard release of next generation of CO\textsubscript{2} pipelines.
- Development of criteria for a safe marine transportation by shipyard.
- Development of criteria for the development of an integrated infrastructure for CO\textsubscript{2} transportation and storage.

Besides, within the framework of the Zero Emissions Platform (ZEP), Task Force Technology, a group of experts from European industries concerned with carbon dioxide transport in the context of Carbon Capture and Storage, has worked to identify the key cost elements and to forecast the long term costs of CO\textsubscript{2} transport by ship, onshore and offshore pipelines, both as pressurized and liquefied gas. The first
results of this “state of art” study have been presented during the spring 2010 ZEP meeting in Copenhagen and the full results will available in a short time.

Finally, the Research Funding Coal and Steel (RFCS) of the European Commission has recently accepted the SARCO2 proposal “REQUIREMENTS FOR SAFE AND RELIABLE CO₂ TRANSPORTATION PIPELINE”. This research project involves an integrated team of pipe producers (Europipe, Salzgitter Mannesmann Line Pipe, V&M Deutschland, Corinth Pipeworks), energy companies (eni S.p.A, GdF Suez, National Grid) and research centres (Centro Sviluppo Materiali, Salzgitter Mannesmann Forschungsinstitut), with the support of EPRG (European Pipeline Research Group). The aim of the project is to contribute to the engineering design of pipelines from the long-term integrity point of view, through the development of specific requirements and design criteria for anthropogenic carbon dioxide transportation using steel pipeline systems. This paper describe both the scope of the work of SARCO2 project and the approach employed to achieve the expected results.

2. Technical challenges for a safe design of CO₂ transportation pipelines

The natural gas industry has extensive experience on pipeline transportation. However, CO₂ (and in particular anthropogenic CO₂) shows significantly different physical properties and behaviour in the pipeline transportation process. Compared to natural gas, the most relevant differences regarding structural integrity issues are:

✔ Higher susceptibility to long-running ductile fracture propagation than natural gas pipeline operating at comparable material usage working conditions, as the CO₂ decompression curve is more severe and as a consequence the driving force is stronger and the crack arrest conditions can be reached only using steel pipes with very high toughness, or using external mechanical devices (Crack Arrestors) and/or using innovative ultra high “equivalent toughness” reinforced pipes. Figure 4 shows, as an example, two possible ductile fracture propagation scenarios for a gas pipeline involving low and high numbers of pipes, while Figure 5 shows a composite crack arrestor before and after the test.

✔ The high likelihood to have lower temperatures during service operation (as during line venting down to -20°C) or in case of a unlikely event of a leakage (down to T = -80°C) due to the significant Joule Thomson cooling effect (as indicated by H. Mahgerefteh, /15) which results in pipe material toughness decreasing.

✔ Increased pipe wall corrosion and/or stress corrosion susceptibility when free water phase is present within the CO₂ mixture.

Regarding the first point, it is worth noting that the decompression behaviour of CO₂ leads to more severe crack propagation driving force compared to natural gas; this has been known since the first studies carried out by Battelle 30 years ago /8/, /9/, /10/ and has recently confirmed by the desk studies of Cosham, and Eiber /1/, /7/. These tests and studies highlight the key role of impurities in the anthropogenic CO₂ mixture, and their detrimental effect on crack propagation driving force /7/ /16/.

Figure 4: Full scale propagation tests with long and short running fracture on a
In the possible event of a leakage, the sudden pressure loss causes a considerable temperature drop in the affected area; as a consequence the pipeline steel may reveal local brittle behaviour and also experience high local residual stress, which can encourage the transition from leak to break and the onset of running fracture propagation. There is also the possibility that lower temperatures will arise during service operation (as during line venting down to -20°C) or in the unlikely event of a leakage (down to T = -80°C) due to significant Joule Thomson cooling effects (as indicated in work of H. Mahgereteh,15/).

**Figure 5: Composite crack arrestor for gas pipelines before and after a fracture propagation test.**

Hence there is a potential risk that a leak may evolve into a break for a CO₂ pipeline. This forces the definition of more stringent requirements in terms of minimum service temperature for both base material and welded joints in anthropogenic CO₂ pipeline compared to those in natural gas pipelines (-5°C to -10°C typically for the onshore natural gas European pipelines grid) down to -25°C to -30°C (used for the CO₂ “Cortez” pipeline constructed recently in USA). These lower design service temperatures reflect in more demanding requirements for welding consumables, and also the need to develop specific Welding Procedure Specifications (WPS) to guarantee girth welded joints with good toughness at the low service temperatures.
Laboratory studies utilising CO\(_2\) at high pressure and corresponding field experiences suggest that corrosion of carbon steel in pure dry CO\(_2\) is negligible. But it is well known that at low to medium CO\(_2\) partial pressure severe corrosion damage will occur if a water-enriched phase is present. Economical considerations in the power plant sequestration process require a minimum degree of humidity. Moreover in the presence of gases like H\(_2\)S, CO, SO\(_x\), NO\(_x\) and probably even H\(_2\), corrosion phenomena like hydrogen assisted cracking, stress corrosion cracking and corrosion fatigue can arise. The likelihood and severity of these different corrosion mechanisms depend on several parameters. Data concerning these effects are non-existent /11//12//13/ (as mentioned above, this knowledge gap will be addressed by the JIP that has been launched in Europe in the summer of 2010).

The consequences and hazards of CO\(_2\) release are somewhat different from a natural gas pipeline. As CO\(_2\) is heavier than air it will accumulate in depressed surroundings. Unlike natural gas it is not explosive or inflammable, but nevertheless it can cause choking and asphyxia depending on the gas concentration and time of exposure; 4-6 % (vol/vol) can be dangerous for a person in a few minutes and 17-20 % (vol/vol) can result in death. Though existing work concerning the failure of gas pipelines suggests that impacts from CO\(_2\) pipeline accidents may be less severe than with natural gas or liquid pipelines, nevertheless data about the release of large amounts of CO\(_2\) are not available, particularly for European population densities which are higher than those in the USA /14/, /15//16/. So, full-scale tests allowing for representative ‘in-service’ dispersion measurements will provide valuable and essential data.

3. Description of the SARCO2 – RFCS Project.

3.1 Aim of initiative
The general aim of SARCO2 project is to give a contribution to “engineering design of pipelines from the long-term integrity point of view”, through the development of the following actions:

- to generate reliable data for determining the feasibility of using steel pipeline systems for the transport of anthropogenic CO\(_2\);
- to contribute to the future development of a guideline for safe design and operation of a CO\(_2\) pipeline network in Europe;
- to develop a specific know-how to be used in order to verify the possibility of employing existing pipeline systems for the safe transport of CO\(_2\).

The use of oil&gas pipeline material and construction approaches (based on conventional pipeline steel grade L415M/Q – L485M/Q according to ISO 3183 and EN 10208 part 2 and EN 1594) and the incorporation of contemporary approaches with crack arrestor solutions will be pursued in order to meet the stringent structural integrity demands for transportation of anthropogenic CO\(_2\). In particular this project is focused on the previously identified major technical challenges that could limit the wider deployment of CO\(_2\) pipelines technology in Europe, and addresses:

- Definition of toughness requirements to control initiation (leak vs. break) and long-running ductile fracture propagation using large and full scale test on real sections of pipeline.
- Collection of experimental data related to the release of large quantity of CO\(_2\) during a representative pipeline failure event, both during a leakage and
during a long-running ductile fracture propagation.
Moreover in regard to the fracture event specific goals of this project will be also:

- Development of crack arrest design tools in order to guarantee safe large diameter CO\textsubscript{2} pipeline and qualification of ultra high “equivalent toughness” reinforced composite pipes to achieve reliable designs of CO\textsubscript{2} pipelines with very severe operational conditions.
- Collection and analysis of existing and available data and knowledge about the corrosion and/or stress corrosion resistance of both pipe body and welded zone working in the anthropogenic CO\textsubscript{2} environment. Improvement of this know-how database through specific laboratory-based activities.

3.2 Overview of experimental activities
The experimental and analytical activities will be developed following three different lines related to the integrity and reliability of an anthropogenic CO\textsubscript{2} pipeline:

- Crack initiation/leak event, with the release of a large quantity of anthropogenic CO\textsubscript{2} during the leak failure of a pipeline,
- Instable ductile fracture propagation event, with the release of very large quantity of anthropogenic CO\textsubscript{2} in very short time during a running ductile fracture failure event
- Corrosion and stress corrosion events.

To study these specific issues, laboratory testing accompanied by full-scale in-service fracture testing will be performed. The SARCO\textsubscript{2} project aims to perform challenging full scale fracture tests for the first time in Europe on CO\textsubscript{2} pipelines. These full scale tests will provide vital data which is essential for the development and verification of adequate approaches and modelling. They will also enable measurements of in-field real-scale dispersion behaviour of anthropogenic CO\textsubscript{2} which will contribute to the development of realistic hazard scenarios.

For the full scale test activities, CSM has specifically devoted a large area of its “Remote Full Scale Testing Laboratory” located in Sardinia, within the Perdasdefogu Military Firing Range to the Carbon Dioxide Full Scale Facility; this was necessary due to the tight safety measures required when handling large amounts of carbon dioxide.

3.3 Crack initiation / leak event
Within the SARCO\textsubscript{2} project, full-scale Leak Before Break tests will be performed on single instrumented pipes (length of single pipe > 6m). For these tests pipes in L415M/Q – L485M/Q steel grade (according to ISO 3183 and EN 10208 part 2) with an external diameter in the range 8” – 16” and thickness 10 – 20 mm will be selected.

The tests will be performed with different chemical compositions of anthropogenic CO\textsubscript{2} at an appropriate pipe usage factor.

All tested pipes will be instrumented to measure:

- pipe internal pressure vs. time using pressure transducers.
- the internal and external temperature vs. time of the pipe in the leak zone, using thermocouples.

Moreover the CO\textsubscript{2} temperature around the leak zone will be mapped versus time using a special thermo-video camera integrated with thermocouples. During these
leak tests experimental data will be collected about the release under stable outflow conditions of CO₂ from the leakage; therefore a map of the concentration of anthropogenic CO₂ vs. time and vs. distance and height around the test pipe will be obtained.

All the above experimental data will be used to identify major factors affecting the evolution during time of a leak in the CO₂ pipeline and the possible occurrence of a break (that is full bore rupture) condition. Then, on the basis of this data as well as experience and results from fracture mechanical models available in the public domain, an updated Leak vs. Break model to be used for CO₂ gas pipeline will be developed, also making use of Finite Element analysis with devoted commercial FE codes.

Such a model is intended for use in pipeline design to determine the toughness requirements (in terms of both ductile/brittle transition temperature and shelf energy at service temperature) to prevent a break occurrence from a leak. Such a model could also be used for sensitivity analyses concerning the relative importance of different parameters (such as diameter and thickness of pipe, initial pressure, temperature and chemical composition of anthropogenic CO₂ etc), providing support to the general guidelines regarding this kind of failure.

3.4 Ductile fracture propagation event

Two full-scale fracture propagation tests will be conducted to study the crack arrest conditions and, in particular, to evaluate the toughness requirements to prevent long (more than one pipe) ductile fracture propagation initiated from an initial defect located in the pipe body. Generally, each test involves a minimum of five test pipes located in a test line including two external reservoirs with the same diameter of test pipes and a length of about six pipes to reproduce the same fluid dynamic conditions that exist in a real pipeline. Specific goals of these tests are:

- evaluation of the ductile fracture propagation behavior using real-size anthropogenic CO₂ gas pipelines, to quantify the minimum pipe toughness requirements to achieve ductile crack arrest conditions; toughness will be expressed in terms of base material toughness and/or “equivalent toughness” in the case of crack arrestor device.

- study of the decompression behavior of CO₂ gas mixtures (anthropogenic CO₂) inside the line during the rupture event to evaluate the real crack driving force;

In accordance with the general aim of this project and the relevant numbers of parameters to be studied, the diameter of pipes will be the same for both tests while the chemical composition of the gas and/or service conditions (as usage factor i.e. pressure) will be changed. Provisionally, the diameter of the test lines has been fixed at 24”.

This diameter has been proposed on the base of two following considerations:

- This is a diameter applicable for the transportation of quantities of CO₂/year of industrial interest (about 6 – 8 Mton/year). See Figure 6.

- The diameter and the expected service conditions (pressure, temperature, etc) could potentially lead to a fracture propagation event.

Figure 6 Pipeline diameter as a function of length for several flow rates in Mt/y for
Regarding this last point, Figure 7 shows the arrest / propagation toughness condition (in terms of Charpy V shelf energy) calculated using the Battelle model coupled with the CSM decompression model (GASMISC), for a pipeline with diameter 24" and thickness of 14.11 mm at a service pressure of 15 MPa. It can be seen that the toughness arrest condition (for a temperature of about 30 °C) could be in a range of 80 - 100 J.

Figure 7: Arrest / propagation for a CO₂ pipelines on the base of Battelle model coupled with the decompression model of CSM, GASMISC

Anthropogenic CO₂ gas mixtures will be used and the specific instrumentation will include:

- Timing wires, to measure the crack speed during fracture propagation;
✓ Pressure transducers to measure the initiation pressure and internal gas decompression behavior during failure;
✓ Thermocouples to measure the temperature both of CO₂ and pipes.

Finally, to reproduce realistic operating conditions for pipelines, the test line will be buried at 1 m depth and the test will be performed at ambient temperature, about 10°C.

The general framework of the planned two full-scale CO₂ pipe burst tests is given below, although the final selection of test parameters will be made later on. The test parameters and layout proposed for the first test are as follows:

✓ Geometry of pipes: Diameter: 24", Thickness: 12-20 mm;
✓ Toughness Charpy V shelf energy in the range of 60-200 J
✓ Grade of pipes: L415M/Q – L485M/Q steel grade (according to ISO 3183 and EN 10208 part 2);
✓ Type of Crack arrestors: Composite glass fiber crack arrestors;
✓ Type of pipes: SAWL and/or HFW and/or composite reinforced pipes;
✓ Gas composition: anthropogenic CO₂, with standard level of impurities (to be fixed);
✓ Test pressure: to be defined (i.e. usage factor);
✓ Test temperature: room underground temperature.
✓ Test line will be buried down to 1 m depth as in a real gas pipeline.

The test is designed to provide an arrest due to pipe body toughness properties, according to the best available know-how; in the case that such an approach dramatically underestimates the minimum toughness energy for having an arrest, external mechanical devices (that is crack arrestor and/or composite reinforced pipes) will be designed and adopted.

Test parameters and layout proposed for the second test are as follows:

✓ Geometry of pipes: Diameter: 24", Thickness: 12 - 20 mm;
✓ Toughness Charpy V shelf energy in the range of 60 -200 J
✓ Grade of pipes: L415M/Q – L485M/Q steel grade (according to ISO 3183 and EN 10208 part 2);
✓ Type of Crack arrestors: Composite glass fiber crack arrestors;
✓ Type of pipes: SAWL and/or HFW and/or composite reinforced pipes;
✓ Gas composition: anthropogenic CO₂, with high level of impurities (to be fixed);
✓ Test pressure: to be defined (i.e. usage factor);
✓ Test temperature: underground temperature.
✓ Test line will be buried down to 1 m depth as in a real gas pipeline.

In parallel to the above full scale running ductile fracture tests, experimental data will be acquired regarding the release of anthropogenic CO₂ from the fractured zone (up to a proper distance) of the test pipeline section will be acquired. The specific goal of this task is to collect experimental data about the gas dispersion map in the region surrounding the test lines during both tests for an appropriate time period. In these tests, unlike the release of CO₂ from leakage, a realistically large quantity of
anthropogenic CO$_2$ will be released in very short time.

### 3.5 Corrosion and stress corrosion events

Laboratory activity will be dedicated towards improving the experimental understanding by increasing the amount of experimental data. The test program will characterize the corrosion and stress corrosion behavior of materials from the welded girth joints developed and used in this project. Autoclave testing will allow the assessment of corrosion rates and risk of localized corrosion in comparison to the base materials. The test program will include different combinations of weld technologies, consumables and base materials.

Tests planned are:

- **Corrosion tests.** Autoclave corrosion testing under stagnant conditions and simulated flow in rotating cage and rotating disc test setups by using various chemical compositions of anthropogenic CO$_2$. The transfer and verification of the usability of corrosion inhibition concepts will be updated based on results from the above tests and from a state-of-the-art review.

- **Stress corrosion tests at constant stress level.** SSC four-point-bend tests of the selected welded joints under different H$_2$S partial pressures, using gas mixtures of H$_2$S in CO$_2$ under test conditions defined in EFC 16.

- **Stress corrosion tests at variable stress level.** Slow-strain-rate (SSR) and cyclic SSR tests, simulating realistic transport environment conditions (anthropogenic CO$_2$ in dense phase and supercritical conditions) and pressure changes. The chemical composition of the anthropogenic CO$_2$ will be fixed in accordance with those used in the other work packages.

### 4. Expected results

The deliverables from this project will be the availability of:

1. Criteria and know-how for the identification of the minimum pipe property requirements for the design of safe and reliable anthropogenic CO$_2$ transportation pipelines. These will include, in particular, requirements for corrosion and toughness of both pipes body and welded joints to control the fracture events (both crack initiation and fracture propagation).

2. Validation of technological options both for composite crack arrestors for large diameter anthropogenic CO$_2$ pipelines and for composite reinforced pipes.

3. Collection of experimental data related to the release of large quantity of CO$_2$ during a relevant pipeline failure, both during a leakage and during a long-running ductile fracture propagation.

In parallel the wide transferability of the results will be ensured by the involvement of the various industrial partners, among them EPRG. Several EPRG members are directly involved in the operation and management of the majority of the European pipeline network and they will guarantee the applicability and rapid uptake of the results obtained.

At the conclusion of the project EPRG, with the substantially contribution of CSM, will organize a Workshop in Sardinia-Pula-Perdasdefogu (test site of the full-scale pipe burst tests) to increase the awareness of the international Carbon Capture Transportation and Sequestration technology community on the anthropogenic CO2 pipeline transportation issue and work of the Project. This Workshop will be open to
specialists only and will focus on promoting a discussion about the results obtained and the remaining open issues, with a view to obtaining consensus on the use of the developed understanding and know-how.

The results from this project will make a significant contribution towards developing European Guidelines for the safe design and operation of anthropogenic CO$_2$ pipelines. At the same time they will support political approaches for the safe and reliable supply of energy to Europe. Hence, the results of this activity will contribute to the acceptability of CO$_2$ capture, transportation and storage (CCTS) in Europe as a key determining factor both to reduce the impact of greenhouse gases and to achieve the 20-20-20 targets agreed by the European Parliament and Council and law of the European Union in June 2009.

5. **Acknowledgements**

The authors wish to acknowledge the considerable contributions made by many of their colleagues and their companies, within the European pipe manufacturing and pipeline operating industries, towards the development and promotion of the research project described above.
REFERENCES