CCTS (CARBON CAPTURE TRANSPORTATION & STORAGE) TRANSPORTATION ISSUES

Carlo Maria Spinelli eni g&p Italy
Antonio Lucci CSM S.p.A Italy

ABSTRACT

Global warming has been attributed to green house gases GHG, having carbon dioxide (CO_2) as the major contributor. It has been evaluated that up to sixty percent of CO_2 emissions originate from anthropogenic sources, mostly fossil fuel power plants. Government authorities and Power Companies worldwide, along with oil and gas field operators are proposing to separate CO_2 from their power plants flue gases and sequestrate it into proper stable geological locations (Saline aquifers) or in depleted reservoirs (oil&gas) or use it for Enhanced Hydrocarbon Recovery (EHR) in over mature oil and gas fields. Actually, CCTS (Carbon Capture Transportation & Storage) is an option to make available to mitigate fossil fuel use impact on global warming.

Emissions of GHG to the atmosphere can be reduced by capture and storage of CO_2. This technique consists of three main stages, carbon dioxide capture at fossil fired plants and other fuel conversions plans, transmission of CO_2 between the site where it is captured and the site where it is to be stored underground.

However the whole chain needs some further step to be fully accepted and applied in industrial countries. Capture and Storage have been extensively studied in the past and currently, but on other hand few attempts have been put in place to fill some existing gaps in CO_2 transportation.

The long lasting experience from the EOR (Enhanced Oil Recovery) technology since the seventies, mainly in North America, induces to consider the carbon dioxide transportation issues as a mature technology and this is one of the reasons because it has not been extensively studied, however some specific deepening, due to the peculiar combinations of impurities related to different capture technology used, suggests to perform a few selected R&D activities on the matter.

TABLE OF C O N T E N T S

2. CCTS

Carbon dioxide is one of the main “Forcing Agents” for increasing the solar radiation retention)see Fig. 1), among the other ones either from anthropogenic and natural analogues; the emissions of carbon dioxide from anthropogenic sources have largely been increased in the last two centuries for the greater need for fossil fuels. This is addressed to as one of the cause for global warming.

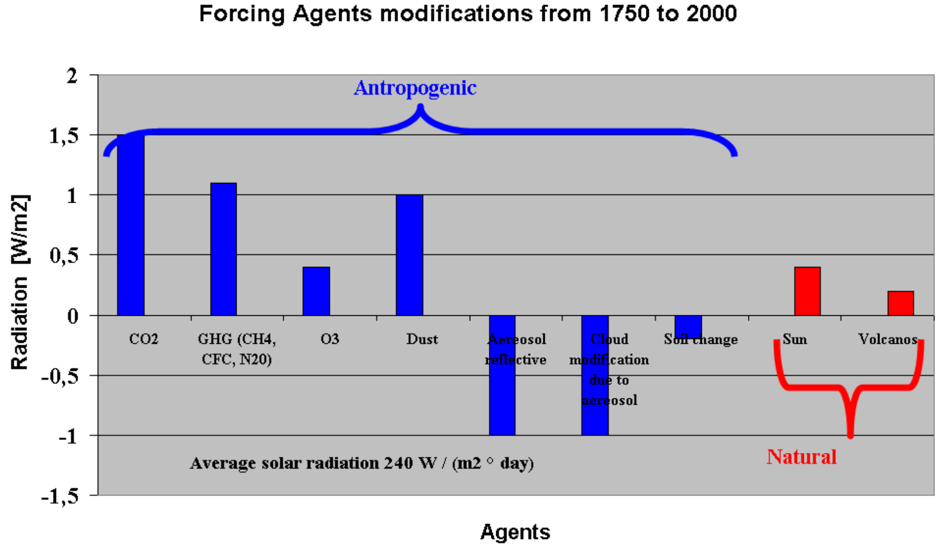


Fig 1. Forcing agents on solar thermal radiation retention 1

Recently, great attention has been given to the carbon dioxide emissions reduction in the atmosphere by concentrate anthropogenic (i.e. by humans) sources such as power plants and industries (refineries, cement and steel, synthetic fuel production, etc). In order to achieve the goal to sensibly cut the emissions down (more than 80%) many researches, pilot plant and demo projects have been developed to test the effectiveness of CCTS technology.

Moreover the “smart use” of anthropogenic CO_2 for ECBM (Enhanced Coal Bed Methane) and EHR (both onshore and offshore) recovery makes this options very promising to combine an ecological friendly solution for permanently carbon dioxide storage and to enhance either O&G in declining production fields or new exploiting actions of unconventional natural gas.

CCTS (Carbon Capture Transportation & Storage) involves three main steps: CO_2 capture; compression and transportation by pipeline or tankers; and storage in deep (>800 m) saline formations, depleted oil and gas reservoirs or coal seams. This means capturing carbon dioxide production sources and sequestrating it into suitable reservoirs. CCTS approach is one of the possible options to reduce fossil fuel power plant emissions down to acceptable levels; technical solutions for capture and sequestration of anthropogenic CO_2 have to be found very timely, in accordance with the European Union Renewable Energy Directive that could pave the way a 20% cut in greenhouse gas emissions by 2020, the so-called “20:20:20 Plan”. As example, the use of CCTS technology allows reducing the CO_2 emission in atmosphere from 0.4 (natural gas combined cycle i.e. NGCC) ÷0.8 (pulverized coal i.e. PC) ton /MWh power plants without CO_2 capture) to 0.05÷0.12 ton/MWh (NGCC or PC plants with CO_2 capture devices), see figure 2.

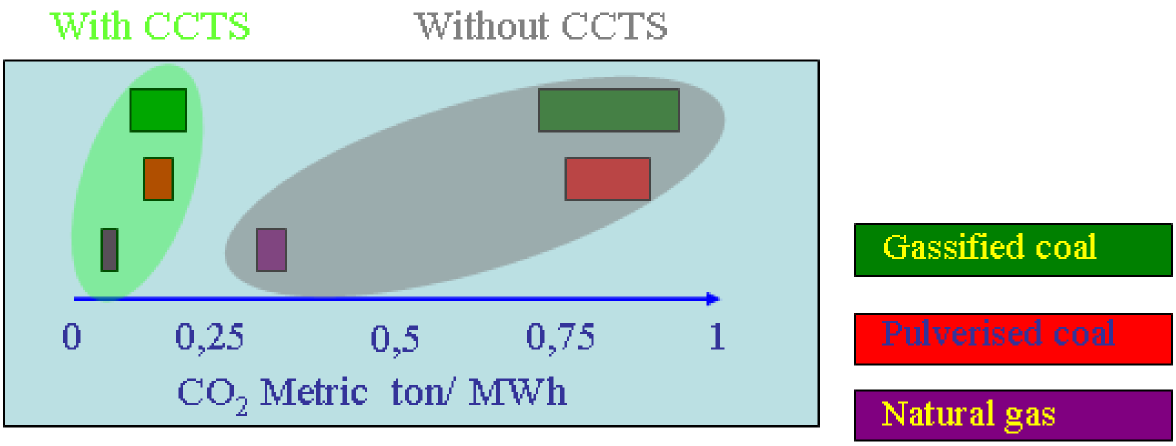


Fig 2. Emissions from different fossil fired power plant (with & without) CCTS

The capture process takes CO_2 (as a gas) from the combustion gases to produce a high purity CO_2 stream, although the final purity required for transport and storage is not yet established in most of the regulations under approval worldwide. A dense form of the captured CO_2 is needed for rational transport scenarios – possibly as a supercritical for reducing cost and maximising the hydraulic efficiency transportation.

There are three main ways to get CO_2 from the exhaust gas stream, they can be applied either before combustion (decarbonisation of fossil fuels) or after combustion (capture from flue gas) using different processes as shown in Fig.3 a,b,c,d.

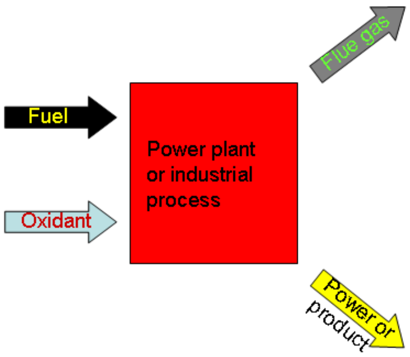


Fig 3 a) Schematic power plant or industrial process.

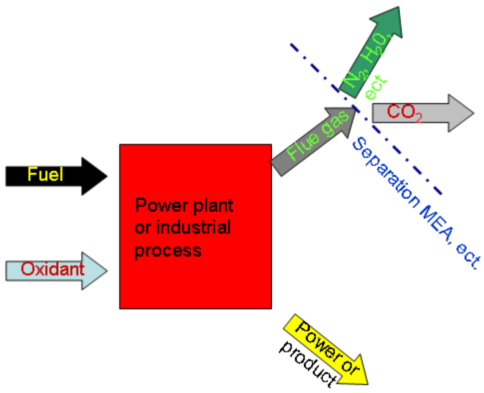


Fig 3 b) Post combustion process.

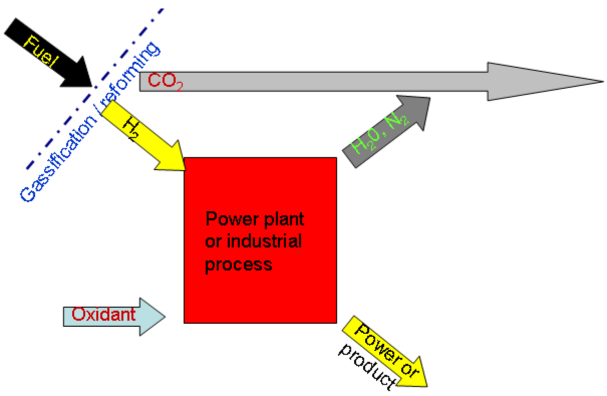


Fig. 3 c) Pre combustion process.

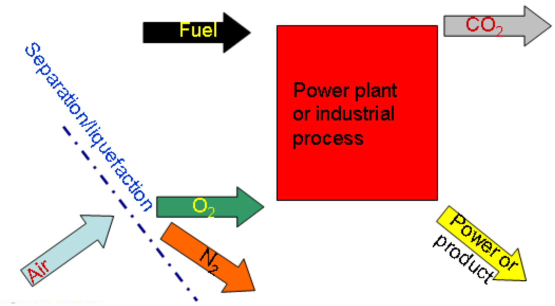


Fig. 3 d) Oxy fuel process.

Having a reference scheme for a power plant, as shown in Fig 3a, the processes are:
Post-combustion capture where CO_2 is separated from the flue gases streams and fed into a compression and dehydration unit to deliver a relatively clean and dry CO_2, it normally uses a liquid solvent to capture the CO_2. Fig 3 b.
Pre-combustion capture, in this process it is necessary to produce from the initial fuel a 'synthesis gas' or 'fuel gas' made mainly by CO and H_2. The carbon monoxide is later on reacted together with steam in a catalytic reactor, called shift converter, to give CO_2 and more hydrogen. CO_2 is then separated from the gas mixture, usually by a physical or chemical absorption process, resulting in a hydrogen-rich fuel which can be used in many applications, such as boilers, furnaces, gas turbines and fuel cells. This technology is also already used in several industrial conversion processes as hydrogen production, and in petroleum refining operations. Fig 3 c.
Oxyfuel capture, here pure oxygen is used for combustion instead of air, resulting in a flue gas that is mainly CO_2 and H_2O. This flue gas stream can directly be fed into a CO_2 compression and dehydration unit. Fig 3 d.
The selection of a proper capture system depends on several factors, the most important key issues are the possibility to be applied to existing power plants by a retrofitting (as in post combustion), as well the energy consumption of the overall capture process and/or other economic issues.

3. TRANSPORTATION ISSUES

Up to now the attention, funds and international projects have been focused mainly on capture enhancing efficiency and on localizing proper and safe sequestration underground and monitoring integrity management plans as well, as witnessed by a lot of financial funds to R&D issues since the 90'. Nevertheless anthropogenic carbon dioxide transportation from energy plant to the sequestration area probably will represent a necessary asset to the diffusion of CCTS technologies. Among the several ways to transport carbon dioxide existing or proposed:

- Truck
- Rail cars
- Pipeline transportation
- Ships

the only option able to assure a continuous, 24-hours/365-days service, without any storage, flow from the production site to the final sequestration appears to be the pipeline link. It also copes with reduced environmental footprint. However, although know how on CO_2 (mostly pure coming from underground natural domes) transportation by pipeline mainly in Northern America (USA & Canada) exists, the combinations of impurities related to the different existing capture technology make CO_2 anthropogenic pipelines a new frontier to explore as there is not any detailed study on the impact of the impurities released from these power plants. Impurities may have effect on the -physico-chemical properties of the CO_2 mixture that consequently affects pipeline design, material selection, compressor power, recompression distance, pipeline capacity and could also have implications in the prevention of fracture propagation. Furthermore CO_2 behavior causes transmission concerns, mainly for possible phase changes. It is captured at atmospheric pressure from the plants flue gases and then dehydrated and pressure boosted in a dense or supercritical phase to achieve an efficient pipeline transport to a storage site. Along the entire pipeline network the pressure must be kept well above the saturation line and it must meet, at the injection point the reservoir requirement. The minimum operative pressure for a dense phase CO_2 pipeline is 7,3 MPa (the presence of impurities may increase this value by 1 MPa too) see Fig 3, this force to design, build and operate a high pressure pipeline network that is above the common operational limit (at least in Europe where onshore transportation upper limit is about 8 -10 MPa).

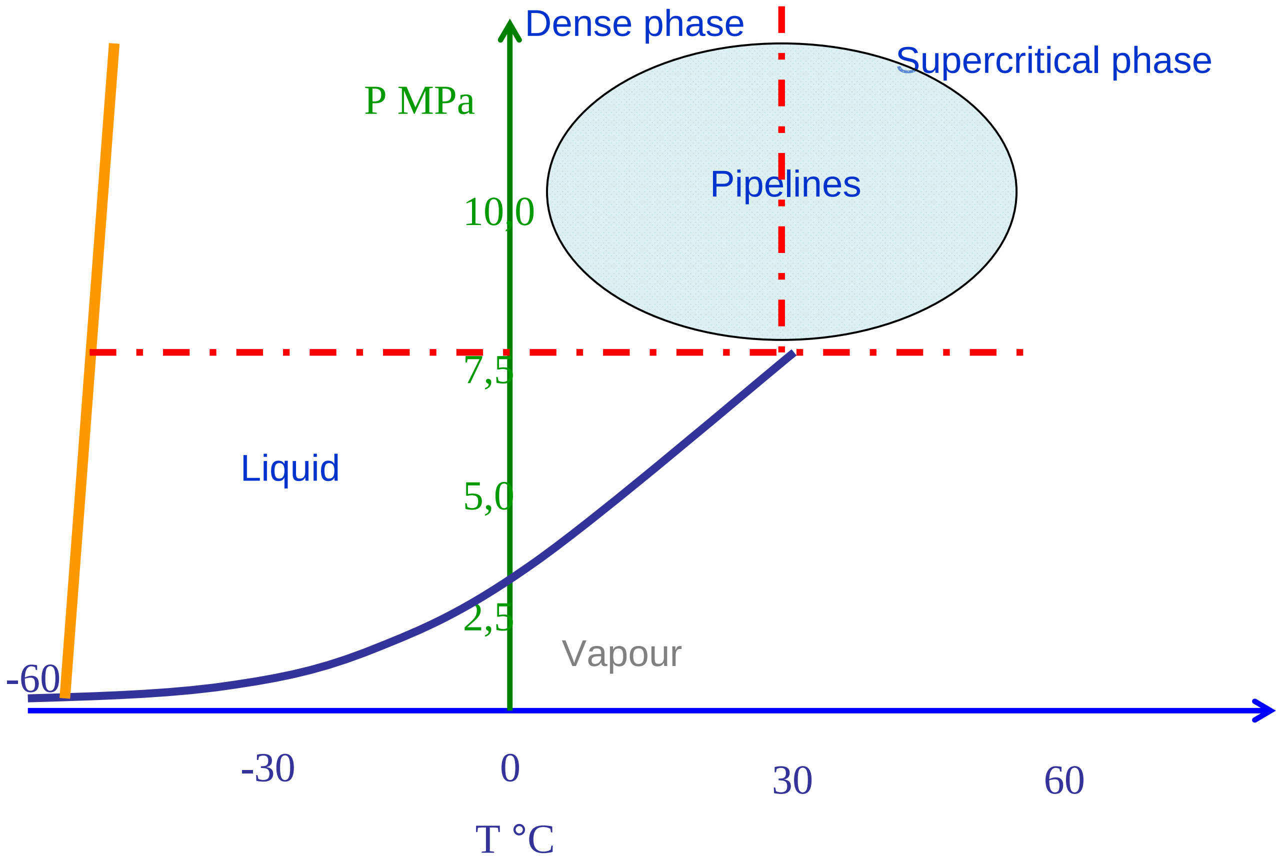


Figure 3. Phase diagram for pure carbon dioxide and pipeline operative range.

Another issue to be considered is the safety issue linked to the CO_2 transportation by pipeline and its reliability over long life time operational periods.

4. TECHNICAL GAPS IN CO_2 TRANSPORTATION

There are a few issues in carbon dioxide transportation, some of them mainly related to technical issues, other ones due to the impact on the public opinion or on business/financial schemes. A short overview will be given with special attention to technical features:

a) financing, legal and regulatory issues,
b) cost and capacity overall evaluation,
c) achieve supply & demand balance.
d) design, material, standards availability, safety issues.

- Financing & legal and regulatory issues. The pipeline industry, for more than one hundred years, has transported hydrocarbon & chemicals mainly for oil & gas applications. A diversity of business models and ownership/financing structures of major infrastructure investment has been used for very large natural gas & oil pipelines networks crossing several countries (in some cases over 3000 km in onshore). Depending on the integrated infrastructure transportation network option including tree-and-branch or hub designs have been successfully built where it is required to connect multi-points of supply and demand. Several measures have been taken to minimize risks, as a phased growth (build up framework) and proper contracts design. Furthermore the minimisation of unit transport costs has been achieved by a proper optimising scale up. Project finance is the most developed investment in the energy industry as in the largest oil and gas pipeline projects recently occurred.
- Cost and capacity overall evaluation. In existing trading schemes actual CO_2 prices are insufficient to support the large investments required to adopt CCTS as a large scale GHG countermeasure. At the present time investors have very low visibility on the price trend of the CO_2 reduction, and in many regions there is no effective CO_2 price. However this issue is outside the scope of this report, as is well documented elsewhere 3.
- Achieve supply & demand balance. The balance in pipeline transportation between supply and demand carbon dioxide inventories depends on the emerging network structure; roughly it could evolve in two basic ways:

- Point-to-point, where each specific capture plant feeds a specific storage location, this option would be funded on a project-by-project basis by individual developers,
- Pipeline networks development, which allow for common CO_2 network from multiple sources to multiple sinks could be an alternative, but increasing cost could not pass project-specific commercial evaluation criteria.

- Design, material, standards availability, safety issues. Engineering a CO_2 network requires long-term planning and adopting a strategy heading to potential magnitude of future deployment scenarios for CCTS; also the nature of incentives policy to CCS and geomorphologic issues are influencing factors to be taken in account.

Within the European borders, natural gas industry has grown a huge transportation net grid and collected an extensive experience on pipeline transportation, as well as a recognized safe track record along with the past 40 years. Due to this long lasting positive score and a strong technically base framework of standards, among the most stringent in the world, it must be highlighted that the only chance to design, build and safely operate integrated pipeline net grid for CCTS aims should exploit the large experience and know how established in this field.

The design (pressure containment plus limit state design) approach, the materials selection as laying and construction techniques (in field welding and pipeline back filling) applicable for natural gas transportation systems must be utilised as much as possible for an economically viable carbon dioxide netgrid infrastructure; however, CO_2 (and in particular the anthropogenic CO_2) shows also remarkable physical properties and behaviour in the pipeline transportation process differing from the natural gas. The European transportation gas natural network is operated up to a maximum allowable operative pressure of 8-10 MPa in onshore applications and up to 30 MPa in sub sea applications; pipes are made by carbon steel according to detailed specifications taking into account different levels of strength (up to 555 MPa of Yield Strength in Europe and above 900 MPa in other international standards), they are available by different production routes from some diameter inches up to 64", with wall thickness up to 40 mm and more. Natural gas transportation has been object of continuous investigation by several groups of R&D initiatives as EPRG (European Pipeline Research Group, made by pipe producers and gas transportation company) or GERG (Groupe Europeen Recerche Gaziere) to face the emerging issue either from new challenging situation or the aging network. Constructions methods are extremely competitive allowing building up to 5 km/day in offshore and about 1 km/day in onshore scenarios are available. Main requirements for pipeline safety long term operation are based on the assumption to contain the fluid shipped, to withstand the external loads as well as from the external environment being protected by coating and electrically protected by the external corrosion. Furthermore in case of accident the extent of the failure should be minimized by the steel property (toughness) even at low temperature.

In this frame, CO_2 transportation has been recently considered as an object worth some specific investigation and recently (from 2009) several JIPs' (Joint Industrial Projects) have been launched to fill the existing gaps on the carbon dioxide anthropogenic transportation by pipeline.

5. APPROACH

CO_2 can be transported in three states: gas, liquid and solid. Commercial-scale transport uses tanks, pipelines and ships for gaseous and liquid carbon dioxide. Gas transported at a pressure close to atmospheric one occupies such a large volume that very large facilities are needed. Gas occupies less volume if it is compressed, and compressed gas is transported by pipeline. Volume can be further reduced by liquefaction; this is an established technology for transferring CO_2

Carbon Dioxide owns properties slightly different from the gases usually transported via pipelines, it shows a critical point at 30,9 °C and 7,36 MPa. Consequently, if the pressure is below 7,36 MPa (the critical pressure), fluctuations in the temperature will cause the coexistence of both gaseous and liquid phase. Transportation of gaseous carbon dioxide is not efficient at all because of the lower density of the vapor phase and the relatively high pressure drop per unit length. CO_2 is typically transported in a dense phase (supercritical or liquid phase) for economical reasons (less energy for compression and smaller pipeline diameter), see Fig.4, and for transportation purposes (avoidance of two phase flow).

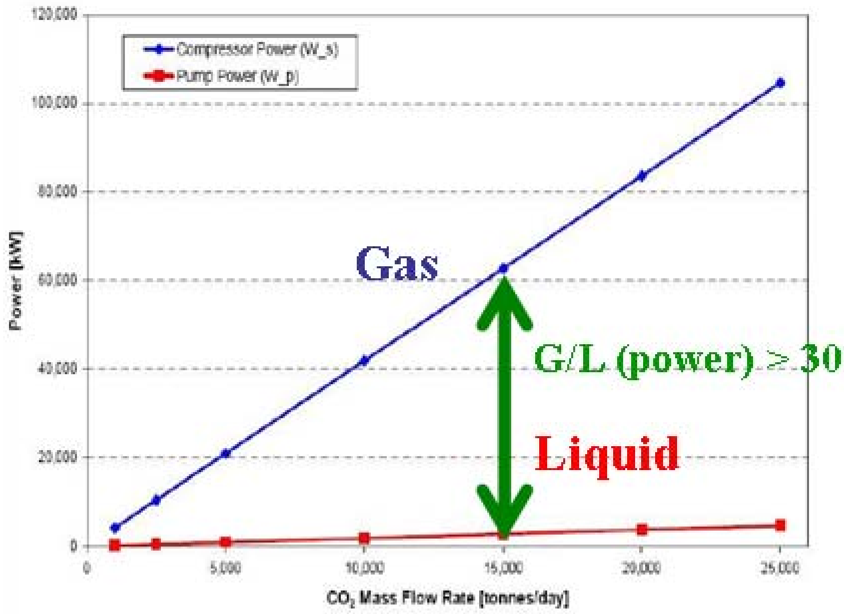


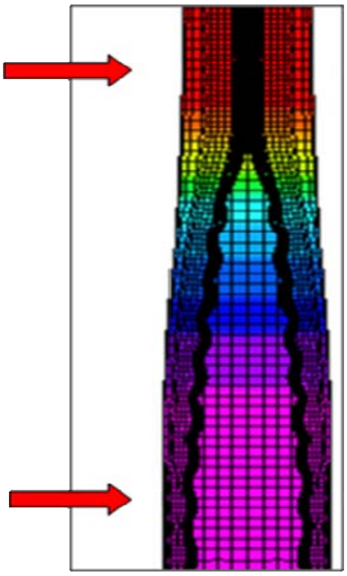
Fig.4 Gas to Liquid power ratio to transport carbon dioxide by pipeline.

In case of leak the liquid to gas expansion can cause great cooling of the pipe body due to the high joule Thompson effect. In this condition the toughness reduction is possible and a rupture event could occur. In the pipe break event the sudden expansion of the dense phase CO_2 causes significant driving force acting on the broken “wing” of the pipe, this event may lead to the long propagation fracture along the pipeline when inappropriate toughness of the pipeline steel cannot act a resistant force as shown in Fig 5. In this figures are also reported the main issues regarding the fracture propagation, in particular:

1. Image of the leak event - was taken after a propagation test on innovative pipe grade steel for natural gas transportation.
2. Fracture propagation event – as it may have some impact on section of pipeline, due to the specific CO_2 behaviour.
3. Fracture event modelling – there is a lot of work to do in order to model the gas mixture decompression behaviour.
4. Crack arrestor to prevent the fracture – need of studies to define the arrest condition for CO_2 decompression.
5. Gas decompression behaviour – has to be studied and models has to be improved in order to give more reliable results. Especially in the presence of impurities in anthropogenic CO_2, the results of gas decompression achieved for the natural gas are not portable to the CO_2 case.

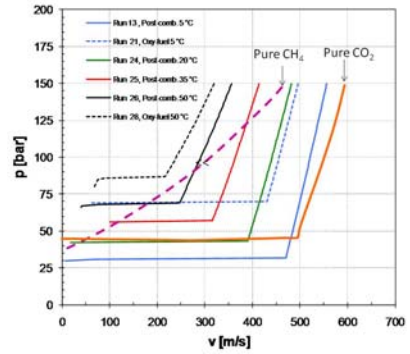
1 – Leak on a pipeline

1 – Fracture propagation



2 – Prediction model for fracture propagation

3 – Crack arrestor for fracture arrest.



4 – Decompression curves for CO_2 and CH_4

Fig 5. Fracture propagation issues. Test performed in a facility range on experimental grade steel for natural gas pipeline operated at high pressure where the pipe resistance force is lower than the driving force.

Several pipeline experts point out that CO_2 pipelines are susceptible to fast running ductile fracture because CO_2 is transported in dense phase (i.e. high saturation pressure and low decompression velocity). Several simulations have been performed, even if based on models developed for natural gas applications (but not validated by experimental testing on carbon dioxide) confirm that carbon dioxide pipelines, under particular design situation (low pressure design, low toughness materials), may suffer a higher susceptibility to long-running ductile fracture propagation than natural gas pipelines operating at similar working. So the achieving of crack arrest conditions can be reached only using steel pipes with very high characteristic (toughness, deformability) or using external mechanical devices (crack arrestors). Up to now, no sound design criteria for ensuring the sure arrest of a fast running ductile fracture propagating in anthropogenic CO_2 pipelines exist.

Decompression modelling of the natural gas which is currently transported safely can not be used for the design and fracture control of the planned dense-phase CO_2 pipelines where they differ significantly from natural gas. Therefore, particularly for the anthropogenic CO_2, analyses and modelling of gas escape from an opened crack need to be developed for predicting the gas decompression behaviour and to quantify the fracture driving force acting at the crack tip during the fracture propagation event.
Furthermore also the consequences in case of hazard are somewhat different from the natural gas pipeline. As CO_2 is heavier than air it will lay in depressed surroundings, especially in case of very low temperatures, see Fig. 6 for a natural carbon dioxide analogue.

Fig. 6 Natural carbon dioxide release from the ground, CO_2 'lake' in the Amiata region (Tuscany,Italy). The gas accumulation has been made visible by igniting a smoke bomb in the morphological depression.

As no evidence on large CO_2 releases, under controlled situations particularly aimed to measure the phenomenon, exists so it has been pointed out from different parts to investigate this specific issue.
Field experiences suggest that corrosion on carbon steel in pure and dry CO_2 is negligible. 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, but experience in dehydrating CO_2 is very well-established and the reduction of the amount of water down to acceptable level for transportation needs is mandatory for the power plant capture system design; otherwise, it should be investigated the effect of impurities as H_2S, CO, SO_x, NO_x and probably even H_2 that potentially could lead to corrosion phenomena like hydrogen assisted cracking, stress corrosion cracking and corrosion fatigue. These examples shown here clearly points out that a specific experience on the anthropogenic CO_2 behaviour, especially in the presence of significant amount of impurities, must be achieved through experimental activities.
A gap analysis has been performed and many of the industrial companies involved in CCTS decided to collaborate to put in place research efforts aimed to fill the lacks; all these efforts are scheduled on a tight timeline to issue guidelines and/or recommended practices; later on they may feed the standardization bodies with a critical mass to issue one or more standards on the matter.
In this respect specific projects dedicated to the transportation of CO_2 by pipeline inside the European Community countries have been launched in these last two years (2008-2010) or are going to be started, (mainly inside the framework of Frame Program-7-Energy-Call). All these new initiatives are focused on some specific aspects of transportation of CO_2 via pipeline with specific focus on the identification of requirements for a safe and reliable carbon dioxide transportation pipeline design and operation.
European Community is going to financially supporting projects to define:

- criteria for a quantitative analysis of failure hazard release from a CO_2 pipeline.
- know-how to enable the determination of steel pipe requirements for anthropogenic CO_2 pipelines. In this case the most critical goal is the definition of base material toughness requirements to avoid running ductile fracture propagation, so full scale fracture propagation tests on real sections of pipeline are planned to be executed.

In parallel, Joint Industrial Projects proposals are in progress with the aim to study:

- the release of pure and/or anthropogenic CO_2 from a small-medium diameter pipeline.
- to collect and produce experimental data about CO_2 mixtures decompression starting from supercritical conditions to be used for a better definition of the driving force during a running ductile fracture propagation event.

Furthermore a European consortium of Integrated Energy Companies and leading pipe manufactures has been formed to cooperatively define requirements for anthropogenic CO_2 transportation pipeline systems with regards to corrosion and stress corrosion issues by performing extensive laboratory testing.
At the least:

- KEMA has already finished the first part of "COSHER" project to create a validated data base of release data from full scale experiment aimed to calibrate existing models and it is going to launch further Phases to perform and interpret full scale release tests.
- DNV launched in 2010 a JIP to complete and update the recommended practice "Det Norske Veritas DNV-RP-J202 Design & operation of CO_2 pipelines, April 2010", filling the gas knowledge on items related to large discharge of carbon dioxide, fracture propagation avoidance criteria and corrosion.

In this context, eni and CSM, since the 2009, have launched an integrated approach to perform all the needed activities on the issues related to the demanding CO_2 network integrity criteria, either as simulation modelling, small scale and large/full scale testing.

Risk assessment for choosing the correct location of these kind hazardous tests has been performed and the testing facilities selected was located in a remote and deserted area within a Military Facility range which access is allowed by the military forces. Specifically CSM has devoted a large area of its own "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 measure to take in account when handling large carbon dioxide amount, the testing devices are devoted to four main classes of tests:

1. long term pressure cycling.
2. leakage test.
3. release test.
4. ductile fracture propagation test.

Pressure tests (static and cycling) can be done up to a maximum pressure of 34 MPa, by mixing impurities as H_2S and CO, SO_x, O_2, etc, even for the corrosion and defect assessment on long term pressure tests, as well as the same plant can perform leakage test, the steady flow condition can assure the complete observation of phenomena related to the Joule Thomson effects.

The release facility comes from a 48" diameter pipeline section, 550 meter long and another pipe section 250 m long (48") can be added in case of need, increasing the total amount of CO_2 stored up to above 800 metric tons with a maximum operative pressure of 15 MPa. The difference of altitude from the top to the bottom of the line is around 50 meter, this is a useful condition to perform release of liquid CO_2 having an intrinsic gas segregation on the top.

A complete instrumentation made by monitoring temperature and pressure transducers is applied inside the pipeline, while infrared camera for jet cloud temperature monitoring, as well as a set of temperature sensors distributed around the release area at different altitude will be available. Heat flux sensors for heat transfer monitoring are present on the area while high speed video recording can be performed by a camera to grasp the starting event evolution till the steady state condition, turbulence and flow path can be detected. Sound detectors are used for monitoring the noise level evolution and propagation around the release point. All this instrumentation is foreseen to collect as much as possible information from the experimental activities to supply useful information in terms of safety health and environment congruence to such an event. Moreover all the recorded data can be used to fine tune modelling.

For the ductile fracture propagation has been studied and selected a specific plant with a pumping system of the following characteristics: a flow capacity 8 metric ton/hour and maximum pressure of 15 MPa.

A weather condition station has also been installed; in fact a very important key issue is the monitoring of the weather condition by means of a local station. It can gives the boundary condition of the ambient parameters as wind speed, solar heat flux, temperature, pressure, atmospheric stability etc. these can usefully be employed in simulation or recorded and associated to a specific test.

5. 6. CONCLUSIONS

The evolution of CCTS technology to permit fossil fuel use in an environmentally friend way will need an emerging CO_2 anthropogenic pipeline transportation as one of the most promising and cheap way to ship captured CO_2 from power plants to permanent underground storage sites for final sequestration or for EOR applications.

In the past ten years many efforts have been pursued to develop reliable and economically viable capture and storage systems, while few industrially feasible initiatives have been spent so far to fill the existing gaps of knowledge in CO_2 handling and transportation in a safely, efficient and convenient manner.

The straightforward application of the know how (design criteria, material requirements, etc.) developed over the years for natural gas transmission pipeline as well as the experience gained (especially in USA) on pure CO_2 pipelines for oil recovery applications is a very important starting point, but it does not completely represent the final solution, since significant differences exist when carbon dioxide, coming from capture system, is not pure. The effect of the impurities on structural integrity, fluid dynamics and related issues, particularly fracture control and corrosion-stress corrosion prevention must be carefully taken in account.

Several projects (some under the EU umbrella) have been recently launched or are about to be launched to fill gaps on a tight timeline, with the final aim to issue guidelines and recommended practices to soon feed

the standardization bodies. It is interesting to mention how several companies (gas transportation companies, integrated energy companies, pipe manufacturers, research centres and standardisation bodies) have launched an integrated research approach which for the experimental part is strongly centred on the new carbon dioxide devoted facilities.
CSM performed a risk analysis to locate the proper area for testing including large release of carbon dioxide in safe manner and is going to build its full scale testing laboratory in Sardinia. Specific effort is being spent on design and installation of suitable instrumentation able to capture all the main parameters of the event under consideration so to allow, through the test data post processing, significant improvement of modelling when large releases and pipe leakages or fracture propagation testing involving large amount of CO_2.

7.REFERENCES

1 Hansen J., Sato M .,Ruedy R.,Nazarenko L., et al, "Efficancy of climate forcing", Journal of Geophysical Research, 110 , 2005

2 Technical challenges to transport anthropogenic CO_2 by pipeline for CCS purposes, G.Demofonti (Centro Sviluppo Materiali) and C.M. Spinelli (eni) Pipeline Technology Conference Hannover 2011 4-5 april.

3 CO_2 pipeline Infrastructure: An analysis of global challenges and opportunities.
Final Report For International Energy Agency Greenhouse Gas Programm 27/04/2010.

6.