Fracture Control Strategy for the Conversion of Oil and Gas Pipelines to Transport CO_2

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Keywords: CCS, CO_2 Transportation, Change of Service, Fracture Propagation, Fracture Initiation

Abstract

This paper discusses work currently being undertaken to develop an integrity based strategy for fracture control during the re-design process for the conversion of oil/gas pipelines to transport CO_2. The paper reviews the requirements that need to be fulfilled to ensure that any potential running fractures (from different defect types - manufacturing, construction, corrosion, etc) are adequately arrested to avoid catastrophic failure following the change of service of the pipeline. The available decompression models for CO_2 are discussed to evaluate their applicability to the transportation of “captured” CO_2.

In order to ensure the suitability of the pipeline for the “change of use” a methodology for the fracture control evaluation from the relevant information derived from the as-design, as-built and as-found condition is discussed. Once the integrity condition of the pipeline has been determined, a comparative risk assessment to define the main threats under the new operating conditions is described.

Both the risks of long running brittle fracture and ductile fractures are important and have been considered. The influence of material properties such as the embrittlement behaviour under low temperatures, and also the influence of the composition of the transported liquid on the fracture of the pipes need to be analysed. The decompression at the location of any opening/defect would result in local changes in pipe temperature which would affect the integrity of the pipe. Key operating parameters such as corrosion control strategy, control of water content, flow assurance, control risk of hydrate formation and the effect of impurities in the gas decompression behaviour have been outlined.

1.0 Introduction

There is overwhelming scientific evidence, as shown in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), that climate change will threaten economic growth and long-term prosperity, as well as the very survival of the most vulnerable populations [1]. The IPCC suggests that to avoid the most catastrophic impacts of climate change, greenhouse gas (GHG) emissions need to peak in the next 10 to 15 years, and be reduced in the order of 50-80%

below 1990 levels by 2050. To achieve these goals necessitates innovative changes in the short and medium-term in technology in all sectors of the economy. Among these technological development Carbon Capture and Storage (CCS) has been considered as a key technique for reducing emissions substantially. The changes in CO_2 capture technologies, fuel cost and potential plant construction costs that have occurred since the IPCC Special Report on CCS was written have been reviewed elsewhere [2, 3]. To ensure the successful implementation of CCS it is recognize that transport of CO_2 via pipelines will play a key role in making the technology economically viable. The transportation of mostly pure CO_2 via pipeline is nothing new with world experience of CO_2 pipeline being about 7500km of which 6000km (3700 miles) are mostly large diameter and operational in the USA[4] mainly for Enhance Oil Recovery (EOR). Experience offshore is quite limited, Norway's state-owned oil company, Statoil has since 1996 been injecting CO_2 from a by product of natural gas recovery into a 32,000 sqkm aquifer 800 m below the North Sea in the Sleipner field [5].

Several authors have discussed the issues to control fracture propagation in CO_2 pipelines [6, 7, 8] and the modelling of the CO_2 fluid [9, 10] from the point of view of design of new pipelines. The same applies to the evaluation of materials compatibility for CO_2 transportation [11]. However, literature on the consideration of fracture control strategies during re-qualification/conversion of existing pipelines for the transport of "capture" CO_2 has not been investigated in the same depth.

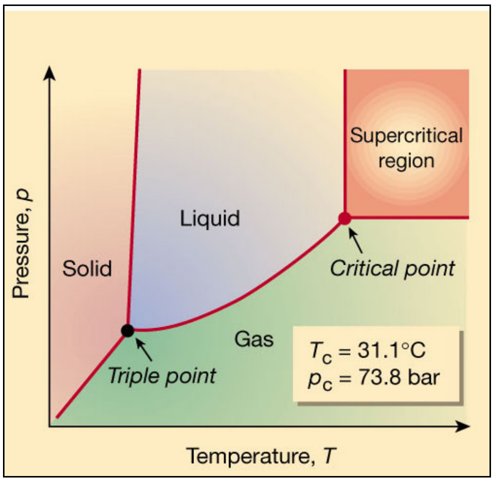
This paper discusses a fracture control methodology to for the conversion of an existing oil and gas pipeline for the transport of CO_2. The focus is on the requirements of "material compatibility" to ensure that fracture initiation and potential propagation of running ductile fractures are tackled during the re-design process.

2.0 Properties of CO_2 and Preferred Conditions for Its Transmission

Figure 1, schematically shows the pure diagram for CO_2. CO_2 can exist as a gas, liquid, or solid. At standard temperature and pressure (STP), CO_2 exists as a gas. At the triple point (5.11 bar, -56.4 °C) all phases exist in equilibrium. At the critical point (31.1°C, 73.8 bar) located upper right in the phase diagram for CO_2), the temperature and pressure at which the liquid and gaseous phases of a pure stable substance become identical. Above this point CO_2 exist as a supercritical or dense phase.

Pipeline transmission of CO_2 over longer distances is considered most efficient when the CO_2 is in the supercritical dense phase, since in this phase the fluid has the density of a liquid and the viscosity and compressibility of a gas. The higher efficiency is due to the lower friction drop along the pipeline per unit mass of CO_2 when compared to the transmission of the fluid as a gas or in a gas-liquid phase.

Figure 1. Phase Diagram for Pure CO_2 [12]



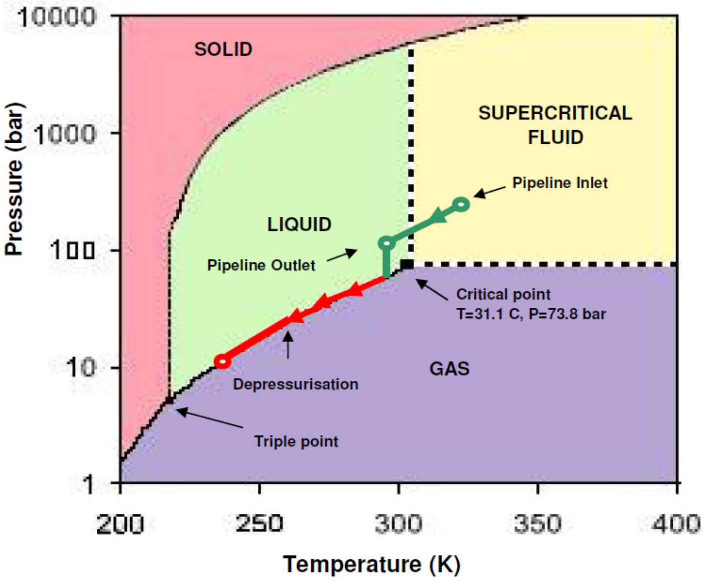
Effects of Impurities on CO_2 Phase Diagram

It is anticipated that ‘captured’ CO_2 will include a series of impurities depending on the capture technology (pre-combustion, post-combustion or oxy-fuel processes). Race et al [5] discusses the potential effect of these impurities (SO_x, NO_x, H2 and Ar) on the phase diagram for CO_2. However, since CO2 containing these impurities is not currently being transported, further work is still required to fully understand their influence on the phase diagram and on the decompression behaviour of the fluid.

Potential Situation if Fracture Failure Occurs

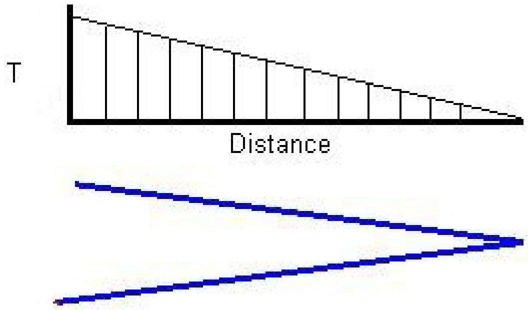
The potential behaviour during a leak/rupture has been discussed by Eldevik et al [13] and is depicted in Figure 2. Eldevik et al argues that if the pipeline is depressurized due to pipeline failure, the pressure will drop until the liquid-vapour line is reached and CO2 vapour starts to form (red line). A too rapid depressurization may cause the CO2 to drop down to the triple point at which solid state CO2 will form with the potential critical implications for the operation of the line.

Figure 2. Potential Phase Transformation During Leak/Rupture[13]



Little has been said in the literature with regards to the potential temperature gradients at the front of the crack tip that could influence the fracture propagation behaviour in pipelines transporting CO_2.There is currently not enough information available from full scale burst test in relation to pipelines transporting CO_2. Figure 3 depicts the gradient temperature anticipated at the crack tip.

Figure 3. Temperature Gradient Ahead of the Crack Tip During Leak/Rupture



3.0 Fracture Control Strategy

Fracture control requires the understanding of the factors governing the fracture behaviour, mainly the initiation, propagation and fracture arrest and their relation with the decompression of the transported fluid.

The fracture control strategy focuses on two key aspects to avoid fracture related events that could cause loss of pipeline integrity at the new operating conditions. The first, fracture initiation control, deals with the identification of defects introduced to the pipe during material manufacturing, fabrication, environmental effects, etc. The second item deals with fracture propagation control which involves the determination of the fracture length should fracture initiation occurs. A comprehensive study on fracture control technology for natural gas pipelines was carried out by Eiber et al [14] and has been used for guidance when comparing the fracture control requirements between pipelines transporting hydrocarbons and pipelines for CO_2 transportation. The work carried out by Leis and Porte [15] as well as Manucci et al [16, 17] has been taken into consideration when dealing with higher grade pipelines. The implementation of an adequate strategy for fracture control should consider hindering the effect of both fracture initiation and fracture propagation.

3.1 Strategy for Fracture Initiation Control

In general, the strategy for fracture initiation control for a pipeline being considered for change of service is based on defining if under the new operating conditions the initiation toughness of the steel, the pipe diameter, wall thickness and grade of the pipe are sufficient to avoid the penetration of the pipe wall by a defect that could produce leak or rupture. The key objective is to ensure that materials properties for both parent metal and welds are appropriate to tolerate the existing flaws under the new operating conditions. In addition, to manufacturing and construction defects, consideration should also be given to flaws that could have developed during service e.g. corrosion, cyclic loading, etc. In order to ensure that the flaws identified by the different inspection methods will not have an affect on the integrity or service performance under the new operating conditions a fitness for purpose assessment based on available guides such as those describe in the following section on defect acceptance criteria should be put in place. The acceptability of crack type defects can not be assessed by using plastic collapse methodologies as in the case of corrosion defects, the framework for the evaluation of these flaws is provided in BS7910 [18] and API 579[19] should be carried out when applicable.

Defect Acceptance Criteria

In order to safely determine the suitability of a pipeline for “re-use” an understanding of the “as-found” condition and confidence in the data generated from an inspection programme are key for an operator to determine future integrity and remaining life assessments for the pipeline. Several methodologies are available for the defect acceptance based on Fitness for Purpose (FFP) evaluation and Engineering Critical Assessment (ECA). Both evaluations can provide safe operating limits for a pipeline in terms of maximum allowable operating pressure, fatigue cycling before failure, etc.

The most common framework for defect assessment criteria is based on the Battelle formulas derived from semi-empirical approaches which provide criteria for assessing the resistance of steel pipelines to initiation of fracture from axial defects. The equations are derived from the effective area method equation:

$$\frac{\sigma_f}{\sigma_0} = \frac{1 - d/t}{1 - d/(M \cdot t)} \tag{1}$$

Where σ_f is the failure stress, σ_0 is the flows stress, d is the defect depth, t the pipe wall thickness and M the folias factor for a through wall defect.

When In line inspection data is available, methodology describe in ANSI/ASME B31G[20], modified ASME B31G, and DNV RP-F101[21] can be used for the evaluation of corroded pipelines to determine the failure pressure and the maximum allowable operating pressure of the section with metal loss reported.

The relationship between materials properties and operating conditions during a fracture mechanics analysis applied for pipelines is illustrated in the simplified example below [22]

Assuming the structure design could be based upon the hoop stress:

$$\sigma_h = \frac{pD}{2h} \tag{2}$$

Where σ_h is the hoop stress, p is the internal pressure, D is the mean vessel diameter, and h is the pipe wall thickness. A safe operating pressure could be evaluated by equating σ_h to σ_Y, the material yield stress and by applying a safety factor *S*:

$$p = \left(\frac{2h}{SD}\right)\sigma_Y \tag{3}$$

Now let’s suppose a shallow axial surface crack of depth a exist in the pipeline and by correlating the stress intensity factor, K for an edge-crack plate in tension with the stress intensity factor for fracture initiation K_{IC}/S then a preliminary conservative estimate of the safe operating pressure for a flawed vessel/pipelines can be given as:

$$p = \left(\frac{2h}{SD}\right)\frac{K_{IC}}{1.12\sqrt{\pi a}} \tag{4}$$

In short, the objective of the defect assessment evaluation is to calculate the failure pressure for the metal loss defects, applying a safety factor and comparing the resulting “safe” pressure with the maximum allowable operating or design pressure of the pipeline [23]:

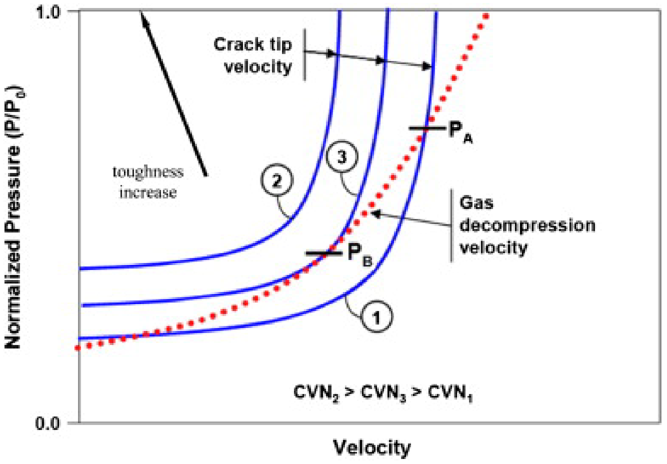
Failure Pressure = P_f
Safety Factor= S
Safe Pressure= P_{safe}
If P_{safe} > MAOP then the defect is acceptable
If P_{safe} < MAOP then the defect is not acceptable

3.2 Strategy for Fracture Propagation Control

Two types of fracture propagation conditions are normally defined in the literature, running brittle fracture (RBF) and running ductile fracture (RDF). The first is no longer a threat for modern steels as they can be design with transition temperatures to ensure their operation regimes is maintained inside the ductile region. To ensure the pipe steel fails in a ductile manner with it is important to ensure the transition temperature of the pipe steel is below the operating temperature of the pipe. When RDF occurs the gas decompression front does not dissipate fast enough and the energy stored is capable of sustaining axial propagation of that rupture. If the crack driving force is greater than the material toughness, the crack will propagate axially through the pipeline. The Battelle two curves semi-empirical analysis has been one of the most popular methods to evaluate dynamic ductile propagating cracks. The method relates the results from full scale burst test with the results obtained from the CVN (Charpy Vee Notch) test. Other testing methods such as drop weight tear test, DWTT, are also used to characterize fracture propagation resistance in terms of percentage shear area transition, CTOD (crack tip opening angle) or the J-Integral.

Figure 4, shoes a schematic representation of the Battelle two curves model (TCM) [25]. Hashemi [24] provides a clear description of the different variables and the evaluation methodology for determining the velocity of a running crack and the rate of pressure decompression at the crack tip. The blue lines indicate three pipes with increasing values of toughness (2 $>$ 3 $>$ 1) and the red line shows the gas decompression behaviour curve. P is the pressure at the crack tip and P_0 is the design pressure of the pipeline. For curve 1, where the two curves overlap, the fracture propagates continuously. In case 2, where the two curves do not intersect, the rate of decompression at the crack tip is higher that the speed of the running crack and fracture arrest occurs. The tangent point for curve 3 can be defined as the equilibrium condition providing the minimum value of toughness for steady crack arrest.

Figure 4. Schematic Representation of TCM [24]



The simple evaluation from the TCM is given in equation 5.

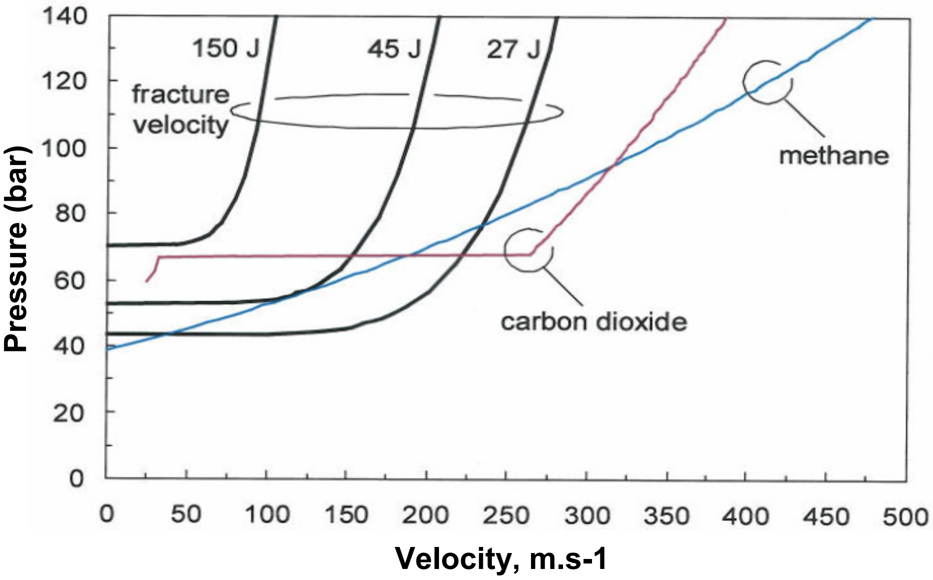
$$CVN = 3.573 \times 10^{-5} \sigma_h^2 \left(\frac{Dt}{2} \right)^{1/3} \qquad (5)$$

Where CVN is the predicted Charpy V-notch energy, σ_h is the applied hoop stress, D and t are pipe diameter and wall thickness respectively. When applied to high strength steels for which the original model was not considered the use of correction factors is becoming the norm to determine the fracture arrest values for high toughness steels (i.e. X70, X80, etc) [25].

3.3 Fracture Arrest and Decompression Behaviour of CO2

Among the best example of the relevance of the TCM to the transport of CO_2 has been presented by Cosham and Eiber [26], the schematic discussed in their paper is presented in Figure 5, in which the toughness values for a series of steel are evaluated for both methane and CO_2 decompressing at the same initial conditions of pressure and temperature. The differences in the decompression curves are due to the differences in thermodynamic behaviour for the different fluids. As can be seen in the curve for CO_2, a plateau region occur when the gas passes the boundary between a liquid and a two phase fluid, this constant pressure is defined as the saturation pressure of CO_2.

Figure 5. Schematic TCM Representation for Methane and CO_2 [27]



The strategy for fracture propagation control involves the evaluation of the balance between the fracture resistance of the material and the crack driving force derived from the decompression energy. Since it is assume the toughness values of the pipeline considered for conversion are known, it is clear that a calculation of the toughness requirements for fracture arrest can be derived from the application of the TCM, when the existing values of propagating toughness in the material are below those derived from the application of the model, it might be necessary to consider the use of mechanical crack arrestors. Please notice that although it is known that backfill can have a significant impact and the propagating velocity and the arrest conditions its effect has not been considered in this review.

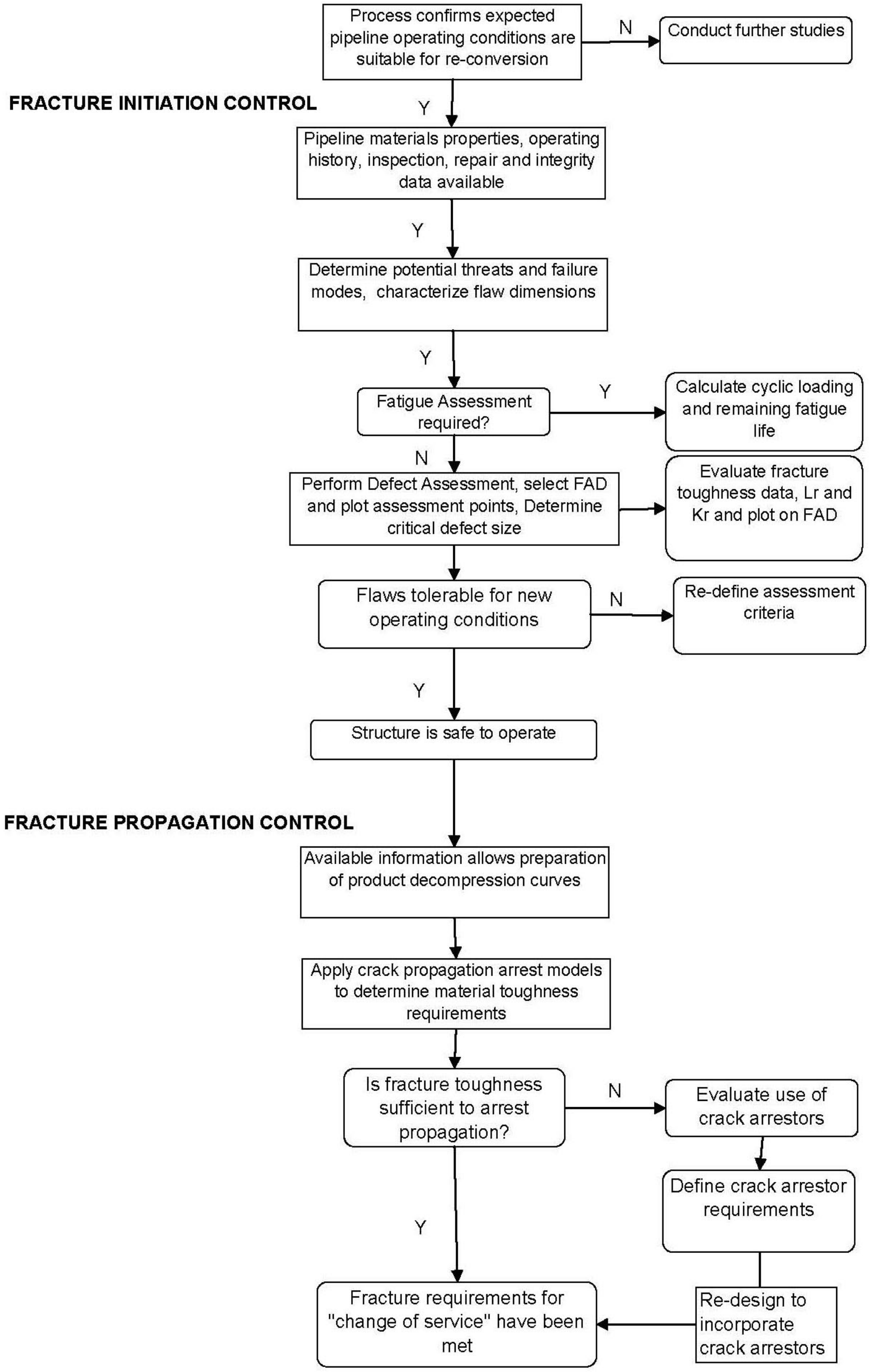
Modelling Crack Arrestor Requirements

The use of crack propagation arrestors can be evaluated with the use of finite elements and computer simulation. Several authors discussed algorithm that could be use to predict the applicability of crack arrestor devices in steel pipelines. These arrestors have the effect of reducing the pipe opening as the crack propagates hence decreasing the crack driving force and assisting crack arrest [27]. In the case of existing pipelines considered for change of service in addition to the requirements for crack arrest an analysis of the operability and installation requirements for the crack arrestors should be carried out to determine if the installation of such aid to control fracture propagation would not become cost prohibitive.

5.0 Methodology for the Development of a Strategy for Fracture Control

A flowchart summarizing the fracture strategy methodology discussed for the determination of the suitability of a pipeline for change of use to transport CO_2 is presented in Figure 6.

Figure 6. Proposed Flowchart for Fracture Strategy



5.0 Risk Assessment

As with any pipeline project a detail risk assessment should be carried at the different stages of the project to ensure the safe and cost effective operation of the pipelines under the new operating conditions. The uncertainties during the preparation of a risk assessment for CO_2 pipelines have been discussed elsewhere[28, 29].

6.0 Knowledge Gaps/ Further Work

Further work is currently being carried out to evaluate the effect of other failure methods on the integrity of the pipeline being investigated for the change of service. Similarly, a review of "*The Applicability of Existing Models to Predict Ductile Fracture Arrest in CO_2 pipelines"* is currently being carried out as part of a wider research programme. Other areas of Interest that required further study before the transport of "captured" CO_2 becomes a reality include among others:

- Materials (both metallic and no metallic)
- Corrosion Assessment
- Flow assurance
- Risk Assessment
- Design Code

The use of CVN to describe fracture toughness and indeed the difficulty in obtaining relevant pipeline fracture toughness measures from standard specimens is currently a hindrance to properly applying advanced fracture mechanics methods to the ECA of pipelines. Constraint, wall thickness, residual stress and loading in ruptured pipelines are often very different to the conditions under which standard fracture toughness tests are carried out and there is therefore a significant amount of work still required before these methods can be properly applied.

7.0 Conclusions

The available literature for transportation of "captured" CO_2 via pipeline focuses on the knowledge transfer from the lessons learned from the CO_2 transportation for enhance oil recovery, EOR, and although the differences between the composition of both product are acknowledged (i.e. level of impurities in CCS CO_2 and the potential routing being close to highly populated areas), the general assumption is that there is enough industry experience to overcome any potential issues during the design, construction and operation of new pipelines. However, the situation is quite not the same when the focus is on the "re-use" of existing pipelines for the transportation of captured CO_2 and more stringent conditions should be applied to ensure the risks and consequences of a pipeline failure are as low as reasonable possible (ALARP).

In this paper, a general conventional methodology for the analysis of fracture arrest during the "change of use" of oil and gas pipelines to transport CO_2 is discussed. A comparison between conventional models to describe the mechanism of fracture initiation, fracture propagation and gas decompression behaviour for the fluid was also discussed. However, there are significant shortcomings in the current application of fracture mechanics for the safe operation of CO_2 pipelines and further work particularly in developing relevant fracture toughness test and assessment methods are needed.

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