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Public abstract

The objective of the task presented in this deliverable report is to synthesise the results of the modelling studies carried out in SP1, SP2 and SP3, focusing on various mitigation and remediation techniques, and carrying out an evaluation of their performance as either threat barriers (for risk reduction) or recovery and preparedness measures (for consequence benefits) that can be achieved. The issues considered were relating to technology specific issues of the techniques, including their implementation costs.

A methodology was proposed to quantify the effectiveness of the techniques in a manner which allows for a comparison of the indicative performance metrics, based on the results of the scenarios that were investigated. The overall performance characterisation was based on five dimensions, as agreed during the course of the project, namely:

- likelihood of success
- spatial extent
- longevity
- response speed
- cost efficiency

The overarching goal is to subsequently feed the outcomes of this report into the on-line remediation selection tool which was developed in parallel under SP5.

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1 INTRODUCTION

1.1 Objective

The overall objective of WP11 is to synthesise the results of CO_2 leakage mitigation/remediation modelling studies carried out during the MiReCOL project and to evaluate their performance as either threat barriers for potential leakage risk reduction, or recovery and preparedness measures for leakage consequence reduction. The technology specific issues of relevant techniques, including their implementation costs, were considered in this deliverable report.

1.2 Bow-tie analysis

A number of projects have adopted the bow-tie analysis for risk management across a variety of business sectors world-wide, and the method has been in widespread use since the mid-1990s. In the bow-tie analysis, a 'top event' is initially identified. In the case of CO_2 storage, this is often an event of leakage from the storage reservoir. The threats such as a leaky fault or injection induced over-pressure, which might trigger the top event, are then identified. The threat barriers, referred to as risk mitigation techniques, are subsequently assessed in order to reduce or eliminate the threat. If the top event is already occurring at the time of analysis, *e.g.* an identified leakage of CO_2 from the storage reservoir, the method considers consequences, such as loss of CO_2 storage permanence or environmental impacts and, using consequence barriers, aims to limit such adverse impacts. Thus, the bow-tie diagram also facilitates the assessment of recovery and preparedness measures, referred to as remediation techniques, in order to reduce the severity of the consequences. Figure 1 illustrates the bow-tie diagram for WP11, indicating all the techniques that were investigated under the scope of the MiReCOL project.

1.3 Assessment methodology

In order to evaluate the mitigation and remediation techniques, the results that were presented previously in the MiReCOL project SP1 to SP3 deliverable reports were analysed. In particular, the quantification of effectiveness of a technique is generally based on either: (a) the delay achieved in the arrival time of the CO_2 plume at the location of a potential threat, *e.g.* leaky faults or fractures; (b) the reduction in amount of CO_2 that could migrate beyond the reservoir spill point; (c) the reduction in amount of CO_2 that may leak through sub-seismic fractures in the caprock into a shallower formation; (d) the reduction in the reservoir pressure which could potentially induce or exacerbate leakage; or (e) the enhancement of the dissolution of injected CO_2 in the reservoir brine to either reduce the local pressure or the amount of CO_2 that may leak.

1.3.1 Success probability estimation

The results obtained for the effectiveness were pooled to generate cumulative probability plots that allow for the quantification of the expected values of success of the implementation of the techniques, however, conditioned only on the mitigation and remediation scenarios that were detailed in the different SP1 – SP3 work packages. It is also important to note that in the mitigation case, the implementation could either improve, or unexpectedly make matters worse, and hence the mitigation effectiveness could range between negative (not effective) and positive (effective) values, whereas for

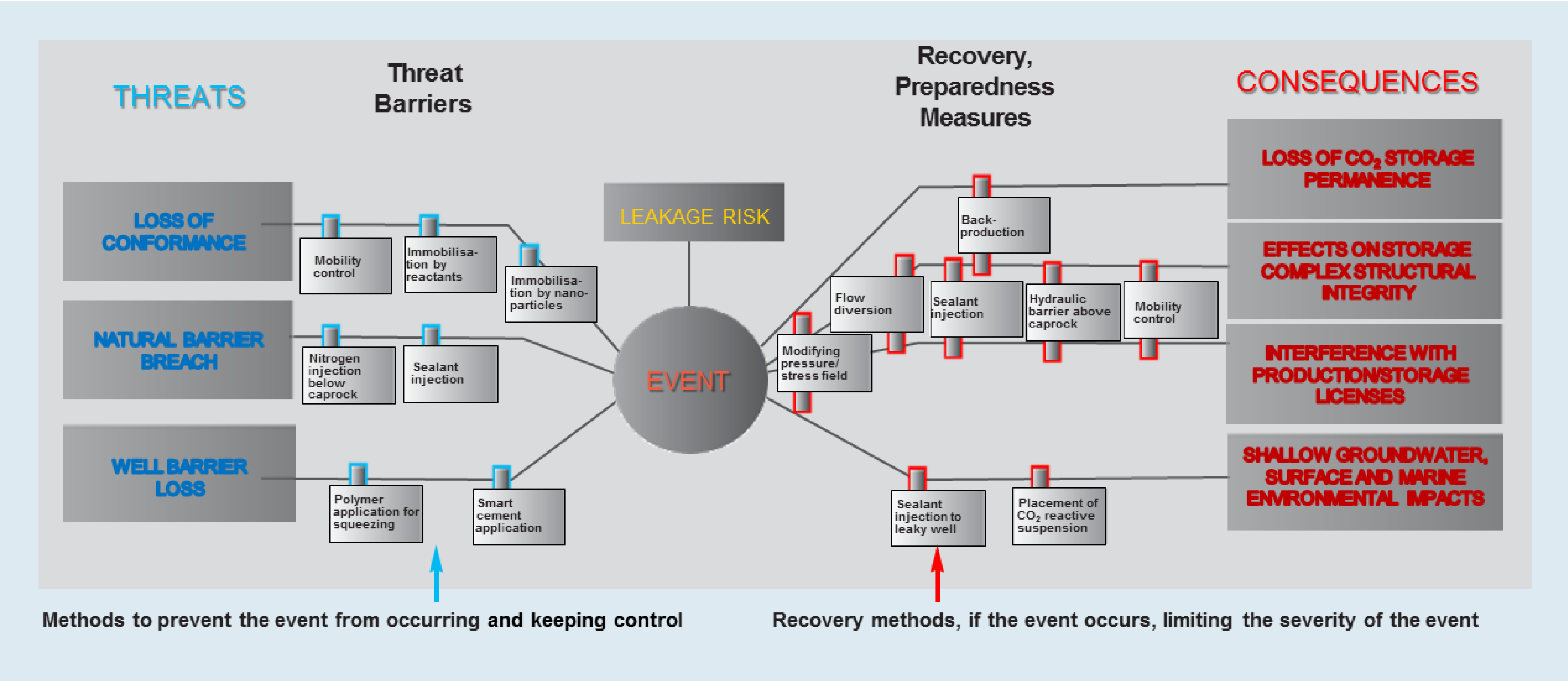


Figure 1. The bow-tie diagram for the MiReCOL project.

the remediation case, effectiveness values were assumed to be strictly non-negative.

1.3.2 Overall performance characterisation

Furthermore, the scoring/ranking of individual techniques was implemented using an ordinal classification (low, medium and high) in five dimensions, namely: (a) likelihood of success (see Table 1); (b) spatial extent (see Table 2); (c) longevity (see Table 3); (d) response speed (see Table 4); and (e) cost efficiency (see Table 5), based on the results that were obtained for different scenarios.

Table 1. . Classification of the likelihood of success dimension.

Rank	Likelihood of Success (%)
Low	0 - 33
Medium	34 - 66
High	67 - 100

Table 2. . Classification of the spatial extent dimension.

Rank	Spatial Extent (km^2)
Low	0 - 1
Medium	1 - 5
High	> 5

Table 3. . Classification of the longevity dimension.

Rank	Longevity (years)
Low	0 - 1
Medium	1 - 10
High	>10

Table 4. . Classification of the response speed dimension.

Rank	Response Speed (years)
Low	>1
Medium	0.1 - 1
High	0 - 0.1

Table 5. . Classification of the cost efficiency dimension.

Rank	Cost Efficiency (M€)
Low	> 10
Medium	1 - 10
High	0 - 1

Despite being a qualitative output, the resulting spider chart outputs represent the best efforts that could possibly be made to standardise the scales in different dimensions in order to ensure that it is indicative of the overall merit of a given technique, and also allowing for making a comparison between techniques.

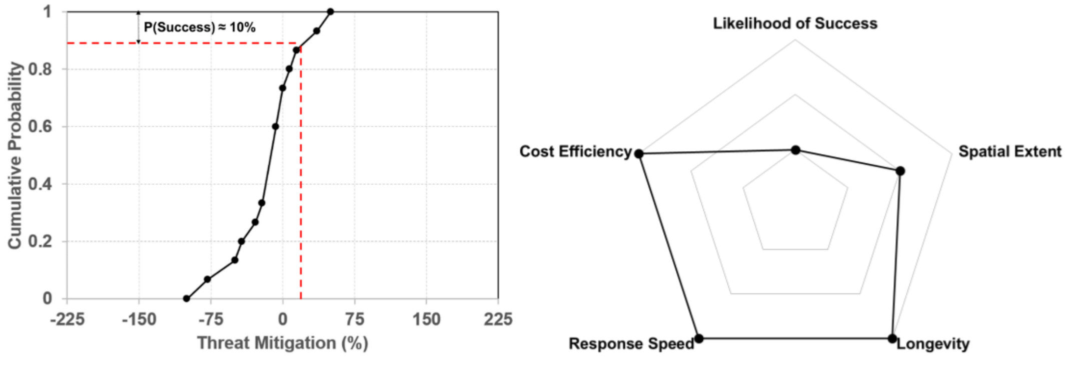
2 ASSESSMENT OF THE CONSEQUENCES RELATED TO MITIGATION TECHNIQUES

2.1 Adaption of injection strategy to control the migration of CO2 plume in the reservoir

The selection of an appropriate CO_2 injection strategy offers the potential for increasing both the safety and longevity of containment in the storage reservoir. It can potentially prevent, or at least retard, CO_2 from arriving at and passing through (pre-defined) undesired migration paths, such as faults, fracture zones or spill points. By doing this, it may also decrease the necessity for active remediation, such as gel and foam injection, brine injection or chemical immobilisation of CO_2, at a later stage of the storage cycle. Therefore, selection of an injection strategy as a proactive measure would be cost efficient when compared to the implementation of an active remediation technique.

The impact of threat mitigation through the variation of injection location and rate, taking into account of the geological conditions, were investigated by GFZ at the Ketzin site, Germany. The results were discussed in detail in deliverable D3.2.

In order to quantify the success of the adaptation of injection strategy in threat mitigation, *i.e.* the percentage of delay achieved in the simulated time taken for the plume to arrive at undesired migration pathways that potentially result in CO_2 leakage, a cumulative probability plot was generated by pooling the results obtained for all the scenarios that were considered. Figure 2a illustrates that if the desirable mitigation level is assumed to be 20% or greater, then the probability of success for threat mitigation is only 10%. Moreover, the probability of occurrence of a situation worse than the baseline scenario (when no mitigation is implemented, corresponding to 0% threat mitigation level) is approximately 75%, which additionally undermines the applicability of the technique in the given context. Figure 2b illustrates a summary of the outcomes of the technique considering all the dimensions.



(a) (b)

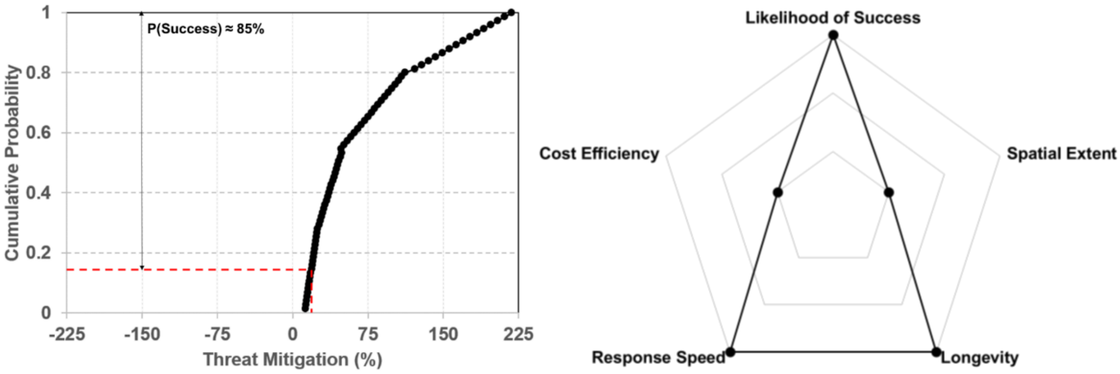
Figure 2. Adaptation of injection strategy technique: (a) success probability; (b) spider chart.

2.2 Novel approaches to lower reservoir pressure by accelerating convective mixing between brine and CO2

The possibility for enhancing the dissolution of CO_2 in brine was investigated with a view that it: (a) potentially lowers the pressure of the reservoir during CO_2 injection; and (b) ensures that CO_2 would no longer migrate as a separate phase, and thus restricted to the migration of reservoir brine which is relatively much slower owing to its higher density. In order to enhance CO_2 dissolution during the injection phase, the co-injection of CO_2 with nanoparticles (NPs) to enhance convective mixing was considered. The proposed method enhances the natural process of convective mixing by increasing the density of the CO_2-saturated brine by using NPs. Heavy NPs (e.g. metals and/or metal oxides, which are in the order of 1-50 nm in size) move into the brine together with the CO_2, which increases the density of the CO_2-saturated brine which results in an increased rate of convective mixing.

To evaluate the feasibility of using NPs for remediation and/or mitigation, TNO evaluated to two aspects, namely: (a) the placement of NPs; (b) the quantification of enhancement of convective mixing, thereby increasing the dissolution of CO_2 into the brine. For the first aspect, investigations included the simulation of the injection of a mixture containing NPs at the interface between the CO_2 and brine in the reservoir. The main question addressed by the NPs placement simulation was relating to the acceptable density of the NP-CO_2 mixture for injection. It was concluded that a homogeneous mixture would be heavier than CO_2, but lighter than brine. If the mixture is too heavy, then it would move into the brine and not spread on the interface. On the other hand, if the mixture is too light (*i.e.* density difference with the CO_2 is small), the spreading would not be efficient. Furthermore, for the second aspect, a situation was assumed wherein a mixture of free CO_2 and NPs layer is present on top of brine (both are assumed stationary). Equations from the literature for the estimation of CO_2 dissolution resulting from convective mixing were implemented. The results obtained were discussed in detail in deliverable D4.5.

In order to quantify the success of the NP injection in threat mitigation, *i.e.* the percentage increased CO_2 dissolution into reservoir brine for the simulated time, a cumulative probability plot was generated by pooling the results obtained for all the scenarios that were considered. Figure 3a illustrates that if the desirable mitigation level is assumed to be 20% or greater, then the probability of success for threat mitigation is 85%. In addition, it is observed that the minimum threat mitigation level is 10%, suggesting that there is a noticeable improvement from the baseline scenario. Figure 3b illustrates a summary of the outcomes of the technique considering all the dimensions.



(a) (b)

Figure 3. Acceleration of convective mixing technique: (a) success probability; (b) spider chart.

2.3 Smart cement with a latex-based component for mitigation of potential well leakage

Although the capacity and injectivity of a geological formation plays an important role in its consideration for CO_2 storage, the prevailing confinement conditions are also necessary. If, however, the formation meets all the required conditions, the only potential means of CO_2 leakage should theoretically be via the wellbore. Wellbores have been identified as the most likely pathways of leakage at a CO_2 storage site. Multiple leakage pathways could be associated with the wellbore that are often formed due to inadequate well completion, or the use of unstable wellbore materials in a CO_2-rich setting. The proposed method using smart cement presents a novelty in the mitigation of the risk of CO_2 leakages from deep reservoirs via wellbores. Imperial College investigated the use of latex-based smart cement for the purpose of CO_2 leakage mitigation at the wellbore. The main objectives were: (a) to investigate the effectiveness of smart cement in the mitigation of leakage either through the casing-cement or casing-rock interfaces, or through the fractures within the cement itself; (b) to characterise the latex-cement mixture for its permeability, mechanical behaviour and strength using core samples; (c) to characterise the permeability of latex-cement under deep reservoir conditions by subjecting samples of the latex-cement to CO_2 flow using Imperial College's wellbore cell; (d) to compare stress-permeability behaviour of the microannulus of the latex-cement with that of Class G Portland cement. The experimental observations of permeability, mechanical properties and sealing characteristics of the latex-cement cement was subsequently used as an input to a wellbore numerical model to study the effectiveness of remediation through the use of latex-cement for overall integrity of CO_2 storage. The results obtained were discussed in detail in deliverable D9.4.

In order to quantify the success of smart cement implementation in threat mitigation, *i.e.* the percentage of the amount of leakage reduction achieved, should leakage unexpectedly occur within the simulated time periods, a cumulative probability plot was generated by pooling the results obtained for all the scenarios that were considered. Figure 4a illustrates that if the desirable mitigation level is assumed to be 20% or greater, then the probability of success for threat mitigation is 70%. In addition, it is estimated that the probability of occurrence of a situation worse than the baseline scenario is approximately 20%. Figure 4b illustrates a summary of the outcomes of the technique considering all the dimensions.

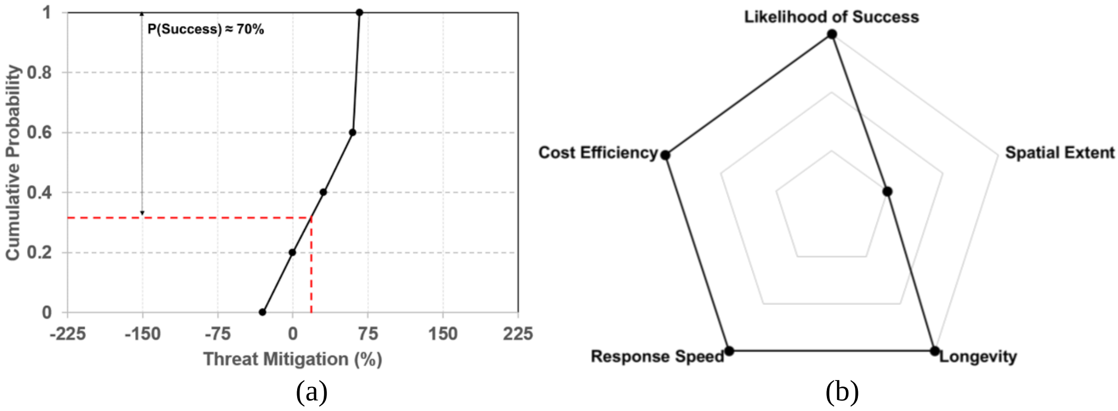


Figure 4. Smart cement wellbore technique: (a) success probability; (b) spider chart.

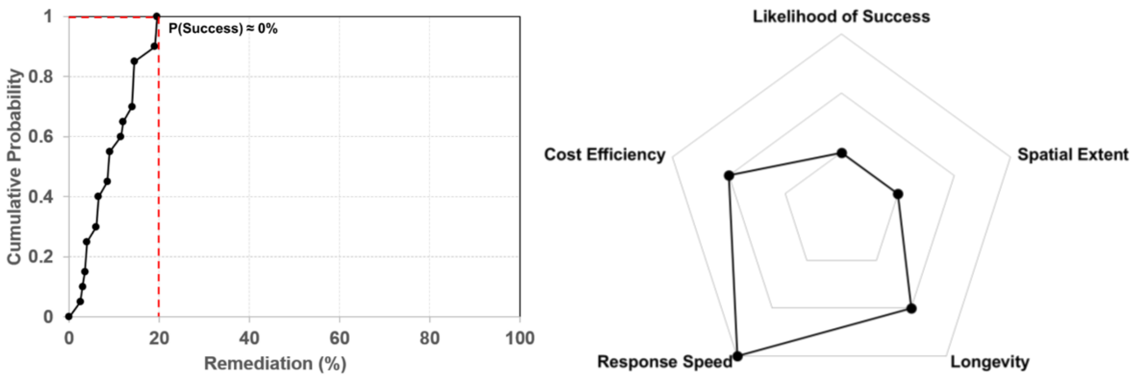
3 ASSESSMENT OF THE CONSEQUENCES RELATED TO REMEDIATION TECHNIQUES

3.1 Options to enable the flow diversion of CO_2 plume

3.1.1 Foam injection

Foam is used in the oil and gas industry for mobility control of gas sweep during enhanced oil recovery. The desired effect is to reduce the mobility of the gas, forcing the injected gas to take alternative paths thus contacting more oil as well as delaying gas breakthrough in the production wells. Foam is also used to reduce gas coning/cresting at production wells. In the current context, foam injection was investigated by SINTEF as a technique to remediate CO_2 leakage, in the event of an unexpected migration of the plume in the reservoir. It primarily involves the injection of a solution comprising of surfactant and brine in the reservoir. The solution reacts with the CO_2 in-place leading to the generation of foam, which causes the reduction in the mobility of the CO_2, thereby minimising potential leakage. The plugging effect of foam treatment depends on several factors, including the reservoir geology, position and type of leakage, injected surfactant volumes, surfactant concentration, adsorption, foam strength and foam stability. The main purpose of the study was to explore the ranges of some of these factors and to quantify their impact on a leakage event. The results obtained were discussed in detail in deliverable D3.3.

In order to quantify the success of foam injection for leakage remediation, *i.e.* the percentage of the amount of leakage reduction achieved after the detection of occurrence of an unexpected leakage within the simulated time periods, a cumulative probability plot was generated by pooling the results obtained for all the scenarios that were considered. Figure 5a illustrates that if the desirable remediation level is assumed to be 20% or greater, there is a nil probability of success for leakage remediation. The threshold remediation level to measure success, however, is dependent on the cumulative amount of CO_2 that is injected prior to leakage detection. In other words, a higher threshold is desirable if a large amount is injected into the reservoir, representing a conservative measure of success. More specifically, in the scenarios considered, the cumulative amount of CO_2 injected is 7.5Mt and the amount leaked beyond the spill point is approximately 4Mt. Hence, a higher threshold remediation level (>20%) would be desirable. Figure 5b illustrates a summary of the outcomes of the technique considering all the dimensions.



(a) (b)

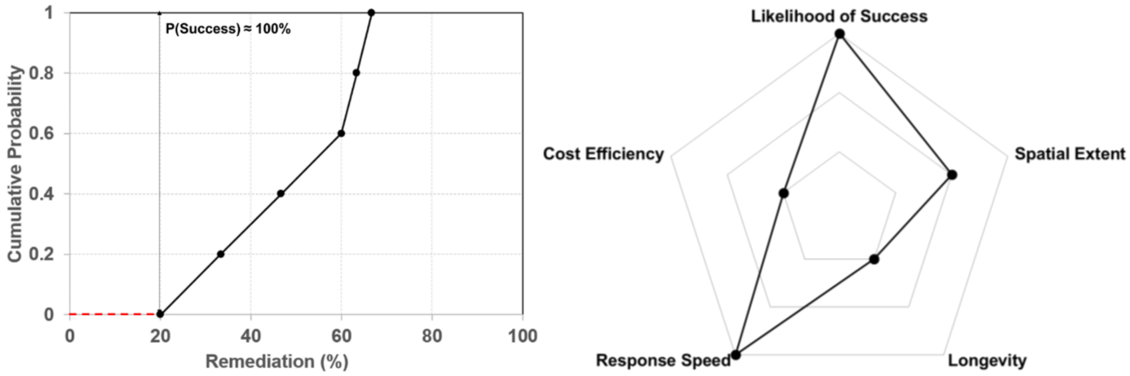
Figure 5. Foam injection technique: (a) success probability; (b) spider chart.

3.1.2 Polymer-based gel injection

Cross-linked hydrolysed polymer-gel injection is used in petroleum industry to improve conformity of fluid flow in the reservoir, remediate leakage around wells, and also used in conjunction with enhanced oil recovery at various temperature and pressure conditions. Water-based gels are highly elastic semi-solids with high water content, trapped in the three-dimensional polymer structure of the gel. Polyacrylamide (PAM) is the main cross-linked polymer used mostly by the industry. The use of biopolymers is more challenging as compared to the synthetic polymers due to chemical degradation at higher temperatures, causing the loss of mechanical strength. Most of polymer-gel systems are based on crosslinking of polymers with a heavy metal ion. The most commonly used heavy metal ion is chromium III. However, in view of its toxicity and related environmental concerns, its application in reservoir conformance and CO_2 leakage remediation is considered to be limited. Therefore, more environmental friendly crosslinkers such as boron, aluminium and zirconium have been proposed and used in recent years.

Imperial College used numerical simulators to implement the known interaction properties of polymer solution and crosslinkers using data from the literature and laboratory tests. The effect of reservoir permeability, polymer and crosslinker concentrations, pH and gelation kinetics were investigated. The property-based results were further translated into the simulation of scenarios for CO_2 leakage remediation using polymer-gel injection in the reservoir. The results obtained were discussed in detail in deliverable D6.3.

In order to quantify the success of polymer-gel injection for leakage remediation, *i.e.* the percentage of the amount of leakage reduction achieved after the detection of occurrence of an unexpected leakage within the simulated time periods, a cumulative probability plot was generated by pooling the results obtained for all the scenarios that were considered. Figure 6a illustrates that if the desirable remediation level is assumed to be 20% or greater, there is a 100% probability of success for leakage remediation. The high success probability in this case is only indicative and, as highlighted for foam injection in the previous section, is dependent on the cumulative amount of CO_2 that is injected prior to leakage detection. Figure 6b illustrates a summary of the outcomes of the technique considering all the dimensions.



(a) (b)

Figure 6. Polymer-gel injection technique: (a) success probability; (b) spider chart.

3.1.3 Brine/Water injection

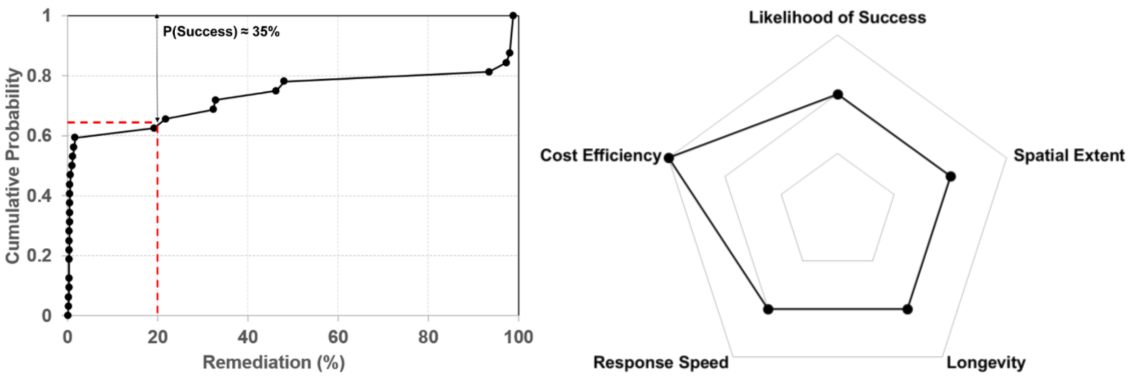
In secondary oil recovery, brine or water injection has a long history either to support reservoir pressure or to displace oil towards producing wells. There is a range of techniques and theories (*e.g.* Buckley Leverett analysis) about how water injection can be used to increase oil recovery. Volumetric sweep management and realignment of production in contiguous layers are the nearest analogues in the oil industry to the use water injection in order to stop the migration of CO_2. Industry has studied several mechanisms by which water injection can be used to reduce CO_2 migration, such as: (1) creating a high pressure barrier in front of the migrating CO_2 plume; (2) chasing CO_2 with brine ensuring storage security; and (3) injecting water directly into the advancing CO_2 plume.

Three different examples of water injection remediation have been investigated by the project partners, listed as follows:

- SINTEF used a portion of the Johansen formation as the basic model with water injection in front of the CO_2 migration plume. The model was modified to represent the key characteristics of twenty other possible CO_2 storage aquifers.
- Using a generic model, Imperial College studied the reduction of CO_2 leakage through a sub-seismic fault by means of water injection via the well previously used for CO_2 injection.
- TNO also used the Johansen model to simulate ten alternative scenarios using a combined approach of water injection and CO_2 back-production as remediation measures.

The results obtained were discussed in detail in deliverable D3.4.

In order to quantify the success of brine/water injection for leakage remediation, *i.e.* the percentage of the amount of leakage reduction achieved after the detection of occurrence of an unexpected leakage within the simulated time periods, a cumulative probability plot was generated by pooling the results obtained for all the scenarios that were considered. Figure 7a illustrates that if the desirable remediation level is assumed to be 20% or greater, the estimated probability of success for leakage remediation is 35%. A summary of the outcomes of the technique considering all the dimensions is illustrated in Figure 7b.



(a) (b)

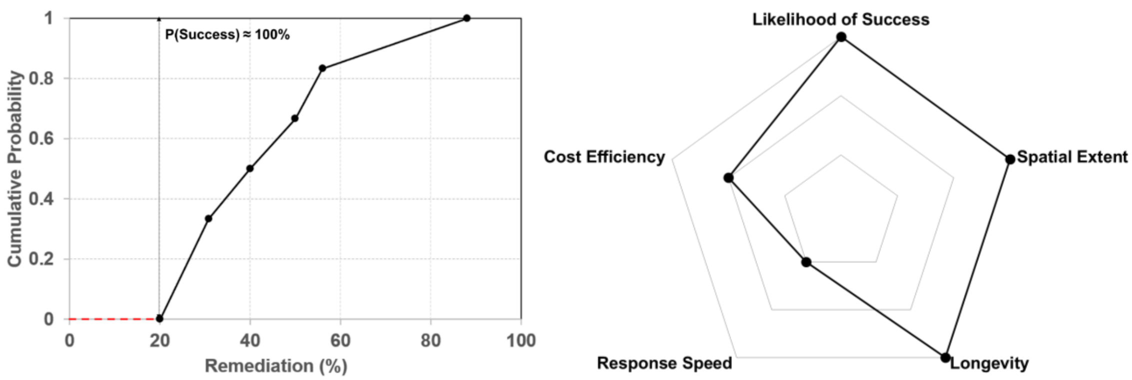
Figure 7. Brine/water injection technique: (a) success probability; (b) spider chart.

3.1.4 Brine/Water withdrawal

The over-pressurisation of the reservoir during CO_2 injection is of concern because it could have a large-scale impact, namely interference with the operations in neighbouring oil and gas fields, or CO_2 storage sites that could co-exist in the same formation. Such interference also has regulatory implications since issuing permits to operators would then be based on the outcome of a multi-site process evaluation, which can be quite involved, and rather unnecessary. In the literature, it was demonstrated that by producing brine from the reservoir, the pressure-driven leakage was minimised and consequently the net of amount of leakage is largely buoyancy-driven, thus reducing the rate of leakage. While pressure management via brine extraction is not be considered a mandatory component for large-scale CO_2 storage projects, it could also potentially provide many other benefits, such as increased storage capacity utilisation, simplified permitting, smaller area of review for site monitoring, and the manipulation of CO_2 plume in order to increase its sweep efficiency.

Imperial College investigated the technique using numerical simulations of CO_2 storage and leakage remediation for an offshore and compartmentalised depleted gas reservoir, called the P18-A block (in the Dutch offshore region). The scenarios considered the study of a cluster of gas fields in the reservoir in order to understand the plume migration and reservoir pressure response during CO_2 injection, and the remediation achieved using brine withdrawal in terms of flow diversion and pressure relief. The results obtained were discussed in detail in deliverable D4.4.

In order to quantify the success of brine/water withdrawal for leakage remediation, *i.e.* the percentage of the amount of leakage reduction achieved after the detection of occurrence of an unexpected leakage within the simulated time periods, a cumulative probability plot was generated by pooling the results obtained for all the scenarios that were considered. Figure 8a illustrates that if the desirable remediation level is assumed to be 20% or greater, the estimated probability of success for leakage remediation is 100% (indicative). A summary of the outcomes of the technique considering all the dimensions is illustrated in Figure 8b.



(a) (b)

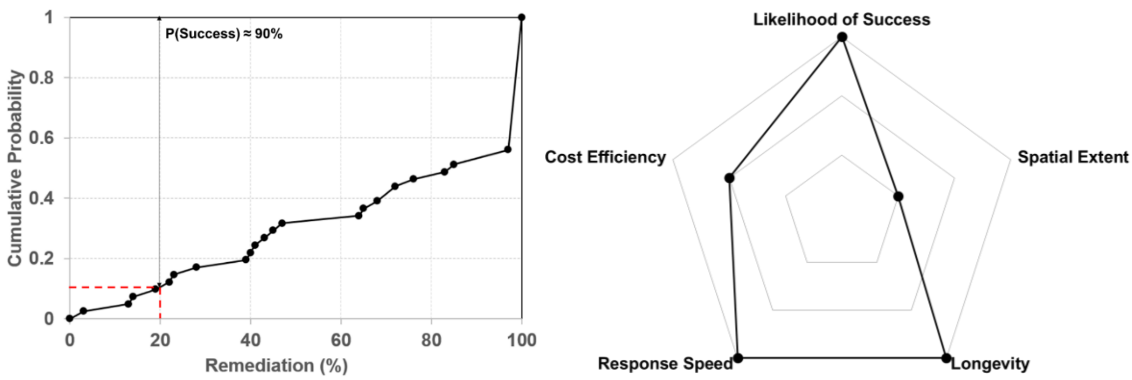
Figure 8. Brine/water withdrawal technique: (a) success probability; (b) spider chart.

3.2 Blocking of CO_2 movement by immobilisation of CO_2 in solid reaction products

Experience with unintentional precipitation or scaling and formation damage, as commonly encountered in the oil and gas or geothermal industries, sheds some light onto the possibilities for forming solid reactants. Minerals observed to form 'naturally' within the reservoir may all be potential candidates for controlled precipitation. Frequently occurring scales associated with oil and gas production are calcite, anhydrite, barite, celestite, gypsum, iron sulphide and halite. Re-injection of production water is prone to scaling of calcium carbonate, while strontium, barium and calcium sulphates are more relevant for seawater injection. In addition to fluid-fluid reactions, fluid-gas interaction could promote mineralisation. Controlled intentional clogging due to salt precipitation, which occurs when the solubility is exceeded by the evaporation into injected dry gas, could potentially prevent the leakage of CO_2. This process is similar to salt scaling in natural gas and oil production, and CO_2 injection in saline aquifers and depleted gas fields.

TNO investigated scenarios to study the feasibility of injecting a lime-saturated solution as a CO_2-reactive solution above the caprock, at the location where the leakage has been detected. The solution has a low viscosity which simplifies the injection process. The results derived for the injection of the lime-saturated solution provided a general insight in leakage remediation using non-swelling CO_2 reactive substances. However, the production and practical use of such a fluid was beyond the scope of the study. The results obtained were discussed in detail in deliverable D3.5.

In order to quantify the success of the injection of CO_2-reactive lime-saturated water investigated in this project, *i.e.* the percentage of the amount of leakage rate reduction achieved after the detection of occurrence of an unexpected leakage within the simulated time periods, a cumulative probability plot was generated by pooling the results obtained for all the scenarios that were considered. Figure 9a illustrates that if the desirable remediation level is assumed to be 20% or greater, the estimated probability of success for leakage remediation is 90%. A summary of the outcomes of the technique considering all the dimensions is illustrated in Figure 9b.



(a) (b)

Figure 9. Polymer-gel injection technique: (a) success probability; (b) spider chart

3.3 CO_2 back-production

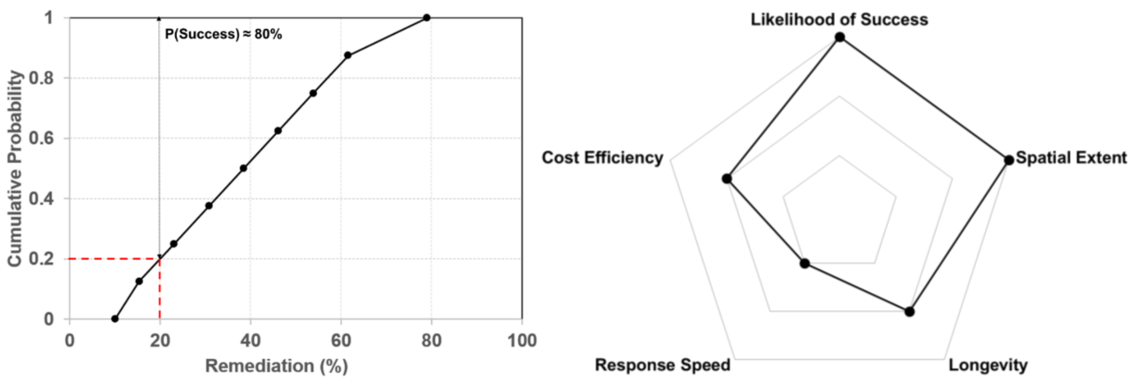
The back-production of formerly injected CO_2 may provide a suitable technique to: (1) mitigate undesired migration of CO_2 in the reservoir by inducing a pressure-gradient driven directed flow of CO_2; and (2) manage the reservoir pressure. Furthermore, the production of CO_2 will also form an integral part of any temporary storage of CO_2 in the frame of a different carbon capture storage and utilisation and/or power-to-gas concepts. In CO_2 storage combined with enhanced hydrocarbon recovery, CO_2 will be co-produced with the recovered hydrocarbons. The production ratio of gas to reservoir fluid is an important design parameter in all contexts. Below a minimum flow velocity in a well, the critical Turner velocity, no fluid is produced, and hence well load up (cone shaped brine accumulation) occurs.

The CO_2 back-production technique was investigated in this project using case studies based on two examples, each an offshore and onshore site, listed as follows:

- GFZ and Imperial College jointly carried out numerical studies prior to and after the Ketzin pilot field test to support its design and demonstrate the performance of the history-matched backproduction model, and thereby estimate the expected reduction in reservoir pressure achieved.
- TNO carried out a case study for the K12-B gas field in the North Sea to investigate the back-production technique. Numerical analyses focused on key factors such as recovery rate, CO_2 ratio, well pressure and water co-production.

The results obtained were discussed in detail in deliverable D4.3.

In order to quantify the success of CO_2 production technique, *i.e*. the percentage of the reduction in reservoir pressure achieved within the simulated time periods as an indirect indicator for potential leakage reduction, a cumulative probability plot was generated by pooling the results obtained for all the scenarios that were considered. Figure 10a illustrates that if the desirable remediation level is assumed to be 20% or greater, the estimated probability of success for potential leakage remediation is 80%. A summary of the outcomes of the technique considering all the dimensions is illustrated in Figure 10b.



(a) (b)

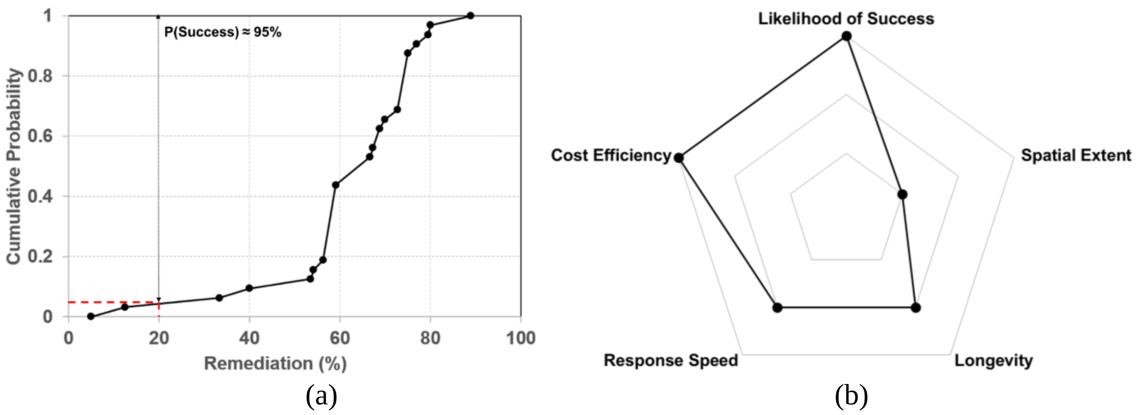
Figure 10. CO_2 backproduction technique: (a) success probability; (b) spider chart.

3.4 Hydraulic barrier

It has been suggested that injection of brine above the caprock, at a higher pressure than the CO_2 pressure in the reservoir, would create an inverse pressure gradient to reverse the flow direction and increase the solubility of CO_2 in the saline water barrier formed, and prevent or limit leakage. Furthermore, coupled with fluid management procedures during aquifer storage (saline water extraction and re-injection above the caprock), this can also be used to minimise displacement and migration of native brine, and avoid pressure build up in closed or semi-closed structures.

Imperial College investigated the effectiveness of pressure gradient reversal (PGR), a hydraulic barrier technique, as a potential remediation technique for CO_2 leakage from deep saline aquifers using a generic and geologically realistic model, comprising of the reservoir, caprock and an overlying shallow aquifer. The focus was on the role of controlling parameters which may affect the success or failure of the hydraulic barrier technology considered. The results obtained were discussed in detail in deliverable D7.3.

In order to quantify the success of the hydraulic barrier technique, *i.e.* the percentage of the amount of leakage rate reduction achieved after the detection of occurrence of an unexpected leakage within the simulated time periods, a cumulative probability plot was generated by pooling the results obtained for all the scenarios that were considered. Figure 11a illustrates that if the desirable remediation level is assumed to be 20% or greater, the estimated probability of success for leakage remediation is 95%. A summary of the outcomes of the technique considering all the dimensions is illustrated in Figure 11b.



(a) (b)

Figure 11. Hydraulic barrier technique: (a) success probability; (b) spider chart.

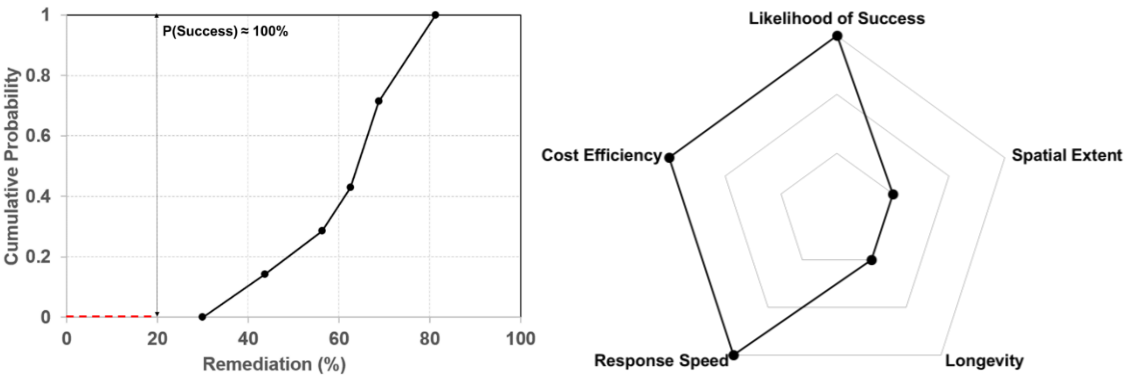
3.5 Polymer-gel-based sealant injection

3.5.1 Well leakage remediation

The use of synthetic and biopolymer solutions by the petroleum industry has been mostly associated with enhanced oil recovery and widely used around the world. For polymer-gel compounds (usually crosslinked with a heavy metal), the application is considered for water-cut and flow conformance control within the reservoir as well as leakage remediation in the near wellbore area. The polymer solution is composed of molecular chains of the chosen polymer, a carrier fluid such as water or brine, and a crosslinker such as chromium III, zirconium, and aluminium. Polymers are made of coiled chains, especially of high molecular weight polymers. Once they are added into solution, the charged areas on the chain repel each other and force the chain to uncoil. As a result, the viscosity of the solution increases. Generally, the charge also affects the speed at which the chain uncoils. The higher charged polymers will uncoil faster, whereas, non-ionic polymers may never fully uncoil since they carry no charge.

Imperial College carried out both laboratory tests and numerical simulations in order to understand the effectiveness of polymer-gel treatment on the permeability reduction of wellbore cement, thereby effectively minimising CO_2 leakage through a microannulus between cement and casing interface, and in near wellbore region of the host/caprock. In particular, deep, high temperature and high pressure reservoir conditions were considered for the simulations. The results obtained were discussed in detail in deliverable D9.3.

In order to quantify the success of the use of polymer-gel based sealant injection for wellbore leakage remediation, *i.e.* the percentage of the amount of leakage reduction achieved after the detection of occurrence of an unexpected leakage within the simulated time periods, a cumulative probability plot was generated by pooling the results obtained for all the scenarios that were considered. Figure 11a illustrates that if the desirable remediation level is assumed to be 20% or greater, the estimated probability of success for leakage remediation is 100% (indicative). A summary of the outcomes of the technique considering all the dimensions is illustrated in Figure 11b.



(a) (b)

Figure 12. Polymer-gel sealant injection technique: (a) success probability; (b) spider chart.

3.5.2 Caprock leakage remediation

Additionally, polymer-gel injection above the caprock (in an assumed shallow aquifer) to seal fractures was investigated by Imperial College in deliverable D6.3. The results obtained suggest that the performance outcomes of the technique are similar to those presented previously in section 3.1.2.

4 CONCLUSION

In this deliverable report, a methodology for assessing the overall performance of various techniques that were investigated under the scope of the MiReCOL project was discussed. Based on the bow-tie analysis approach, the techniques were broadly placed under two groups. The techniques that deal with a potential threat (or risk), such as a leaky fault or injection induced over-pressure, were referred to as mitigation techniques that reduce or eliminate the threat. On the other hand, those that deal with the consequences of leakage, such as loss of CO_2 storage performance or environmental impacts, were referred to as remediation techniques that reduce the severity of the consequences.

In order to standardise the assessment for the two groups of techniques, five performance metrics (dimensions) were considered, namely: (a) likelihood of success; (b) spatial extent; (c) longevity; (d) response speed; and (e) cost efficiency. The results obtained from the scenarios analysed for each technique in the MiReCOL project were used to classify (or rank) the performance of the technique based on these dimensions, leading to overall performance outcomes in the form of probability plots and spider chart visualisations.

Such visualisation tools are considered to be particularly useful in facilitating the general comparison between techniques, or choosing a portfolio of techniques, for operators dealing with a situation where CO_2 storage security may be compromised in the field. In view of this, the project aimed to use the results presented in this report to design a portfolio optimisation protocol to enable the selection of a subset of techniques for a given leakage scenario. Moreover, the purpose is also to subsequently feed the outcomes of this report into an on-line remediation selection tool which has been developed in parallel under SP5.