CO_2CARE

CO_2 Site Closure Assessment Research

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D4.12 Plan for risk management supporting site abandonment

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Executive Summary

Risk Management in the context of closing and abandoning a CO_2 storage site encompasses all the measures required to demonstrate the long-term safety of a CO_2 storage site. The latter represents a pre-condition to transfer the responsibility for the abandoned site from the operator to the Competent Authority (CA) on a national level.

The aim of this study was to establish a corresponding risk management plan covering the requirements of the EC Directive on the geological storage of carbon dioxide (DIRECTIVE 2009/31/EC) and the OSPAR Guidelines. The timeline considered by this plan encompasses the final injection period within the operational phase as well as the post-closure/pre-transfer and post-transfer period of a storage project.

Before such a transfer can be approved it is required that

a) all available evidence indicates that the stored CO_2 will be completely and permanently contained,

b) the financial obligations have been fulfilled,

c) the site has been sealed and the injection facilities have been removed.

Before the transfer of responsibility can be approved by the CA, the operator has to demonstrate

a) the conformity of the actual behaviour of the injected CO_2 with the modelled behaviour,

b) the absence of any detectable leakage,

c) the storage site is evolving towards a situation of long-term stability.

Within this study a milestone chart in accordance to given EC regulations has been developed to facilitate an industrially applicable procedure for risk management measures in the context of responsibility transfer and abandonment of a CO_2 storage site. The chart consists of 17 milestones, which have been specifically allocated to the different phases and sub-phases of the timeline of CO_2 storage site, specifically during the final operational and post-closure phases. The developed milestone chart has been evaluated for the K12-B CO_2 injection site, the findings of which have been used for updating the milestone chart.

Monitoring is an essential element in risk management, also in the post-operational phase. Appropriate site-specific monitoring measures are to be set up during the licensing procedure for a CO_2-storage site, which establishes the starting-point for demonstrating how the requirements for the transfer of responsibility can be met.

DIRECTIVE 2009/31/EC and its Guidance Documents (GD) propose minimum periods to fulfil certain key criteria, which are not based on any scientific fundament, such as:

- a default period of 20 years after site closure for the transfer of responsibility for a CO_2 storage site; this time span can be reduced, if the long-term safety of the site could be sufficiently proven in a shorter period (DIRECTIVE),
- a minimum period of absence of leakage of 10 years immediately before the time of transfer (GD),

- for at least 5 years before the transfer, the 3D static geological model does not need any significant update (GD),
- the monitoring plan shall be updated in any case every 5 years (DIRECTIVE).

It is recommended that the decision if a criterion for the safety of a site has been met should be based on technical aspects only and should not be linked to prescriptive time spans.

Instead, a post-operational CO_2 storage site should be sealed as soon as possible after all criteria for the transfer have been fulfilled and the Competent Authority is convinced of the long-term integrity of the storage site. The definition of *criteria* for responsibility transfer and abandonment are included in a separate CO_2CARE document.

1. Introduction

The EC Directive on the geological storage of carbon dioxide (DIRECTIVE 2009/31/EC; herein also referred to as EC Storage Directive, EC 2009) has put forward a series of requirement for the safe storage of CO_2. According to the Directive the responsibility for the storage site can be transferred from the operator to the state, represented by a Competent Authority (CA), if specified safety criteria have been fulfilled and a certain timespan after site closure has elapsed (suggested are a minimum of 20 years after site-closure).

The purpose of this document is to outline a plan for risk management for the final phase of operational phase and the post-closure/pre-transfer phase of a CO_2 storage site.

The development of the plan for risk management supporting site abandonment reported in this study has been mainly based on the regulatory framework of the EC Storage Directive, the related EC Guidance Document 3 (EC 2011a) and the OSPAR Guidelines, providing scientific input for practical implementation of risk management measures specifically required in the mentioned project phases.

In this document Section 2 will review the requirements of the EC Storage Directive for the responsibility transfer of a CO_2 Storage site back to the state with particular focus on risk management demands and on which criteria have to be fulfilled.

Section 3 describes the timeline of a CO_2 storage project and explains the different project phases with special focus on the phases relevant for the transfer of site responsibility. Furthermore, a risk management plan in form of a milestone chart is presented in order to provide an industrially applicable roadmap for risk management measures in the context of CO_2 storage site abandonment.

The developed milestone chart has been evaluated on the K12-B site (CO_2CARE D4.6, 2013a) and is used as input for setting up more specific criteria for site abandonment in CO_2CARE Deliverable D4.22 “Criteria for decision making in site abandonment” (CO_2CARE, 2013b).

1.1. Definition of “irregular site behaviour” and “significant irregularity”

The EC storage directive states that if significant irregularities occur during the storage process corrective measures specified in a risk management plan have to be taken in order to ensure the safety of the site. According to the Storage Directive Article 3 (17) a “significant irregularity” is defined as any irregularity during the injection, post-injection/pre-closure and even post-closure phase, which pose a risk of leakage or implies a risk to the environment or humans.

Hence, irregular site behaviour can be defined as a state or evolution of the site which is deviating from the predicted regular behaviour. Parameters or indicators of regular or irregular behaviour need to be identified (like pressure or plume extent) and one or more threshold values are to be defined for verifying regular or irregular behaviour. A priori, it is not clearly technically specified what counts as irregularity and which deviations of the project plan (e.g. Monitoring-Model-Conformity) or uncertainty ranges (e.g. for models) are acceptable.

These specifications need to be defined by the responsible operator and Competent Authority (CA) and will highly depend on the characteristics of each single site, as stated in the EC Guidance Document 3 (EC GD3): “*The choice of the percentage (of monitoring-modelling offset) would be determined by the CA and different ranges of tolerances can be specified for* *each particular measured parameter in order to determine conformity. The CA should specify the applicable percentages for various parameters for each storage site at the time of the storage permit, taking account of site specific characteristics".*

In practice, it can be expected that the operator will propose tolerable offset percentages for each performance indicator, which will then be agreed upon with the CA.

2. Requirements of EC Directive 2009/31/EC

In this section we will review the Risk Management requirements in the context of site abandonment demanded by the EC Directive on the geological storage of carbon dioxide (2009/31/EC), herein referred to as “EC Storage Directive” (EC, 2009), and the OSPAR Guidelines. According to the EC Storage Directive, the responsibility for the storage site can be transferred from the operator to the state, represented by a Competent Authority (CA), not earlier than 20 years after site-closure. Site closure and the transfer of responsibility have to be approved by a competent authority (CA) on a national level.

2.1. Transfer of responsibility

The details of the transfer of responsibility are outlined in Article 18 of the EC Storage Directive. According to Article 18(1) the transfer can be approved when the following conditions are met:

a) all available evidence indicates that the stored CO_2 will be completely and permanently contained,

b) the financial obligations referred to in Article 20[1] have been fulfilled,

c) the site has been sealed and the injection facilities have been removed.

A minimum period between site closure (cf. Section 2.2) and the transfer of responsibility has to be determined by the CA and shall not be shorter than 20 years unless the CA concludes that criterion (a) is met before that period has elapsed.

Following Article18 (2), prior to the transfer of responsibility the operator has to provide a report to the CA, for approving the transfer. The document shall at least demonstrate that:

a) the conformity of the actual behaviour of the injected CO_2 with the modelled behaviour,

b) the absence of any detectable leakage,

c) the storage site is evolving towards a situation of long-term stability.

2.2. Site Closure

Site closure is defined by Article 3 of the *DIRECTIVE 2009/31/EC* as the definitive cessation of CO_2 injection into that storage site. Article 17 of the EC Storage Directive defines the conditions for a site closure. In Article 17 (1) it is stated that a site shall be closed:

a) if the relevant conditions stated in the permit have been met,

b) at the substantiated request of the operator, after authorization of the CA, or

c) if the competent authority so decides after the withdrawal of a storage permit.

If a site closure refers to the reasons (a) or (b), it will be referred to as “regular site closure”, whereas site closures according to (c) will be termed “irregular site closure”. Following Article 17(2), in case of site closure based on (a) or (b) the operator will remain responsible for

[1] Delivery of a financial contribution to the competent authority, to cover at least the anticipated cost of monitoring for a period of 30 years.

monitoring, reporting and corrective measures until the transfer to the CA. In case of an irregular closure the CA will be responsible for monitoring and corrective measures. In fact, there is no difference for the implementation of the risk management. The conditions stated in Article 18(2) (see paragraph 2.1) finally have to be met in any case.

2.2.1. Provisional and updated post-closure plan

A provisional closure plan is already provided during the characterisation phase of the storage complex, before any CO_2 storage operation commences (Phase 2 in Figure 1). It is obligatory to get a storage permit. Before site closure the initial plan has to be updated with all relevant information gained through the operational phase. Particularly irregularities, leakages and corrective measures taken during the CO_2 injection period need to be taken into account. Also improvements in technology and best practices should be regarded.

The updated and adjusted models should incorporate all information obtained during the site operation (EC GD1, 2011b).

EC GD1 (2011b) states that the (updated) close-plan should contain:

1. a list of surface and subsurface facilities that will be removed once the injection has stopped;
2. plugging and abandonment plans for wells to be removed after the cessation of injection;
3. a plan for monitoring (including the needed wells and equipment) in the post-closure/pre-transfer phase;
4. a list of monitoring benchmarks that will be tracked to determine when the transfer conditions are met; and
5. a plan for site sealing and reclamation.

2.3. Risk Management

CO_2 storage-related risk management is defined as a measure to demonstrate how a risk-bearing event (e.g. leakage[2], induced seismicity, ground movement, brine displacement), if it happened, would be managed in order to prevent it will be leading to significant adverse consequences for the terrestrial and/or marine environment, human health and other legitimate uses of the terrestrial or maritime area (modified after CATO-2, 2010).

Before being able to manage risks, site-specific risks have to be identified and quantified, effective risk mitigation measures have to be available and there has to be an adequate monitoring plan, to be able to detect adverse effects on health, safety and environment (HSE) due to failures of the storage system.

Identification and quantification of site specific risks is termed risk assessment. Consequently, risk management encompasses risk assessment, a monitoring program and a distinct and appropriate portfolio of risk mitigation measures, and appropriate counter measures.

The EC Storage Directive provides a clear framework for the elements of risk assessment to be applied on CO_2 storage sites, particularly with respect to monitoring. As pointed out by Article 7(3), the characterization of the storage site is an integral part of the application for

[2] The EC storage Directive defines leakage as “Leakage is defined as migration of CO_2 out of the storage complex to the atmosphere or marine environment”.

storage permits and has to be conducted pursuant to Article 4(3). The latter article states that the site characterization has to follow Annex I. Annex I points out that risk assessment is part of the site characterization. According to Article 7(6, 7) a monitoring plan as well as a plan for corrective measures are integral to the application procedure. Furthermore, Article 7(8) demands a provisional post-closure plan. **Hence, a risk management plan is already in place at the beginning of the operational phase, as well as a preliminary closure plan.** The final post-closure plan will rely on the risk assessment and the planning of the corrective measures must already be in place. However, the monitoring activities will be adapted to comply with the three main conditions required for transferring the responsibility to the CA.

The requirements for monitoring are determined in Article 13. The conditions stated in Article 13 (1) are in principle all covered by the three conditions to be met for a transfer of responsibility, stated in Article 18 (1) (see also Section 2.1 of the current report). In paragraph 2 of Annex II it is clearly stated that post-closure monitoring "shall serve in particular to provide information required for the determination of Article 18 (1)". This means that the goal of post-operational monitoring serves to ensure that "the stored CO_2 will be completely and permanently contained". This aim can be ascertained by directing the monitoring activities to confirm the three conditions to be discussed in the report to be delivered to the CA prior to the transfer of responsibility as stated in Article 18(2).

2.4. Mandatory Monitoring Requirements

The obligatory parameters to be monitored according to the EC Storage Directive are defined in Annex II of the Storage Directive, including

1) fugitive emissions of CO_2 at the injection facility,
2) CO_2 volumetric flow at injection wellheads,
3) CO_2 pressure and temperature at injection wellheads (to determine mass flow),
4) chemical analysis of the injected material,
5) reservoir temperature and pressure (to determine CO_2 phase behaviour and state).

These mandatory parameters and additional parameters determined in the site-specific monitoring plan have to be maintained until site closure. It is obvious that after injection cessation some of the items listed above are not applicable any more or have to be adapted. This applies for the items (1), (2), and (4). The same may apply for additional monitored parameters due to the monitoring plan applied during the operational phase.

Items (3) and (5) are referring to wellhead and downhole pressure and temperature monitoring. Additional required monitoring measures are discussed later on.

2.5. Conformity of Modelling and Monitoring

The conformity of model predictions and monitoring data demonstrates the understanding of the storage behaviour. Models of high importance are static geological models; geomechanical models considering the hydraulic integrity and reactivation potential of faults; reservoir models and geochemical models which are all valuable to demonstrate the understanding of the site's behaviour.

Reservoir models are the key for predicting the pressure evolution and the movement of a CO_2 plume within the containment. Ideally, there may be more than one reservoir model established by different tools for the purpose of comparison, evaluation and benchmarking. This applies for other model types as well. Geochemical models are representing the expected chemical interactions within the system CO_2 – brine – rock. Such models are generally not treated separately. Usually, certain models deliver the input for others or are even coupled to one another. For instance, static geological models are delivering input to all dynamic models, such as reservoir, geomechanical or geochemical models.

Static geological models and reservoir models are obligatory. Concerning other model types a prioritisation may be conducted dependent on the site's properties. For instance, if a site was not influenced by any faults, geomechanical models for evaluating fault integrity and reactivation potentials would not be required. At a given site geochemical reactions might not impact the integrity of the cap rock, for instance. Therefore such models would be of minor priority to demonstrate the long-term integrity of the cap rock. At the same site, geochemical models, though, may be required to model the mineralization of injected CO_2 when mineralization was part of the storage concept. These examples show that a **prioritisation of model types** has to be made with respect to their importance for demonstrating understanding of a site's behaviour and the complete and permanent storage of CO_2 there. This prioritisation is part of the risk management plan established within the scope of the site characterisation prior to the operational phase and required for the licensing procedure.

All models can be compared to and calibrated by monitoring data. When observing differences between monitoring data and model predictions, **a crucial question is whether the models have to be merely adjusted or are indicating significant irregular behaviour of the storage system.**

This study is based on the presumption that the models required to demonstrate the understanding of the site's behaviour have been calibrated accurately during the injection phase. However, as relaxation of the reservoir is expected following the operational phase, the models may require adjustment in the post-operational phase. The distinction whether to conduct model adjustments or to consider the reservoir behaviour as irregular depends on a thorough and qualified interpretation. If the physical conditions required supporting a re-calibrated model fit well those of the storage site, the adjustment can be considered legitimate, otherwise irregular site behaviour has to be suspected and consequently additional monitoring and corrective measures might have to be applied.

2.5.1. Acceptance criteria for tolerated Model-Monitoring Offset (MMO)

Acceptance criteria for tolerated mismatches between model predictions and monitoring data are still a matter of research and discussion. Increasing experience with CO_2 storage operations will resolve many aspects of this issue. **Deviation margins between model predictions and monitoring data are dependent on the accuracy of the monitoring techniques applied and the specific site features.** Consequently, appropriate deviation margins for each model type are to be determined within the scope of the risk assessment and may be expressed in absolute or relative terms. Since the site will become responsibility of the CA, they will discuss with the operator on appropriate and reasonable conformity criteria for relevant parameters, also considering site-specific aspects.

However, more important than absolute or relative deviations are deviation trends. A divergent evolution of monitoring and model data is a clear indication for the mismatch of these two domains, requiring model adjustment or taking measures for evaluating and counter-acting irregular site behaviour. Conversely, a convergent trend implies predictive stability and an evolutionary improvement in system understanding. Thus, modelling is an iterative process. The highest frequency of iterative looping is expected in the early operational stages and again in the final operational sub-phase and the early stage of the post-operational phase. From a risk management point of view it is inevitably required that the iterative looping will come to an end in the post-operational phase. Matching between models and monitoring observations serves as the demonstration that the site behaviour is well understood by the operator.

2.6. Absence of any Detectable Leakage

The EC Storage Directive defines key elements in the argument for no detectable leakage, which are:

- No detectable changes in the overburden above the storage reservoir (e.g. no visible changes on time-lapse seismic).
- No detected emissions at the surface or surface water-column
- No measured irregularities in storage performance that might be indicative of leakage

One example of the third element, applicable to closed-system reservoirs is the pressure evolution of the reservoir after site-closure. Pressure as a function of time would be expected to approach an asymptotic behaviour (i.e. declining pressure drop as a function of time) due to the reservoir relaxation in the post-operational phase. The expected relaxation pressure can be calculated based on reservoir model simulations. If the monitored reservoir pressure shows deviation outside the tolerable uncertainties of the expected (modelled) equilibrium pressure (as previously defined by the CA, see also Section 1.1 and 2.5.1), the site does not behave as expected/predicted. This does not directly indicate a leakage, but could also be the result of non-accurate model predictions (e.g. error in input data or incorrect assumptions of CO_2 dissolution behaviour). Further investigation has to be conducted to explain the irregularity and to specify if existing models has to be adjusted, additional monitoring is required or if CO_2 has been leaking out of the storage containment. In the latter case corrective measures have to be initiated.

Further monitoring approaches referring to the absence of leakage are enlisted in guidance document 3 of the EC Storage Directive (EC GD3, 2011a):

- Mechanical well integrity tests by well logs,
- Pressure, temperature and resistivity monitoring of the injection zone and storage complex to monitor the plume position within the storage complex,
- Pressure, temperature and resistivity monitoring of zones above the cap rocks to verify that no CO_2 is leaking outside the storage complex,
- Periodic seismic surveys,
- Groundwater, soil and air monitoring,
- Geochemical tests.

2.7. Site Evolvement towards a situation of long-term stability

The guidance document GD3 reveals four indicators which may indicate the long-term stability:

- The models project eventual stability of the CO_2 plume within the storage complex (i.e. the plume will be completely and permanently contained).
- Key monitored parameters (over a defined time period, e.g., five years) are close to the future stable values (as predicted by modelling).
- The rate of change of key monitored parameters is small and declining.
- The backcasted values from the modelling are within the confidence intervals of the historical monitored parameters.

The following key monitoring parameters are enlisted: pressure within the storage complex, movement of the plume, geochemical changes in the storage complex and the wells, and integrity of materials used to construct or abandon wells.

These crucial recommendations of the guidance document, however, can be put into a higher level context of the effectiveness of the storage system. This might include for example, robust convergence in the degree of matching of the pressure relaxation path and plume movement with model predictions. Furthermore, it refers to the verification of the envisaged storage concept, which may involve residual trapping, dissolution and mineralization. The difficulty associated with this strategy is the long-term time scale of certain storage processes. In case long-term processes have to be evaluated, trend indications derived from thoroughly calibrated models have to serve as proxies for the verification of the storage processes.

3. Timeline and Site-Closure Milestones (SCM)

Figure 1 illustrates the time line of the project phases covered by the present study. The respective phases are the final phase of the operational phase, the post-closure/pre-transfer and the post-transfer phase (Phase 4-6 according to EC GD3).

Risk management activities, i.e. the cycle of risk assessment, monitoring and risk reducing measures, are continuously revolving during all phases of the CO_2 storage lifetime and is thus not exclusive for the closure milestone and the post-closure phases of a CO_2 storage project. Actually risk management in terms of assessment and planning already starts in the site qualification phase. A storage permit should already address the major items of closure and post-closure, which includes the risk management plan, post-closure plan, transfer requirements, and abandonment plan. As the early phases of the storage lifetime deal with the *planning* the closure and post-closure activities, the latest stages focus on updating the plans and *implement* them. The more detailed description of activities and milestones for site closure and post-closure in this report assumes that a complete risk assessment and a set of plans with optional updates in the operational phase are available once a project arrives in the final operational phase.

In order to provide a well-structured procedure for risk management within these project phases, 17 Site-Closure Milestones (SCM) have been introduced which are implemented into the different project phases The milestones are closely link to the requirements of the EC Storage directive and describe key actions or key moments in time during site closure and transfer.

The proposed SCMs (not to be confused with the milestones mentioned in EC GD3) lie in operational Phase 4 and post closure/pre-transfer Phase 5, which are, for a better understanding, split into three sub-phases based on the terms used in the EC Storage Directive (Figure 1):

- final operational sub-phase (Part of Phase 4, including site closure)
- post-closure sub-phase (first phase of Phase 5)
- pre-transfer sub-phase (second phase of Phase 5, including transfer of the site)

The final operational sub-phase is defined to start with the initiation of the reduction of the injection rate until the closure when the injection rate reaches zero. The moment of closure is followed by the post-operational phase subdivided into post-closure/pre-transfer and post-transfer phases (Figure 1). Start of the final operation sub-phase and closure are singular moments in time. The final operation sub-phase phase represents a time-limited period and the post-operational phase an indefinite period. The post-closure and pre-transfer sub-phases are limited periods, while the post-transfer phase represents an indefinite period. Each period mentioned requires different and specific risk management methodologies.

The final operational sub-phase can be used for proving the understanding of the short-term site behaviour of the operator. The CA will, according to given regulations, ask the operator for adequate reservoir models. It will vary from site to site which information from the operator/site has to be included in the models, e.g. if the operator would have to provide a reservoir model to the CA, predicting the wellhead and downhole pressure evolution of certain monitoring and injection wells during the final injection phase.

This final operational sub-phase may encompass few days to a few weeks. If the model predictions are in accordance with the monitoring observation within sensible tolerances, the CA will acknowledge a successful site closure and the initiation of the post-closure/pre-transfer period. Finally, the reservoir pressure at closure has to meet the predicted value. Pressures that are significantly below the expected level may indicate unexpected fluid migration or leakage of CO_2 from the storage complex.

While the final operational phase is intended to demonstrate understanding of the short-term site behaviour, the post-closure sub-phase refers to the understanding of the mid-term site behaviour. The latter will form a continuum with iterative prediction and verification during the operational phase which should show a robust convergence with time.

The pre-transfer sub-phase shall encompass proof of understanding of the mid-term behaviour and the plausibility of a safe long-term behaviour revealing negligible residual risk. This shall be conducted by a formal report submitted by the operator to the CA. Following approval of the report, the responsibility transfer will be accomplished and the post-operational post-transfer sub-phase will be initiated.

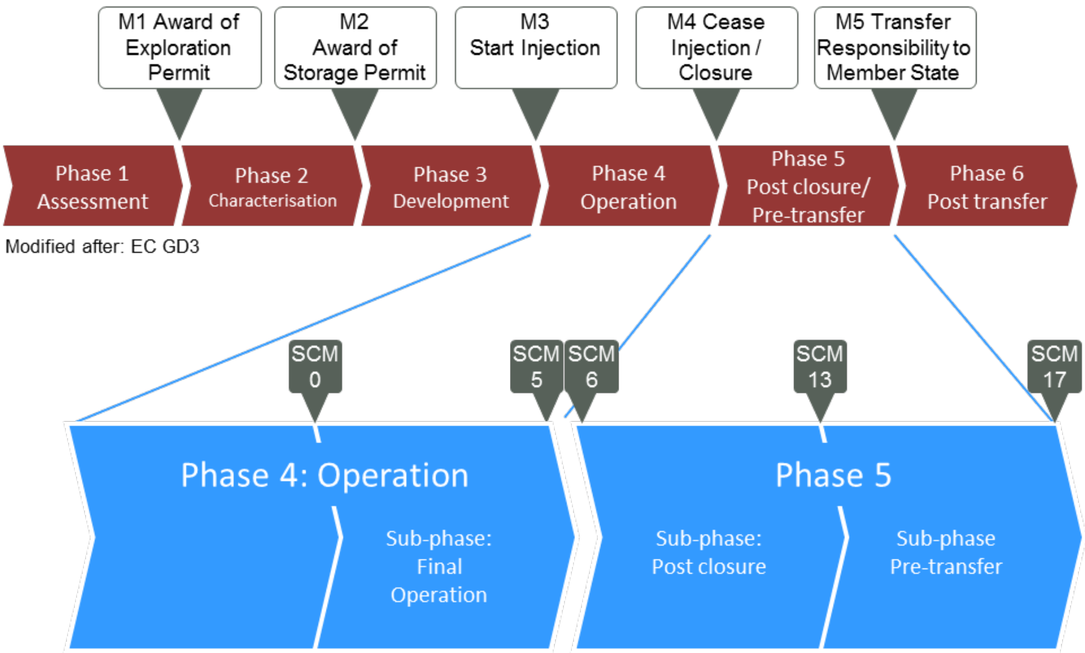

Figure 1. Timeline for CO_2 storage site closure risk management modified after EC Guidance Document 3. M=milestone defined in the EC Storage Directive, SCM= New defined Site-Closure Milestones for risk management of CO_2 storage site closure

3.1. Risk Management Plan: Site-Closure Milestone Chart

In order to condense the more general statements above into a risk management plan applicable in an industrial context, a milestone chart has been developed (Table 1), covering the final operational and the post-closure/pre-transfer phase.

The milestones are ordered on a temporal basis allowing the operator and the CA to monitor the progress of the transfer-preparation. Furthermore, the requirements of Article 18 (EC Storage Directive) have been integrated into the set of milestones ensuring that all conditions for responsibility transfer are fulfilled when the set of milestones is passed. In the context of this strategy it is the operator's responsibility to fulfil the milestone requirements, while the CA bears the responsibility of verification, assuming a regular site closure. In case of an irregular site closure (see Article 17(1c), EC Storage Directive) the CA bears the responsibility for passing the milestones as well. Passing all milestones leads to the approval of the responsibility transfer by the CA. The milestone chart covers the timeline beginning from the final operational sub-phase until the transfer of responsibility. The post-transfer phase will be treated outside the scope of the milestone chart.

Article 18(1b) of the EC Storage Directive recommends a minimum period of 20 years for the post-closure/pre-transfer phase, but additionally leaves the CA the opportunity to reduce this period. It is recommended to ease the default duration of the post-closure/pre-transfer phase and to rather commit to the fulfilment of the milestone chart rather than follow the proposed 20-year criterion of the EC Storage Directive. Determination of this period is two-fold: The period should be sufficiently extended to meet the requirements of Article 18(2) on the one hand, and yet enable the shortest possible period until site abandonment (particularly well abandonment) on the other. This perspective provides a more objective determination of the duration of the post-closure/pre-transfer phase than a rigid set time.

In the following paragraphs, the introduced site-closure milestones (SCM) are discussed in the context of the corresponding period in the timeline. The correspondence between SCMs and timeline is summarised in Table 1. It is important that the milestones must be passed one after another. For instance, the final evaluation of the absence of leakage must be undertaken after accordance of modelling and monitoring data have been provided, i.e. the behaviour of the storage complex is shown to be understood by the operator.

Table 1. Site-closure milestone chart leading to the transfer of responsibility according to Article 18 (EC Storage Directive).

Site-Closure Milestone (SCM)		Description	Sub-Phase	Phase/Moment
0		Specify selected models and monitoring for conformity check	final operational	Operational
1		Check model/monitoring conformity during final operational phase; if necessary update models		
2		Provisional post-closure plan updated		
3		Final (updated) post-closure plan submitted		
4		Final (updated) post-closure plan approved		
5		Site Closure	-	Site Closure
6		Optional update of risk management plan	Post-Closure	Post-Closure/Pre-Transfer
7		Model check-update loop is ending		
8		Models and monitoring data are within acceptable conformance after M7 has been reached without significant adjustment (EC GD3 proposes a minimum period of five years)		
9		Optional final update of risk management plan		
10		Evidence of absence of leakage		
11		Effectiveness of storage concept: Evolution to long-term stability		
11a	a	Pressure evolution is matching model prediction		
11b	b	Plume movement is within an acceptable match of model predictions		
11c	c	Optional verification of other parameters/features related to the storage concept		
12		Final wellbore check before abandonment (logging)		
13		(Draft) Report for transfer of responsibility submitted	Pre-Transfer	
14		Report approved		
15		Surface facilities removed		
16		Well abandonment accepted		
17		Transfer of responsibility approved and accomplished	-	Site Transfer

3.2. Final operational sub-phase and site closure

This phase covers the final part of the operational phase until injection ceased and the site is closed. This period encompasses five milestones SCM1-SCM5.

SCM0: Specify selected models and monitoring for conformity check

A set of models and monitoring methods have to be in place, tailored to the safety requirements of the site. Required monitoring and modelling measures and the prioritisation of the modelling approaches, i.e. the classification of all models used in mandatory and optional ones have to be defined. The arrangement of these methods is highly site-specific.

SCM1: Check model/monitoring conformity during final operational phase; if necessary update models

As discussed at begin of this section, the final operational sub-phase can be regarded as a test for the reliability of the models with respect to short-term responses to injection cessation and pressure relaxation of the storage system. As the models applied are assumed to be well calibrated, no highly significant deviations from the actual reservoir behaviour are expected. The models though, may not have been calibrated to pressure relaxation beforehand and may require re-adjustment to a certain degree. Mainly downhole and wellhead pressure and temperature predictions are to be correlated with monitoring data. Geochemical effects are not likely to be observed on such a short time scale. If adjustment is necessary, a physically sensible reasoning must be provided.

SCM2: Provisional post-closure plan updated

The site-specific provisional post-closure plan delivered to obtain a storage license by the CA in the pre-operational phase according to Article 7 (EC Storage Directive) has to be updated. It mainly refers to available data, updated models and required monitoring or corrective measures for the post-closure phase (see also Section 2.2.1).

Consequently, all monitoring measures added to the initial monitoring plan during operation and all applied counter measures that are still relevant after injection cessation have to be kept effective in the post-operational phase. Such additional elements established during the operational phase have to be included in the post-closure plan including an update of the risk assessment (summarized in risk register and risk matrix).

SCM3: Final (updated) post-closure plan submitted

The updated post-closure plan has to be submitted to the CA for evaluation.

SCM4: Final (updated) post-closure plan approved

Evaluation of the final post-closure plan by the CA is focused on the following criteria:

- The implementation of all elements of the provisional post-closure plan and evaluation of the rationale, when elements have been removed,

- Implementation of all required monitoring measures and evaluation of rational when monitoring measures effective during the operational phase have been removed,
- Implementation of required corrective measures and evaluation of rationale when corrective measures effective during the operational phase have been removed,
- Implementation of additional monitoring measures found to be required due to observations during the terminal injection cessation.

If those criteria are not considered fulfilled by the CA, the post-closure plan has to be revised before continuing with further milestones. The post-closure plan may also be modified with respect to a more economic operation due to advancements in technology and science. For instance, new knowledge in monitoring configuration may lead to sufficient performance by using a reduced number of monitoring points. In general, compared to the operational phase, a reduced set of monitoring measures will be applied during the post-operational phase.

SCM5: Site Closure

When the post-closure plan is approved by the CA, the final operational sub-phase will be terminated by a formal site closure. As of this moment the site will be considered being in the post-operational phase.

3.3. Post-closure/pre-transfer phase

This phase has been separated into two Sub-Phases using the terms of the EC Storage Directive.

3.3.1. Post-closure sub-phase

The pre-transfer sub-phase contains the most crucial milestones to be passed by the operator. The operator must provide evidence that the conditions for a responsibility transfer stated in Article 18 (EC STORAGE directive) are met.

SCM6: Optional update of risk management plan

All risk-related requirements stated in the updated post-closure plan have to be implemented in an updated version of the risk management plan. If there have not been any requirements for updates, this milestone can be passed without any review of the risk management plan.

SCM7: Model check-update loop is ending is ending

As discussed before, accordance or robust convergence of modelling and monitoring data is provided when no more adjustment of the models is required, particularly with respect to reservoir models (wellhead and downhole pressure and temperature, plume movement, dissolution) and geochemical (ion speciation in reservoir water samples) models. Furthermore, the backcast of the updated models must properly reproduce the storage site evolution during the operational phase. This milestone will be passed when the models applied for the specific site are in accordance with the monitoring data within reasonable tolerances, or show that the possibility of future significant irregularities developing is negligible.

SCM8: Models and monitoring data are within acceptable conformance after M7 has been reached without significant adjustment (EC GD3 proposes a minimum period of five years)

In order to demonstrate that the SCM7 milestone is stable and robust, a certain period has to be defined during which no significant deviation between monitoring data and model predictions occur as a threshold value for the empirical evidence. To correct for heterogeneity errors affecting the predicted plume propagation is tolerated. The EU guidance document suggests a default period of five years. There is no scientific fundament for this figure; however, from the perspective of reservoir engineering such a period seems sufficient to demonstrate the understanding of the site behaviour. In case a good model-based understanding of the site is obvious and evident, the CA may reduce the duration of the period. If deviations are detected before the end of this period, the operator has to step in the adjustment loop again and has to pass M7 and M8.

Although this seems to be a safe and reasonable procedure in principle, it may be difficult to be controlled by the CA.

SCM9: Optional final update of risk management plan

In case any further risks have been identified during the model-looping, those must be considered in a final update of the risk management plan. Otherwise this milestone can be skipped.

SCM10: Evidence of absence of leakage

Within the scope of this milestone all monitoring measures applied in accordance with the monitoring plan have to proof any absence of leakage. If implemented following best practices, the monitoring plan should cover any significant leakage risk. Monitoring measures defined in the storage license and the monitoring plan have to be applied (see also Section 2.5), except extensive well integrity tests like logging. Those should be undertaken whenever it appears reasonable and as close to the responsibility transfer of the site as practically and economically feasible. Site Closure Milestone 12 covers well abandonment, in order to document the latest state of the well integrity in the transfer process.

Among others, the list of monitoring measures contains groundwater, soil and air monitoring. A specific large scale surface survey might be necessary to pass this milestone if this was found necessary in the storage licence, e.g. an Eddy Covariance Survey. Such an approach allows the detection of emissions over large areas. This is important as CO_2 migration may occur along faults, generating emissions at some distance to the actual storage site.

A crucial aspect is the pressure development. Assuming a hydraulically well confined depleted gas reservoir the bottomhole pressure will drop after injection cessation and will approach an equilibrium pressure asymptotically in the short-term. As the reservoir models are reflecting the true behaviour of the reservoir at this stage, the pressure evolution to the equilibrium pressures can be forecasted. Pressure drops below the calculated equilibrium pressure may indicate leakage or unexpected fluid migration (still assuming a tank model) if it could be ensured that the model is accurate and does not need adjusting to account for errors in the model (e.g. wrong assumption of dissolution kinetics, wrong input data, etc.).

An indication of leakage is more difficult to detect in largely extended aquifers as the pressure relaxation is expected to occur more slowly there. Long-term processes within the reservoir, e.g. mixing of CO_2 and methane in case of injection into a depleted gas field, CO_2 dissolution and mineralization, will certainly cause volume changes within the reservoir. Depending on the sign of such changes the pressure may rise or drop after the initial pressure drop observed as a consequence of the injection cessation. Such long-term pressure effects are very difficult to predict and therefore a major subject to ongoing research (e.g. CO_2CARE Deliverable D3.4 "Assessment of long-term integrity and site stabilisation by coupled THMC modelling" (CO_2CARE, 2013c).

In any case models and monitoring data must not show any indication of leakage out of the storage complex. In general, it must be assured that the position of the CO_2 plume remains inside the storage complex. In case of aquifer storage, this could be monitored by (periodic) seismic surveys, taking into account that sensitivity and resolution of seismic monitoring techniques are dependent on local rock and site properties. Permanent seismic networks are currently tested and seem to be promising (Arts et al., 2010). 4D seismics can provide reliable information on the movement and position of the CO_2-plume in the subsurface (Chadwick et. al., 2009); however such approaches are cost-intense and therefore more suitable for very large-scale storage projects. With respect to CO_2-storage in depleted gas fields seismic surveys are generally of very limited value for plume monitoring as the contrast in seismic impedance between the residual gas (e.g. methane) and the supercritical CO_2-phase is too low (e.g. Arts and Winthaegen, 2005). In this case, wellbore monitoring can help to locate the extension of the CO_2 plume if this seems necessary.

There must be no leakage detected for an extended period, at least until the long-term integrity of the site is proven. Again EC GD3 proposes a default duration (of at least 10 years including the operational phase), but in practice the CA in agreement with the operator have to specify a reasonable time span. To summarise, the most important criteria for passing this milestone are:

- Pressure evolution according to the reservoir models,
- No detectable indication of leakage by monitoring measures applied within the scope of the monitoring plan,
- Evidence for the location of the CO_2-plume within the storage confinement by periodic seismic surveys or other appropriate measures,

Leakage has not been detected for a certain period specified by the CA and the operator (10 years including the operational phase are proposed in EC GD3)

SCM11: Effectiveness of storage concept: Evolution to long-term stability

This milestone is split into three sub-milestones:

- Pressure evolution is matching model prediction (SCM11a),
- Plume movement is matching model predictions (SCM11b),

- Optional verification of other parameters/features related to the storage concept (SCM11c).

SCM11a is partly contained in SCM10. However, there pressure is used as an indicator for leakage. As an indicator for the evolution of the storage complex to a long-term stability pressure change with time might be appropriate. A negative pressure change with time, verified by modelling and monitoring data, might be a requirement to pass sub-milestone SCM11a. Furthermore the asymptotic approach to an equilibrium pressure should be demonstrated by models and, if possible, by observations. It has to be noted though, that such observations might be not possible in case of largely extended aquifers, where the pressure relaxation may take place on a large time-scale.

SCM11b is also connected to SCM10. But here the focus lies on the stabilisation of the plume movement. The plume must either approach a lateral steady-state situation or the lateral movement must be sufficiently slow to ensure that storage mechanisms like residual trapping and mineralization will prevent leakage out of the reservoir in the long term. It is additionally recommended that - if lateral movement is occurring – the lateral acceleration is negative. The selection of an appropriate monitoring technique for observing the plume movement is to be determined in the post-closure monitoring plan. Some related aspects have already been discussed above.

SCM11c relates to additional key monitoring parameters pointed out in the site specific (post-closure) monitoring plan. A conceivable example could be additional well monitoring parameters in case of a depleted hydrocarbon field with a number of abandoned production wells has been used as a storage site. The verification of the storage concept is a second very important aspect. The evolution and trends of the behaviour of the storage complex must significantly tend to the storage concept envisaged in the site characterisation. As the storage mechanisms are often mid- and long-term processes, this evaluation largely relies on models. However, storage mechanisms such as dissolution and residual trapping may be also observable by monitoring during the post-closure sub-phase in their initial states. Mineralisation is highly unlikely to be observed in real-time. If structural trapping has been pointed out as the major storage mechanism, there must be clear indication of the reservoir models applied that the plume is moving towards the envisaged structures, at best confirmed by monitoring data. At this stage probabilistic models are to be applied verifying the evolution of the storage system to a state revealing very low probabilities of

- Leakage,
- Adverse effects and health safety and the environment.

SCM12: Final wellbore check before abandonment (logging)

Before sealing and abandoning the wells a quality check of the well materials identified to constitute identified risk with respect to leakage have to be undertaken. There are four crucial aspects for evaluating the integrity of well materials:

- Mechanical deformation of the casing,
- Corrosion of the casing,
- Quality and degradation of the wellbore cementation,

- Debonding of the interfaces (e.g. cement/casing).

It is recommended to apply current best practices for wellbore quality control. The IEA-GHG report on oil and gas well abandonment (IEA-GHG, 2009) provides a review of numerous national regulations for well abandonment requirements. Logging methods, appropriate to check for the four aspects enlisted above are multi-finger caliper logs (MFC) for evaluating mechanical deformation of the wellbore and electromagnetic logging for measuring the casing thickness. The wellbore cement quality can be checked by cement evaluation logging and the application of an Isolation Scanner™. Well-related leakage may be checked by electric resistivity monitoring (ERT).

In addition the quality of performed cement jobs in all relevant wells and their verification should be examined by evaluating available drilling and well reports.

3.3.2. Pre-transfer sub-phase

The pre-transfer sub-phase is entered by submitting a draft report for responsibility transfer to the CA and is finalised with the transfer of responsibility for the storage site from the operator to the state. It comprises SCM 13 to 17 which are more of regulatory than of technical nature.

SCM13: (Draft) Report for transfer of responsibility transfer submitted

The draft version of the report for responsibility transfer should demonstrate that the conditions stated in Article 18(2) of the EC STORAGE directive are fulfilled:

a) Conformity of the actual behaviour of injected CO_2 with the modelled behaviour,

b) The absence of any detectable leakage,

c) The storage site is evolving towards a situation of long-term stability.

Condition (a) is fulfilled when reaching milestone SCM8. Fulfilment of condition (b) refers to the accomplishment of milestones SCM10 and SCM12. Fulfilment of condition (c) coincides with the accomplishment of milestone SCM11.

Consequently, it is recommended to demonstrate the fulfilment of the three conditions by incorporating the milestones SCM6 to SCM12 into the report. The Guidance Document 3 recommends a specific reporting format (Table 2).

Table 2. Format for the report concerning the request for transferring responsibility according to EC GD3.

Evidence for complete and permanent storage	Required documentation from the operator
Conformity with Models	1) For a certain, continuous period immediately before the transfer, there has been no need to significantly change the 3D static geological model assumptions for the characteristics of the storage complex during history matching exercises incorporating monitored parameters from monitoring taking place over regular intervals (five years are suggested in EC GD3). 2) Results of the backcasting with the final model are within or close to the confidence interval of the monitored parameters over the entire life of the project.
Absence of Any Detectable Leakage	For over a certain, continuous period immediately before transfer

	(10 years suggested in EC GD3), show that: 1) Integrity of all wells (monitoring and injection) remains in a good shape without any leaks or unexpected deterioration or damage 2) Regular and periodically monitored data (including seismic surveys and monitoring of groundwater, soil and air) indicates that the CO_2 plume has remained within the storage complex, i.e., there are no leakages. 3) Regular and periodic geochemical analyses indicate that all measured and imputed data is consistent with the geochemical modelling
Evolution towards Long Term Stability	1) Show that the final models run out into the future project an eventual stability of CO_2 plume within the storage complex. 2) The monitored parameters have moved close to the expected stable values, as determined by modelling (e.g., by providing a table or graph of differences between the monitored and stable values) 3) Graphs and tables showing that the rate of change in the monitored parameters is small and declining.

Guidance document 3 additionally recommends adding the following points to the report:

1) Narrative history of the site, including site characterisation, operations, leakage events and anomalies, corrective measures, and summary of monitoring results. This history should cover the entire EC STORAGE lifecycle phases;
2) History of injection facility construction and what activities were undertaken in the closure and post-closure periods;
3) A revised finalised site characterisation report, including information from the final static and dynamic models;
4) Compilation of all results from modelling and simulation activities, the associated history matching, and the corresponding uncertainty analysis;
5) Description of how uncertainties have been analysed and managed, and review key decisions made under uncertainty in retrospect;
6) An updated project risk assessment showing how all individual risks that were identified have evolved throughout the project life;
7) Explanations for upgrading or downgrading risks during the life of the project;
8) Proof of site sealing and removal of injection facilities.

For the draft closure report it is suggested here to consider points (1) to (7) only. It is considered crucial that the site is not sealed until it has been approved by the CA. Therefore the draft report requires additionally:

- A plan for the removal of the facilities
- A detailed plan for well abandonment following current best practices

Reasons have been set out above as to why the present study does not generally concur with the 20 years criterion or the other strict timelines of the EC Storage Directive considering the transfer of responsibility. Following this rationale and the explanations given above, two crucial annotations concerning Table 2 have to be considered from the perspective of the present study:

- The five year period mentioned under the aspect “Conformity with Models” may be reduced by the CA when conformity is obvious and evident
- The ten year period mentioned under the aspect “Absence of Any Detectable Leakage” includes the operational phase, but could also be reduced if the long-term integrity of the site is proven earlier and the CA is content with the decision.

SCM14: (Draft) closure report approved

The CA will evaluate the draft report for approval. At that stage the injection facilities must not be removed and all the wells might not have be abandoned. This is important because the CA may request additional measures concerning the well integrity (monitoring or additional completion measures), impossible to conduct after well abandonment. If all milestones have been sufficiently fulfilled, the draft report will be approved by the CA.

SCM15: Surface facilities removed

After the draft report has been approved by the CA, the surface facilities are to be removed by the operator, following the plan included in the draft report. There may be a request by the CA to leave equipment for the purpose of ongoing post-closure monitoring.

SCM16: Well abandonment accepted

The wells are to be abandoned following the plan included in the draft closure report which should follow current industry best practices and given regulations. The CA approved and accepted the abandonment procedure and configuration of all wells in the storage complex.

SCM17: Transfer of responsibility approved and accomplished

After milestones SCM16 and SCM17 have been fulfilled, and evaluated by the CA, the transfer of responsibility will be approved and accomplished by the CA. As of this moment, the operator will be relieved from his liabilities concerning the storage site.

3.4. Post-transfer phase

The transfer of responsibility implies fulfilment of all milestones by the operator. Leakage is absent, models are calibrated to reflect the site’s behaviour and the site is evolving to a stable situation. Consequently, the risks posed by the storage site are minimised to a residual risk.

Therefore, a monitoring program is not required anymore; however, there may be some post-transfer monitoring desired by the CA to deal with the residual risk. Any post-transfer monitoring will have to be based on the final risk assessment and the monitoring program until the transfer of the site responsibility (EC GD3). It will be highly site specific (see also EC GD2 (2011c), Section 4.2.3).

The monitoring approaches applied within this scope should require limited operational expenditures. Suitable monitoring approaches are ones that can be applied on a routinely basis, such as groundwater monitoring and soil gas monitoring. Soil monitoring may be most appropriate in the vicinity of abandoned onshore wells. Offshore, post-transfer-monitoring would be more demanding; periodic sea bottom echosounding might be appropriate in this case.

4. Evaluation of the milestone chart (SCM) on the K12-B site

In CO_2CARE D4.11 (CO_2CARE, 2011b) a draft milestone chart for risk management in the final stages of a CO_2 storage project has been introduced. In CO_2CARE Deliverable D4.6 the milestone chart was tested on the K12-B CO_2 injection site in the Dutch North Sea (CO_2CARE, 2013a).

The test focused on the model-monitoring conformity of pressure data and considered the individual milestones from SCM0 up to and including the submission of the draft transfer report (SCM 13).

The evaluation of the proposed method did result in a number of recommended changes, which represent incremental changes of the milestone chart and have no effect on the overall approach. The milestone chart in the current report has been updated with the new knowledge of the test on the K12-B site.

It has been demonstrated that the milestone chart is a practicable tool to support decision making in CO_2 site abandonment and to achieve the transfer of responsibility.

For detailed information on the evaluation of the milestone chart on the K12-B site, please refer to CO_2CARE D4.6 (CO_2CARE, 2013a).

5. Conclusions

As pre-requisites for the transfer of responsibility from the operator to the CA, the EC Directive on the geological storage of carbon dioxide (DIRECTIVE 2009/31/EC; requires to demonstrate the conformity of models and monitoring data, the absence of any detectable leakage and the evolution of the storage complex to a long-term stable situation. In this way the transfer of responsibility from the operator to the state can be justified.

A milestone chart has been constructed to detail the site-closure and post-closure requirements for a storage site in order to provide an industrially applicable procedure for risk management measures including site abandonment. The developed milestone chart is used as input for setting up more specific criteria for responsibility transfer and site abandonment in CO_2CARE Deliverable D4.22 “Criteria for decision making in site abandonment” (CO_2CARE, 2013b).

A crucial question in meeting the criteria for the transfer of responsibility of the site is whether the applied models have to be merely adjusted or are indicating significant irregular behaviour of the storage system, if a mismatch of predicted and observed site behaviour has been observed. However, deviation margins between model predictions and monitoring data are dependent on the accuracy of the monitoring and modelling techniques applied and the specific site features. Consequently, appropriate deviation margins for each model type are to be determined within the scope of the risk assessment and quantitative process modelling. Since the site will become responsibility of the CA, they will decide together with the operator on appropriate and reasonable site-specific conformity criteria for relevant parameters. These aspects should already have been regarded in the characterisation phase of the project (in the provisional post-closure plan which is part of the storage permit), before CO_2 injection commences.

The DIRECTIVE 2009/31/EC as well as Guidance Document 3 propose minimum periods to fulfil certain key criteria for the transfer of responsibility, which are not based on any scientific fundament. It is recommended that the decision if a criterion for the safety of a site has been met or the site responsibility can be transferred should be based on technical aspects only and should not be linked to prescriptive time spans. Instead, a post-operational CO_2 storage site should be sealed as soon as possible after all criteria for the transfer have been fulfilled and the Competent Authority is convinced of the long-term integrity of the storage site.

As there will be a residual risk after the responsibility transfer, post-transfer monitoring programs which was not the main focus of this report, should be limited to measures requiring low operational expenditures to be undertaken on a routinely basis.

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