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Transferring responsibility of CO_2 storage sites to the competent authority following site closure

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Abstract

The requirements for pre-qualifying a site for CO_2 storage are well developed. Less attention has been paid to rehearsing and preparing for the transfer of responsibility of the storage site from the operator to a governmental authority following closure of the site at the end of the injection period. This is not surprising because the industry is in its infancy and most effort has been focussed on working towards the early stages of the various projects.
A procedure for complying to the regulatory requirements for the transport of responsibility in the CCS Directive has been proposed, which consists of a chart with Site Closure Milestones and a traffic light system for treating irregularities in observed behaviour of the storage site, and accompanying criteria. The procedure was successfully tested on the K12-B CO_2 injection pilot. Conclusions have been drawn on the basis of several dry runs for reporting the requirements for transfer of responsibility including feedback from operators and regulators.

Peer-review under responsibility of the Organizing Committee of GHGT-12
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1. Introduction

The two key milestones in the lifetime of a CO_2 storage project are the licensing by the competent authority before the start of injection operations and the handover to the competent authority after site closure, respectively M2 and M5 in Fig. 1. The rules for achieving these two milestones are embedded in the EC Directive on the geological storage of carbon dioxide abbreviated as CCS Directive [1] and the accompanying guidance documents [2-5]. The form of adoption of the CCS Directive into law will inevitably vary country by country and the permitting procedures will follow country specific requirements.

The requirements for pre-qualifying a site for CO_2 storage are well developed. Less attention has been paid to rehearsing and preparing for the transfer of responsibility of the storage site from the operator to a governmental authority following closure of the site at the end of the injection period. This is not surprising because the industry is in its infancy and most effort has been focussed on working towards the early stages of the various projects.

This paper presents an outline procedure for meeting the regulatory requirements for transferring the responsibility of a CO_2 storage site from the operator to a governmental authority. The procedure is evaluated on the basis of anticipating eventual closure at 1) the ongoing CO_2 storage pilot utilising pressure depleted compartments of the K12-B gas reservoir in the Netherlands offshore, 2) the ongoing CO_2 storage activities in the Utsira Formation near Sleipner offshore Norway and 3) the onshore CO_2 injection pilot near Ketzin in Germany [6]. The K12-B example will be illustrated in this paper. The evaluations or dry runs are virtual examples as in reality these injection are subjected to the rules in the CCS Directive.

Nomenclature

CA	Competent authority
EC	European Commission
GD	EC Guidance Document
M1	Milestone 1 defined in the EC Guidance Document 3
MMO	Model-Monitoring Offset or deviation of modelled and monitored site behaviour
R1	“R-type” or risk criterion 1
SCM	Site Closure Milestone
T1	“T-type” or technical criterion 1

2. EU regulation on transfer of responsibility

The essence of regulation including the CCS Directive is to provide rules for confirmation of regular behaviour of the site and assurance of absence of significant irregular behaviour. The CCS Directive (Article 18) stipulates that before a transfer of responsibility 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.

A minimum period between site closure and the transfer of responsibility has to be determined by the competent authority and shall not be shorter than 20 years unless the CA concludes that criterion (a) mentioned above is met before that period has elapsed. According to the same Directive, the operator has to demonstrate and report the following:

a. the conformity of the actual behaviour of the injected CO_2 with its modelled behaviour
b. the absence of any detectable leakage
c. the storage site is evolving towards a situation of long-term stability.

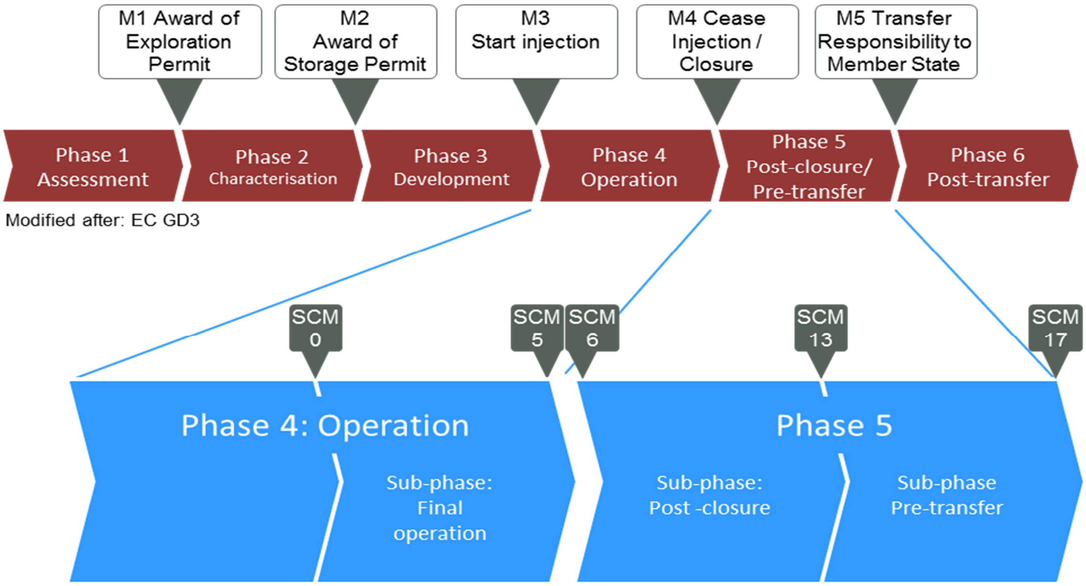

Fig. 1. Timeline for CO_2 storage site closure risk management modified after EC Guidance Document 3 [4]. M=milestone defined in the EC Guidance Document 3, SCM= Newly defined Site Closure Milestones for risk management of CO_2 storage site closure, transfer and abandonment. A complete list of SCMs is provided in Appendix A.

3. Risk management

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.

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.

This paper concentrates on the latest stages consisting of the final operation sub-phase of the operational phase 4, the post-closure and pre-transfer sub-phases in Phase 5 and the post-transfer Phase 6 (Fig. 1). The risk management activities and milestones connected with site closure and post-closure start from the assumption 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 sub-phase.

3.1. Site Closure Milestone chart and criteria

A practical milestone chart has been developed to clarify and catalogue risk management measures in the context of site closure, transfer of responsibility and site abandonment according to the rules in the CCS Directive. The chart consists of seventeen milestones and a number of risk criteria connected with these milestones (Fig. 1, Appendices A and B).

The milestones 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 sub-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.

The complete list of Site Closure Milestones is included in Appendix A and a full account of all SCM descriptions can be found in [6]. The Site Closure Milestones shown in Fig. 1 are briefly characterized below.

SCM0: Specify models and monitoring selected for conformity check

A set of models predicting the performance of the storage site and an appropriate set of monitoring methods will have been in place during the operation phase of the project, tailored to the safety requirements of the site. The first milestone in the final operation phase of the project life cycle is to define:

1. Which modelled and monitored parameters are the most important in predicting the future performance of the site.
2. What constitutes conformance between modelling and monitoring, i.e. what differences between predicted and observed results should be tolerated.

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 to be in the post-operational phase.

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.

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

The draft version of the report for responsibility transfer should demonstrate that the three conditions stated in Article 18(2) of the CCS Directive are fulfilled:

SCM17: Transfer of responsibility approved and accomplished

After the previous milestones 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 their responsibilities concerning the storage site.

As the criteria in the CCS Directive are defined at a high abstraction level they have to be complemented with more specific risk management and technical criteria that can be applied on an operational level. The risk management criteria, termed “R-type” criteria, are linked to the risk management milestones which have been described above. Some of these R-type criteria refer to input from models and monitoring measurements. If a parameter is predicted by modelling and measured by monitoring, the high-level criterion “the conformity of the actual behaviour of the injected CO_2 with its modelled behavior” is of primary application. A complete overview of the risk management criteria is shown Table 1 and a detailed description of these criteria is included in [7].

Table 1. List of the criteria connected with the Site Closure Milestones

R-type criteria	Description of criteria	EC requirements and Site Closure Milestones (SCM)	Sub-Phase
R1	Pressure evolution conforms to the reservoir models	Absence of leakage (SCM10 & SCM12)	Post-closure
R2	No detectable indication of leakage by monitoring measures		
R3	Evidence for the location of the CO_2 plume within the storage site by periodic seismic surveys or other appropriate measures		
R4	Leakage has not been detected for at least 10 years, this period may include the operational phase		
R5	Well integrity is checked directly before abandonment according to best practices		
R6	Model recalibration iteration loop is ending, i.e. model recalibration is not required any more	Conformity of monitoring data and model predictions (SCM7 & SCM8)	
R7	Model recalibration iteration loop ended at least five years ago		
R8	Pressure is developing towards an equilibrium pressure and according to models	Site evolvement towards long-term stability (SCM11)	
R9	Plume movement is matching model predictions		
R10	Plume is not moving out of the storage site, confirmed by modelling and monitoring		
R11	Optional verification of other parameters/features related to the storage concept		

3.2. Traffic-light system for managing significant irregularities and criteria

If a significant irregularity should occur then additional risk management actions would need to be deployed including monitoring and corrective measures. To highlight the conditions where such additional actions would be needed a traffic light system with a set of technical criteria ("T-type") has been drawn up (Fig. 2 and Table 2).

The major goal of the traffic light system is to provide a framework for dealing with offsets of model predictions and monitoring data (MMO, i.e. Model-Monitoring Offset). Fig. 2 depicts the flow diagram of the proposed traffic light system. The system consist of a decision workflow determining the state by which the site in question is characterized. Three different states have been distinguished:

1. Status green: MMO of all parameters are within tolerance, i.e. the site is in a regular and expected condition;
2. Status orange: MMO of one or more parameters are off tolerance; the operator has to prove whether the models in question have to be recalibrated or irregular site behaviour is present; this involves a discussion between operator, experts and the CA;
3. Status red: Irregular site behaviour is present; additional monitoring, counter measures, and mitigation measures have to be applied.

The criteria implemented in the traffic light system (T-type criteria) provide more detail for the evaluation of MMO and how to proceed after detection of significant offsets between monitoring data and model predictions. Consequently, the T-type criteria represent a subset of all R-type criteria which refer to modelled and monitored parameters. If the traffic light system relying on the T-type criteria is on status green, the corresponding R-type criterion is fulfilled. The T-type criteria have been differentiated in generic (T1, T2) and parameter-specific ones (T3-T11).

The three criteria levels, i.e. the high-level criteria of the CCS Directive, R-type criteria and T-type criteria have been connected to each other in order to form a coherent generic set of criteria for transfer of responsibility and abandonment of a CO_2 storage site (see Appendix B).

The approach to define criteria leading to the responsibility transfer of the site revealed that, although based upon a generic framework, the definition of such criteria is highly site dependent. Particularly the definition of tolerable model-monitoring deviations and accuracies of models requires thorough considerations by the operator of the site and the Competent Authority. The traffic light system is suitable for treating irregularities through all phases of the storage lifetime.

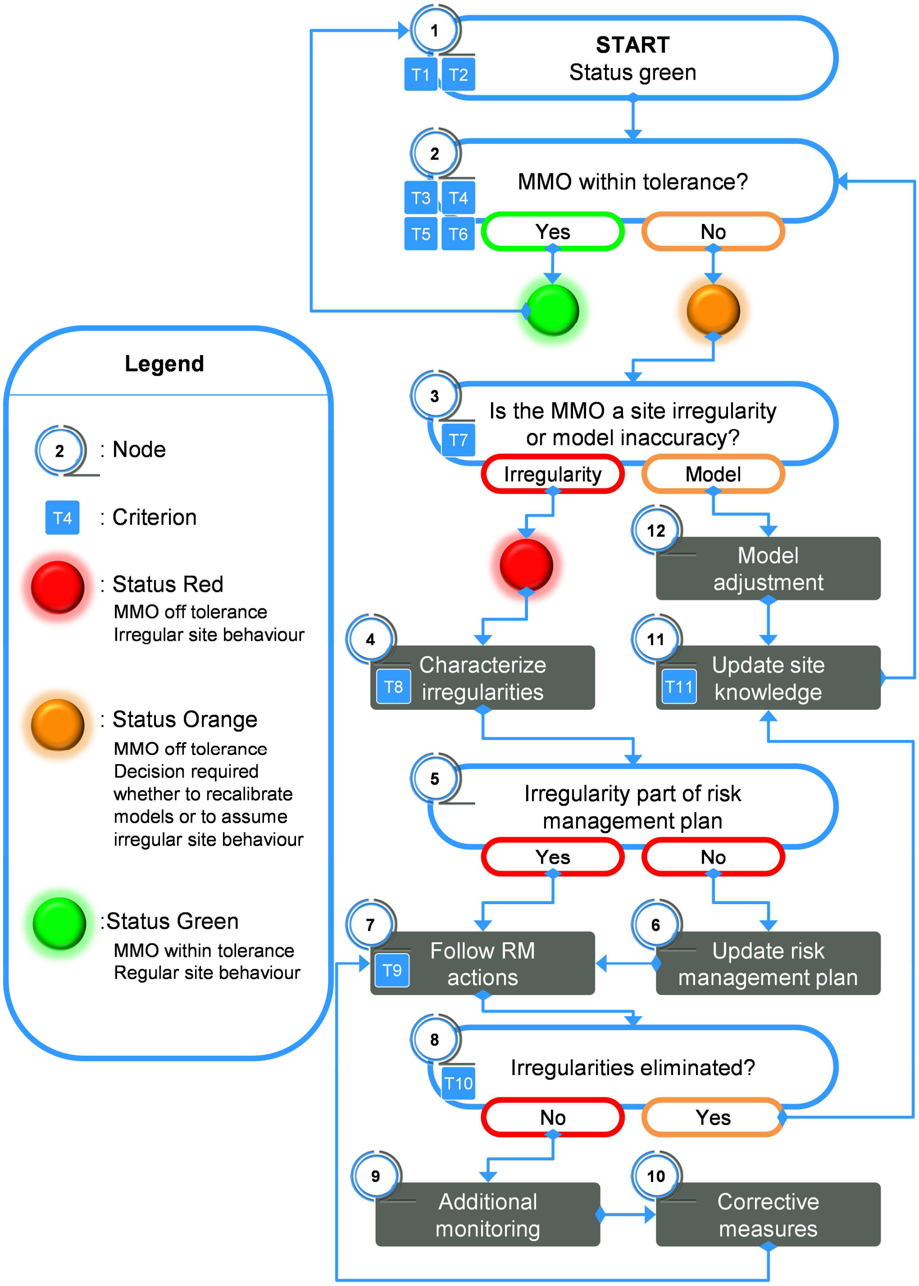

Fig. 2. Flow diagram of the traffic light system for risk-related decision making in the post-closure sub-phase and definition of the three risk priorities (status red, orange and green). MMO= Model-Monitoring Offset; note that the CCS Directive exclusively refers to ‘significant irregularities’ instead of ‘irregularities’

Table 2. Criteria supporting the traffic light system (T-type criteria)

Criterion code	Description	General Criterion
T1	Models and monitoring of required site-specific monitoring parameters are implemented	yes
T2	A list of prioritised models is in place and the mandatory models are implemented	yes
T3	Duration of the time interval to check for MMO	no
T4	Relative amount of the tolerable MMO	no
T5	Accuracy/precision of monitoring technique	no
T6	Accuracy/precision of models	no
T7	Does an observed MMO refer to site irregularity or is model recalibration required?	no
T8	In case of site failure: Are the primary and all connected irregularities identified?	no
T9	In case of site failure: are all required RM measures ready to be applied?	no
T10	Are the irregularities eliminated by the RM measures applied?	no
T11	Is there data to improve the site knowledge?	no

4. K12-B CO_2 injection pilot

The milestone chart and traffic light system have been applied to the ongoing K12-B CO_2 injection pilot [8]. It should be noted that the CO_2 injection activities at K12-B are executed under an existing hydrocarbons production license and do not have to comply with the transposed rules of the CCS Directive. The K12-B gas field is located in the Dutch sector of the North Sea. The top of the reservoir lies approximately 3,800 meters below sea level, and the ambient temperature of the reservoir is over 127 ºC. The K12-B gas field has been producing natural gas from 1987 onwards and is currently operated by GDF SUEZ E&P Nederland B.V. The natural gas has an initial CO_2 content of 13%, which is relatively high. Since the start of the gas production the CO_2 component has been separated from the natural gas stream on-site and since 2004 part of the separated CO_2 is re-injected into the gas field.

The test on the K12-B injection pilot has proven that the proposed milestone chart, traffic light system and related criteria were effective and efficient. Based on the available data and knowledge, the three requirements for transfer of responsibility in the CCS Directive were answered, which establishes a promising basis for future application in CO_2 storage projects.

The following overall findings were obtained for the K12-B injection pilot [8]:

a. The modelling-monitoring conformity is high. The difference between measured and modelled pressures have generally been no more than a few bars and where such irregularities occurred, concrete explanations could be found, and it could be demonstrated that these explanations are not conflicting with the solidity of the storage concept.
b. Since the K12-B reservoir has very good top and side seals and their effectiveness has been demonstrated by the reservoir containing gas for millions of years under high pressures, the only possible leakage pathways that could develop should be along the wellbores. The absence of significant irregularities during the years of gas production and during the ongoing CO_2 injection phase, and the fact that there is the absence of evidence for gas migration along the wellbores, confirms well integrity to this date. There has been no detectable leakage.
c. Since the reservoir will be closed in before reaching the original reservoir pressure, the surrounding rocks will contain fluids at a greater pressure and the long-term evolution will be one of a gradual return to equilibrium hydrostatic pressure.

The traffic light system could be tested on an observed anomaly in the Top Hole Pressure of the injector K12-B6 [8]. Initially, the simulator could not reproduce the observed shut-in bottom hole pressure for the injection well K12-

B6. An excellent match exists for the periods with CO_2 injection, but during shut-ins of the injector well the bottom hole pressure does not drop as much as the simulator indicates and definitely not to a level near the average reservoir pressure. The observed BHP in injection well K12-B6 is significantly larger than is observed in the production wells K12-B1 and K12–B5.

The explanation is that the plugged well section between the lower high pressure water bearing unit and the upper gas producing low-pressure unit is not perfectly sealed enabling cross-flow of fluids, probably water (Fig. 3). When the well was initially drilled it was intended that the well would also produce gas from the lower unit (the Lower Slochteren Member). Because of the high water production from the Lower Slochteren Member, this unit was isolated from the upper unit by a cement plug to prevent cross-flow between both units but apparently there was still communication between both units behind the casing (Fig. 3). In the shut-in state, water is migrating upward from the Lower Slochteren Member with high pressure towards the Upper Slochteren Member with a relatively low pressure. The low relative permeability of the Slochteren Formation to water causes the water to rise into the production tubing during shut-ins explaining the relatively high pressure during these passive phases. Inside the tubing the water will reach a stable level if pressure equilibrium between the wellbore and in the adjacent formation is established. The observed pressure during shut-ins could be explained with analytical calculations. As this cross-flow is an intra-reservoir phenomenon it has no effect on the containment of CO_2 in the reservoir. This example was nevertheless very useful in testing the traffic light system. More details can be found in [8].

Overall, it was recognised that the injection masses for K12-B was small. To enable more robust recommendations for the closure and transfer of responsibility, additional simulation work of site evolution should consider more realistic injection rates and storage capacity.

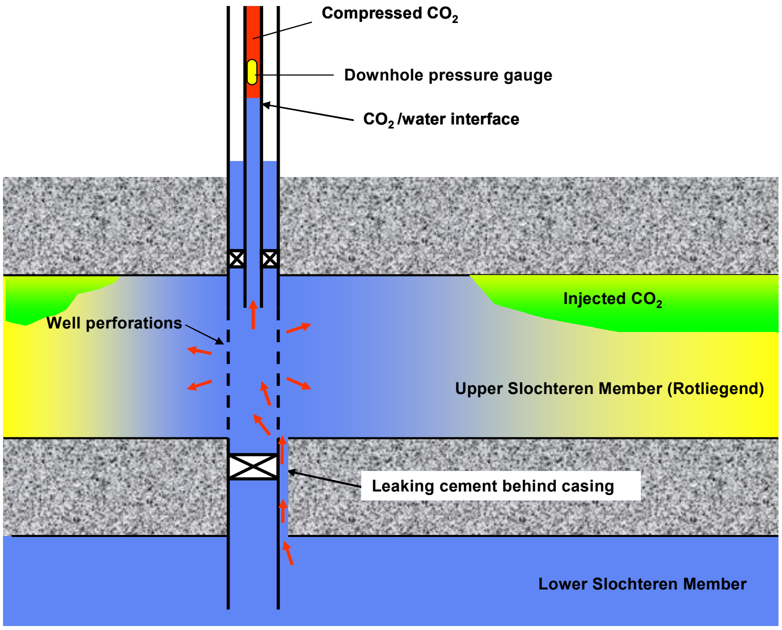

Fig. 3. Schematic of configuration of well K12-B6 with possible migration pathway

5. Conclusion and stakeholder feedback

5.1. Conclusion

Conformance of modelled and measured behaviour

Demonstrating conformance between predictive models of reservoir performance and monitoring observations is technically challenging because a unique and perfect match is near-impossible to achieve. CO2CARE recommends that conformance is based on demonstrating that predictive modelling capability increases systematically with time as monitoring data is progressively acquired. This indicates that storage processes are well understood and the modelling approach is robust [9].

Regulators should realise that a level of residual uncertainty in the predictive modelling is unavoidable, and is acceptable provided that end-members of the predicted range will not lead to unacceptable outcomes. At the point of transfer of liability, predictive models calibrated by monitoring data will have a residual uncertainty envelope, but this should be sufficiently small for unexpected or divergent future outcomes to be ruled out.

No detectable leakage

All leakage monitoring systems have a finite (and site-specific) CO_2 detection capability. It is recommended that regulators use the term "no detectable leakage" in the context of whether the leakage monitoring system can show a site is performing effectively in terms of health, safety, environmental and greenhouse gas emissions mitigation.

Emphasis should be on achieving the earliest possible detection of CO_2 migration from the reservoir, to maximise the time available for suitable mitigation actions to be implemented before leakage (migration of CO_2 out of the Storage Complex), actually occurs, and also to provide sufficient time for full remediation prior to any planned transfer date.

Long-term stability

Proving that a site is evolving towards long-term stability is challenging because predictive modelling of the longer-term processes is subject to significant uncertainty, and so far we have little field experience of post-injection processes. Full use of additional analogue information is important therefore, to develop a logical case for site stabilization. Use should be made of monitoring data from sites already in the post-injection period (e.g. Nagaoka), experimental data and relevant geological analogues which demonstrate stabilization processes in similar circumstances and the time-scales on which they operate.

5.2. Stakeholder feedback

Regulators an operators have been asked to respond to the proposed procedure and the dry run reports for transfer of responsibility [9]. Some of their findings are presented below.

General

The transfer report marks the end of a process that began with site selection and a permit application many years previously. Communication between Operator and Regulator should have been continuous during that period, so the transfer report should contain no surprises. The transfer report is part of a process which should build mutual confidence between regulator and operator.

The Competent Authority may wish to undertake its own simulations based on static models developed by the operators, to make an independent evaluation and consider the effectiveness of monitoring. Static geological models and numerical reservoir simulations that are developed on in-house software platforms rather than commercially available platforms such as Petrel and Eclipse may not be acceptable for transfer purposes because the Competent Authority would not be able to run the models.

Conditions of transfer

The Transfer report has the function of a contract – and it needs to contain key messages for the public. The State is likely to produce a counterpart document as well.

From an operator's perspective, it may be necessary to include a statement in the storage permit along the lines of: "if the storage site performs as predicted, no leakage is detected by the monitoring technologies deployed according to the monitoring plan, the site is evolving towards a state of long term stability, and all the terms and conditions in the storage permit are met, then the Competent Authority will accept transfer of the site". This would provide comfort to the investors and operator that the State would accept the site back once the storage operation had been successfully completed.

Managing uncertainty

As predictions of the future site performance are based purely on forward modelling, more numerical reservoir simulation runs in which more model parameters are varied may be necessary. It may also be necessary to conduct modelling of other aspects of the site performance, e.g. geomechanical stability. Predictions based on single lines of evidence are likely to be insufficient.

A far greater level of detail on how models were constructed and how they evolved throughout the storage site characterisation, construction and operation should be included. Furthermore, information on how such models take uncertainty into account would likely be necessary.

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Appendix A. Proposed Site Closure Milestone chart

The proposed chart supports the transfer of responsibility according to Article 18(2) in the CCS Directive.

Site Closure Milestone (SCM)		Description	Sub-Phase	Phase/Moment
0		Specify models and monitoring selected for conformity check	Final Operation	Operation
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 terminates		
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 presented to CA		
11		Effectiveness of storage concept: Evolution to long-term stability demonstrated		
11a	a	Pressure evolution demonstrated to match model prediction		
11b	b	Plume movement is demonstrated to be an acceptable match to model predictions (within tolerances)		
11c	c	Optional verification of other parameters/features related to the storage concept		
12		Final wellbore check before abandonment (final well 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

Appendix B. Criteria for post-operational decision making for responsibility transfer

The scheme below shows the R-type criteria (and the general T-type criteria) for post-operational decision making for responsibility transfer as well as the interconnection between the high-level criteria in the CCS Directive, R-type criteria, and the traffic light system.