Legal and related scientific issues with regard to the transfer of responsibility of CO_2 storage sites

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Executive summary

In this report a number of issues are put forward associated with the Transfer of Responsibility as defined in art. 18 of the EU Directive on the geological storage of carbon dioxide (2009/31/EC). The most important conclusion is that the added value of a post-closure delay, for example 20 years, until the responsibility take-over by the Competent Authorities is basically nil. The work done in risk assessment and characterization before a storage permit is requested must already have been convincing on health, safety and environmental (HSE) issues before a CO_2 storage permit is issued. In the subsequent injection phase ongoing modeling and monitoring have added to the conviction that the storage takes place in accordance with the requirements of the Directive. Furthermore, the injection phase presents the most severe test on the storage container, whereas post-closure the subsurface system approaches equilibrium.

In discussing equilibrium timescales it is put forward that container-wide geochemical equilibrium may take many thousands of years to establish. Pressure equilibrium (hydrostatic equilibrium) may take hundreds of years for large containers. Thus, in many cases it will be impractical to install a waiting period for even hydrostatic equilibrium to have occurred.

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1. Introduction

In the EU Directive on the geological storage of carbon dioxide (Directive 2009/31/EC)[1], Article 18 describes the terms under which a Transfer of Responsibility takes place of the Storage Site from the responsible operator to the Competent Authorities (henceforth CA). Art.18. states that the responsibility will be transferred to the CA if a number of conditions are met. One of the conditions that will concern us in this deliverable is explicitly stated in art.18 1(b) “a minimum period, to be determined by the competent authority has elapsed. This minimum period shall be no shorter than 20 years, unless the competent authority is convinced that the criterion referred to in point (a) is complied with before the end of that period;” In point (a) we find that all available evidence should indicate“.. that the stored CO_2 will be completely and permanently contained;”

Article 18.1(b) thus opens the possibility for the CA to take over the responsibility in a time that might be significantly less than the minimum of 20 years. One may speculate about the reasons for this article, but it seems clear that the Storage Directive is sympathetic to the idea that an operator wants to get rid of the burden of responsibility as soon as possible, as discussed in deliverable CATO2 WP4.1-D01. Indeed, if CCS is to take off large-scale hurdles like that must be removed or at least adapted, and art. 18.1(b) could be viewed by some as an attempt to remove one such hurdle. In actual fact the article creates a tension between the short-term industry interests and the long-term climate and security interests. In D01 it was advocated, for this very reason, to standardize the length of the transfer to responsibility period. But as it is, the various Member States of the EU can use the possibilities offered in art. 18.1(b) to shorten the stated 20-year period.

An obvious research question, then, is how one should scientifically establish a situation as described in art. 18.1(a). That is, how one should come to the judgment that the CO_2 is stored completely and permanently - or not, as the case may be. Indeed, one might also ask how the European Commission decided on a 20 year minimum transfer of responsibility during the development of the Storage Directive. This deliverable will review the various aspects of the research question as well as issues that are somehow related. Fortunately we can draw upon various CATO2 deliverables that have been forthcoming since the project started, notably WP4.1 D01 (henceforth D01) and WP4.1 D08 (henceforth D08), respectively on the implementation of the CCS Directive into national law and assessment of risks and uncertainties in CCS. (In the open literature the contents of D01 is essentially contained in Lako et al., 2011).

We shall restrict, hence, the discussion to the strictly scientific part of the issue of transfer of responsibility. In this deliverable we try to give material substance to the purely legal requirements in art. 18.1 (a) and (b).

[1] Will be referred to as the ‘Storage Directive’ for the remainder of the document.

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2. Legal and scientific issues

Before a certain geological formation is actually used for CO_2 storage there is a lot to be done. In chapter 3 of deliverable D01 the necessary steps are outlined in detail.
First of all there is a *screening* phase in which all available data is used to make a quick-and-dirty assessment whether the site could possibly qualify as storage site. Is there sufficient volume? Are there other activities in the vicinity that might preclude storage? Are there logistic impediments? Etc. In this phase it is decided whether the answers to such questions are problematic. If not, then one enters the *selection* phase. This phase will usually start with acquiring more data. Then characterization and assessment of the proposed site commences. If this work ends successfully the site might be positively selected, and the injection of CO_2 may begin. The interested reader is referred to the Storage Directive and D01 for concomitant details like permitting, monitoring plans, etc. that are not subject of this deliverable.

In *selecting* the geological formation the CA expresses the serious expectation that all further steps that will eventually lead to transfer of responsibility can be taken successfully. There is no absolute guarantee of success, of course, but the work must have provided thrust in a successful outcome. Indeed, the work that has been done prior to the decision will always have been extensive. The different scientific disciplines operate along the lines described in the aforementioned chapter of D01, and the results are combined (“digested”) as described in deliverable D08. After all this work has been completed there are, we expect, a number of feasible subsurface models available. On the basis of what these models tell us about the events during and after injection the CA‘s decision is made to select the site and go ahead, or not to select it after all.

First issue: *modeling future operations*
But here we note a peculiar situation. The modeling to assess and characterize is based on data acquired *before* the injection phase has even started, and this is necessarily the case on account of the demands in the Storage Directive. During the various modeling exercises something must be assumed about the way CO_2 is injected: which pressures are applied at the wellhead, or alternatively what volume CO_2 per unit time is sent down. This is not clear at the moment of the assessment and characterization phase. Maybe different operational choices matter for the theoretically obtained results and subsequent monitoring, maybe not. Here the use of various (sub)-models as documented in D08 already pays off: one can follow the evolution in various operational circumstances, and this will tell the investigators to what extent differences are to be expected in what one may observe during monitoring. It is clear that the (sub)-models constructed in order to get a permit for starting the CO_2 injections are *provisional;* with new incoming data these models will almost certainly need updating.
[Note: in the following we will use the term “models” to denote both structural models and the various sub-models, except where the difference is explicitly called for. For our purposes this does not lead to confusion.]

Second issue: *significant deviation?*
If and when an injection phase is started more data can be collected. That happens by way of monitoring, which consists of a whole array of measurements over time and space. A different work package (WP4.5) within CATO2 is devoted to this issue, and the technicalities are not discussed in this deliverable.

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Monitoring is based on modeling results and according to the risk assessment analysis. In art. 13.1 of the Storage Directive the explicit monitoring purposes are mentioned, the first of which states the purpose of "comparison between the actual and modeled behavior of CO_2 and formative water in the storage site".

A difficult, but very important issue follows from a demand explicitly formulated in Annex II,1.2, on criteria for establishing and updating the monitoring plan (Art. 13(2): "Where there is a significant deviation between the observed and the predicted behavior, the 3-D model shall be recalibrated to reflect the observed behavior.
The recalibration shall be based on the data observations from the monitoring plan, and where necessary to provide confidence in the recalibration assumptions, additional data shall be obtained."
This statement calls for some scientific comments.

1) The text mentions "the 3-D model". However, until the very last stage one should entertain *various* geological models, i.e. geological models that differ substantially, usually in structural build-up. With each structural 3-D earth model one will define many *sub* models with different content as regards porosity and permeability.
   At the moment that it has to be proven before the CA that the site is a safe and permanent container a definite choice will have to be made between these (sub)-models. Until that moment it is unwise to part company with (too) many sub-models altogether, even if some seem to do clearly better than others at the time. This means that all sub-models that one wants to preserve have to be updated upon new data, at least on a regular basis.
2) There is an obvious practical issue involved in the expression "significant deviation between the observed and predicted behavior". Neither in D01, nor in Lako et al. (2011) there is any comment on what this means. Again, we can get some idea about conformity between modeling results and measurements when using various models. If observed behavior of (say) the CO_2 plume is different from that predicted in each and every model entertained so far there is a good reason to speak of "significant deviation". By having recourse to many different models we can make this expression acquire an *operational* meaning. Had we only used one single model from the outset to compare observed behavior and modeled behavior we might quickly be forced to call a deviation significant. After all, that one single model is "a lucky shot" in the infinitude of all possible models compatible with the observed data, and we cannot reasonably expect that chosen model to be "spot on". We shall have more to say about this later on.

Third issue: *added value post-closure monitoring?*

When the storage site is closed one enters the post-closure phase. The operator remains responsible for the site, and he has explicit monitoring (and corrective measure) obligations as laid down in art. 17(2). Unless unwanted events take place the site is left untouched; the operator just monitors while the subsurface system evolves towards some sort of equilibrium situation. The next question forces itself upon us: What is the added value of the monitoring by the operator as regards establishing a situation of complete and permanent containment?

When the site is closed a new phase enters in which, as mentioned, the subsurface system evolves to some sort of equilibrium. Certainly one expects pressures to subside in the wells. CO_2 in the containing compartment(s) will partly dissolve in the other reservoir constituents present, like water, and remnant oil and gas - which also contributes to lowering the reservoir pressure. The CO_2 plume will presumably spread to some maximal extent; it is expected not spread beyond bounds formed by any closed compartments, identified in the

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characterization and assessment process. Geochemical processes like CO_2 induced mineralization will evolve, and will continue to evolve for many thousands of years. Geo-mechanically one expects equilibrium as well in this phase – induced seismicity in this stage would seem strange, potentially alarming. Various monitoring techniques may assist in tracking down the evolution in the subsurface by comparing the measurements with the models still "on offer".
Monitoring in this post-closure phase can do two things for us.

1) Tracking down whether the general trend in evolution is followed, comparing measurements with the various models. One cannot reasonably expect the measurements to be completely in line with one single model, as discussed earlier. Rather, one should hope that most models show similar trends. One might expect that to happen, but there is no absolute guarantee. Many models showing similar trends makes the issue of how to identify "significant deviations" operationally probably less acute. Moreover, "Quality Control" of any one model makes it possible to assess whether the models (or a subset of them) can act as an acceptable description of what actually happens – if there is a match to a sufficient degree. See Appendix II, third bullet, of D08 for a numerical criterion.
2) Post-closure monitoring gives data that further assist in making the choice of a final model. At some point one stops updating the models, and uses incoming data henceforth to pass judgment on the models. The wealth of data obtained in the injection phase (presumably some 10-50 years) will have led at some point to a fixed collection of models that fare best and that are kept in store for continued comparison with data. If there are models that turn out to be comparable in likelihood after Model Comparison as described in D08 their relative rankings will certainly be further affected by the post-closure monitoring. In this way post-closure monitoring further assists in making the desired final choice. The only difference with injection phase monitoring is that the monitoring post-closure cannot be used exclusively to improve the models: at some point in time post-closure a definite choice must be made for the best model. This moment can be chosen at will. It would certainly be possible to choose the time of site closure itself. Post-closure monitoring data would then exclusively be used to choose the final model.

Fourth issue: *the waiting period after closure*

The Storage Directive defines a minimum timespan of twenty years before the responsibility can be handed over to the CA (Art.18.1(b)). Curiously enough, in the same article this demand is immediately weakened by the stipulation "…, unless the competent authority is convinced that the criterion referred to in … is complied with before the end of that period." In D01 and Lako (2011) it was commented that this addition is not conducive to a "level playing field"; some authorities may emphasize climate and security interests, others may be inclined to let industry interests prevail.
Let us now consider the minimum period from a scientific perspective. Is there a scientific reason to require a minimum time span? And if so, why twenty years?
The characterization and assessment must be completed before any injection can take place. Already in such an early phase the CA eventually decides that these activities have shown that a situation prevails as mentioned in Art.4(4): there is no significant risk of leakage and no significant environmental or health risk. That is, the modeling with all the provisos described in D08, shows *in the pre-injection phase* that the criteria set in the Storage Directive, and perhaps detailed in the national legal systems, are met.
What is the situation post-closure? During the injection phase the provisional models – already deemed good enough to issue the injection permit - monitoring has provided new data with which models are updated and regularly ranked. Furthermore, apparently no

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events have emerged that brought the whole enterprise to a grinding halt. If anything, it is this operational phase that provides the hardest test to the container and its surroundings as it is the phase of re-pressurization. In the discussion of the third issue we have indicated two things that post-closure monitoring (and modeling) can do for us. These actions do not differ in methodology from modeling and monitoring actions while injecting CO_2 and the real "stress test" for the subsurface has been performed already during the injection phase. The only difference post-closure is that wells are closed. During these technical closure operations tests will have been performed so as to show that closure has been done properly. Monitoring will go on, but from a scientific point of view the post-closure phase does not require specific *new* know-how that necessarily requires an operator to deal with it. Now realizing that at some point in time there should be a transfer of responsibility - the Storage Directive requires it - site closure is as good a time as any time later. *There is no compelling scientific reason, then, why a further timespan has to elapse before the CA take over the responsibility*, let alone a timespan of twenty years.

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3. Timescales of equilibrium

Now let us suppose for the sake of argument that the Competent Authority wants to define a waiting period equal to the equilibration time of the processes in the container. During this period the operator would still have full responsibility, and only after the CA would allow transfer of responsibility. What waiting periods would be expected in most general terms?

When the injection wells are closed the subsurface will tend to an equilibrium situation. In the reservoir that contains the CO_2 a lot of processes evolve. Foremost there is some residual flow till hydrostatic equilibrium is attained. Surely, part of the injected CO_2 will dissolve in water. The temperature in the subsurface, being somewhat disturbed by the CO_2 injection, will resume an equilibrium distribution in accordance with the geothermal gradient. Geochemical mineralization processes will take place, whereas the original pH is changed. For the development of the reservoir and its integrity as a CO_2 storage container pressure equilibration and geochemistry stand out as being of prime importance.

Pressure evolution

After the injection phase the reservoir is left to its own. Residual flow will take place until hydrostatic equilibrium has been reached. In standard texts on reservoir engineering (for instance Dake, 1978) it is shown that the pressure evolution in the reservoir is governed by a so-called diffusion equation. This equation enables us – inter alia - to make *order of magnitude* estimates of the time to equilibrium. If we consider a radial reservoir, with width much larger than height, then a typical time scale to equilibrium can be roughly estimated as

$T_{equilibrium} = L^2 . (\varphi\ \mu\ c / k)$ with

L= radius of the reservoir,
φ = porosity,
μ = dynamic viscosity
c = compressibility of the liquid-rock system
k = permeability

In obtaining the above formula it is assumed that the properties of the fluid and the reservoir rock are uniform. The diffusive character of the pressure equilibration is borne out by the fact that the time depends quadratic on size.
Again, the above formula represents a (very) crude approximation of the equilibrium time.
If we take $L = 10^3$ m, φ =0.2, μ = 0.2 Pa.s , c = 10-9 Pa^{-1}, k= 10^{-14} m^2 (= 10 milliDarcy) for the radius of a reservoir, and the porosity, the dynamic viscosity, the compressibility and the permeability we estimate $T_{equilibrium}$ to be ≈ 130 years. The numbers used are by no means “canonical”, quite some variation being possible. This example shows, however, that pressure equilibration may well take up to centuries for large storage containers.

Geochemistry

In a paper by Tambach et al. (2013, forthcoming) the authors calculate by numerical simulation what happens in the subsurface in terms of pH, mineralization and porosity when the injection phase begins and how things broadly evolve after closure. For us their description of the long term evolution is important. The pH value seems to attain values above 5., and CO_2 is being trapped in part into carbonate minerals all over the storage

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reservoir. This has a minimal effect on the porosity (a few percentage points). The regions around the injection wells are mostly affected. The question is how much time the above processes will take. This depends on the conditions in the reservoir, and most clearly on the temperatures. It is safe to say that for all practical situations the evolution in the reservoir will at least take some thousands of years (Koenen, private comm.). Hence, geochemical equilibrium is not attained within the canonical 20 year's period mentioned in the Storage Directive.

Taking the above results together one arrives naturally at the conclusion that waiting for geochemical equilibrium to have occurred over the storage container is not a practical possibility. For the CA to define a waiting period during which the container reverts to hydrostatic equilibrium might perhaps be feasible for relatively small reservoirs; it is not feasible if timescales of the order of a century are to be expected. However, the analysis on equilibrium timescales given here leaves untouched our previous conclusion that such a waiting time is not strictly necessary from a purely scientific point of view.

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4. Concluding remarks

In this report a number of issues were brought up associated with the Transfer of Responsibility as defined in art. 18 of the Storage Directive. The most important conclusion from a practical point of view is *that, from a scientific perspective, the added value of a post-closure waiting time till the responsibility take over by the Competent Authorities is, in fact, nihil*. The work done in Risk Assessment and Characterisation before a storage permit is requested must already have been convincing on HSE issues before a storage permit is issued. In the subsequent injection phase ongoing modeling and monitoring have added to the conviction that the storage has taken place in accordance with the requirements of the Storage Directive, otherwise the whole project would have been abandoned / reversed in that phase. In fact, the most severe test on the storage container is to be expected just in the injection phase, whereas the subsurface system is not stirred post-closure, but approaches an equilibrium state.

In discussing timescales to equilibrium it was put forward that container-wide geochemical equilibrium may take many thousands of years. Also pressure equilibrium (hydrostatic equilibrium) may take hundreds of years for large containers. Thus, in many cases it will be impractical to install a waiting period for even hydrostatic equilibrium to have occurred.

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5. References

CATO2 WP4.1-D01: Support to the implementation of the CCS Directive, 2010

Dale L.P., Fundamentals of Reservoir Engineering, 1978, Elsevier Scientific Publishing Company

Lako P., van de Welle A.J., Harmelink M., van der Kuip M.D.C., Haan-Kamminga A., Blank F., de Wolff J., Nepveu M., 2011, issues concerning the implementation of the CCS Directive in the Netherlands, Energy Procedia 4, 5479-5486

EU, 2009, *Storage Directive 2009/31/EC*,

(http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0114:0135:EN:PDF)

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Appendix 1: Recent developments on Model Comparison in site closure context.

In the context of EU-project CO2CARE the Model Comparison method was recently used on two different models regarding gas field K12-B. In this field gas is produced with a sizable fraction of CO_2 . At the same time, however, CO_2 is injected into the field, and hence we deal here with EGR. The data used in the Model Comparison exercise were the Bottom Hole pressures in an injection well, and the CO_2 content (expressed as volume %) in the gas produced (Source: Deliverable D4.5 Results from comparison of modelled and measured behaviour at the K12-B site, submitted to the CO2CARE website in September 2012).

The method used follows the general lines as described in Appendix II of CATO2 deliverable D08 on Bayesian Model Comparison. Measured and predicted values of the above data must be compared, and to that end the typical measuring errors in the data and computational errors in the predictive tools must be known. It became soon apparent that for both models the values of the measuring errors, expressed as a "sigma" on the data were not really known, at least not preserved for posterity. With a lack of clear figures an assumption of some kind had to be made. The way forward was to assume values that would render the average chi-squared per data point of the *best* model of order unity. That is, we were basically *assuming* the best model to be acceptable as a description for the site. Obviously this is an unsatisfactory road to travel in the process, as one would normally have it the other way round. However, it seemed the only one option at the time.
The question thus emerged how to deal more satisfactorily with such an unknown sigma. Fortunately, Bayesian probability offers an elegant way to deal with this problem of the so-called "nuisance" parameters. (see e.g. Gregory, 2010 for an elaboration on what follows). The correct Bayesian procedure, then, to deal with this is as follows. One computes the model probabilities for several sigma's over some pre-defined interval [σ_{low}, σ_{high}] in which the true, unknown, sigma is believed to be. Each set of model probabilities now depends on a certain σ in the prescribed interval. Next, one integrates the results over the sigma-range weighted with the so-called Jeffrey's prior $p(\sigma) \infty 1./\sigma$ between the chosen lower and upper limits of sigma, and one thus ends up with a result that does not explicitly depend on one single, and perhaps too arbitrarily chosen, value of sigma. Note, that one still must be able to pinpoint some acceptable interval for σ, but that is generally not so problematic in view of background knowledge one surely possesses.

If one deals with many data of different types and associated different sigma's this may become a computational burden (integrating out N nuisance parameters means integrating over a space with N dimensions) when approached in an unsophisticated way, but modern Monte Carlo simulation techniques will alleviate this burden. It might well be that these techniques will have to be used in Model Comparison in our context.

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