CO_2CARE

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CO2CARE

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Table of Contents

List of tables

List of figures

List of Abbreviations

CCS	Carbon Dioxide Capture and Storage
DEA	*Danish Energy Authority*
EPA	Environmental Protection Agency
ERCB	Energy Resources Conservation Board
IEA	International Energy Agency
IOGCC	Interstate Oil and Gas Compact Commission
OGCA	Oil and Gas Conservation Act
OGCR	*Oil and Gas Conservation Regulations*
OPA	Offshore Petroleum Act
OSPAR FRAM	OSPAR Framework for Risk Assessment and Management
RGIE	*French General Regulations for the Extractive Industry*
UIC	Underground Injection Control
UKOOA	UK Oil and Gas Association
USDW	Underground Sources of Drinking Water
WRI	World Resources Institute

CO2CARE

1. Executive Summary

The objective of this document is to discuss the European and international regulations covering carbon dioxide storage and specially the site abandonment period starting after the end of CO_2 injection. According to these regulations, the liability for the storage site can be transferred to the licensing authority/government once the safety and conformity of monitoring with model predictions has been demonstrated. In the EU the CO_2 storage Directive 2009/31/EC set out the regulatory regime and guidance for permitting CO_2 storage and while a few EU countries have already transposed this directive to national law, most are still tasked with formulating their own national regulations. Around the world, relevant bills and regulations have been introduced in recent years too. In addition, regulations originating from the oil and gas sector concerning well abandonment are also relevant to CO_2 storage well abandonment.

To demonstrate the safety of the injected CO_2 all regulations require a combination of monitoring, modelling and risk assessment tasks. Although there is large variation in the specific requirements it is standard to require approval for these tasks as part of a plan submitted to the authority in charge. To demonstrate the safety of the injected CO_2, the results of monitoring, modelling and risk assessment, regulations require demonstration of no leakage, conformity with modelling predictions and that the site is evolving towards long term stability. Some regulations contain additional requirements including demonstrating no environmental problems, that the plume will not encounter any leakage pathways and demonstrating well integrity. There is a variation in the time period over which safety must be shown in different regulations, and an optimum time period is considered flexible.

Particularly in relation to well abandonment, it is recognised that there are different methods, materials and tests that could be used and most CO_2 storage regulations do not specify techniques to be followed or standards to be met. Specific details on plugging are provided by regulations on the abandonment of hydrocarbon wells and sometimes other injection wells and these provide the best available guidance for CO_2 storage well abandonment, although they may require updating to deal with CO_2 injection specific issues.

Regulations typically contain a provision for transfer of liability once safety (CO2 and well plugging) has been demonstrated. The EU Directive 2009/31/EC requires further monitoring after liability transfer as a back up measure, while other regulations (e.g. EPA UIC) do not. The IEA model regulatory framework contains a clause that the operator should also provide suggestions for the monitoring to be conducted after liability transfer.

2. Introduction

The main objective of this document is to present the regulations covering carbon dioxide storage with a special focus on CO_2 storage site abandonment. Site abandonment represents the period which starts after the cessation of CO_2 injection. There are a number of regulations that govern the work which must be performed after this point in the CO_2 storage site life time. Subject to meeting these requirements, the liability for the storage site can eventually be transferred to the licensing authority/government. This essentially requires demonstrating the safety and conformity of monitoring with model predictions. The introductory chapter to this document discusses the regulations in place across the world covering CO_2 storage. Then a brief discussion of the terminology used throughout the report is provided.

2.1 National and international regulatory requirements

The two most important functions of regulation are to provide operators with the necessary guidance for required practices and to ensure the safety of operations in the interest of citizens and society as a whole. A range of relevant regulations, both specific to CO_2 storage and more general, are available in different countries. These are listed in the table provided as part of Annex I accompanying this document. The current state of CO_2 storage regulations is summarised in the following paragraphs.

International regulations

The *London Convention*[1] and the *London Protocol*[2] are the international treaties that limit the discharge of land based waste at sea. The *London Protocol* permits offshore CO_2 storage after an *Amendment agreed in 2007,* however, it provides no specific details on abandonment.

The *OSPAR Convention*[3] also provides regulations on protection of the marine environment. The *OSPAR Decision 2007/2*[4] signed by 15 countries, updates the convention to allow CO_2

[1] London Convention, 1972. Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter

[2] London Protocol, 1996. Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (http://www.imo.org/KnowledgeCentre/HowAndWhereToFindIMOInformation/IndexofIMOResolutions/Pages/London-Convention-(LDC,-LC)-and-London-Protocol-(LP).aspx)

[3] 1992 Convention for the Protection of the Marine Environment of the North East Atlantic (OSPAR) (http://www.ospar.org)

[4] OSPAR Decision 2007/2 on the Storage of Carbon Dioxide Streams in Geological Formations (http://www.ospar.org/v_measures_spider/browse.asp?menu=00820431000000_000000_000000&v0=OSPAR+Decision+2007%2F2+on+the+Storage+of+Carbon+Dioxide+Streams+in+Geological+Formations)

storage. The Decision and the *Amendments to the Convention*[5] provide regulations on how to obtain permits for CO_2 storage. The '*OSPAR Framework for Risk Assessment and Management of CO_2 Streams in Geological Formations (FRAM)*'[6] covers risk assessment in detail but does not specifically cover abandonment.

The International Energy Agency (IEA) produced a model regulatory framework[7] for countries wanting to create their own CO_2 storage regulations.

EU Regulations

In the European Union (EU), '*Directive 2009/31/EC*'[8] entered into force on 25/6/2009. It sets out a regulatory regime for permitting CO_2 storage and there are accompanying guidance documents[9,10,11and12] to provide further detail. There are also EU directives covering CO_2 emissions, which have relevance to CO_2 storage ('*2003/87/EC*'[13], *'2009/29/EC*[14]' and *'2010/245/EU*[15]').

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[5] Amendments of Annex II and Annex III to the Convention in relation to the Storage of Carbon Dioxide Streams in Geological Formations' (http://www.official-documents.gov.uk/document/cm76/7696/7696.pdf)

[6] OSPAR Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations (http://www.ospar.org/v_measures_spider/browse.asp?menu=00820431000000_000000_000000 &v0=OSPAR+ FRAM)

[7] IEA CCS Model Regulatory Framework (http://www.iea.org/ccs/legal/model_framework.pdf)

[8] Directive 2009/31/EC (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0114:0135:EN: PDF)

[9] Implementation 2009/31/EC on the geological storage of carbon dioxide - Guidance Document 1 - CO_2 Storage Life Cycle Risk Management Framework (http://ec.europa.eu/clima/policies/lowcarbon/docs/gd1_en.pdf)

[10] Implementation 2009/31/EC on the geological storage of carbon dioxide - Guidance Document 2 Characterisation of the Storage Complex, CO_2 Stream Composition, Monitoring and Corrective Measures (http://ec.europa.eu/clima/policies/lowcarbon/docs/gd2_en.pdf)

[11] Implementation 2009/31/EC on the geological storage of carbon dioxide - Guidance Document 3 - Criteria for Transfer of Responsibility to the Competent Authority (http://ec.europa.eu/clima/policies/lowcarbon/docs/gd3_ en.pdf)

[12] Implementation 2009/31/EC on the geological storage of carbon dioxide - Guidance Document 4 - Financial Security (Art. 19) and Financial Mechanism (Art. 20) (http://ec.europa.eu/clima/policies/lowcarbon/docs/gd4_en. pdf)

[13] 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:275:0032:0032:EN:PDF)

[14] 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0063:0087:en:PDF)

[15] 2010/345/EU Commission Decision of 8 June 2010 amending Decision 2007/589/EC as regards the inclusion of monitoring and reporting guidelines for greenhouse gas emissions from the capture, transport and geological

CO2CARE

EU countries are now tasked with formulating their own national legislation that incorporates the *2009/31/EC directive*[8]. The UK was the first country to have performed this through *'The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010'*[16]) which came into force on 1st October 2010. The '*UK Energy Act 2008'* also provides regulations for CO_2 storage but does not contain specific engineering stipulations. In Spain the CCS Act 40/2010[17] entered into force on 31 December 2010 with a statute that is a full, simple and uncomplicated transposition of the Directive. In Denmark the CCS Bill was presented based on an amendment of the Subsoil Act, while the more technical aspects of the CCS Directive will be implemented into an executive order. The proposed Bill was adopted by the Danish Parliament in May 2011. In Germany, the EU Directive has not been transferred into national law yet. However, on the 13 April 2011 the German Federal Cabinet has approved a Draft Act[18] with main objective to create a legal framework for testing, demonstration and application of the CCS technology in a few, small to moderate storage sites. A first reading by the German Bundesrat took place in early May 2011. After parliamentary committee meetings a second or third reading is planned for June 2011. The German CCS Act is scheduled to enter into force in autumn 2011. If the Draft Act becomes German law in 2011 it will be fully evaluated again in 2017. Other countries will soon be producing their own legislation. Dutch legislation should be implemented in national law by 25/6/2011.

The EU countries do have regulations from the oil and gas sector concerning well abandonment[19, 20, 21, 22 and 23], which are relevant to CO_2 storage well abandonment.

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storage of carbon dioxide (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:155:0034:0047:EN:PDF)

[16] UK The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010 (http://www.legislation.gov.uk/ssi/2011/24/contents/made?view=plain)

[17] Spanish CCS Act 40/2010 De almacenamiento geológico de dióxido de carbono. (http://www.congreso.es/constitucion/ficheros/leyes_espa/l_040_2010.pdf)

[18] German Draft Act for the Demonstration and application of technologies to capture, transport and permanent storage of carbon dioxide, 2011 (http://www.bmwi.de/BMWi/Redaktion/PDF/Gesetz/entwurf-abscheidung-transport-kohlendioxid,property=pdf,bereich=bmwi,sprache=de,rwb=true.pdf)

[19] UK Oil and Gas Association (UKOOA) Guidelines for the Suspension and Abandonment of Wells (http://www.ukooaenvironmentallegislation.co.uk/Contents/Topic_Files/Offshore/Well_abandonment.htm#performance)

[20] Danish Energy Authority (DEA) A Guide to Hydrocarbon Licenses in Denmark (http://www.ens.dk/en-us/oilandgas/licences/guide/documents/guidetohc.pdf)

[21] French General Regulations for the Extractive Industry (RGIE)

[22] NORSOK Standard D-010 Norway (http://www.npd.no/Global/Norsk/5%20-%20Regelverk/Skjema/Br%C3%B8nnregistrering/Norsok_standard_D-010.pdf)

[23] Mining Regulations of The Netherlands (2003) (http://www.nlog.nl/resources/Legislation/MBREnglishAug%2009.pdf)

Finally, Norway has regulations[24,25] that cover some aspects of CO_2 injection related to petroleum activity (e.g. the Sleipner CO_2storage site).

Regulations in the USA

The USA Environmental Protection Agency (EPA) has produced CO_2 storage regulations under the authority of the Safe Drinking Water Act[26]. This is an addition to the existing Underground Injection Control (UIC) program, which applies to other types of underground injection. These regulations specify minimum federal requirements for individual states that perform CO_2 storage. States may apply to the EPA to have primary enforcement over UIC projects, provided that they meet minimum federal requirements. So far, thirty-three states have done so with the remaining states either sharing authority over UIC projects with the EPA or being under EPA authority for UIC projects.

The Interstate Oil and Gas Compact Commission (IOGCC)[27] and the World Resources Institute (WRI)[28] has produced model statutes that individual states can base their own regulations on.

Some states have produced legislation on the storage requirements for CO_2 storage. The relevant ones are from the states of Washington[29], Wyoming[30], Texas[31], North Dakota[32] 'Louisiana[33] and Montana[34]. These bills describe regulations on permit applications, financial matters, authority, liability etc. However, they do not typically go into detail about particular requirements for how to close a site, how to perform well plugging etc.

[24] Norwegian Pollution Control Act (1981) (http://www.regjeringen.no/en/doc/Laws/Acts/pollution-control-act.html?id=171893)

[25] Norwegian Pollution Control Act (1996) (http://www.npd.no/en/Regulations/Acts/Petroleum-activities-act/)

[26] EPA Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide Geologic Sequestration Wells; Proposed Rule 2010 (http://www.federalregister.gov/articles/2010/12/10/2010-29954/federal-requirements-under-the-underground-injection-control-uic-program-for-carbon-dioxide-co2#p-577)

[27] IOGCC. CO_2 Storage: A Legal and Regulatory Guide for States 2008 (http://iogcc.publishpath.com/Websites /iogcc/pdfs/Road-to-a-Greener-Energy-Future.pdf)

[28] WRI Guidelines for Carbon Dioxide Capture, Transport, and Storage 2008 (http://pdf.wri.org/ccs_ guidelines.pdf)

[29] Washington 173-218 UIC (http://apps.leg.wa.gov/WAC/default.aspx?cite=173-218-115)

[30] Wyoming HB 90 (http://legisweb.state.wy.us/2008/Enroll/HB0090.pdf)

[31] Texas HB 1796 (http://www.legis.state.tx.us/tlodocs/81R/billtext/pdf/HB01796F.pdf)

[32] North Dakota SB 2095 (http://www.legis.nd.gov/assembly/61-2009/bill-text/JQTA0100.pdf)

[33] Louisiana HB 661 (http://www.legis.state.la.us/billdata/streamdocument.asp?did=668800)

[34] Montana HB 498 (http://data.opi.mt.gov/bills/2009/billpdf/SB0498.pdf)

There are also state level regulations from the oil and gas sector concerning well abandonment[35, 36, 37, 38 and 39] which are likely to be relevant to CO_2 storage well abandonment.

Australian regulations

The Australian government has jurisdiction in offshore areas (over 3 nautical miles from the coast), while the states and territories have jurisdiction onshore and in coastal waters. The government produced a plan to form the basis for a nationwide consistent regulation[40]. The first step was an amendment to the Offshore Petroleum Act (OPA)[41] to regulate offshore CO_2 storage. Associated documents were the Impact Statement[42] and explanatory guidelines to the OPA amendment[43].

Victoria has created onshore[44] and offshore[45] legislation for regulating CO_2 storage. Queensland has created CO_2 storage legislation in the form of an Act[46] and a Regulation[47]. New South Wales has created CO_2 storage legislation in the form of a Bill[48].

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[35] Wyoming Oil and Gas Conservation Commission 7928 Ch. 3 (http://soswy.state.wy.us/Rules/RULES/7928.pdf)

[36] Administrative rules of Montana Title 36 Chapter 22 Oil and gas conservation (http://www.mtrules.org/gateway/ChapterHome.asp?Chapter=36%2E22)

[37] Texas Administrative Code 3.14 (http://info.sos.state.tx.us/pls/pub/readtac$ext.TacPage?sl=R&app=9&p_dir=&p_rloc=&p_tloc=&p_ploc=&pg=1&p_tac=&ti=16&pt=1&ch=3&rl=14)

[38] California Code of Regulations. Title 14 Division 2 (ftp://ftp.consrv.ca.gov/pub/oil/regulations/PRC04.PDF)

[39] Alaska Administrative Code 25.112. Well plugging requirements (http://www.touchngo.com/lglcntr/akstats/aac/title20/chapter025/section112.htm)

[40] Australian Regulatory Guiding Principles for Carbon Dioxide Capture and Geological Storage (http://www.ret.gov.au/resources/Documents/ccs/CCS_Aust_Regulatory_Guiding_Principles.pdf)

[41] Offshore Petroleum Amendment Bill 2008 (http://www.ret.gov.au/resources/Documents/ccs/os_Petroleum_Amendment_Bill_2008.pdf)

[42] Australian Regulatory Impact Statement (http://www.ret.gov.au/resources/Documents/ccs/Regulation_Impact_Statement.pdf)

[43] Revised Explanatory Memorandum to the Offshore Petroleum Amendment (Greenhouse Gas Storage) Bill (http://www.ret.gov.au/resources/Documents/ccs/Revised_EM.pdf)

[44] Victoria Greenhouse Gas Geological Sequestration Act 2008 (http://www.legislation.vic.gov.au/Domino/Web_Notes/LDMS/PubStatbook.nsf/51dea49770555ea6ca256da4001b90cd/7E4801FE0E8E3A55CA2574F80019A141/$FILE/08-61a.pdf)

[45] Victoria Offshore Petroleum and Greenhouse Gas Storage Act 2010 (http://www.legislation.vic.gov.au/Domino/Web_Notes/LDMS/PubStatbook.nsf/f932b66241ecf1b7ca256e92000e23be/6D3C2CCB18FB08C3CA2576EF001E64F4/$FILE/10-010a.pdf)

[46] Queensland Greenhouse Gas Storage Act 2009 (http://www.legislation.qld.gov.au/LEGISLTN/ACTS/2009/09AC003.pdf)

There are also state level regulations from the oil and gas sector concerning well abandonment which are relevant to CO_2 storage well abandonment[49, 50].

Canadian regulations

In Canada, CO_2 storage legislative power is split between federal and provincial governments. Provinces have jurisdiction within the respective provincial territory and offshore provincial waters, while the federal government has jurisdiction over Canada's territorial waters, the three northern territories and in all trans-boundary (provincial or international) matters, including CO_2 transport. Legislative power to cover site closure will fall mostly under the remit of the provincial governments. At the federal level, there are currently no CO_2 storage specific regulations. At the provincial level, only Alberta has produced regulations specific to CO_2 storage site closure[51]. However, provinces have regulations from the oil and gas sector on underground storage, which may be applicable to CO_2 storage. In Alberta, there is legislation that permits underground injection of fluids[52], and three regulatory directives that describe the requirements regarding permitting for injection, including acid gas disposal and CO_2-EOR, well construction for injection[53] and well abandonment[54]. In Saskatchewan there are also regulations on Enhanced Oil Recovery (EOR)[55] and well abandonment[56] that are relevant to CO_2 storage.

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[47] Queensland Greenhouse Gas Storage Regulation 2010 (http://www.legislation.qld.gov.au/LEGISLTN/CURRENT/G/GreenGasSR10.pdf)

[48] New South Wales Greenhouse Gas Storage Bill 2010 (http://www.parliament.nsw.gov.au/prod/parlment/nswbills.nsf/0/d5a532019610547dca2577e4001806bc/$FILE/b2010-109-d10_House.pdf)

[49] Queensland Petroleum and Gas (Production and Safety) Regulation 2004 (http://www.legislation.qld.gov.au/LEGISLTN/CURRENT/P/PetrolmGasR04.pdf)

[50] Western Australia Schedule of Offshore Petroleum Exploration and Production Requirements 1991 (http://www.dmp.wa.gov.au/documents/schedule_onshore_PGERA67%281%29.pdf)

[51] Alberta Carbon Capture and Storage Statutes Amendments Act 2010 (http://www.qp.alberta.ca/546.cfm?page=CH14_10.CFM&leg_type=fall)

[52] Oil and Gas Conservation Act of Alberta (OGCA) (http://www.ercb.ca/docs/requirements/actsregs/ogc_act.pdf)

[53] Alberta Energy Resources Conservation Board (ERCB) Directive 65

[54] Alberta Energy Resources Conservation Board (ERCB) Directive 20 (http://www.ercb.ca/docs/documents/directives/directive020.pdf)

[55] The Oil and Gas Conservation Act (http://www.qp.gov.sk.ca/documents/English/Statutes/Statutes/O2.pdf)

[56] The Oil and Gas Conservation Regulations (OGCR) (http://www.ercb.ca/docs/requirements/actsregs/ogc_reg_151_71_ogcr.pdf)

CO2CARE

2.2 A note on definitions

The term 'closure' has multiple definitions for different authorities, as shown in Table 1. Therefore it will not be used here in the general text but will be referred to in discussion of specific regulations.

Table 1: Definitions of closure in a selection of regulations

	Closure	Closure period	Post closure
EU/UK	End of injection		Period after closure (including transfer of liability period)
US UIC	Point at which the operator is released from site care		
IEA	Point at which the operator is released from site care	Time between cessation of injection and closure	Period after a closure certificate issued
IOGCC		Time after cessation of injection	Time after release of bond and transfer of liability
WRI	Period during which injection ceases and thesite is certified for closure		Period of time after certification of closure

The following terminology will be used here in the general text:

- Cessation of injection - when CO_2 injection has stopped
- Abandonment – the general process that occurs after cessation of injection
- Plugging – plugging the wellbores
- Transfer of liability – the point at which liability is transferred from the site operator to the appropriate authority (if this is possible) OR the point that the authority is satisfied that the site is safe.

2.3 Steps involved in CO_2 storage site abandonment

After injection has ceased, there are a number of actions that should be followed to accord with regulations. These actions are for the purpose of demonstrating that that the site is safe. Once the site has been demonstrated to be safe to the satisfaction of the relevant authority then a certificate can be issued which, depending on the regulator, will remove some/all of the operator's liability for the site. The following is a list of the general steps to be followed in abandonment regulations. Note that some regulations do not contain all of these steps.

- Injection ends

- A ‘post cessation of injection plan’ must be approved (this may be derived prior to injection and later updated). This plan is for the purposes of demonstrating the long-term safety of the site and so should include modelling, risk assessment, monitoring and plugging. The plan should also typically involve showing that injection was performed as planned and any required correction/remediation work was performed satisfactorily.
- Wells not used for monitoring are plugged
- Monitoring and modelling carried out as per plan requirements
- Application made to demonstrate the safety of the site. This involves demonstrating:
    - The safety of the CO_2 plume, i.e. no leakage, an evolution towards long-term stabilisation and conformity of monitoring with model predictions.
    - The safety of well plugging
    - Surface equipment has been removed
    - Obligations set out in application permit have been fulfilled (injection was performed as planned and any necessary corrective/remediation work has been carried out)
    - Financial obligations have been met
    - Suggesting any monitoring to be continued after transfer of liability
- Monitoring wells that will not be further used are plugged
- Site is certified as safe

Certifying a site as safe will typically change in some way the operator’s responsibility for the site. It may just mean that the operator is no longer required to perform monitoring or can reduce monitoring to a low level. It may however mean that the regulatory body/state takes on full liability (there may be a fund paid into by operators for this purpose).

The steps specified in site abandonment regulations can be condensed into two key areas:

- Demonstrating the safety of CO_2.The ‘post cessation of injection plan’ will be required to show safety and conformity of CO_2 plume with predictions and no leakage. Considerations are therefore: what must be included in the plan, how exactly the CO_2 can be shown to be safely contained and over what time period it is shown to be so
- Plugging wells safely (and removing equipment). There may not be specific regulations but there will be at least guidelines and authorities will assess whether plugging has been performed appropriately.

The safety of CO_2 will be discussed in Chapter 3. Then in Chapter 4, well abandonment regulations will be described. In a sense these requirements are related because if the wells are improperly plugged then a leakage pathway for the CO_2 may be created. However, these points will be considered separately. Chapter 3 will consider the integrity of the operational well as a potential leakage route but will assume that wells are plugged properly and safely. Chapter 4 will then separately consider how to abandon wells properly and safely.

Finally, regulations surrounding the actual transfer of liability will be discussed along with any post-liability transfer requirements (e.g. further monitoring, financial requirements etc) in Chapter 5.

3. Demonstration of CO_2 safety

3.1 Introduction

To demonstrate the safety of the injected CO_2 as part of the post-injection plan, a number of different pieces of information can be used. There is great variation in how prescribed this stage is by the regulator. Requirements include:

- The monitored CO_2 plume is behaving as expected compared to models
- No leakage is detected
- The CO_2 plume is stable or evolving towards stability
- No environmental problems
- Integrity of the injection well
- Integrity of wells within the area of impact

To meet these requirements one must carry out a combination of monitoring, modelling and risk assessment activities. Baseline monitoring, predictive modelling and risk assessment will have been performed prior to injection and all three will have been performed during injection. These areas will be presented first to form the basis on which the safety of the CO_2 storage site can be discussed.

There are two main document types with relevance to monitoring, modelling, risk assessment and CO_2 safety. The first type comprises laws/regulations which state what must be performed. These documents are not typically detailed, as they require the operator to submit a plan, which will be approved or rejected by the authority. The second type of documents contains guidelines on how to create a plan. These documents provide detail in the considerations that must be made when creating a plan which is likely to be approved by the authority.

The general documents will be discussed first, followed by the specific regulations. Therefore the order followed in this chapter will be:

- A general discussion on modelling and risk assessment (Section 3.2)
- A general discussion on monitoring (Section 3.3)
- A general discussion on demonstrating CO_2 safety (Section 3.4)
- Then these points will be discussed with reference to specific regulations (Section 3.5).

CO2CARE

3.2 Modelling and risk assessment

A necessary requirement to gain authorisation to store CO_2 at a site will be to characterise a site sufficiently to show that storage is likely to be performed safely. Site characterisation is an ongoing process that will continue throughout the operation as more information becomes available. Site characterisation involves monitoring and producing models of the site using information from measurements. There are a number of major elements to modelling:

- Data collection
- Creation of static geological models
- Performing dynamic modelling
- Performing risk assessment

Data collection is required in order to create models. Initial data collection methods will not be discussed here but in the following section, monitoring techniques that provide information on the operation of a CO_2 storage site will be discussed. Having collected data, static geological models will then be created. These provide the basis upon which dynamic modelling can be performed. Risk assessment makes use of the outcomes of modelling and so there is an overlap/interaction between risk assessment and the previous elements. Considerations to be made in static modelling, dynamic modelling and risk assessment will now be discussed on the basis of the EC directive *2009/31/EC* Guidance document 2[10] the *WRI Guidelines*[28] and other general documents.

Considerations in creating the static geological model should include:

- Gathering enough data to populate the model.
- Defining the model area. The static model should cover the whole area that may be affected by storage.
- Assigning the correct geometry. This can strongly affect flow characteristics in the dynamic modelling
- Determining the size of gridding for numerical modelling
- Assigning the correct properties to model grid nodes or cells, including heterogeneity and accounting for uncertainty
- Identification of migration pathways, fractures, faults etc.
- Recalibrating models based on new data.

Considerations for the dynamic modelling include:

- Flow modelling
    - Extent of plume
    - Trapping mechanisms
    - Displacement of formation fluids
- Coupling flow models with other models (geomechanical, geochemical)
    - Stress and pressure changes
    - Geochemical changes

- Using different simulators for comparison
- Short and long term simulations
- Assessment of uncertainties
  - Sensitivity testing
  - Multiple scenarios
- Recalibrating models based on new data, particularly pressure.

Risk Assessment should consider:

- Evaluation of likelihood of leakage scenarios occurring. In particular
  - Leakage through faults
  - Leakage through wells
  - Leakage through fracture networks
  - Potential for geomechanical failure
  - Potential for geochemical reactions increasing permeability
- Rates/magnitudes/severity of leakage
- Critical parameters affecting leakage
- Assessment of secondary containment
- Identifying locations for monitoring
- Updating risk assessment as new data becomes available
- Environmental concerns
  - Drinking water
  - Humans
  - Ecosystems.

3.3 Monitoring

3.3.1 General guidelines

A monitoring plan will typically be required to be submitted as part of site authorisation. Upon the cessation of injection, with the results of monitoring and modelling available, a post-injection monitoring plan will then be modified and resubmitted to the authorities. The authority will then assess the submitted plan and accept or reject it. Due to the wide variations between sites, regulations on monitoring plans should not consist of a uniform set of requirements[57]. Additional monitoring experiences are required to determine the level of monitoring that will be required from commercial operators[58]. However, wherever possible it

[57] DOE/NETL-2006/1236, 2006. International Carbon Capture and Storage Projects Overcoming Legal Barriers (http://www.netl.doe.gov/energy-analyses/pubs/CCSregulatorypaperFinalReport.pdf).

[58] DNV Report no 2008-0185 to the North Sea Basin Task Force, Phase II. Updated Gap Analysis – Legal, Regulatory and Economical Issues related to Carbon Capture and Storage. The Ministry of Petroleum and

would be desirable to be consistent. One way to achieve this is for regulations to state objectives and performance standards as opposed to specific monitoring techniques. This also allows for new technologies to be accommodated.

According to the EC directive *2009/31/EC*[8] *the WRI Guidelines*[28] *and other general documents*, the monitoring plan should consider:

- Site specificity. The monitoring plan should be tailored to each individual site based on the particular nuances of a site.
- Linking monitoring to identified risks from site characterisation and risk assessment. For example identified high risk areas should be monitored more heavily.
- The size of the region to be monitored. It should be sufficiently extensive to cover the plume and surrounding environment.
- Preventative/corrective measures. Monitoring should be linked to any preventative/corrective measures to assess if they have been effective.
- Best practice technology. What is best practice at the time of writing regulations may not be best practice in 20 years' time and so monitoring plans must be flexible enough to account for this.
- Temporal frequency of monitoring. Consider what frequency is required for each technique. Also, consider regular and routine reporting and interpretation of monitoring data.
- Flexibility. Update monitoring plans to account for changes in risks, technology etc.
- Baselines are required to make inferences from monitoring. The quality/quantity of baseline data should also be considered.
- Whether the post-injection plan differs from the operational plan. Perhaps consider a lower frequency of monitoring after cessation of injection.
- Whether monitoring is required post-liability transfer. To transfer liability then safety at the site must have been demonstrated. However, it may be desirable to continue low level monitoring to confirm this.

3.3.2 Monitoring options

There are a range of parameters to be monitored with techniques that may be available for a particular site. This list provides a guide but is not intended to be exhaustive:

- Injection well parameters
    - Injection rate
    - Pressure and temperature at well head
    - Chemical analysis of injected material
    - Volume of injected CO_2

Energy Norway (http://www.regjeringen.no/upload/OED/pdf%20filer/Rapporter/Det_norske_veritas_GAP-analyse.pdf)

CO2CARE

    - Formation pressure and temperature
- Well performance and integrity
    - Mechanical integrity
    - Corrosion monitoring of well
- Pressure fall off testing. Designed to determine if reservoir pressures are tracking predicted pressures and modelling inputs.
- Monitoring well parameters (in confining zone and above confining zone)
    - Pressure and temperature data
    - CO_2 saturation
    - Geochemical data
- Geophysics. Images of the plume
    - Seismic
    - Electrical surveys
    - Microgravity
- Surface deformation. Provides information on the CO_2 plume
- Surface detection
    - Groundwater samples
    - Soil-gas surveys.

When evaluating individual monitoring techniques, the following points should be considered:

- Characteristics of the site. Some monitoring methods require certain site characteristics, e.g. rock properties, depth, onshore/offshore etc.
- State of development. Has it been proven for CO_2 storage applications?
- Accuracy, uncertainty etc. How accurate is the technique. Can the uncertainty be quantified?
- Detection limit
- Direct or indirect method. If indirect then how strong is the relation between the measured quantity and CO_2.
- Required spatial and temporal frequency for satisfactory results
- Cost. In particular the cost/benefit ratio considering the previous points.

Figure 1 demonstrates an approach to selecting monitoring techniques based on the In-Salah site. Monitoring is ranked along two axes: cost and benefit. Low cost, high benefit monitoring tools will definitely be used. High cost, low benefit tools are unlikely to be used unless vital. Monitoring tools meeting the other criteria are considered on a case by case basis.

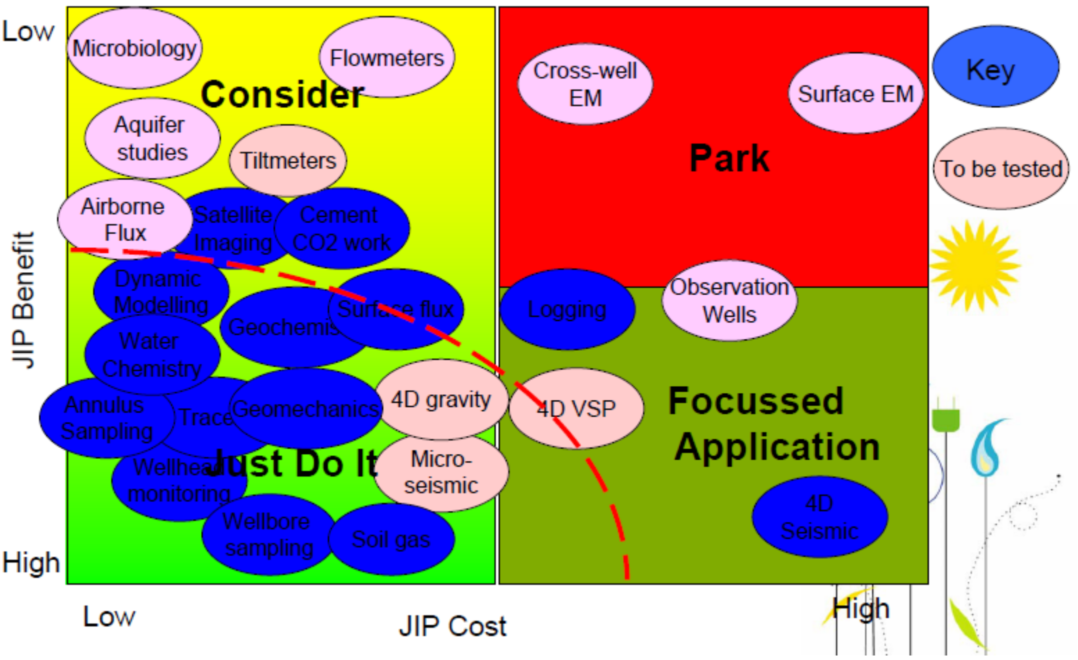

Figure 1: CO_2 Storage Monitoring options at In Salah (After Wright, 2007[59]).

3.4 *Demonstrating the safety of stored CO_2*

To demonstrate the safety of the injected CO_2, the results of monitoring, modelling and risk assessment throughout the lifetime of the project will be used. Different regulations have different wordings on how to demonstrate the safety of stored CO_2 but there are three main requirements that are common:

- The evolution of the monitored plume should conform to model predictions
- There should be no leakage
- The site should be evolving towards long term stability, e.g.
    - The plume should be stable
    - There should be no environmental problems
    - Well integrity is proven.

The next section will discuss how to demonstrate these points.

[59] Wright, I., 2007. CO_2 Storage at In Salah. 2nd International CCS Symposium Paris, October 4th 2007 (http://ec.europa.eu/clima/faq/lowcarbon/docs/ColloqueCO2-2007_Session2_3-Wright.pdf)

3.4.1 *Comparing monitoring data and modelling results to demonstrate that the plume is behaving as expected*

One CO_2 safety requirement is that the monitored plume is conforming to model predictions. The basic method to demonstrate conformity between modelling and monitoring is as follows:

- Based on initial data, dynamic modelling is performed to assess the future location of the CO_2 plume, geochemical changes, stress changes etc.
- As CO_2 is injected then more monitoring information becomes available and the results of modelling can be compared to the actual monitored values
  - o If the modelled and monitored data agree then there is confidence that the model is correctly predicting the actual behaviour
  - o If the modelled and monitored data differ significantly then the model requires updating. Future monitored data can then be compared to results based on the updated model.

Particularly significant monitoring information that warrants model updating (or mitigation) includes:

- Significantly higher/lower pressures
- Loss of injectivity
- Unexpected plume shape change.

Updating should be largely done at an early stage so that a best fit model has been derived long before monitoring has ceased. If the model requires updating towards the end of injection or during the post-injection period then there cannot be confidence that the model is predicting behaviour well. The main points that arise are: How similar must modelled/monitored CO_2 be to be classed as 'behaving as expected', can this be quantified, and for how long must this be demonstrated for? The EU guidance document[11] suggests the following conditions to show conformity with models:

a) For at least 5 years prior to transfer of liability, the model does not need any recalibration
b) The modelled results over the entire length of the project match the observed results to within X%.

The value of X could be specified by the authority. It may include:

- Well pressures
- Vertical/horizontal locations of CO_2 plume
- Chemical composition
- Active processes such as dissolution, density currents and mineralisation
- Surface deformation.

Considering the time period for conformity demonstration (which in the example case is 5 years), there is a balance between reducing the risk that the site is not behaving as expected and the cost to operator of continued monitoring.

It is worth considering the limitations of the method of comparing model predictions with monitoring to demonstrate safety. One limitation is that model/monitoring conformity may be found even if diffuse CO_2 leakage is occurring. The time period required for monitoring to demonstrate significant variation from model predictions with diffuse leakage may be long. Another limitation is that there may be a number of different scenarios or geological models that can match the observed data and these models are associated with markedly different risks, then model conformity with one scenario or geological model may not demonstrate safety.

3.4.2 Demonstration of no leakage

Another CO_2 safety requirement is that there is no leakage. A discussion on this criterion requires 'leakage' to be properly defined. The *EU directive 2009/31/EC*[8] classifies as leakage any release of CO_2 from the storage complex (the complex includes secondary containment formations). The *WRI Guidelines*[28] define leakage as 'significant movement of CO_2 outside the confining zone and similarly the OPA *Bill*[60] defines leakage as 'CO_2 migrating outside the expected migration path'. However, the '*IEA CCS Model Regulatory Framework*'[7] defines leakage as 'the unintended release of CO_2 from a storage complex into the atmosphere'. Some leakage definitions are clearly far more restrictive than others. The Australian definition is a particularly restrictive definition while the IEA definition focuses on the ETS requirements only and does not address the potential impacts of CO_2 leakage on the subsurface environment. .

Demonstration of no leakage out of the confining zone or the expected migration path can be performed similarly to demonstration of no leakage into layers containing drinking water, hydrocarbons etc. Methods would include well monitoring of pressure/geochemistry in the permeable layer above the confining zone, geophysical imaging of the plume, surface detection methods etc. Demonstration of no leakage from the surface can be performed with the techniques previously mentioned as well as with surface detection techniques, such as soil gas monitoring. The monitoring used must be tailored to the particular risks identified in the project in order to reliably detect leakage.

An important point that arises is the spatial/temporal monitoring frequency which is required to demonstrate no leakage. Seismic surveys are expensive and so their temporal and spatial frequency is limited by cost. It would be desirable for seismic surveys to cover an area of at least the size of the CO_2 plume. The number and position of monitoring wells and surface

[60] Revised Explanatory Memorandum to the Offshore Petroleum Amendment (Greenhouse Gas Storage) Bill 2008 - C2008B00177 (http://www.comlaw.gov.au/Details/C2008B00177)

detection methods should be based on the results of risk assessment. These points are site specific and so are hard to include in regulations. Authorities and operators will have to judge what is reasonable and this will become easier over time when there is greater experience. A point that is related to the temporal/spatial frequency question is the disparity between 'no leakage being detected' and 'certainty in there being no leakage'. Increasing monitoring levels will reduce uncertainty in the disparity of these statements but the disparity will always remain to some degree. There are also the considerations of the lower detection limit of leakage and the reliability of baselines to which leakage monitoring is compared. In terms of regulation, however, if a monitoring plan has been approved and the results of this monitoring demonstrate no leakage, then this will be sufficient to meet the condition of no leakage.

Another point, not considered in regulations so far, is whether any leakage should be acceptable. For example, the document, '*Current status of risk assessment and regulatory frameworks for geological CO_2 storage*' discusses acceptable leakage rates. Acceptable leakage rates can be discussed in terms of climate effects but a more appropriate basis for discussion is environmental impacts of leakage. If there is a very diffuse leakage case, where a very small volume of CO_2 is leaking, then remediation may be unfeasible and the effects of this leakage may be minor. In such a case, the condition of 'no leakage' may be overly restrictive.

3.4.3 Demonstration of CO_2 storage site evolution towards long term stabilisation

Another CO_2 safety requirement is that the system is stable or is evolving towards a situation of long-term stability. This requirement follows on from the 'demonstration of conformity of observations with model predictions' requirement, but goes a step further. The model conformity requirement could be met for a CO_2 storage site that could be behaving in a potentially high risk manner. The long term stabilisation condition requires that this is not the case. There are a number of different indicators that could be used demonstrate long term stability:

- Rate of change of key parameters is small and declining. Run simulations for thousands of years to check this. This could be quantified by requiring a rate of change of less than X% in a key parameter over a certain time period
    - o CO_2 being completely and permanently contained in the storage complex (both modelled and monitoring data showing no CO_2 detection above seal)
    - o Pressure is lower than fracturing pressure and declining (after injection has stopped)
    - o Geochemistry monitoring and modelling indicate no danger
    - o No corrosion of well
- No indication of fault/fracture opening: far-field micro-seismic events or injection pressure signature

- No problems with injection. Either direct measurements (e.g. mechanical integrity of the well is good) or models using information such as temperature which require further processing through a model to assess the risk associated with them
- Any corrective measures implemented have been effective.

Where stability is not defined then it could reasonably be expected to refer to all of the points discussed above. Regulations may state some of these points individually, they may require complete stability or they may require an evolution towards long-term stability. The requirement of complete stability in the CO_2 plume for example is overly restrictive. This is because it is possible for modification of the plume to occur without danger as the examples below demonstrate[11]:

- The plume can migrate horizontally at a very slow rate and still be safely stored.
- The plume may migrate vertically through a non-conventional seal interval over timescales of hundreds of thousands of years. In the process the majority of CO_2 will dissolve or be lost as residual gas saturation and so be safe.
- The plume may be trapped by buoyancy and be slowly dissolving or mineralising. This would be safe.

A point should be made about risk assessment. Risk assessment is most pertinent prior to or at early stages of injection because risks will typically decrease with time after injection has ceased. However, this is not always the case. Geochemical effects can be slow acting and as such reach maximum risk at some point after injection. Slow migration of the CO_2 plume could bring CO_2 closer to a leaky well or an open fault. Additionally, tectonic activity could cause breaching of physical storage traps and be dangerous if CO_2 is still in the mobile stage. Geochemistry and migration risk assessment should be a component of the assessment of evolution towards long-term stability. If the risk of tectonic activity has changed since the site was approved, then this should also be included.

3.5 Specific regulations

3.5.1 International regulations

Modelling and risk assessment

The '*OSPAR FRAM*'[6] sets out a framework for assessing the risks posed by a CO_2 storage project to the marine environment. The six stages of FRAM are:

a. *Problem formulation*: critical scoping step, describing the boundaries of the assessment;

b. *Site selection and characterisation*: collection and evaluation of data concerning the site;

c. *Exposure assessment*: characterisation and movement of the CO_2 stream;

d. *Effects assessment*: assembly of information to describe the response of receptors;

e. *Risk characterisation*; integration of exposure and effect data to estimate the likely impact;

f. *Risk management*: including monitoring, mitigation and remediation measures.

The FRAM document is very prescriptive and a good model for performing a risk assessment. '*Decision 2007/2'* of the OSPAR parties[4] requires use of the FRAM when issuing CO_2 storage permits.

The '*London Protocol*'[2] is accompanied by specific guidelines requiring use of the '*OSPAR FRAM*'[6] and separately to this, explicitly requires many elements of risk assessment. It is required to consider migration and leakage pathways over time as well as potential effects to the marine environment of leaking CO_2. Migration pathways to consider are listed along with a requirement for short- and long-term simulations of the fate of stored CO_2. This is performed to assess leakage rates and the likelihood of leakage. Detail is also provided on the assessment of impacts of leakage.

The '*IEA model regulatory framework*'[7] also uses the '*OSPAR FRAM*'[6] as the basis for its risk assessment.

Monitoring

'Decision 2007/2'[4] of the OSPAR parties requires a monitoring plan to be approved when issuing CO_2 storage permits.

The '*London Protocol*'[2] is accompanied by specific guidelines requiring a monitoring plan that contains at least:

- injection rates
- injection and formation pressures
- mechanical integrity
- properties and composition of the CO_2 streams.

A list of other monitoring techniques that may be included is also listed. It is stated that the monitoring plan should be based on detecting CO_2 migration and leakage. The monitoring requirements are reasonably prescriptive.

The '*IEA model regulatory framework*'[7] requires monitoring that meets specific objectives:

- performing a baseline survey
- monitoring various aspects of site
- comparing monitoring to baseline
- comparing monitoring to modelling
- detecting and assessing leakage/migration
- quantifying leakage/migration
- detecting adverse effects
- assessing any corrective measures and
- updating the monitoring plan.

No specific monitoring techniques are required. This approach therefore provides monitoring standards, while also allowing flexibility.

CO_2 safety

The '*OSPAR*'[3] and '*London Convention*'[1] requires a site abandonment plan that includes a post cessation of injection monitoring plan. It is stated that monitoring should continue 'until there is confirmation that the probability of any future adverse environmental effects has been reduced to an insignificant level'. This statement is open to interpretation but implicitly contains the three statements discussed in Section 3.4. Whether the condition has been met is subjective and the relevant authority will make the decision on this.

The '*IEA model regulatory framework*'[7] requires 'no significant risk of future leakage or irregularity'. This is required to be shown with a report on the behaviour of CO_2 (during injection and post injection), modelling results and the anticipated future state of the system. The minimum time period is not specified. Again, this statement implicitly contains the three statements discussed in Section 3.4 because it refers to risk and therefore requires an accurate model and evolution towards stability.

3.5.2 European regulations

Modelling and risk assessment

The modelling guidelines in the '*EU directive 2009/31/EC*'[8] are very prescriptive of the required outcomes of modelling. The reference document[10] discusses many of the issues related to modelling that were mentioned in Section 3.2. The regulations and guidance document do not prescribe the particular tools required to perform this modelling, nor required are the levels of accuracy. This would appear to be the optimum regulatory situation as it prescribes standards while allowing for updated technology and practice.

Risk assessment in the EU directive is based on the '*OSPAR FRAM*'[6]. The actual directive only specifies what should be considered in risk assessments but the '*Guidance document 2*'[10] and the '*OSPAR FRAM*'[6] go into great detail about this risk assessment process. This framework more than covers the points raised in Section 3.2 regarding the requirements of risk assessment and is the most detailed of the different national/international regulations.

Monitoring

At the end of the injection period, an operator must submit a plan of their post-injection actions to the authority (Article 17 of '*EU directive2009/31/EC*'[8]). The EU directive gives few specific guidelines on what monitoring methods must be used. Sensibly, a plan will be approved based on best practice at the time and the results of risk assessment. The explanatory document goes into detail about the considerations that must be made in creating the monitoring plan[10]. The directive specifies that monitoring must include:

- fugitive emission of CO_2 at injection facility

- CO_2 volume flow at wellheads
- CO_2 pressure/temp at well head
- Chemical analysis of injected material
- reservoir temp/pressure.

There are no further specific guidelines on what monitoring methods to use. However, Article 13 of '*EU directive2009/31/EC*'[8] states that monitoring should compare modelled/actual CO_2 behaviour, detect significant irregularities, detect CO_2 migration, detect CO_2 leakage, detect significant adverse effects to the surrounding environment, assess effectiveness of corrective measures and update assessments of the safety/integrity of the storage complex in the short/long term. Monitoring plans will therefore be assessed based on their ability to meet these criteria. Annex 2 of the '*EU directive2009/31/EC*'[8] states that when considering monitoring options to fulfil these criteria, the following options should be considered:

- technologies that detect the presence, location and migration of CO_2
- technologies that provide info on pressure-volume behaviour and areal/vertical distribution of CO_2 plume to refine numerical simulations
- technologies that provide a wide areal spread in order to capture info on previously undetected potential leakage pathways across the storage complex and beyond.

While a monitoring plan that meets these regulations will be site specific, it is likely to contain as a minimum:

- monitoring wells in the first permeable layer above the confining zone (geochemistry, pressure)
- either monitoring wells in the confining layer or geophysical techniques
- monitoring of well integrity.

The regulatory authority will expect the operator to have considered the general points at the beginning of this section when forming their monitoring plan. The monitoring plan should be updated at least every 5 years and if monitoring indicates significant deviation from the modelled predicted behaviour then the monitoring plan should be updated.

The monitoring requirements in the UK regulations are analogous to those prescribed in the EU directive.

In addition to the '*EU directive2009/31/EC*'[8] on CO_2 storage, CO_2 storage emissions are regulated by the EU Emissions Trading Directive (ETS). The initial ETS directive ('*2003/87/EC*')[61] was amended to include CO_2 storage emissions ('*2009/29/EC*'[62]).

[61] Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:275:0032:0032:EN:PDF).

Guidelines on monitoring and reporting CO_2 emissions[63] effectively require monitoring to be of sufficient quality to quantify any CO_2 that is released from the storage site to the atmosphere/water column.

The '*Norwegian Petroleum Activities Act'*[64], which regulates the Sleipner Injection site, requires a decommissioning plan to be submitted and approved at the end of injection. As part of this process, conditions on long term monitoring will be made. The '*Norwegian Pollution Control Act*'[24] has required a monitoring plan for the Sleipner injection site[58,65].

CO_2 safety

Article 18 of '*EU directive 2009/31/EC*'[8], requires the operator to show that CO_2 is permanently and completely contained, conformity to modelled behaviour, no leakage and evolution towards long term stability. These points were discussed in detail in Section 3.4. Further detail on demonstrating these points is discussed in the guidance document[11]

In the UK, the demonstration of CO_2 safety will be part of a later legislation.

The '*Norwegian Petroleum Activities Act*'[64] requires a high level of safety to be maintained and further developed in accordance with technological development.

3.5.3 Regulations in the USA

Modelling and risk assessment

The UIC regulations[26] state that the lateral and vertical extents of the CO_2 plume and formation fluid should be assessed with computational modelling that accounts for the physical and chemical properties of all phases of CO_2. There is a requirement to consider whether CO_2 will affect USDW (Underground Sources of Drinking Water) and includes migration through faults, fractures and artificial penetrations in models. The accompanying notes provide some extra detail requiring computational multiphase flow modelling, accounting for geological heterogeneities and assessment of the risk associated with CO_2 leakage. It is stated that modelling should be updated periodically or when significant

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[62] Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0063:0087:en:PDF).

[63] Commission Decision 2010/345/EU of 8 June 2010 amending Decision 2007/589/EC as regards the inclusion of monitoring and reporting guidelines for greenhouse gas emissions from the capture, transport and geological storage of carbon dioxide (notified under document C(2010) 3310) (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do ?uri=OJ:L:2010:155:0034:0047:EN:PDF).

[64] Norwegian Petroleum Activities Act, 29 November 1996 No. 72. Last amended by Act 19 June 2009 No 104. (http://www.npd.no/en/Regulations/Acts/Petroleum-activities-act/)

[65] Bellona Paper: Burying CO_2: The New EU Directive on Geological Storage of CO_2 from a Norwegian Perspective. (http://www.bellona.org/reports/Burying_Co2)

irregularities are seen in monitoring. The regulations, which on their own do not provide great detail, are supplemented by the UICPG83[66] document for pilot projects. This document does not contain legal requirements, but provides further detail on risk assessment and modelling, by discussing scenarios, model types, uncertainty management and risk acceptability criteria.

The IOGCC guide regulations[27] do not specify a modelling/risk assessment plan, although there is a requirement to characterise the basic properties of the site.

The WRI provides guidelines[28] on what a risk assessment should achieve and summarises many of the risk assessment points discussed in Section 3.2. It is stated that the risk assessment should 'examine the potential for leakage of injected or displaced fluids via wells, faults, fractures and seismic events, and the fluids' potential impacts on the integrity of the confining zone and endangerment to human health and the environment.' Points are made about considering the short and long term, using risk assessment to identify monitoring requirements, using risk assessment to provide a basis for mitigation, updating periodically and being site specific. No particular models or methods are requested though. As with the '*EU directive 2009/31/EC*'[8], this would appear to be the optimum regulatory situation as it prescribes standards while allowing for updated technology and practice.

Washington regulations[29] require modelling to predict the extent of the CO_2 plume and the response of the geological system. Tools acceptable to the authority must be used for this purpose and discussion of risk must be clearly presented. Risk assessment must identify and quantify hazards, probabilities, features, events and processes that might result in undesirable impacts to public health and the environment.

Wyoming regulations[30] require an assessment of the impact to fluid resources, subsurface structures and land surface, though no further detail is given.

Louisianan[33], Montanan[34] and Texan[31] regulations do not specify any modelling or risk assessment. However, it is stated in these regulations that the commissioner shall uphold the safe drinking water act which contains the *EPA UIC* regulations[26].

North Dakotan regulations[32] do not specify modelling or risk assessment.

Monitoring

As part of the '*EPA UIC'* regulations[26], at the end of the injection period, an operator must submit a plan of their post-injection actions to the authority. If the post-injection plan has not been modified, the EPA requires the operator to demonstrate why this is the case using monitoring and modelling results. The EPA is more specific in the type of monitoring required than the EU. The '*EPA UIC'* regulations[26] state that the director has control over the type and frequency of monitoring to be performed. Testing and monitoring associated with geological storage projects must, at a minimum, include:

[66] USEPA UICPG83 2007. Class V Experimental Technology Well Guidance for Pilot Geologic Sequestration Projects (http://www.epa.gov/ogwdw000/uic/pdfs/guide_uic_carbonsequestration_final-03-07.pdf).

- *Analyse CO_2 stream* (chemically and physically) and the effects it may have. If the stream is hazardous then further rules apply.
- *Mechanical integrity testing*. There is flexibility in this testing.
- *Corrosion monitoring* of well material is mandatory
- *Groundwater/ geochemical monitoring*. Periodic monitoring of the ground water quality and geochemical changes above the confining zone in a site specific flexible monitoring regime. Sampling via wells in the target formation may be desirable in some circumstances, e.g., to perform geochemical monitoring in wells used for direct pressure monitoring.
- *Pressure fall off testing*. Mandatory at least once every five years.
- *CO_2 plume and pressure front monitoring*. Direct pressure monitoring via monitoring wells in the first formation overlying the confining zone is mandatory. Spatial frequency of wells must be based on specific information about the geological storage project, including injection rate and volume, geology, the presence of artificial penetrations and other factors. Indirect geophysical techniques such as seismic profiling, electrical, gravity, and electromagnetic surveys are site specific.
- *Surface air/soil gas monitoring*. Directors have discretion to require surface air and/or soil gas monitoring at storage sites to monitor the flux of CO_2 out of the subsurface.
- *Additional requirements*. As technologies develop, the Directors have discretion to require additional monitoring.

The '*EPA UIC'* approach of specifying minimum temporal frequencies for some tests is useful for standardisation. However, variation in approach is allowed for most tests and the director has the final decision. This is a useful approach as it provides guidance to operators as well as minimum safety standards while still providing flexibility.

The '*IOGCC guidance regulations'*[27] require:

- Corrosion monitoring.
- A leak detection and monitoring plan that addresses:
  - Release of CO_2 to the atmosphere
  - Migration of CO_2 to aquifers
  - Migration of CO_2 to other oil/gas reservoirs
- Injection rate and composition
- Periodic mechanical integrity testing
- Wellhead pressure and temperature.

It is suggested that other further testing may also be requested by the relevant authority.

The '*WRI guidance regulations'*[28] suggests that individual monitoring techniques should not be specified in regulations. Instead, regulations should focus on key information required such as for example injected volume, spatial distribution of the CO_2 plume, well integrity and determination of any measurable leakage. The operator can choose what techniques to use to obtain this information. The monitoring plans should be based on site characterisation and risk assessment while also being updated as needed.

Washington regulations[29] require the monitoring plan to identify movement of the CO_2, baselines, pressure response above the caprock, failure of the caprock, release to the atmosphere, degradation of groundwater and migration into oil/gas reservoirs. They also state that monitoring should include injected fluid characterisation, injection pressure, injection rate, injection volume, annulus pressure, leak detection and sufficient monitoring to confirm CO_2 plume shape.

Wyoming regulations[30] require a monitoring plan to assess CO_2 migration and ensure retention within the site. A plan for periodic well mechanical testing is also required. A detailed plan for post-injection monitoring should be submitted by the operator but there are no stipulations on what the plan must contain.

Louisiana regulations[33] require operators to install monitoring equipment when requested by the commissioner. Also, the commissioner shall uphold the safe drinking water act which contains the '*EPA UIC'* regulations.

Montanan regulations[34] also require monitoring which at a minimum is pursuant to the safe drinking water act.

Texan regulations[31] also requires monitoring to comply with EPA regulations. Furthermore, the commission may establish monitoring requirements to be performed by the Bureau of Economic Geology at the University of Texas, Austin.

North Dakotan regulations[32] require monitoring to assess the location and migration of CO_2 but does not provide specific details.

CO_2 safety

The '*EPA UIC'*[26] requires that the operator must monitor the site to show the 'position of the carbon dioxide plume and pressure front and demonstrate that USDWs are not being endangered'. The operator must show 'that the carbon dioxide plume and pressure front have stabilized and that no additional monitoring is needed to assure that the geological storage project does not pose an endangerment to USDWs'. This must be shown for 50 years after the cessation of injection although the time period is at the director's discretion. Note here the condition that the CO_2 plume 'has stabilised' as opposed to the condition of 'evolving towards a situation of long term stability' in the '*EU directive 2009/31/EC'*[8]. The '*EPA UIC'* regulations[26] are therefore stricter and could potentially mean a time period much longer than 50 years is required[67]. Note also that only endangerment to USDWs is considered and not other environmental factors.

[67] DNV CO2QUALSTORE Guideline for Selection and Qualification of Sites and Projects for Geological Storage of CO_2 (http://www.dnv.com/binaries/CO2QUALSTORE_guideline_tcm4-412142.pdf).

The '*IOGCC guidance regulations*'[27] specify that monitoring/modelling information should be included in a closure application but does not describe what safety conditions must be shown.

The '*WRI guidance regulations*'[28] suggest that demonstrating safety of the CO_2 requires showing:

- The location, magnitude and extent of the CO_2 plume and region of elevated pressure
- CO_2 movement and pressure matches model predictions
- No evidence of significant leakage or the failure of integrity of the confining zone
- Injected or migrated fluids are not expected to encounter a potential leakage pathway
- Wells are not leaking and retain integrity

Further the accompanying notes discuss pressure drop matching and monitoring leakage in both the zone above the primary confining zone and at the surface. These conditions are more prescriptive than most although it should be noted that minor leakage may be permitted which is untypical in regulations.

Washington regulations[29] state that modelling should be updated with monitoring information to establish the effectiveness of the geological containment system and require an assessment of the model's accuracy to date with projections of project response. Observed anomalies from predicted behaviour shall also be identified and explained. Modelling and monitoring must be continued until they demonstrate 'that conditions in the geological containment system indicate that there is little or no risk of future environmental impacts and there is high confidence in the effectiveness of the containment system and related trapping mechanisms'. A time frame is not specified.

Wyoming regulations[35] do not state CO_2 safety rules.

Louisianan regulations[33] require demonstration that 'the reservoir is reasonably expected to retain mechanical integrity and the carbon dioxide will reasonably remain emplaced', 10 years after injection has ceased.

Montanan regulations[34] require for at least 15 years it be shown that the reservoir will retain the CO_2, wells and other equipment retain mechanical integrity and that either the CO_2 is stable (either stationary or chemically combined) or if it migrates it will not cross the reservoir boundary.

Texan regulations[31] require that permanent storage has been verified.

North Dakotan regulations[32] require that, for 10 years, the storage reservoir to be behaving as expected to retain the CO_2 and that the CO_2 is stable (stationary or not migrating out of reservoir boundary).

3.5.4 *Australian regulations*

Modelling and risk assessment

The OPA Bill[41] requires modelling the behaviour of the injected CO_2 but does not specify any further detail. The accompanying document[60] discusses making predictions of the short, medium and long term behaviour of the CO_2 as well as assessing risk to natural resources, geotechnical integrity, environment and human health.

The '*Victoria Offshore Petroleum and Greenhouse Gas Storage Act 2010*'[45] is the same as the '*OPA*'. The '*Victoria Greenhouse Gas Geological Sequestration Act 2008*'[44] requires assessment of potential leakage/migration pathways, assessment of the effect of leakage, assessment of the likelihood of leakage.

The '*New South Wales Greenhouse Gas Storage Bill 2010'* [48] does not specify modelling or risk assessment.

The *'Queensland Greenhouse Gas Storage Act 2009'*[46] requires modelling of the CO_2 but does not specify further detail.

Monitoring

The '*OPA*'[41] requires a monitoring plan but does not specify what it should contain. The accompanying document[60] discusses monitoring that can detect significant events in a timely manner.

The '*Victoria Offshore Petroleum and Greenhouse Gas Storage Act 2010*'[45] is the same as the '*OPA*'. The '*Victoria Greenhouse Gas Geological Sequestration Act 2008*'[44] requires just a description of the monitoring techniques to be used.

The '*New South Wales Greenhouse Gas Storage Bill 2010*'[48] does not specify monitoring.

The Queensland regulations[46,47] do not specify monitoring requirements.

CO_2 safety

The '*OPA*' requires the injected gas to behaving as expected in the originally submitted site plan and for there to be no risk of adverse impact on natural resources, geotechnical integrity, the environment, or human health and safety. It is also a requirement that the short and long term CO_2 plume migration and associated consequences be shown. This is not really an extra requirement to those described so far. If stability and no leakage have been shown then the consequences are model outputs, i.e. new chemistry of confined zone, new mineralisation in confined zone etc. If stability and leakage have not been shown then there may be negative consequences, e.g. contamination of drinking water. In this case however, then closure without remediation would not be allowed to happen.

The '*Victoria Offshore Petroleum and Greenhouse Gas Storage Act 2010*'[45] is the same as the '*OPA*'. The '*Victoria Greenhouse Gas Geological Sequestration Act 2008*'[44] requires that the CO_2 continues to behave in a predictable manner, that risks associated with the CO_2 have been reduced as far as possible and that the CO_2 will not present risk to the environment or public health. As with the '*OPA*', assessment of migration and leakage pathways with associated consequences are also required.

The '*New South Wales Greenhouse Gas Storage Bill 2010*'[48] requires CO_2 to be behaving as predicted.

The *'Queensland Greenhouse Gas Storage Act 2009'*[46] only requires the results of monitoring, modelling and risk assessment to be submitted to the authority. The authority will then decide if all risks have been reduced as much as is reasonably practicable.

3.5.5 Regulations in Canada

Modelling and risk assessment

The '*Alberta Carbon Capture and Storage Statutes Amendments Act 2010*'[51] does not specify modelling or risk assessment procedures.

The '*ERCB Directive 65*'[53], describing regulations on acid gas disposal, requires characterisation of the site including modelling of the radius of influence of the injected acid gas, offset wells within the radius of influence and an assessment of fracturing since maximum bottomhole injection pressure is limited to 90% of the rock fracturing threshold. '*Underground disposal of acid gas in Alberta, Canada: Regulatory concerns and case histories*'[68] provides further details on what should be included in acid gas injection applications although it is not a legal document. Relevant to site closure, the document discusses reservoir containment, caprock threshold displacement pressure, fracture pressure and geochemical effects.

Saskatchewan EOR regulations[52,56] do not specify standards for modelling and risk assessment but do require a plan to be submitted which contains discussion of the effect of injection ('*Application for Enhanced Oil Recovery Project'*[69]). This allows the authority flexibility in its requirements[70]. Salt water storage regulations require an approved system to monitor horizontal and vertical seepage[56].

Monitoring

The '*Alberta Carbon Capture and Storage Statutes Amendments Act 2010*'[51] requires a monitoring plan to be submitted for approval without specifying the required contents of the

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[68] Underground disposal of acid gas in Alberta, Canada: Regulatory concerns and case histories

[69] http://www.er.gov.sk.ca/EOR

[70] The Regulatory Framework Governing Injection and Storage of Carbon Dioxide at the Cenovus Weyburn and Apache Midale Enhanced Oil Recovery Operations in Saskatchewan'.

plan. Alberta is currently developing regulations for CO_2 storage, with recommendations expected to be made to the Minister by the end of 2012.

The '*ERCB Directive 65*'[53], describing regulations on acid gas disposal, requires monitoring of wellhead pressure, temperature, flow rate and gas composition and monitoring of offset well. No subsurface monitoring is required. '*Underground disposal of acid gas in Alberta, Canada: Regulatory concerns and case histories*'[68] discusses monitoring to include annular fluid pressure, wellhead pressure, wellhead temperature and fluid analysis.

Saskatchewan EOR regulations[55,56] do not specify standards for monitoring but do require a monitoring plan to be submitted ('*Application for Enhanced Oil Recovery Project*'[69]).

CO_2 safety

The '*Alberta Carbon Capture and Storage Statutes Amendments Act 2010*'[51] requires that 'the captured carbon dioxide is behaving in a stable and predictable manner, with no significant risk of future leakage'.

3.6 Summary and Discussion

Modelling, risk assessment and monitoring

- There is large variation in the requirements for modelling, risk assessment, monitoring and demonstrating safety between the regulations.
- With regulations on modelling, risk assessment and monitoring, it is standard for those aspects to require approval as part of a plan submitted to the authority. This therefore allows the authority flexibility in what it requires as technology improves and experience is gained.
- However, prescribing what is required from monitoring, modelling and risk assessment provides the operator with a clearer picture of what is expected of them.
- To allow for updated technologies and methodologies, it is undesirable to specify particular modelling techniques in regulations. Instead, specifying outcomes of the risk assessment process will provide desired results in a flexible environment. The '*OSPAR FRAM*'[6] provides an excellent basis for modelling and risk assessment. The framework is referenced in other regulations (e.g. '*EU directive 2009/31/EC*'[8], *'IEA model regulations*'[7]) and it would be desirable if all operators/authorities referenced the framework when constructing risk assessments.
- Similarly for monitoring, it is largely undesirable to specify particular methods. Instead, specifying the outcomes of monitoring is a more flexible method of achieving an up to date and site-specific monitoring plan. For example the '*IEA model*

regulations'[7] and *'EU directive 2009/31/EC'*[8] list the considerations/outcomes of monitoring.

- Despite the desirability of a flexible monitoring plan, there are some site properties, which are easy and necessary to monitor, such as injection pressures, stream compositions etc. These are specified in some regulations and such requirements are desirable to achieve a constant base level of monitoring in all sites. Regulations such as the '*EPA UIC*'[26] and the '*IEA model regulations'*[7] provide a good balance of strictly prescribed monitoring and flexible monitoring.

- The purpose of modelling, risk assessment and monitoring is to demonstrate the safety of the CO_2 storage. Therefore, when assessing these plans, the major consideration should be whether the plans can demonstrate the safety of the CO_2 storage to acceptable standards. If they cannot then the plans should be reconsidered.

CO_2 safety

- The wording of requirements on CO_2 safety varies. However, they can be summarised into three main points: demonstration of no leakage, demonstration of conformity with modelling predictions and demonstration of long term stability. These requirements approach the safety aspect of CO_2 from different angles and should all be included in regulations in one form or another.

- Some regulations contain additional requirements: demonstrating no environmental problems, demonstrating that the plume will not encounter any leakage pathways and demonstrating well integrity. However, these conditions are implicitly included in the previous requirements.

- Considering the no leakage requirement, as discussed in Section 3.4.2, demonstrating this is heavily dependent on what monitoring has been used. It is therefore important for the monitoring plan that has been approved to be of sufficient quality to detect leakage. If the monitoring plan is not good enough, then no leakage may be detected even though leakage is occurring. The ETS requires quantification of leakage. However, the accuracy with which this can be achieved is difficult to quantify. Furthermore, no regulation permits any leakage, although it may be necessary for authorities to permit minor leakage in some cases.

- Another point arising is whether the no leakage condition is overly restrictive. The '*EU directive 2009/3/EC*'[8] classifies leakage as any release of CO_2 from the storage complex (the complex includes secondary containment formations). In this context the no leakage condition is reasonable. However, if leakage was defined as CO_2 release from the primary confining layer as in the *'WRI Guidelines*[28], then secondary containment is not permitted.

- Considering the model conformity requirements. As discussed in Section 3.4.1, it may be desirable that the authorities quantity this, e.g. X% difference between model and monitoring over Y years, where X and Y are variable to be determined.

- Considering the stability requirement. The '*EPA UIC*' regulations[26] require complete stability which may be an overly strict requirement.

- The Australian '*OPA*' regulations[41] are more prescriptive in how safe a site must be than other regulations by specifying no 'adverse effects on navigation, fishing etc'. These conditions may be slightly unnecessary, however, an appropriate 'no leakage' condition will implicitly include the 'no adverse effects on navigation, fishing etc' conditions.

- The Australian regulations[41] also require demonstrating long-term consequences as well as suggesting future measures after liability has been transferred. This latter step in particular could be a very useful addition to other regulations.

- There is variation in the time period over which safety must be shown in different regulations. It is difficult to conclude an optimum time period but this time period should be flexible. The main consideration when setting a time period should be how much monitoring time is required to demonstrate safety.

4. Well abandonment

As well as demonstrating the safety of the CO_2 storage, the other major requirement to abandon a site is the abandonment of wells and removal of surface equipment. The major stage in well abandonment is plugging of the well, which ensures that the well does not become a conduit for CO_2 leakage. Proper abandonment of wells will facilitate safety through the long-term retention of CO_2 in the reservoir. Well abandonment involves removing equipment, flushing the well with a buffer fluid and placing (typically cement) plugs in the well that effectively seal the wellbore at a given height and prevent fluid movement. There are different methods, materials and tests available that could be used in the well abandonment process.

Most CO_2 storage regulations merely require wells to be plugged without specifying techniques to be followed or standards to be met. However, well plugging has been regulated previously in the oil and natural gas sector and so there are minimum plugging standards. It should be noted that the unique nature of CO_2 may require additional considerations. As discussed by the WRI[28], proper CO_2 well plugging is important because of three critical factors associated with CO_2 injection: (1) CO_2 is buoyant; (2) it can be reactive and corrosive; and (3) reservoir pressure increases with injection. These factors could lead to degradation of well components.

This section will briefly discuss the general principles of well abandonment in section 4.1, along with extra considerations required for CO_2. Then well abandonment regulations specific to CO_2 storage, including dismantling of surface equipment, will be discussed in Section 4.2. In Section 4.3, general well abandonment regulations from the oil and natural gas sector will be described.

4.1 General principles of well abandonment

The first stage of well abandonment is removal of any downhole equipment from the wellbore. Then the wellbore is cleaned of debris by flushing the wellbore with a circulation fluid. The next and major stage is the creation of plugs in the well to create impermeable barriers. A common plugging material is cement. The cement plug consists of a volume of cement that fills a length of casing or open hole. Variables are the type of plugging material used, the method of plugging, the size of plugs, the depths of plugs and the number of plugs.

Portland cement is the most common plugging material (‘*IEA Long Term Integrity of CO_2 storage well abandonment*’[71]). However, there are different grades of cement used which are based on mechanical requirements at the different temperatures and pressures experienced at different depths. Additives can be used to enhance Portland cement properties to meet these requirements. Portland cement has to date been proven to perform well in EOR and acid-gas operations[28]. However, the carbonic acid formed due to CO_2 injection could lead to Portland cement corrosion. This could cause loss of cement density and strength, as well as increasing porosity which would reduce the effectiveness of the plug seal. Laboratory experiments have confirmed cement degradation with CO_2. However, it is suggested that risks are manageable. Furthermore, field core sample studies show cements becoming more resistant to corrosion with time. Newer corrosion resistant cements are being studied. However, there are concerns about the strength and overall performance of these new materials.

There are a number of different methods available[72] for plugging which are discussed briefly below.

Balanced plug: A common method where tubing is placed at the plug target depth and cement slurry is injected onto a plug base. This plug base could be a bridge plug (a mechanical isolation tool), a viscous fluid or mud. The slurry is pumped through the tubing until the cement level in the annulus is equal to that inside the casing. The tubing is pulled out once the plug is balanced. This method is relatively simple although there is the potential for cement contamination.

Dump bailer method: A dump bailer is a tool which contains a measured amount of cement and is lowered into the wellbore. Cement from this tool is dumped onto a bridge plug which is

[71] IEA GHG Technical Reports 2009. Long Term Integrity of CO_2 storage well abandonment.

[72] Nelson E.B. and Guillot D., 2006. Well Cementing (2nd ed.), Schlumberger, Sugar Land, TX, U.S.A. (2006).

placed below the desired cement plug depth. This technique is easily controlled and relatively inexpensive.

Two-plug method: This method involves a special tool that sets a cement plug at a particular depth accurately and with minimum contamination. A bottom plug is launched ahead of the cement slurry and allows cement slurry to pass through. Then a top plug, with a solid body, is pumped behind the cement slurry. The drill pipe is then pulled up until the lower end reaches the calculated depth for the top of the cement plug.

Squeeze cementing: If cement behind the casing is inadequate, then remediation methods can be used. One method of which is squeeze cementing. Cement slurry is forced into a specified location in a well through perforations in the casing or liner. The liquid phase of the slurry will be forced into any permeable formation it encounters, leaving the cements solids behind.

The depth and sizes of plugs will be largely dependent on the depths and thicknesses of permeable formations. Similarly, the number of plugs will be site specific, though typically at least three plugs will be used. Typically, a cement squeeze will be used at the level of producing/injecting perforations, a plug will be located near the middle of the wellbore, a surface plug will be located at shallow levels and further plugs may be placed based on site specific conditions.

After the well has been plugged, it must be tested to ensure that it is functioning correctly. Tagging the top of the cement enables exact determination of the depth of the top of the plug and can allow determination of plug's integrity. Another method is to perform a pressure test using pump pressure. Alternatively pressure can be tested with swabbing methods.

Once plug testing has been performed, the well can be capped and if onshore then backfilled with soil.

4.2 Well abandonment regulations for CO_2 storage

This section discusses well abandonment regulations that are found in CO_2 storage specific regulations.

4.2.1 International regulations

The '*IEA model regulatory framework*'[7] article (6.10) requires evidence that 'the storage site has been decommissioned as required by the relevant authority'. The regulations require 'a description of the location, condition, plugging procedures and any integrity testing results for every well that has been or will potentially be affected by the storage site' as well as a description of the decommissioning performed.

The '*OSPAR* and *London Protocol FRAM*'[2,3] states that 'particular attention should be paid to the integrity of the wells. Over the longer term, the risk assessment should also address any change in the integrity of the seal and of the plugs in the abandoned wells and might include the effects of CO_2 dissolution and mineralisation.

4.2.2 EU regulations

The '*EU directive 2009/31/EC*'[8] requires that 'the site has been sealed and injection facilities have been removed'. Guidance document 3[11] states that this should be performed using appropriate best practices and materials. No further details are provided on how this must be performed. The UK CO_2 storage regulation[16] similarly does not specify plugging details.

The relevant regulation for sealing deep wells in Germany is the Directive of the Superior Board of the Mines in Clausthal-Zellerfeld from 1998[73] and the unpublished Directive of 1987[74]. This regulation is currently applied by the respective competent authorities in all Federal States in Germany. These regulations do not specify plugging details either.

4.2.3 Regulations in the USA

EPA UIC regulations[26] require that prior to well plugging, the operator must flush the well with a buffer fluid, determine bottom reservoir pressure and perform a final mechanical integrity test. A well plugging plan must be approved by the authority and the application should contain a bottom hole reservoir pressure test, an appropriate mechanical integrity test, the type and number of plugs to be used, the placement of each plug, the type and grade of the plugging material and the method of placing the plugs. The regulations do not specify the types of materials or tests that must be used during well plugging, acknowledging that there are a variety of methods that are appropriate and new materials and tests may become available in the future. However, all plugging materials must be compatible with the injectate (i.e., such that plugging materials would not degrade over time).

The IOGCC guide regulations[27] requires operators to gain approval before plugging wells. Then 'the well casing shall be cut off at a depth of 5 feet below the surface and a steel plate welded on top identifying well name and that it was used for CO_2 injection'. Then 'following well plugging, all associated surface equipment shall be removed and the well site returned to its original land use to the extent possible'.

The WRI guide regulations[28] states that conventional materials and techniques should be used unless site-specific conditions warrant variation from this.

Wyoming regulations[35] require the UIC regulations to be followed.

Louisianan regulations[33] require the UIC regulations to be followed. They also specify plugging to prevent CO_2 migration between strata, 'the closure of associated surface

[73] Richtlinie des Oberbergamtes in Clausthal-Zellerfeld über das Verfüllen auflässiger Bohrungen vom 29.Juli 1998 – 20.1 – 3/98 – BIII d 1.2 – IV- 5 pages plus illustrations.

[74] Richtlinie vom 1.06.1987 – 20.d2 – 2/87 – B III d d1.2 – III.

facilities, the removal of equipment, structures, and trash, and to otherwise require a general site cleanup of such abandoned wells.' No detail is provided on how plugging should be performed.

Montanan regulations[34] require demonstration that wells have been plugged and equipment has been removed as required by the board. Surface lands must be returned to their previous grade and productive capability. Wells must be plugged according to board rules, though they are not specified in these regulations.

North Dakotan regulations[32] require demonstration that the operator has 'plugged wells, removed equipment and facilities, and completed reclamation work as required by the commission.' No detail is provided on how plugging should be performed.

Texan regulations[31] do not specify well plugging.

Washington regulations[29] do not specify well plugging.

4.2.4 Australian regulations

The amendment to the OPA[41] requires the operator to remove all property brought to the operating area. The act also requires the operator to demonstrate to the Minister that wells have been plugged or closed off in a way that:

- minimises damage to the petroleum-bearing qualities of geological formations
- maintains the suitability of a part of a geological formation for the permanent storage of greenhouse gas substances.

The '*Queensland Greenhouse Gas Storage Regulation 2010*'[47] requires well decommissioning to be reported. The report must contain:

- details of the casing and equipment installed in the well with diagrams showing the major dimensions and features of the casing and equipment
- a full description of all equipment, including prescribed equipment retained in the well, including, for example, the size and nature of the equipment and any features of the equipment that may cause a hazard to underground mining operations
- the surveyed location of any prescribed equipment
- the method of the cementing operations carried out in or on the well, including, for example, the location and type of plugs, the intervals covered, the volume and type of cement used, any losses of cement due to voids or permeable strata, and the methods used to overcome losses of cement
- the method, materials and volume of cement used to cement voids
- a description of any other abandonment procedures used for the well
- any other details of the activities carried out in drilling, completing and plugging and abandoning the well, and an assessment of their possible impacts, that would assist a person in making an assessment of potential risks to safe and efficient underground mining.

The '*Queensland Greenhouse Gas Storage Act 2009*'[46] requires the operator to remove equipment from the land unless the owner of the land agrees otherwise.

The '*Victoria Offshore Petroleum and Greenhouse Gas Storage Act 2010*'[45] contains the same plugging and closure criteria as the amendment to the OPA.

The '*Victoria Greenhouse Gas Geological Sequestration Act 2008*'[44] requires the operator to remove all infrastructure associated with the injection activities including plugging or closing off any wells.

The '*New South Wales Greenhouse Gas Storage Bill 2010*'[48] requires a site closure plan which contains:

- measures that are to be taken to decommission and remove the injection plant
- measures that are to be taken to plug or seal any underground bores or shafts
- measures that are to be taken to rehabilitate the site.

4.2.5 Canadian regulations

The '*Alberta Carbon Capture and Storage Statutes Amendments Act 2010*'[51] requires the operator to submit a closure plan for approval and that the operator has abandoned all wells and facilities in accordance with the requirements under the '*Oil and Gas Conservation Act*'[55]. Provincial regulations define well abandonment procedures and requirements[54].

4.3 General well abandonment regulations

Countries that have previously been involved in hydrocarbon production or injection operations, such as natural gas storage or acid gas injection, are likely to have regulations on the abandonment of wells. These regulations are likely to apply to CO_2 storage operations unless new CO_2 storage specific regulations are created. This section will now discuss these regulations.

4.3.1 EU regulations

Well abandonment regulations within the EU are country specific.

UK

The '*UK Petroleum Act 1998*' requires the operator to prepare and agree plans to secure and make safe old oil and gas installations, including plugging of wells. Offshore well abandonment should be carried out according to the '*UK Oil and Gas Association (UKOOA) Guidelines for the Suspension and Abandonment of Wells*'[19]. These guidelines state standards for the plugging material in permanent barriers. The standards require a low permeability material with long-term integrity that is, non-shrinking, ductile, non-brittle, resistant to down hole fluids and able to bond to the casing. Cement plugs of at least 30m are acceptable in cased or open holes. It is also stated that alternative materials can be used if they meet the stated requirements. The highest barrier should be set across or above the highest point of inflow and should extend at least 30m above the highest point of inflow. If a distinct permeable zone is present below the casing shoe then a plug extending at least 30m should be set across the casing shoe. A cement plug of at least 30m is also required above the top of any perforated casing. Cemented casing is described as an acceptable barrier to vertical flow in the annulus and requires at least 30m of good cement. The guidelines do not outline specific requirements for verification but require demonstration of the adequacy of a barrier to conform to guidelines.

Denmark

The Danish Energy Authority (DEA) has produced '*A Guide to Hydrocarbon Licenses in Denmark*'[20]. The abandonment section of this document requires plugging to ensure that there is no fluid flow through the well and no communication from a downhole formation to the seabed/surface via the casing or annulus. Multiple plugs are required. One plug should be placed at least 50m above and below individual permeable zones if the well is uncased. If there is an open hole below the deepest casing then either a cement plug extending 50m above and below the casing shoe should be placed or a mechanical plug should be placed in the casing within at least 50m of the casing shoe with a 50m cement plug above it. Perforated intervals should either be isolated with cement plugs of specified lengths or with a combination of mechanical plugs and squeeze cementing. A cement plug of at least 100m should be placed near the surface. The Top of plugs should be located by load testing and pressure testing should be performed to detect possible leaks or mechanical failure.

France

French well abandonment regulations are specified in the '*General Regulations for the Extractive Industry (RGIE)*'[21]. The required steps to officially close a well depend on the age and state of the wells as well as the operator's knowledge of the primary casing and cementing. Without sufficient casing reporting then an investigation into the cement and casing is performed. If cementing is poor or non-existent then new cementing is performed. Abandonment must be performed in such a way that reservoirs are isolated from each other, permeable layers remain permeable and no mixing of fluids between different permeable layers occurs. The materials used must not degrade over time and plug length is site specific but should be at least 50m to 100m. Cement is suggested as a plug but sediments or resin are allowed. Any material used must have known characteristics and the material used is location dependent. After plugging, load and pressure tests should be performed and the height and quantity of cement should be monitored by a cement bond log.

Norway

The '*Norwegian Petroleum Activities Act (1996)*'[64] requires operators to submit a decommissioning plan to the Ministry of Petroleum and Energy at least two years prior to the end of a licence of the termination of a facility. This plan must contain a disposal plan and an impact assessment. The '*NORSOK Standard D-010*'[22] provides specific well abandonment regulations. This document requires wells to be plugged with the aim of eternal integrity. At least one well barrier is required between a potential source of inflow and the surface unless a reservoir contains hydrocarbons in which case two well barriers are required. Plugs must extend at a minimum 50m above a source of outflow or leakage point and must be at least 100m total length. Plugs that are in transition from open hole to casing should extend at least 50m below the casing shoe. Plugs set inside the casing with a mechanical plug as a foundation should have a minimum length of 50m. The position of plugs should be verified by tagging or pressure tests. If a cement plug is placed on top of a mechanical plug then only the mechanical plug requires verification.

Randhol *et al.* (2007)[75] criticises the '*NORSOK Standard D-010*' regulations[22] for their relevance to CO_2 storage applications. The document states that material requirements should be more specific, e.g. the type of cement used. It also states that cement plug in the caprock should be specified. Furthermore, the *NORSOK* regulations permit the tubing to be left in place which is inappropriate for CO_2 storage applications.

The Netherlands

The '*Mining Regulations of The Netherlands (2003)*'[23] is concerned with regulating well abandonment. For the base of partially uncased borehole, a cement plug of at least 100m or a mechanical plug with a cement plug above it of unspecified length should be used. The bottom of the plug should be as close to the case shoe as possible. For the uncased portion of the borehole, all reservoirs should be plugged at the height of the reservoir or above it. Furthermore, plugs must be placed between reservoirs with a length of at least 100m or the separation distance of the reservoirs. For perforations in the cased hole, plugging should be performed above the perforations following the same guidelines as for the base of a partially uncased borehole. Multiple perforations should have plugs between them. Annular spaces should have at least 100m of annular seal and if it cannot be demonstrated that the annulus between casings has been sealed off, then there are further regulations. The top of the borehole should be finished with at least 100m of cement plug or a mechanical plug topped by at least 50m of cement plug. Packers, mechanical or cement plugs should be tested with for a shut off and a weight test, a pressure test or an inflow test should be performed.

[75] Randhol P., Valencia K., Taghipour A., Akervoll I., Manfred Carlsen I., 2007. Ensuring well integrity in connection with CO_2 injection SINTEF Report 31.6920.00/02/07 (http://www.ptil.no/getfile.php/z%20Konvertert/Helse,%20milj%C3%B8%20og%20sikkerhet/Sikkerhet%20og%20arbeidsmilj%C3%B8/Dokumenter/web_sluttrapportbronnintegritet_co2.pdf).

4.3.2 Regulations in the USA

EPA regulations

The US EPA has set standards for the abandonment of wells[76] under the UIC program. States decide on enforcement of EPA regulations. The class II wells from these regulations are most relevant to CO_2 storage. It is stated that 'the well shall be plugged with cement in a manner which will not allow the movement of fluids into or between USDWs'. Before commencing abandonment, the EPA must be notified. Mechanical integrity must be demonstrated and debris removed from the well. Uncemented casing should be removed where possible. If this is impossible, then the casing should be perforated, circulation should be established and then the perforations squeeze cemented. Plugging of the well should be performed with cement to prevent movement of fluids from the injection zone to any drinking water aquifer. The injection zone should be plugged with a mechanical plug topped by a cement plug with minimum length of 76 or 15m depending on the mechanical plug type. At points where the casing is cut or ripped, a minimum of 30m cement plug is required, extending from at least 15m below to rip point to 15m above the rip point. A cement plug must be placed from at least 50m below the lowest drinking water aquifer to the surface. At the surface, the casing should be cut off and the surface restored to its original state.

API regulations

The '*American Petroleum Institute (API) Bulletin E.3*'[77] provides guidance on environmentally sound well abandonment practice. The document requires a minimum cement plug length for wellbore isolation of 30m. Cement plugs should extend 15m above and below the casing shoe or the zone being isolated. For long zones of impermeable rock, a 30m plug can be placed at the top of the interval. Perorated zones should be plugged using the displacement method, squeeze cementing or a permanent bridge plug. The placement of critical plugs should be verified by tagging and pressure testing of plugs may be required.

Wyoming regulations

The '*Wyoming Oil and Gas Conservation Commission 7928 Ch. 3 - Operational Rules, Drilling Rules*'[35], provides abandonment regulations in Section 18. Cement must consist of API class cement and additives. Wells without production casing must be plugged with cement plugs of at least 30m. These plugs are required:

- over open holes and permeable formations

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[76] EPA plugging and abandoning well guidelines (1994) (http://www.epa.gov/r5water/uic/r5guid/r5_04.htm#iii).

[77] API BULL E3, 2000. Environmental guidance document: well abandonment and inactive well practices for U.S. exploration and production operations.

- at least every 762m
- in the base of surface casing and at least 30m inside surface casing
- at any other depths requested by the supervisor.

Wells without production casing must be plugged with cement plugs of at least 30m at least every 762m, in the base of surface casing and at least 30m inside the casing at the surface. Prior to plugging, flushing must be performed. All perforations must be isolated by squeeze cementing using a cement retainer no more than 15m above the uppermost perforation. A minimum of 30m of cement plug must be placed above the retainer. Production casing may remain in place if it exhibits mechanical integrity. Any fresh water containing formation that was not sealed must be perforated and squeeze cemented. Horizontal wells require a continuous cement plug from at least 30m in the lateral to 30m in the vertical position of the wellbore. Cement verification shall be performed.

Montana

The *Administrative rules of Montana*[36] *Title 36, Chapter 22* provides abandonment regulations. It requires notice and approval of intention to abandon a well. All abandoned wells to be marked with a permanent monument and the surface should be restored to its previous condition.

Texas

The '*Texas Administrative Code 3.14*'[37] provides abandonment regulations. It requires notice and approval of intention to abandon a well. Plugs are required up to the base of usable quality water strata. All formations bearing usable water, oil, gas or geothermal resources are to be protected. Cement plugs should be set to isolate each productive horizon and usable water strata. Cement plugs should be placed using the circulation or squeeze methods and the placement of plugs should be verified. The cement used should be an API approved cement. Specific mixes may be requested by the director in special situations, e.g. highly corrosive sections. Alternative materials and methods require approval by the director. For onshore wells, a 3m cement plug should be placed in the top of the well and the casing cut off 1m below the ground surface. There are further requirements for wells with specific casings. Required extensions of plugs range from 15 to 30m.

Alaskan regulations

The '*Alaska Administrative Code 25.112: Well plugging requirements*'[39] provides abandonment regulations. It states that 'plugging of the uncased portion of a wellbore must be performed in a manner which ensures that all hydrocarbons and freshwater are confined to their respective indigenous strata and are prevented from migrating into other strata or to the surface. For the uncased portion of wellbore, the displacement method must be used to place a cement plug from the well base to 30m above the top of all hydrocarbon bearing strata and similarly for abnormally geopressured strata and freshwater strata, albeit with differing plug heights. The segregated cased and uncased portion of the well must be plugged using either the displacement method or the downsqueeze method with plug height requirements ranging from 15 to 30m above and below the casing shoe depending on the plug type. Perforated intervals of cased portions must be plugged with similar but more detailed requirements than the segregated cased and uncased portion. The surface must be plugged either with the displacement method creating a cement plug of at least 45m or with alternate methods. The integrity of plugs should be verified.

Californian regulations

The '*California Code of Regulations*[38] *Title 14, Division 2'* provides abandonment regulations for onshore and offshore wells. Common requirements will be described first. Plugging and abandonment requires agreement from the state oil and gas supervisor. In uncased portions of the well, cement plugs shall be placed to extend from at least 30m below to 30m above each oil/gas zone. At least 60m of cement plug should be used across freshwater-saltwater interfaces. The casing shoe requires a cement plug from at least 30m (15m onshore) below to 30m (15m onshore) above. Perforated intervals require a cement plug opposite all perforations extending to at least 30m above them. Location and hardness tests of each cement plug shall be performed and all casing shall be cut off not more than 1.5m (3m onshore) below the ocean floor. Considering specific offshore well regulations, it is also required that a 30m long cement plug is placed above each cased oil/gas zone and 60m across each cased freshwater-saltwater interface. Annular space requires plugging with at least 60m of cement at the casing shoe. 30m of cement plug shall be placed between 15m and 45m from the ocean floor. Considering specific onshore well regulations, bridge plugs are allowed under some conditions. 30m of cement plug is required above a cased freshwater-saltwater interface. The hole and annuli shall be plugged at the surface with at least 7.5m of cement.

4.3.3 Australian regulations

Queensland regulations

The '*Queensland Petroleum and Gas (Production and Safety) Regulation 2004*'[49] provides abandonment regulations. Good industry practices are required. The well must be capped with a metal plate and the casing must be sealed below ground level. In non-horizontal wells, aquifers or porous formations must be isolated to prevent interconnection of gas or water. Casing must be removed from sections adjacent to coal seams if possible. Cement for plugs must be an industry accepted grade and must be tested. There must be a surface cement plug in the casing and at the top of any inner casing strings that do not reach the surface. Packers in or adjacent to coal seams must be removed or adequately secured. Perforated casing must be cemented. Casing must be cut off approximately 1.5m below the surface and welded fully across the top. Required lengths of cement plug are not included in the requirements.

Western Australia regulations

The '*Western Australia Schedule of Offshore Petroleum Exploration and Production Requirements 1991*'[50] provides abandonment regulations. Wells must be plugged and abandoned with 2 years of the surrender of production license or when required by the director. Uncased portions of well must have cement plugs placed to extend a minimum of 30m above and below any significant oil, gas or fresh water zones. The casing shoe must be plugged where there is open hole below using one of three methods, one of which is a cement plug placed with the displacement method to extend a minimum of 30m above and below the casing shoe. The other two methods are a cement retainer with plug or a permanent bridge type plug with cement plug. Cut casing string must have a cement plug placed to extend a minimum of 30m above and below the cut end. Casing perforations can be sealed using one of three methods, one of which is a cement plug placed opposite the perforations and extending a minimum of 30m above and below the perforated interval. The other two methods are a cement retainer with plug or a succession of retainers. A surface cement plug shall be placed to extend at least 15m below the surface and any annular space that extends to the surface and which is open to the drilled hole shall be plugged with sufficient cement to fill at least 30m. The location and integrity of plugs shall be tested. Casing should not be removed if its removal would expose any abnormal pressure, lots circulation or petroleum and water zone.

4.3.4 Canadian regulations

Alberta

The '*Alberta Energy Resources Conservation Board (ERCB) directive 20*'[54] provides abandonment regulations. Considering open holes first, plugs must extend a minimum of 15m above and below the porous zone being covered. At depths less than 1500m the plugs must be a minimum length of 30m and at depths greater than 1500m the plugs must be a minimum length of 60m. Plugs may extend over more than one porous zone and there is no minimum distance between plugs. Plugs may be staged and the location of plugs must be confirmed by an approved method. There are further specific requirements for different types of wells which specify the requirements on plugging at the surface. Considering cased holes that do not penetrate oil sand zones, non-perforated wells do not require additional cement plugs. Wells without cemented liners require abandonment according to open-hole requirements and the porous zones behind the liner to be cemented. Wells with a cemented liner require a minimum of 30m cement plug across the liner top with at least 15m above and below. Horizontal wells have separate regulations. Considering cased holes that have been completed, one of five methods can be used for plugging. These are bridge plugs, cement retainers, permanent packers, squeezing cement or cement plugs. These plugs must extend 15m above the perforations.

Saskatchewan regulations

The '*Oil and Gas Conservation Regulations (OGCR) of Saskatchewan*'[56] provides abandonment regulations. All wells must be plugged once they are no longer used for their original purpose and the minister can also request plugging. Permission for plugging must be granted by the Minister. Considering dry holes first, porous zones must be isolated with a cement plug extending 15m above and below the porous zone. The casing shoe must be plugged with a cement plug of at least 30m across the casing shoe. Surface casing must be cut off 1m below the ground surface and welded over completely. Cement can be placed by pumping through tubing, pump and plug or any other approved method. All plugs must be probed and reset if they fail to withstand the required force. Considering cased wells with zones not within pools and without danger of contamination, or where insufficient gas has been produced to be called a gas well, a mechanical bridge plug should be set immediately above perorations or the open hole with a 3m cement plug set on the bridge. Alternatively a cement plug set by displacement can be set to extend from below the perforations or casing shoe to 15m above. Again testing should be performed and the surface casing cut off and welded. Considering cased wells with zones within pools, in danger of contamination, or where sufficient gas has been produced to be called a gas well, a cast iron retainer should be set above the highest perforated interval or open hole with cement squeezed into the formation.

4.3.5 Summary and Discussion

- CO_2 storage specific regulations only provide detail on enforcing that wells should be plugged and some details on the removal of surface equipment.
- However, they do not provide detail on the particular mechanisms that should be used for plugging.
- Specific details on plugging are provided by regulations on the abandonment of hydrocarbon wells and sometimes other injection wells.
- It is often unclear whether these regulations will directly apply to CO_2 storage wells. However, in the absence of further information these regulations provide the best available guidance for CO_2 storage well abandonment.
- Most well abandonment regulations contain similar details. The main variations are in the extent of required plug and the particular placement of them.
- These general abandonment regulations are likely to be applicable to CO_2 storage wells. However, they may require updating to:
    - Specify plugging across the injection zone and the caprock
    - Update plugging material requirements using knowledge gained from the performance of standard plugging materials in CO_2 environments
    - Require tubing to be removed.

5. Overall abandonment steps and transfer of liability

Sections 3 and 4 have described regulations in the two key areas required during site abandonment: demonstrating the safety of the CO_2 storage site and plugging of wells. These actions are required to demonstrate that operational work on the site can be either stopped or reduced to a background level. In the process, liability for the site may be formally passed to an authority/state/nation etc. After this has occurred, the authority/state/nation may continue monitoring the site and there may be a financial mechanism in place for operators to pay for this. In this Section, regulations surrounding the actual transfer of liability will be discussed along with any post-liability transfer requirements (e.g. further monitoring, financial mechanisms etc). General points related to liability will first be discussed in Section 5.1. Specific regulations on abandonment will then be discussed in Section 5.2 in the context of how they differ from the general prescribed steps (Section 2.4) and liability transfer

5.1 General discussion

Liability takes different forms and can be summarised as follows (‘*International Carbon Capture and Storage Projects Overcoming Legal Barriers*’[57]):

- Operational liability, i.e. the cost and responsibility for remediation and monitoring
- Environmental/climate liability. i.e. liability for CO_2 release causing harm to the global climate or affecting credits for CO_2 reduction agreements
- In-situ liability. i.e. liability for CO_2 release affecting the natural environment: humans, drinking water, contaminated hydrocarbon reserves etc.
- Trans-border liability, i.e. issues related to liability issues that affect multiple countries caused by CO_2 release in one country.

Operational liability is short-term focussed whereas the other three liability types are long-term focussed. The type of liability referred to in regulations is typically not clear. The term ‘responsibility’ is also used to refer to liability in regulations.

After liability has been transferred, the state/authority may continue to monitor the site. The ‘*IEA model regulatory* framework’[7] contains a clause that the operator should also provide suggestions for monitoring after liability transfer. Some regulations contain a mechanism for which operators contribute to a collective fund. This fund is then used to cover the states/authorities costs after liability has been transferred. The specific regulations regarding the overall abandonment procedure and liability transfer are discussed in the following Sections.

5.2 Specific regulations

5.2.1 European regulations

The '*EU directive 2009/31/EC*'[8] states that a certificate for closure will be released to the operator when injection has ceased provided that the operator can demonstrate that all relevant conditions of the storage permit have been met and an updated 'post cessation of injection' plan has been approved. Then after 20 years, if CO_2 and well plugging safety has been shown and financial obligations met, responsibility can be passed to the competent authority. Responsibility is not defined and so presumably refers to any costs incurred as a result of the stored CO_2. The operators financial obligation is to make a financial contribution available to the competent authority that covers any costs related to ensuring the safe containment of CO_2 and should cover at least the costs of a further 30 years monitoring. After responsibility has been transferred, the competent authority will continue monitoring at a reduced level for detection of leakages or significant irregularities.

The UK CO_2 storage regulations ('*UK The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010*')[16] do not yet cover transfer of liability. In the oil and gas industry, liability resides with the owners but this has not been tested in practice (*see NSBTF document*[58]*, p86*).

The '*Norwegian Petroleum Activities Act*'[64] states that the Ministry will make a decision on long- term liability of Sleipner at the time of decommissioning.

5.2.2 Regulations in the USA

Under EPA UIC regulations[26], the EPA does not have authority to transfer liability. However, provided that CO_2 plume and well plugging safety has been shown, a site closure certificate can be awarded. Due to the strict rules on CO_2 plume safety requiring 'no additional monitoring is needed to assure that the geological storage project does not pose an endangerment to USDWs', no further monitoring is required after the site closure certificate is issued.

The IOGCC guidance regulations[27] states that 10 years after the plugging of injection wells, responsibility for the site shall be passed to designated federal agency, the operator is released from liability and the operational bond shall be returned to the operator. After this time, monitoring shall be performed by the federal agency using a shared fund paid into by operators. Note that these regulations differ strongly from other regulations in that the only requirements for liability transfer are reporting of monitoring, well plugging and removal of equipment. There are no requirements on the safety of the CO_2 plume.

The WRI guidance regulations[28] state that when CO_2 plume and well plugging safety has been shown, operators are released from liability and any future costs associated with the site. The site risk assessment should be updated and periodic monitoring continued by an entity to be decided and using a funding structure to be decided.

Washington regulations[29] state that the post-injection plan, which must be updated and approved, must be enacted within a set timeframe. Once the safety of the CO_2 plume has been shown, any of the remaining financial bond paid by the operator will be returned to the operator.

Wyoming regulations[30] do not state any abandonment rules.

Louisiana regulations[33] state that after CO_2 safety has been shown and a completion certificate issued, ownership of the site will pass to the state. The operator will be released from all terms of the regulations and any liability. A shared fund will be developed to pay for any operations after this point. The same structure applies to Montana[34].

Texan regulations[31] require CO_2 safety to be shown and that the site has met all state and federal requirements for closure. Liability is then transferred to the state.

North Dakota regulations[32] require CO_2 and well safety to be demonstrated to issue a certificate of project completion. Liability is then passed to the state and monitoring will be carried by state using a fund paid into by operators.

5.2.3 Australian liability regulations

The OPA regulations[41] require the application for closure to include demonstration of safety as well as suggestions for long term monitoring once closure has been granted. If a closure certificate is granted then liability is transferred to the Commonwealth.

The '*Victoria Greenhouse Gas Geological Sequestration Act 2008*'[44] requires all wells to be plugged and infrastructure removed, CO_2 safety to be shown and a risk management plan to be produced in order to surrender the injection license. The Act does not cover general liability.

The '*New South Wales Greenhouse Gas Storage Bill 2010*'[48] describes the application procedure for site closure, which includes demonstrating CO_2 safety. If the closure certificate is granted then the operator is released from liability.

5.2.4 Canadian liability regulations

The '*Alberta Carbon Capture and Storage Statutes Amendments Act 2010*'[51] requires CO_2 and well plugging safety as part of application for a closure certificate. The Crown then assumes liability. A post-closure stewardship fund will be established to meet the costs of monitoring after the closure certificate has been issued.

EOR liability in Saskatchewan resides with the operator during and post operation[70].

5.3 Summary and discussion

- Regulations typically contain a provision for liability of the site to be transferred once safety (CO_2 and well plugging) has been demonstrated. An argument against this is that operators may make decisions differently if they know they will not be liable in the future. An argument in favour of liability transfer is that without such a provision, operators may be deterred from investing in CO_2 storage.
- Provided that safety of the site has been demonstrated rigorously then issues of liability should not arise. However, it is nonetheless a vital part of regulations to ensure understanding between all involved parties.
- The '*EU directive 2009/31/EC*'[8] requires further monitoring after liability transfer while other regulations (e.g. '*EPA UIC*'[26]) do not. Despite this difference both require safety to be shown before liability transfer. The extra EU monitoring is a backup measure.
- Some regulations do not specify a value of the financial contribution required by operators. While this is beneficial in that the true costs will not yet be clear, it may be beneficial to indicate supposed costs, so as not to deter operators.
- The '*IEA model regulatory framework*'[7] contains a clause that the operator should also provide suggestions for monitoring after liability transfer. This is a desirable condition for abandonment regulations.

6. Annex I

International Regulations		
Convention for the Protection of the Marine Environment of the North East Atlantic, 1992 (OSPAR)	http://www.ospar.org	A convention for the protection of the marine environment in the North-East Atlantic signed by fifteen Governments.
Amendments of Annex II and Annex III to the Convention in relation to the Storage of Carbon Dioxide Streams in Geological Formations	http://www.official-documents.gov.uk/document/cm76/7696/7696.pdf	Amended in June 2007 to allow geological CO_2 storage provided that it does not lead to adverse consequences for the marine environment
OSPAR Decision 2007/2 on the Storage of Carbon Dioxide Streams in Geological Formations	http://www.ospar.org/v_measures_spider/browse.asp?menu=00820431000000_000000_000000&v0=OSPAR+Decision+2007%2F2+on+the+Storage+of+Carbon+Dioxide+Streams+in+Geological+Formations	Amended in June 2007 to allow geological CO_2 storage provided that it does not lead to adverse consequences for the marine environment
OSPAR Guidelines for Risk Assessment and Management of CO2 Streams in Geological Formations	http://www.ospar.org/v_measures_spider/browse.asp?menu=00820431000000_000000_000000 &v0=OSPAR+FRAM	Regulations of member states are made in accordance with the OSPAR Guidelines for Risk Assessment and Management of CO_2 Streams in Geological Formations.
Risk Assessment and Management Framework for CO_2 Sequestration in Sub-Seabed Geological Structures (April 2006)		Same as OSPAR framework

International Regulations		Cont.
Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (London Convention)	http://www5.imo.org/SharePoint/blastDataOnly.asp/data_id=16925/LC1972.pdf	The 1972 London Convention, signed by 82 states, and the 1996 London Protocol, signed by 37 states, are international treaties that limits the discharge of wastes that are generated on land and disposed of at sea.
Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1996 (London Protocol)	(http://www.imo.org/KnowledgeCentre/HowAndWhereToFindIMOInformation/IndexofIMOResolutions/Pages/London-Convention-(LDC,-LC)-and-London-Protocol-(LP).aspx)	The 1972 London Convention, signed by 82 states, and the 1996 London Protocol, signed by 37 states, are international treaties that limits the discharge of wastes that are generated on land and disposed of at sea.
2007 Amendment to the Protocol to cover CCS	http://www.aph.gov.au/house/committee/jsct/co2sequestration/treaties/co2_text.pdf	The Protocol was amended in 2006 to allow the storage of CO_2 streams from capture processes in geological formations, providing that the stored stream consists overwhelmingly of CO_2.
Specific Guidelines for Assessment of Carbon Dioxide Streams for Disposal into Sub-seabed Geological Formations (November 2006)	http://www.sprep.org/publication/MEA/London/9-CO2SequestrationEnglish.pdf	Specific guidelines were developed to embody a mechanism that national authorities can use to evaluate applications to store CO_2, including issues relevant to CCS site abandonment.
IEA CCS Model Regulatory Framework	http://www.iea.org/ccs/legal/model_framework.pdf	

European Regulations		
Directive 2009/31/EC of the European Parliament and of the Council of 23rd April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006	http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0114:0135:EN:PDF	Talks about monitoring, closure, post-closure etc. No guidelines on plugging. Individual member states have to make their own laws too. Most have not been done yet.
Implementation 2009/31/EC on the geological storage of carbon dioxide - Guidance Document 1 - CO_2 Storage Life Cycle Risk Management Framework	http://ec.europa.eu/clima/policies/lowcarbon/docs/gd1_en.pdf	
Implementation 2009/31/EC on the geological storage of carbon dioxide - Guidance Document 2 Characterisation of the Storage Complex, CO_2 Stream Composition, Monitoring and Corrective Measures	http://ec.europa.eu/clima/policies/lowcarbon/docs/gd2_en.pdf	

European Regulations		Cont.
Implementation 2009/31/EC on the geological storage of carbon dioxide - Guidance Document 3 - Criteria for Transfer of Responsibility to the Competent Authority	http://ec.europa.eu/clima/policies/lowcarbon/docs/gd3_en.pdf	
Implementation 2009/31/EC on the geological storage of carbon dioxide - Guidance Document 4 - Financial Security (Art. 19) and Financial Mechanism (Art. 20)	http://ec.europa.eu/clima/policies/lowcarbon/docs/gd4_en.pdf	
UK Energy Act 2008	http://www.legislation.gov.uk/ukpga/2008/32/contents	Gives some regulations on licensing, abandonment etc of CCS sites
UK The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010	http://www.legislation.gov.uk/ssi/2011/24/contents/made?view=plain	CCS law is a UK specific law following on from EU directive
UK Oil and Gas Association (UKOOA) Guidelines for the Suspension and Abandonment of Wells	http://www.ukooaenvironmentallegislation.co.uk/Contents/Topic_Files/Offshore/Well_abandonment.htm#performance	UK guidelines on well abandonment
UK Petroleum Act 1998	http://www.legislation.gov.uk/ukpga/1998/17/contents	Provides regulations on gaining approval for installation abandonment
Norwegian Pollution Control Act (1981)	http://www.regjeringen.no/en/doc/Laws/Acts/pollution-control-act.html?id=171893	Has some relevance to CCS
Norwegian Petroleum Activities Act (1996)	http://www.npd.no/en/Regulations/Acts/Petroleum-activities-act/	Has some relevance to CCS

European Regulations		Cont.
NORSOK Standard D-010	http://www.npd.no/Global/Norsk/5%20-%20Regelverk/Skjema/Br%C3%B8nnregistrering/Norsok_standard_D-010.pdf	Specific well abandonment regulations
French General Regulations for the Extractive Industry (RGIE)	http://www.ineris.fr/rgie/?q=consult_doc/navigation/2.250.190.28.8.6547/2.250.190.28.6.7596	Includes regulations for well abandonment
Spain, Act 40/2010, 29 December 2010, De almacenamiento geológico de dióxido de carbono.	http://www.congreso.es/constitucion/ficheros/leyes_espa/l_040_2010.pdf	Provides regulations on gaining approval for installation abandonment and transfer of responsibility
German Draft Act for the Demonstration and application of technologies to capture, transport and permanent storage of carbon dioxide, 2011	http://www.bmwi.de/BMWi/Redaktion/PDF/Gesetz/entwurf-abscheidung-transport-kohlendioxid,property=pdf,bereich=bmwi,sprache=de,rwb=true.pdf	Original title: Gesetz zur Demonstration und Anwendung von Technologien zur Abscheidung, zum Transport und zur dauerhaften Speicherung von Kohlendioxid" – Kohlendioxid-Speichergesetz KSpG
Mining Regulations of The Netherlands (2003)	http://www.nlog.nl/resources/Legislation/MBREnglishAug%2009.pdf	Section 8.5 covers well abandonment
Danish Energy Authority (DEA), "A Guide to Hydrocarbon Licenses in Denmark"	http://www.ens.dk/en-us/oilandgas/licences/guide/documents/guidetohc.pdf	Provides guidelines for hydrocarbon well abandonment (p247)
Richtlinie des Oberbergamtes in Clausthal-Zellerfeld über das Verfüllen auflässiger Bohrungen vom 29.Juli 1998 – 20.1 – 3/98 – BIII d 1.2 – IV- 5 pages plus illustrations.		

USA Regulations		
EPA Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide (CO2) Geologic Sequestration (GS) Wells; Proposed Rule (2010)	http://www.federalregister.gov/articles/2010/12/10/2010-29954/federal-requirements-under-the-underground-injection-control-uic-program-for-carbon-dioxide-co2#p-577	Guidelines on when closure can occur, monitoring required for closure, some description of the type of plugging available, post closure regulations etc. Regulation is at state level and so states can choose the enforcement of EPA regulations.
EPA plugging and abandoning well guidelines (1994)	http://www.epa.gov/r5water/uic/r5guid/r5_04.htm#iii	EPA provides guidelines on how to plug and abandon injection wells
IEA Long term integrity of CO_2 storage - well abandonment (2009)		API provides guidelines on environmentally sound practices for well plugging
CO_2 Storage: A Legal and Regulatory Guide for States (2008)	http://iogcc.publishpath.com/Websites/iogcc/pdfs/Road-to-a-Greener-Energy-Future.pdf	Provides guidelines for CO_2 injection and lays them out in bill format so that states could copy them if required
WRI Guidelines for Carbon Dioxide Capture, Transport, and Storage (2008)	http://pdf.wri.org/ccs_guidelines.pdf	A diverse group of 80 stakeholders helped to developed example regulations to help authorities make their own regulation
EPA Vulnerability Evaluation Framework for Geologic Sequestration of Carbon Dioxide (2008)	http://www.epa.gov/climatechange/emissions/downloads/VEF-Technical_Document_072408.pdf	This document is a first step towards a conceptual framework that aids regulators. It could serve as a reference document for regulators issuing permits
Wyoming (HB 90) HEA25 (2008)	http://legisweb.state.wy.us/2008/Enroll/HB0090.pdf	CCS regs. About termination. Wells must be plugged according to rules of commission
Wyoming Oil and Gas Conservation Commission 7928 Ch. 3 - Operational Rules, Drilling Rules	http://soswy.state.wy.us/Rules/RULES/7928.pdf	Plugging rules

USA Regulations		Cont.
Louisiana HB 661 (2009)	http://www.legis.state.la.us/billdata/streamdocument.asp?did=668800	CCS regs. Directions to plug but no detail
Montana Senate Bill 498 (2009)	http://data.opi.mt.gov/bills/2009/billpdf/SB0498.pdf	CCS regs. Monitoring, closure etc
Administrative rules of Montana, Title 36, Chapter 22	http://www.mtrules.org/gateway/ChapterHome.asp?Chapter=36%2E22	rules on plugging
North Dakota Senate Bill 2095 (2009)	http://www.legis.nd.gov/assembly/61-2009/bill-text/JQTA0100.pdf	CCS regs. Closure etc
Texas House Bill 1796 (2009)	http://www.legis.state.tx.us/tlodocs/81R/billtext/pdf/HB01796F.pdf	CCS regs.
Texas Administrative Code 3.14	http://info.sos.state.tx.us/pls/pub/readtac$ext.TacPage?sl=R&app=9&p_dir=&p_rloc=&p_tloc=&p_ploc=&pg=1&p_tac=&ti=16&pt=1&ch=3&rl=14	Well plugging regs
Washington WAC 173-407-110 (2008)	http://apps.leg.wa.gov/WAC/default.aspx?cite=173-218-115	CCS regs
California Code of Regulations. Title 14, Division 2	ftp://ftp.consrv.ca.gov/pub/oil/regulations/PRC04.PDF	well plugging regs
Alaska Administrative Code 25.112. Well plugging requirements	http://www.touchngo.com/lglcntr/akstats/aac/title20/chapter025/section112.htm	Well plugging regs

Australian Regulations		
Australian Regulatory Guiding Principles for Carbon Dioxide Capture and Geological Storage	http://www.ret.gov.au/resources/Documents/ccs/CCS_Aust_Regulatory_Guiding_Principles.pdf	Detailed the need for regulation and the advantages and disadvantages for regulation taking different forms
Australian Regulatory Impact Statement	http://www.ret.gov.au/resources/Documents/ccs/Regulation_Impact_Statement.pdf	Describes how regulatory changes will be made
Offshore Petroleum Amendment Bill 2008	http://www.ret.gov.au/resources/Documents/ccs/os_Petroleum_Amendment_Bill_2008.pdf	The OPA is amended to cover CCS
Revised Explanatory Memorandum to the Offshore Petroleum Amendment (Greenhouse Gas Storage) Bill	http://www.ret.gov.au/resources/Documents/ccs/Revised_EM.pdf	Explanatory guide to OPA amendment s
New South Wales Greenhouse Gas Storage Bill 2010	http://www.parliament.nsw.gov.au/prod/parlment/nswbills.nsf/0/d5a532019610547dca2577e4001806bc/$FILE/b2010-109-d10_House.pdf	CCS regs
Queensland Greenhouse Gas Storage Act 2009	http://www.legislation.qld.gov.au/LEGISLTN/ACTS/2009/09AC003.pdf	CCS regs
Queensland Greenhouse Gas Storage Regulation 2010	http://www.legislation.qld.gov.au/LEGISLTN/CURRENT/G/GreenGasSR10.pdf	CCS regs
Queensland Petroleum and Gas (Production and Safety) Regulation 2004	http://www.legislation.qld.gov.au/LEGISLTN/CURRENT/P/PetrolmGasR04.pdf	Well plugging regs (p187)

Australian Regulations		Cont.
Victoria Offshore Petroleum and Greenhouse Gas Storage Act 2010	http://www.legislation.vic.gov.au/Domino/Web_Notes/LDMS/PubStatbook.nsf/f932b66241ecf1b7ca256e92000e23be/6D3C2CCB18FB08C3CA2576EF001E64F4/$FILE/10-010a.pdf	CCS regs. Closure on page 476
Victoria Greenhouse Gas Geological Sequestration Act 2008	http://www.legislation.vic.gov.au/Domino/Web_Notes/LDMS/PubStatbook.nsf/51dea49770555ea6ca256da4001b90cd/7E4801FE0E8E3A55CA2574F80019A141/$FILE/08-61a.pdf	
Western Australia Schedule of Offshore Petroleum Exploration and Production Requirements 1991	http://www.dmp.wa.gov.au/documents/schedule_onshore_PGERA67%281%29.pdf	Well plugging regs (529 and 636)

Canadian Regulations		
Oil and Gas Conservation Regulations (OGCR)	http://www.ercb.ca/docs/requirements/actsregs/ogc_reg_151_71_ogcr.pdf	Consolidated to AR 65/2011
Oil and Gas Conservation Act of Alberta (OGCA) 2000	http://www.ercb.ca/docs/requirements/actsregs/ogc_act.pdf	Updated to May 13, 2011
Oil and Gas Conservation Act of Saskatchewan	http://www.qp.gov.sk.ca/documents/English/Statutes/Statutes/O2.pdf	

Canadian Regulations		Cont.
Alberta Carbon Capture and Storage Statutes Amendments Act 2010	http://www.qp.alberta.ca/546.cfm?page=CH14_10.CFM&leg_type=fall	CCS regs
Alberta Energy Resources Conservation Board (ERCB) directive 20 Well Abandonment	http://www.ercb.ca/docs/documents/directives/directive020.pdf	Well abandonment Latest release: July 1, 2010
Alberta Energy Resources Conservation Board (ERCB) Directive 51 Injection and Disposal Wells - Well Classifications, Completions, Logging, and Testing Requirements	http://www.ercb.ca/docs/documents/directives/Directive051.pdf	Well abandonment Latest release: March 1994
Alberta Energy Resources Conservation Board (ERCB) Directive 065 Resources Applications for Oil and Gas Reservoirs	http://www.ercb.ca/docs/documents/directives/Directive065.pdf	Revised edition: August 9, 2010
Alberta Specified Gas Emitters Regulation: Quantification Protocol for Acid Gas Injection	http://environment.gov.ab.ca/info/library/7910.pdf	EOR regs
Alberta Specified Gas Emitters Regulation: Quantification Protocol for Enhanced Oil Recovery	http://environment.gov.ab.ca/info/library/7961.pdf	Acid gas injection regs