Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development

Australian Government

Department of the Environment

Background review

Bore integrity

This background review was commissioned by the Department of the Environment on the advice of the Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining. The review was prepared by Sinclair Knight Merz Pty Ltd and revised by the Department of the Environment following peer review.

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Acknowledgements and contributors

This background review was commissioned by the Department of the Environment on the advice of the Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining. The review was prepared by Sinclair Knight Merz Pty Ltd. It was revised by the Department of the Environment following peer review by John Henrich (Bergerson Caswell Inc.) and Don Scott (Pennington Scott) and relevant Queensland, New South Wales and South Australian Government departments.

Addendum

Changes to state government departments have occurred since the finalisation of this report by the authors. The Queensland, New South Wales and South Australian Government agencies were contacted and updated information provided in September 2013; however, no guarantees can be made as to the completeness of these updates. Up-to-date information should be sourced from the relevant department.

On 1 January 2013, the Queensland Water Commission (QWC) ceased operations. The Office of Groundwater Impact Assessment (OGIA) retains the same powers as the former QWC under Chapter 3 of the *Water Act 2000* (Qld).

Sinclair Knight Merz Pty Ltd is now Jacobs SKM.

Contents

Summary

This report provides an overview of bore construction, integrity, monitoring, reporting, decommissioning and legacy issues in Australia. It focuses on bore integrity issues as they relate to coal seam gas extraction in Australia and is informed by the international context and relevant experience in other sectors. It refers to bores constructed for water supply, coal mining exploration and coal seam gas exploration and production. With the exception of coal seam gas wells, onshore and offshore petroleum and gas wells are not considered.

In this report the terms ‘well’ and ‘bore’ are used interchangeably, but most often ‘well’ is used when referring to the extraction of coal seam gas and ‘bore’ when referring to the extraction, exploration or monitoring of water and the exploratory sampling of coal where a bore is required.

Key points

- Bore integrity failure can cause adverse changes in groundwater levels, flow rates and flow directions and can also lead to changes in groundwater quality.
- Bore integrity depends on good bore design, appropriate selection of construction materials and a high standard of cementing.
- In Australia, different types of bores are regulated under different legislation. Existing guidelines and regulations provide frameworks to establish bore integrity; driller and operator compliance is essential.
- Opportunities for future research include more detailed assessments of the frequency of, mechanisms for and consequences of bore integrity failure.
- Monitoring and reporting of bore and well integrity across all industries will be important to provide information needed to assess bore integrity and to act if there are issues.

The significance of bore integrity

In the context of this report “bore integrity” means:

> *‘…instantaneous state of a well, irrespective of the purpose, value or age, which ensures the veracity and reliability of the barriers necessary to safely contain and control the flow of all [gases] and fluids within or connected to the well’.*
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A failure of bore integrity is a failure to prevent fluid flow between aquifers and between the surface and the aquifer. Bore integrity is fundamental to protect the target aquifer and surrounding aquifers for the full life cycle of the well.

Hundreds of thousands of bores have been drilled and constructed across Australia and many of these are located in key groundwater resources. Where bore integrity is not maintained, or bores are not decommissioned properly, there is the potential to impact on groundwater resources, which can affect existing and future groundwater users as well as the environment. Bore integrity failure can cause adverse and unintended changes in groundwater levels, flow rates and flow directions and can also lead to changes in groundwater quality. A further impact often associated with bore integrity failure is the contamination of aquifers by leakage of gas or water of a different quality, either through the bore casing, the bore annulus or open (i.e. uncased) bores.

In relation to coal seam gas development, understanding bore integrity is essential to:

- understanding the risk of coal seam gas loss to overlying aquifers, and subsequent risks to groundwater quality and human safety
- predicting the impacts on aquifers from depressurising coal seams, as degraded or inappropriately constructed boreholes may provide sufficiently increased connectivity of aquifers to require factoring into groundwater flow analysis.

Causes and incidence of bore integrity failure

Bore integrity failure is usually due to one or more of the following scenarios.

- Poor construction methods – for example, a poorly sealed annulus that allows contaminated surface water to enter the bore, or the inappropriate placement of bore openings against multiple aquifers that link aquifers of differing water quality.
- Poor monitoring and maintenance – for example, inadequate monitoring or routine maintenance of bore casings and associated headworks results in bore integrity failures not being detected or corrected.
- Failed integrity of bore materials – for example, a corroded bore casing or a failed grout seal allows cross flow of water between aquifers.
- Poor decommissioning – decommissioning refers to work undertaken to properly shut down a bore. All failed or unwanted drill holes, bores and wells should be decommissioned properly, to restore aquifer-isolation and prevent surface water inflow, uncontrolled discharge of gas or fluids and flow between aquifers.

Bore integrity failure is most likely to occur as a result of poor construction techniques. Therefore, good bore design, appropriate selection of construction materials and a high standard of cementing are essential to the integrity of a new bore. Existing guidelines and regulations provide frameworks to establish bore and well integrity; driller and operator compliance is essential.

Bore integrity regulation and management

Coal seam gas wells

The construction and integrity of Australian coal seam gas wells is managed through a combination of state and territory legislation, industry standards and codes of practice. For example, Australia’s petroleum and gas legislation is largely based on international standards such as the American Petroleum Institute (API) and Standards Norway (NORSOK). The Norwegian petroleum industry developed the NORSOK standards to ensure adequate safety, value-adding and cost-effectiveness for petroleum industry developments and operations. The API publishes a range of practice notes that are used by many countries to guide well construction and operations, including Australian codes of practice for coal seam gas. The regulatory regime in Australia for the petroleum and gas industry is regarded to be leading practice.

In Queensland and New South Wales there are specific codes of practice for coal seam gas well integrity. Queensland has a *Code of practice for coal seam gas wellhead emissions detection and reporting*, and New South Wales has a *Code of practice for coal seam gas well fracture simulation activities* and *Code of practice for coal seam gas well integrity*. These codes of practice outline monitoring and reporting requirements to ensure well integrity as specified by each regulator. Standards and the level of compliance within the coal seam gas industry are higher than that of the water and mining industries.

Water bores

The water bore industry is regulated by various acts, standards and guidelines, many of which are based on international standards. The design, drilling, construction, maintenance and decommissioning of water bores in Australia are guided by the *Minimum construction requirements for water bores in Australia* (MCRWBA), which was first published in 1997. However, at a national and state level there are no regulatory requirements for monitoring the integrity of water bores, either upon completion, over their workable life, or upon decommissioning. This is considered to be the responsibility of the bore owner.

Mining and exploration bores

Mining and coal exploration bores are regulated in Australia under the relevant legislation in each jurisdiction. Similar to water bores, there is little published on the adequacy of the mining regulatory framework and the level of compliance. Drillers are not required to be licensed, there is little information about decommissioning of exploration bores in the public domain and there are no regulatory requirements for monitoring the integrity of decommissioned exploration bores.

Integrity monitoring

Monitoring the integrity of a bore through its life cycle is crucial to ensuring the bore is maintained. Bores can deteriorate with age, operation and site-specific conditions, reducing their capacity for the intended use. Bore monitoring and maintenance is required to ensure the bore is preserved and its components are in good condition for the life of the bore. There are a variety of tools and techniques available to assess bore integrity, including technologies available for measuring well integrity in a coal seam gas field. These techniques apply equally to other well types, including coal seam gas wells and water bores. However, the cost of integrity assessment techniques may be a barrier to their use, especially for bores that are shallow and/or of simple construction, and may be replaced at a relatively low cost.

Monitoring and reporting of bore and well integrity across all industries will be important to ensure that there is sufficient information available to assess bore integrity and to act if there are issues. Research to assess the most appropriate and cost-effective techniques to locate legacy bores throughout Australia and to determine the scale of the issue would also be of benefit.

Abbreviations

Abbreviation	Description
ADIA	Australia Drilling Industry Association
ADITC	Australian Drilling Industry Training Committee
API	American Petroleum Institute
APPEA	Australian Petroleum Production and Exploration Association
AQF	Australian qualifications framework
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
ASR	Aquifer storage and recovery
ASV	Annulus safety valve
BGL	Below ground level
CBT	Cement bond tools
CCS	Carbon capture and storage
CCTV	Closed circuit television
CMA	Catchment management authority
CO_2	Carbon dioxide
CSG	Coal seam gas
DEEDI	QLD Department of Employment, Economic Development and Innovation
DEHP	QLD Department of Environment and Heritage Protection
DERM	QLD Department of Environment and Resource Management.
DMITRE	SA Department for Manufacturing, Innovation, Trade, Resources and Energy
DNRM	QLD Department of Natural Resources and Mines
DSE	VIC Department of Sustainability and Environment
ECP	Extracellular polymers
FRP	Fiberglass-reinforced polymer
GAB	Great Artesian Basin
GMV	Goulburn Murray Water
G-WMW	Grampians-Wimmera Mallee Water
H_2O	Water molecule
IESC	Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development
ISWD	International School of Well Drilling
MCRWBA	Minimum construction requirements for water bores in Australia
ML	Megalitre (1 million litres)

Abbreviation	Description
MRSD Act	*Mineral Resources (Sustainable Development) Act 1990* (Vic)
NMBSC	National Minimum Bore Specifications Committee
NORSOK	Norsk Sokkels Konkuranseposisjon (Standards Norway)
NSW	New South Wales
NSW T&I	Department of Trade and Investment, Regional Infrastructure and Services (known as NSW Trade & Investment)
NUDLC	National Uniform Drillers Licensing Committee
ODNR	Ohio Department of Natural Resources (US)
OGIA	Office of Groundwater Impact Assessment
PGE Act	*Petroleum and Geothermal Energy Act 2000* (SA)
PGER Act	*Petroleum and Geothermal Energy Resources Act 1967* (WA)
PN	Nominal pressure
PSA	Petroleum Safety Authority, Norway
PVC-U	Polyvinyl chloride
QWC	Queensland Water Commission
REF	Review of environmental factors
RPL	Recognised prior learning
SA	South Australia
SCER	Standing Council on Energy and Resources
SCVF	Surface-casing-vent flow
SEO	Statement of environmental objective
SRW	Southern Rural Water
UK	United Kingdom
US	United States of America
VIT	Vertical interference test
WA	Western Australia

Glossary

Term	Description
Annulus	The space between the bore casing and borehole, or between bore casings, or between casing and tubing, in coal seam gas wells.
Aquifer	Rock or sediment in a formation, group of formations or part of a formation, that is saturated and sufficiently permeable to transmit quantities of water to wells and springs.
Aquitard	A saturated geological unit that is less permeable than an aquifer, and incapable of transmitting useful quantities of water. Aquitards often form a confining layer over an artesian aquifer.
Artesian	Pertaining to a confined aquifer in which the groundwater is under positive pressure (that is, a bore screened into the aquifer will have its water level above ground).
Bore	A narrow, artificially constructed hole or cavity used to intercept, collect or store water from an aquifer, or to passively observe or collect groundwater information. Also known as a borehole, drill holes or piezometer. This report uses the term 'bore' in reference to the extraction, exploration or monitoring or water.
Bore development	The vigorous agitation of water and air in the borehole to remove fine particles and other material introduced in the drilling process and to provide a good hydraulic connection between the bore and the aquifer.
Bore failure	The condition of a bore once it becomes unserviceable to the point of requiring refurbishment, replacement or decommissioning.
Borehole	Refer to Bore.
Bridge	A solid fixture that is positioned in a drilled hole, to form a base for grout or backfill material, when the drilled hole is to be only partially infilled.
Casing	A tube used as a temporary or permanent lining for a bore. *Surface casing*: The pipe initially inserted into the top of the hole to prevent washouts and the erosion of softer materials during subsequent drilling. Surface casing is usually grouted in and composed of either steel, PVC-U or composite materials. *Production casing*: A continuous string of pipe (casing) that is inserted into or immediately above the chosen aquifer and back to the surface through which water or gas is extracted / injected.
Cement grout	A fluid mixture of Portland Cement and water of a consistency that can be forced through a pipe and placed as required.
Cementing	The process of placing grout into the annulus around the casing to provide a permanent seal. Is also known as grouting.
Clearbore	A biodegradable granular chemical designed to remove the blockage of sludge and hard encrustations that result from dissolved iron and iron-related bacteria. Is manufactured by Clearbore Pty Ltd.
Construction	The entire process of creating a bore from initial drilling and inserting the surface casing and screen, completing the bore and developing it for use.
Confined aquifer	An aquifer which is isolated from the atmosphere by an impermeable layer. Pressure in confined aquifers is generally greater than atmospheric

Term	Description
	pressure.
Contaminant	Biological (e.g. bacterial and viral pathogens) and chemical introductions capable of producing an adverse response (effect) in a biological system, seriously injuring structure or function or producing death.
Corrosion	The act or process of dissolving or wearing away a material.
Decommissioned (abandoned)	A bore for which the purpose and use have been permanently discontinued.
Dewatering	The lowering of static groundwater levels through complete extraction of all readily available groundwater, usually by means of pumping from one or several groundwater bores.
Disinfection	A preventative measure against iron bacteria, potential encrustation and resulting decline in bore efficiency. Disinfection generally involves chemical treatment such as chlorination.
Drilling fluids	A medium used to stabilise the formation, control groundwater flow and remove the drill cutting from the hole as drilling takes place.
Exploration bore	A bore, or hole, drilled with the purpose to collect samples of geology.
Fugitive emissions	The unintentional release of gases or vapours, generally from industrial activities.
Good oilfield practice	A long held industry concept that is defined as 'all those things that are generally accepted as good and safe in carrying out exploration or recovery operations'.
Gravel pack	Granular material introduced into the annulus between the borehole and casing / screen, to prevent or control the movement of finer particles from the aquifer to the bore. Also referred to as a filter pack.
Groundwater	Water occurring naturally below ground level (whether in an aquifer or other low permeability material), or water occurring at a place below ground that has been pumped, diverted or released to that place for storage there. This does not include water held in underground tanks, pipes or other works.
Groundwater injection bore	A bore installed to facilitate the injection of liquid (e.g. H_20) or gas (e.g. CO_2) into an aquifer. Commonly used in Managed Aquifer Recharge schemes or groundwater remediation.
Groundwater monitoring/ observation bore	A bore installed to determine the nature and properties of subsurface groundwater conditions, provide access to groundwater for measuring level, physical and chemical properties, and permit the collection of groundwater samples and/or conduct aquifer tests.
Groundwater pumping (production) bore	A bore installed primarily to extract groundwater for productive/consumptive purposes from a particular hydrogeological formation by means of a pump.
Headworks	The part of a bore that protrudes at the ground surface. It usually entails a concrete collar and pad around the bore casing raised above the natural surface to prevent surface water entering the borehole.
Hydraulic fracturing	Also known as 'fracking', 'fraccing', or 'fracture stimulation', is the process by which hydrocarbon (oil and gas) bearing geological formations are 'stimulated' to enhance the flow of hydrocarbons and other fluids towards the well. The process involves the injection of fluids, gas, proppant, and other additives under high pressure into a geological formation to create a network of small fractures radiating outwards from the well through which

Term	Description
	the gas, and any associated water, can flow.
Integrity	The instantaneous state of a well, irrespective of the purpose, value or age, which ensures the veracity and reliability of the barriers necessary to safely contain and control the flow of all fluids within or connected to the well. A failure of integrity is a failure to prevent fluid flow between aquifers and between the surface and the aquifer.
Legacy bore	A bore, or well, that is no longer used and has not been decommissioned/abandoned correctly.
Production well	A well drilled to produce oil or gas.
Rehabilitation	The restoration of a bore to its most efficient condition using a variety of chemical or mechanical techniques, which may include replacing the production casing and/or screens.
Screen	The intake portion of a bore, which contains an open area to permit the inflow of groundwater at a particular depth interval, whilst preventing sediment from entering with the water.
Tubing (coiled)	Tubing refers to metal piping, normally 2.5 cm to 8.3 cm in diameter, used for interventions in oil and gas wells and sometimes as production tubing in depleted gas wells.
Unconfined aquifer	An aquifer which has the upper surface connected to the atmosphere.
Vadose zone	The vadose zone, also called the unsaturated zone, extends from the top of the ground surface to the water table. In the vadose zone, the water in the soil's pores is at atmospheric pressure.
Water quality	The physical, chemical, and biological attributes of water that affects its ability to sustain environmental values.
Water table	The upper surface of a body of groundwater occurring in an unconfined aquifer. At the watertable, pore water pressure equals atmospheric pressure.
Well	A human made hole in the ground, generally created by drilling, to obtain fluid or gas.
Yield	The rate at which water (or other resources) can be extracted from a pumping well, typically measured in litres per second (L/s) or megalitres per day (ML/d).

1 Introduction

This review is one of a number commissioned by the Department of the Environment on the advice of the Interim Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining. These reviews aim to capture knowledge on the water-related impacts of coal seam gas extraction and large coal mining, but do not aim to provide detailed analysis and evaluation of methods for identifying and managing impacts, or to develop such methods.

The focus of this report is bore integrity, which is defined as the:

> *"…instantaneous state of a well, irrespective of the purpose, value or age, which ensure the veracity and reliability of the barriers necessary to safely contain and control the flow of all fluids within or connected to the well."*
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In this report the terms 'well' and 'bore' are used interchangeably, but most often 'well' is used when referring to the extraction of coal seam gas and 'bore' when referring to the extraction, exploration or monitoring of water and the exploratory sampling of coal where a bore is required.

A failure of bore integrity is a failure to prevent fluid flow between aquifers and between the surface and the aquifer. Bore integrity is fundamental to protect the target aquifer and surrounding aquifers for the full life cycle of the bore (or well). Hundreds of thousands of bores have been drilled and constructed across Australia and many of these are located in key groundwater resources. If bore integrity is not maintained, or bores are not decommissioned appropriately, there is the potential to impact on groundwater resources, which can affect existing and future users of groundwater as well as the environment.

This report focuses on bore integrity issues as they relate to coal seam gas extraction in Australia and is informed by the international context and relevant experience in other sectors. It examines issues associated with bore construction, integrity, monitoring and reporting, decommissioning, and legacy issues. Bores constructed for water supply, coal mining exploration and coal seam gas exploration and production are reviewed, whilst other onshore and offshore petroleum, oil and gas wells are not.

This report provides a summary and synthesis of the relevant and available literature without focusing on the results of any specific study or research project. The report was prepared from information available in the public domain and discussions with industry representatives. The major sources of information were:

- scientific journal articles
- conference proceedings
- scientific text books
- government department reports, guidelines and policies
- industry technical reports and standards.

This report begins with a review of the regulations governing bore management in Australia (Chapter 2) and established methods for bore design and construction (Chapter 3).

Chapter 4 explores methods and requirements for bore monitoring and reporting and Chapter 5 reviews aspects of bore decommissioning.

The final section of this report (Chapter 6) identifies the major knowledge gaps that present a risk to the future management of water resource impacts from bores and wells in Australia. These gaps include uncertainties in the understanding of frequency, mechanisms, criteria and consequences of bore integrity failure; and uncertainties in the understanding of cumulative issues associated with multiple incidents of bore integrity failure.

2 Regulations governing bore management

2.1 Overview

In Australia, different types of bores are regulated under different legislation. All water bores, including water supply bores for agriculture, irrigation and stock and domestic use, and dewatering bores are regulated under the relevant state or territory water acts. Mining exploration bores are regulated under the relevant state or territory mining acts. Coal seam gas extraction is generally regulated in the same way as other onshore petroleum upstream activity through the state and territory petroleum and gas acts. As the majority of coal seam gas and coal mining is located in New South Wales and Queensland, this review of legislation is focused largely on these states.

2.2 Drilling licences

2.2.1 Water bores

Australia has a National Water Well Drillers' Licensing System, which requires anyone who drills bores for the purpose of accessing groundwater to be licensed (ADITC 2010) (unless state or territory legislation provides an exemption). The Australian Drilling Industry Training Committee Limited (ADITC) coordinates the licensing program. Drillers' licences are classified according to the type of aquifers and drilling methods:

- class 1 – restricted to drilling operations in single non-flowing aquifer systems, such as water table aquifers
- class 2 – in addition to operating in Class 1 conditions, permits drilling operations in multiple on-flowing aquifer systems, such as confined aquifers
- class 3 – in addition to operating in Class 1 and 2 conditions, permits drilling operations in flowing aquifer systems, such as artesian aquifers.

All jurisdictions use the National Water Well Drillers' Licensing System as a common basis for a national examination so that technical skills at the national level have a benchmark (ADITC 2010). If a driller is licensed in one state they can apply for their licence to be converted to the equivalent class of licence in another state. Each jurisdiction also requires drillers to meet minimum requirements to ensure they are aware of the local legislation and conditions (ADITC 2010).

2.2.2 Mining, petroleum and gas wells

Drillers operating in the mining and petroleum and gas industries are required to be qualified in accordance with the Australian Qualification Framework (AQF), but they are not required to hold a National Water Well Drillers' Licence (ADITC 2011). The AQF is a national qualifications framework that comprises a series of qualifications that are formally named Certificate I, II, III and IV, Diploma and Advanced Diploma (ADITC 2011). The process of assessment is either carried out on-the-job with a qualified industry assessor or through a Recognised Prior Learning (RPL) process involving the preparation of a portfolio outlining the participant's experience in drilling (ADITC 2011).

There is no legal requirement by the Commonwealth or state governments for drillers to comply with the AQF (ADITC 2012, pers. comm., September). For example, in Queensland while it is the tenure holder, rather than the driller, who has primary responsible for ensuring bore construction meets the regulatory requirements, the Queensland Government requires that all drillers be appropriately qualified and drilling inspectors may close a site if drillers are operating without appropriate qualifications. In Victoria, these qualifications are not mandated. In New South Wales, drillers need to be licensed to drill a bore that meets the definition of a 'water bore' under the *Water Management Act 2000* (NSW). This is also the case for CSG activities in New South Wales. This variation in qualifications across industries and jurisdictions reflects the differences in responsibilities of the driller. However, most companies require drillers to hold these qualifications despite it not being a national legal requirement.

This review found no published literature discussing the adequacy of Australia's drilling licensing systems. However, the Australian Drilling Industry Association (ADIA) recommends that all drillers be certified or licensed, which would help ensure aquifers are protected across the different industries (Fitzgerald (ADIA) 2012, pers. comm., September). ADIA's primary concern is with mining exploration bores, particularly ensuring they are decommissioned appropriately.

2.3 Water bores

Water bore construction is now required to meet mandatory construction standards across Australia unless state or territory legislation provides an exemption. For example, in Western Australia, stock and domestic and monitoring bores are not regulated and do not need to be drilled by a licensed driller. Queensland and the Northern Territory do not require bores outside of certain management areas to be licensed (Scott 2013). State governments have implemented bore construction licensing programs at various stages, in alignment with their respective legislative requirements. Bores drilled prior to the introduction of particular regulatory requirements may pose a higher risk for the loss of bore integrity.

2.3.1 Water supply and monitoring bores

Water bores include any bores that have been drilled for water supply, including that for stock and domestic use, irrigation and commercial purposes, groundwater monitoring and dewatering. Table 1 provides a summary of the regulatory context in each state and territory of Australia.

Design, drilling, construction, maintenance and decommissioning of water bores anywhere in Australia is governed by the *Minimum construction requirements for water bores in Australia* (MCRWBA) (NUDLC 2012), first published in 1997. Prior to 1997, there were no national guidelines. The current version of the MCRWBA is referred to extensively by regulators and the drilling industry, as it provides a consistent standard reference across Australia. It focuses on protecting groundwater resources and providing a good water supply. Mandatory requirements are enforceable for the protection of the groundwater resource. It also includes recommendations for 'good industry practice' for some methods and techniques. Legislation and the regulations that follow are managed by water regulators in each state and territory.

Previous versions of the MCRWBA (i.e. NMBSC 2003; ARMCANZ 1997) were reviewed to identify changes in standards relating to bore integrity. On a broad scale, very little change was observed between the 1997 and 2003 revisions of the document. However, a complete re-structure of the document was evident in 2012, with a higher level of requirements and more detailed standards, particularly in the casing and grouting/cementing/bore sealing sections. The mandatory requirements within the report clearly summarise the standards and requirements for each aspect of bore installation.

Table 1 Overview of the regulatory framework for water bores in Australia.

Jurisdiction	Regulatory Framework for Water Bores
Australian Capital Territory	The *Water Resources Act 2007* controls licensing of drillers, construction of bores and groundwater extraction. The ACT government Environment and Sustainable Development Directorate is the body that regulates licensing and a ‘requirement’ of each driller’s licence is to undertake work on bores as per the *Minimum construction requirements for water bores in Australia* (MCRWBA) (NUDLC 2012). The NSW drilling licence is also recognised in ACT (Fitzgerald (ADIA), pers. comm., September).
New South Wales	The Department of Primary Industries (Office of Water) is responsible for the management of and access to groundwater. Approval to construct a bore and extract groundwater is governed by the *Water Management Act 2000,* which ‘recommends’ that all water bores be constructed to meet MCRWBA (NUDLC 2012).
Northern Territory	The protection and control of groundwater is covered by the *Water Act 1992* and regulated by the Department of Land Resource Management. Water bores in the Northern Territory are required to comply with MCRWBA (NUDLC 2012).
Queensland	All bores are required to comply with the MCRWBA (NUDLC 2012). If a bore is located in the Great Artesian Basin (GAB), it must also comply with *Minimum standards for the construction and reconditioning of water bores that intersect the sediments of artesian basins in Queensland* (DNRM 2013). These standards apply to both artesian and sub-artesian water bores intersecting artesian water beds in the area managed under the *Water Resource (Great Artesian Basin) Plan 2006* (Queensland Government 2006).
South Australia	Groundwater resources are managed under the *Natural Resources Management Act 2004* and regulated by the Department of Environment, Water and Natural Resources. Water bores in South Australia are required to comply with the MCRWBA (NUDLC 2012) and the general specification for well construction modification and abandonment in South Australia pursuant to well construction permits issued under the *Natural Resources Management Act 2004*.
Tasmania	Water bores ‘should’ be constructed in accordance with the MCRWBA (NUDLC 2012) and groundwater access is regulated by the Department of Primary Industries, Parks, Water and Environment and controlled under the *Water Management Act 1999*. There is a requirement, under Part 7 of the *Water Management Act 1999*, that the occupier of land on which a water bore is situated must ensure that the bore, including the casing, lining, screen and mechanism used to cap the well (if any), is properly maintained. It is also an offence under the Act to introduce any matter into a well that could cause pollution of groundwater.
Victoria	The *Water Act 1989* provides the basis for the rules under which Victoria's water users can access and take and use water. The Department of Sustainability and Environment (DSE) is responsible for coordinating state-wide groundwater management activities and providing groundwater policy direction. There are three water corporations in Victoria that regulate drilling and construction of water bores – Goulburn Murray Water (GMW), Grampians Wimmera Mallee Water (G-WMW) and Southern Rural Water (SRW). All bores in Victoria ‘must’ be constructed to an ‘acceptable’ standard and meet the MCRWBA (NUDLC 2012).
Western Australia	The Department for Water administers the *Rights in Water and Irrigation Act 1914* to issue groundwater licences in all proclaimed areas and for all artesian water bores in the state. Water from sub-artesian bores can be taken without a licence in unproclaimed areas. Drillers are required to ‘perform all work’ under the MCRWBA (NUDLC 2012).

At the time of writing there was no published literature reviewing the adequacy of the MCRWBA but the water industry accepts that the third edition of the MCRWBA (NUDLC 2012) provides a sound framework for the design and construction of water bores (Fitzgerald (ADIA) 2012, pers. comm., September). However, there are no regulations at a national and state level for monitoring the integrity of water bores, either upon completion, during operation or upon decommissioning.

The level of compliance by drillers within the guidelines is largely unknown and/or unpublished. The *National framework for compliance and enforcement systems for water resource management* outlines offences that regulators must endeavour to prevent (DSEWPaC 2012). These include bore construction by an unlicensed water driller and non-compliance by licensed water drillers such as non-lodgement of drilling logs or faulty bore construction (DSEWPaC 2012). Regulators in all jurisdictions have compliance officers to ensure that bores are drilled and constructed in accordance with guidelines (e.g. SRW 2011). The number of bore inspections that are actually undertaken is not published.

2.4 Coal mining exploration bores

Mining exploration bores are regulated under the mining legislation specific to each Australian jurisdiction. A mining exploration licence is granted and exploration holes can be drilled and should also be decommissioned when finished. If a mining lease is located in an area where there are important groundwater resources, the application is referred to the appropriate water department, so that specific conditions can be included in the conditions of the licence to ensure the groundwater resources are protected. However, this referral process does rely on the regulators having the right processes and capacity to deal with these referrals (SKM 2012a). At the time of writing, documentation on how often this actually occurs, or if the regulator has the capacity to assess each case and how it may vary across the jurisdictions was not found.

As part of the conditions on the mining lease permit, annual reports are often required to be submitted to the regulators detailing the exploration activities that have been undertaken. The relevant mining legislation in each jurisdiction is outlined below:

- in New South Wales, mining activities are governed under the *Mining Act 1992*
- in Northern Territory, mining activities are governed under the *Mineral Titles Act 2010*
- in Queensland, mining activities are governed under the *Mineral Resources Act 1989*
- in South Australia, mining activities are governed under the *Mining Act 1971*
- in Tasmania, mining activities are governed under the *Mineral Resources Development Act 1995*
- in Victoria, mining activities are governed under the *Mineral Resources (Sustainable Development) Act 1990* and the *Mineral Resources Development Regulations 2002*
- in Western Australia, mining activities are governed under the *Mining Act 1978*.

2.5 Coal seam gas wells

The practice of drilling and constructing coal seam gas wells in Australia is governed by a number of petroleum and gas international standards, national and state legislation, guidelines and codes of practice. Australia's petroleum and gas legislation is largely based on international standards such as the American Petroleum Institute (API) and Standards Norway (NORSOK). The Norwegian petroleum industry developed the NORSOK standards to ensure adequate safety, value adding and cost-effectiveness for petroleum industry developments and operations (NORSOK 2004). The API publishes a range of practice notes that are used by many countries as guidance for well construction and operations, including Australian codes of practice for coal seam gas (NSW T&I 2012a; DEEDI 2011a; API 2009). A summary of the relevant legislation, codes and recommendations in these states is provided below. This information is largely based on a stock take report of existing coal seam gas legislation undertaken by Norton Rose (2012).

2.5.1 New South Wales

The Department of Trade and Investment, Regional Infrastructure and Services (known as NSW Trade & Investment) is largely responsible for regulating the coal seam gas industry under the *Petroleum (Onshore) Act 1991 (*Roth 2011), which is supported by the *Petroleum (Onshore) Regulation 2007* and the *Schedule of Onshore Petroleum and Production Safety Requirements 1992*.

The Schedule of Onshore Petroleum and Production Safety Requirements states that all work activities of title holders must comply with 'good oilfield practice' and that all materials and equipment employed by title holders must follow good oilfield practice. 'Good oilfield practice' is used throughout the Petroleum (Onshore) Act, however there is no definition provided in the Act. In the *Petroleum (Offshore) Act 1982* (NSW), 'good oilfield practice' is defined as:

> *"…good oilfield practice means all those things that are generally accepted as good and safe in the carrying on of exploration for petroleum, or in operations for the recovery of petroleum, as the case may be."*
>
> © Copyright, NSW Government (2014)

The concept of 'good oilfield practice' is discussed more in the following section.

NSW Trade & Investment has also developed codes of practice for coal seam gas exploration. They include the *Code of practice for coal seam gas well integrity* and *Code of practice for coal seam gas well fracture stimulation activities* (NSW T&I 2012a; NSW T&I 2012b). The code of practice for coal seam gas well integrity aims to provide a practical guide for coal seam gas titleholders on how to comply with a condition of title for coal seam gas exploration, extraction or production under the Petroleum (Onshore) Act and the Petroleum (Onshore) Regulation. The code includes (NSW T&I 2012a):

- mandatory standards for well design and construction to ensure the environmentally sound, safe production of coal seam gas and the protection of groundwater resources
- well monitoring and maintenance requirements
- management of back flow or 'co-produced' water from the coal seam gas extraction process
- design of all coal seam gas wells to ensure the safe and environmentally sound production of gas by:
  - preventing any interconnection between coal seams and aquifers
  - ensuring that gas is contained within the well and associated pipework and equipment without leakage
  - ensuring isolation between different aquifers and water bearing zones
  - not introducing substances that may cause environmental harm

- requiring all chemicals used to be disclosed during the approvals process.

2.5.2 Northern Territory

Petroleum activities including coal seam gas are governed by the *Petroleum Act 1984* and the *Petroleum Regulations 1994,* which are administered by the Department of Resources. The Petroleum Act requires that a licensee for exploration, retention or production of petroleum conduct all operations with ‘good oilfield practice’ and ‘approved technical works programme’.

2.5.3 Queensland

The primary legislation that governs petroleum including coal seam gas well drilling, construction and abandonment is the *Petroleum and Gas (Production and Safety) Act 2004* and the *Petroleum and Gas (Production and Safety) Regulation 2004*. The Petroleum and Gas (Production and Safety) Regulation sets out mandatory and recommended codes of practice (Norton Rose 2012). There is also the *Queensland Petroleum Act 1923* and associated *Petroleum Regulation 2004,* which are relevant to the coal seam gas industry.

The *Code of practice for constructing and abandoning coal seam gas wells in Queensland* (DEEDI 2011a) was developed by the Department of Employment, Economic Development and Innovation (DEEDI) and the Department of Environment and Resource Management (DERM) in liaison with the coal seam gas industry and coordinated by the Australian Petroleum Production and Exploration Association (APPEA). The code is a mandatory standard for a prescribed well, proposed well or abandoned wells (Norton Rose 2012). Queensland also has a *Code of practice for coal seam gas well head emissions detection and reporting* (DEEDI 2011b).

2.5.4 South Australia

Unconventional gas including coal seam gas activities are administered by the Department for Manufacturing, Innovation, Trade, Resources and Energy (DMITRE) under the *Petroleum and Geothermal Energy Act 2000* (PGE Act, onshore) and the *Petroleum and Geothermal Regulations 2010* (DMITRE 2012). Norton Rose (2012) states that well integrity matters are also covered under the fitness for purpose provisions under the PGE Act and Regulations and a licencee is required to demonstrate that the well design and construction methods deployed are fit for the purpose of satisfying the requirements of the Statement of Environmental Objective (SEO).

2.5.5 Tasmania

Coal seam gas development is regulated under the *Mineral Resources Development Act 1995* and overseen by Mineral Resources Tasmania. The approval and regulation of onshore exploration for petroleum, coal seam gas and geothermal energy is governed by Appendix 1 of the *Mineral exploration code of practice* (Bacon & Pemberton 2012), which states that activities must be undertaken in accordance with ‘good oilfield practice’.

2.5.6 Victoria

The *Mineral Resources (Sustainable Development) Act 1990* (MRSD Act) is the primary legislation governing mineral related activity. Unlike other jurisdictions, the MRSD Act defines mineral as:

> *'…any substance which occurs naturally as part of the earth's crust, including oil shale and coal; and hydrocarbons and mineral oils contained in oil shale or coal or extracted from oil shale or coal by chemical or industrial processes; and any substance specified in Schedule 4; [but excludes] water, stone, peat or petroleum…'*
>
> © Copyright, Victorian Government (2010)

This includes coal seam gas. Since 2000, a number of mineral exploration licences have been issued in Victoria for exploration for coal seam gas but no production of coal seam gas has occurred (DPI 2012). There are no specific standards or guidelines relating to coal seam gas well integrity in Victoria.

2.5.7 Western Australia

Western Australia has a high potential for shale and tight gas, which are very different to the coal seam gas resources targeted in Queensland and New South Wales (Hunter 2011). The main difference is that shale and tight gas occur in shale and fine-grained sediments rather than coal seams and are typically found at significantly greater depths, usually beyond 2000 m. Coal seam gas is generally found between 300 to 1000 m. Because the shale and tight gas reserves are a lot deeper and have low permeability, hydraulic fracturing is routinely used.

The unconventional gas industry including shale gas, tight gas and coal seam gas development is governed by the *Petroleum and Geothermal Energy Resources Act 1967* (PGER Act). The PGER Act is supported by several other schedules and regulations. However coal seam gas well integrity is regulated solely by the PGER Act (Norton Rose 2012). This Act requires that all petroleum exploration and production be carried out in a proper and workmanlike manner and in accordance with 'good oilfield practice' (Norton Rose 2012).

2.5.8 Summary

The petroleum and gas regulations for well construction are considered adequate to maintain well integrity for coal seam gas wells (SKM 2012a). SKM has completed the *Leading practice framework for coal seam gas development in Australia* (SKM 2012a). This report recommended 22 leading practice strategies. One strategy is the adoption of existing standards and regulations consistent with the principles, mandatory requirements and good practices detailed in the *Code of practice for constructing and abandoning coal seam gas wells in Queensland* (DEEDI 2011a). SKM noted that the legislation and standards within Australia are considered leading practice and are capable of addressing and mitigating the risks associated with well integrity.

The Queensland code of practice is considered to be leading practice in Australia as it is specific to coal seam gas and outlines principles as well as mandatory requirements and good practice. The New South Wales code of practice is consistent with the Queensland code of practice. While SKM (2012a) identified these regulations as leading practice for the construction of coal seam gas wells, this review has not identified any scientific evidence confirming that if bores are constructed to these standards they will not fail.

There are other jurisdictions where the regulatory framework may not be sufficient to ensure the protection of the environment. Hunter (2011) highlights that the regulatory regime for resources and the environment in Western Australia lacks legal enforceability because resource management and environmental regulations are not included in the PGER Act. One of Hunter's (2011) 15 recommendations was that the:

> *'…WA Department of Mines and Petroleum undertake to write environmental regulations to regulate onshore petroleum activities, including the recovery of coal seam gas.'*
>
> © Copyright, Hunter (2011)

SKM (2012a) also highlighted that it is important to ensure that compliance measurement by the regulator occurs and that the results of this are transparently reported, and that the regulators have the skill and capacity to meet their responsibilities.

2.5.8.1 Good oilfield practice

'Good oilfield practice' is a long held industry concept that is generally stated as all those things that are generally accepted as good and safe in carrying out exploration or recovery operations. There is flexibility in the design of the regulatory framework to allow innovation or optimisation (Manifold 2010). This also allows for different interpretation of the regulations and standards, which means the concept of good oilfield practice and the subsequent application and engineering will vary from site to site and between operators. New South Wales has recently stated what it considers is 'good industry practice' through the two codes of practice on coal seam gas well integrity and fracture stimulation activities. This helps to define what is expected of New South Wales coal seam gas operators.

The concept of good oilfield practice also appears to be focussed on safety and minimising gas explosions. However, SKM (2012a) note that the extent to which good oilfield practice protects the surrounding groundwater resources or environment is not well understood. Unlike coal seam gas, conventional oil and gas does not need to depressurise the gas bearing layer. Some depressurisation will occur inevitably, but it is not a prerequisite to release conventional gas. Depressurisation at the scale that is required for coal seam gas extraction can cause significant impacts to groundwater resources and the environment if not managed appropriately and whether good oilfield practice can achieve the right management balance needs to be considered further (SKM 2012a).

2.5.8.2 Wells for hydraulic fracturing

Hydraulic fracturing, also known as 'fracking', 'fraccing' and 'fracture stimulation', is the process by which hydrocarbon (oil and gas) bearing formations are 'stimulated' to enhance the flow of hydrocarbons to the wellhead (NSW T&I 2012b). It involves the injection of fluid (and other materials) under high pressure into a geological formation from which hydrocarbons are intended to be extracted (NSW T&I 2012b).

NSW introduced a moratorium on hydraulic fracturing in April 2011 and this was lifted in September 2012, with the introduction of the NSW Strategic Land Use Policy (Herbert 2012). Victoria is the only jurisdiction with a moratorium on hydraulic fracturing, which was introduced in August 2012 (Wilkinson 2012).

Generally the hydraulic fracturing regulatory framework incorporates a range of regulations and guidelines relating to petroleum and gas, environmental protection, water and safety. Information on the NSW regulatory environment for coal seam gas hydraulic fracturing is provided below, as an example.

As mentioned previously, NSW Trade & Investment have recently published two codes of practice for coal seam gas well integrity and fracture simulation activities (NSW T&I 2012a; NSW T&I 2012b). The *Code of practice for coal seam gas fracture stimulation activities* sets out the different components of the NSW regulatory framework which includes:

- *Petroleum (Onshore) Act 1991*
- *Petroleum (Onshore) Regulation 2007*
- Petroleum title conditions
- NSW *Code of practice for coal seam gas well fracture stimulation activities* (NSW T&I 2012b)
- NSW *Code of practice for coal seam gas well integrity* (NSW T&I 2012a)
- ESG2: Environmental Impact Assessment Guidelines
- Additional Part 5 REF requirements for petroleum prospecting - a supplement to ESG2: Environmental Impact Assessment Guidelines
- *Work Health and Safety Act 2011* and subsidiary regulatory requirements
- *Environmental Planning and Assessment Act 1979* and subsidiary regulatory requirements
- *Water Management Act 2000* and subsidiary regulatory requirements
- *Protection of the Environment Operations Act 1997* and subsidiary regulatory requirements.

New South Wales is the only jurisdiction to have a specific code of practice for hydraulic fracturing. Hydraulic fracturing in other jurisdictions is regulated under the wider regulatory framework.

2.6 Conversion to a water bore

If a mining exploration bore or coal seam gas well is converted to a water bore for production or dewatering, then a special permit is required under the relevant mining or petroleum and gas act (Fitzgerald (ADIA) 2012, pers. comm., September). Also, the bore must be designed, constructed and decommissioned compliant with the MCRWBA (NUDLC 2012). A licensed water driller must also either undertake the drilling, or supervise the drilling and construction.

3 Bore design and construction

3.1 Overview

Bores or wells are physical assets that connect an underground resource to the surface (Manifold 2010). They also connect the surface with a source of energy pressure within the groundwater or gas resource. It is vital to design and install a bore in such a way that it provides sufficient barriers to contain and control the flow of material under pressure from the resource (Manifold 2010).

Leakage can occur through multiple pathways in the 'disturbed zone' surrounding a bore casing (Gasda et al. 2010). The disturbed zone is defined as the annular region along the exterior of the casing that includes Portland cement, the damaged host rock and the casing-cement-rock interfaces (Gasda et al. 2010). Bore integrity is maintained through barriers or controls within the disturbed zone to control well fluids and pressures. These controls are established through (Manifold 2010):

- bore design and construction techniques
- selection of appropriate bore construction materials such as casings, screens and grout materials
- appropriate placement of seals within the bore annulus
- an appropriate bore decommissioning process.

3.2 Bore design and leakage pathways

Bores with poor integrity have the potential to provide a pathway for gases and liquids to migrate into or between aquifers (Nygaard 2010). Nygaard (2010), Gasda et al. (2004) and Watson and Bachu (2009) outline the leakage pathways from a carbon dioxide (CO_2) injection bore, which is indicative for all bores. Watson and Bachu (2009) state that three elements must exist for leakage in a bore to occur:

- leak source
- driving force such as buoyancy or pressure head differential
- leakage pathway.

In cased wells, cement should be placed in the annulus between the formation and the casing. Cementing is done from the bottom of the bore by injecting the cement into the casing and forcing the cement to flow up within the annulus. Once dried, the cement then seals the annulus and protects the outside surface of the casing (Nygaard 2010). Leakage pathways are generally associated with poor cementing in the annulus, casing failure (associated with corrosion) or physical damage and abandonment failure (Watson & Bachu 2009).

Figure 1 highlights the possible leakage pathways from a cased bore or well. These pathways include leakage along the interfaces between different material (such as the casing and cement interface, the cement plug and casing interface or the rock and cement interface), as well as through the cement or fractures in the cement (Gasda et al. 2004). Casing corrosion can also lead to casing failure and leakage (Nygaard 2010; GHD 2010).

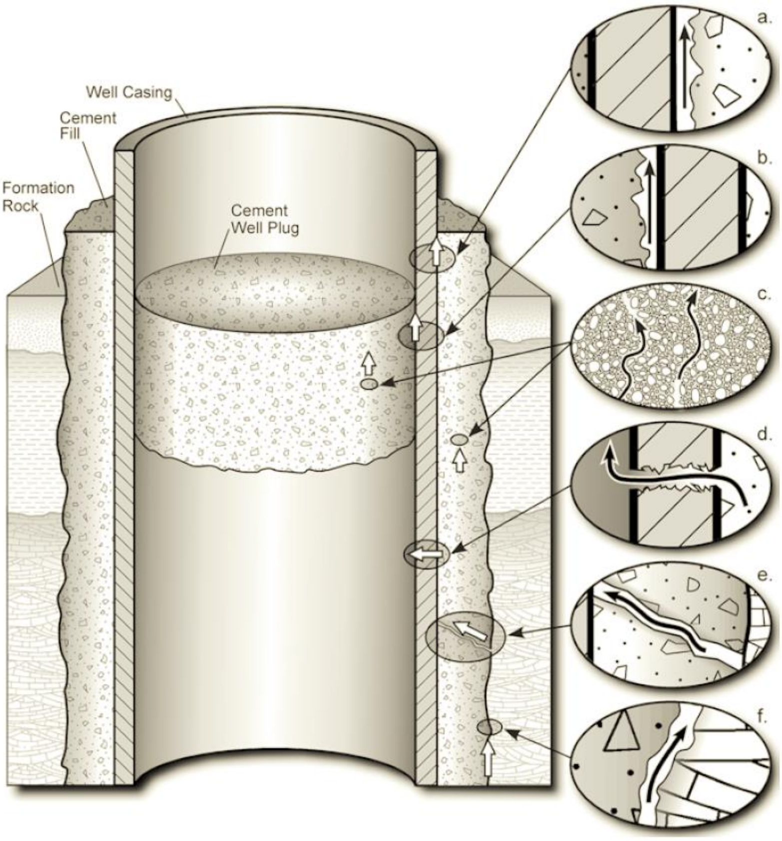


Figure 1 Diagrammatic representation of possible leakage pathways from a cased and abandoned bore or well. (a) Between casing and cement; (b) between cement plug and casing; (c) through the cement pore space as a result of degradation; (d) through casing as a result of corrosion; (e) through fractures in cement; and (f) between cement and rock (© Copyright, Gasda et al. 2004).

Different types of bores and the operational status of a bore also create different leakage scenarios (Nygaard 2010). For example, an exploration bore is drilled but is not cased. After drilling, the exploration bore is decommissioned using cement plugs placed across the porous formations (Nygaard 2010). The main leakage pathways from a decommissioned bore are caused by problems that occur when the cement plugs are set, or if the plugs are missing (Nygaard 2010). The cement plug in a decommissioned bore is much thicker compared to the cement in the annulus of a cased bore. Cased bores can also have casing exposed directly to the formation because the casing is not always cemented all the way up to the surface (Nygaard 2010).

A workshop on well integrity for the long term geological storage of CO_2 was held in Texas in 2005 (Pearce 2005). One of the key findings from the workshop was that it is not possible to promise a leak-free well. State of the art technologies in well construction will reduce risks associated with poor well integrity. Pearce also noted that industry and researchers should be careful not to present well designs and constructions as providing a leak proof solution, but rather that industry is constructing the best wells possible. Pearce suggested that it may not be necessary to demonstrate well integrity for 1000 years and instead provide shorter term integrity (e.g. 100 years). If proven it can then be extrapolated over longer time frame.

Much of the information available on well integrity for CO_2 storage can be extrapolated to other industries. However, there is a key difference between wells used for CO_2 storage and other wells. CO_2 causes degradation to Portland-based cements, which are commonly used in well construction (Pearce 2005). The key reactions involve carbonation of the major cement components resulting in loss of density and strength and an increase in porosity (Pearce 2005). New cements are being developed for wells for CO_2 storage.

3.3 Bore deterioration

There are different processes that cause or accelerate the deterioration of groundwater bores including fouling (such as microbial encrustation (biofouling), mineral scaling and particulate fouling) and corrosion of metal and plastics (GHD 2010).

3.3.1 Fouling

Bore fouling can be attributed to physical, chemical or biological sources. Plugging of the formation around the well screen by fine particles may cause the bore to become physically blocked resulting in reduced yield. The small particles can accumulate in the cracks, fissure, joints, fractures, or cavities that provide most of the water to the well (Driscoll 1986). The images below show examples of bore encrustation (Figure 2) and iron fouling (Figure 3) of submersible pumps.

Figure 2 Example of encrustation within a bore (© Copyright, DSE 2004).

Figure 3 Example of iron fouling on a submersible pump (© Copyright, Forward 2008 in GHD 2010).

Biofouling or microbial encrustation is the most common type of bore fouling and is considered to be widespread in Australia and abroad (GHD 2010). This is evident in the data collated from government agencies worldwide on the occurrence of iron bacteria by Cullimore and McCann (1977) and more recently noted by the Department of Sustainability and Environment (DSE) which recorded an increase in reports of iron bacteria in bores throughout Victoria (DSE 2004). Particulate and mineral scale deposits can also lead to bore fouling but these processes are much less common.

Biofouling occurs where bacteria are present in the groundwater and play a key role in numerous chemical reactions that occur in groundwater systems (McLaughlan 2002; McLaughlan 1996). Biofouling deposits are the result of the bacterial production of extracellular polymers (ECP) and the subsequent accumulation of various inorganic compounds and particles (McLaughlan et al. 1993). They create a biological film (biofilm) that forms on solid surfaces such as a bore casing. The rate of biofouling is a function of three processes: bacterial activity within the groundwater system, particle availability and biofilm shear forces (GHD 2010). These processes depend on several factors including nutrient availability, ECP production rate, aquifer characteristics and flow rate, and have been found to vary geographically (GHD 2010; Houben 2008).

Bore design and environmental aspects can also influence the biofouling of groundwater bore casings. For example, biofouling may occur as a result of (GHD 2010; DSE 2004):

- alterations in groundwater biochemistry or hydrogeochemistry over time due to natural processes or anthropogenic activities (e.g. drilling can introduce or stimulate the growth of existing bacteria)
- inadequate or incomplete groundwater bore development resulting in drilling materials and fines remaining in the aquifer and filter pack, and therefore hindrance to good hydraulic connectivity between the bore and the aquifer
- spread of bacteria introduced by the drilling rig or pumping equipment if not properly cleaned
- natural bacteria
- airborne bacteria contaminating unsealed bores
- inappropriate selection of bore casing materials for a particular hydrogeological setting or groundwater biochemistry, which can lead to excessive turbulence and potentially increase biological activity.

Symptoms of biofouling range from decreased flow, and gradual-to-severe decrease in bore performance to a short pump life and high variability in water quality. There is often a decrease in water quality in terms of taste, colour, staining and odour (GHD 2010).

There are several treatments for biofouling but they provide only short-term rehabilitation solutions (GHD 2010; SAMDBNRM 2006). Some involve non-chemical products but the majority involve chemical treatment or acid dosing with chlorine (Cl), sulphamic acid (NH_3SO_3) or Clearbore (a biodegradable granular chemical). Preventative maintenance measures of biofouling in saline water bores includes electrolytic chlorination. This involves disinfection of the bore materials with chlorine that is produced by electrolysis of the saline water.

Fouling by mineral scale deposits occurs due to the mixing of incompatible waters and/or changes in groundwater temperature or pressure during pumping (GHD 2010; McLaughlan 1996). Mixing of groundwater from different aquifers with unique characteristics and/or water chemistry signatures can occur if the bore is screened over multiple aquifers or if the casing deteriorates/corrodes allowing water from different aquifers to mix within the bore. If the waters are incompatible then a rapid accumulation of mineral scale can occur, such as when carbonate rich water mixes with highly saline water that is high in calcium. Mineral scaling can also result from degassing of carbon dioxide (CO_2) in groundwater when it is pumped to the surface (GHD 2010). Precipitation can occur in response to changes in groundwater CO_2 or temperature due to the resultant chemical reactions (GHD 2010).

Particulate fouling occurs when there is a build-up of fines close to the bore, which enter the bore causing particulate deposits and/or pump corrosion. This type of fouling generally results from poor bore design, inadequate bore development or operational factors (McLaughlan 1996). It is typically more prevalent in injection bores than extraction bores and where the quality of injected water is also an important factor in particulate fouling occurrence (GHD 2010).

3.3.2 Corrosion

Casing or well screen corrosion is a major source of well failure and can occur on both plastic and metal bore components (GHD 2010; Driscoll 1986). The corrosiveness of various metals reflects their different tendencies to form ions and dissolve in water (McLaughlan 1996). Corrosion can also occur through erosion resulting from the physical removal of protective layers of iron oxides and carbonate films by particles. This type of corrosion often occurs above a critical flow rate, particularly where there is a restriction of flow or change in flow direction of extraction and injection (McLaughlan 1996). Figure 4 shows examples of corrosion on steel casing and Figure 5 shows corroded casings in regional Victoria.

Figure 4 Examples of corrosion of bore casing (© Copyright, McLauchlan 2002).

Figure 5 Examples of corroded casing (© Copyright, Mallee CMA 2005).

Biofouling can lead to corrosive effects where microorganisms within biofilm help to sustain a chemical environment, different to that of the surrounding groundwater, which favours electrochemical corrosive processes (GHD 2010). Several physical/physiochemical properties of groundwater also influence corrosive processes in groundwater bores. For example, CO_2 can form a weak, corrosive acid in water. These low pH conditions accelerate the corrosion of most metals and as salinity increases, the corrosion rate increases (GHD 2010). Previous research in the north of the Great Artesian Basin measured in situ borehole corrosion rates over three years and found pH to be the principal rate-controlling factor on the corrosion of mild steel casing, with CO_2 concentrations a contributing factor (GABCC 1998).

PVC casing can also be susceptible to structural degradation where organic compounds are present in the groundwater. The degradation processes can be oxidative, mechanical, microbial and chemical (McLaughlan 1996). McLaughlan (1996) describes that plastics are degraded where chemicals penetrate the plastics causing swelling and softening, which leads to structural failure. Bore screens are typically more susceptible as they are often in contact with the highest contaminant concentrations in the aquifer (GHD 2010).

3.3.3 Extent of bore casing deterioration

GHD (2010) assessed the extent of bore casing deterioration in water bores in a project commissioned by the National Water Commission. They highlighted that there was very limited information in the public domain on existing bore condition assessment and limited access to groundwater databases, so they relied heavily on sourcing information from stakeholders. However there was a similar scarcity of information or reports on bore condition assessment from stakeholders (GHD 2010). From the information available to GHD (2010) the following conclusions were drawn:

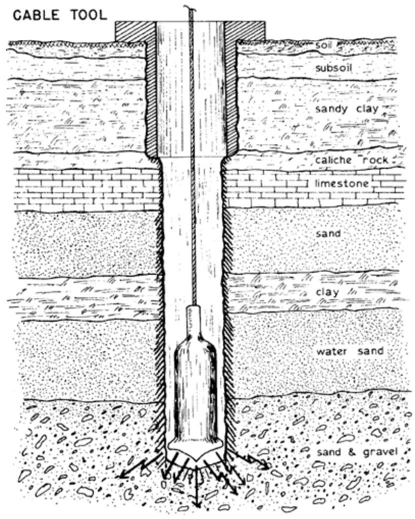
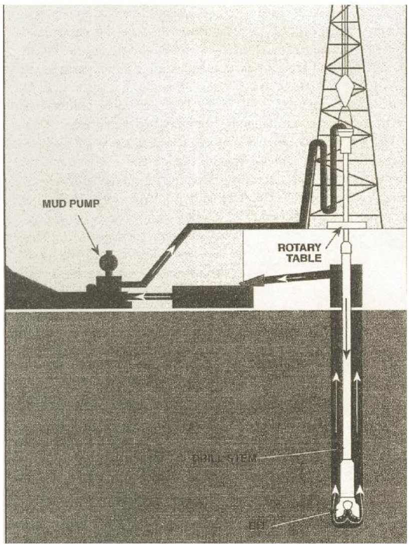
- iron biofouling of groundwater bores was the most dominant bore failure process. In most cases the reason for bore casing deterioration was not documented and presumably unknown
- a range of different rehabilitative and preventative measures have been used to manage bore casing deterioration due to iron biofouling. The most successful rehabilitation and prevention method identified in managing iron biofouling is chemical treatment such as acid dosing
- the corrosion of steel cased bores was very common, particularly in ageing groundwater bores. The frequency of such failures is expected to decrease as groundwater bore assets are replaced with inert casing materials
- rehabilitation measures have generally been introduced once bore deterioration processes have been identified. In most of the case studies assessed for this project, preventative measures were not introduced prior to identification of bore deterioration
- casing studies of fouling and corrosion have been documented in the Carnarvon Basin (Western Australia), South Australia, Mallee (Victoria) and the Great Artesian Basin (Queensland) (GABCC 2011; SKM 2009; Mallee CMA et al. 2005; Astill 2002).

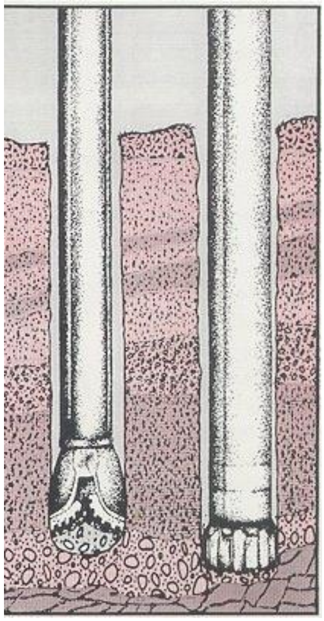
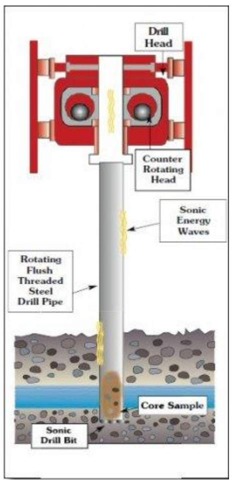
3.4 Drilling methods

3.4.1 Water bores

Drilling methods will vary depending on the anticipated geology, groundwater pressures, bore diameters and depths encountered during the drilling operations. The MCRWBA guidelines (NUDLC 2012), the Australian Drilling Manual (ADITC 1992) and the International School of Well Drilling (ISWD 2012) provide a detailed description of the methods used to drill water bores. A brief summary of typical drilling methods is provided in Table 2.

Table 2 Summary of drilling methods (© Copyright, ISWD 2012; NUDLC 2012; ADITC 1992).

Drilling method	**Description**	**Image**
Cable tool	This method of drilling is the oldest drilling method in Australia and was used for all bores drilled in the early 1900s. Drilling involves lifting and dropping a string of solid steel drilling tools suspended from a wire rope to hit the bottom of the hole, a process that drives the cutting bit to fracture or pulverise the formation. Cable tool method is well suited to remote settings due to its low fuel and water consumption. It is also very cost-effective in terms of capital cost, operation and maintenance and only requires one driller to operate. Key disadvantages of the method are the slow drilling rates, in particular through hard rock.	
Rotary drilling techniques	Rotary drilling uses a sharp rotating drill bit to drill into the formation, much like a common hand held drill.	
Mud rotary	Rotary mud drilling is a method commonly used for water bores. Drilling mud is pumped down the drill string to provide wall support for the bore prior to the bore casing being inserted and drill cuttings removed from the borehole. The fluid serves to cool and lubricate the bit. The mud slurry then flows upwards in the annular space around the drill pipe to the surface, carrying the cuttings with it in suspension.	
Rotary air	The rotary air method is used to drill holes in consolidated or semi-hard formations such as sandstone or shales that are self-supporting. This process produces cuttings that are cleared by circulating air, which is derived from a compressor and fed down the drill pipe to emerge through a bit. The up-hole annular air velocity must be maintained to remove cuttings effectively.	

Drilling method	Description	Image
Down-hole hammer	The down-hole hammer method involves a pneumatically operated drill bit that effectively combines a percussion action with a turning action. The image to the right shows a rotary drill bit on the left and a down hole hammer drill bit on the right. A pneumatic drill bit can be used on a standard rotary rig with a high pressure air compressor of sufficient capacity. Down-hole hammers are used for hard rock drilling and enable water bores to be established from fractured hard rock aquifers. Down-hole hammer is generally the fastest method of penetrating hard rock. Foaming additives are occasionally used to increase the volume of cuttings that can be removed by the air returning to the surface. The method is not used for loose unconsolidated materials.	
Reverse circulation drilling - air and mud	Reverse circulation drilling was developed to allow for larger borehole drilling without being limited by drilling fluid pump capacities. Drill rigs are much larger and the drilling method requires a lot of water and sediment handling. The bore is kept filled to the surface during drilling to provide water pressure support to the sides of the hole until the permanent production casing is installed. It is not a common method for water bores; however, it is sometimes used for water sampling programs.	
Sonic drilling	Sonic drilling, also known as a rotary vibratory drill, is a relatively new technique that uses a high-frequency vibration in combination with rotation to drill. It is capable of high speeds and continuous coring and can collect undisturbed samples without the use of drilling fluids.	

3.4.2 Coal exploration bores

Exploratory drilling can be undertaken to recover core samples of coal and non-coal strata for detailed geological description, analytical studies and geotechnical testing, or to recover broken fragments or ‘cuttings’ of the material penetrated (Kang 2009). The aim is to provide information on the depth, thickness and quality of the coal and it is only the core or cuttings that are of interest. Consequently, bore construction with casings and screens is not used for coal exploration bores. As with water bores, drilling methods will vary depending on the anticipated geology, groundwater pressures, bore diameters and depths encountered during drilling.

Rotary drilling is the most widely used method of non-core drilling in coal exploration and is described above in Table 2 (Kang 2009; Ward 2009). Reverse circulation is also used for mineral sampling to obtain an uncontaminated geological sample because sampling is less precise with rotary drilling techniques.

The most effective method of core drilling is diamond drilling. A hollow cylindrical drill bit impregnated with industrial diamonds is attached to a series of metal drill rods and rotated under controlled downward pressure. A circle of rock is ground away and the cutting removed by water flushing. A cylindrical core remains in the centre of the drill string. A triple tube core barrel is preferential for coal seams and other soft or friable strata, recovering core in a split metal tube that allows it to be exposed for inspection with minimal disturbance (Ward 2009).

Cores of between 45 mm and 85 mm diameter are typically taken for coal exploration programs. Large diameter cores (e.g. 150 mm to 200 mm) may be taken for bulk sampling and pilot-scale coal preparation tests. Keyhole samplers, where a large diameter hole is scooped out by an expanding head at the bottom of a relatively narrow hole, may also be used to gather bulk samples (Ward 2009).

3.4.3 Coal seam gas wells

Coal seam gas wells are generally drilled using rotary or percussion techniques, which require the use of drilling fluids or mud during the drilling process to lubricate the drill bit and remove the cuttings. The drilling fluids in Australia are typically water based, comprising fresh water and organic polymers or clay additives such as bentonite, which are added to increase viscosity, inhibit clay and shale swelling and sticking, and flocculate drilled solids (Zvomuya et al. 2008).

3.5 Construction materials

The materials used in the drilling and construction of bores vary with the drilling method and construction design and can have a large impact on the overall integrity of the bore. Bore design and the materials used are commensurate with the value and purpose of the bore. Every constructed bore should include the following components:

- casing to ensure the bore stays open and sealed
- screened interval over the target aquifer/zone to allow water/gas to flow into the bore
- a seal to isolate and protect the target aquifer/coal measure.

The most common types of materials used for bore casing construction are mild steel, stainless steel, galvanised iron and plastics (SKM 2012b). Steel is the main material used as well casing in the petroleum and gas industry (API 2009).

Statistical studies to determine the effective life of bores based on construction material and installation environments have not yet been undertaken. Information on the reason for a bore coming to the end of its useful life does not appear to have been collected in Australia. Modern non-metallic well materials have not been in the ground long enough to determine deterioration rates or to reach their expected maximum life to confirm predictions of integrity behaviour (SKM 2012b).

3.5.1 Water bores

The third, and current, edition of the *Minimum construction requirements for water bores in Australia* (MCRWBA) (NUDLC 2012) provides a sound framework for the design and construction of water bores (NUDLC 2012). Most jurisdictions require the construction of water bores to comply with MCRWBA. However, issues with bore integrity can arise as a result of different interpretations of construction requirements and the subsequent design and construction variation that follows (Manifold 2010).

The following figures show typical designs of a monitoring bore (Figure 6) and a production bore (Figure 7). A monitoring bore is typically constructed with PVC casing, a bentonite plug to isolate the target aquifer and a cement grout seal at the surface. A production bore is often larger in diameter, constructed using steel or PVC, with a stainless steel screened interval over the target aquifer, a gravel pack and a longer cement grout seal.

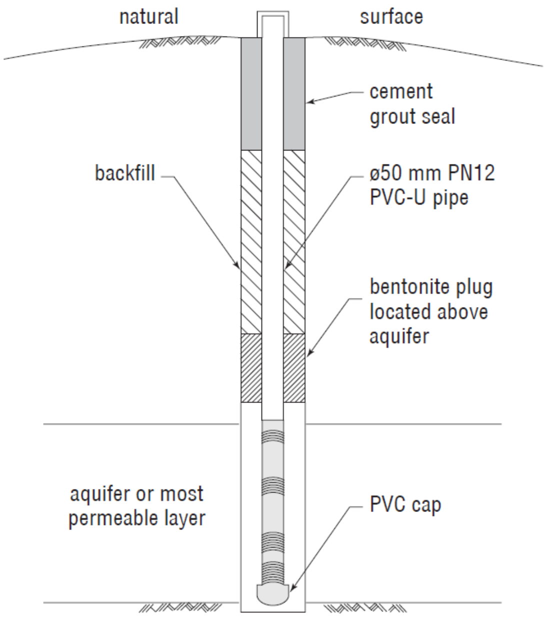


Figure 6 Typical design of a monitoring bore with a bentonite seal (© Copyright, NUDLC 2012).

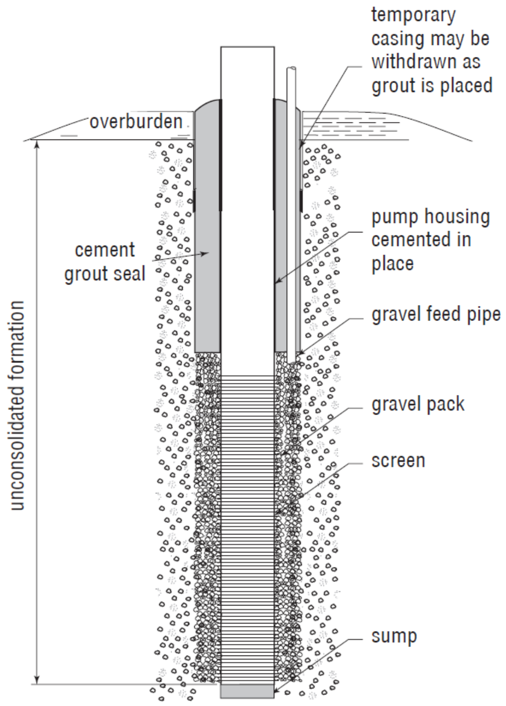


Figure 7 Typical design of a production bore with gravel pack and casing cemented in place (© Copyright, NUDLC 2012).

The key to maintaining bore integrity is the reliability of the cement around the casing to prevent migration paths and effectively isolate the targeted zone from other hydrogeological layers (SKM 2012b). Bore integrity issues mostly develop from poor design and construction techniques. For example, ensuring the cement has had sufficient time to cure is imperative to maintaining good bore integrity (DEEDI 2011a; Dunnivant et al. 1997). Drillers may be under time constraints and may not allow sufficient time for the cement to cure. Therefore, the professional integrity of the engineers and technicians engaged by the operator to design and construct the bores is also a key consideration in ensuring bore integrity (Manifold 2010).

Prior to 1940, bores were typically constructed with mild steel casing because of its strength and ability to withstand high groundwater temperatures (GHD 2010). However, steel casing is particularly vulnerable to corrosion from corrosive soils and water resulting in a service life of only five to 10 years in some locations (GHD 2010).

Polyvinyl Chloride (PVC) casing replaced mild steel as the preferred construction material between the 1970s and 1980s as it is a low cost, light weight and corrosion resistant alternative to steel (Driscoll 1986). However, PVC is less resistant than steel to pressure and temperature, so is rarely used in bores deeper than 200 meters. PVC is available in different nominal pressure (PN) ratings, with the correct rating to be used depending on the depth of the bore. The MCRWBA (NUDLC 2012) states that PN9 can be used with care for shallow bores, but PN12 piping is the recommended casing for most bores to avoid problems associated with inappropriate rating selection. For example, temperatures greater than 20 °C can reduce the pressure rating of the casing, whether it is from groundwater or by cement grouting of the annulus. In these instances, strength de-rating needs to be considered. PVC is not recommended to service temperatures greater than 60 °C (NUDLC 2012).

Fibreglass-reinforced polyester (FRP) casing is typically used for deep and large diameter production bores due to its strength, corrosion resistance and ability to withstand temperatures between 60 °C and + 80 °C. It was popular in the early 1980s as it was used by the South Australian Department of Mines and Energy for the construction of deep bores into the Great Artesian Basin for high temperature and corrosive environments (GHD 2010). The availability of FRP casing significantly extended the service life of groundwater bores and it continues to be used in bores ranging from 50 m to more than 500 m deep. FRP has good ultraviolet resistance and is inert in most environments but must be made-to-order because it cannot be cut in the field.

The screen material is generally perforated steel or PVC (Figure 8), although some bores may be constructed with stainless steel wire-wound screens (Figure 9) or even left with an open hole if the formation is stable enough. Stainless steel wedge wire design screens were first used in 1964, where they gained popularity due to the improved corrosion resistance over mild steel and the efficient inflow of water due to a larger percentage of open area (GHD 2010). From 1980 onwards, the use of stainless steel wire wound screens became prevalent throughout the drilling industry due to increased availability, reductions in cost and an increase in the open area and corrosion resistance (GHD 2010).

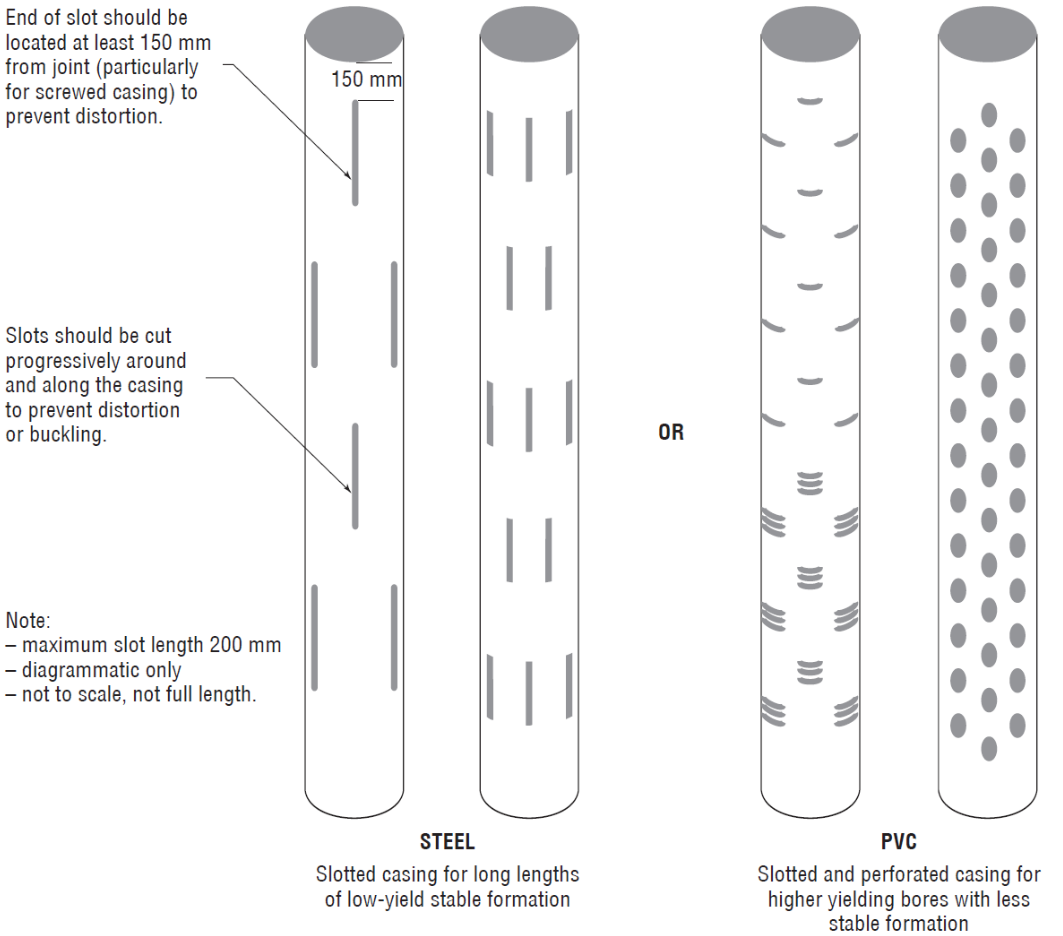


Figure 8 Examples of perforated and slotted casing (© Copyright, NUDLC 2012).

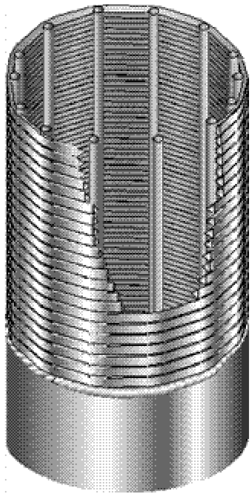


Figure 9 Example of stainless steel wire wound screen (© Copyright, NUDLC 2012).

Slots and screens alone may not be sufficient in allowing water to flow into the bore without bringing surrounding material with it, particularly in relatively fine, loose formations. In these instances, placing a suitably graded, well-rounded (not crushed) gravel pack in the annulus surrounding the casing and hole will effectively filter water coming into the bore from the surrounding strata (NUDLC 2012). Filter material should only be placed adjacent to the target aquifer and not across overlying/underlying units, which could promote inter-aquifer leakage.

3.5.2 Injection bores

Injection bores can be divided into two general categories:

- those used for injection only
- those used for injection, storage and subsequent recovery out of the same bore in a process known as Aquifer Storage and Recovery (ASR).

The drilling method, design and construction of an injection bore is fundamentally the same as a water production bore, but additional testing for geological parameters and mechanical integrity is usually conducted. Pyne (2005) and Maliva and Missimer (2010) provide a guide for the design, construction and operation of an ASR scheme and highlight that the following key issues should be considered:

- maximising bore efficiency
- bore development
- bidirectional flow through gravel pack
- preventing cascading water flow and associated entrainment, or development of bubbles, during injection
- removal of all drilling fluids
- corrosion of casing, pumps and other downhole equipment
- access to bore for rehabilitation activities
- regulatory requirements for construction and operation.

3.5.3 Coal exploration bores

Coal exploration bores are generally not cased, and are decommissioned after the drilling is complete. If an exploration bore was cased, it would be constructed in accordance with the Minimum Construction Requirements for Water Bores in Australia (NUDLC 2012) either by a licensed water driller or supervised by a licensed water driller.

3.5.4 Coal seam gas wells

Coal seam gas is typically extracted from coal seams between 300 m and 1000 m depth in Australia, although some deeper prospects are being explored. Unlike conventional natural gas reserves, coal seam gas is held in the coal seams by water pressure. The water and gas is accessed by drilling a well into the coal seam. The water is then pumped from the coal seams to lower the pressure and release the gas.

New South Wales and Queensland are the only jurisdictions with specific codes of practice on coal seam gas well construction (NSW T&I 2012a; DEEDI 2011a). While SKM (2012) identified these regulations as leading practice, this review has not identified any scientific evidence confirming that if bores are constructed to these standards failure will not occur. Well integrity is therefore monitored throughout the life of a well as a preventative measure to ensure that integrity is maintained. This is discussed further in Section 4.

Wells are designed to ensure the environmentally sound and safe production of gas and other fluids. This includes sealing the well appropriately to contain gases and fluids, protecting the groundwater resources, isolating the targeted formations from surrounding water bearing formations, and by proper execution of treatment, stimulation and completion operations (DEEDI 2011a). Well design must also consider whether hydraulic fracturing will be required and any implications this may have on the design.

A coal seam gas well is designed to provide multiple barriers that prevent fluids moving between aquifers or migrating to the surface. The primary barriers are the casing and cement, where the cement isolates formation fluids from moving behind the casing or from coming to the surface. The well head also provides another barrier at the surface and often contains a blowout preventer, which consists of a series of large valves which can be closed to control the well in the event formation fluids enter the well.

Coal seam gas wells are constructed using steel casing manufactured to American Petroleum Institute (API) standards and designed to withstand the various compressive, tensile and bending forces that are exerted during drilling and construction. A well is constructed using a number of steel casing sections in the upper parts and each casing section is cemented in place, ensuring aquifers above the coal seam are protected. The number of casings reduces with depth, along with the diameter, so there is a single production casing in the production area. The production casing is run to the bottom of the drill hole and perforated, or a slotted liner is installed to allow gas to enter the well. A schematic diagram of a typical Australian coal seam gas well is shown in Figure 10.

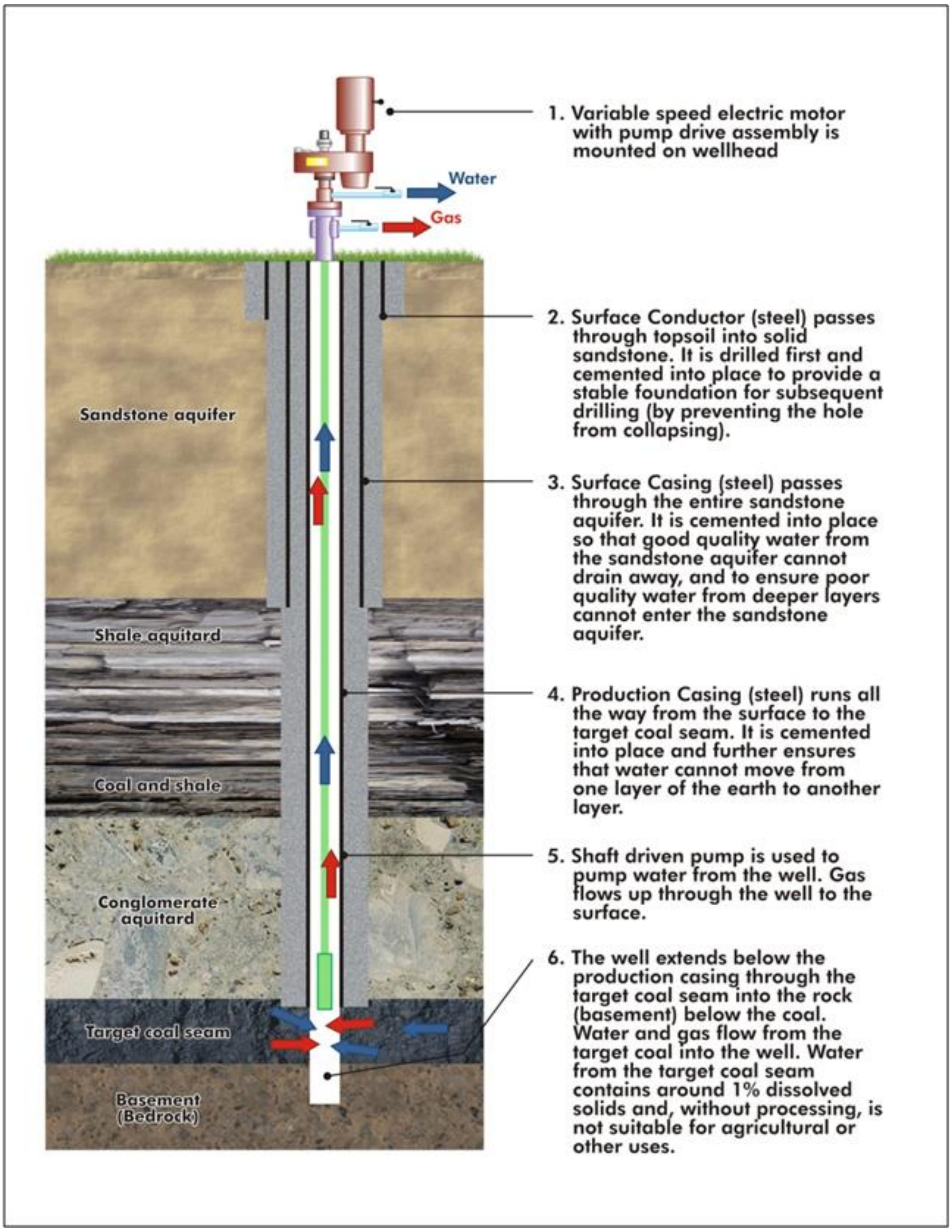


Figure 10 Schematic of a coal seam gas well (© Copyright, SKM 2012a).

3.6 Seals and cement

3.6.1 Water bores

The annular space between the casing and the formation must be properly sealed to minimise the potential for vertical migration of water (Pearce 2005; Dunnivant et al. 1997). The seal protects against infiltration from the surface and provides a discrete sampling zone and minimises the potential for vertical leakage (Dunnivant et al. 1997). The cement around the well casing will isolate the targeted zone from other aquifers to prevent migration pathways, protect surrounding aquifers from contamination and depressurization and protect the casing from corrosion. Materials recommended for backfilling and sealing the annulus include bentonite, cement grouts and mixtures of bentonite and cement (NUDLC 2011; Aller et al. 1989).

Ross (2010) highlights that grouting in water bores has advanced significantly since the late 1980s as a result of education and changes in regulations in the US, and this has generated change in the industry worldwide. Bentonite has been used for sealing and decommissioning since the 1980s because it provides a low permeability seal, is easy to use and does not affect the quality of the groundwater (Dunnivant et al. 1997). Cement grout is also commonly used worldwide. Although cement grouts can shrink during the curing process and separate from the well casing or the formation interfaces, this can be mitigated with the addition of bentonite (Ross 2010; Dunnivant et al. 1997). The most common hydraulic cements in use today are either Portland cements or similar-use cements called 'blended' or 'composite' cements that are made of a Portland cement base plus additives (van Oss & Padovani 2003). NUDLC (2011) provides guidance on cement-water and cement-bentonite-water ratios for mixtures for both Portland general purpose cement and blended builders' cement.

3.6.2 Coal exploration bores

Coal exploration bores are generally not cased, nor decommissioned after drilling is complete. Decommissioning of bores is discussed in Section 5. If an exploration bore is cased, it would be sealed and grouted consistent with the Minimum construction requirements for water bores in Australia (NUDLC 2012).

3.6.3 Coal seam gas wells

Cementing the casing in coal seam gas wells is a key component in ensuring well integrity. The American Petroleum Institute (API 2009) states that although the selection of materials for cementing and casing is important, it is secondary to cement placement. The key to good cementing is good operational practices (Nygaard 2010; Corneliussen et al. 2007; Bourgoyne et al. 1999). Primarily cement failures are due to poor cementation practices including the failure of the cement soon after it has cured (Nygaard 2010). Cement for petroleum and gas wells are engineered products that are governed by the American Petroleum Institute technical standards. The recommended practices for cementing operations are well documented and available to all drilling companies (API 2009). DEEDI (2011) also references the American Petroleum Institute technical standards in recommending benchmarks for cementing wells. The petroleum industry uses Portland cement with several additives such as density reduction materials, viscosifiers, accelerators and retarders to refine the cement slurry (Nygaard 2010).

Cement is forced under pressure down the centre of the casing and allowed to flow within the annulus back to the surface or to an appropriate safety overlap distance of at least 50 m back inside the previous casing shoe. Once the cement has cured, pressure tests are performed and recorded to verify aquifer or zonal isolation (DEEDI 2011a). More information on the testing performed is outlined in Section 4.

Australia has comprehensive standards, codes and legislation to international standards which regulate the design, material, construction, maintenance, decommissioning and rehabilitation of wells (SCER 2013). Successful application of standards, codes and legislation governing well integrity depends on consistent compliance and continual improvement by industry and thorough and effective enforcement by qualified regulators

(SCER 2013). As stated by Nygaard (2010), good cementing relies on good operation practices. Drillers must ensure that bores and wells are cemented appropriately and that there is the appropriate level of compliance to ensure that this is done. Unlike the water industry, the petroleum and gas industries require monitoring of the integrity of coal seam gas wells upon completion, over its workable life, or upon decommissioning. There are a variety of techniques used to monitor the integrity of a well and these are discussed in Section 5.

3.7 Headworks

The headwork on a water bore, or wellhead on a coal seam gas well, is required to ensure bore integrity at the surface by effectively sealing and capping the bore to protect the aquifer and control the flow of water or gas from the bore (DEEDI 2011; NUDLC 2010).

3.7.1 Water bores

A framework for headwork requirements for a water bore to ensure controlled flow is provided by NUDLC (2012). Ensuring that all bores are appropriately sealed at the surface has been an issue in the past. Declining groundwater levels in both the Carnarvon Artesian Basin of Western Australia and the Great Artesian Basin (GAB) have occurred as a result of bores that do not have appropriate headworks to control the flow of water (GABCC 2011; Astill et al. 2002). Bores were permitted to flow uncontrolled for many decades and this has impacted the pressures and flows in the Great Artesian Basin aquifers. The figures below show examples of appropriate headworks for a flowing bore (Figure 11) and a flowing bore that has not been capped appropriately (Figure 12).

Figure 11 Example of a headwork for a flowing bore, where water supply is under control (© Copyright, NDULC 2012).

Figure 12 Example of a headwork for a flowing bore, where water supply is out of control (© Copyright, NDULC 2012).

3.7.2 Coal seam gas wells

A coal seam gas well is completed with a wellhead designed to contain various protection equipment, such as blow out preventers, valves and flanges for control and connection of gas and water to pipelines, and pressure monitoring ports and pumping. Coal seam gas wellheads in New South Wales and Queensland are required to facilitate the installation of a blow-out preventer (NSW T&I 2012; DEEDI 2011). An example of a typical Australian coal seam gas wellhead is shown in Figure 13.

Figure 13 Typical coal seam gas wellhead in Queensland (© Copyright, DSEWPaC 2013; courtesy B. Gray and Origin Energy).

4 Monitoring and reporting

4.1 Introduction

Monitoring the integrity of a bore through its life cycle is crucial to ensuring the bore is maintained. Bores can deteriorate with age, operation and site-specific conditions reducing their capacity for the intended use (DEEDI 2011a). Bore monitoring and maintenance is required to ensure the bore is preserved and its components are in good condition for the life of the bore (NUDLC 2012).

There are a variety of tools and techniques available to assess bore integrity. Duguid et al. (2007) outlined technologies available for measuring well integrity in a carbon capture and sequestration field. These techniques apply equally to other well types, including coal seam gas wells and water bores. However, the cost of integrity assessment techniques may be a barrier to their use, especially for bores that are shallow and/or of simple construction, and may be replaced at a relatively low cost.

There are two primary strategies for monitoring bore integrity described by GHD (2010):

- Failure-based strategies: usually takes place after bore integrity has already been compromised and, subsequently, represents a high risk approach.
- Performance-based strategies: represent a lower risk approach to maintaining bore integrity as they can identify the potential effects of potential bore integrity issues at an early stage and can be managed appropriately.

A failure-based approach may be appropriate where there is little risk to the resource or the environment. A performance-based approach is more likely to be undertaken when resources are available for this more expensive approach, or where it is required through legislation.

Oil and gas wells, including coal seam gas wells, are typically a series of nested casings and well cement and a variety of measurements are necessary to assess their integrity (Duguid & Tombari 2007). There is no one tool or method that can assess all of the leakage criteria at once. A suite of measurements must be run to fully analyse well integrity.

4.2 Simple performance-based tests

Simple performance-based indicators are most appropriate for a water bore, but can also be used for other well types. They are a cheaper alternative to other more expensive ways to measure bore integrity, such as geophysical logging, and include:

- visual inspections of the structural integrity of the bore casing, pumps and wellhead
- changes in power consumption
- analysis of bore performance through review of:
  - water quantity: declining water levels, flow rates or daily pumped volumes can indicate a decrease in bore efficiency
  - water quality data: the most common water quality indicators are sand content, salinity, iron and manganese concentrations.

In addition to direct investigation methods, long-term water level and water quality testing can be used to infer compromised bore integrity and leakage. Trend analysis of long-term monitoring data allows changes to be identified that can trigger further investigation. Data of this type should be collected as part of a bore monitoring and management strategy. However, it requires that the data is sufficiently interrogated on a regular basis.

GHD (2010) found that groundwater bore casing deterioration is generally managed when a problem has been identified. In some cases, this is too late to successfully manage the deterioration and failure occurs. GHD (2010) and Forward (2008) suggested some preventative measures, including:

- development of a performance-based monitoring and maintenance strategy that commences when the bore is commissioned
- analysis of bore performance through reviews of hydrographs showing water levels over time, pump operation, flows rates and water quality
- use of preventative chemical treatments to control bore and pipeline fouling.

These preventative measures and maintenance will assist in reducing the frequency and magnitude of bore casing deterioration and failure, increase the operational life of the bore and reduce the need for costly rehabilitation or replacement. GHD (2010) also recommended that groundwater bore licensing organisations develop methods and procedures for bore owners to monitor bore integrity and report on compliance with construction standards.

4.3 Logging tools

Logging tools are used to examine the condition of the casing and cement and the interfaces between casing, cement and formation in bore water and coal seam gas wells (Duguid & Tombari 2007). Logging tools do not physically change the well in any manner. They include downhole camera, packer tests, multi-finger calliper tools, sonic bond tools and ultrasonic bond tools (Duguid & Tombari 2007).

4.3.1 CCTV down hole camera

A simple and cost-effective method for investigating the internal condition of a bore is to undertake a visual inspection using a CCTV camera logging tool. This will identify problems such as corrosion pits and cracks and poor casing joins.

4.3.2 Packer tests

Packer tests involve isolating a section within a bore with inflatable packers or bladders to test the aquifer or collect water quality data (Driscoll 1986). A series of tests can provide a definition of the vertical distribution of water quality and hydraulic conductivity, which can indicate pathways for water and contaminant movement. Monitoring water levels in nearby bores can also identify permeable intervals in the aquifer beyond the bore. At the time of writing, there was no information found in the public domain of this method being used as a key assessment tool of bore integrity.

4.3.3 Multi-finger caliper tools

Multi-finger caliper tools have fingers protruding radially from the body of the tool (Figure 14), which measure the internal radius of the bore in 360 degrees. Any changes in the internal radius of the bore casing can indicate a bore integrity issues, such as corrosion or other damage (Figure 15). These tools can only give information on the condition of the inside of the casing, and do not provide information on the outside condition or the casing thickness.

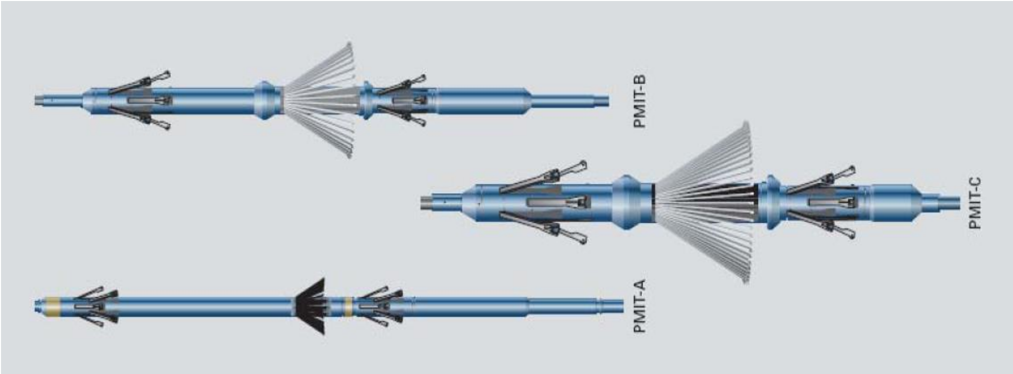


Figure 14 Multi-finger caliper tools (© Copyright, Schlumberger 2008).

Figure 15 A 3D presentation of calliper data showing a damaged casing (dark blue) (© Copyright, Duguid & Tombari 2007 (modified); image courtesy of Schlumberger Limited).

4.3.4 Sonic bond tools

Sonic bond tools or cement bond tools (CBT) transmit a signal through the bore to the casing, cement and formation array. The magnitude and transit time of the refracted signal is then measured to provide information about the bond between the casing and the cement, the density of the cement and the bond between the cement and the formation (Duguid & Tombari 2007). Duguid and Tombari (2007) state that in a bore with a good bond between the cement and casing, the transmitted sound waves will be attenuated when the signal returns from the well to the receiver. In a bore with a poor cement-casing bond, the returning signal will show little attenuation.

CBT are generally effective in most fluids encountered in a bore and not affected by the roughness of the casing (Duguid & Tombari 2007). However, while CBT measurements provide information on the average bond integrity between the cement and the casing, they do not identify specific pathways or locations where the bond may be poor (Duguid & Tombari 2007). This means that where there is little attenuation (indicating a poor cement bond) a CBT will not provide information on the cause (Duguid & Tombari 2007). Furthermore, CBT are less accurate in the unsaturated zone and can falsely indicate good cement bonds.

4.3.5 Ultrasonic bond tools

Like the CBT tools, ultrasonic tools also use acoustic waves to investigate the integrity of a bore (Duguid & Tombari 2007). Sound waves are used to measure multiple criteria, including the internal condition of the casing, the internal radius of the casing, the thickness of the casing and the acoustic impedance of the material outside the casing. Ultrasonic measurements also provide information on the interface between the cement and casing. More modern ultrasonic tools can provide information on the next interface moving outwards from the bore. In many cases this is the cement-formation interface but could also be another cement-casing interface depending on the bore construction. A schematic of ultrasonic wave reflections in a bore is shown in Figure 16.

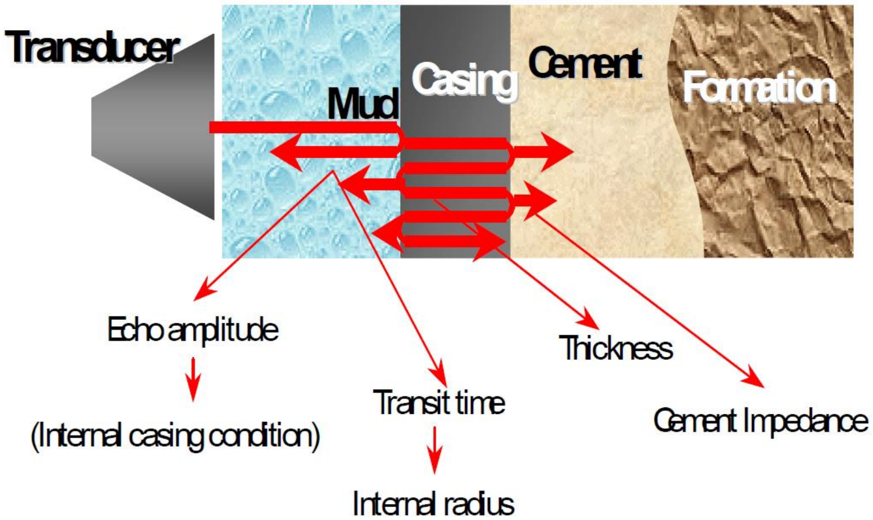


Figure 16 Schematic diagram of the reflections of ultrasonic waves (© Copyright, Duguid & Tombari 2007; image courtesy of Schlumberger Limited).

The acoustic impedance of a material is a product of the acoustic velocity and density of the material. From the acoustic impedance signature, the material outside the casing can be classified. Unlike the sonic tools, ultrasonic tools can image the bore in 360 degrees and specific pathways or de-bonded areas can be identified (Duguid & Tombari 2007).

Although this is a more costly technique than sonic tools, the advantage of using ultrasonic tools is that they can provide information on the condition of the casing and the surrounding cement on the same logging pass (Duguid & Tombari 2007). They provide a detailed image of the bore and can differentiate different types of materials behind the casing.

Duguid and Tombaris (2007) showed that each of the logging tools provide different information about the integrity of a bore and that the best overall view of integrity is achieved using a combination of tools. If an initial caliper tool investigation shows a heavily damaged casing pipe, the integrity assessment program can be halted and the bore can be repaired or decommissioned. If caliper measurements indicate good casing integrity then subsequent sonic and ultrasonic logs can confirm this. For deep injection or production wells Duguid and Tombaris (2007) recommended a minimum combination of multi-finger caliper, sonic and ultrasonic logging tools. In addition to the non-destructive logs, physical testing and sampling techniques provide a good opportunity to correlate the physical and laboratory measurements with the logging results.

4.4 Sampling and testing

Sampling and testing tools can include in situ tests and sample recovery for laboratory testing, including pressure testing, fluid analysis and side wall coring.

4.4.1 Pressure testing

Measurements of the cement and formation permeability can be performed in situ using tools that drill through the casing, draw down the pressure on the exposed material and measure the response. The drawdown test is sometimes also referred to as a 'pre-test' or vertical interference test (VIT). From the pre-test, the mobility and permeability of the tested material can be calculated. There are a variety of analytical solutions available to assess the test data depending on the type of pressure test used and the bore construction.

Gasda et al. (2010) proposed a simple pressure test to determine the effective permeability of existing wells. The test involves perforating the casing and inducing a pressure below an aquitard formation and measuring the response above it. The test can also be conducted within an aquitard formation (Gasda et al. 2010).

Arnold (1991) successfully modelled variations in annular pressure due to fluid injection as part of a study of liquid waste injection wells. The pressures inside the well casing and the hydraulic pressure applied to the liquid-filled annular volume were monitored. If the temperature of the system is stabilised and the system is not subjected to changes in injection pressure, a constant annular pressure demonstrates mechanical integrity (Arnold 1991). Arnold (1991) was able to account for pressure and temperature changes caused by injection via numerical modelling techniques and broaden the integrity monitoring to non-steady state conditions.

Chesnaux et al. (2006) developed a method to detect and quantify leakage through faulty seals using non-reactive chemical tracers. For an aquifer-aquitard-aquifer system, a constant rate pumping test can be initiated in the lower aquifer and a tracer injected via a piezometer in the upper aquifer. If a defect is present in the intervening seal, the tracer will be detected in the pumped water. Knowledge of tracer concentration, tracer injection rate and pumping rate allows numerical analysis and quantification of leakage rate and, hence, effective permeability.

4.4.2 Fluid analysis

Fluid analysis tools take fluid samples through a hole in the casing, using a fluid sampling module, to analyse the formation fluid in situ and to collect and retrieve a fluid sample for further laboratory analysis (Duguid & Tombari 2007). Results can indicate bore leakage and mixing of waters.

4.4.3 Sidewall coring

Sidewall coring tools have a coring bit capable of cutting through the casing, the cement and the formation and retrieving a composite sample - a core containing each material (Duguid & Tombari 2007). The retrieval of sidewall cores allows the detailed inspection of wellbore materials for damage at a small scale. However, it is important to run a temperature and pressure module, in conjunction with the integrity logging and sampling tools, to record these conditions so they can be factored into interpretation and modelling work (Duguid & Tombari 2007).

4.5 Integrity assessment

In order to gain a better understanding of well integrity status on the Norwegian Continental Shelf, the Petroleum Safety Authority (PSA) in Norway initiated a well integrity survey to investigate instances of integrity failure (Birgit & Aadnoy 2008). The survey found that most of the integrity problems were within barrier elements such as tubing, annulus safety valve (ASV), casing, cement and wellhead (Figure 17).

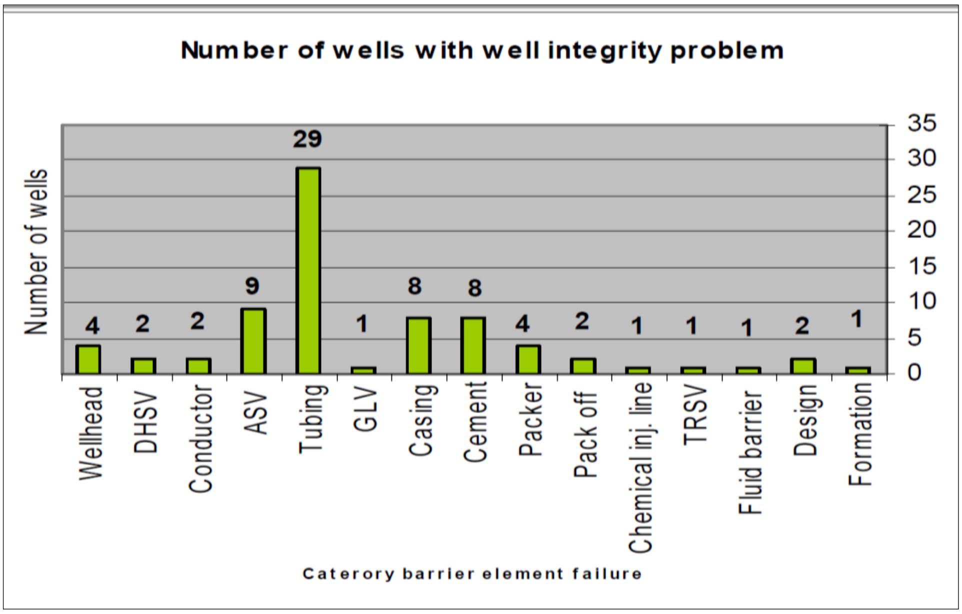


Figure 17 Categories of barrier element failure (© Copyright, Birgit & Aadnoy 2008).

While a direct comparison cannot be made between coal seam gas wells and the offshore wells in this survey, the results from the survey are useful in gaining an understanding of the possible failure mechanisms of coal seam gas wells. Offshore wells are drilled in a very different, difficult environment and therefore the failure rates would be expected to be much higher than that for onshore wells.

The Birgit and Aadnoy (2008) survey concluded that the majority of well integrity problems occurred within the tubing in wells constructed during the early 1990s and that the tubing leaks were likely to be through the telescopic expansion joints, possibly from damage occurred when the production tubing was lowered into the well. The survey also found that:

- eighteen per cent of wells had either integrity failure, issues or uncertainties and seven per cent of them were decommissioned as a result of well integrity issues
- the key factors in well failure related to:
  - operational decisions made during abnormal situations
  - design issues where the long-term effects were not considered
  - an inability to account for rare events that may lead to major incidents.

Gasda et al. (2010) assessed the applicability of the vertical interference test (VIT) by analysing test results with different numerical techniques to estimate the effective permeability of a given well. It was found that field VIT testing was an effective well integrity testing technique and that automated parameter estimation can be useful in reducing uncertainty in identifying key parameters associated with well integrity.

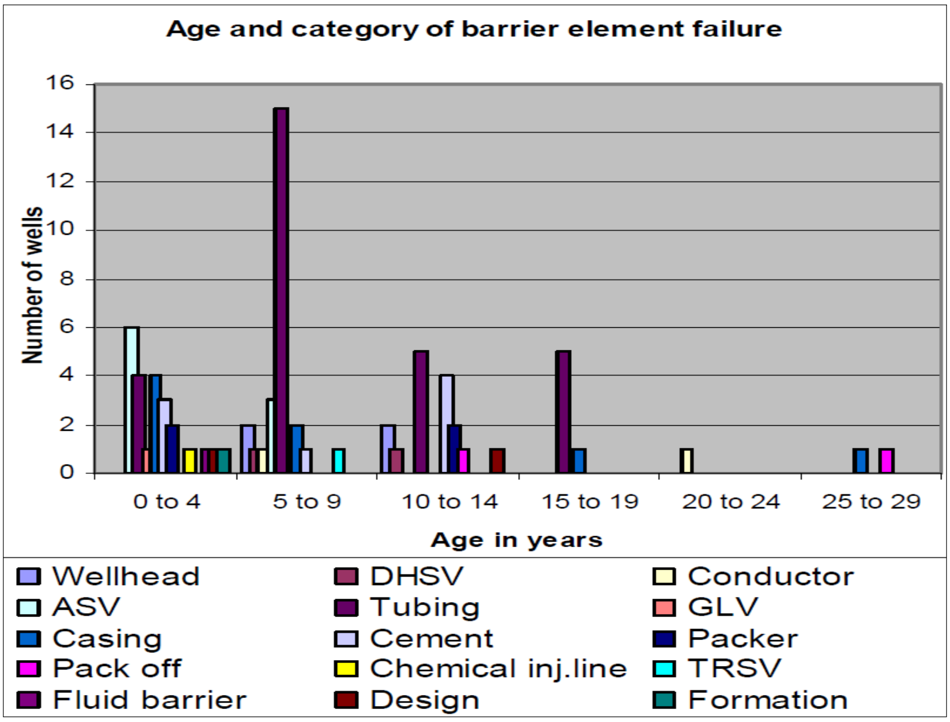


Figure 18 Age and category barrier element failure (© Copyright, Birgit & Aadnoy 2008).

Watson and Bachu (2009) studied records from industry of well leakage at the surface as surface-casing-vent flow (SCVF) through well annuli and gas migration outside the casing, for Alberta, Canada. They found that leakage occurs in 4.5 per cent of wells within the region.

Crow et al. (2009) undertook a well integrity study of a 30 year old production well installed in a high CO_2-bearing formation. A range of monitoring tests were used including sidewall cores that were taken to recover casing, cement and formation samples for laboratory analysis, down-hole ultrasonic imaging, multi-finger caliper logs and a vertical interference test (VIT) that was conducted to measure the response of an applied pressure across a cemented shale section. A simulated numerical analysis was undertaken using the VIT data. It was found that there was discrepancy between simulated and measured results, with increased permeability using the VIT data. This was considered to be due to a scaling issue whereby core sample testing did not include communication along material interfaces and that the most likely leakage path would be along interfaces. Crow et al. (2009) concluded that current technologies are suitable to determine well barrier condition. The logging results were found to correlate well with the VIT results and the side wall core sampling results.

A review of hydraulic fracturing activity in the UK was commissioned by the UK Government to evaluate risks associated with shale gas extraction and develop best practice (Royal Society 2012). The bore integrity aspects addressed in the review are applicable to other wells, in addition to those used for hydraulic fracturing, and focuses on design and construction as the most important issues to ensure integrity. The report reviewed current assessment techniques and recommended that during drilling and installation operations bore casing integrity be assessed by pressure testing of mechanical strength. Formation pressure tests (as discussed in Section 4.4.1) were also recommended to be carried out to understand local stress regimes in the surrounding rocks, which will inform changes to the well design, as required.

Confidence in cement emplacement and integrity (as well as casing integrity) can also be gained by pressure tests and acoustic techniques. Royal Society noted that:

> *'…despite the quality of the initial cementation, some wells can still leak over time'.*
>
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An explanation for this was given as cement shrinkage. Shrinkage can lead to circumferential cracks that can grow due to changes in pressure gradients and cause leakage, although modern cement formulations are resistant to shrinkage. To mitigate leakage the report suggested that best practice is to cement casings all the way back to surface (Royal Society 2012).

In the UK the *Offshore Installations and Wells Regulations 1996* requires an independent and competent person to examine well design and construction information. The Royal Society (2012) review recommended that the existing well examiner scheme should be widened to include environmental perspectives in addition to health and safety. In terms of post-construction monitoring of coal seam gas wells, there is no legislative requirement in the UK for pressure tests or geophysical analysis. However, emphasis is placed on operators continuing to monitor and verify well integrity during operations. This monitoring should include:

> *'…regular sampling of near surface aquifers'* and *'…continuous monitoring of ground gas emissions.'*
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The Nebraska Grout Study (Ross 2010) demonstrated that bentonite grout issues can occur in water bores. The Nebraska Grout Task Force was established in 2001 and used clear PVC casing to monitor bore integrity and increase the awareness of regulatory personnel on well design and construction. The bores were inspected 16 months after construction and video footage showed that there were large voids and cracks in the grout column. The study highlighted that all of the grouts tested performed as expected in the saturated zone below the water table. However, in the unsaturated zone above the water table, all grouts developed cracks and voids within the first month after construction. Bentonite chip grout was found to perform the best out of all the grout recipes even in the unsaturated zone. While the study provided useful information on how bentonite grout may fail, care must be taken in extrapolating these findings to the failure of the cement grouting used in Australian bores.

Bourgoyne et al. (1999) reported that a large number of producing wells on the outer continental shelf of the US developed undesirable and sometimes potentially dangerous sustained casing pressure in one or more of the casings. The study highlighted that many well integrity problems were the result of poor primary cement jobs and that the most significant cause was a poor cement bond. Gas flow or water flow through unset cement was identified as a major cause of sustained casing pressure in the outer casing. About one-third of the casings exhibited sustained casing pressure in wells that were active.

The Bourgoyne et al. (1999) study recommended that implementing best cementing practices when designing and completing a well may prevent sustained casing pressure in many instances. Best cementing practices would include consideration of cement quality and weight, waiting time, hole size, mud properties, pipe centralisation and pre-cementing circulation procedures.

The results of desk-based studies of potential leakage (across a given area) as a result of poor bore integrity can be useful to inform risk assessments and the prioritisation of remedial works. However, good data sets are required and models also require calibration using field-based investigations. One of the key input parameters is a reliable estimate of well effective permeability/leakage. This can be obtained by direct measurement of a subset of wells followed by application of statistical analysis to include other wells. Field methods, such as those discussed in previous sections, are used to determine the well integrity and effective permeability of a small number of wells. This information is then extrapolated using an analytical or numerical model to determine if there are any spatial correlations. Another approach is to indirectly estimate effective permeability using data such as well age and depth etc. Some recent studies to develop basin-scale predictive models for carbon capture and storage (CCS) wells are summarised below.

Gasda et al. (2004) used a combined spatial and statistical analysis to characterise the CO_2 leakage potential of abandoned oil and gas wells in the mature Alberta Basin. Two sets of parameters were identified as key inputs: the spatial location of wells and the effective permeability of each well. This required a high-quality database of well information and quantification of hydraulic properties using techniques discussed previously. The study presented possible leakage pathways of CO_2 through an abandoned well (refer to Figure 1). These leakage pathways apply to fresh water, brine and natural gas movement, given allowances for the specific physical properties of the particular fluid of interest.

An analytical solution was developed by Cihan et al. (2012) to assess pressure build up and leakage rates in a multi-layered aquifer system. Pressure build up was studied in the context of gas (CO_2) injection and storage in saturated aquifers, although the solution used single-phase fluid flow parameters instead of more complex two-phase gas and water attributes. Leakage via wells and faults was described as ‘focused’ leakage in contrast to the ‘diffuse’ leakage across aquitard layers. They note that induced pressure changes can extend across thousands of square kilometres in the horizontal direction and many local wells and bores may need to be considered.

Localised gas leakage, or fugitive gas emissions, associated with the coal seam gas industry can be a significant issue. In Ohio, US the Clinton sandstone is an oil and gas bearing reservoir with over 79 000 wells (ODNR 2008). An explosion occurred in December 2007, which damaged a house in the Bainbridge township as a result of a leaking gas producing well (ODNR 2008). The high pressures in the annulus of the production well caused gas to migrate into the natural fractures in the formation and into the overlying aquifers, where it discharged through local water wells (ODNR 2008). The primary factors thought to have caused the leakage included poor cementing during construction and the hydraulic fracturing program. The hydraulic fracturing program allowed a long time lag (31 days) between the completion of the hydraulic fracturing and recovery of the fracturing fluids and subsequent pressure released from the formation (ODNR 2008). Experience in hydraulic fracturing in Australia and the US has demonstrated that minimising the time between completing the hydraulic fracturing process and the recovery of fracturing fluids will minimise the likelihood of the fracturing fluids migrating out of the gas-bearing layer (Green et al. 2012).

4.6 Reporting requirements in Australia

4.6.1 Water bores

Australian state and territory governments regulate drilling contractors and consultants to ensure compliance with construction licences, and meet minimum standards for bore construction (i.e. MCRWBA) (NUDLC 2012). Most jurisdictions require a bore to be registered and this involves submitting a bore completion report detailing the location, geology, construction, water quality, bore yield and other details as required.

In many states and territories, there are also dedicated drilling inspectors that will inspect a drilling site to ensure compliance. However there is no regulatory requirement to monitor the integrity of the bore. Some jurisdictions may also undertake bore condition assessment reports on a periodic basis.

4.6.2 Coal exploration bores

In Australia, reporting requirements for coal and mineral exploration bores vary between jurisdictions. A mining exploration licence generally entitles drill exploration holes, among other activities. The exploration holes may have special requirements for drilling or construction techniques to ensure that groundwater resources are protected. In most jurisdictions mining exploration activity reports must be submitted to the regulator on a regular basis showing the type of work that has been undertaken in the mine lease exploration area, including exploration holes that have been drilled, constructed and decommissioned.

It is the responsibility of the mining company to ensure that exploration holes meet the appropriate legislative requirements, are decommissioned appropriately and that relevant reports are submitted to the regulators. Some regulators will undertake audits to ensure that mining companies are compliant with regulations and the conditions of the mining lease. However, only a small proportion of exploration sites are audited and the extent of compliance of most exploration activities is unknown.

4.6.3 Coal seam gas wells

Similar to mineral and coal exploration bores, reporting requirements will vary from jurisdiction to jurisdiction in Australia. Coal seam gas exploration and production activities are governed under the relevant petroleum and gas act, which clearly specify the design and construction requirements for a coal seam gas well. A post-completion report is required to be submitted to the regulator, which details the actual construction of the well and any deviations from the design. If hydraulic fracturing has been undertaken on a well, a report detailing the hydraulic fracturing process, including volumes and chemicals used, is also required to be submitted to the regulator.

The integrity of a coal seam gas well is monitored using the methods discussed in Section 4.3 and 4.4 on a regular basis (i.e. bi-annually or annually) to ensure well integrity is maintained and these reports are submitted to the regulator on an annual basis.

5 Bore decommissioning

5.1 Introduction

Bores have a finite life. Bores are typically designed for a particular productive purpose and when this is no longer being fulfilled they should be decommissioned (or abandoned). The terms ‘decommission’ and ‘abandon’ are used interchangeably in this report. However, the terms mean different things in different industries and in different jurisdictions. For example, the term ‘decommission’ generally refers to work undertaken to properly shut down a bore or well, except in Queensland where the term ‘abandon’ is used for shutting down coal seam gas wells. This can be confusing as in New South Wales the term ‘abandon’ infers that the owner of a bore has ceased using the bore indefinitely but has not properly shut down the bore.

All failed or unwanted drill holes, bores or wells should be decommissioned to restore, as far as possible, the previous aquifer isolation (NUDLC 2012). Decommissioning aims to protect the aquifers intersected by the bore from contamination, either by migration of surface water into the bore or mixing of water from different aquifers. Decommissioning may also be necessary to prevent uncontrolled discharge of fluids or gas. The complexity of the decommissioning procedure depends primarily on the hydrogeology, well construction and groundwater quality.

In Australia, jurisdictional regulations provide a framework to ensure that water bores and exploration bores are decommissioned appropriately and this work reported to the appropriate regulator. However, the level of compliance and enforcement could be expected to vary between jurisdictions and at the time of writing, information on decommissioning was not readily accessible by the public.

5.2 Water bores

A list of mandatory requirements to be met when decommissioning water bores is set out in the MCRWBA. Decommissioning requirements include (NULDC 2012):

- elimination of any physical hazards such as filling in holes
- prevention of groundwater contamination
- prevention of water intermixing
- conservation of yield and maintenance of hydrostatic head of the aquifers.

Bores may be decommissioned for a number of reasons and the preferred method of decommissioning is full grouting from the base to the surface of the hole (NUDLC 2012). Where it can be justified economically and environmentally, an alternative is to install a grout seal in the screened zone, followed by earth fill and then another grout seal at the surface. Similar methods may be used for multiple aquifer bores and flowing bores although each aquifer must be isolated. Regardless of the decommissioning methods used, a concrete or grout surface seal to a minimum depth of 5 m must be installed. It is also recommended to perforate the casing to allow grout to fill any voids between the casing and the formation, to prevent water migrating outside of the casing.

The industry mandatory requirements for decommissioning water bores are also applicable to all test bores that have not been cased. The MCRWBA sets out mandatory requirements for reporting the decommissioning of water bores (NULDC 2012). Various state legislation also have requirements to report decommissioning of water bores including the *Water Act 2000* in Queensland. It needs not only to be mandatory and enforceable to ensure that water bores are decommissioned appropriately but regulators also need to have the capacity to ensure compliance.

5.3 Coal mining exploration bores

Mining exploration bores must be decommissioned or abandoned under the relevant Australian mining legislation. Some jurisdictions have produced specific guidelines outlining decommissioning requirements for exploration (DoR 2011; DMP 2002; DPI 2002). For example, in Queensland, the *Code of environmental compliance for exploration and mineral development projects* (DEHP 2013) sets out the following requirements for exploration drill holes:

> *'The holder of the environmental authority must decommission all non-artesian drill holes, apart from those still required for monitoring purposes as soon as practical, but no later than 6 months after the hole was drilled by undertaking the following actions:*
>
> - *where practical dispose of all unused drill chips to the hole or to a sump pit*
> - *cap the hole at a depth that is appropriate for the previous land use of the area (unless the land owner stipulates a future use which requires the cap to be placed deeper)*
> - *backfill the hole above the cap with soil or material similar to the surrounding soil or material'.*
>
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In addition to the above, non-artesian aquifers must be isolated from each other:

> *'…where a drill hole intersects more than one water bearing strata by casing or plugging the hole as soon as practical after the hole is no longer required, but no later than 2 months after the hole was drilled, apart from those holes that are still required for monitoring purposes if:*
>
> - *the flow difference between aquifers exceeds 500 L/hour*
> - *the difference in electrical conductivity of water is greater than 10% of the lower value'.*
>
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Bridges are sometimes used where it is not possible to grout a bore fully. A bridge is a solid fixture that is positioned in a drilled hole to form a base for grout or backfill material, when the drilled hole is to be only partially in-filled (DPI 2002). Bridges can be made from wooden plugs or metal plates, cementing baskets, formation packers and, in some cases, hessian bags (DPI 2002).

Although there are regulations that specify the decommissioning process, it is difficult to determine the level of compliance in remote areas. For example, mining companies may require that the hole remain open so that they can return to collect further data. Where and if decommissioning actually occurs is not well documented. The level of compliance is not measured by regulators and at the time of writing information on completed bore decommissioning was not in the public domain.

5.4 Coal seam gas wells

Coal seam gas well abandonment is undertaken in a way to ensure the environmentally sound and safe isolation of the well to protect ground water sources, to isolate the productive formations from the surrounding formations and to prevent migration of gas and fluids from the productive formation to the surface. This involves sealing the hole completely from the base to the surface using a series of cement plugs to provide a seal preventing any cross flow of water and gas (APPEA 2012). The wellhead is then removed and the steel casing filled with cement is cut off at least 1.5 m below ground level, sealed with a metal identification plate and buried (APPEA 2012). The cement used in well construction and abandonment is designed to have a life span in excess of 100 years.

DEEDI (2011a) describes in detail the mandatory requirements and good industry practice relating to well abandonment in Queensland and provides a framework for ensuring all Queensland coal seam gas wells are abandoned appropriately.

The level of compliance with abandoning wells in the coal seam gas industry is expected, by the author, to be higher than other industries, although there is no information on the compliance rates available in the public domain. The health and safety risks associated with not abandoning a coal seam gas well appropriately are greater than that of a water bore, or mineral exploration bore. Consequently, appropriately decommissioning a petroleum or gas well has both mandatory and best practice requirements (see, for example, DNRM 2013).

5.5 Legacy bores

Bores that are not decommissioned appropriately are often referred to as 'legacy bores' and their number in Australia is not known but likely to be substantial. Legacy bores can be any type of bore, although the most common types are:

- oil and gas wells
- water supply bores
- coal exploration wells
- state government owned bores
- government exploration bores.

There are several significant implications of legacy bores, including:

- localised connectivity of aquifers, which can have further detrimental implications on local groundwater quality
- potential direct access between the ground surface and the aquifer, which is therefore a potential source of aquifer contamination
- potential to release fugitive gas emissions as potential coal seam gas bearing layers are depressurised and release gas, which can ignite.

At the time of writing there was little or no information available in the public domain on legacy bores. However, discussions with representatives at the Queensland government Department of Natural Resources and Mines (DNRM) highlighted that this information may be available in company reports and paper-based bore log records (Free 2013, pers. comm., 28 February).

In Queensland, legacy bores are likely to exist from all types of bores; however, coal exploration wells are the most significant legacy type for Queensland, largely due to their abundance and possible lack of appropriate decommissioning, both of which is at this stage unquantified. It has been estimated some 30 000 coal exploration wells have been drilled in the Surat Basin, with a further 100 000 in the Bowen Basin (Free 2013, pers. comm., 28 February). It is unknown however how many of the bores were decommissioned or, if they were decommissioned, the standard of the decommissioning work.

Many states in the US require that all unused wells be decommissioned, as per state regulation, by a licensed well contractor, and a report be filed with the state agency overseeing the industry. In Minnesota, when a property is sold there is a requirement for disclosure on the transaction document of any 'legacy' bores on the property (Minnesota Statues 2013). Minnesota has sealed over 250 000 legacy wells and it is considered that approximately three-quarters of these well were identified via property transfer disclosures.

The Queensland government *Code of environmental compliance for exploration and mineral development projects* (DEHP 2013) is described in Section 5.3 and allows for capping of non-artesian exploration holes at an appropriate depth for future land use, and backfilling above the cap. Coal exploration bores decommissioned under these specifications may therefore lack an adequate cement plug (appropriate seal) and could be considered as legacy bores.

An example of a coal mining exploration bore that was not decommissioned appropriately was reported in the media in August 2012 (Kennedy 2012). The media report stated that the exploration bore was found after it caught on fire and started a local bushfire (Figure 15). The exploration bore, located 25 km west of Dalby in Queensland within Arrow Energy's Daandine gas field but not installed or used by Arrow Energy, was at least 1 km from any coal seam gas activity and leaking gas, which caught fire (Kennedy 2012). The fire was reported to have been 1 to 2 m high in a depressed section of earth about 50 cm deep and wide (Kennedy 2012). The well was presumed to have been drilled at least 20 years ago. The fire was extinguished by filling the hole with water and the site was then monitored for 24 hours while it was allowed to cool. Following cooling, the bore and surrounding area was filled with concrete (Rowling 2012).

Figure 19 Photo of coal mining bore burning 25 km west of Dalby, Queensland (© Copyright, Kennedy 2012).

Jordan and Hare (2002) outline several methods that can be used to locate abandoned wells such as:

- remote sensing or geophysical methods - the thermal band in remote sensing data, such as Landsat images, can be used to detect temperature changes between the cool land surface and a warmer leaking abandoned well
- a range of geophysical methods such as magnetic, ground penetrating radar and some electromagnetic techniques have been used successfully to detect buried or abandoned wells
- methods such as resistivity, self-potential and transient electromagnetic sounding techniques can detect subsurface plumes of brine or other borehole leakages, which may be the only remaining evidence of a leaking bore.

The type or range of methods employed will depend on the available data, size of the area to be searched and the construction material of the abandoned bore.

6 Summary and knowledge gaps

6.1 What does the science tell us?

Bores with poor integrity have the potential to provide pathways for gases and liquids to migrate into and between aquifers, causing contamination of the groundwater. The Petroleum Safety Authority (PSA) in Norway completed a bore integrity survey to investigate instances of integrity failure and found that 18 per cent of the wells had either failure of, issues with or uncertainties in integrity, and seven per cent of these were decommissioned as a result of integrity issues (Birgit & Aadnoy 2008). Similarly, Watson and Bachu (2009) noted that 4.5 per cent of Alberta's bores leak.

There are many factors that can impact on the integrity of a bore, some of which involve the breakdown of the physical barriers, while others involve the professional integrity of the engineers and technicians engaged to design, drill and construct the bore, or the regulatory regime, which depends on the intended purpose of the bore (Manifold 2010). Birgit and Aadnoy (2008) suggested that the key factors in instances of bore failure in Norway related to operational decisions made during abnormal situations, design issues where the long-term effects were not considered, and the inability to account for rare events that may lead to major incidents.

The bulk of recent international research on bore integrity relates to wells for long-term storage of CO_2; however, much of this information can be extrapolated to other industries in different countries. A key difference between wells used for CO_2 storage and other wells is that CO_2 causes degradation to Portland-based cements, which are commonly used in well construction (Pearce 2005).

One of the key findings from a well integrity workshop for long term storage of CO_2 suggested that it is not possible to promise a leak-free well. However, state-of-the-art technologies in well construction will reduce risks associated with poor well integrity (Pearce 2005). Minimising leakage pathways in the annulus of the bore requires good cementing practices (Nygaard 2010; GHD 2010). These include appropriate cement quality and weight, waiting time, hole size, mud properties, pipe centralisation and pre-cementing circulation procedures (Bourgoyne et al. 1999). However, the Royal Society (2012) noted that despite the quality of the initial cementation, some wells can still leak over time, due to factors like cement shrinkage. In recent years there has been increased awareness of the importance of good cementing practices and more research is required to improve this understanding (Pearce 2005).

6.2 What is current practice?

The water bore industry operates within a complex regulatory framework that includes various acts, standards and guidelines, many of which are based on international standards. The design, drilling, construction, maintenance and decommissioning of water bores in Australia is guided by the *Minimum Construction Requirements for Water Bores in Australia* (MCRWBA) (NUDLC 2012). The MCRWBA was first published in 1997 and prior to this there were no national guidelines. The current edition of the MCRWBA provides a framework to address bore integrity issues during drilling and construction. However, there is no regulatory requirement to monitor the integrity of a water bore, neither upon completion, over the workable life, or upon decommissioning, as this is considered to be the responsibility of the bore owner.

Mining bores, including those for coal exploration, are regulated under the relevant jurisdictional mining acts. The level of compliance is uncertain as there was little information available on this in the public domain at the time of writing. Drillers of coal exploration bores are not required to be licensed and there is no regulatory requirement to monitor the integrity of decommissioned exploration bores.

The broader regulatory regime covering the petroleum and gas industry in Australia is considered to be leading practice (SKM 2012a). It is based on international standards such as the American Petroleum Institute (API) and Standards Norway (NORSOK). The API publishes a range of practice notes that are used by Australian regulators as guidance for well construction and operations, including Australian cods of practice for coal seam gas (NSW T&I 2012a; DEEDI 2011; API 2009).

In Queensland and New South Wales there is significant coal seam gas exploration and production and there are specific codes of practice for coal seam gas well integrity and hydraulic fracturing (NSW T&I 2012a; NSW T&I 2012b; DEEDI 2011a). These codes of practice outline monitoring requirements to ensure well integrity and the reporting requirements specified by each regulator.

From this review, it appears that compliance with regulatory requirements within the coal seam gas industry is generally better than that of the water and mining industries, and is helped by the monitoring of well integrity and reporting requirements for coal seam gas operators. However, whilst drillers operating in the mining and petroleum and gas industries are required to be qualified in accordance with the Australian Qualification Framework (AQF), they are not required to hold a water well drillers' licence (ADITC 2011). This reflects the responsibilities in different industries and jurisdictions. In Queensland, it is the tenure holder, rather than the driller, who has primary responsible for ensuring bore construction meets the regulatory requirements.

Bore integrity issues mostly develop as a result of poor construction techniques. Key elements to ensure bore integrity include good bore design, selection of appropriate construction materials to withstand pressures and deterioration processes and a good cement job (DEEDI 2011a; Dunnivant et al. 1997). Existing guidelines and regulations provide frameworks to establish bore integrity, and it remains up to the driller and tenure holder to use best practices and regulators to ensure compliance.

6.3 Knowledge gaps

Information on well integrity is documented for the petroleum and gas industry. However, at the time of writing there was very limited information in the public domain on bore integrity for the water and mining industries. GHD (2010) highlighted the lack of information in the public domain on existing bore condition assessment and, with limited access to existing groundwater databases, relied heavily on sourcing information from stakeholders. However, GHD reported a similar scarcity of information or reports on bore condition assessment from stakeholders. Some jurisdictions do have reporting requirements when decommissioning bores; for example, in South Australia a well construction permit is required for the decommissioning of a well and a well construction report is to be submitted on completion of the works. However, this is not the case in all jurisdictions and information on bore integrity is not readily available.

In the oil and gas industry, broad areas for future research opportunities have been identified (Pearce 2005):

- frequency of failure: there is insufficient information available from regulators or oil and gas operators, water bore owners, or the coal industry to enable the frequency of failures to be estimated, either within bores or between bores of a similar or different type. A key contributing factor to this is the commercial sensitivity and inconsistent definitions of failure classes
- mechanisms for failure: there are many mechanisms that can result in bore failure. However, little is known about how these failure mechanisms should be classified, or the detailed processes that ultimately lead to failure
- criteria for failure: there is a need to clearly define criteria against which failure can be judged
- consequences of failure: the consequences of bore integrity failure for water resources, both in terms of quantity and quality, are dependent on a variety of factors including the location of the bores, their depth, the surrounding groundwater resources, the purpose of the bore, its age and construction materials, and the rigour of its monitoring and maintenance program. However, detailed consequence assessments for water resources could not be readily identified in the literature.

In addition, in the context of coal seam gas extraction and coal mining, investigations of cumulative issues associated with multiple incidents of bore failure could not be readily identified in the literature.

6.4 Options to address knowledge gaps

Monitoring and reporting of bore integrity needs to improve for wells and bores across all industries to ensure that there is sufficient information available to assess bore integrity and inform research needs. Research is also required to assess the most appropriate and cost-effective techniques to locate legacy bores throughout Australia, to determine the scale of the issue.

Many states in the US require that all unused wells be decommissioned, as per state regulation, by a licensed contractor, and a report be filed with the state agency overseeing the industry. In Minnesota, when a property is sold there is a requirement for disclosure on the transaction document of any ‘legacy’ bores on the property (Minnesota Statues 2013). Such a policy may have value in Australia to address the issue of legacy bores that are left without being appropriately decommissioned.

The level of compliance by bore owners in maintaining the integrity of their bores through rehabilitation and appropriate decommissioning varies nationally. In several cases, such as in the Great Artesian Basin, the Commonwealth and state governments have provided funding to ensure that bores are rehabilitated and decommissioned to ensure the groundwater resources are protected. However, existing legislation outlines that it is the bore owner’s responsibility to maintain their bores and increased awareness is required to ensure compliance.

Water bore condition monitoring and reporting requirements could be integrated with groundwater bore licencing conditions to improve accountability (GHD 2010). GHD (2010) also recommended developing guidelines for bore casing condition assessments that include:

- a diagnosis program based on bore performance indicators
- specified minimum monitoring and data review requirements
- a matrix array of physical and geophysical testing methods for casing condition integrity assessment.

The Australian Drilling Industry Association (ADIA) believe it should be mandated that all drillers be certified/licensed, not just water drillers, and that this would go some way to ensuring aquifers are protected across the different industries. However, requiring all drillers to be licenced may not be effective if the driller is not the one responsible for ensuring proper bore construction, such as in the Queensland coal seam gas industry. Underpinning many of these options is the need for regulators to have the capacity and processes to deal with increased regulatory requirements.

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Appendix A: further reading

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