# CCS Communications Framework
# Appendix: Summarising Key Findings on Induced Seismicity

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# 1. Introduction

This report examines whether there is a correlation between CCS and seismicity through a review of key existing literature on the subject. This report is a contribution to the second phase of a project being undertaken for the Global Carbon Capture and Storage Institute (GCCSI) entitled “Development of Knowledge Sharing Framework for Japan”.

## 1.1 Defining induced seismicity and its causes

Seismicity refers to earthquakes and ground tremors that are the result of stresses and strains on the Earth's crust. Induced seismicity is, broadly, seismicity caused or triggered by human actions. Most cases of induced seismicity are of an extremely low magnitude. A wide range of human activities may induce seismicity, including:

- fluid injection underground;
- fluid withdrawal from sub-surface rock formations;
- creation of underground excavations;
- the collapse of underground excavations (e.g. mine instability);
- and loading of rocks by structures or water retained by structures (e.g. reservoirs behind dams).

The main underlying causes of induced seismicity are:

- pressure build-up due to fluid injection;
- pressure draw-down due to fluid extraction; and
- sudden temperature changes.

## 1.2 Resulting impacts of induced seismicity

To cause a damaging seismic event requires a fracture to slip over a sufficiently large enough area. From a theoretical perspective damage will be caused only very rarely by induced seismicity. The depth at which seismicity is induced will influence the effects. Broadly, for a given release of energy the impacts will be less the greater is the depth. The likelihood of adverse impacts from induced seismicity will also depend upon the nature of the impacted land, including the ecosystems present and the uses to which the land is put. For example, potential impacts would probably be more significant in areas with dense human populations than in sparsely populated areas.

### 1.3 Research materials for this report

This report involved a literature view and the drawing of materials from key sources on this subject of induced seismicity. Throughout the report, points made are illustrated by cross references to two documents that describe aspects of induced seismicity that potentially could be caused by a wide range of human activities (Cysper and Davis, 1998; NRC, 2012) and a single report that presents a protocol for addressing induced seismicity associated with enhanced geothermal systems (Majer et al. 2012). A broader set of materials do exist on the subject but these materials were should to be the strongest sources for reference.

## 2. Executive Summary

This report summarizes information and knowledge relevant to each level of the so-called Carbon Capture and Storage (CCS) "Safety and Security Pyramid" (Figure 1) in relation to induced seismicity. Supplementary detail to this report covers each level of this pyramid, starting at the bottom and working upwards to the top, for each of the following chapters,

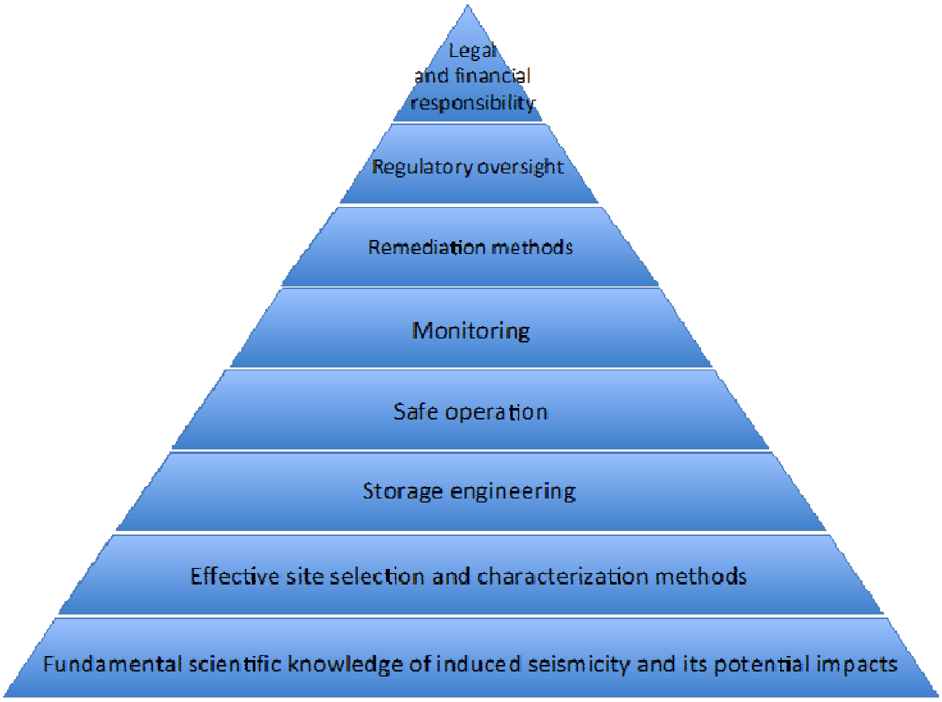

Figure 2-1 Safety and Security Pyramid.

Carbon storage is essentially a form of fluid injection and the mechanisms by which it might induce seismicity are generally similar to those operating in other cases where humans inject fluid underground, such as:

- Secondary or tertiary oil recovery;
- Fracking connected with non-conventional hydrocarbon recovery (notably shale gas extraction);
- Waste water management;
- Development of geothermal resources;

The research collected in this paper shows that human activities that involve sub-surface fluid injection or extraction rarely induce seismicity that can be felt by humans (generally with a moment magnitude > 2, also roughly equivalent to a magnitude of >2 on the well-known Richter Scale). To date, there had been no known incidents of induced seismicity at a magnitude at any of the sites where $CO_2$ storage is presently being demonstrated (e.g. Sleipner and Snøhvit, offshore from Norway, or In Salah in central Algeria). It should be noted that current CCS demonstration projects are small (in the order of 1 million tonnes $CO_2$ per year being injected), compared to the size of projects that will be needed should CCS be adopted to mitigate climate change. Storage of large $CO_2$ volumes could potentially make it more difficult to manage sub-surface formation pressures than in other activities where fluids are injected underground. The main mechanisms by which induced seismicity may occur are well understood, but reliable predictions of induced seismicity cannot be made without site-specific data. In those situations where induced seismicity has been proven or thought to occur, sufficient site-specific data to allow accurate predictions is not available.

## 3. Fundamental Scientific Knowledge of Induced Seismicity and its Potential Impacts

Induced seismicity is, broadly, seismicity caused or triggered by human actions (NRC, 2012). In the former case, the seismicity is caused by the creation of new fractures within rocks, whereas in the latter case human actions cause movement along pre-existing natural fractures. Some workers distinguish between these two cases, whereas other workers make no distinction.

A wide range of human activities may induce seismicity (NRC, 2012), including: fluid injection underground (NRC, 2012); fluid withdrawal from sub-surface rock formations (NRC, 2012); creation of underground excavations; the collapse of underground excavations (e.g. mine instability); and loading of rocks by structures or water retained by structures (e.g. reservoirs behind dams). Carbon storage is essentially a form of fluid injection and the mechanisms by which it might induce seismicity are generally similar to those operating in other cases where humans inject fluid underground (NRC, 2012).

These other cases are predominantly: secondary or tertiary oil recovery; fracking connected with non-conventional hydrocarbon recovery (notably shale gas extraction) (NRC, 2012); waste water management (NRC, 2012); and development of geothermal resources (NRC, 2012). This last case can be subdivided into: (1) situations where water is injected into a geothermal field in order to maintain fluid pressures in circumstances where water and / or steam circulate naturally; and (2) situations where fluid is injected at high pressure in order to fracture the rock and create an artificial geothermal reservoir (a so-called "Enhanced Geothermal System (EGS)). However, important differences between $CO_2$ storage and these other forms of fluid injection are (NRC, 2012): (1) the very large volumes of $CO_2$ that will need to be stored in order for $CO_2$ storage to be effective for mitigating climate change (likely between 6 Gt to 10 Gt globally (NRC, 2012)); (2) the phase relations of $CO_2$ which result in very large volume changes as pressure and temperature change (NRC, 2012); and (3) the high aqueous solubility of $CO_2$ and the high chemical reactivity of the $CO_2$-charged aqueous solutions with respect to rocks (NRC, 2012). In particular the complex thermal-hydraulic-mechanical coupling that is characteristic of $CO_2$-water-rock systems are not understood fully.

The main causes of induced seismicity are: (1) pressure build-up due to fluid injection; (2) pressure draw-down due to fluid extraction; and (3) sudden temperature changes. Records of human activities involving sub-surface fluid injection or extraction reveal little induced seismicity when there is fluid balance (added fluids balanced by fluids removed). Similarly, there is little induced seismicity when a relatively small volume of fluid is injected, whether into a relatively well-connected reservoir or a relatively impermeable reservoir. Thus generation of artificial fractures by fracking during extraction of unconventional hydrocarbons (principally shale gas) has relatively little potential to induce seismicity. Although very high pressures, above lithostatic, are achieved in this case, relatively small fluid volumes are injected and the pressure increase is transient.

The injection or extraction of fluid from rocks induces seismicity mainly as a result of affecting the stress state across pre-existing fractures, or stressing the rock to the extent that new fractures are created (NRC, 2012). For example, increasing the pressure of fluid within a pre-existing fault will cause the effective normal stress across the fault to decrease (NRC, 2012). This normal stress reduction may occur to the extent that the natural stress parallel to the fault causes the fault to move, thereby inducing seismicity. It is said in this case that the “Coulomb Criterion” is met (NRC, 2012).

The available evidence suggests that naturally, rocks at depths that might be considered for $CO_2$ storage (to a few km below the surface) often have stresses and pore pressures that are close to the critical conditions under which brittle deformation could occur. In these cases a relatively small stress and/or pore pressure perturbation could cause displacement of a suitably oriented fault.

Those human activities that involve sub-surface fluid injection or extraction rarely induce seismicity that can be felt by humans (NRC, 2012)(generally with a moment magnitude > 2, also roughly equivalent to a magnitude of >2 on the well-known Richter Scale). There are no known incidents of induced seismicity at such a magnitude at any of the sites where $CO_2$ storage is presently being demonstrated (e.g. Sleipner and Snøhvit, offshore from Norway, or In Salah in central Algeria (NRC, 2012)). However, these demonstration projects are small (in the order of 1 million tonnes $CO_2$ per year being injected), compared to the size of projects that will be needed should CCS be adopted to mitigate climate change (a single, medium sized 500 MW coal-fired power station generates c.3.5 Mt of $CO_2$ annually, equivalent to about 4.3 $Mm^3$ per year taking a supercritical $CO_2$ density of 800 $kgm^{-3}$; the largest coal-fired power stations presently in operation produce around 10 times this amount of $CO_2$ each year). Storage of such large volumes could potentially make it more difficult to manage sub-surface formation pressures than in other activities where fluids are injected underground (NRC, 2012). Additionally, compared to other fluid injection activities, if fully implemented, $CO_2$ storage would influence much larger rock volumes, making it more likely that pre-existing faults and fractures would be affected. Both these factors might make induced seismicity with magnitude of >2 more likely for $CO_2$ storage than for other fluid injection operations. However, it should be noted that $CO_2$ storage would not necessarily result in sub-surface rock formation pressures greatly in excess of $CO_2$ pre-injection pressures. For example, it is frequently proposed to store $CO_2$ in depleted hydrocarbon reservoirs within which the pressure has already been drawn down far below initial values by hydrocarbon extraction. Furthermore, injection wells can be sited and operated to manage formation pressure build-up and it might also be possible to withdraw pre-existing fluids deliberately to manage pressures. This latter strategy is being adopted in the Gorgon Project in Australia. It is also possible to design $CO_2$ storage operations to avoid major faults and fracture zones along which seismicity might be induced.

The main mechanisms by which induced seismicity may occur are well understood, but reliable predictions of induced seismicity cannot be made without site-specific data. In those situations where induced seismicity has been proven or thought to occur, sufficient site-specific data to allow accurate predictions is not available.

The magnitude of any induced seismicity depends generally on the area of the fracture that is displaced and the size of the displacement (NRC, 2012); the larger the area and the greater the displacement, the larger will be the seismic event. Any fractures that are created by fluid injection or removal will tend to be small and thus the corresponding induced seismicity will be low in magnitude. Similarly, most pre-existing fractures in rocks are small in scale and movement along them caused by fluid injection or withdrawal will be small, mostly with $M<2$. To cause a damaging seismic event requires a fracture to slip over a sufficiently large enough area. For example, a seismic event of M4 involves displacement of about 1m over an area of about 1.4 $km^2$. Damaging earthquakes generally have a magnitude >M5. Thus, from a theoretical perspective damage will be caused only very rarely by induced seismicity.

The main potential adverse effect of induced seismicity at the ground surface is shaking (NRC, 2012). If the seismic event is sufficiently large, this could potentially damage structures at the surface. Underground the main effects will be the actual rock displacements that cause the seismicity. Depending upon their locations and magnitudes, these displacements could potentially damage underground infrastructure, notably well seals and casings.

The depth at which seismicity is induced will influence the effects (NRC, 2012). Broadly, for a given release of energy the impacts will be less the greater is the depth. Similarly, the impacts of induced seismicity at the surface will diminish with increasing horizontal distance from the fracture displacement (NRC, 2012). The likelihood of adverse impacts from induced seismicity will also depend upon the nature of the impacted land, including the ecosystems present and the uses to which the land is put. For example, potential impacts would probably be more significant in areas with dense human populations than in sparsely populated areas. Additionally, the potential impacts will generally be correlated positively with the size of the area over which $CO_2$ injection occurs.

## 4. Effective Site Selection and Characterisation Methods

**Key Messages:**

- Site characterisation is a process that should commence prior to the injection of $CO_2$, but continue throughout the lifetime of a project, during $CO_2$ injection and likely thereafter during a period of monitoring.
- Continued characterisation will allow the operation of a site to be modified as appropriate to minimise the risk of induced seismicity.
- Information **must be acquired for** characterisation **must include baseline data** for a given $CO_2$ **storage plan,** including details of $CO_2$ quantities to be stored and rates of injection**.**

This section focusses on the site characterisation methods that might be used to determine the potential for seismicity to be induced by $CO_2$ storage. However, these site characterisation methods are broadly similar to the methods that are employed in other cases where humans inject or withdraw fluid underground. Given the lack of reported induced seismicity connected with $CO_2$ storage, this section draws heavily on experience gained in other fluid injection activities.

Site characterisation is a process that should commence prior to the injection of $CO_2$, but continue throughout the lifetime of a project, during $CO_2$ injection and likely thereafter during a period of monitoring. The length of this latter period will depend upon the particular legal and regulatory regime under which a project is undertaken. Continued characterisation will allow the operation of a site to be modified as appropriate to minimise the risk of induced seismicity.

It follows from the fundamental understanding of induced seismicity outlined in Section 3 that site characterisation for $CO_2$ storage should include acquisition of information required to establish, for a given $CO_2$ storage plan (including details of $CO_2$ quantities to be stored and rates of injection):

- The likelihood and magnitude of any induced seismicity;
- The potential impacts of such seismicity; and
- Potential approaches to managing or mitigating risks.

A pre-requisite for achieving these goals is to obtain baseline data on natural seismicity (NRC, 2012). These data are needed to to help distinguish induced seismic events from those that occur naturally. This baseline data should include the frequency, locations (including depths and geographical coordinates) and magnitudes of natural earthquakes. The relationship between natural seismicity geological structures, such as faults and fracture zones, should also be established. Thus, it is required to obtain results from long-term seismic monitoring, such as those obtained by a regional network of seismometers, and detailed geological information, such as those obtained from surface mapping, borehole investigations (including rock core and wireline studies) and surface seismic investigations are needed.

Information concerning the natural stress state of the rocks into which $CO_2$ is to be injected, and the surrounding rocks, is also required (NRC, 2012). These data include both the magnitudes and orientations of the stresses. These data can be acquired by various methods, including:

- Examining rock deformation (breakouts) around boreholes and any underground excavations that exist in the area being considered for $CO_2$ storage (NRC, 2012);
- Analysing records of past natural seismicity (NRC, 2012); and
- Carrying out direct geological observations, such examining deformation along faults (which can indicate the orientation of stresses) (NRC, 2012).

Pore pressure measurements in the rock formation into which $CO_2$ will be injected are also required . This information can be obtained by direct testing carried out in boreholes. Generally this testing takes the form of closing off a section of borehole within packers and then admitting water from the formation to the sealed off section. The pressure of this fluid is then measured.

In order to predict the pore pressure evolution during $CO_2$ injection, it is also required to determine the spatial extent (areal extent and thickness) and petrophysical properties of the proposed $CO_2$ storage reservoir and surrounding rock formations. In particular the permeability of the rocks and the distribution of this permeability is required, as well as the mechanical properties of the rocks (elastic moduli etc). These properties can be measured directly in rock core samples and / or estimated from seismic survey data.

Natural subsurface temperature data are also needed in recognition of the fact that fluid densities are temperature-dependent and there is a coupling between temperature and pressure. Additionally, rock formations into which $CO_2$ will be injected could be at a significantly higher temperature than the injected $CO_2$, leading to the possibility that thermal shock could contribute to induced seismicity. Temperature data can be obtained from wireline observations in boreholes.

Chemical data for pre-existing porefluids and mineralogical data for the rocks, both in the $CO_2$ storage reservoir an in the surrounding rock formations, are also needed. At the least total salinity data should be obtained for pre-existing porewaters since this influences the density of the waters, and hence the sub-surface pore pressures. Information about the water chemistry and the rock mineralogy can be used to predict the likelihood that the injection of $CO_2$ will lead to chemical reactions that modify the petrophysical properties of the rock, and hence the likelihood of induced seismicity. Chemical data for porefluids can be obtained by sampling boreholes whereas mineralogical data can be obtained from rock core or rock cuttings obtained from boreholes and / or, to some extent estimated from wireline geophysical data.

Based on these various kinds of information, a site should be screened initially using a bounding analysis that is broadly similar to a typical detailed risk assessment, but emphasising qualitative or semi-quantitative approaches (Majer et al. 2012). A pre-requisite is an understanding of the criteria by which unacceptable risks of induced seismicity could be recognized (Majer et al. 2012).

In order to determine the risks that could arise from any induced seismicity that occurs, site characterisation should also identify and characterise any potentially impacted spatial domains where there are sensitive human populations, ecosystems, resources (e.g. groundwater resources), or other assets (e.g. structures such as dams) (NRC, 2012). Outputs of this activity should be (Majer et al. 2012):

- A map showing the ground motions that might be caused by any induced seismic event, and the frequency at which these events might occur;
- A description of induced seismic effects (both direct and indirect) that could constitute nuisances;
- A statement of the impact levels perceived to be safe by the stakeholders (regulators, community, operator, etc.)

an estimate of the number of people, institutions, and industries located in the region that might be exposed to any impact of concern, the expected frequency of occurrence, and possible mitigation measures.

# 5. Storage Engineering

**Key Messages:**

- The likelihood that induced seismicity will occur during $CO_2$ injection, and the associated risks if it does, can be minimised by appropriate engineering of the storage site.
- As far as practicable this engineering should ensure that the injected $CO_2$ avoids pre-existing structures that are judged at risk of being caused to move and also minimise the perturbation to in-situ stresses.
- The characteristics of engineering that are needed will depend upon the nature of a particular storage project and the legal, regulatory and political / social context within which it is carried out.
- Site characterisation is a process that should commence prior to the injection of $CO_2$, but continue throughout the lifetime of a project, during $CO_2$ injection and likely thereafter during a period of monitoring.

The likelihood that induced seismicity will occur during $CO_2$ injection, and the associated risks if it does, can be minimised by appropriate engineering of the storage site. As far as practicable this engineering should ensure that the injected $CO_2$ avoids pre-existing structures that are judged at risk of being caused to move and also minimise the perturbation to in-situ stresses. The characteristics of engineering that are needed will depend upon the nature of a particular storage project and the legal, regulatory and political / social context within which it is carried out. Relevant characteristics of the storage project are the volumes of $CO_2$ to be stored and the rates at which it should be injected, the geographical location of the storage site (e.g. whether on-shore or off-shore) and the geological of the storage reservoir and surrounding rocks.

Generally there are two main aspects of engineering associated with $CO_2$ storage:

- Well engineering, which can be illustrated by regulatory requirements on wells of various kinds in the U.S.A. (NRC, 2012); and

- Reservoir engineering, which can be illustrated by oil industry practices, including secondary and tertiary oil recovery (NRC, 2012).

The first of these aspects concerns the overall design of the well bore (whether vertical, deviated, inclined, its width, length and orientation etc) and the engineered materials emplaced within it (nature of casings, casing cement, cement seals, perforated zones in the casing etc). Reservoir engineering covers all the measures taken to manage optimally the sub-surface fluid flow within a reservoir and petrophysical properties of the reservoir. These measures include appropriately siting boreholes for the injection and abtraction of fluids and optimally extracting fluids so that reservoir pressures are managed effectively thereby causing sub-surface fluids to migrate in a desired fashion (e.g. to prevent $CO_2$ migrating in an undesirable direction). It may also be possible to design and site the injection wells to minimise the potential consequences of any induced seismicity that does occur. For example this can be done by maximising the distance between the injection location and potentially impacted sensitive spatial domains (e.g. human populations, structures, ecosystems or natural resources).

Regulations for well engineering vary according to jurisdiction. However, in most countries there is a requirement for wells to be engineered so as to protect sub-surface assets such as groundwater resources. For example, under the USEPA’s Underground Injection Control (UIC) Programme, wells intended for disposal of Oil and Gas related water (Class II wells according to the USEPA’s designation) are required to be cased and cemented to prevent movement of fluids into or between underground sources of drinking water (NRC, 2012). $CO_2$ storage wells must have surface casing that extend through the base of the lowermost underground source of drinking water (USDW). This casing must be cemented to the surface by using a single or multiple strings of casing and cement. Furthermore, at least a single long casing string must extend to the injection zone. This string must be cemented by circulating cement to the surface in one or more stages. Injection of $CO_2$ must take place through tubing within a packed-off section of borehole with cemented casing.

# 6. Safe Operation

**Key Messages:**

- Appropriately designing the storage operations from the onset minimises the chances that any induced seismicity will impact adversely upon any spatial domains.
- Appropriately designing the storage operations from the onset helps to ensure that porefluid pressures will not rise to levels likely cause induced seismicity.
- Managing the pressure within the reservoir should be by a combination of fluid withdrawal and / or injection, since a large body of evidence shows that induced seismicity will be correlated with pore pressure.
- Changing the locations at which $CO_2$ is injected is important for safe operations.

One important aspect of the safe operation of a $CO_2$ storage site is to minimise the likelihood of induced seismicity occurring and the potential adverse consequences of such seismicity should it occur. That is, sites should be operated to reduce or eliminate (where possible) the factors that give rise to risks (NRC, 2012). These objectives can be achieved by means of:

- Appropriately designing the storage operations from the onset to minimise that chances that any induced seismicity will impact adversely upon any spatial domains (e.g. human populations, ecosystems, natural resources or structures), for example by maximising as far as possible the distance between $CO_2$ injection and these sensitive domains (NRC, 2012);
- Appropriately designing the storage operations from the onset to ensure that porefluid pressures will not rise to levels likely cause induced seismicity (NRC, 2012), and to prevent $CO_2$ from approaching geological structures that are judged to have potential for stimulation, thereby causing induced seismicity (NRC, 2012);
- Continuously modifying $CO_2$ injection operations to ensure that porefluid pressures and the spatial distribution of the injected $CO_2$ continue to minimise the likelihood

and risk of induced seismicty, in the light of $CO_2$ injection data (volumes and rates) and monitoring results, which could include:

- Monitoring the location of the injected $CO_2$ in relation to any geological structures that are thought to have potential for stimulation, thereby causing induced seismicity;
- Records of micro-seismic activity;
- Porefluid pressures; and
- Geomechanical measurements (e.g. surface uplift and its location relative to geological structures that are thought to have potential for stimulations, thereby causing induced seismicity).

The precise operational variations that are made to minimise the hazard and risk of induced seismicity are likely to be one or more of:

- Reducing the rates at which $CO_2$ is injected (or ceasing $CO_2$ injection altogether if an unacceptable risk of induced seismicity arises), as can be illustrated by experience with waste water injection and EGS (NRC, 2012);
- Reducing the total volume of $CO_2$ that it is stored, since evidence from a wide range of activities shows a correlation between volumes of fluid injected and induced seismicity (NRC, 2012);
- Managing the pressure within the reservoir by a combination of fluid withdrawal and / or injection, since a large body of evidence shows that induced seismicity will be correlated with pore pressure (NRC, 2012)(this may include removing formation water from the reservoir, or adding formation water to the reservoir and may involve using existing wells and / or drilling additional wells);
- Changing the locations at which $CO_2$ is injected (which may involve drilling new injection wells or extending existing wells), since:
  - The depth and distance of a surface point from potentially impacted sensitive domains will influence the potential impacts (NRC, 2012); while

  - The distance between the injected fluid and geological structures that might be stimulated will influence the likelihood of seismicity being induced (NRC, 2012).

The operational plans must be based on robust assessments of the seismic hazard and the assessed risk of induced seismicity (NRC, 2012). These assessments should be incorporated into the wider hazard and risk assessments that will be undertaken during any $CO_2$ storage project. Such assessments should be undertaken before the start of $CO_2$ storage and subsequently at intervals throughout the period of $CO_2$ injection. The intervals at which the induced seismic hazard and risk assessments are undertaken will depend upon:

- The timing of new information becoming available (normally a new hazard and risk assessment would be undertaken only when new information make this worthwhile);
- Legal and regulatory requirements;
- The needs of the various stakeholders (e.g. it might be necessary to undertake new hazard and risk assessments to build confidence among a local population that $CO_2$ storage will not induce seismicity).

The operations that are permitted will depend upon the legal, regulatory and social / political framework under which storage is undertaken. However, many jurisdictions are likely to regulate the $CO_2$ injection in ways that would minimise the risk from induced seismicity. For example, for $CO_2$ storage in the U.S.A regulations require that, except for stimulation, injection pressure should not exceed 90% of the fracture pressure. More generally, the pressure of fluid injection connected with oil and gas operations should not cause fracturing or propagation of existing fractures. Additionally the UIC regulations of the USEPA prohibit fluid injection between the casing and the wellbore.

There are also likely to be also be additional regulations that affect operations in order to prevent risks other than those of induced seismicity, but which, when implemented, will nevertheless tend to decrease the risk of induced seismicity. For example, regulations may be designed to prevent contamination of drinking water. The operations required to meet these regulations (e.g. ensuring wells are appropriately cased and porefluid pressures are appropriately managed) may well help to reduce the risks from induced seismicity.

# 7. Monitoring

**Key Messages:**

- Most jurisdictions require that stored $CO_2$ and the surrounding rocks are monitored, from the onset of storage until some period has elapsed after storage operations have ceased.
- Seismic monitoring should be stared as soon as possible after a $CO_2$ storage site is selected, but should in any case be undertaken for a period prior to the commencement of injection
- Depending upon the $CO_2$ storage location, there may be an existing regional seismic network that is sufficient for initial seismic monitoring.

Most jurisdictions require that stored $CO_2$ and the surrounding rocks are monitored, from the onset of storage until some period has elapsed after storage operations have ceased. The precise length of this post-injection period will depend upon the particular jurisdiction. According to most developing legal and regulatory frameworks, operators of $CO_2$ injection projects will usually be required to submit a monitoring plan to regulators prior to the start of the project. Most likely the monitoring plan will evolve as a project proceeds to take into account new information, developing legal and regulatory requirements and changing stakeholder concerns. However, a general principle is that monitoring will in practice need to be prioritized according to the risks that may arise from a project. Therefore, these plans will need to be based upon suitable hazard and risk assessments (NRC, 2012; Majer et al. 2012).

The monitoring plan will need to include induced seismicity (Majer et al. 2012). For example, in the U.S.A. protocols that have been proposed to address induced seismicity include the development of monitoring plans (NRC, 2012). It is noteworthy that experience from fluid injection and withdrawal operations other than $CO_2$ storage suggests that potentially induced seismicity could continue for a substantial time following the end of $CO_2$ injection (NRC, 2012). Hence, it will be necessary to monitor induced seismicity until it is certain that there is no significant remaining possibility of further induced seismicity.

Phenomena that are relevant to assessing hazards and risks associated with induced seismicity and that should be monitored are (NRC, 2012):

- The spatial distribution of the injected $CO_2$ plume and particularly its location relative to geological structures such as faults that are judged to have potential for stimulation (NRC, 2012);
- Porefluid pressures (NRC, 2012);
- Seismicity (including micro-seismicity) (NRC, 2012; Majer et al. 2012); and
- Mechanical deformation of the $CO_2$ storage reservoir and surrounding rocks (including variations in surface elevations) (NRC, 2012).

In addition it is important that accurate records are maintained of the volumes of stored $CO_2$, the rates at which the $CO_2$ was injected and the timing of injection (NRC, 2012). These records are essential in order to interpret the monitoring data, for example by establishing whether there is any correlation between the rate of $CO_2$ injection and seismic events. Such correlations are required in order to distinguish natural seismicity from induced seismicity.

Seismic monitoring should be stared as soon as possible after a $CO_2$ storage site is selected, but should in any case be undertaken for a period prior to the commencement of injection (NRC, 2012). The seismic monitoring should be sufficiently comprehensive to allow baseline seismicity to be established within an area that is considerably larger (e.g. 2 x) than the area over which the $CO_2$ plume is expected to extend. The instrumentation should be able to detect seismic events at least as small as magnitude 1.0 and preferably to magnitude 0.0.

Depending upon the $CO_2$ storage location, there may be an existing regional seismic network that is sufficient for initial seismic monitoring. For example, in the U.S.A. there is the National Earthquake Information Centre (NEIC) regional network (NRC, 2012).

However, probably it will be necessary to establish a local seismic network around the $CO_2$ storage site (NRC, 2012). The density and location of instruments will depend to some extent on whether induced seismicity is suspected. If so, the instruments may be deployed appropriately to investigate the suspected seismicity.

Microseismic monitoring can be undertaken to measure earthquakes that are many orders of magnitude smaller than those that are sensible to humans (NRC, 2012). Microseismicity is thought to be due to small displacements of pre-existing microfractures, caused by increased porefluid pressures. Microseismic data is obtained by using either an array of seismic instruments in one or several wellbores, or with a large number (perhaps 100 to >1000) geophones at or near the ground surface. The acquired data can be processed to locate the microseismic events precisely both temporally and spatially and to estimate parameters such as seismic moment, magnitude and moment tensors.

## 8. Remediation Methods

**Key Messages:**

- Remediation methods refer to the methods by which any adverse impacts due to induced seismicity as a result of $CO_2$ storage could be rectified
- Most jurisdictions will require an operator of a $CO_2$ storage site to develop a plan to prevent or minimise undesirable consequences in the eventuality that storage does not proceed as planned
- Technical approaches to remediation aim to prevent a recurrence of induced seismicity or minimise the intensity and / or impacts of future induced seismicity.
- Non-technical approaches to remediation aim to rectify any damage caused by induced seismicity.

In this report remediation methods refer to the methods by which any adverse impacts due to induced seismicity as a result of $CO_2$ storage could be rectified. The term “remediation” is closely related to “mitigation”, which covers actions taken to stop the adverse impacts from occurring; in this case it refers to actions taken to prevent further induced seismicity after an incident of induced seismicity has been confirmed. Here, “mitigation” is considered together with “remediation”.

Most jurisdictions will require an operator of a $CO_2$ storage site to develop a plan to prevent or minimise undesirable consequences in the eventuality that storage does not proceed as planned. Such plans will need to cover the possibility that induced seismicity will occur. It follows that they will need to be based upon suitable hazard and risk assessments (NRC, 2012; Majer et al. 2012).

An example of such a remediation / mitigation plan and its place in an overall protocol for addressing induced seismicity was proposed by the NRC in the U.S. (NRC, 2012), based on a protocol developed by the United States Department of Energy (USDOE) to address induced seismicity associated with EGS (NRC, 2012; Majer et al. 2012). Usually the plan will need to be presented to regulators as part of the licensing process (i.e. prior to injection being started). However, the plans will normally evolve during the course of a project, to take into account new information that is acquired, evolving legal and regulatory circumstances and the requirements of stakeholders, in particular local populations.

Requirements for remediation cannot be predicted a priori from estimates of the plausible magnitudes of induced seismicity. This is because the impacts will depend upon a wide range of site-specific factors depend, such as the distance between the location where seismicity is induced and the impacted domain.

There are two groups of approaches to remediation:

- Technical approaches, which aim to prevent a recurrence of induced seismicity or minimise the intensity and / or impacts of future induced seismicity;
- Non-technical approaches, which aim to rectify any damage caused by induced seismicity.

The first group of approaches essentially involves changing $CO_2$ injection plans appropriately. Most likely $CO_2$ injection rates would be decreased or $CO_2$ injection would be stopped altogether. This latter course of action was taken in an EGS project in Basel in Switzerland (NRC, 2012). In waste water wells, reducing the rates and volumes of water injection has been shown to reduce the frequency and intensity of induced seismicity (NRC, 2012). However, depending upon the nature of the site it may also be possible to prevent adverse effects from induced seismicity by changing the location or depth of injection (NRC, 2012). Even where $CO_2$ injection needs to stop, it may be possible to re-commence injection at a lower rate after a suitable period has elapsed to allow reduced seismicity to diminish to an acceptable level. What level is acceptable will normally need to be agreed between the site operator, regulatory agencies and other stakeholders, in particular local populations.

Best practice protocols should be developed to ensure that mitigation and remediation is carried out appropriately (NRC, 2012). In the U.S.A it has been proposed that checklists and a “traffic light system” should be adopted to help mitigate the effects of induced seismicity (NRC, 2012). Such a system would specify a set of criteria that would trigger remediating mitigating actions. For example a “traffic light” system can allow operations to continue (green), or require changes in the operations to reduce the seismic impact (amber), or require a suspension of operations (red) to allow time for further analysis.

The second group of approaches to mitigation will include community support and compensation (NRC, 2012). To work these approaches will require a high degree of dialogue between site operators, regulators and other stakeholders, in particular local people (Majer et al. 2012). To provide appropriate compensation there needs to be a mechanism for establishing that any damage has been caused by induced seismicity. Experience at the Geysers geothermal development in California illustrates how this approach may operate in practice (NRC, 2012). Here the operator of the geothermal plant, regulators and local people have developed a system of receiving, reviewing and approving damage claims attributed to induced seismicity. During the last 6 years the geothermal operators have compensated homeowners for the damages caused.

## 9. Regulatory Oversight

**Key Messages:**

- Depending upon the jurisdiction there may be multiple agencies that regulate $CO_2$ storage in different places and / or circumstances
- Depending upon the jurisdiction, different activities that may induce seismicity will be regulated in different ways.
- A potential issue for regulators occurs where there are several $CO_2$ storage site operators and / or other underground activities unrelated to $CO_2$ storage in a particular area as it may prove difficult or impossible to prove responsibility for any induced seismicity that occurs.

No regulations have been identified that are specific to induced seismicity connected with $CO_2$ storage. However, insights into the regulatory issues concerned can be gained from regulations concerning other aspects of underground fluid injection or withdrawal.

For example, in the USA at a Federal level there are regulations focussed on groundwater protection that are relevant, while local regulations concerning groundwater protection have been applied to induced seismicity concerning other kinds of underground fluid injection and withdrawal.

Generally the agency that is authorised to permit new $CO_2$ injection permit or to revise an existing injection permit is the most appropriate agency to oversee decisions made about activities that may induce seismicity. However, usually a number of parties will have an interest in regulatory oversight to a greater or lesser degree (NRC, 2012), depending upon the nature of the jurisdiction in which $CO_2$ is stored. For example in the USA, interested parties are:

- Land owners / mineral rights owners;
- State governments;
- National governments; and
- Regulatory agencies.

Of course land owners and mineral rights owners have an interest in effective regulatory oversight in order to protect their personal safety, safety of their material assets and economic interests. However, there may also be a contractual relationship between the owners of land and / or mineral rights and the operator of a $CO_2$ injection site. The owner of the land or mineral rights may agree to an operator storing $CO_2$ within their land or the area covered by their resource. In this case the terms of the contract could specify certain conditions on storage. Typically there will need to be mechanisms established by the contracting parties to ensure that there is adherence to the terms of the contract.

Depending upon the jurisdiction there may be multiple agencies that regulate $CO_2$ storage in different places and / or circumstances (NRC, 2012). For example, in the USA, the US Bureau of Land Management (BLM) is responsible for licensing injection on land owned by the federal government land (NRC, 2012). The United States Forest Service (USFS) fulfils a similar function in areas designated as national forests (NRC, 2012). The licenses place restraints on what operators may or may not do. In contrast the United States Environmental Protection Agency (USEPA) is responsible for ensuring that groundwater resources are not contaminated by $CO_2$ storage operations, but does not regulate induced seismicity explicitly (NRC, 2012). In addition to these federal agencies, each state has its own local agencies that will regulate $CO_2$ storage.

While not a regulatory agencies, in the USA, the United States Geological Survey (USGS) and local state geological surveys play important roles in regulation because they provide basic geoscientific information that can be used by regulators (NRC, 2012). Of particular relevance to the potential future regulation of induced seismicity is the fact that USGS is the sole federal agency with responsibility for recording and reporting earthquake activity worldwide. Consequently it is frequently asked to assist state agencies to investigate possible induced seismicity.

Again, depending upon the jurisdiction, different activities that may induce seismicity will be regulated in different ways. For example, in the USA a distinction is made between fluid injection and fluid withdrawal. The USEPA, BLM, USFS and state agencies regulate fluid injection, but fluid withdrawal is unregulated. States require permits to drill wells and inject fluids, but not to extract oil and gas. These differences are significant because in the USA waste water injection and fluid withdrawal during secondary oil recovery both appear to induce roughly equal numbers of seismic events. This implies that the present regulatory regime may not cover induced seismicity adequately.

A potential issue for regulators occurs where there are several $CO_2$ storage site operators and / or other underground activities unrelated to $CO_2$ storage in a particular area. In such cases it may prove difficult or impossible to prove responsibility for any induced seismicity that occurs. Furthermore, where several differing activities that may induce seismicity occur in a single area (e.g. $CO_2$ storage and adjacent hydrocarbon extraction) potentially different regulatory authorities may be involved. These authorities may employ different approaches to regulate the different activities. Thus, in such cases there will be a need for different regulators to work together to ensure consistent regulation and for the clear responsibilities to be among different operators to be established. Agreement of these responsibilities may be an opportunity for regulation of $CO_2$ injection in such a way as to reduce the risk of induced seismicity. Lessons for regulators can be drawn from the so-called “unitization” of hydrocarbon assets in the U.S.A (NRC, 2012).

Potentially regulation of $CO_2$ injection to minimise the risks from induced seismicity could employ a so-called “traffic light system” (NRC, 2012). An example of such a system is the one employed in the U.S.A by the BLM to regulate the development of EGS (NRC, 2012). Hydraulic fracturing is allowed to proceed (green light) if it does not cause ground motion with an intensity in excess of Mercalli IV “light” shaking (an acceleration of less than 3.9%g, where g is the acceleration due to gravity), at a location of concern to the public. However, if ground accelerations range between 3.9%g and 9.2%g repeatedly, which is equivalent to Mercalli V “moderate” shaking, then hydraulic fracturing is required to be reduced in scale (yellow light) to diminish the potential for repeated seismic events. If the operation ground acceleration greater than 9.2%g, resulting in “strong” Mercalli VI or more severe shaking, then hydraulic fracturing is required to cease immediately (red light).

## 10. Legal and Financial Responsibility

**Key Messages:**

- Most commonly the liability for losses caused by induced seismicity will lie with the responsible operator of the injection operations.
- In many jurisdictions, in order for a $CO_2$ storage site operator to be held liable for injury or losses due to induced seismicity, it is likely that a plaintiff must establish a relationship of cause and effect between the induced seismicity and the damage to the suffered
- Any judgement of negligence is an assessment of risk and the results of an appropriate risk assessment, based on a proper site investigation and suitable monitoring, are required to develop risk mitigation plans

Legal and financial responsibility for any seismicity that might be caused by $CO_2$ storage will vary to some degree between different jurisdictions. However, most commonly the liability for losses caused by induced seismicity will lie with the responsible operator of the injection operations. Here, general principles that are likely to determine legal and financial responsibility are overviewed, based on examples from U.S. tort law.

In the many $CO_2$ storage projects it is likely that there could be several responsible persons or organisations. Examples of this joint responsibility are frequent in the hydrocarbon industry (NRC, 2012). In such a case the proportionate liability of the different parties will need to be established (Cysper and Davis, 1998). In cases where a $CO_2$ storage site operator enters into a contract with a land owner or mineral rights owner to permit $CO_2$ storage, the contract may well specify liabilities for induced seismicity. However, the contractual position may be complex because different rights to a piece of land may have different owners. For example, in the U.S.A these rights are termed “estates of land” and can include ownership of the surface and ownership of minerals rights etc.

Again depending upon the jurisdiction the liability for damage caused by induced seismicity could be based on several of one or more legal theories (Cysper and Davis, 1998) . In the U.S.A for example, liability may be on the basis of trespass, strict liability, negligence or nuisance. In this latter case, there may be liability even if no physical damage occurs, as mighr be the case, for example, if a person suffers stress as a consequence of induced seismicity (Cysper and Davis, 1998). Under U.S. law induced seismicity caused by $CO_2$ storage could be deemed a private nuisance if it is an “unreasonable interference with the use and enjoyment of real property”.

An operator of a $CO_2$ storage site may also be deemed liable if induced seismicity accelerates the failure of support for another activity, which then leads to that other activity causing losses to a third party (Cysper and Davis, 1998). In such a case, the operator of the $CO_2$ storage site and the operator of the other activity could be held proportionally liable to the injured parties. In most states of the U.S.A owners of land have a duty to maintain lateral support to adjacent landowners. Additionally in some states, mineral estate owners and lessees also have a duty of support to surface owners, if these are different.

In countries with legal systems based on English Common Law, such as the United States and Canada, there will be no liability to an operator if a phenomenon that causes loss or injury is judged to be an “act of God” (Cysper and Davis, 1998). That is, if the injurious phenomenon occurs within the spatial domain for which a $CO_2$ storage operator is responsible, but is without human influence (e.g. a natural earthquake), then the operator will not be deemed liable. However, if the operator is deemed to have taken actions that exacerbate the adverse effects of the natural phenomenon, then the operator may be held liable.

In many jurisdictions, in order for a $CO_2$ storage site operator to be held liable for injury or losses due to induced seismicity, it is likely that a plaintiff must establish a relationship of cause and effect between the induced seismicity and the damage to the suffered (Cysper and Davis, 1998). In the U.S.A, courts must limit the scope of liability, typically by restricting the length of a chain of causation that may be considered, or by testing whether liability should be applied to a particular cause out of many contributing causes.

Another potential basis for liability is trespass (Cysper and Davis, 1998). In the U.S.A a plaintiff need show only that someone or something controlled by someone, has disturbed their property. This disturbance could occur in the sub-surface or the surface and potentially could simply be the vibrations caused by induced seismicity.

Negligence may also be a reason for liability being apportioned (Cysper and Davis, 1998). In the U.S.A. courts are likely to establish whether damage due to induced seismicity has been caused negligible based on an assessment of: whether there was a foreseeable risk of harm; precautions have been taken to avoid that harm; a standard of care; and the damage due to failing to meet that standard. Nevertheless, when engaging in activities deemed to be "abnormally risky" liability for any damage caused may be assigned to a site operator, even if the damage did not arise through negligence

Thus, implicit in any judgement of negligence is an assessment of risk (Cysper and Davis, 1998). The results of an appropriate risk assessment, based on a proper site investigation and suitable monitoring, are required to develop risk mitigation plans. Potentially, failure to carry out these activities could be viewed as negligence by a court of law.

## 11. References

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