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Monitoring and verification of geological and ocean carbon dioxide disposal

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Through all of the noise of natural variation, the evidence of anthropogenic influence on climate is becoming clear. Vast challenges remain in refining the science, but the questions are increasingly shifting from 'if' to 'when, and how much'. Meanwhile, even as the problem comes into sharper focus, we are faced with political stagnation and ever-rising greenhouse gas emissions. Seeking a way through the stand-off between the entrenched powers of the present day and impending ecological disaster, some have proposed 'engineering' solutions to climate change. Among them is capturing carbon dioxide from combustion and disposing of it in subsurface geological formations and the oceans.[1] While the solution seems attractive to many people (including those in the fossil fuel industry), the long-term environmental benefits have yet to be proved.

Whether they can be proved through monitoring and verification is indeed one of the sticking points of the whole concept.

The context for capture and disposal

The primary culprit in anthropogenic climate change is carbon dioxide (CO_2) emitted from the combustion of fossil fuels such as coal, oil and natural gas. Between 1751 and 2000, total world carbon emissions from fossil fuel combustion were approximately 277 gigatonnes of carbon (GTC).[2] Currently some 6.5 GTC are emitted annually to the atmosphere, of which about 3.3 GTC are retained in the atmosphere.[3] As a result, the concentration of CO_2 in the atmosphere has risen from around 280 parts per million by volume (PPMV) prior to the industrial age to approximately 368 PPMV in the year 2000.[4] It is estimated that a rise to 450 PPMV could mean a global temperature rise of 2°C.[5] Even this level of warming would produce serious impacts,[6] but it may well be at the lower end of the range of achievable levels given current trends.

Given that approximately 4,000 GTC of accessible fossil fuel reserves still remains in the ground—the vast bulk of it as coal rather than oil or gas—there is more than enough carbon available to cause serious damage to the global climate. The reluctance of major emitters such as the United States to engage seriously in limiting emissions, the desire of developing countries to spur economic growth by developing emitting industries,[7] and overall rising standards of luxury are all reasons for concern about the prospects for reining in emissions.

The realisation that avoiding climate change would not be easy struck home in the early 1990s. The United Nations Framework Convention on Climate Change (UNFCCC), agreed in 1992, exhorted parties to limit their emissions but resulted in little action.[8] The result was the negotiation of the 1997 Kyoto Protocol—a framework for a binding agreement with clearly defined targets to reduce emissions in five-year increments.[9] The first five-year increment, or 'commitment period', would be from 2008 to 2012. Greenhouse gas (GHG) emissions from industrialised countries would be reduced by 5 percent below 1990 levels.[10]

As parties began considering their options in order to meet this goal, it became clear that what many envisioned as the 'obvious' answers—wasting less energy, switching from fossil fuels to renewable energy, promoting public transport—were going to meet challenges from traditional polluting industries wishing to retain their dominant position. The initial reaction was largely to denounce global warming as an unsubstantiated environmentalist fad. Facing mounting scientific evidence to the contrary, however, these industries began to look for mitigation options—preferably such as would keep them in business. Among the most promising concepts has been geological and ocean carbon dioxide disposal. Geological and ocean disposal means basically taking the CO_2 from power plants and putting it in the ground or deep in the sea. While this idea is conceptually attractive to industry because it will allow it to continue using fossil fuels, it brings with it a host of challenges and problems—technical, financial and environmental.

At present, the cost of separating CO_2, either from flue gases or prior to combustion, is prohibitively high for anything but specialised applications such as natural gas purification. The immediate challenge to a carbon-constrained world is therefore to motivate industry to research capture options intensively and bring costs down—a challenge that is being met with some success. Among the options for geological disposal sites—aquifers, oil and gas fields, and coal beds—there is usually one fairly close to most power plants. It is estimated, for example, that some 65 percent of power plants in the US are located close to a saline aquifer.[11] Power plants are also commonly sited in coastal areas, making the oceans a tempting disposal option.

Still, the existence of potential disposal sites and the cost of achieving disposal are only part of the picture when the future role of the concept is considered. Its ultimate contribution to the mitigation of emissions will depend on a much more detailed understanding of the appropriateness of disposal sites in two regards: (a) local environmental impacts and safety, and (b) the long-term effectiveness of disposal. Assessment of both of these will depend in large measure on effective monitoring and verification.

Monitoring and verification of disposal sites will probably be technically complex and demanding: while the fossil fuel industry has extensive experience in subsurface geology and engineering, for example, it still faces the challenge of dealing with a new substance with different physical and chemical characteristics from hydrocarbons—CO_2—and a new paradigm—injecting for the long term rather than extracting in the short term. As a commercial operation, CO_2 injection will also have to be affordable, and may well come up against an unwillingness to expend the resources to monitor and verify accurately, and a reluctance to act on findings of leakage, soil acidification, fish kills or similar unwanted side effects.

Capture and disposal: a brief overview

Capture and disposal options range in sophistication from collecting CO_2 from a smoke stack and putting it in a hole in the ground to using advanced chemical and combustion techniques that represent a significant change in the way power plants work.

Capture

The most basic CO_2 capture technique is post-combustion capture from flue gases. These typically contain only 5–20 percent CO_2, so capturing significant quantities is difficult and energy-intensive. The most developed technique is to filter flue gases through alkanolamines, which absorb CO_2 selectively. When subjected to the right changes in temperature and pressure, the CO_2 is released and collected for disposal. Alternatively, the flue gases can be brought into contact with substances like zeolites that adsorb CO_2 on their surface. Finally, gases can flow past membranes that selectively allow CO_2 to pass through. Usually several stages are needed to reach desired levels of purity.

An ancillary technique is to enhance the level of oxygen in combustion to yield a purer stream of CO_2 in the flue gases, which makes the CO_2 much easier to separate. While this has the disadvantage of requiring a source of oxygen, in itself a challenge, it can yield CO_2 concentrations of up to 90 percent.

Perhaps the most conceptually elegant solution is to avoid CO_2 being produced by combustion in the first place. This can be achieved by subjecting the hydrocarbon fuel—coal, oil or gas—to a process which breaks it down chemically and separates it into two streams: hydrogen, which may be used to power an engine or a fuel cell, and CO_2, which is collected and disposed of.

Disposal

Some two-thirds or more of the cost of capture and disposal can be ascribed to capture, and there are serious concerns about the energy used in the process that may challenge its widespread adoption. But, although capture faces real technical and financial barriers, the solutions lie in the controlled realm of engineering. Disposal, on the other hand, releases CO_2 into the natural environment, where it is exposed to the vagaries of natural processes that are difficult to predict. The long-term effectiveness and short-term risks are a matter of complex conjecture.

One potential method of disposal is a process known as enhanced oil recovery (EOR), of which the operators of oil fields have considerable experience. For 30 years, particularly in North America, CO_2 has been injected into oil-bearing formations to increase pressure behind the oil and force it towards wells, also making it less viscous and thereby improving flow. The impact can be dramatic, increasing yields by between 5 percent and 50 percent above initially recovered amounts. The CO_2 used in this process is mainly mined from underground sources but, because EOR has economic value, the cost of capturing anthropogenic CO_2 for use in EOR would be offset somewhat, making it one of the first likely options for widespread disposal.

From a monitoring and verification standpoint, EOR has several distinct advantages. First, it occurs in formations for which the geology is well documented thanks to petroleum industry activity; in these areas wellbores are available to mount monitoring equipment; and machinery and manpower, including personnel experienced in environmental health and safety precautions, are at hand. There are also two main disadvantages. First, by its nature, EOR will recover a certain amount of CO_2 as it pumps up the oil that has been pushed towards the wells and this has to be dealt with properly to avoid release; it is only once the EOR operation stops and the wells are sealed that long-term storage begins. Second, while the proximity of petroleum industry operations can be an advantage, in places with a long history of drilling it is possible that wells with degraded seals will allow escape routes for disposed CO_2. Texas alone has some 1,500,000 oil and gas wells.[12]

A second technique that offers economic returns is enhanced coal-bed methane extraction (ECBM). Coal seams contain methane, which can be drilled for and pumped out in much the same way as oil or gas. CO_2 injected into the seam will replace the methane that adheres chemically to the surface of the coal, simultaneously increasing production while locking the CO_2 into the coal bed. For each methane molecule release, two molecules of CO_2 adhere to the surface. ECBM theoretically represents a chance for secure storage with economic returns.

In practice, however, there are limitations to the ability to inject CO_2 into coal without clogging pores around the well, while increased pressure may cause fracturing. Sometimes coal beds are intentionally fractured to facilitate the collection of methane, but this may create escape pathways for CO_2. Given that some relevant coal beds are relatively shallow and not sealed by thick layers of rock, there may be less certainty about the long-term containment of CO_2 if it fails to adhere successfully to the coal.[13]

A third possibility is storage in saline (brine, salty water) aquifers. These offer the greatest potential of any type of geological storage site in terms of volume. Injected to depths of over 800 metres, CO_2 enters a liquid-like 'supercritical' state,[14] allowing condensed storage. Naturally more buoyant than salt water, it must be kept down by thick layers of impermeable caprock above the storage formation. Over time it may dissolve and sink in the water, or partially react with rock and mineralise. Crude estimates show that globally saline aquifers could accommodate 50–200 times the amount of fossil fuel emissions predicted in the coming 50 years. How much of this volume would be well sealed or accessible and how much of the potential aquifers would be economic to use is still under study, however.

Compared to EOR as a disposal method, aquifer storage offers some advantages. Potential storage volumes are larger, they are not limited to hydrocarbon-bearing areas, and they are less frequently penetrated by wells, which may become sources of leakage. The main disadvantage is that they have never been commercially exploited and geological information about specific sites is therefore far more limited than the information for oil and gas fields.

Fourth, in principle the oceans offer a tempting sink for captured CO_2. After all, they already contain 40,000 GTC, and there is a natural air–ocean exchange of 90 GTC a year, of which 2 GTC is retained in the oceans.[15] Because CO_2 emitted from power plants enters the atmosphere and most of it eventually enters the ocean anyway, proponents of ocean CO_2 disposal like to say that they would just be speeding up a natural process.

The primary concern with this approach is that concentrated CO_2 releases in the ocean will cause acidification and potential ecological damage. The challenge of monitoring and verifying emissions is another major impediment. The oceans are naturally in constant flux, and determining what happens to a given amount of injected CO_2 in the long run can only be estimated by modelling. While deeper injection should tend to delay release to the surface significantly, unanticipated shifts in upwelling (perhaps due to climate change itself) could nullify the advantage. Given this uncertainty, the acidification problem and the fact that international law proscribes it,[16] the environmental community has been particularly sceptical about this option and political pressure has so far forced the cancellation of proposed pilot projects.

Monitoring and verification of CO_2 disposal

Each kind of CO_2 disposal presents its own challenges from a monitoring and verification standpoint, but the principles for each are the same: (a) verifying the suitability of a location as a disposal site and predicting the behaviour of CO_2 at the site; (b) monitoring a site for seismic impacts, effects on fresh water, and leakage to soils or air that may have local health or ecological impacts, and meeting relevant regulatory requirements; (c) long-term monitoring of CO_2 releases to the atmosphere to verify effectiveness from a climate mitigation point of view; and, last but not least, (d) confirming that disposal activity takes place as claimed.

Monitoring CO_2 underground

Given the immense natural variation in underground geology, finding a site suitable for disposal requires intensive study. Highly detailed maps of fractures in geological formations are necessary to spot breaks in otherwise acceptable sites. Even very small fissures can offer a significant escape route over time. Bearing in mind that a site might be used for decades and then left alone for centuries, finding a suitable area is no mean feat. Any failure to perform detailed pre-injecting characterisation would be an invitation to future leakage.

Once CO_2 is in the ground, kilometres of rock separate observers from what is happening. Detection technologies are therefore needed to monitor whether and how the plume of injected CO_2 is spreading. A standard technique in the industry is to lower into wells detectors that log a variety of data, mostly about the condition of the well. By detecting the composition of fluids seeping from the rocks lining the well, the resulting data can give an idea if there is any seepage of CO_2. Because the well itself would be an important escape pathway, this is useful, but it is of limited value in describing the movement and size of the plume.

Geophysical monitoring techniques allow geologists to monitor a larger area. A long-standing petroleum industry exploration technology is seismic monitoring, where sound waves are directed at a formation and devices record the reflections. This can be done at the surface, down a well, or from one well to another (cross-well). Seismic monitoring takes advantage of the differences in the density and elastic stiffness of different materials. Comparing monitoring data to known values for CO_2 and those for surrounding water, gas, oil or rock makes it possible to form a picture of the location of CO_2.

The most important factor in seismic monitoring is resolution—the size of a feature that can be detected. Cross-well seismic monitoring will yield more information than monitoring from a single well, while using a third well to form a three-dimensional (3-D) image is even better. Even so, this still only yields a picture across a particular slice of a formation at a certain depth. A surface seismic image can cover a broader area over a large range of depths, but there will be kilometres of rock between the sensors and the disposal formation, complicating interpretation of the image. Research shows that in the order of 20,000 tonnes of CO_2 can be detected in a formation using surface seismic techniques but the risk of false readings cannot be ruled out when dealing with volumes 20 times less.[17] Given that a power plant might inject 1 megatonne (MT) of CO_2 every year, the plume should be easy to spot, but smaller amounts of CO_2 migrating away from the plume, perhaps in undesirable directions, could be missed. A promising technique, less used in petroleum exploration, is time-lapse detection, where the difference between images taken over time helps spot movement of CO_2 in a formation. This can also be done in 3-D.[18]

CO_2 injected under the surface may increase the pressure of a formation to such a degree as to cause the land to buckle, however slightly. Meters exist that can measure this deviation extraordinarily accurately—to fractions of a millimetre. Coupled with the possibility of satellite or aeroplane-based monitoring, small land shift changes can give an indication of pressure changes underground over a wide area that may be due to CO_2 injection.

Monitoring impacts

Fresh well water is an important and, in many places, increasingly scarce resource. Maintaining both sufficient quantities and drinkable quality is a primary goal of the regulations that govern various activities affecting the underground, such as hazardous waste disposal. CO_2 will obviously not be allowed to be disposed of in potable water sources; they will be in much deeper saline aquifers. However, two mechanisms at work could affect water sources. Either injected CO_2 could displace saline water away from the injection site until it reaches a fault that connects it upwards to fresh water, or the CO_2 could itself find similar faults and migrate to fresh water. While the geophysical techniques can indicate plume movement, CO_2 or saline water migration can also be detected by directly taking fluid samples, including at wells themselves—and there is already a serious problem if anything is detected there.

Once CO_2 leaks into soil near the surface, it can start to have an impact on plants and animals. Normally the gas content of soil is up to 1 percent CO_2. At elevated levels, the CO_2 can kill trees by inhibiting the uptake of oxygen and nutrients by their roots. This process is already evident in areas with naturally elevated CO_2 levels, such as the carbogaseous regions of France, areas of northern Hungary and Mammoth Mountain, California, where CO_2 of volcanic origin is killing 40 hectares of pine forest.

As CO_2 reaches the air, direct measurement would be needed to protect both humans and animals from dangerous exposure and to estimate the magnitude of any leakage. Current technology is far more directed to the former, given that CO_2 is a workplace hazard in certain industries and standards exist regarding acceptable levels. Two types of hand-held chemical sensors are already in use, one using gas chromatography and one using Draeger tubes. These are more appropriate for spot checks to determine human exposure than for large-area, long-term monitoring. They are adequate to check for dangerously high levels, but not for subtle changes. Direct measurement of CO_2 in air is most commonly done through infrared (IR) sensors. Small infrared gas analysers (IRGA) are commonly used to ensure safety in workplaces such as breweries, for example, by being linked to ventilation systems. Field sensors to detect CO_2 flux from the ground are also employed in locations like Mammoth Mountain. This group of detectors is useful for measurements at a single point, but to cover a wide area either need to be mobile or in large numbers.

Other sensors employing shorter wavelengths allow distances of up to 1 kilometre to be covered. This has the advantage of covering a large area but the disadvantage that the readings are cumulative for the whole length of the path. If a reading is high, it may be due to a cumulative effect or to one hot spot along the way. Portable monitoring may then be necessary to detect the source more accurately.

Even broader coverage could be achieved by aircraft or satellites equipped to detect both CO_2 and disposal impacts such as deformation of the land surface. The US National Aeronautics and Space Administration (NASA) believes that satellites could theoretically detect increased CO_2 levels to a 100 square metre area. However, because variations in topography may have a significant impact on measurability, and measurements are of the whole air column, it is difficult to discern differences in concentrations of CO_2 at ground level, which is of most interest. Satellite monitoring could therefore be used as a warning system to prompt further investigation. A suitably capable satellite would naturally have to be in the right place to cover a particular site, which may limit its widespread applicability. To be more site-specific and to reduce the distance from the surface, aircraft may be a more effective alternative.

Compliance monitoring

While much research is currently focused on technologies that will enable us to understand the complex geological factors affecting CO_2 disposal, much of their success as a mitigation measure will depend on verifying that disposal takes place as claimed. With recent corporate accounting scandals fresh in people's minds, it should come as no surprise that corporate carbon accounting may be equally susceptible to foul play. CO_2 capture and disposal will be expensive, complicated, and seen as an environmental burden that is tangential to a company's core business, and this may tempt companies to cut corners. However, carbon dioxide is the centrepiece of international agreements and a marketable commodity.[19] Parties to the UNFCCC and the Kyoto Protocol will want to know that accounting for mitigation activities is credible in their own and other countries. Similarly, businesses trying to reduce emissions or participating in an emissions trading system will want to know that their competitors are living up to their obligations as well.

In addition to straightforward monitoring to verify that CO_2 is captured and flowing through pipes to disposal sites as claimed, techniques are being developed to assign responsibility for the long-term fate of CO_2. To aid in distinguishing the source of the CO_2 it may be possible to inject tracers into the injected CO_2 or formation water at the injection site. Possibilities include noble gases mixed with the CO_2, and perfluorocarbons.[20] Another possibility is that isotopic measurements (of the C13/C12 [$^{13}C/^{12}C$] ratio) may 'tag' specific CO_2 sources; the ratio in CO_2 from a specific power plant would very likely be different from that found in the atmosphere, allowing it to be recorded and detected later should there be leakage from the disposal site. However, there are still questions about the impact sub-surface storage may have on the isotopic ratio: by the time it has leaked the CO_2 may have undergone a change. Oxygen isotopic ratios could also be exploited for the same purpose.

Isotope measurement is typically done via isotope ratio mass spectrometry (IRMS). This is accurate but expensive and requires laboratory preparation of the samples, making it inappropriate for cheap, large-scale or real-time measurement. One company, Aerodyne Inc., is developing 'tunable infrared laser differential adsorption spectroscopy' (TILDAS) techniques. These could allow real-time measurement in the field or from aircraft. Developments are currently overcoming the difficulty of retaining precision over long path lengths.

Ocean disposal monitoring

While geological disposal is supposed to contain CO_2 in a defined area, the opposite is true for ocean disposal, which generally operates according to the old catchphrase 'the solution to pollution is dilution'. The disadvantage is that CO_2 creates acids in water that may lower pH (alkalinity) to levels that are dangerous to marine life, in addition to having narcotic and asphyxiant effects on marine life just as it is does on terrestrial life. The dilution sought is of course only lateral: the hope is that CO_2 will not migrate vertically, and ultimately out to the atmosphere. In any case, dispersal in the ocean complicates monitoring. On-site monitoring is in practical terms limited to verifying quantities on their way to disposal. Once those verified quantities are dispersed into the ocean, movement is most likely only to be estimated using computer models.

A number of options for injecting CO_2 into the ocean have been proposed, but they generally involve pipes leading down to a depth of 1,000–3,000 metres or more. Flow meters on pipes leading to an injection point could accurately establish quantities, while video cameras could be placed at the injection point to verify flow, check for problematic blockages and estimate volumes. Sensors at the injection point could also check for CO_2 concentration and pH changes.

Unmanned undersea vehicles could be used to check both the integrity of the injection site and CO_2 concentrations and pH at intervals from it. Repeated sampling could give some data as input to models on movement of the plume and the impact it is having on the water, and by extension anything in the water.

Monitoring far from any specific injection site is not likely to yield data specific enough to say much about that site. It will reveal more about the cumulative impact of ocean disposal globally. Estimates place the potential pH drop from injecting all power-plant CO_2 into the ocean over the coming decades as of the order of .3 units.[21] This is a relatively unlikely scenario and a relatively small drop, but it says nothing about the much more important local changes in areas with concentrations of power plants, the coastlines near major population centres being an obvious example.

An alternative to the dilution method is the possibility of retaining a single large pool of liquid CO_2 in an underground 'lake'. While everything under it would be destroyed, at least the destruction would be confined. That kind of thinking has done little to win the concept friends; and a further problem is verifying that the liquid CO_2 does not expand or disperse. It could be possible to set fixed monitors or regularly visit the site with a remote submersible to verify the action of the CO_2.

This would give a view of overall behaviour, but estimates of the mass would still only be approximations: losses to dissolution, for example, would still have to be modelled.

Modelling effectiveness: accuracy and acceptability

There will always be a trade-off between cost (or effort) and accuracy: IR equipment capable of very precise CO_2 measurements can monitor a specific point. However, over decades of injection, a saline aquifer may fill with CO_2 that extends over hundreds of square kilometres.[22] Options for monitoring possible leakage to the air include many individual monitors, field staff with monitors taking samples, monitors with long path lengths but lower accuracy, and aircraft and satellite imaging with broader ranges and even lower accuracy. Detecting large leaks in order to protect the public may involve placing monitors only near likely leakage sites, such as wells, or using remote sensing, which can spot the rough variations. Spotting steady, low-level leakage and quantifying it would require closer detection. Ultimately, combinations of approaches would be needed.

Estimates have been made for the cost of 3-D time-lapse seismic measurements which would provide a relatively good picture of how a plume is evolving. Each image might cost in the range of US$1.5 million; if images are taken at five-year intervals during the 30-year injection time from a power plant, total costs would come to US$9 million—which, in the context of the 300 MT of CO_2 disposed of, amounts to only US$0.03 a tonne.[23] But the kind of commitment that would be necessary to monitor the site for the duration of the intended disposal period is still poorly understood. To be effective, storage must keep CO_2 from entering the atmosphere for hundreds or thousands of years. Who will take responsibility for making sure a disposal site will not leak 300 years from now? Who will monitor and guarantee it, and how? A US$1.5 million 3-D monitoring effort may be acceptable once every five years for 30 years, but what about for 300 years? Will people even be aware of the danger in 300 years? At the moment there are still no good answers to these questions, and it is largely because of this (and a feeling that the answers we do get may be incomplete) that many consider it premature and perhaps ultimately rash to consider disposal as a major tool in mitigating climate change.

To some degree estimation and modelling will have to be used to give an indication of how CO_2 is moving within a site, leaking to the atmosphere, or affecting the environment. But confidence in compliance with health and safety regulations, Kyoto targets, national legislation or emissions trading requires that all parties involved feel that emissions estimates are as uniform and precise as possible. Precision, that is, reproducible results for similar activities, is a prerequisite for fairness. However, it is possible to be precise without being accurate: while everyone may agree to use the same emissions factor and probability of emissions, these may not actually represent reality well.[24] The challenge is therefore twofold: reaching agreement on methodologies for accounting, and being sure that the accounting can be done accurately enough to represent the real risk to the atmosphere. For this reason, the process of setting standards cannot precede a scientific understanding of the likelihood of leakage. At the moment we are far from that understanding for any type of disposal.

Despite the gaps in understanding, research and development on CO_2 capture and disposal has gained pace over the past decade and includes efforts by industry, academia and governments in Europe, Australia, North America and Japan. Recognising the growing base of knowledge, the Intergovernmental Panel on Climate Change (IPCC) decided to initiate a special report on the subject, which will be finalised in 2005. It will be an important assessment of relevant technical advances and will probably influence ongoing discussions both nationally and internationally. Among the most important issues will be defining the monitoring and verification standards and practices that will pass muster under the UNFCCC and its Kyoto Protocol.

The IPCC will also address the issue in its review of the revised 1996 guidelines for national GHG emissions inventories, which should be completed in 2006.[25] Emissions from sources relevant to CO_2 capture and disposal, such as those from large power plants, are currently included in national GHG inventories in one of three ways.

The first is the reference approach, which basically takes the amount of fuel consumed in the economy and multiplies it by the appropriate emissions factors. This approach covers all sources. The second is the sectoral approach, which does the same thing but with data sector by sector; and the third is a bottom–up approach, which uses empirical data on either fuel consumption or actual measured CO_2

emissions from the stack of individual emission sources. CO_2 capture would skew the first two measurements because it changes the relationship between fuel used and emissions. But it would be far too simplistic to merely count plants that employ capture as non-emissive. Not all capture methods would have the same effectiveness: CO_2 could be reduced by close to 100 percent in some cases, but might be much less in others, depending on the technology. Accurate measurement would require plant-by-plant information, making the bottom–up approach a necessity. In the European Union countries, and possibly other parts of the world, legislative measures such as emissions trading will mean that plant-level monitoring is in any case required. Since with such systems the pollutant being monitored has a financial value, there may be a stronger incentive on all sides to ensure high levels of accuracy.

Capture alone would not necessarily require a new methodology for the good practice guidelines, given that the relevant data point—CO_2 emitted from the stack—is the same as today. In that sense capture is like any other mitigation technology (such fuel switching and improved engine efficiency) that reduces stack emissions. The more complex side of the equation is disposal and the long-term measurement of leakage. Because of its own unique complexities, a separate protocol for biological sequestration was completed in 2003;[26] a similar effort will be needed for geological and ocean disposal.

Any international guidelines will be general, but relevant national and local regulations can be complex and demanding. In North America, Europe and Japan, CO_2 monitoring regulations are currently being reviewed for their relevance to capture and disposal. Until now, CO_2 regulations have focused exclusively on the health and safety of workers in chemical manufacturing, breweries and other places where it can be a local hazard. Regulation routinely establishes safe limits for exposure to CO_2 and mandates checks or continuous monitoring in danger areas. More relevant to disposal are analogous storage and disposal efforts regarding other substances, such as natural gas, waste water and nuclear waste. These cases indicate not only that is it important to adopt relevant technical standards and management procedures but also that lessons should be learned from the political battles surrounding their safe and acceptable development. Looming behind the development of carbon capture and disposal is the spectre of the divisive battles over nuclear waste disposal that are in large measure responsible for the stagnation of an entire industry.

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Endnotes

[1] There is an active debate about the proper terminology for this concept. The most common term is 'sequestration' , but this is easily confused with terrestrial sinks. The forthcoming Intergovernmental Panel on Climate Change (IPCC) special report will use the term 'storage', but this is clearly a misnomer as it implies action of a temporary and easily reversible nature. 'Disposal' is most accurate because it describes what is in fact happening.

[2] Gregg Marland, Thomas A. Boden and Robert J. Andres, 'Global, regional, and national CO_2 emissions', in Trends: A Compendium of Data on Global Change, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, TN, 2003, available at the website of the Carbon Dioxide Information Analysis Center, http://cdiac.esd.ornl.gov/trends/emis/tre_glob.htm.

[3] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis,* Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2001, p. 207 (chapter 3.5.1: Observations, trends and budgets).

[4] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (chapter 3.4.1: Anthropogenic sources of CO_2), p. 204.

[5] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (chapter 9.3.3: Projections of future climate change), p. 558.

[6] See Climate Action Network website at www.climnet.org/publications/adequacy.htm.

[7] While in absolute terms increasing developing country emissions are a concern, in general they are nowhere near the per capita emissions of developed countries, and thus, as long as the latter maintain their high emission levels, growth in developing country emissions is defensible.

[8] The text of the UNFCCC can be found at http://unfccc.int/resource/docs/convkp/conveng.pdf.

[9] The text of the protocol can be found at http://unfccc.int/resource/docs/convkp/conveng.pdf. See also Molly Anderson, 'Verification under the Kyoto Protocol', in Trevor Findlay and Oliver Meier (eds), *Verification Yearbook 2002,* The Verification Research, Training and Information Centre (VERTIC), London, December 2002, pp. 147–69.

[10] When the impact of credits due to the enhancement of terrestrial sinks is included, actual industrialised country emissions may not be reduced but rather stabilised at 1990 levels. Worse still, countries such as Australia and Russia effectively renegotiated their original Kyoto targets by forcing concessions that enable them to earn higher credits from existing domestic carbon sinks. The withdrawal from the protocol negotiations of the US, which contributes more than a third of GHG emissions in industrialised countries, means that its share of the initial 5 percent target will not be achieved either. Considering the current growth trends in US emissions, this could lead to industrialised countries' emissions being up by 5 percent rather than down in 2008–12.

[11] Howard Herzog, Elizabeth Drake and Eric Adams, *CO_2 Capture, Reuse, and Storage Technologies for Mitigating Global Climate Change,* White Paper Final Report (order no. DE-AF22-96PC01257), US Department of Energy, Washington, DC, January 1997, p. 28.

[12] Michael Celia and Stefan Bachu, 'Geological sequestration of CO_2: is leakage unavoidable and acceptable?', Proceedings of Greenhouse Gas Technologies Conference no. 6 (GHGT-6), Kyoto, October 2002, p. 1.

[13] The CO_2 would be put it in unmineable coal seams, although whether seams that are unmineable today will be so in the future is another question.

[14] Gases enter supercritical state when the temperature is too high for the vapours to form liquids, but the pressure compresses them to the density of the liquid state. They retain the viscosity of a gas. The supercritical point for CO_2 is 74 times atmospheric pressure at 31°C. Density is on the order of 600–800 kg/cubic metre.

[15] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis,* pp. 197–98 (chapter 3.2.3: Ocean processes).

[16] The 1982 Law of the Sea Convention and the 1992 Convention for the Protection of the Marine Environment of the North-East Atlantic (the Oslo–Paris (OSPAR) Convention), covering the North Sea, use similar language in which only specific kinds of waste are allowed to be dumped. Carbon dioxide is not one of them.

[17] Larry Myer, Michael Hoversten and Erika Gasperikova, 'Sensitivity and cost of monitoring geologic sequestration using geophysics', Proceedings of Greenhouse Gas Technologies Conference no. 6 (GHGT-6), p. 5.

[18] Time-lapse seismic monitoring of Statoil's reinjection of CO_2 separated from natural gas into the Sleipner field of the North Sea has provided a wealth of information for researchers. See www.statoil.com.

[19] There has already been a forward trade of carbon credits bought by Ontario Power Generation, generated from an EOR project in conjunction with the Partnership for Climate Action. See www.pca-online.org.

[20] These are, ironically enough, very strong greenhouse gases, but quantities would be minute.

[21] Howard Herzog, Ken Caldeira and Eric Adams, 'Carbon sequestration via direct injection', in John H. Steele, Steve A. Thorpe and Karl K. Turekian (eds), Encyclopedia of Ocean Sciences, Vol. 1, Academic Press, London, September 2001, pp. 408–414.

[22] Sean T. Brennan, 'Specific disposal volumes: a useful tool for CO_2 storage capacity assessment', in Proceedings, Second Annual Conference on Carbon Disposal, Washington, DC, May 2003.

[23] Myer, Hoversten and Gasperikova, p. 6.

[24] For example, the Kyoto Protocol uses a global warming potential (GWP) of 21 for methane, but a subsequent study puts it at 23. So, while consistent application of 21 will yield fair and precise results across the board, they will be inherently inaccurate.

[25] The revised 1996 guidance on national greenhouse gas inventories is available at www.ipcc-nggip. iges. or.jp/public/gl/invs1.htm.

[26] The protocol is still in draft version. See www.ipcc-nggip.iges.or.jp/.