

Artificial Geologic Seafloor Storage of CO₂

Supplementary Information for “Negative Carbon via Ocean Afforestation”

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I. OVERVIEW

Ocean Afforestation with anaerobic digestion can remove CO₂ from air that can then be stored as pure gas or liquid CO₂ with a variety of carbon storage technologies:

1. Geologic Storage where the CO₂ is either a gas, a supercritical fluid, or dissolved in saline aquifers several kilometers below the surface of the earth or the seafloor;
2. Near sub-seafloor storage, proposed by House, et al. (2006) where the CO₂ is either a liquid or a hydrate perhaps 100 meters below the seafloor for a combined depth in excess of 3 kilometers;
3. Solid snow, proposed by Agee, et al. (2012) where the CO₂ is a frozen solid “landfill” in Antarctica;
4. Artificial geologic seafloor storage, a novel method described below; or
5. Other future technology.

This paper assesses the potential for storing CO₂ on and under the seafloor in layers of materials that become secure geologic formations over millennia. Section II focuses on storing CO₂ as a solid hydrate, initially encapsulated in geosynthetics on (and eventually in) the seafloor at depths over 500 meters, and the possibility of storing liquid CO₂ encapsulated in geosynthetics where the seafloor is below 3,000 meters. Section IV, permanent encapsulation methods, explains a cost effective use of silicate minerals with geosynthetics to become a geologic layer.

Our analysis indicates the technical, economic, and environmental feasibility of artificial geologic layers that begin as geosynthetic containers:

- Achieving better than 99.9% storage permanence sealing CO₂ hydrates and CO₂ saturated brine in advanced geosynthetics.
- Storing CO₂ at rates in excess of 5,000 tons per hour without pressurization or sealing issues.
- Identifying potentially trillions of tons of CO₂ permanent storage locations with competitive storage, monitoring, repair, insurance costs, and without private property issues.
- Providing effective dissolved CO₂ sensors and other forms of reliable, accurate real-time monitoring, verification, and accounting of stored CO₂.

The initial geosynthetic hydrate storage involves CO₂ hydrate as a stable solid denser than seawater, in essence a heavy geologic ice. It can only dissolve if water with less than the equilibrium dissolved CO₂ is in direct contact and heat is available. Like any ice, it must be melted. Geosynthetic hydrate storage becomes artificial geologic seafloor storage over time as additional layers are added. Humans may add artificial layers within years, decades, or centuries if needed. The ocean adds layers of marine snow over millennia. Optional kinds of artificial geologic layers are discussed in Section IV, Environmental Considerations.

The research indicates that appropriate undisturbed geosynthetics will prevent contact with seawater for millennia and that, should the geosynthetic be damaged, insignificant CO₂ hydrate dissolves before the damage can be detected and repaired. Hydrate storage can be permanent with inexpensive geosynthetic containers made of materials similar to those used to line landfills and encapsulate hazardous waste. The life expectancy of water-tight high-density polyethylene films in landfills exceeds 3,000 years when the liner temperature is always below 30°C (Rowe, et al., 2009a, 2009b). We expect even longer life expectancy when the temperature is always below 10°C, as will be the case in the deep ocean.

In summary, time and nature transform geosynthetic hydrate storage into geologic storage. The CO₂ hydrate will be denser than the surrounding seawater. Plus, in some locations nature will be constantly adding to the cover over the stored CO₂ as the detritus of the ocean (marine snow) gently adds a blanket of low-permeability ooze. In thousands of years when the manufactured materials could degrade, nature will have encapsulated the CO₂ permanently. (In areas without marine snow, fresh containers, dredged sediments, or any of the methods described in Section IV, Environmental Considerations, could re-encapsulate any deteriorated containers as necessary.)

Earlier ocean sequestration research did not include manufactured containment for the initial barrier to prevent dissolution. The closest technology to our approach is shallow seafloor injection explained by House, et al. (2006) where liquid CO₂ would be injected into coarse sediment aquifers or cracked basalt below a layer of impermeable sediments, at a depth where the CO₂ would either remain liquid or convert to hydrate. PODenergy conducted an extensive search before and after its 2007 patent filing (Capron, 2007) and found one discussion (Palmer, et al. 2007) mentioning a container to prevent liquid CO₂ from dissolving or dispersing into the ocean. Many researchers have studied CO₂ hydrate formation (Lund, et al. 1994, Honda, et al. 1995, Nakajima, et al. 2005, Chow, et al. 2009, Kojimaa, et al. 2002). For example, Brewer, et al. (1998, 1999, 2000, 2001, 2002) carried out a series of experiments examining CO₂ hydrate formation at different depths. Hydrate formation has been examined in hopes a hydrate “skin” would seal a pool of liquid CO₂, but this was unsuccessful (Teng, et al. 1997, Brewer 1999, Uchida, et al. 1997, Wannamaker 2002, Teng, et al. 2004, and references therein). PODenergy has not detected research on storing CO₂ as a hydrate in a manufactured container.

II. DISCUSSION OF GEOSYNTHETICS

Economics

Seafloor container carbon storage combines reductions in risks, property rights issues, and costs, relative to the substantially researched “geologic” (deep-earth) injection. Geosynthetic storage reduces cost, particularly for coastal communities without nearby oil or gas reservoirs. The cool and high-pressure nature of the deep ocean allows the CO₂ to become a solid (hydrate) denser than seawater at the same time it ensures geosynthetics will remain serviceable for millennia. A thin geomembrane covering is all that is needed to prevent the hydrate from dissolving. Because hydrate requires heat to “melt,” it cannot fail catastrophically. The ease of access and sensor placement in the ocean allows detecting and repairing leaks and ultimately demonstrating that 99.9% of injected CO₂ remains contained. There is no pressure build-up during filling.

Based on a preliminary examination of the potential economics of available geosynthetic fabrications, we concluded that it is likely that CO₂ could be stored as a hydrate in ocean floor

containers for a cost of less than \$4 per ton of CO₂ for stored volumes as small as 100,000 tons of CO₂ with minor cost decreases for larger stored volumes. This price includes the containers, converting liquid CO₂ and seawater to hydrate, monitoring sensors, and associated electronics.

While \$4/ton of CO₂ is on the high end of Eccles, et al. (2009) estimate of \$1 - \$5/ton of CO₂, there is more potential for additional costs not anticipated by Eccles et al. with saline aquifer storage than with geosynthetic hydrate storage. For example, regulators could require dissolving the CO₂ in the saline water before the CO₂ is injected into the aquifer in order to ensure the stored CO₂ is always denser than the surrounding saline water. Or they could require multiple injection wells to create more surface area at the CO₂:water interface in order to dissolve CO₂ and reduce pressure sooner. The volume of the saline water saturated with dissolved CO₂ is about 20 times the volume of the liquid CO₂. That is, regulators could require either deep geologic aquifer storage have an uneconomically slow injection rate or an uneconomically elaborate process.

Physics and Chemistry

The physics and chemistry of the deep ocean relative to CO₂ storage in containers is relatively straightforward. As mentioned above, the formation of hydrate at depth has been demonstrated many times. Geosynthetic hydrate storage can work with either gas or liquid CO₂. Gas CO₂ requires more expensive processes because of the buoyancy of gas in situations where the geosynthetic container is filled with hydrate, CO₂ saturated seawater, and gas CO₂.

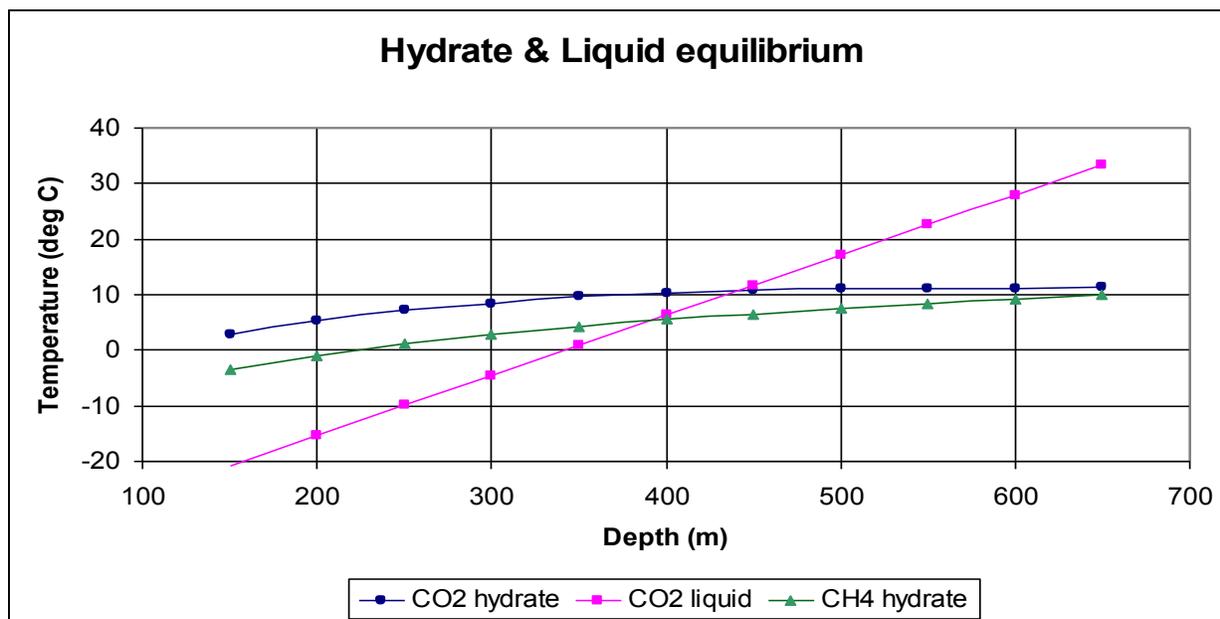


Figure 1. - Conditions for CO₂ hydrate formation (Rui 2005)

Figure 1 charts the temperature vs. depth equilibrium for CO₂ hydrate formation. Temperate climates, such as the West Coast of California as far south as San Diego, often have seawater temperatures reliably below 8°C when below 400 meters depth. In the tropics, water cooler than 10°C may be as shallow as 800 meters. In cold locations, CO₂ hydrate storage depth can be as shallow as 150 meters deep, if the seawater at that depth and location is reliably less than about 3°C. When operating near the limits of hydrate formation, the hydrate will form more readily with fresh water.

Placing containers below 400 meter depth and below 5°C reduces density issues. The container would initially include liquid CO₂ at about 900 kg/m³, hydrate at about 1,100 kg/m³, and seawater with dissolved CO₂ and impurities near 1,060 kg/m³. Ambient seawater will be near 1,030 kg/m³. At a depth of 500 meters, liquid CO₂ will be about 1 kg/m³ less dense than seawater. The filling will be done slowly enough to ensure that the container remains heavier than seawater.

Figure 2 charts approximate densities for the materials involved. These densities vary with temperature in addition to depth. Also, the equilibrium condition for dissolved CO₂ becomes nearly constant with depths below about 500 meters.

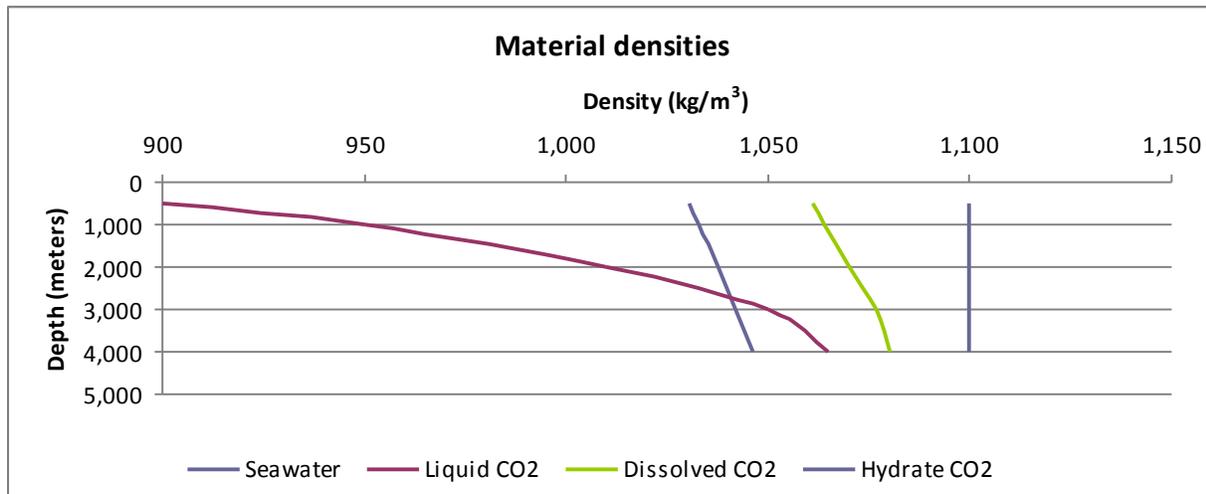


Figure 2 – Approximate material densities as a function of depth
From: seawater. (2012); others interpolated from Van der Meer, (2005) and (Rui 2005)

The hydrate consists of six water molecules for each CO₂ molecule (5.75 mol H₂O per mol CO₂). The hydrate occupies about 4 times the volume of liquid CO₂. Although the hydrate is about 4 times the volume of liquid CO₂, it can be less expensive to sequester permanently because it is heavier than seawater at much shallower depths, as shown in Figures 1 and 2. In addition, if some unforeseen event opens a hole in the manufactured containment, the hydrate remains immobile. It cannot flow out the opening. Only that small part of the hydrate structure that can dissolve into unsaturated seawater will slowly escape into the ocean. The slow dissolution is endothermic, requiring heat to continue. The hydrate has structural strength allowing more volume per surface area of the container than when storing a liquid. That is, a hydrate more resembles a rock than a bubble of liquid on the seafloor. Its container can be higher, occupying less seafloor space than liquid containers and it is stronger allowing more layers of heavier artificial geologic materials than is the case for a liquid.

The hydrate heat of formation is about 60 kJ/mol of CO₂. The water liquid-to-ice heat of formation is about 6 kJ/mol of H₂O. The heat capacity of water is about 0.08 kJ/mol/°C. The heat capacity of gaseous CO₂ is about 0.04 kJ/mol/°C. That is, forming a mole of CO₂ into a hydrate from CO₂ dissolved in water requires raising 750 moles of water by 1°C. Conversely, should a mole of CO₂ in hydrate be suddenly exposed to seawater, the disassociation cools 750 moles of water by 1°C. The system design benefits by allowing decades for hydrate to form and requiring decades to warm the hydrate if the artificial geologic layers are breached. Also, simple

thermometers can detect leaks.

Salts and other impurities are excluded during hydrate formation while also changing the pressure-temperature conditions of hydrate formation. As the hydrate forms there is left a very concentrated liquid with salts and the impurities that came with the CO₂. It may be that hydrate formation would allow recovery of impurities. Or that removing the salt concentrated liquid will improve the structural properties of the hydrate.

The salt and impurity exclusion properties of hydrate formation could be a future benefit. If society eventually finds a better way to store or recycle CO₂, it is possible to recover fresh water from the stored CO₂ hydrate that was made with seawater. The IEA Report (2004) predicts the equilibrium concentration of CO₂ at the surface of pure hydrate at for seafloor depth near 400 meters deep seabed temperature conditions will be near 4% wt (40,000 ppm mass fraction). This corresponds to a local pH of about 3.5. The seawater in a container at 2,700 meters may have a peak dissolved CO₂ equilibrium of 70,000 ppm mass fraction suggesting the seawater inside the container may have a pH below 3. In the long-term, the equilibrium dissolved CO₂ concentration decreases as the salt and impurity concentration increases. This means there would be some brine left after hydration. This brine may be stored with the hydrate, stored separate from the hydrate in stronger containers, or recovered and mined for minerals.

While the pH and the CO₂/impurities permeability will require careful engineering of the geosynthetic system and the sensors, the low temperature and the no-light conditions are ideal.

Producing a hydrate inside the container may be as simple as first injecting the container with seawater at a ratio of 5.75 moles of water (in the seawater) for each mole of CO₂ (about 2.5 liters of water for each liter of liquid CO₂.) At depths between about 500 and 3,000 meters, remaining liquid CO₂ will float to the top of the container. The hydrate will sink to the bottom of the container. The natural stratification ensures water is in contact with the liquid CO₂ until it has all reacted to form a hydrate.

While IEA GHG (2004) report by Aker Kvaerner indicates forceful mixing is required for efficient and dense hydrate formation, we believe time (years to decades) can replace mixing energy. It may be the unmixed process will result in separate “bubbles” of salty water and liquid CO₂. Unlike the uncontained Kvaerner hydrates, the artificial geologic process allows several centuries, if not millennia, for hydrate formation. The only requirements are that the overall container be denser than seawater when the container is first filled.

If mixing is essential, we could employ a specially designed nozzle to dissolve the CO₂ in the seawater and create the CO₂ hydrate, analogous to the demonstrations of a nozzle to create methane hydrate. As the mixture exits the nozzle, it quickly forms hydrate, which looks like snow. (Brown, et al. 2010, Chow 2009) Kastner, et al. (2000) have also studied the potential analogy of in-situ natural creation of methane hydrates over the course of a year.

Near 500 meters deep, CO₂ will reach saturation at about 40 moles of water for each mole of CO₂ (about 15 liters of water for each liter of liquid CO₂). Near 3,000 meters deep, saturation is about 35 moles of water for each mole of CO₂. Saturation concentration nearly ceases changing with depth below about 500 meters. Although liquid CO₂ density increases with depth, the 15 liters of water for each liter of liquid CO₂ is nearly constant between 500 – 3,000 meters depth.

See the online Supplemental Information “OMA Artificial Geologic Seafloor Storage” for a graph of CO₂ solubility versus pressure (depth).

Geosynthetics: First of Several Artificial Geologic Layers

Low permeability of potential geosynthetic materials is important to prevent escaping CO₂ and salt osmosis issues. Dr. R. Kerry Rowe suggests considering a co-extruded geomembrane with high-density polyethylene (HDPE) or linear low-density polyethylene (LLDPE). (Rowe, 2010) Either polyethylene would be on the outside and a layer of ethylene vinyl alcohol copolymer (EVOH) on the inside or vice versa. The polyethylene keeps the water and salt contained while the EVOH is vastly superior as the CO₂ barrier (see Table 1). Queen’s University has been working with these co-extruded materials as a vapor barrier for benzene, toluene, ethylbenzene, and xylenes (BTEX), and the combination is excellent. Still other materials are available, some of which are listed in Table 2. (Oxygen transmission is proportional to methane and carbon dioxide transmission and provides a useful indication where transmission rates for another gas through the specific material are not available.) Also, some materials may become much stiffer, stronger, less permeable, or more penetration-resistant when compressed with 50-bar (750 psi, 500 meters deep) pressure (even though the pressure differential across the material will be negligible).

Table 1 – Gas barrier properties of EVOH vs. HDPE

Gas	EVOH*	HDPE**
Nitrogen	0.019	190
Oxygen	0.25	2300
Carbon Dioxide	0.6	17526
Sulfur Dioxide	0.3	21844
Methane	0.4	2845

The permeability is reported as a permeation rate in cc · 20μ/m² · day · atm, (cubic centimeters of gas which will pass through a square meter of 20μm thick material in a day when the pressure across the membrane is one atmosphere) *Actual materials will be millimeters thick, not micrometers thick.*

* From ASTM D1434 measurements: 32 mol% EVOH, by Armstrong, R., and Chow, E. (2009)

** From Massey, L. K. (2003)

Table 2 – Oxygen transmission rates for potential geosynthetic materials

Oxygen Transmission Rate of Films	
Polyolefin	Oxygen Transmission at 20C, 65%RH
EVOH - 32 mol%	0.4
EVOH – 44 mol%	0.8
PVDC copolymer (Extrusion Grade)	2.6
Nylon	38.0
PET	54.0
HDPE	2300.0
C-PP	3000.0
PC	5000.0
LDPE	10000.0
EVA	18000.0

Unit : cc · 20 μ m / m² · day · atm

Another geosynthetic construction may be a multi-layer fabrication such as: 15-mil LLDPE-EVOH con-extrusion, a 4 oz. fabric (~140 gm/m²), a 1-cm thick net, a 4 oz. fabric, and an outside layer of 15-mil reinforced polypropylene. The interior liner needs to resist low pH and water being drawn in by osmotic pressure or CO₂ being pushed out by the small pressure difference. Diffusion through geomembranes is discussed by McWatters and Rowe (2010, 2011). A 1-cm thick net covered by geosynthetic fabric could maintain a 0.5 to 1 cm space filled with pure water. Pure water would be a biocide in this environment. If any creatures tunnel into the pure water, osmosis will expand their cells, which could seal potential leaks. The outer layer would contain only the pure water.

This storage approach does not rely solely on the manufactured reservoir. The seafloor is constantly accreting. It generally consists of ooze, the biological detritus that has fallen through the water column as marine snow. The seafloor ooze is very light, easily disturbed, and constantly accumulating. The ooze in certain locations may be so soft that manufactured containers will settle into and be covered by it immediately.

The seawater-CO₂ hydrate is denser than seawater. The seawater with concentrated salt that develops at the edge of hydrate formation is denser than seawater. Every component of CO₂ tends to descend further into the ooze. Therefore a very thin layer (perhaps as little as one cm) of ooze (assuming nearly zero current) above a possible break in the geosynthetic container could become an effective confining zone. See Section IV, Environmental Considerations, for additional confinement methods.

Monitoring and Maintenance

If the artificial geologic container is leaking, leaks can be detected in real time by monitoring dissolved CO₂ external to the container either directly with CO₂ sensors, or indirectly by sensing changes in pH or density of the seawater adjacent to the container. If the container is eventually buried under a layer of ooze, the leak can be detected with buried sensors, by monitoring for anomalies in ooze elevations, time-lapse photography, or sonic sensors. Because we can detect leaks in real time, we can repair leaks in real time. Most leaks on unburied containers can be repaired by attaching a sheet of geosynthetic film over the area where the leak appears on the container surface. Artificial geologic patches over partially buried containers would extend tens of meters beyond the leak.

In addition to leak detection, the geosynthetics can contain damage detection sensors. For example engineers routinely include strain gages and other sensors in the construction materials of important structures: bridges, hospitals, etc. One possibility for artificial geologic layers would include continuous lengths of fiber optic cables. Light signals sent into the cable reflect in a pattern. The reflection pattern changes if the cable is pinched or bent. The system can be used to listen to nearby whales talking. The system also detects the location of any damage.

Existing dissolved CO₂ sensors include: a) indirect measure via pH, b) gas spectroscopic sensors which detect the CO₂ partial pressure of gas diffusing through a membrane such as PTFE (polytetrafluoroethylene), c) chemical CO₂ gas sensors, d) indirect measure via sound speed to determine liquid density, e) indirect measure via temperature changes for either hydrate disassociating or liquid dissolving, and more to be invented. Ultrasonic transducers can be

arranged to produce 3D images of the stored CO₂ volume to as additional confirmation that none has leaked. (Such precise post-storage volume verification is not possible with most deep geologic formations.)

An example of a potential more robust sensor could use lengths of hollow fiber membrane tubes generally employed for reverse osmosis, but with pore size appropriate for the constituents of dissolved CO₂. Such tubes are a few millimeters in diameter. The tube could be filled with a salt water solution and a small solid-state pressure sensor (which may be a fiber optic cable). When dissolved CO₂ permeates into the tube, the tube will swell due to increased internal volume. The swelling could be detected as stretching and squeezing of the fiber optic cable. If creep becomes an issue, ceramic membranes could be used.

The proposed solid-state dissolved CO₂ sensors are similarly robust to varying conditions, although the geosynthetics or ceramics will need adjustments for the differing ambient temperatures of the deep ocean or the deep well.

The sensors and artificial geologic storage accommodate water and other pollutants mixed with the CO₂. The cool conditions and low pressure differentials at depth mean all the components: pipe; valves; containers; etc. can be the most chemically suitable geosynthetics. No expensive metals or ceramics are necessary. Hydrate storage is a more flexible receiver of CO₂ than deep geologic storage since the CO₂ may be delivered in pulses, as from a tanker ship, if that is more economic than a pipeline.

Relative Risk

A series of small (100 kg) demonstrations in several potential locations will identify the likelihood of sea creatures making holes in the manufactured materials and if the holes are made mechanically or chemically. The demonstration may also show that accumulating biofilms (slime, barnacles, etc.) could contribute to the thickness and integrity of the geologic layers. Octopi are expected to investigate the containers within a few days, but are not expected to harm them. Other biologic issues, if any, should be revealed within a few months. The monitoring system will show the nature of the biologic threat to container integrity, and the team could consider deploying new designs as needed.

Some of the other potential risks for both demonstration and full-scale storage are likely to include: subsea landslides, warming of hydrates (if the range temperatures at a site was not sufficiently investigated), space-use conflicts with existing ocean users (e.g. commercial and recreational fishing), and working fluid leaks. Most of these risks can be minimized by careful site selection. There are plenty of sites available outside of earthquake/tsunami zones, and at depths well below reach of commercial and recreational fishing hooks.

III. LEGAL ISSUES

Dumping of liquid CO₂ into the ocean is prohibited by the OSPAR Treaty for the North Atlantic ([Convention for the Protection of the Marine Environment of the North-East Atlantic](#), 2007), various other international accords, and probably national laws, which rightly regard uncontained CO₂ as a pollutant. All potential forms of uncontained CO₂, dissolved, hydrate, or liquid, eventually dissolve and disperse, increasing ocean acidification. Ocean acidification, even without accompanying ocean warming and other adverse human activities threatens mass

extinctions of sea life. Human food supplies will also be greatly impacted by the change in dominant ocean species.

The OSPAR treaty specifically states “dumping of all wastes or other matter is prohibited, except” . . . [it allows] “carbon dioxide streams from carbon dioxide capture processes for storage, provided disposal is into a sub-soil geological formation,” and “they are intended to be retained in these formations permanently and will not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area.”

OSPAR Decision 2007/1 prohibits the placement or disposal of carbon dioxide streams in the water column or on the seabed, while OSPAR Decision 2007/2 provides for potential permanent storage of carbon dioxide streams in geological formations, subject to a defined permitting process that takes into account the usual concerns of risk assessment, mitigation, stakeholder input, and long term monitoring.

“Geological formations” is defined to mean “geological formations in the sub-soil of the OSPAR maritime area, including sub-seabed geological formations.” These recent changes to OSPAR and the London Protocol have no doubt been motivated by a desire to store carbon dioxide in old offshore oil and gas wells.

Although OSPAR might be read to permit storage in containers in the sub-soil, a better approach might be to advocate for container storage as a good faith change in existing law and treaty obligations, by providing studies, experts, and reports to indicate that geosynthetic seafloor containers will either (a) last long enough for an immediate fix until a more permanent storage solution can be implemented, (b) can last millennia as claimed, or (c) can be further confined in leak-proof artificial geologic structures of satisfying geologic permanence, as mentioned in Section IV.

It is important to remember that suitable secure geologic formations (of unlimited size) are not available in many places, and large scale economical Ocean Afforestation needs storage in close proximity to the digestion operations.

IV. ENVIRONMENTAL CONSIDERATIONS

Long-term stability

It is correct to be concerned about artificial geologic seafloor storage because all non-maintained human-made structures eventually fail. Even natural features, such as mountains, seashores, and geologic formations, are constantly “failing” from erosion, earthquakes, geochemical reactions, human activities, etc.

However, humans can design secure containers for CO₂ on or in the seafloor that are stable for millions of years because:

1. Density – The stored CO₂ will be denser than seawater in all three forms: seawater with dissolved CO₂; CO₂ hydrate when below between 300 - 600 meters; or liquid CO₂ when below about 3,000 meters depth;
2. Operational transparency – The containers can be monitored in real time with video and other sensors providing information via the internet to any interested party. Some sensors can be built into the containers. This allows detecting leaks as small as a few grams of CO₂ from

- millions of tons of contained CO₂ before those few grams can move more than a few meters.
3. Slowness of failure – CO₂ hydrate requires heat and circulating water to dissolve. At typical ocean seafloor temperatures below 8°C, a ten meter long slit might leak a kilogram of dissolved CO₂ per day. It would be best to conduct a computational fluid dynamics study or in-situ experiments because the leak rate will vary widely depending on slit orientation, local current velocity, and numerous other factors. In contrast, we can detect a leak of one kilogram per day within a day and have it repaired with pre-positioned materials within a month.
 4. Maintainability – The permanence of the storage can be continually improved while any leaks are sealed, perhaps using some of the plans outlined below.

Permanent encapsulation methods

It may be easier to visualize geosynthetics as geologic layers when realizing geosynthetics can be employed to inexpensively extend the effectiveness of geologic materials.

Example 1: Portland cement filled geosynthetic fabric quilts in thicknesses from 0.5 to 3 centimeters are commercially available. The quilts are flexible during transporting and placement. After a few hours immersion, the quilts form a geosynthetic reinforced rigid concrete structure. This is a layer of reinforced “rock.”

Example 2: Make quilts filled with silicate minerals ground to the optimal particle size for reacting slowly with background dissolved CO₂ concentrations but reacting relatively quickly with any CO₂ leaked from a geosynthetic membrane. The quilt becomes a rock made from the combination of silicate, CO₂ and seawater.¹

Weathering of silicate minerals (olivine or serpentine) is a natural method for removing CO₂ from the air. (Schuiling & Krijgsman, 2006). Essentially, the weathered silicates cause the CO₂ to precipitate as carbonate (rock). Silicates, such as Olivine are abundant. However the reaction is extremely slow (centuries for gravel size particles) but can be sped-up by grinding the minerals into a fine powder. Mining and grinding minerals requires energy. If the energy to grind the minerals into a fine powder is supplied by fossil fuels, the carbon debt limits the net CO₂ absorption.

Of course there are many existing and many yet to be discovered ways to improve the layers used for artificial geologic seafloor storage. The use of silicate minerals as a composite with geosynthetics is but one example employing a tiny amount of materials for a large benefit.

Realistic in-situ trials of artificial geologic seafloor storage can be made on extremely small scales (tens to hundreds of kilograms of CO₂). Such trials will gather extensive information on seafloor ecosystems.

During those trials and continuing into full-scale operations, engineers can refine the leak protections and the economics for plans A – E suggested below. Regulators can use the trials and even the full-scale operations to refine the permitting process.

¹ Example 2 is patent pending.

For example, Plan A could be a 100% geosynthetic multi-barrier and multi-structural container. Plan B may incorporate Portland cement concrete, perhaps in the form of commercially available “blankets.” Plans C and D may include layers of a silicate mineral (either olivine or serpentine) distributed by barge. Plan E may include layers of geosynthetic quilts filled with silicate minerals ground to near nano-particle sizes. More plans will become available once systems are operating. The plans can be layered quickly should earlier plans prove victim to unexpected situations.

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