

# Secure Seafloor Container CO<sub>2</sub> Storage

Mark E. Capron, P.E., Jim R. Stewart, PhD, and R. Kerry Rowe, PhD\*

**Abstract**—Oceans, islands, and coastal areas are at least as threatened by humanity's rapidly increasing atmospheric greenhouse gas concentrations as the remaining 30% of Earth's surface. Yet most of the discussion for sequestering the dominant greenhouse gas, CO<sub>2</sub>, involves deep sub-earth geologic structures limited to relatively small areas in continental plates. Humanity needs a secure carbon storage alternative that is available in more countries. Secure Seafloor Container Storage (SSCS) is an alternative that could safely store trillions of tons of CO<sub>2</sub>. The paper presents a computational geophysical, chemical, and economic model of SSCS. Our research shows that appropriate undisturbed geosynthetics will prevent contact with seawater for millennia (<0.06% osmosis loss per millennium). CO<sub>2</sub> hydrate below 500 meters is a rock-like solid denser than water. Our life cycle assessment predicts a mass ratio of stored-CO<sub>2</sub>:materials needed of 1,700:1. The projected cost to compress pure gaseous CO<sub>2</sub> to a liquid, convert the liquid to hydrate inside a geosynthetic membrane, monitor and maintain the structures is approximately \$16 per ton of CO<sub>2</sub>.

**Index Terms**—carbon dioxide storage, climate change, CO<sub>2</sub> hydrate, geosynthetics, global warming, ocean seafloor storage, secure seafloor container storage.

## I. INTRODUCTION

Carbon dioxide levels have recently hit 400 ppm [1] and ocean acidity levels are threatening coral reefs and many other marine animals [2]. Recent research [3] shows that the combination of human-caused global warming factors, including emissions of CO<sub>2</sub> from burning fossil fuels, methane and other gases, black soot, land use changes, etc., require substantial removal of CO<sub>2</sub> from the atmosphere and oceans. Steinacher [3] indicates that when one includes temperature rise, sea level rise, ocean acidification, and other effects humanity should limit total CO<sub>2</sub> emissions to 2,200 Gt to avoid the worst effects.

However, the cumulative total of CO<sub>2</sub> emissions in 2011 was 1,100 Gt (calculations based on data from U.S. EIA [4]). Fig. 1 shows predicted business as usual emissions are accelerating toward a cumulative 2,800 Gt about when world population is expected to peak near 2050. Even if humanity somehow then manages to decrease fossil CO<sub>2</sub> emissions to zero by 2100, the cumulative total will be near 3,400 Gt. Possible emissions from disassociating methane hydrates

could add several thousand Gt of CO<sub>2</sub>. Since it is very difficult to economically remove the other global warming gases, climate efforts should develop more systems for the rapid removal and secure storage of at least of 2,000 Gt of CO<sub>2</sub>.

N'Yeurt et al. [5] proposed an economical and ecological way to reduce total carbon emissions as well as capture existing CO<sub>2</sub>: ocean macroalgal afforestation (OMA). In fact, compared to other negative carbon technologies reviewed by McLaren [6], [7] and McGlashan et al. [8], macroalgae capture of CO<sub>2</sub> from air and water may be the most feasible method to remove many thousand Gt of CO<sub>2</sub>. OMA would require an ocean-accessible secure storage method, such as that proposed in this paper.

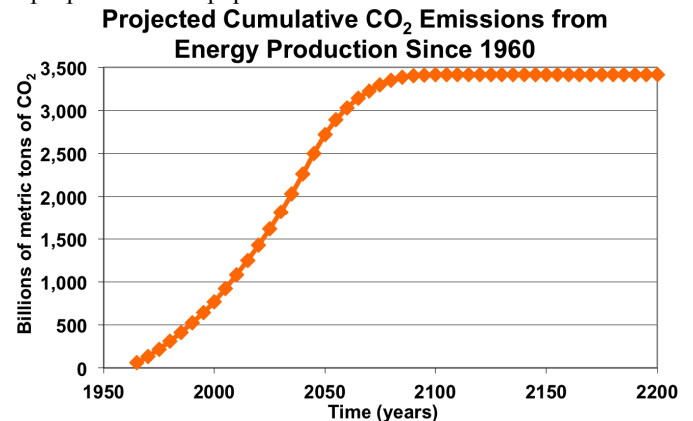


Fig. 1. Projected cumulative CO<sub>2</sub> emissions from energy since 1960 (based on U.S. EIA data [4])

Most of the proposals for sequestering CO<sub>2</sub> involve deep sub-earth geologic structures limited to relatively small areas in continental plates. In addition, some authors have expressed concern about potential leakage ([9]-[12]). Farhat et al. [13] recently examined saline aquifers potential for only interim storage purposes.

This paper assesses the potential for Secure Seafloor Container Storage (SSCS) to store CO<sub>2</sub> on the seafloor in secure containers that eventually become similar to geologic formations over millennia. The paper presents a computational geophysical, chemical, and economic model of SSCS, including:

- How typical ocean pressures, temperatures, biota, seafloor seafloor sediments, and CO<sub>2</sub> in water affect the service life of geosynthetic structures on the seafloor.
- Details of the concentrations, volumes, density stability, chemical stability, and structural properties of CO<sub>2</sub> and water inside a geosynthetic structure on the seafloor.
- The thermo chemical stability of CO<sub>2</sub> hydrate in geomembranes.
- The fluid dynamics of SSCS.
- The transparency of monitoring, maintaining, and in-situ improving the containers.
- The economics of SSCS.

Section II briefly reviews other storage technologies. Section III summarizes some advantages of SSCS. Section IV discusses the security of geosynthetic materials for CO<sub>2</sub> storage. Section V provides an introductory economic analysis and life cycle assessment. Section VI focuses on the physics,

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M. E. Capron, P.E., is President, PODenergy, Inc., 2436 E. Thompson Blvd., Ventura, California 93003 (email: MarkCapron@PODenergy.org).

J. R. Stewart, PhD, is Vice President, PODenergy, Ventura, California (email: JimStewart@PODenergy.org).

R. K. Rowe, PhD, is Professor and Canada Research Chair in Geotechnical and Geoenvironmental Engineering, Queen's University, Kingston, Ontario, Canada (email: Kerry@civil.queensu.ca).

chemistry, and biology of storing CO<sub>2</sub> as a solid hydrate, initially encapsulated in geosynthetics on (and eventually under) the seafloor at depths over 500 meters. It mentions the possibility of storing liquid CO<sub>2</sub> encapsulated in geosynthetics where the seafloor is below 3,000 meters. Section VII discusses potential monitoring and maintenance methods and discusses reduction of leakage risks. Section VIII reviews the international legal and treaty issues and outlines a potential solution. Section IX mentions additional permanent encapsulation methods, including a cost effective use of silicate minerals with geosynthetics to become a geologic layer.

## II. OVERVIEW OF STORAGE TECHNOLOGIES

A variety of carbon dioxide storage technologies have been examined by other authors, including:

1. Geologic Storage where the CO<sub>2</sub> is either a gas, a supercritical fluid, or dissolved in saline aquifers several kilometers below the surface of the earth or the seafloor ([9]-[12]);
2. Near sub-seafloor storage, proposed by House et al. [14] where the CO<sub>2</sub> 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. [15] where the CO<sub>2</sub> is a frozen solid "landfill" in Antarctica.

Many researchers have studied CO<sub>2</sub> hydrate formation [16]-[21]. For example, Brewer et al. [21]-[27] carried out a series of experiments examining CO<sub>2</sub> hydrate formation at different depths. Hydrate formation has been examined in hopes a hydrate "skin" would seal a pool of liquid CO<sub>2</sub>, but this was unsuccessful and the CO<sub>2</sub> rapidly dispersed into the ocean [24], [28]-[34], and references therein).

Palmer et al [35] examined the pipelines and membranes required for permanently storing liquid CO<sub>2</sub> below 2800 m, concluding that the cost could be below \$4/ton of CO<sub>2</sub>. Their proposal is analogous to that presented in this paper, except that we propose storing CO<sub>2</sub>-hydrate because the shallower depth (500 m) allows many more sites closer to shore, lowers costs, greatly reduces dangers of rapid dispersal in the event of a leak, and increases accessibility for monitoring and repairs (if needed). About the same time Capron [36] began filing a series of patent applications, some of which relate to this approach for CO<sub>2</sub> storage.

## III. ADVANTAGES OF SECURE SEAFLOOR CONTAINER STORAGE

Our analysis of Secure Seafloor Container Storage indicates the technical, economic, and environmental feasibility of creating artificial geologic layers that begin as geosynthetic containers could:

- Achieve better than 99.9% storage permanence sealing CO<sub>2</sub> hydrates and CO<sub>2</sub> saturated brine in advanced geosynthetics.
- Store CO<sub>2</sub> at rates in excess of 5,000 tons per hour without pressurization or sealing issues.
- Identify permanent storage locations for potentially trillions of tons of CO<sub>2</sub> with competitive storage, monitoring, repair, insurance costs, and without the private property issues found on land.
- Provide effective dissolved CO<sub>2</sub> sensors and other forms of

reliable, accurate real-time monitoring, verification, and accounting of stored CO<sub>2</sub>.

## IV. DISCUSSION OF GEOSYNTHETIC MATERIALS

CO<sub>2</sub> hydrate is a stable solid denser than seawater (see discussion of physics in Section V). It can only disassociate if water with less than the equilibrium dissolved CO<sub>2</sub> 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 additional 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 IX.

The research indicates that appropriate undisturbed geosynthetics will prevent contact with seawater for millennia and that, should the geosynthetic be damaged, insignificant CO<sub>2</sub> hydrate disassociates 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 watertight high-density polyethylene geomembranes in landfills has been projected to exceed 3,000 years when the liner temperature is mostly 10°C [37], [38]. We expect even longer projected service-life 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 CO<sub>2</sub> hydrate will be denser than the surrounding seawater. Plus, in some locations nature will be constantly adding to the cover over the stored CO<sub>2</sub> 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 CO<sub>2</sub> permanently. (In areas without marine snow, fresh containers, dredged sediments, or any of the methods described in Section IX could re-encapsulate any deteriorated containers as necessary.)

However, low permeability of potential geosynthetic materials is important to prevent escaping CO<sub>2</sub> and salt osmosis issues.

Our model considers a co-extruded geomembrane with high-density polyethylene (HDPE) for its structural properties and a layer of ethylene vinyl alcohol copolymer (EVOH) for its low permeability. While 18,000 cubic centimeters of gas will pass through a square meter of 20 μm thick HDPE in a day when the pressure across the membrane is one atmosphere, only 0.6 cubic centimeters of CO<sub>2</sub> will pass through the same thickness of EVOH.

Low permeability of potential geosynthetic materials is important to prevent escaping CO<sub>2</sub> and salt osmosis issues. Based on McWatters and Rowe [39], [40] there appears to be considerable potential for the use of a co-extruded geomembrane with high-density polyethylene (HDPE) or linear low-density polyethylene (LLDPE) because polyethylene is an excellent barrier to water and salt (e.g., [41] and [42]). The construction may be a sandwich with polyethylene on both sides and a layer of ethylene vinyl alcohol copolymer (EVOH) in the middle. The polyethylene keeps the water and salt contained while the EVOH is vastly

superior as the CO<sub>2</sub> barrier (see Table I). Queen's University at Kingston (Canada) [43] is working with these co-extruded materials as a vapor barrier for benzene, toluene, ethylbenzene, and xylenes (BTEX), and found the combination is excellent. 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 mechanical pressure differential across the material will be negligible).

Table I – Gas barrier properties of EVOH and 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 permeation rate units are cubic centimeters of gas passing through a square meter of 20 µm thick material in a day when the pressure across the membrane is one atmosphere.

\* From ASTM D1434 measurements: 32 mol% EVOH, by Armstrong and Chow [44], [45]

\*\* From Massey [46]

As an estimate of potential leakage by permeation, consider a cylinder of liquid carbon dioxide lying on the seafloor is 100 meters in diameter and 1,000 meters long. The contained volume would be 7.9 million m<sup>3</sup> (~7,500,000 metric tons). The surface area would be 330,000 m<sup>2</sup>. If the thickness of the EVOH is 40 µm and the osmotic pressure of the CO<sub>2</sub> to escape is 60-atm, the result calculated loss would be:

$$0.6\text{-cc} / 2\text{-thicknesses} \times 60\text{ atm} \times 330,000\text{ m}^2 \sim 6,000,000\text{ cc of gas/day} (\sim 0.01\text{ metric tons/day})$$

$$0.01\text{ tons} \times 365\text{ days} \times 1,000\text{ years} / 7,500,000\text{ tons} = 0.06\% \text{ loss per millennium}$$

In reality, solid hydrate, not dissolved or liquid CO<sub>2</sub>, will be in contact with the majority of container wall surface after the first few years, which should result in potentially lower losses.

To minimize possible defects in the geosynthetic structure, complete containers could be prefabricated, thoroughly leak tested, and rolled-up in a shaded dry dock on top of the barge that will deploy them.

Another geosynthetic construction may be a multi-layer fabrication such as: 0.38 mm (15-mil) LLDPE-EVOH co-extrusion, a 140 g/m<sup>2</sup> fabric, a 1-cm thick net, a 140 g/m<sup>2</sup> fabric, and an outside layer of 0.38 mm reinforced polypropylene. The interior liner needs to resist the low pH inside and water being drawn in by osmotic pressure or CO<sub>2</sub> being pushed out by osmotic pressure. Diffusion through geomembranes is discussed by McWatters and Rowe [39], [40].

A double-wall construction is possible with a 1-cm thick net covered by geosynthetic fabric could maintain a 0.5 to 1 cm space filled with pure water over a hectare of surface. Or enclosing the pure water in a "bubble wrap" construction would create many small volumes. Each double-wall area may have a leak detection sensor. The size of the continuous

area will depend on the cost of sensors and the largest areas that can be fabricated and installed without leaks.

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.

When employing osmosis to make pure water from seawater, the water passes through the membrane much more readily than the salts. The same applies for dissolved CO<sub>2</sub>. Therefore, we can expect some pure water entering the container driven through the geomembrane by osmosis. This pure water will combine with CO<sub>2</sub> to become hydrate without leaving a salty slush. Or we pump out the water before it causes the container to swell. Experiments will determine what, if any, osmotic pressure remains when the CO<sub>2</sub> hydrate presses against one side of the geomembrane and seawater (or an intermediate double-wall fluid) is on the other side of the geomembrane.

## V. ECONOMIC ANALYSIS

Seafloor container carbon storage has the potential to address risk reduction, property rights issues, and costs, relative to "geologic" (deep-earth) injection.

Based on a preliminary examination of the potential economics of available geosynthetic fabrications, we concluded that it is likely that CO<sub>2</sub> could be stored as a hydrate in ocean floor containers for a cost of less than \$16 per ton of CO<sub>2</sub> for stored volumes as small as 100,000 tons of CO<sub>2</sub> with minor cost decreases for larger stored volumes. This price includes the containers, energy converting liquid CO<sub>2</sub> and seawater to hydrate, monitoring sensors, and associated electronics.

While \$16/ton of CO<sub>2</sub> is higher than Eccles et al. (2009) estimate of \$1 - \$5/ton of CO<sub>2</sub> for saline aquifer storage, there is more potential for additional costs (or limits on low-cost capacity) not anticipated by Eccles et al. [46] with saline aquifer storage than with geosynthetic hydrate storage. For example, regulators could require dissolving the CO<sub>2</sub> in the saline water before the CO<sub>2</sub> is injected into the aquifer in order to ensure the stored CO<sub>2</sub> is always denser than the surrounding saline water to minimize leakage. Or they could require multiple injection wells to create more surface area at the CO<sub>2</sub>:water interface in order to dissolve CO<sub>2</sub> and reduce pressure sooner. The volume of the saline water saturated with dissolved CO<sub>2</sub> is about 20 times the volume of the liquid CO<sub>2</sub>. That is, regulators could require either deep geologic aquifer storage have an uneconomically slow injection rate or an uneconomically elaborate process. In addition, we have not seen careful calculations of potential leakage rates for saline aquifer storage.

In conjunction with the University of Virginia [48] we have done a life cycle assessment, which includes projections of the materials and energy required to compress, transmit, make hydrate, store, and monitor the CO<sub>2</sub> for a millennium. The calculation yields a mass ratio of stored-CO<sub>2</sub> divided by materials and energy needed of 1,700:1.

## VI. PHYSICS, CHEMISTRY, AND BIOLOGY

The physics and chemistry of the deep ocean relative to  $\text{CO}_2$  storage in containers is relatively straightforward. As mentioned above, the formation of hydrate at depth has been demonstrated many times. Geosynthetic hydrate storage can start with either gas or liquid  $\text{CO}_2$ . Gas  $\text{CO}_2$  requires more expensive processes because the buoyancy of gas is so much larger than hydrate or  $\text{CO}_2$  saturated seawater.

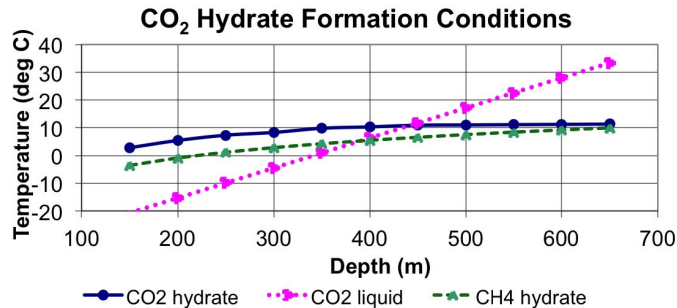


Fig. 2. Conditions for  $\text{CO}_2$  hydrate formation compared to  $\text{CO}_2$  liquid [49]

Fig. 2 charts the temperature vs. depth equilibrium for  $\text{CO}_2$  hydrate,  $\text{CO}_2$  liquid, and  $\text{CH}_4$  hydrate. Temperate climates, such as the West Coast of California as far south as San Diego, often have seawater temperatures reliably below  $8^\circ\text{C}$  when below 400 meters depth [50], [51]. In the tropics, water cooler than  $10^\circ\text{C}$  may be as shallow as 800 meters. In cold locations,  $\text{CO}_2$  hydrate storage depth can be as shallow as 150 meters deep, if the seawater at that depth and location is reliably less than about  $3^\circ\text{C}$ . When operating near the limits of hydrate formation, the hydrate will form more readily with fresh water than with saltwater.

Fig. 3 charts the solubility of  $\text{CO}_2$  with depth. The curve becomes nearly horizontal at the point where the undissolved  $\text{CO}_2$  would be either hydrate or liquid.

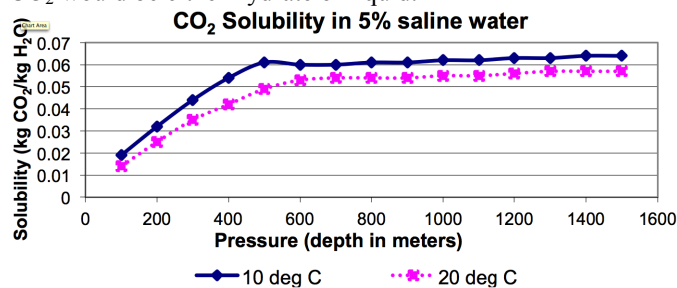


Fig. 3.  $\text{CO}_2$  solubility in salt water

Fig. 4 charts approximate densities for the materials involved. These densities vary with temperature in addition to depth.

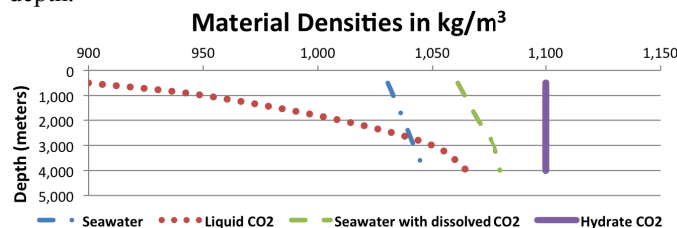


Fig. 4. Approximate material densities as a function of depth (data interpolated from [49], [52], [53])

At all likely depths, the hydrate will be the densest material in the container (about  $1.1 \text{ kg/L}$ ) and the liquid  $\text{CO}_2$  would float on the seawater with dissolved  $\text{CO}_2$ . Producing a hydrate inside the container may be as simple as first injecting the container with  $\text{CO}_2$  and seawater at a ratio of 5.75 moles of water (in the seawater) for each mole of  $\text{CO}_2$  (about 2.5 liters of water for each liter of liquid  $\text{CO}_2$ .) Fig. 4 depicts how the hydrate would form at the interface of liquid  $\text{CO}_2$  and seawater, then settle to the bottom. The form-sink action continually exposes fresh interface, allowing constant hydrate formation, limited primarily by the rate at which heat is conducted from the exothermic reaction. After some time the container will be full of hydrate on the bottom and a layer of water with higher salt concentration and lower dissolved  $\text{CO}_2$  concentration at the top. The equilibrium concentration of salt and dissolved  $\text{CO}_2$  will depend on pressure and temperature.

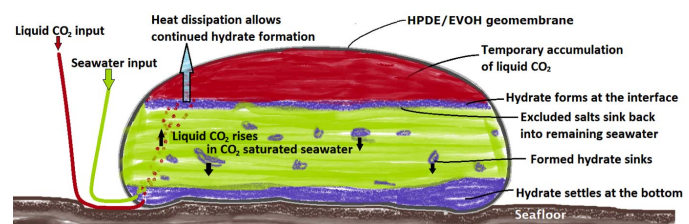


Fig. 5. Cross section of seafloor container during hydrate formation

Although the hydrate is about 4 times the volume of liquid  $\text{CO}_2$ , it can be less expensive to sequester permanently because it is heavier than seawater at much shallower depths, as shown in Figs. 2 and 4. In addition, if some unforeseen event opens a hole in the manufactured containment, the hydrate remains immobile. It cannot flow out the opening. The disassociation is an endothermic reaction requiring a constant supply of heat and unsaturated seawater at the surface of the hydrate to proceed. 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 or a supercritical fluid in the earth. The containers can be higher, occupying less seafloor space than liquid containers and its strength allows application of more layers of heavier artificial geologic materials than is the case for a liquid.

The hydrate heat of formation is about  $60 \text{ kJ/mol}$  of  $\text{CO}_2$ . The water liquid-to-ice heat of formation is about  $6 \text{ kJ/mol}$  of  $\text{H}_2\text{O}$ . The heat capacity of water is about  $0.08 \text{ kJ/mol/}^\circ\text{C}$ . The heat capacity of gaseous  $\text{CO}_2$  is about  $0.04 \text{ kJ/mol/}^\circ\text{C}$ . That is, forming a mole of  $\text{CO}_2$  into a hydrate from  $\text{CO}_2$  dissolved in water raises 750 moles of water by  $1^\circ\text{C}$ . Conversely, should a mole of  $\text{CO}_2$  in hydrate be suddenly exposed to seawater, the disassociation cools 750 moles of water by  $1^\circ\text{C}$ . 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 liquid brine with much higher concentrations of sea-salts and the impurities that came with the  $\text{CO}_2$ . It may be that hydrate formation would allow recovery of impurities as well as sea salt.

Fig. 6 shows the Fig. 5 container after nearly all the  $\text{CO}_2$  has been locked into hydrate and most of the remaining brine has been pumped out. Pumping out the brine allows ambient pressure to squeeze the hydrate into a structurally solid mass with reduced porosity and surface area.

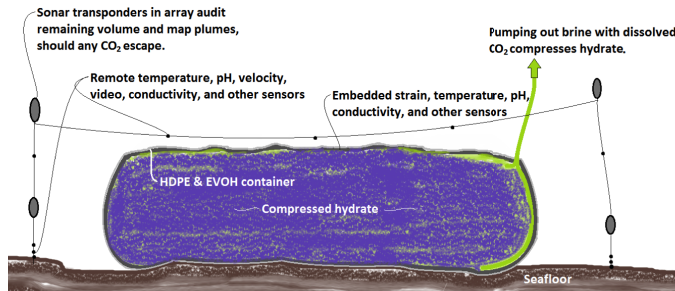


Fig. 6. Cross-section of seafloor container after hydrate formation, plus leak sensors

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  $\text{CO}_2$ , it is possible to recover fresh water from the stored  $\text{CO}_2$  hydrate that was made with seawater.

At all stages the environment inside the container will be hostile to local sea life. Initially, the  $\text{CO}_2$  saturation implies pH between about 2.5 and 3.5. Later the salinity will be several times that of seawater. However, the container walls will need a design that prevents local sea life from penetrating the walls or harnesses the local sea life to improve the containment.

A series of small (100 kg) demonstrations in several potential locations will identify any 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 developing new designs as needed.

## VII. MONITORING AND MAINTENANCE AND DISCUSSION OF RISKS

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.

Unlike  $\text{CH}_4$  hydrate,  $\text{CO}_2$  hydrate is denser than seawater. Yet  $\text{CH}_4$  hydrate remains captured in seafloor sediments for

millennia. Except for the time before all the liquid  $\text{CO}_2$  dissolves or converts to hydrate,  $\text{CO}_2$  can only escape as a fluid denser than seawater. Therefore a very thin layer (perhaps as little as one cm) of ooze or biologic growth above or beside a possible deterioration in the geosynthetic container could become an effective confining zone. See Section IX, Confining Systems, for additional confinement methods.

Fig. 5 shows an array of sensors that would both detect any leaks in real time and continuously verify the stored volume. If the container is eventually buried under a layer of ooze, the leak can be detected with the wall-embedded sensors, by monitoring for anomalies in ooze elevations, time-lapse photography, or sonic sensors. In addition to leak detection, the geosynthetics can contain damage detection sensors. Because we can detect leaks and damage 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 to seal against the seafloor.

Existing dissolved  $\text{CO}_2$  sensors include: a) indirect measure via pH, b) gas spectroscopic sensors which detect the  $\text{CO}_2$  partial pressure of gas diffusing through a membrane such as PTFE (polytetrafluoroethylene), c) chemical  $\text{CO}_2$  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 3-D images of the stored  $\text{CO}_2$  volume as additional confirmation that none has leaked. (Such precise post-storage volume verification is not possible with most deep geologic formations.)

The sensors and container storage accommodate water and other pollutants mixed with the  $\text{CO}_2$ . The cool conditions and low pressure differentials at depth mean all the components, pipes, 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  $\text{CO}_2$  than deep geologic storage since the  $\text{CO}_2$  may be delivered in pulses, as from a tanker ship, if that is more economic than a pipeline.

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 of water 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 or off-limits for commercial and recreational fishing hooks.

## VIII. LEGAL ISSUES

Dumping of liquid  $\text{CO}_2$  into the ocean is prohibited by the OSPAR Treaty for the North Atlantic [54], various other international accords, and probably national laws, which rightly regard uncontained  $\text{CO}_2$  as a pollutant. All potential forms of uncontained  $\text{CO}_2$ , 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 that satisfy geologic permanence, as mentioned in Section VII.

It is important to remember that suitable secure geologic formations (of unlimited size) are not available in many places, and large scale economical storage locations needs to be in close proximity to the source, such as Ocean Macroalgal Afforestation operations or coastal power plants.

#### IX. ADDITIONAL CONFINING SYSTEMS

It may be easier to visualize geosynthetics as similar to geologic layers when realizing geosynthetic containers can be employed to inexpensively improve 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 in seawater, the quilt cement hydrates to a geosynthetic reinforced rigid concrete structure. This might be considered 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 CO<sub>2</sub> concentrations but reacting relatively quickly with any CO<sub>2</sub> leaked from a geosynthetic

membrane. The quilt becomes a rock made from the combination of silicate, CO<sub>2</sub> and seawater.\*

Weathering of silicate minerals (olivine or serpentine) is a natural method for removing CO<sub>2</sub> from the air [55]. Essentially, the weathered silicates cause the CO<sub>2</sub> 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 CO<sub>2</sub> absorption.

Of course there are many existing and many yet to be discovered ways to improve the layers used for container 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 container seafloor storage can be made on extremely small scales (tens to hundreds of kilograms of CO<sub>2</sub>). Such trials will gather extensive information on how containers interact with 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.

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 additional plans can be added quickly should earlier plans prove victim to unexpected situations.

We note that 2,100 billion tons of CO<sub>2</sub> stored as hydrate occupies 8,300 km<sup>3</sup>, which would raise global sea level only 24 millimeters.

#### X. CONCLUSION

This analysis indicates that governments and institutions should provide funding and facilities to conduct trials of contained seafloor CO<sub>2</sub> storage as soon as possible. SSCS should be considered as an option to add to other methods for permanent storage of trillions of tons of fossil CO<sub>2</sub>. It is important that all countries have access to storage options.

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\* Example 2 is patent pending.

demonstration have been incorporated into this technical description.

#### BIOGRAPHIES

**Mark E. Capron** is a marine, civil, and wastewater engineer. He received an M.S. in marine engineering from the University of California, Berkeley. He is an engineering innovator in the field of waste to energy and developed Ocean Macroalgal Afforestation to address the GHG-challenged world. He serves as the President of PODenergy, Inc. based in Ventura, California. Mr. Capron is a registered Professional Engineer in the State of California.

**Jim R. Stewart** received his Ph.D. degree in physics from Yale University, New Haven, Connecticut. He has worked as a researcher in nuclear and chemical physics, as well as a professor at the University of New Haven in Connecticut and the University of the West in Rosemead, California. Currently, Dr. Stewart is Vice President of PODenergy as well as volunteer co-chair of the Sierra Club California Energy-Climate Committee.

**Ronald Kerry Rowe**, BSc, BE, PhD, D.Eng, FREng, FRSC, FCAE, FEIC, FIE(Aust), FCSCE, FASCE, P.Eng, CP.Eng., is Professor and Canada Research Chair in Geotechnical and Geoenvironmental Engineering, Queen's University, Kingston, Ontario, Canada. Dr. Rowe was recently elected to the Royal Society, a fellowship of distinguished scientists.

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