GRAPHYTE

Graphyte Carbon Sequestration: Empirical Monitoring of Carbon Stability in Dry-tomb Chambers

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EXECUTIVE SUMMARY

This white paper presents one year of monitoring results from Graphyte's inaugural site, Project Loblolly in Sheridan, Arkansas. To date, Project Loblolly has sequestered more than 6,000 metric tons of carbon dioxide equivalent (CO_2e) in six sequestration chambers (zones). Direct gas measurements of carbon dioxide (CO_2) and methane (CH_4) concentrations within these zones demonstrate that the Carbon Casting system is preserving carbon captured by biomass (i.e., decomposition of sequestered biomass is not occurring).

Specifically, the data show no measurable increases in CH4 in any zone and minimal increases in CO2. The CO2 rates we observe are 50-100x lower than what would be expected from decomposing biomass and are consistent with the slow oxidation of trace organic carbon found within the sand infill material. In other words, the observed CO2 rates show no sign of biomass decomposition and instead indicate sand carbon oxidation. In addition, pressures are stable and temperatures move in line with seasonal variation, indicating that no biomass decomposition is occurring within the detection limits of the system.

These results provide direct evidence that Graphyte's Carbon Casting method prevents biomass decomposition at commercial scales for appreciable time periods. The monitoring framework enables ongoing verification of carbon stability with better than part-per-million (ppm) sensitivity, offering high-confidence durability assessments over project lifetimes. Graphyte's analytical system can detect anaerobic carbon degradation at sub-ppm levels, and will allow for ongoing direct measurement when all oxygen is depleted from a zone and thus becomes anaerobic.

INTRODUCTION

In its most recent report (AR6), the Intergovernmental Panel on Climate Change (IPCC) acknowledges that limiting warming to 1.5 °C will require not only dramatic reductions in greenhouse gas emissions, but also the large-scale deployment of carbon dioxide removal (CDR) technologies (IPCC, 2023). CDR plays two essential roles: first, to counterbalance “hard-to-abate” residual emissions—sectors like cement, steel, aviation, and shipping that are unlikely or difficult to decarbonize fully—and second, to draw down atmospheric CO_2 in the event of temporary overshoot beyond temperature targets.

CDR credibility depends on rigorous measurement, reporting, and verification (MRV) systems. In short, the most credible CDR technologies are the ones that can (1) directly measure the CO2 removed from the atmosphere and (2) verify that it remains out of the atmosphere. Focusing on CDR technologies that have high-fidelity MRV systems ensures that we focus our limited time and capital on solutions that are most likely to deliver credible climate benefits in the immediate future. Working inside rigorous carbon credit protocols, like the Isometric protocol under which this project is validated, further ensures high quality MRV and net removal claims.

BACKGROUND

Carbon naturally cycles between atmosphere, vegetation, soils, and long-term reservoirs. Most plant carbon returns to the atmosphere within years to decades, while only a fraction is stabilized in soils, peat, or fossil deposits. Graphyte’s dry-tomb method creates an engineered sink by physically isolating biomass so it cannot oxidize back to CO_2 or reduce to CH_4. This approach removes carbon from the active cycle, providing durable sequestration.

Most biomass decomposition is biologically mediated: aerobic microbes produce CO_2 while anaerobic decomposition pathways produce CH_4 and CO_2. Both biomass decomposition pathways require water, nutrients, and oxygen (in the aerobic case) to proceed. When exposed to surface conditions where water, oxygen and nutrients are abundant, unprotected biomass decays on short time scales. But restricting any one of these ingredients will sufficiently limit microbial growth for decomposition to come to a halt. Graphyte’s method interrupts these pathways by: (1) drying the biomass to a moisture content below 10%, (2) encasing the biomass material within a hermetically sealed, impermeable container, and (3) placing the encased biomass material in an enclosed dry-tomb made of impermeable membranes. In short, Graphyte’s method includes redundant barriers to necessary ingredients for biomass decomposition (i.e., water and oxygen) through encapsulation of the biomass material and placing the encased biomass within a dry-tomb made of impermeable membranes. A variation of this approach and its scientific basis was recently published by Yablonovitch and Deckman in the Proceedings of the National Academy of Sciences (Yablonovitch and Deckman 2023).

Most MRV systems for carbon removal technologies rely on indirect, model-heavy methods (e.g., seismic surveys in geologic carbon storage, soil coring for soil organic carbon, or flux towers/remote sensing for forest carbon projects). These approaches can be costly, uncertain, and slow to verify, often requiring assumptions about subsurface behavior or complex system dynamics. In addition, none of these approaches have ppm sensitivity for detection of biomass degradation. In the case of geologic sequestration for example, Li and Zhang conclude that accurate monitoring of CO_2 saturation and diffusion pathways around individual wellbores is only possible by combining seismic monitoring and logging technology together. They find that the strongest reported results limit error in CO_2 saturation estimates to 2% (Li and Zhang 2024) In contrast, Graphyte's MRV system measures the carbon contained within the biomass, directly monitoring the gases within the zones to provide ppm sensitivity (0.0001% or 20,000x more sensitive than geologic monitoring) for detection of biomass degradation. This type of monitoring is an extensible method for providing direct evidence that sequestered carbon is not being re-emitted to the atmosphere, verifying carbon stability at scale.

SYSTEM DESIGN

Cell and Dry-Tomb Design

Graphyte's dry-tomb zones are specifically designed to stop decomposition by eliminating access to the two ingredients that aerobic microbes need most: water and oxygen. These sealed, underground structures use a protective multilayer system to keep moisture and air out, creating conditions in which microbial activity is arrested. Should all oxygen be consumed, properly constructed dry-tomb structures eliminate access to the primary ingredient anaerobic microbes need: water.

The storage site cell, which includes the dry-tomb zones, is built above the local water table and shaped to promote natural drainage. Layers below and around the tombs are designed to route water away, while the biomass is stored in fully encapsulated zones. At the completion of a storage site cell, a cover system is installed on top to shed precipitation, manage runoff, and block infiltration.

All materials in the system are chosen for their long-term durability and ability to adapt to shifting terrain without cracking. The result is a redundant, multi-barrier structure that keeps stored biomass dry and sealed off from the elements for 1,000+ years.

Gas Monitoring System Design and Operation

To evaluate the integrity of Graphyte's dry-tomb carbon storage system, a fully automated gas monitoring network has been implemented across the burial site. The monitoring system is made up of two major components: a central control room which houses an analytical train of instrumentation inside a temperature-controlled enclosure and a sampling system made up of a network of piping and valves (see Box 1). Gas samples are conveyed from individual storage zones to the instrumentation room through a network of underground plumbing conduits and flexible tubing. Each conduit is connected to a dedicated sampling line inserted into the headspace of a given zone, where gas passively accumulates through diffusion into perforated piping inside.

Once a sample is drawn into the instrumentation room, it passes through an analytical train of sensors that gathers parameters which are essential for interpreting microbial viability, gas solubility and volumes, and the physical transport of gases within each sealed system.

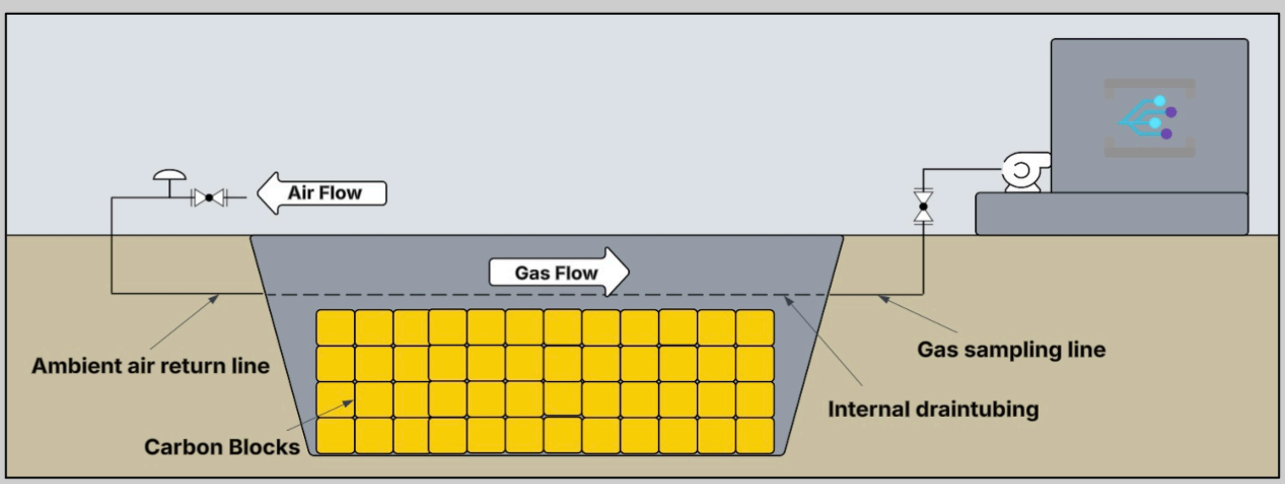
The sensors include:

- Temperature sensors and pressure gauges to characterize the sample conditions.
- A multi-gas sensor that provides simultaneous CO_2 and CH_4 concentration estimates along with relative humidity
- An oxygen sensor for detecting O_2 ingress or depletion.
- A cavity ring-down spectrometer (CRDS) for measurements of isotopic ratios of CO_2 and CH_4

Sampling cadences are fully configurable and can be adjusted between continuous real-time monitoring and scheduled discrete events, depending on the needs of the site or specific experimental protocols. This flexible architecture enables both routine surveillance and high-frequency temporal resolution during critical periods (e.g., early post-sealing or environmental perturbations).

Box 1.

The gas monitoring system consists of a series of sensors, piping, and control valves that pump gas samples from dry-tomb zones to an analytical train of sensors. Gas collects inside internal drain tubing and is conveyed to a housing where a control panel manages sampling cadences and measurements of the gas.



ANALYTICAL METHODS

Modeling Gas Exchange

Gas composition data and additional biophysical parameters do not directly indicate carbon loss from the system. The data must be processed and analyzed using an understanding of the physical geometries of the storage chambers, their volumes, and physical modeling of mass transport. The incorporation of additional environmental data, like barometric pressure, and the timing of sampling must also be considered.

After accounting for gas residence times and advection, concentrations are converted to molar volumes using Standard atmospheric, temperature and pressure (SATP) conditions (25 C, 1 bar) and finally to mass using a 1:1 molar ratio between carbon and CO_2. On these short time scales, first-order kinetic models describing reaction rates are used to characterize generation processes and linear approximations are applied, resulting in change in carbon mass over time. Rates of evolved carbon can then be normalized in various ways to assess competing hypotheses.

Exposure Pathways

Biomass within the storage site faces the following potential water exposure pathways:

- **Pathway 1:** Insufficient Drying. Biomass that was insufficiently dried could be encased and subsequently placed in the dry-tomb. The biomass would decompose and would cause the encasing layer to rupture resulting in CO_2 or CH_4 being released into the dry-tomb.
- **Pathway 2:** Humid Air. Moisture contained in humid air could migrate into the biomass if holes were present in material immediately encasing the biomass. The biomass would decompose and would either leak out of the holes in the encasing layer or cause the encasing layer to rupture resulting in CO_2 or CH_4 being released into the dry-tomb.
- **Pathway 3:** Water Incorporation Into Dry-tombs During Construction. Rain could enter the dry-tombs while they were being filled with the encased biomass and/or sand infill materials used to secure the fill can be wet. This moisture could then migrate into the biomass if holes were present in material immediately encasing the biomass. The biomass would decompose and would either leak out of the holes in the encasing layer or cause the encasing layer to rupture resulting in CO_2 or CH_4 being released into the dry-tomb.
- **Pathway 4:** Flooding Post Closure. The storage site itself could become flooded during an extreme flooding event if the design features (i.e., the post-filling contours to route water away from the dry-tombs, the compacted clay fill on the top of the storage site, the welds on the geomembrane system) were to have leaks or to all fail simultaneously.

Under pathway 1, biomass decomposition would be expected to occur rapidly as the biomass would be intimately exposed to water at the outset of burial. Pathways 2 and 3 would result in decomposition but on time scales limited by moisture diffusion rates into and out of package defects. This depends on the size and type of defect but on this pathway, biomass would reasonably begin to show signs of decomposition within months to years. Pathway 4 represents a different type of exposure pathway (i.e., an extreme flooding event overcoming design features) and thus is more appropriately assessed through an evaluation of the engineering of the storage site design (i.e., the probability of concurrent failure of multiple design features).

This white paper focuses on Pathways 1, 2, and 3. As explained below, the monitoring results demonstrate that the biomass is not decomposing and thus the Carbon Casting system is effectively blocking moisture through Pathways 1, 2, and 3.

RESULTS—ANNUAL ASSESSMENT OF CARBON STABILITY

Laboratory results

Before discussion of the field results, it is helpful to look at decomposition rates as measured in the laboratory. In collaboration with North Carolina State University, we prepared biomass samples and incubated them within closed chambers. The generated CO2 was measured using the titration of a NaOH solution which gives fine resolution of the evolved CO2. Carbon Casted biomass (dry, densified) as well as raw, undried biomass were tested and measured for a period of 2 years. As is evident in the chart below, the Carbon Casted biomass has shown no CO2 releases (within the detection limits of the method) while the undried biomass has released nearly 4.5% of its carbon. This provides evidence that the Carbon Casting method halts decomposition and gives a good counterfactual control scenario for what would occur if the biomass were undergoing decomposition.

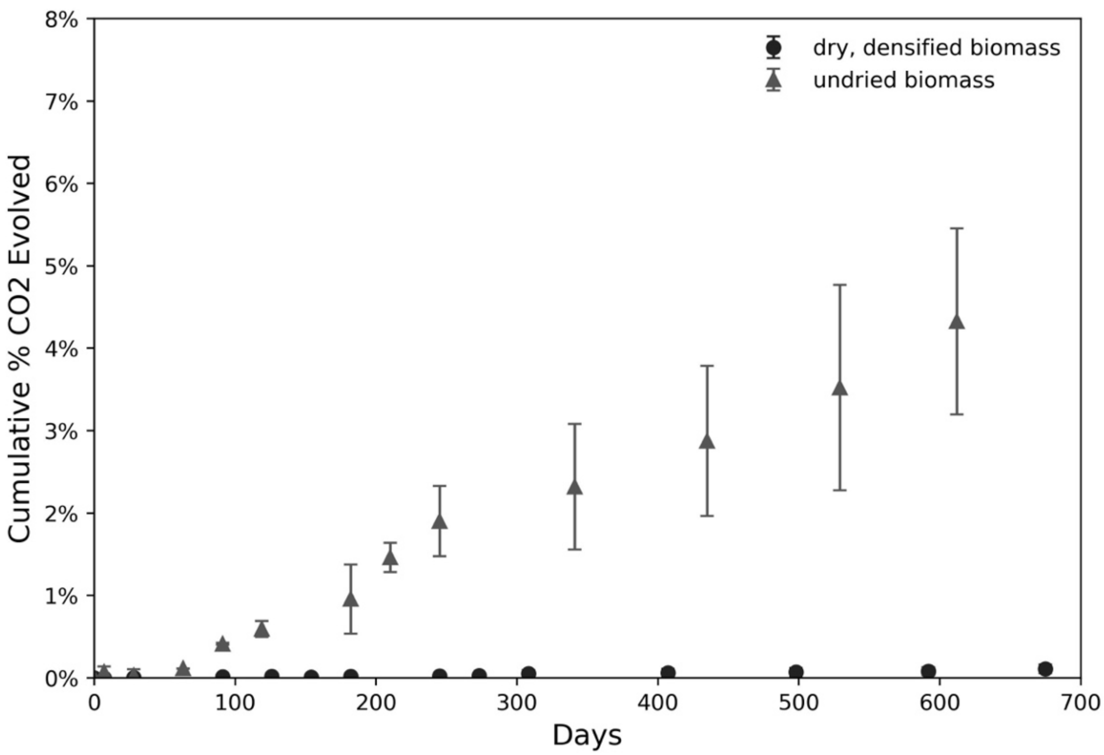


Figure 1. Laboratory measured cumulative carbon evolved (% of total carbon in biomass). Biomass samples of the same type used in Graphyte's commercial process were measured for carbon decomposition over time. One set of samples were left undried and the other set were Carbon Casted (dried, densified). Biomass was sealed in glassware and headspace gas was periodically sampled over 22 months. Carbon dioxide mass was determined using sodium hydroxide titration.

FIELD RESULTS

From direct measurement of gas concentrations at the Sheridan storage site, we report here the amount of gas produced within each dry-tomb zone. The following section analyzes the results based on the very low levels of measured CO2 within the headspace of each zone. As mentioned earlier, there were no detectable methane levels above levels measured in the atmosphere. Figures 2 and 3 below show the carbon generated within each zone in the period of time since closing the zone.

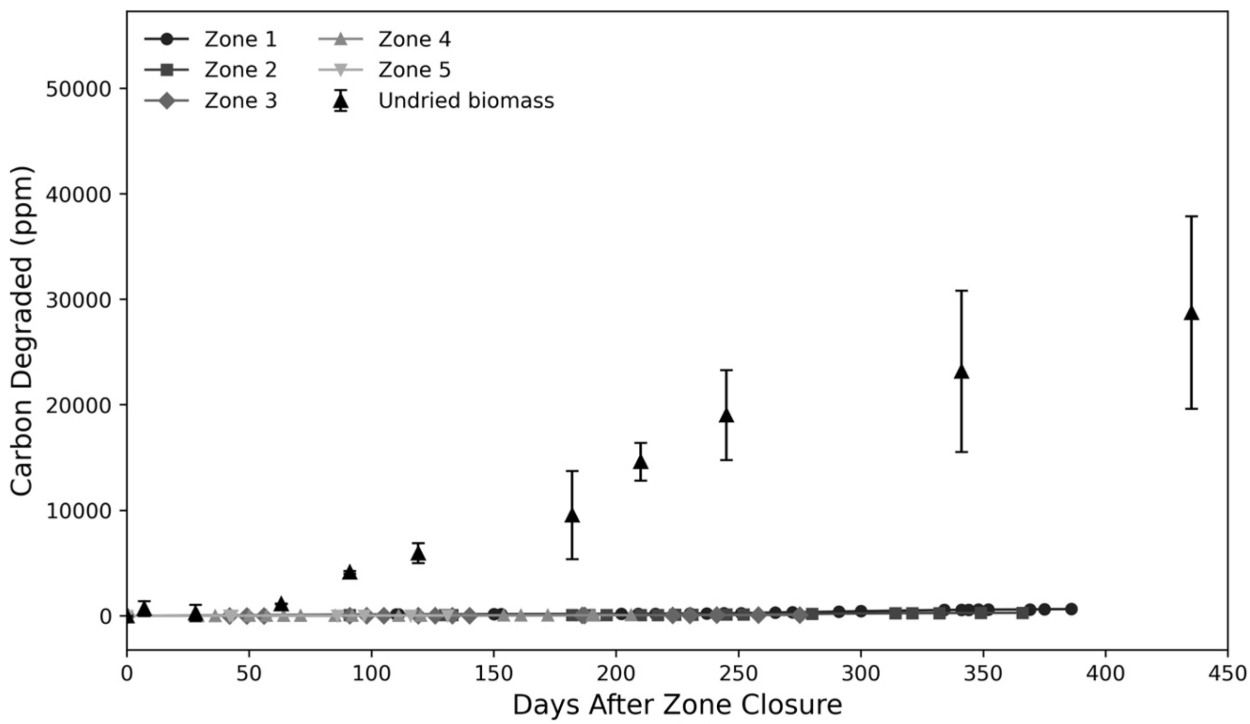


Figure 2. Part-per-million (ppm) carbon degradation for undried biomass and observed carbon degradation from Graphyte dry-tomb zones. Carbon loss rates for undried biomass are characteristic of typical environmental biomass decay while Carbon Casted material remains stable.

Overlaying the observed CO2 data in zones 1-5 against laboratory measured biomass decomposition results in a stark contrast in carbon decomposition rates. Undried biomass decays at rates observed in open systems while Graphyte's Carbon Casted material remained stable over the same time frame.

To assess observed carbon degradation on a finer scale, we multiply the literature rates for soil/sand organic carbon decay by the organic carbon content of the infill sand (220 mg / kg), which gives a predicted observed degradation rate in a range from 0.037 to 0.74 g C /m3 of sand infill /day. This range is shown in the shaded grey region in Figure 3 below.

As is evident in Figure 3, all of the zones exhibit CO_2 rates consistent with slow oxidation of trace organic carbon found within the sand infill material. Zones 1-3 and Zone 5 follow a similar path while Zone 4 is set slightly apart. There are many possible explanations, one of which is that natural variation in the sand results in different organic carbon content in the Zone 4 sand. The reported organic carbon content of the sand was taken from a limited sample set of sand and spatial variation of organic carbon content in sands/ soils is well-known to be variable. Another explanation is that Zone 4 has a significantly smaller fraction of sand (see SI) and because it also showed a higher mean temperature during the analysis period, likely due to seasonal variation, (see Table 1), it is possible the zone has a slightly higher reaction rate. The initial rate of carbon degradation is somewhat steeper but by day 150 returns within the literature rates. Regardless, Zone 4 is still well within the expected generation of CO_2 based on the literature rates for degradation of organic carbon.

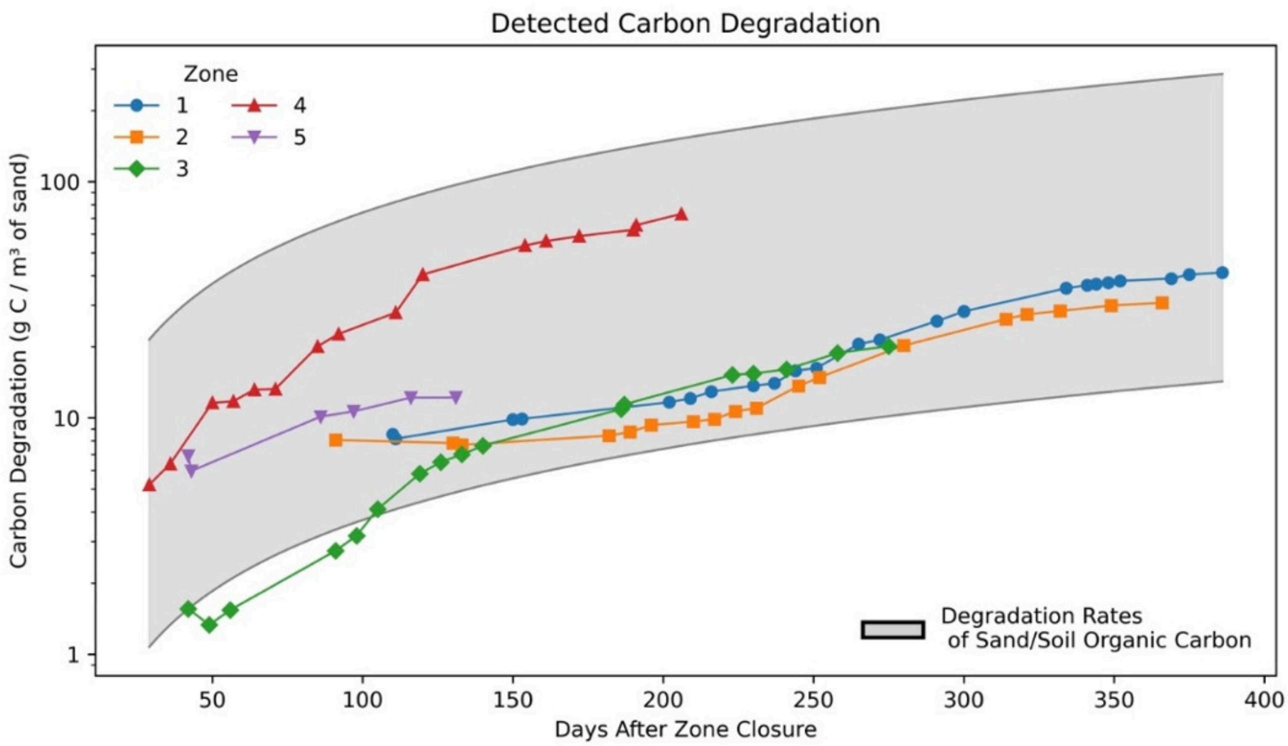


Figure 3. Log-scale carbon degradation rates in Graphyte zones 1-5 normalized by total sand infill volume. The shaded grey region represents literature rates for sand/soil organic carbon decomposition. Observed degradation rates fall within the expected region for decomposition of organic matter from sand infill.

In contrast, if biomass were absorbing moisture and degrading, we would expect to see much higher levels of CO_2 generation. In laboratory tests performed at North Carolina State University, degradation rates of 70-90 ppm/day were measured for the same time frame (roughly 50-400 days of decomposition). This rate is more than 100 times faster than the observed carbon degradation in the five zones in this analysis, representing very different behavior than measured.

Temperature and pressure data also support the observed gas composition analysis – that there is no biomass decomposition and only slow decomposition of trace organic carbon on the infill sand. Table 1 shows the range of temperatures and pressures observed inside each commercial zone. The observed temperatures remain consistent with ambient temperature and seasonal variation, while pressures deviate less than 1kPa (4" WC) from atmospheric, showing no signs of sustained pressure build up. With significant microbial activity, especially under anaerobic conditions, temperatures in municipal landfills can reach above 130 degrees F and gauge pressure can reach 10 - 50kPa (Ng, 2022). Typical municipal landfills have an organic fraction that is only 40-60% indicating that if they were of a similar organic fraction to a Graphyte Zone, we may expect to see even higher levels of gas generation and decomposition. The Graphyte zones are not approaching those levels, indicating biomass decomposition is not occurring within the measurement detection limits.

Zone	Temperature (°F)	Pressure Deviation ("WC)
Zone 1	72.38 ± 4.37	± 0.45
Zone 2	72.21 ± 4.90	± 1.12
Zone 3	74.67 ± 4.85	± 1.29
Zone 4	85.69 ± 9.34	± 1.14
Zone 5	63.38 ± 8.09	± 3.91

Table 1. Average temperature and pressure data from commercial zones 1-5. Temperatures remain within range of ambient conditions while no pressure increases have been observed. Zone 4 temperature is somewhat elevated compared to zones 1-3 and zone 5 due to a higher surface area exposure to the sun during the summer months in the analysis period. Pressures deviate both above and below atmospheric, indicating no directional trend in pressure.

From these results, we can conclude that the biomass was dry when it was placed into the tomb (i.e., Pathway 1 is not present) and that no water has entered the biomass within dry-tombs (Pathways 2, 3 are not present).

Any future decomposition would have to be a result of a major breach of the storage zone followed by a flooding event (Pathway 4). Anything short of those two combined events is unlikely to have impact on the water activity of the biomass due to the direct encapsulation of the biomass. For example, using the permeability of the encapsulation film, we have calculated that a continuous flow of 100% humid air throughout the zone would merely raise the biomass moisture content from 10% up to 11.4% over 1000 years. Similarly, the zone could be filled with liquid water for 115 years before the moisture content within the directly encapsulated biomass would rise above 12%, roughly corresponding to the water activity above 0.6 at which decomposition can begin.

Combining all of these analyses, it is clear that for future decomposition to occur, there would have to be a major seismic event beyond what the site is designed for (a probability less than 10% within 250 years) followed by a 1000-year flooding event. Even in that scenario, it is likely that only a fraction of the biomass encapsulation layers would be impacted, resulting in a partial exposure of the biomass to water. If 10% of the biomass encapsulation films were impacted in this cataclysmic event, and we apply the probabilities of these events occurring simultaneously, it results in a risk of decomposition from 1.12% of the biomass, well within the buffer pool (currently 7%).

CONCLUSIONS

Measurements from within Graphyte's dry-tombs indicate that the Carbon Casting system is preserving carbon captured by biomass (i.e., there is no evidence of biomass decomposition). Observed CO_2 concentrations are consistent with slow oxidation of trace organic carbon present in the sand infill that would have occurred naturally as part of the carbon cycle. The character of the change in gas composition and concentration is what we would expect in sealed, dry environments where biomass remains isolated from humid air, liquid water, and oxygen. We therefore conclude that the biomass was dry upon placement into the tomb, no water has been introduced during the first year of operation and any future decomposition would require introduction of water through a cataclysmic series of events. Additionally, we conclude that the monitoring system is performing as designed and is enabling the direct measurement of minute gas concentrations, an unprecedented level of accuracy for monitoring of carbon reversals.

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