THERMONUCLEAR EXPLOSIONS FOR LARGE-SCALE CARBON SEQUESTRATION: A CALL FOR EXPLORATION

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Climate change is a rapidly accelerating problem that requires fast and large-scale carbon sequestration to prevent catastrophe. This paper proposes a novel approach to use explosives for large-scale carbon sequestration. Combining the long-practiced method of explosive mining with newer enhanced rock weathering techniques, we propose a faster, greener, and potentially profitable method of large-scale carbon sequestration. This method is applicable for all explosives, including nuclear, and can be done safely with minimal anthropological and ecological impact. We estimate a cost of $5.16/ton of CO_2 sequestered with a potential profit of $2.12/ton of CO_2 sequestered.

Climate change is one of the biggest problems facing life on Earth today. Climate change refers to long-term shifts in global temperatures and weather patterns primarily caused by human activities, primarily the combustion of fossil fuels [1]. Its effects include more intense and frequent extreme weather events such as heatwaves, storms, droughts, and wildfires; accelerated melting of ice sheets and glaciers which drive sea-level rises; disruption of ecosystems and biodiversity loss; and growing risks to human health from heat stress, degraded air and water quality, and the spread of vector-borne diseases. Failure to properly tame climate change would result in millions of lives lost and hundreds of trillions of dollars lost [2, 3, 4].

One of the most severe issues of climate change is ocean acidification. Ocean acidification is the decrease in the average pH in the oceans due to the dissolution of carbon dioxide into the water. This carbon dioxide then turns into carbonic acid. This increased acidity increases the solubility of many chemicals, including calcium carbonate which many key species need to survive. Some of the most notable of these organisms are phytoplankton that produce much of the chemical energy in the marine ecosystems and corals that support 25% of all species living in the oceans [5]. For all of these reasons, many experts believe that ocean acidification is one of the most severe effects of climate change. [6]

The primary approach to reducing the impacts of climate change is through the reduction of carbon dioxide emissions. This approach has been accelerating, but many estimates, including the Intergovernmental Panel on Climate Change (IPCC), indicate that this approach will be too slow to prevent the worst impacts of climate change [7]. The IPCC estimates that 9 gigatons of CO_2 will need to be sequestered every year [3]. There are many approaches to large-scale carbon sequestration, including afforestation, direct air capture, carbon capture and storage, etc. Each of these approaches are estimated to cost $1 trillion per year to meet this 9 gigaton carbon sequestration level [8].

Enhanced rock weathering (ERW) is a newer approach to carbon sequestration in which the natural weathering process of rocks is accelerated by increasing the surface area of the rocks through pulverization. This process involves multiple reactions, such as the following using dissolved inorganic carbonates (DIC): $Mg_2SiO_4 + 4H_2CO_3 \rightarrow 2Mg^{+2} + 4HCO_3^- + H_4SiO_4$. ERW is estimated to sequester carbon for more than 10,000 years [9]. Most implementations of ERW involve crushing rocks using ball mills and spreading them over agricultural fields or on coasts. This process is expensive and slow. [10] When ERW is exposed to the ocean's DIC, it is often called ocean alkalinity enhancement (OAE).

ERW can be accelerated through the use of explosives. Explosives have been used for mining since their inception and for good reason. Explosives are cheap, easy to deploy, and effective at breaking rocks. Explosives are dangerous because they release large amounts of energy quickly and produce dangerous shockwaves. However, every explosive can be completely contained through a deep enough burial. The most powerful and cheapest per yield explosives are nuclear explosives. Nuclear explosives harness the energy of the strong nuclear force through fission and fusion to release tremendous amounts of energy in a chain reaction. The byproducts of nuclear explosives are dangerous because they are radioactive. However, these radiotoxins can also be contained through burial. [11]

To use explosives for large-scale ERW, we recommend a multi-stage process of identifying a suitable location, manufacturing suitable explosives, excavating deep cavities, allowing the explosives to settle, retrieving the pulverized rock,

exposing the rocks to DIC, and utilizing the coarser rocks for other purposes.

First, we need to identify a suitable location. The ideal location is very isolated from humans, possesses abundant weatherable rock, and is tectonically stable. These explosives can be detonated in relatively calm ocean waters or in isolated terrestrial locations. There is no shortage of locations that meet these criteria. It is imperative that this plan be conducted in such a location that the nearest humans are not affected physically or socially.

Next, we need to construct suitable explosives. These explosives must be very high yield, relatively inexpensive, and produce a shockwave with a high enough strain rate. Of the known explosives, thermonuclear devices fueled by natural lithium deuteride appear as a strong contender [12]. These devices are very high yield while also producing minimal radiotoxins, are relatively inexpensive, and produce very high strain rate shockwaves. Under this design, which is detailed in the Calculations Section, we estimate that a combined explosive yield of 9.24 gigatons of TNT equivalent is required. This yield can be split among multiple explosives to ensure safer and easier logistics. At $100 per kg of lithium deuteride, we estimate a total explosive cost of $92.4 million.

Next, the deep subseafloor cavities need to be excavated, denoted by (a) in Figure 1. The naïve approach to drilling these holes would be to drill a single vertical hole for each explosive. However, it may be optimal to use horizontal drilling for close placement of the explosives without the added cost of additional vertical drilling. Through the assumptions and calculations in the Calculations Section we show that burying each device 5.51 km below the seafloor should ensure complete containment of the explosion and allow for effective decay of short-lived isotopes. Our calculations indicate that a detonation at this depth would induce seismic-like activity equivalent to a local magnitude 4.66 event on the Richter scale. This "earthquake" would behave differently from a natural earthquake and would cause only slight disturbance to the surface. We also hypothesize that longer-lived radiotoxins (e.g. Cs-137, Sr-90) can be reduced to near-background levels within a few kilometers of burst zero using melt-glass encapsulation coupled with sorptive media (zeolites, illites, Prussian blue, sodium titanate, Sr-phosphate precipitation). Under these assumptions, excavation costs are estimated at approximately $19.2 billion.

Once the cavities are excavated the explosives can be buried and detonated, denoted by (b) in Figure 1. This explosive force will release a tremendous amount of energy that pulverizes the surrounding rocks. The explosives can be detonated simultaneously to improve the pulverization. The shockwave from these explosives will be completely contained due to the depth of burial. A side effect from these explosives is the radioactive products from fission and the neutron activation products.

After the explosion, we can simply allow the short-lived radiation to decay, denoted by (c) in Figure 1. One year after the detonation, the short-lived radionuclides will decay to negligible levels. While this step is not strictly necessary or functionality, this step further minimizes risks to marine organisms and any future human activities in the area.

After this delay, the pulverized rocks need to be retrieved from their depths, denoted by (d) in Figure 1. Using standard hydraulic dredging and lifting techniques, we assume recovery of the rock particles from several kilometers' depth is feasible. Our calculations in the Calculations Section estimate costs at $17.0 billion. It should be noted that both drilling and retrieval are much less expensive terrestrially, which may be an option for this idea if there is little concern of ecological or anthropogenic harm in a desolate location.

After retrieval, there are a few options to allow these particles to weather and sequester carbon. The first is to spread the particles on the seafloor. This option is easy and cheap, but could result in catastrophic destruction of the sensitive seafloor ecosystem if done improperly. One key candidate for this alkaline rock spreading is dead zones. Dead zones are areas of the ocean that have very low dissolved oxygen concentrations and result in very little macrobiodiversity [13]. Due to the lack of life, spreading additional basalt powder would likely have minimal effect on the local biodiversity. The area of these dead zones is 245,000 km^2 [13]. At a rock powder thickness of 0.1 m, sequestering 9 Gt of CO_2 would require 200,000 km^2, which is less than the area of the dead zones in the ocean. Another option for rock particle weathering is to expose these particles to the ocean water on sub-surface rafts. These rafts can expose very large surfaces with a thin layer of rock, denoted by (e) in Figure 1. In addition to preventing benthic disturbance, these rafts would likely benefit the local marine populations, serving as fish aggregating devices [14]. In the Calculations Section we estimate that these rafts would cost $10.2 billion to construct and implement. The third option is to use these alkaline particles as a targeted relief effort against ocean acidification, using the delivery mechanisms above. Coral reefs are a key ecosystem, particularly vulnerable to ocean acidification and decalcification. By spreading large amounts of alkaline particles near coral reefs, they can be shielded from global ocean acidification, through a process called alkalinity injection [15]. Another vulnerable population is the seafloor. Through a mild application of these alkaline rock particles, the local environment would be more alkaline and the calcifying organisms would be more likely to survive. The fourth option is to use terrestrial rock weathering either on shorelines or on agricultural fields. Clearly, there are a lot of options for these alkaline particles and they should be spread in a manner that is beneficial to the environment as well as easy and quick to implement.

At this point, the pulverized rocks are on their way to sequestering billions of tons of carbon dioxide from the ocean, and thus, the atmosphere. However, the byproducts of these buried explosives are also valuable. The pulverized rocks that

are too large to weather in reasonable time spans can be used for aggregate, denoted by (f) in Figure 1. Our calculations shown in the Calculations Section show that billions of dollars in profit can be expected.

To further emphasize the minimal effects of this idea on marine life, we will break down each of the effects. First, in a few hundred square meters, the seafloor will unavoidably be destroyed by the drilling. Second, there will be a massive shockwave. However, due to the depth of the burial, this shockwave will have zero influence above the rock and will not affect wildlife in any way. Next, the rocks themselves will release a fair amount of pollutants like mercury and lead. These pollutants can be minimized by using rocks with lower concentrations of the pollutants. Additionally, the amount of pollutants released into the oceans is orders of magnitude less than the amount of lead and mercury released into the environment every year through other anthropogenic activities. Finally, and perhaps most feared, is the release of radiotoxins. Nuclear explosives release large amounts of radiotoxins, from short- to long-lived isotopes. Due to the delayed retrieval after the explosion, we only need to discuss the effects of the medium- to long-lived isotopes. Of these isotopes, Cs-137 and Sr-90 are the most deadly to life. However, we postulate in the Calculations Section that we can contain the release of these dangerous isotopes by more than 99.999%. At this reduction of dangerous isotopes, the remaining released dangerous isotopes are barely above background levels. The reduction methods for Cs-137 and Sr-90 are studied and well-known and include melt-glass confinement, sorption by zeolites, illites, Prussian-blue, and sodium titanate. Through these measures we can be very confident that almost zero marine life will be affected with the worst effects being the hole drilling. However, these negative effects are wildly overshadowed by the positive effects of reducing the effects of climate change, reducing the mining of the seafloor for concrete aggregates, and additional environments created by fish aggregating devices.

Politically, this plan presents challenges and opportunities. Large explosives, especially nuclear explosives, are dangerous. Treaties like the Non-Proliferation of Nuclear Weapons and the Comprehensive Nuclear-Test-Ban Treaty prevent any nuclear explosions for fear of nuclear proliferation. Although this plan is aimed to prevent global catastrophe, the use of nuclear explosives is not to be taken lightly. For these reasons, the choice of the implementing country is crucial. The ideal nation would need to possess nuclear weapons and the technological capacity to conduct this operation safely, while also maintaining a relatively neutral position with other nuclear-capable nations. While this plan presents political challenges, it also presents political opportunities. Climate change will contribute to global tensions and preventing some of these tensions will reduce global conflicts [16].

In conclusion, this proposed plan uses explosives buried deep under the seafloor in an extremely isolated place to pulverize rocks into carbon-absorbing particles. These carbon-absorbing particles are then suspended in rafts to increase their surface area to allow for faster carbon sequestration. Additionally, the byproducts of this plan can be used to make the entire venture profitable. With our assumptions and calculations, we estimate that the total cost is $5.16 per ton of CO_2 sequestered at gigaton scales. All possible negative effects like earthquakes, radiotoxicity, and heavy metal pollution are estimated (in the Calculations Section) to be negligible. This idea introduces political challenges, but similar challenges have been overcome before. While we are hopeful that other actions can be taken to prevent global catastrophe from climate change, we open the door to study for a "Plan B" in the event that appropriate decarbonization is not done.

Calculations

The following calculations support the hypothesis that this idea is physically and economically feasible and far better than other carbon sequestration options. To reiterate: these calculations are not expected to be exact. There are still many unknowns for this idea. We are proposing this idea to open the door to further study.

1. MISCELLANEOUS CONSTANTS

First, we have a few oceanographic constants that we will use throughout our calculations.

Constant	Value	Unit
Global water volume	1.33×10^9	km^3
Global ocean surface area	3.62×10^8	km^2
Assumed average water depth in abyssal plains	5	km
Total volume of the oceans	1.33×10^{18}	m^3
Density of seawater	1030	kg/m^3

Table 1: Key oceanographic constants

2. AMOUNT OF ROCK REQUIRED

Through the ERW reaction, 1 ton of rock can sequester 0.15 tons of CO_2 [1]. To sequester 9 Gt of CO_2, this requires 60 Gt of rock, as shown below:

$$\frac{9 GtCO2}{\frac{0.15 tCO_2}{1 trock}} = 60 \text{Gt rock}$$

A single sphere of this amount of rock has a diameter of 3.36 km, through the calculations below with the assumption that rock has a density of 3 tons/m^3 [17]:
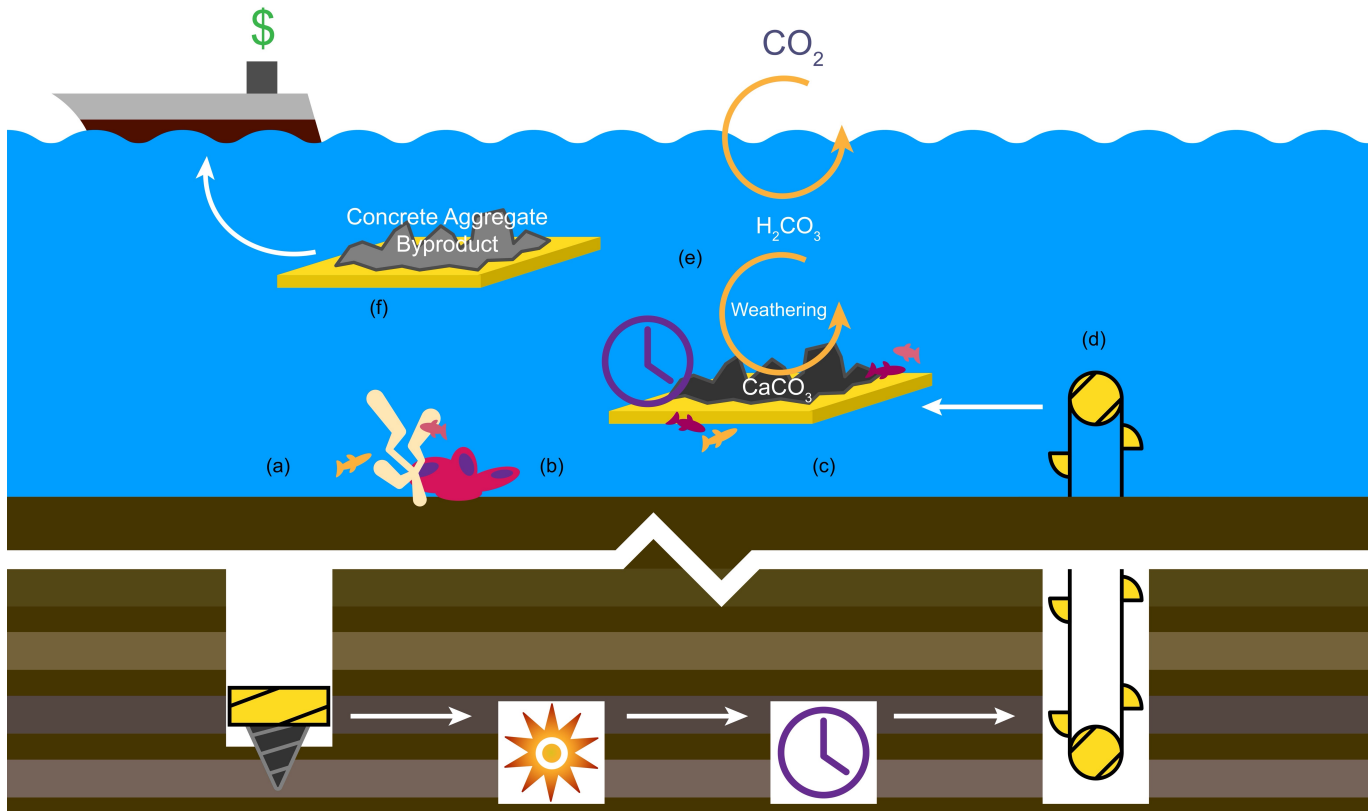
Fig. 1: Concept of the Plan to use Nuclear Explosions for Large-Scale Carbon Sequestration in which **(a)** the hole is drilled into the seafloor **(b)** the explosive is detonated **(c)** the radioactive isotopes decay **(d)** the carbon-capturing rock powder is transported out of the hole **(e)** the rock powder is suspended upon rafts underneath the surface to allow for the weathering reaction to sequester large amounts of dissolved inorganic carbonates **(f)** and the byproducts are used as concrete aggregate to make this concept profitable. This figure also shows the lack of effects of marine life around the detonation site as well as the fish aggregating around the rafts.

$$V = 60E9t * 1m^3/3t * (1km/1000m)^3 = 20km^3$$

$$d = \left(\frac{6V}{\pi}\right)^{\frac{1}{3}}$$

3. TOTAL EXPLOSIVE YIELD

We need to determine the explosive yield required to pulverize 60 Gt of rock. To calculate this, we need to make some assumptions:

1. Specific energy of fragmentation of rock, $E_{frag-rock} = 205MJ/m^3$ [18]

2. Efficiency of the explosion = 10.6% (calculated in Subsection 6)

Using these values, we can perform the following calculation:

$$\frac{V * E_{frag}}{efficiency}$$

This results in a yield of 9.24 Gt of TNT equivalent.

4. PRICE OF NUCLEAR EXPLOSIVES

The price of nuclear explosives is not publicly available. However, for this analysis we are assuming that the fission cores for these explosives will be free. This is a reasonable assumption because the fission cores are continuously decaying and thus need to be replaced or refurbished frequently. This is commonly called "use it or lose it" and by using only these nearly expired cores we can save a lot on the price of these explosives. Therefore, we can just calculate the amount of fusion fuel that will be needed. The following are assumed.

1. Yield per kg of a real weapon, which includes the efficiency = $10kt/kg$. This value can be reasonably assumed from the Castle Romeo and Castle SHRIMP tests which used natural (unrefined) lithium deuteride as the fuel. [12]

2. Price of lithium deuteride fuel = $100/kg

Now, the cost of the fusion fuels can be calculated:

1. Mass of fusion fuel required = Total yield / Yield per kg of real weapon / 1000 = 924 tons.

2. Cost of fusion fuel = Mass of fusion fuel required / $/kg = $9.24E7

This is a very modest price for the value that this proposal provides. Additionally, depleted uranium tampers are waste products that can massively enhance the yield of these explosives cheaply, at the expense of more radiotoxins released.

5. DESIRED PARTICLE SIZE

Enhanced rock weathering is a slow process and its reaction time is directly related to the particle size. As a result, smaller particles weather faster. Using the assumptions and requirements:

1. Desired weathering time < 20 years. This value is chosen subjectively to balance the urgency of large-scale carbon sequestration, the energy scaling of fragmentation, and the particle size distribution that is generated upon explosion.

2. Weathering rate = 2.31E-11 mol $m^{-2}s^{-2}$ [19]

3. Molar mass of rock = 216.549 g/mol [20]

The following are the calculations:

1. Estimate particle radius = 3.1um

2. Particle surface area (perfect sphere) = $4*pi*$particle radius$^2 = 1.21E - 10m^2$

3. Particle mass = $4/3 * pi * r^3 *$ rock density $= 3.74E - 10g$

4. Moles of rock = $1.73E - 12mol$

5. Weathering time = Moles of rock / (WeatheringRate * Particle surface area) = 6.18E8 s = 19.61 years

We can conclude that a particle size of approximately 6.2 μm is suitable for weathering within 20 years.

5.1. Particle Size Distribution

The particle size distribution (PSD) for a nuclear explosion can only be roughly estimated with existing public data. There is limited data on the existing nuclear explosions and their PSD. Additionally, conventional mining attempts to reduce the creation of fine particulates, so we cannot rely on conventional mining as well. However, we still must estimate the PSD.

5.1.1. Specific Charge

To begin, we first need to estimate the specific charge for a nuclear blast (specific energy per unit volume, with energy written in terms of kilograms of TNT-equivalent) for the blast. The pulverized volume depends significantly on the depth of burial [11]. For this proposed plan, the blast will be completely contained. However, there is even less data on completely contained nuclear explosives, so we will use the data for the optimal depth of burial to maximize crater formation. The depth of burial that maximizes the ejecta volume in hard wet rock is

$$d^* = 40m \cdot \left(\frac{W}{1kt}\right)^{0.3}$$

where W is the explosive yield (nominally in kilotons of TNT equivalent). As an example, the 1.2 MT B83 nuclear explosion from the U.S. arsenal would have an optimal depth of burial of about 340 meters. To completely contain the explosion, as is proposed herein, the depth of burial for a 1.2 MT nuclear explosion must be at least 1.3 km deep.

Since we need to find the charge density of the pulverized rock volume, we first need to estimate the total volume of the true crater, assuming optimal depth of burial. Glasstone and Dolan describe the evacuated zones as approximately parabolic, and a relationship is given for the apparent depth, but not the true depth [11].

To estimate the true depth, let us assume that the optimal depth of burial is the focus of a parabola tracing out the true crater boundary. Under this assumption, we can estimate the true depth (the vertical distance from the vertex of the parabola to the original seafloor) using just R_a, and the depth of the burst d^*, as:

$$D_{true} = \frac{\sqrt{(d^*)^2 + R_a^2} - d^*}{2}$$

,

where the apparent radius R_a is given by Glasstone and Dolan as

$$d^* = 46m \cdot \left(\frac{W}{1kt}\right)^{0.3}$$

is the above equiation 40 or 46? previously it was 40

The (true) crater volume, estimated as a paraboloid, is

$$V = \frac{\pi}{2}D_{true}R_a^2$$

,

and the specific charge is

$$q = \frac{W}{V} \approx 29W[\text{kt}]^{0.1}[\text{kgTNT/m}^3]$$

.

For our B83 example, this computes to a specific charge of 59 kgTNT/m³ = 2.5×10^8 J/m³ = 8.4×10^4 J/kg-rock. This is about 100 times the speciic charge typically used in conventional blasting, which places this into a high-energy regime and affects our ability to predict the median particle size using traditional blast data.

we get 8.33 if we use basalt density of 3.0 g/cm³

5.1.2. Estimation of the Swebrec Fit Parameters

To calibrate the Swebrec function, we need to predict the particle sizes at which different percentiles in the mass passing fraction occur. These can be obtained for an arbitrary specific charge using the fragmentation-energy fan method. Specifically, this approach is based on the observation that when the logarithm of sieve size is plotted against the logarithm of the specific charge, all the data for a given mass-passing percentile (regardless of the speciic charge) will lie in a straight line in log-log space. The different percentiles form a set of lines, each with a different slope converging at a single focal point that depends on the type of rock being blasted, thus forming a 'fan' shape [21]. However, once the specific charge exceeds roughly 2 kgTNT m⁻³ (depending on the material), the blast enters the high-energy regime and the straight lines exhibit a kink and turn to a more shallow slope [22]. This occurs well above the specific charges for normal blasting, but well below the specific charge of a nuclear blast. This regime is found mainly in mechanical rock crushing. To cope with this regime, the double fan theory was developed that joins the two slopes for each percentile class at the inflection points.

From the fragmentation-energy-fan theory [21], we have

$$b = \frac{ln(\frac{1-P}{P})}{ln(\alpha_p/\alpha_{50})}$$

where P is any percentile class other than P = 50.

For "very fresh basalt," sieving data from Faramarzi are published as Figure A6.1 in [22], which is reproduced here as Figure 2. Ouchterlong et al. [22] report that for basalt, the Swebrec undulation parameter of our Eq. 1 was found to be $b = 2.19 \pm 0.27$. They also report that the log-space slope of the 50th-percentile line in the high-energy fan is $\alpha_{50}^H = 0.8817$. Other data in Fig. 2 have been non-dimensionalized in terms of particle sizes and scaled in terms of blast energy.

An expression for the medial (50th-percentile) fan line in the high-energy regime (H) is given by

$$x_{50}'^H = CE'^{-\alpha_{50}^H}$$

.

Inserting α_{50}^H and solving for C using the intersect point $(E_0', x_0') = (0.0719, 1.8031)$, we have:

$$x_{50}'^H = 0.177E'^{-0.8817}$$

.

The same procedure for the 20th-percentile fan line in the high-energy regime will give

$$x_{50}'^H = 0.05225E'^{-1.3452}$$

.

We now make the change of variables to rescale the energy redimensionalize the particle size:

$$E' \Rightarrow E_{cs}(D/D_0)^\lambda = E_{cs}(x_{\text{max}/25\text{mm}})^{0.5142}$$
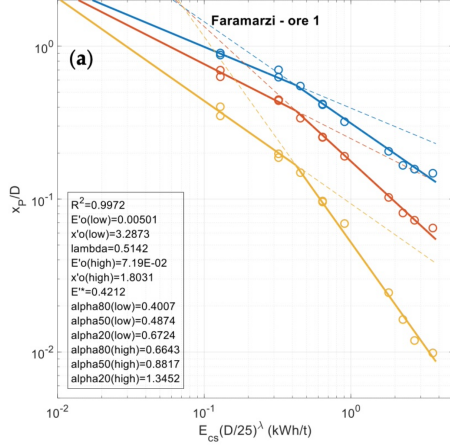
Fig. 2: The double fragmentation-energy fan for Basalt samples collected by Faramarzi reported as Figure A6 in [22]. The bottom yellow line is the 20th percentile, the red middle line is the 50th percentile, and the top blue line is the 80th percentile. Note that here D is the original particle size before crushing, equivalent to $x_{\max}$, and the axes have ben non-dimensionalized.

$$x_p'^H \Rightarrow x_p/D$$

giving expressions in D. Noting also that, per [22], $D \equiv x_{\max}$, we have:

$$x_{\max}/x_{50}^H = [0.177(E_{cs}(x_{\max}/25\text{mm})^{0.5142})^{-0.8817}]^{-1}$$

$$x_{\max}/x_{20}^H = [0.05225(E_{cs}(x_{\max}/25\text{mm})^{0.5142})^{-1.3452}]^{-1}$$

,

which we can relate to each other through the Swebrec function:

$$F(x) = \left[1 + \left(\frac{ln(x_{\max})/x}{ln(x_{\max})/x_{50}}\right)^b\right]^{-1}$$

For the 20th-percentile gives us:

$$0.2 = \left[1 + \left(\frac{ln(x_{\max})/x_{20}}{ln(x_{\max})/x_{50}}\right)^b\right]^{-1}$$

$$0.2 = \frac{1}{1 + \left(\frac{\ln\left[19.1388\left(E_{cs}(\frac{x_{\max}}{25\text{mm}})^{0.5142}\right)^{1.3452}\right]}{\ln\left[5.64972\left(E_{cs}(\frac{x_{\max}}{25\text{mm}})^{0.5142}\right)^{0.8817}\right]}\right)^{2.19}}$$

Solving now for $x_{\max}$, we have

$$x_{\max} = 25\text{mm} \cdot 0.14833 E_{cs}^{-1.94477}$$

.

Here E_{cs} is the specific communition energy in units kWh/tonne$_{\text{rock}}$, which is the energy version of the specific charge calculated previously. We computed that for the 1.2 MT explosive we have 8.4×10^4 J/kg-rock = 23 kWh/tonne, which is the appropriate units for these relations. This gives $x_{\max} = 8.3\mu$m.

In fact, by comparison to the inflection point, we find our energy is actually in the low-energy regime. The log-space slope of the 50th percentile line in the *low-energy* fan is $\alpha_{50}^\ell = 0.4874$. Using the intersect point $(E_0'^\ell, x_0'^\ell) = (0.00501, 3.2873)$, we have:

$$\left(\frac{x_{\max}}{x_{50}^\ell}\right) = \left[0.24874\left(E_{cs}\left(\frac{x_{\max}}{25\text{mm}}\right)^{0.5142}\right)^{-0.4874}\right]^{-1}$$

,

$$\left(\frac{x_{\max}}{x_{50}^\ell}\right) = \left[0.09337\left(E_{cs}\left(\frac{x_{\max}}{25\text{mm}}\right)^{0.5142}\right)^{-0.6724}\right]^{-1}$$

.

Relating these through the Swebrec function

$$0.2 = \frac{1}{1 + \left(\frac{\ln\left[10.7100\left(E_{cs}(\frac{x_{\max}}{25\text{mm}})^{0.5142}\right)^{0.6724}\right]}{\ln\left[4.02031\left(E_{cs}(\frac{x_{\max}}{25\text{mm}})^{0.5142}\right)^{0.4874}\right]}\right)^{2.19}}$$

.

Solving now for $x_{\max}$, we obtain

$$x_{\max} = (25\text{mm})\cdot 0.13897 E_{cs}^{-1/\lambda} = (25\text{mm})\cdot 0.13897 E_{cs}^{-1.94477}$$

,

where $T = \frac{R\ln(4.02031) - \ln(10.7100)}{\alpha_{20}^\ell - R\alpha_{50}^\ell}$ and $R = (1/0.2 - 1)^{1/b} = 4^{1/2.19}$. For $E_{cs} = 23$ kWh/tonne in the low-energy regime, we find $x_{\max} = 7.8\mu$m.

While these results are just estimates, we will assume that they are approximately correct. We will use the estimate that 20% of all particles are smaller than 8.3μm. While this is not exactly the 6.1μ, particle size predicted to weather within 20 years, the average particle size is nearly the same size and an 8.3μm particle weathers in approximately 26.5 years.

6. ENERGY EFFICIENCY FOR CREATING DESIRED PARTICLE SIZES

The efficiency of the energy used to pulverize the rock to the desired particle size is calculated in this section. First, we have the assumptions:

1. Blasting energy proportion transferred to the rock = 0.53 [23]

2. 20% of rocks by mass pulverized are acceptably small (taken from Subsection 5.1).

Followed by the calculations:

1. Energy efficiency of creating desired particles = Blasting energy proportion transferred to rock * mass fraction of desired particle size = 0.106

Therefore, approximately 10.6% of the energy released in the explosion will produce particles that will weather within 26.7 years. It should be noted that there is very little and antiquated information around the blasting properties of nuclear explosives, so much more study or publication of information is required in this respect. Additionally, multiple thermonuclear explosives have ever been detonated simultaneously in close proximity, so any conclusions drawn are extrapolations of conventional or single-burst nuclear explosions.

7. BURIAL DEPTH AND PRICE TO COMPLETELY CONTAIN THE EXPLOSION

Nuclear explosives are extremely dangerous and produce a massive shockwave. In order to completely contain this explosion we can bury the explosives far beneath the seafloor. This ensures that the only destruction to the seafloor is the area required to drilling the hole, which should be in the range of square meters. To start with the calculations, we have the assumptions:

1. Number of explosives = 100. This number of explosives is on the order of magnitude of expiration of nuclear explosives as well as a good number to reduce the cost of digging holes.

2. Time to dig a 5.5 km deep hole < 60 days [24]

3. Price to dig a 5.5 km deep hole = $96 million [24]

4. Number of holes drilled per explosion = 2. This is for placement of the explosive and retrieval of the rocks.

Followed by the calculations:

1. Yield of each explosive = Total yield / number of explosives = 92.4 Mt

2. Depth of burial of each explosive = $400*0.3048*(\text{yield of each explosive})^{\frac{1}{3}}/1000 = 5.51$ km [11]

3. Price of hole burials = Price to dig a single hole * number of explosives = $19.2 billion

Therefore, if the nuclear explosives are buried 5.51 km under the seafloor, there will be no adverse impacts from the shock waves on the wildlife or humans. The cost to bury all of the explosives is estimated at $19.2 billion.

8. PRICE OF PUMPING THE ROCK OUT OF THE HOLE

After the rock is pulverized it will not simply weather in the hole; the rock powder needs to be exposed to the water. This requires excavating the rock powder out of the hole, which requires energy and costs money. Due to the sizes of the particles, with 18% of the particles being smaller than 2 μm and 99% of the particles being smaller than 62.5 μm, the pulverized basalt would be considered clayey silt. Hydraulic dredging is often the most economical and efficient method for large-scale excavation of clayey silt [25]. Starting with the assumptions:

1. Efficiency of pumping = 70% [26]

2. Electricity price = $0.0132/kWh [27]

Followed by the calculations:

1. Energy to lift the rock out of the chimney = total rock mass * g * depth of burial = 9.25E11 kWh

2. Price to lift the rock out of the hole = energy required to lift the rock out of the chimney * electricity price per kWh / efficiency of pumping = $17.4 billion

Therefore, we estimate that it will cost $17.4 billion to lift the rock powder out of the holes.

In addition to the benefits of cheaper drilling terrestrially, it may be desired to spread these particles very quickly using a thermonuclear explosive. This will be much more effective terrestrially due to the more freely moving air than water. It is possible to detonate multiple thermonuclear explosives deep underground, wait until the radiation decays, then use another explosive to spread this pulverized rock. In this scenario, most of the radiation may be reduced while simultaneously spreading the rocks in a wide area. This spreading mechanism would likely reduce the excavation cost to a negligible value.

9. PRICE OF FLOATING THE ROCKS ON RAFTS

Next, we want to expose the rocks to the water. Spreading the rocks over the seafloor will likely require rafts of similar magnitude in size. An environmentally friendly way to expose this rock to the water is by floating it on rafts. Starting with the assumptions:

1. Rock powder thickness = 0.1 m. This value is chosen as a nice medium between raft area required and exposure to the water.

2. Number of rafts = 10000. This number is chosen as it keeps the individual raft size from being excessive.

3. LDPE density = 920 kg/m^3 [28]

4. Film thickness = 200 micrometers. This number is chosen as a normal thickness of LDPE films.

5. Price of LDPE = 1.25 \$/kg [29]

6. Cost of recycling LDPE per ton = \$138.4589 [30]

Followed by the calculations:

1. Total area of rafts required = total volume of rock / rock powder thickness = 200,000 km^2

2. Area of each raft = 20 km^2

3. Assuming the cheapest possible design of 2 layers of cheap recycled plastic containing air with rock on top.

4. Price per area = plastic film thickness * plastic density * plastic price per area = \$0.230/m^2

5. Price of plastic film for all rafts = \$46 billion

6. Recycling monetary efficiency = (price of plastic - cost of recycling) / price of plastic = 89%

7. Total price of plastic for the entire lifecycle = \$5.1 billion

8. Doubling this price to account for engineering effort results in a price of \$10.2 billion

Therefore, we estimate that it will cost \$10.2 billion to sustain floating all of this rock in the ocean.

10. FINAL PRICE PER TON OF CARBON DIOXIDE SEQUESTERED

Summing the prices of the fusion fuel, digging the holes, lifting the rock out of the holes, and floating the rock on the plastic rafts, we estimate that it will cost \$46.5 billion to sequester 9 GtCO2, which amounts to \$5.16/ton of CO_2. Even without using the byproducts we see that this is likely one of the cheapest and most feasible methods of sequestering carbon dioxide on a global scale.

11. MISCELLANEOUS EFFECTS

This proposal will certainly have consequences besides carbon sequestration.

11.0.1. Radioactive Contaminants Released

Nuclear explosions produce radioactive waste that is extremely dangerous at high levels. We are assuming that the fission cores contain 10 kg of plutonium [31], but the same analysis for uranium cores contains similar amounts of radioactive contaminants. Additionally, we are assuming that these explosions will be completely contained underground for a year before they are mixed with the seawater. As a result, the most notable radiotoxins are Cs-137 and Sr-90.

For this analysis we are assuming 100 explosions, which results in a combined total fission core yield of 1000 kt of TNT.

Cesium-137
Starting with Cs-137, we have the assumptions:

1. Half-life = 30 years [32]

2. Fission product yield = 6.5% [33]

3. Confinement to melt glass = 40% [34]

4. Sorption by zeolites = 95% [34]

5. Sorption by illite = 93% [?]

6. Sorption by Prussian-blue = 99.81% [35]

7. Sorption by sodium titanate = 40.67% [36]

8. Background level = 1 Bq/m^3 [37]

Followed by our calculations:

1. The mass of Cs-137 produced per kg of fissile fuel = 1000 g / 239 g/mol * fission product yield * 137 g/mol = 37.3 g/mol

2. Initial radiation = 1.2E17 Bq

3. Radiation after 1 year's delay = 1.17E17

Through confinement to melt glass, sorption by zeolites, sorption by illite, sorption by Prussian-blue, and sorption by sodium titanate under ideal conditions results in a total mitigation of Cs-137 released into the ocean of 99.9998%. This results in 2.77E11 Bq of Cs-137 released into the ocean. Upon dilution into a radius of 133 km in the ocean, this results in double the background level. When diluted in the entire ocean volume, this results in a miniscule 2.08E-7 Bq/m^3, which is millions of times less than the background levels.

Sr-90
The second major anthropological hazard is Sr-90, as it behaves like calcium and is deposited in bones. Here we have our assumptions:

1. Half-life = 29 years [38]

2. Fission product yield = 7.32% [33]

3. Confinement to melt glass = 50% [34]

4. Sorption by zeolites = 40% [39]

5. Sorption by sodium titanate = 99.9% [36]

6. Sr-phosphate precipitation = 99% [?]

7. Background level = 1 Bq/m^3 [40]

Followed by our calculations:

1. The mass of Sr-90 produced per kg of fissile fuel = 1000 g / 239 g/mol * fission product yield * 90 g/mol = 27.6 g/mol

2. Initial radiation = 9.18E16 Bq

3. Radiation after 1 year delay = 8.96E16 Bq

Through confinement to the melt glass, sorption by zeolites, sorption by sodium titanate, and Sr-90 phosphate precipitation under ideal conditions results in a total mitigation of Sr-90 released into the ocean of 99.9997%. This results in 8.96E16 Bq of Sr-90 released into the ocean. Upon dilution into a radius of 131 km in the ocean, this results in double the background level. When diluted in the entire ocean volume, this results in a miniscule 2.02E-7 Bq/m^3, which is millions of times less than the background levels.

11.0.2. Nonradioactive Contaminants Released into the Ocean

Rocks are very dirty, so pulverizing and spreading them into the ocean produces significant amounts of pollution. Starting with our assumptions for lead:

1. Average concentration of dissolved lead in seawater = 2.00E-09 g/L [41]

2. Pb concentration in rock = 570 ppb [42]

3. Percent of Pb that dissolves in a year = 0.011% [43]

Followed by our calculations for lead:

1. Amount of existing Pb in the ocean = Average concentration of dissolved Pb in seawater * volume of the ocean = 2.66E+06 tons

2. Amount of Pb released = Pb concentration in rock * amount of rock weathered = 3.42E+04 tons

3. Percent of existing = amount of Pb released / amount of existing Pb in the ocean = 1.28%

4. Portion of Pb that dissolves = Percent of Pb that dissolves in a year * time weathering in the ocean = 2.16E-3

5. Amount of Pb that dissolves = Amount of Pb released * portion of Pb that dissolves = 7.38E+01 tons

6. Percent of existing Pb that dissolves = amount of Pb that dissolves / amount of existing Pb in the ocean = 2.07E-03%

Next, we have our assumptions for mercury:

1. Existing Hg in the ocean = 6E4 tons [44]

2. Hg concentration in rock = 1.36 ppb [45]

3. Percent of Hg that dissolves in a year = 0-100%. There have not been studies that we believe can accurately be used to predict the dissolution of Hg in this situation.

Followed by our calculations for mercury:

1. Amount of Hg released = Hg concentration in rock * amount of rock weathered = 8.16E1 tons

2. Percent of existing = amount of Hg released / amount of existing Hg in the ocean = 1.36E-1%

From these calculations we can see that this proposal will introduce significant amounts of lead and mercury into the ocean water, but a relatively insignificant amount when diluted in the entire ocean. This is likely the worst environmental impact of this proposal. This is a difficult and not well studied topic and our error bars are large, especially for mercury dissolution.

12. SEISMIC EFFECTS

These explosives are extremely large and will cause an earthquake if they are all detonated at the same time. We want to know how large this explosion really is. We can rearrange the equation $log_{10}E = 11.3 + 1.5M$, to estimate the magnitude of the earthquake from the amount of energy released: $M = \frac{2}{3}(log_{10}E - 11.3)$ [46]. In the worst case scenario in which all of the explosives are detonated at the same time at the same point, with 5% coupling efficiency [11], the magnitude of the earthquake on the Richter scale is 4.66. While this seems like a relatively large earthquake, it is not to be treated the same as a natural earthquake. There is little to no permanent displacement on the surface of the seafloor and only minor and temporary shaking should be expected [11]. The aftershocks of the explosion will be insignificant as well. The local wildlife should not be significantly affected and the effects of this earthquake will dissipate long before reaching humans. Additionally, there is no displacement of water so a tsunami will not form [11].

13. DAILY SOLAR ENERGY RECEIVED BY EARTH

There is concern that the energy released by these explosions will warm the planet. However, as this analysis shows, these explosives will produce far less energy than the sun provides daily.

The total solar power received by Earth is approximately:

$$P_{\odot} = 1.73 \times 10^{17} \text{ W} \tag{1}$$

Given that one day consists of $86,400$ seconds, the total energy received by Earth per day is:

$$E_{\text{day}} = P_{\odot} \times 86,400 \tag{2}$$

$$E_{\text{day}} = 1.494 \times 10^{22} \text{ J} \tag{3}$$

To express this in terms of TNT equivalent, where 1 ton of TNT corresponds to 4.184×10^9 J:

$$E_{\text{day,TNT}} = \frac{E_{\text{day}}}{4.184 \times 10^9} \tag{4}$$

$$E_{\text{day,TNT}} = 3.57 \times 10^{12} \text{ tons of TNT} \tag{5}$$

Thus, Earth receives approximately 3.57 teratons of TNT equivalent energy from the Sun every day.

14. CONVENTIONAL EXPLOSIVES IMPLEMENTATION

In order to test this carbon sequestration method, non-thermonuclear explosives should be used. For this implementation, we are assuming that we are using ammonium nitrate fuel oil (ANFO) as the explosive in a quarry next to a river within 100 km of an ocean. There are plenty of quarries that meet these criteria. The additional assumptions are:

1. CO_2 to be sequestered = 50 tons.

2. Additional produced CO_2 in this implementation = 0. We can use entirely green biodiesel and ammonium nitrate for all fuel requirements. Green biodiesel is more expensive but it simplifies the calculations tremendously.

3. The price of the ANFO is $0.66 per kg.

4. The relative effectiveness of ANFO is 0.74 [47].

5. The price of basalt purchased from a quarry is $13 per ton.

6. The depth of the holes to be drilled in the basalt are the same as the diameter of the sphere that is equivalent to the volume of rock being pulverized.

7. The price to dig a hole 16 meters into the basalt is $7806 [48].

8. The number of holes required is 10. This is a rough estimate as the exact blasting parameters for this high pressure blasting is unusual and rare.

9. The price per ton per mile of rock transport on a river is $0.01 [49].

10. The distance from the quarry to the ocean via river is 100 km.

11. The barge can unload the rocks for free.

With these assumptions in place, we can follow through with the calculations. We are using relative numbers to the thermonuclear detonations to ensure simpler and easier to follow calculations.

1. Rock pulverized = Amount of CO_2 to be sequestered in this pilot test / Amount of CO_2 to be sequestered in the thermonuclear detonation * Basalt pulverized in the thermonuclear detonation = 333 tons.

2. Volume of the rock = Basalt needed / basalt density = 1.11E2 m^3.

3. Diameter of the sphere of rock with equivalent volume =
$$V = 1.11E2t * 1m^3/3t = 5.96m^3$$
.

4. Total yield = Rock pulverized in this pilot test / rock pulverized in the thermonuclear detonation * total yield of the thermonuclear detonation = 51.4 tons of TNT.

5. Price of TNT equivalent per kg of ANFO = Price of ANFO per kg * ANFO relative effectiveness = $0.89 per kg.

6. Total price of TNT equivalent = Total yield * price of TNT equivalent per kg of ANFO = $45.8k.

7. Total price of basalt = price of basalt per ton * amount of basalt pulverized = $4.3k.

8. Total price to drill all holes = price to drill a single hole * number of holes required = $29,000.

9. Total price to transport and release rocks into the ocean = Price per ton per mile of rock transport on river * tons of rock * price to transport rocks = $207.

10. Total price of the experiment = total price of TNT equivalent + total price of basalt + total price of rock transport to the ocean = $79k.

11. Price per ton of CO_2 sequestered = $1,582.

For this implementation with conventional explosives we estimate a price of $1,582 per ton of CO_2. Although this is a much more expensive method of carbon sequestration than we calculated before for thermonuclear explosives, this method of carbon capture can help to verify the assumptions for carbon sequestration using thermonuclear explosives.

15. VALUE OF BYPRODUCTS

These explosives will create many particles that are useless for ERW because they are too big and take millenia to weather. However, these particles will be useful as concrete aggregate. Starting with our assumptions:

1. Global aggregate market size = \$442 billion/year [50]

2. Typical price per ton of aggregate (low end) = \$15/ton [51]

3. Typical freight rate (high end) = \$0.097/ton-km [52]

4. Typical freight distance = 80 km [53]

This concrete aggregate will likely not release significant amounts of radiation. However, people still do not want to use concrete that has any possibility of radioactivity. Therefore, we will assume that only approximately a third of all concrete can use this aggregate.

Next, our calculations:

1. The typical freight price = Typical freight rate * typical freight price = \$7.76/ton

2. The electricity cost to raise 1 ton of material out of the burial depth = \$0.291/ton

3. The profit per ton = \$6.95/ton.

This results in a total profit compared to leaving the rock in the hole of \$65.4 billion per year. Subtracting the cost of the rest of this proposal, we find a total profit of \$30 billion per year. This is the only proposed method of sequestering carbon that is profitable on such a large scale.

16. ROCK CHOICE

The seafloor has vast amounts of rocks, but not all can be used for enhanced rock weathering and some have excess amounts of contaminants, so the choice of rock is important. Additionally, in order to use the byproduct rocks as concrete aggregate it is important to use rocks that can actually be used as aggregate. Basalt and other seafloor aggregates have been used before, so this is possible [54, 55]. Due to the freshwater requirements for desalinating the seafloor aggregates, it may be better to use a (mostly) dry rock transport method.

The alkali-silica reaction (ASR) for concrete should be considered when choosing the rock for this reaction. Basalt is generally suitable as an aggregate but some forms of basalt are not suitable due to this reaction [56]. An example form of basalt that is suitable for the ASR is that in which the acidic intermediate character and the matrix are comprised of volcanic glass.

Given the vast possibilities for the locations and types of rock that can be used for this proposal, we do not expect excessive issues with the use of basalt as a concrete aggregate.

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