Supplemental File 1
Coral Reef Ark: An *In Situ* Mesocosm and Toolkit for Assembling Reef Communities

1 PVC ARMS Manufacture & Assembly

PVC ARMS are made of plates of dark PVC and stainless-steel rods, nuts, and bolts. They are comprised of between seven and nine PVC plates that are approximately one foot squared and one quarter inch thick. The plates are stacked with gaps that separate them by approximately one inch using PVC crossbars or circular plugs. The bottom of the ARMS is a rectangular PVC baseplate that is 18 x 14 inches and half an inch thick. The stack of foot-square plates is connected to the baseplate by stainless steel rods at all four corners of the plates that bolt into the baseplate. The baseplate is attached to the reef, most commonly by driving rebar posts through gaps on either side of the baseplate.

ARMS were designed to census cryptic reef diversity on benthic marine and freshwater ecosystems [1]. To carry out a census with ARMS, a unit is secured to the sea-, lake-, or river-floor for a set period of time—usually one to three years—during which time the ARMS unit passively aggregates organisms. On coral reefs, our research group has found that 1 year is sufficient to collect most local taxa. It is important to note that qualitative accounts suggest long deployments (e.g., 4 years) lead to lower diversity of organisms and overgrowth of the ARMS unit by a few taxa.

Table S1: Manufacturing and assembly of PVC ARMS.

| Component	Task #	Basic description	Detailed description	Tools required	Time estimate per unit (min)	Total number needed per ARMS	Total time to complete task (min)	Refer to drawing #
PVC ARMS	1	Cut PVC baseplate	Cut 0.5" thick PVC sheet on Waterjet to match ARMS baseplate drawing	Waterjet	10	1	10	Figure SI 1
PVC ARMS	2	Cut PVC long cross spacers	Cut 0.5" thick PVC sheet on Waterjet to match ARMS long cross spacer drawing	Waterjet	2	4	8	Figure SI 2
PVC ARMS	3	Cut PVC short cross spacers	Cut 0.5" thick PVC sheet on Waterjet to match ARMS short cross spacer drawing	Waterjet	2	8	16	Figure SI 3
PVC ARMS	4	Cut PVC layering plates	Cut 0.25" thick PVC sheet on Waterjet to match ARMS layering plate drawing	Waterjet	5	9	45	Figure SI 4
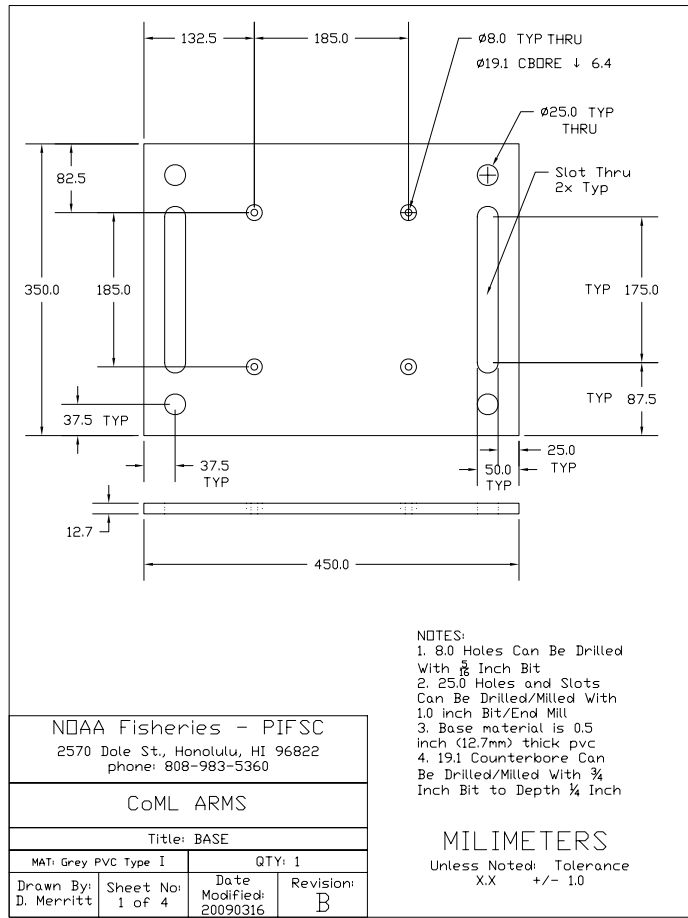
Figure S1: Technical drawing for manufacture of PVC baseplates.
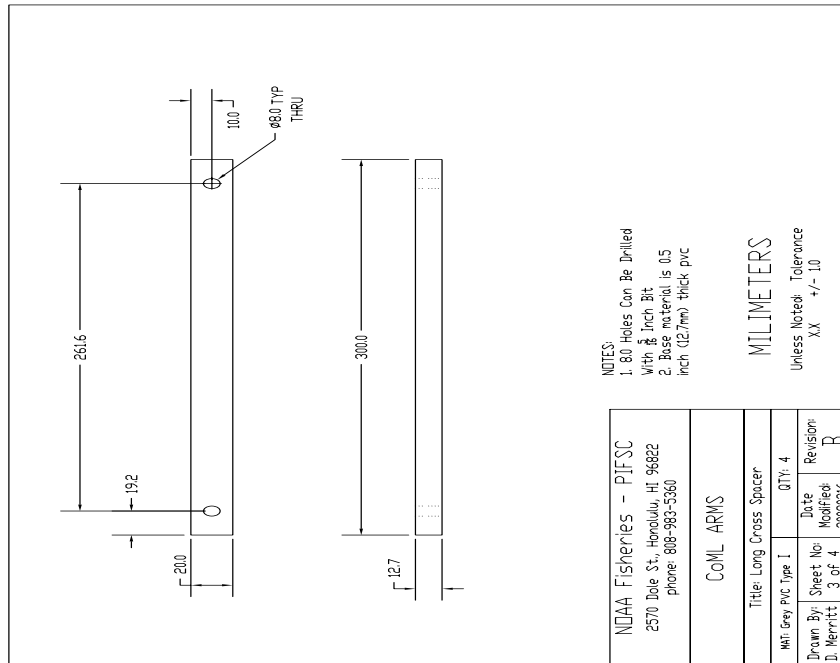
Figure S2: Technical drawing for manufacture of PVC long cross spacers.

20.0

Ø8.0 THRU

140.0

19.2

10.0

12.7

Figure S3: Technical drawing for manufacture of PVC short cross spacers.

185.0

20.0

20.0

225.0   185.0

Top and Bottom Surfaces
to be lightly roughened
(single pass, weight of
sander only) with 220 Grit
Sand Paper using Random
Orbit Sander.

Ø8.0 TYP
THRU

225.0

6.3
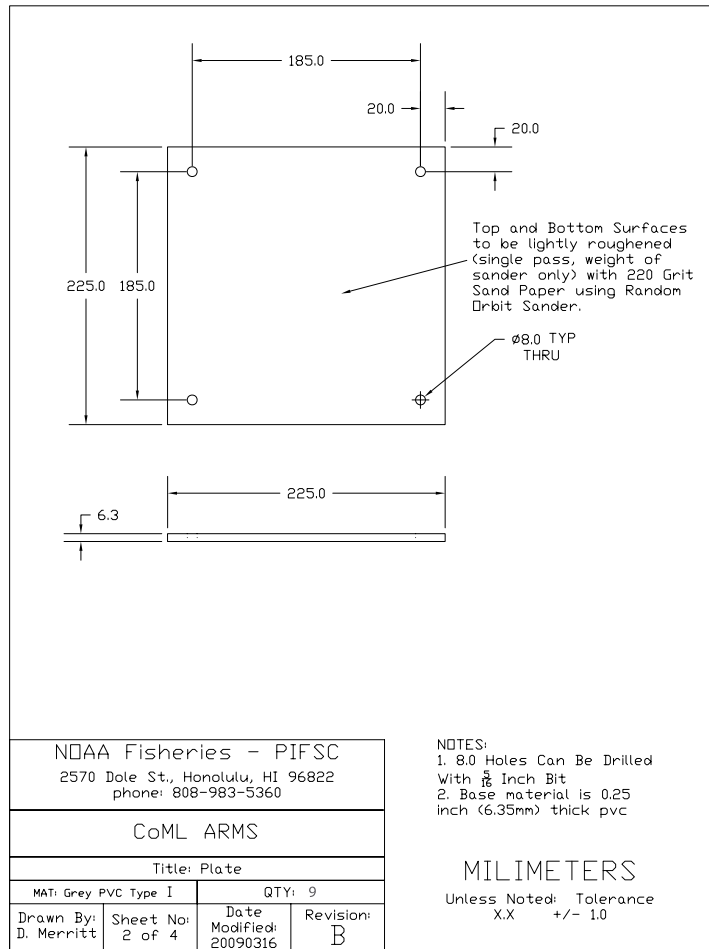
Figure S4: Technical drawing for manufacture of PVC layering plates.
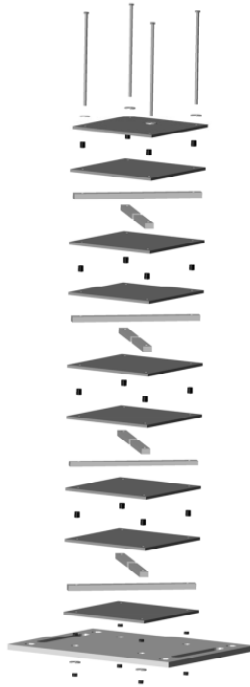
Figure S5: Exploded diagram of ARMS units and instructions for assembly.

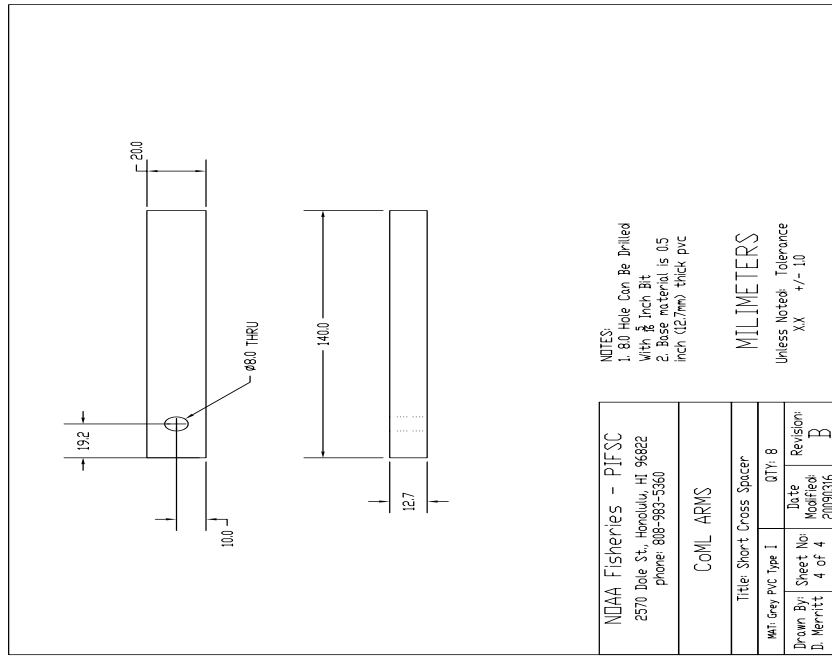Drawstring bag
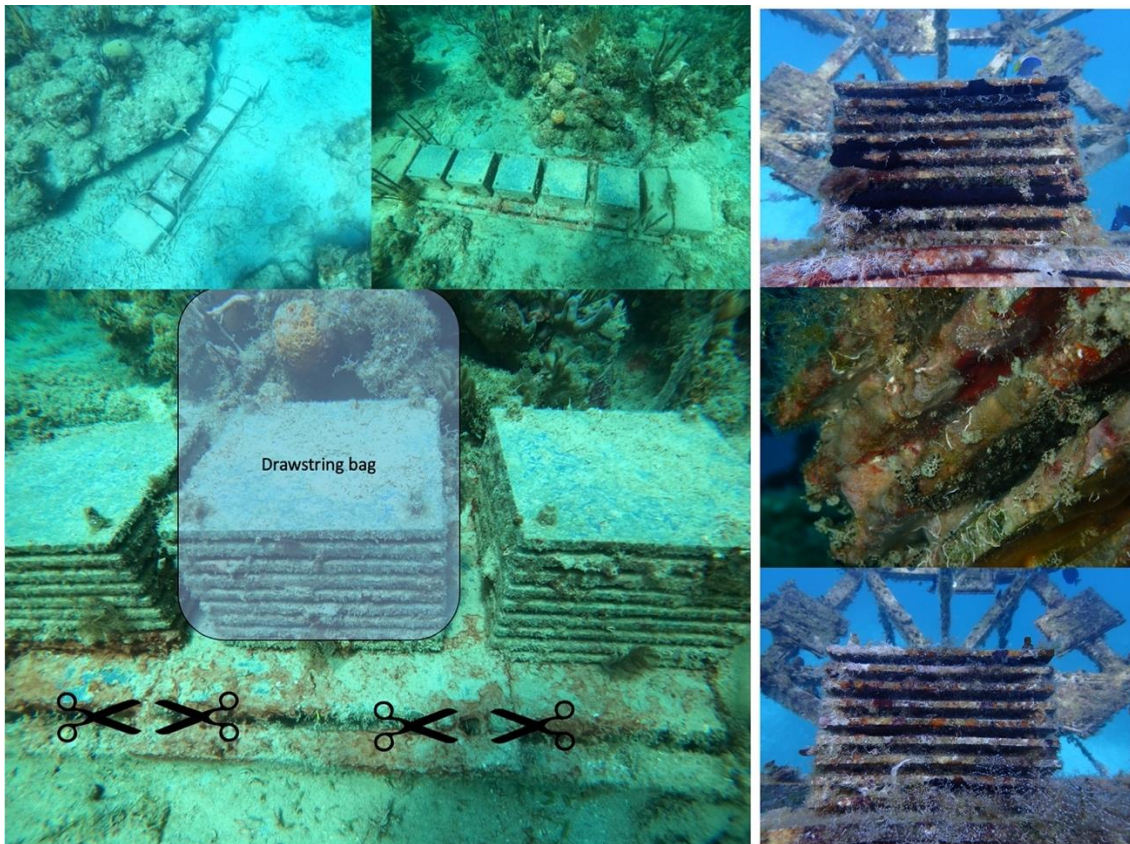
Figure S6: Alternative methods for ARMS deployment. (Top) Chains of ARMS are connected using heavy duty cable ties and the ends of these chains are anchored with hardened concrete bags. (Bottom) Seeded ARMS should be covered temporarily with 100 μm mesh bags to transfer from seafloor sites to Arks without losing small mobile invertebrates. (Right) Seeded ARMS after transfer to Shell Arks.

2   Limestone ARMS Manufacture & Assembly

Limestone ARMS are constructed from unfinished limestone or travertine tiles and a two-part, quick-setting marine grade epoxy. A single limestone ARMS unit may consist of 5–6 tile layers separated by tile spacers, cut using a tile saw from the same limestone tiles. These spacers may be different sizes of rectangular and square pieces and are organized on ARMS layers in configurations that mimic the three-dimensional complexity of hardbottom substrates. Some layers may be stacked higher (2 cm) or lower (1 cm) than others to create crevices while leaving space for organisms to colonize the interior of the structure. Approximately 10 one-foot squared limestone tiles (1 cm thick) are used for the construction of one limestone ARMS. The quick-setting epoxy is used to glue the tile to the material below it. Limestone ARMS are not fastened to a baseplate.

Limestone tiles provide a cryptic environment made of the same material as hardbottom substrates found on coral reefs, and therefore, better replicate the natural habitat of the organisms that they are passively aggregating.

Table S2: Manufacture and assembly of Limestone ARMS.

Component	Task #	Basic description	Detailed description	Tools required	Time estimate per unit (min)	Total number needed per ARMS	Total time to complete task (min)	Refer to drawing #
Limestone ARMS	1	Cut limestone tile	Use tile saw to cut limestone tile into appropriate sized pieces for assembling limestone ARMS with desired internal complexity. Let dry.	Wet tile saw	5	10	50	Figure SI 7 & 8
Limestone ARMS	2	Assemble ARMS	Glue smaller travertine pieces to a larger travertine layering plate along a pre-drawn grid pattern. Allow to cure based on manufacturer recommendation.	Two-part marine epoxy putty	10	5	50	Figure SI 7 & 8

Figure S7: Limestone ARMS deployed on reefs passively aggregate sessile and mobile invertebrate communities. Mobile invertebrates tend to take refuge in ARMS whose internal complexity most closely matches their body size.

Internal surface area for 1ft³

19,232 cm²   13,400 cm²   8,592 cm²   6,464 cm²
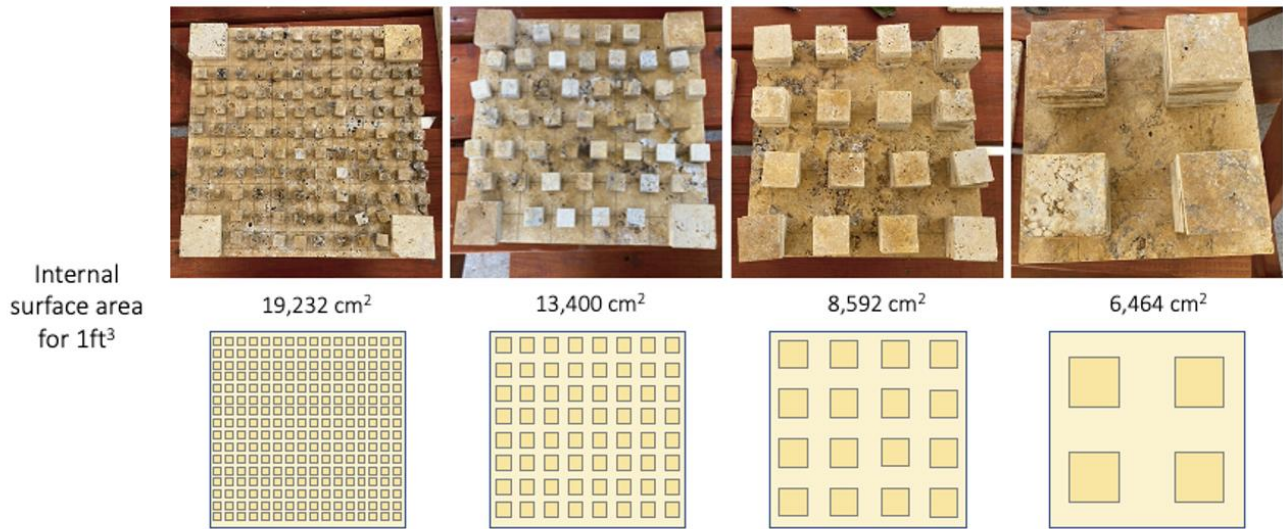
Body size of organisms recruited

Internal surface area : volume ratio

Figure S8: Limestone ARMS can be built with differing internal complexities. Smaller, more numerous internal components yield higher internal surface area, with implications on fouling (biofilms and sessile invertebrate communities) and a correspondingly lower internal surface area to volume ratio. ARMS complexities can be designed based on desired recruitment patterns, with higher complexity ARMS recruiting smaller mobile organisms.

3   Shell Ark Manufacture & Assembly

"Shell" Coral Arks are 2V frequency, geodesic, buoyant, submerged structures attached to an anchoring system to provide a midwater artificial reef structure. The structures deployed in Vieques, Puerto Rico, are 8' in diameter and primarily comprised of 2" diameter foam-filled fiberglass struts, connected to one another with stainless steel hardware. Buoyancy is provided by 14" diameter plastic trawl floats. The Shell Arks have five mooring attachment points around their base and are attached to three previously installed sand anchors using a mooring system comprised of lines, chain, shackles, and swivels made of stainless steel and galvanized components. They also include HDPE baseplates that are designed to receive limestone plates onto which corals requiring translocation have been secured and seeded ARMS

(autonomous reef monitoring structures) that are used to translocate non-coral reef biodiversity to the Arks. See below for detailed manufacture and assembly instructions.

In air, each Shell Ark weighs 700 lbs fully constructed, and is top-heavy because the buoyant trawl floats are concentrated at the top of the structure. Ten of the trawl floats can be removed, bringing the weight in air down to 500 lbs, to allow for potentially easier transport to the installation site.

Table S3: Manufacture and assembly of components for Shell Arks frame.

Ark	Component	Task #	Basic description	Detailed description	Tools required	Time estimate per unit (min)	Total number needed per Ark	Total time to complete task (min)	Refer to drawing #
Shell	Struts	1	Cut struts (S1)	Cut to 20.905" long (531 mm) on miter saw	Miter saw, saw blades	2	55	110	Figure SI 9
Shell	Struts	2	Cut struts (S2)	Cut to 24.331" long (618 mm) on miter saw	Miter saw, saw blades	2	60	120	Figure SI 9
Shell	Struts	3	Cut struts (stainless)	Cut to 20.905" long (531 mm) on miter saw	Miter saw, saw blades	10	5	50	Figure SI 9
Shell	Struts	4	Drill bolt holes in struts (fiberglass)	Drill two 7/32" holes at the end of each strut (thru entire rod). Center of first hole dilled at 0.98" from end of strut (25 mm). Distance from the center of the first hole to the center of the second hole is 1.06" (27 mm). The distance between the two inside holes on S1 struts is 16.81" (427 mm) and for S2 struts is 20.24" (514 mm).	Drill press, drill bit (7/32")	2	115	230	Figure SI 9
Shell	Struts	5	Drill bolt holes in struts (stainless)	Hole dimensions same for both S1 and S2 struts. Drill template stainless strut and set up vertically in vice, with non-drilled stainless strut behind it. Use template screw holes (7/32") as a guide to drill the remaining stainless struts (both sides).	Drill press, drill bit (7/32")	10	5	50	Figure SI 9
Shell	Struts	6	Cut foam into strips for struts	Rip to 1.5" wide and thick on table saw, and to 15.5" long for S1 and 19" long for S2 struts	Table saw, exacto blade	1	115	115	
Shell	Struts	7	Add foam into struts	Push into strut until flush using a firm tap against a table; then use a marked piece of wood and mallet to insert so that the foam sits in the middle of the strut	Mallet	1	115	115	
Shell	Struts	8	Epoxy to seal foam in struts	Stand foam-filled struts on end, mix epoxy and hardener in small batches, pour about 5 ml (~0.3-0.4 cm depth) into one side of each strut. Leave to harden overight, then flip struts and repeat	Two-part epoxy	1	115	115	
Shell	Stars	1	Prepare 5x N2 stars for stainless connections	Drill larger bolt hole on outer hole of one arm for Padeye connector	Drill bit (1/4")	3	5	15	Figure SI 10
Shell	Stars	2	Prepare 10x N2 stars for floats	Drill out larger central hole to accommodate 1" threaded fiberglass rod	Use 2x step bits: first High-Speed Steel Multidiameter Drill Bit, 10 Inch Sizes (part 89315A42 from McMaster) and then 12 Inch Sizes (part 89315A42 from McMaster)	15	10	150	Figure SI 10
Shell	Stars	3	Prepare 2x N1 stars for top/bottom connections	Machine/weld connections to insert top and bottom of central unthreaded fiberglass structural rod	*Outsourced*	*Outsourced*	*Outsourced*	*Outsourced*	Figure SI 10
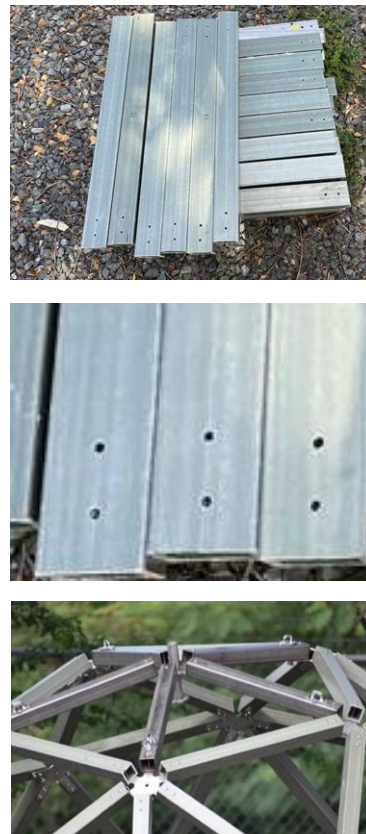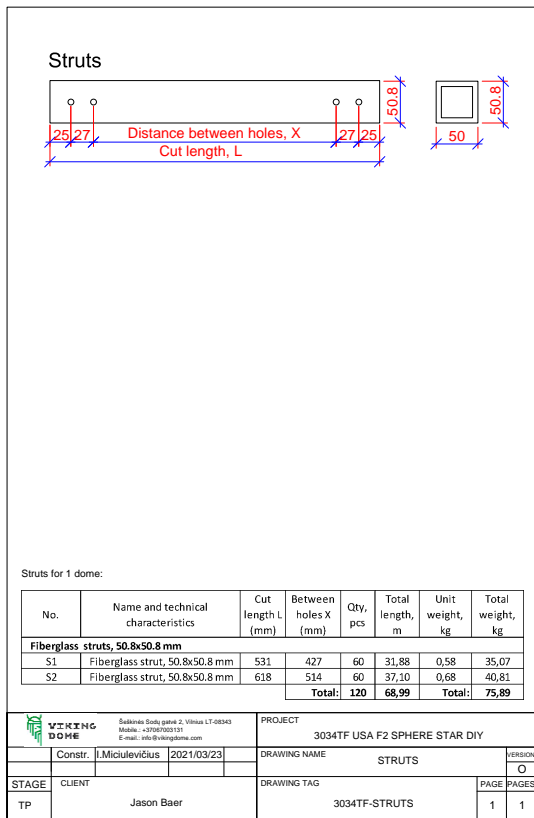
Figure S9: Types of struts. (Left) Technical drawing for manufacture of fiberglass square struts (adapted from VikingDome assembly materials). (Right) Images of cut and drilled fiberglass and stainless steel struts.
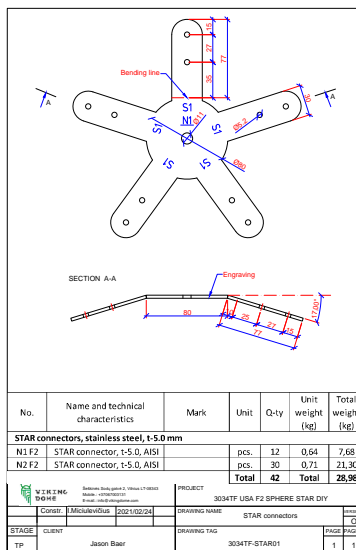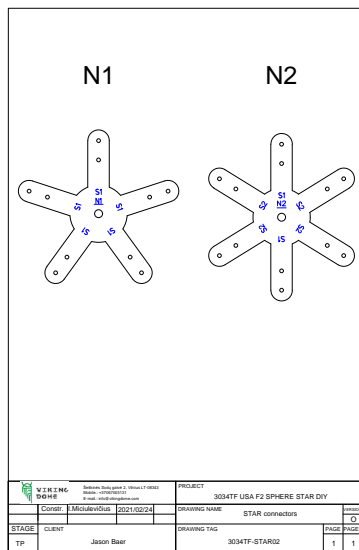
Figure S10: STAR connectors. (Left and middle) Technical drawing for manufacture of STAR connectors (adapted from VikingDome assembly materials). (Right) Images of STAR connectors modified for top/bottom of Arks and for float attachments.
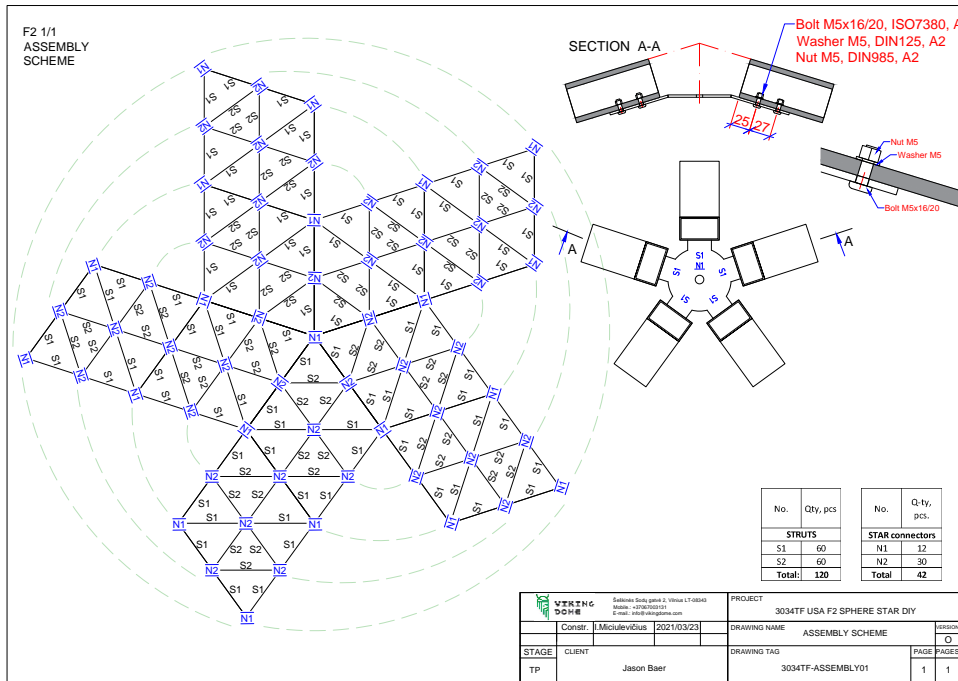
Figure S11: Assembly of Struts and STAR connectors in geodesic spheres. Technical drawing for assembly of struts and STAR connectors into 2V geodesic sphere (adapted from VikingDome assembly materials).
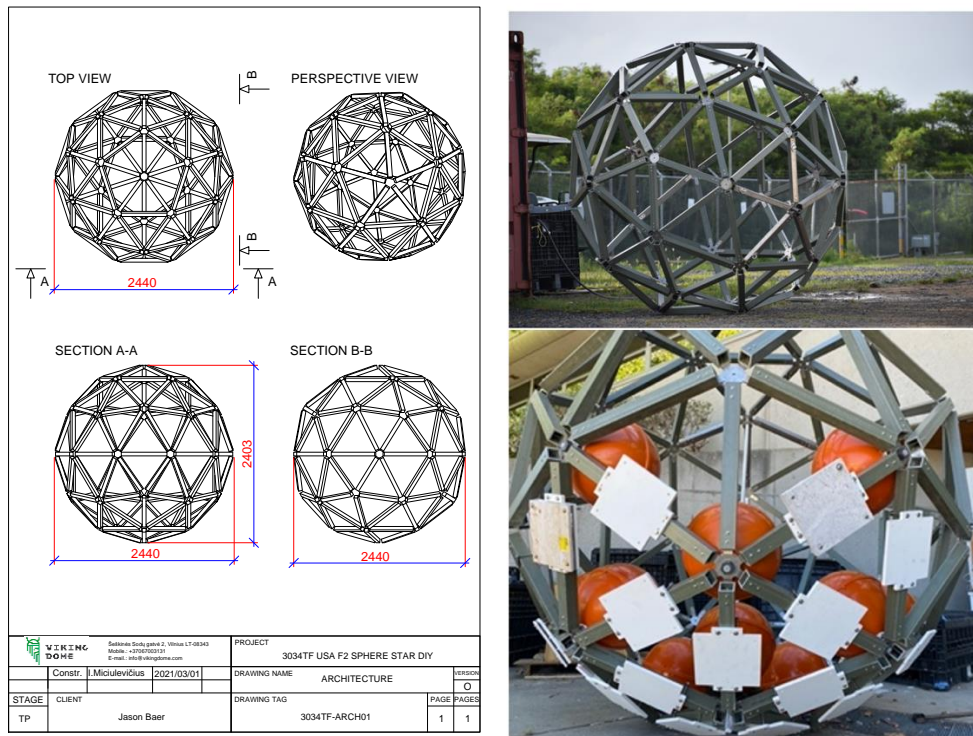

Figure S12: Assembly of a 2V geodesic sphere. (Left) Technical drawing for complete assembly of 2V geodesic sphere (adapted from VikingDome assembly materials). (Right) Images of a fully assembled sphere.

Table S4: Manufacture and assembly of components for ARMS and coral plates and attachment to Shell Ark frame.

Ark	Component	Task #	Basic description	Detailed description	Tools required	Time estimate per unit (min)	Total number needed per Ark	Total time to complete task (min)	Refer to drawing #
Shell	ARMS and Coral Plate Baseplates	1	Waterjet baseplates	For each 48"x48" sheet of HDPE, 6x ARMS and 5x coral baseplates can be cut. Each sheet takes ~1 hour of waterjet time.	Waterjet	10	20	200	Figure SI 13 & 14
Shell	ARMS and Coral Plate Baseplates	2	Heat shrink connector plates	Cut 0.5" thick heat-shrink tubing into 1.5" lengths. Slide heat shrink over a stainless steel u-bolt bracket and use heat gun to tighten heat shrink onto bracket.	Scissors, heat gun	1	60	60	Figure SI 15
Shell	ARMS and Coral Plate Baseplates	3	Cut PVC standoffs	Cut 1/4" pipe into 1.75" long sections.	Miter saw	0.5	10	5	
Shell	Coral plates	1	Waterjet PVC baseplates	For each 48"x48" sheet of 0.25" thick PVC, 25x coral baseplates can be cut.	Waterjet	10	20	200	Figure SI 4
Shell	Coral plates	2	Cut travertine tiles to size	Cut on a wet tile saw to match size of coral baseplates (9" x 9") and let dry.	Wet Tile Saw	3	20	60	Figure SI 15
Shell	Coral plates	3	Mount tiles onto coral baseplates	Add liberal amount of 3M 5200 sealant to a coral baseplate and press the limestone tile down onto it. Add weight while setting.	3M 5200, weights	5	20	100	Figure SI 15
Shell	Coral plates	4	Drill out corners of coral plates	Use 1/4" masonry bit to drill out all four corners of each coral plate, through limestone and PVC plate.	Drill press, masonry bit (1/4")	2	20	40	Figure SI 15
Shell	Coral plates	5	Prepare numbered tags for coral plates	Stamp stainless steel washers with numbered stamps for desired numbers. Glue to one corner of coral plate, over corner hole.	Hammer, vice, numbered stamps	1	20	20	Figure SI 15
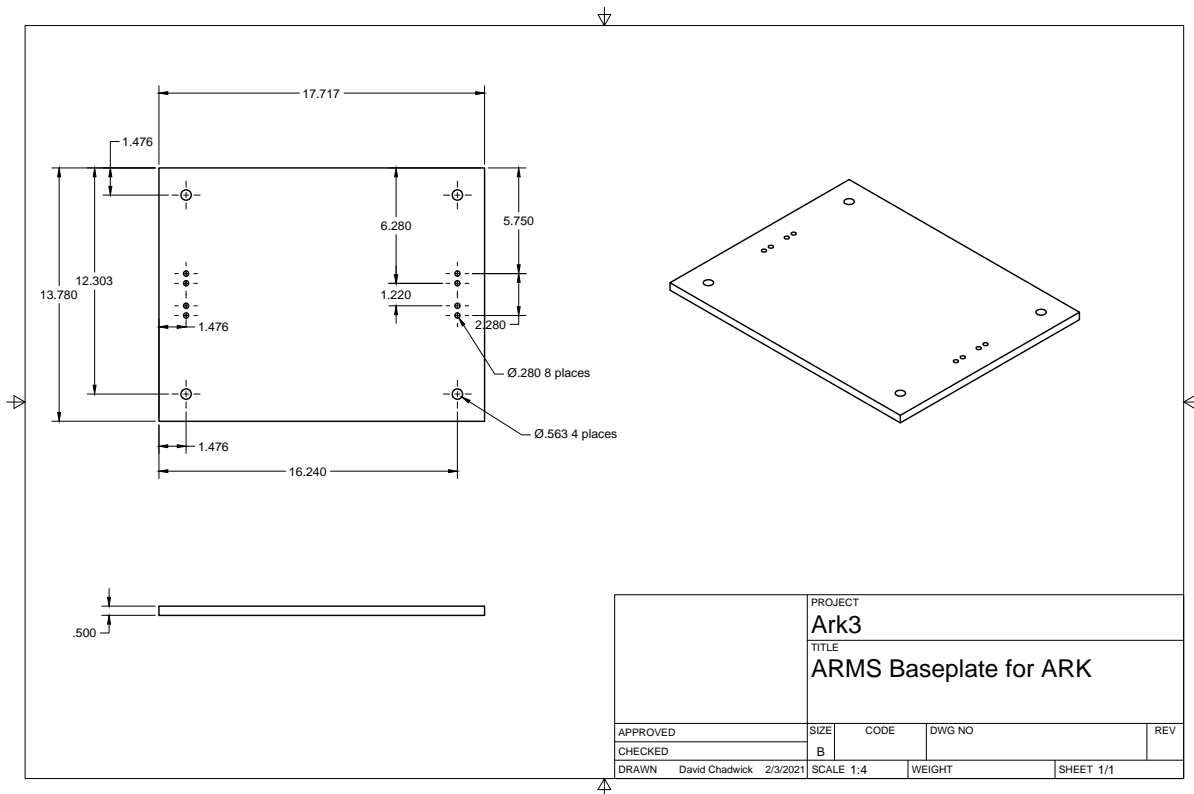
Figure S13: Technical drawing for manufacture of baseplates for mounting ARMS to Ark frame.
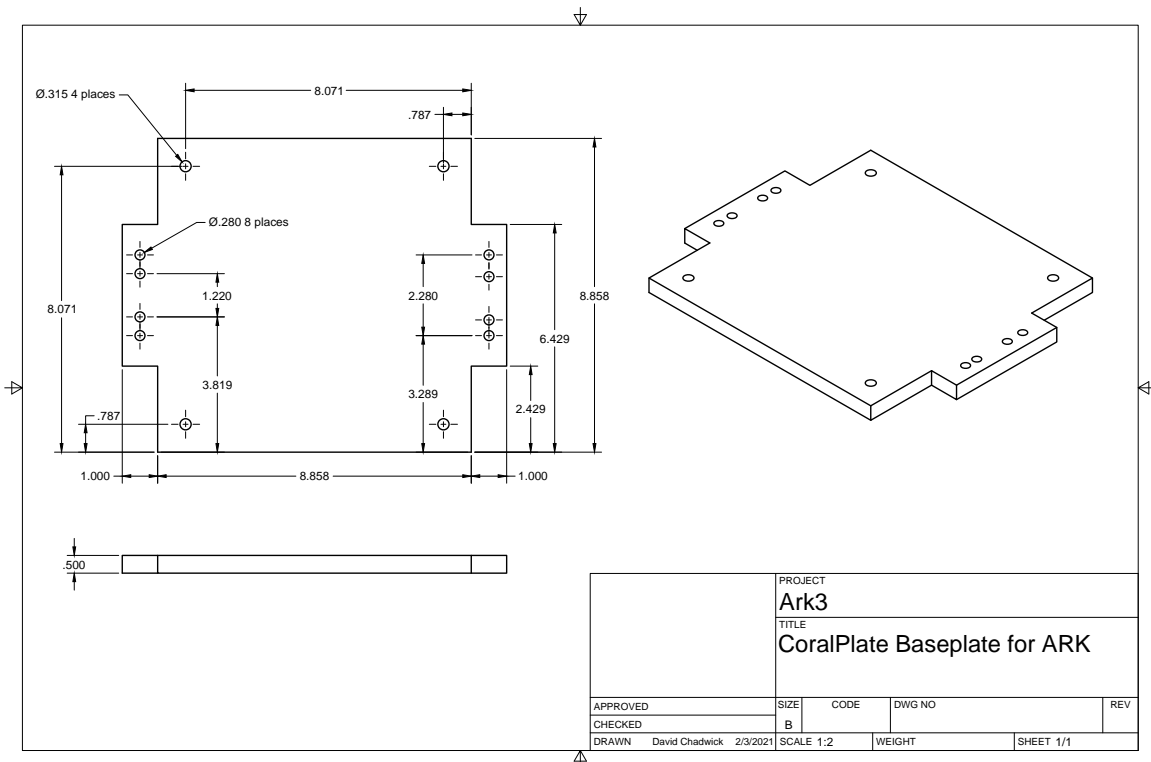
Figure S14: Technical drawing for manufacture of baseplates for mounting coral plates to Ark frame.
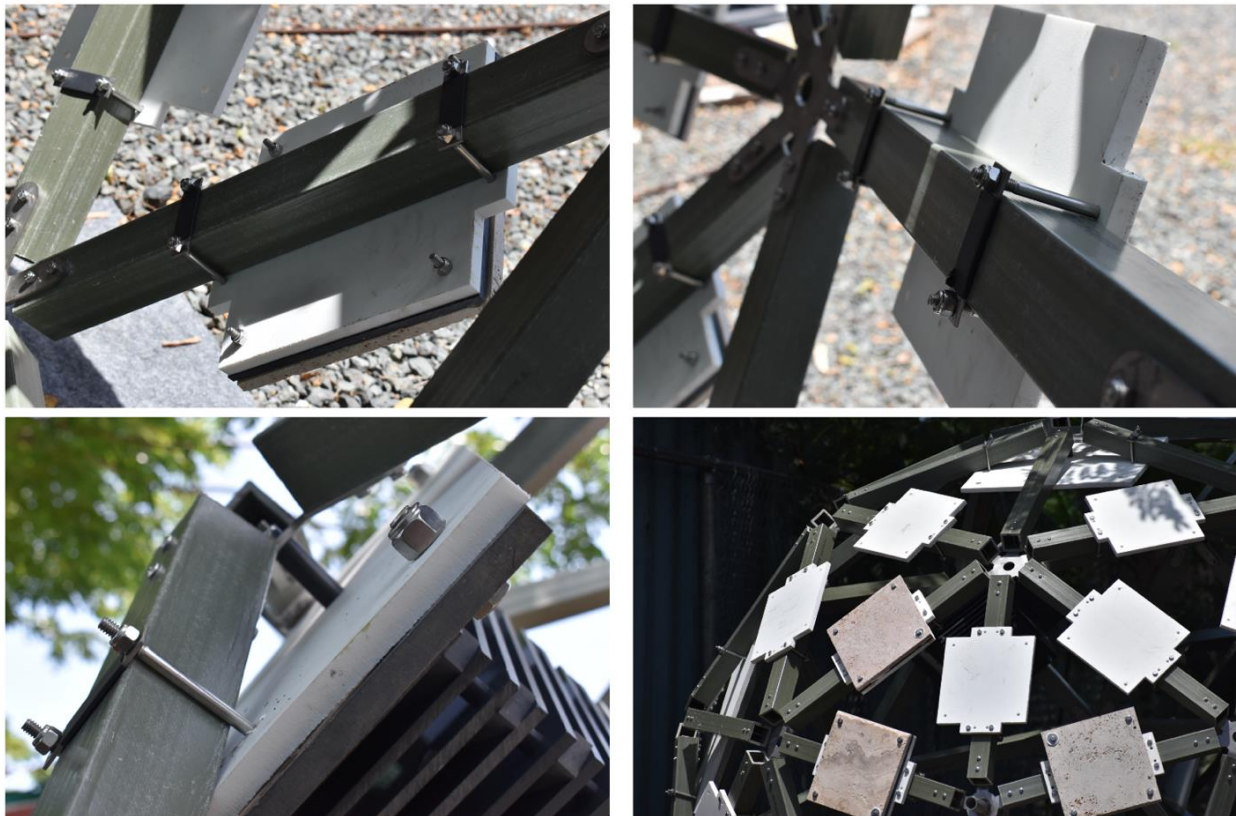

Figure S15: Images of coral plate and ARMS baseplates mounted to Shell Ark fiberglass struts using hardware and "non-slip" U-bolt brackets wrapped in heat-shrink tubing.
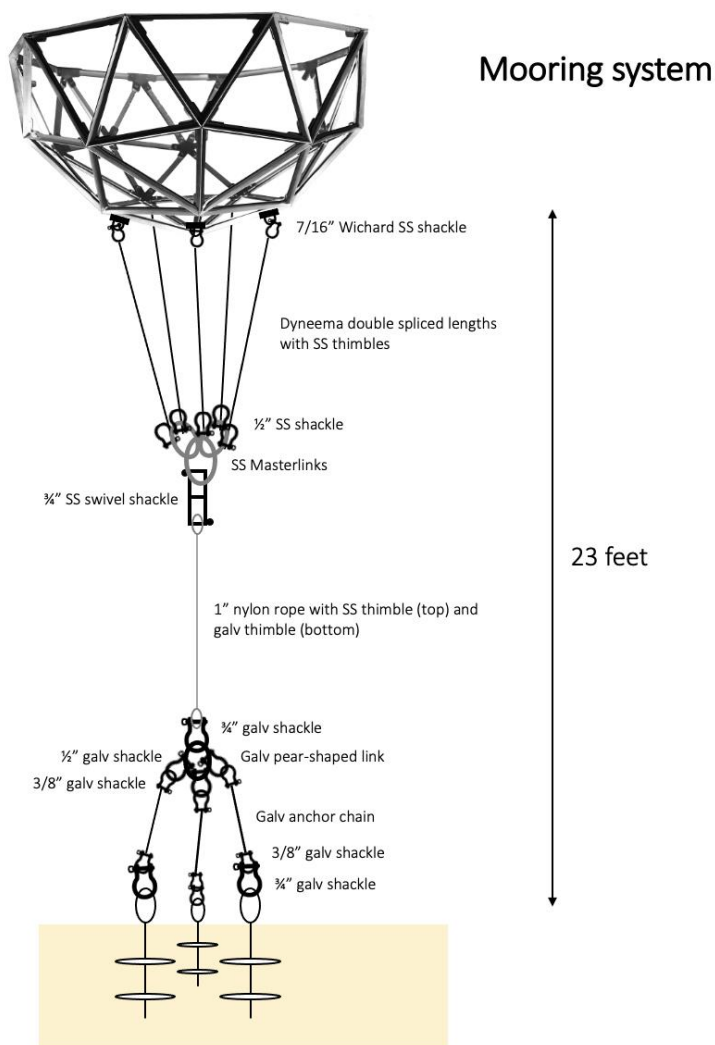
Table S5: Manufacture and assembly of components for buoyancy and mooring system design of Shell Arks.

Ark	Component	Task #	Basic description	Detailed description	Tools required	Time estimate per unit (min)	Total number needed per Ark	Total time to complete task (min)	Refer to drawing #
Shell	Floats	1	Cut fiberglass unthreaded rod	Cut to Ark diameter. Drill two holes at either end to match holes on machined top and bottom Stars.	Miter saw, drill bit (1/4")	5	1	5	Figure SI 16
Shell	Floats	2	Cut fiberglass threaded rods	Cut to 17-1/4" on miter saw	Miter saw, saw blades	1	10	10	Figure SI 16
Shell	Floats	3	Add heatshrink to rods	Cut 2" thick heat shrink tubing into 14" lengths. Slide onto fiberglass rods with 1" exposed on one end and 2-1/4" exposed on the other. Use a heat gun to shrink until snug.	Scissors, heat gun	3	10	30	Figure SI 16
Shell	Floats	4	Mount and seal rods into trawl floats	Slide fiberglass rod with heat shrink through trawl float. Add stainless washer and fiberglass hext nut on both sides. Before tightening, add a generous amount of 3M 5200 sealant on the inside of the washers. Tighten nuts down.	3M 5200, wrench	5	10	50	Figure SI 16
Shell	Mooring system	1	Make double-spliced Spectra lengths for Ark mooring bridle	Splice a 1/2" stainless steel sailmaker thimble into one end of a length of 5/8" Spectra rope. Splice another 1/2" stainless steel sailmaker thimble into the other end. Repeat for 5 total lines of equal length.	*Outsourced*	*Outsourced*	*Outsourced*	*Outsourced*	Figure SI 17
Shell	Mooring system	2	Make double-spliced Nylon length for Ark downline	Splice a 1" stainless steel sailmaker thimble into one end of a length of 1" nylon rope. Splice a 1" heavy duty galvanized thimble into the other end. Total length will depend on anchoring depth.	*Outsourced*	*Outsourced*	*Outsourced*	*Outsourced*	Figure SI 17
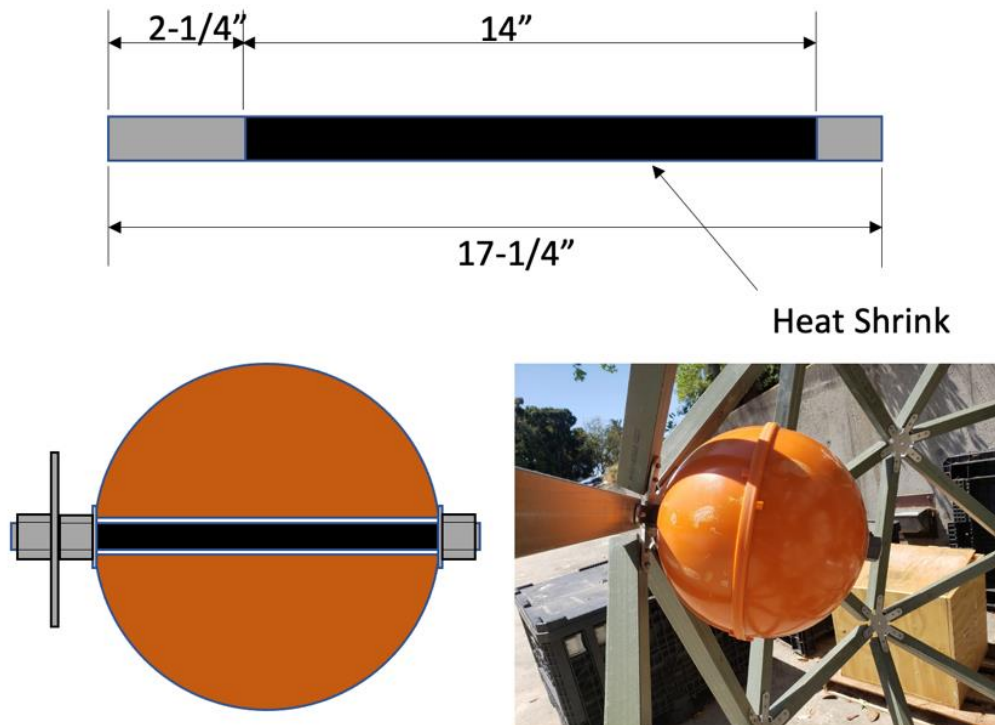
Figure S16: Technical drawing for manufacture of trawl floats (fixed buoyancy) and attachment to Ark frame.

Mooring system

7/16" Wichard SS shackle

Dyneema double spliced lengths with SS thimbles

½" SS shackle

SS Masterlinks

¾" SS swivel shackle

23 feet

1" nylon rope with SS thimble (top) and galv thimble (bottom)

¾" galv shackle

½" galv shackle

Galv pear-shaped link

3/8" galv shackle

Galv anchor chain

3/8" galv shackle

¾" galv shackle

Figure S17: Ark Mooring system. (Left) Diagram of Ark mooring system. (Top right) Bottom of Coral Ark structure showing 5-point mooring bridle (3/4" Dyneema lines) connected to the 5 padeyes at the base of the Ark. (Mid right) The lower portion of the Ark mooring bridle, showing 3 of the Dyneema mooring bridle lines connected to the left link, and 2 of the Dyneema mooring bridle lines connected to the right link, at the top of the stainless Masterlink using ½" stainless shackles. Also shown is the stainless swivel connecting the bottom of the stainless Masterlink to the top of the 1" nylon downline. (Bottom right) The 1" nylon downline connects the mooring bridle to a chain anchor bridle, consisting of 3 lengths of chain that meet at a single galvanized pear-shaped link and are each attached to their own sand anchor eye at the opposite end using 3/8" galvanized shackles.

Location	Component	Condition - Good	Condition - Worn	Condition - Corrosion	Condition - Angled load	Condition - Fouling invasion	Comments
Ark	Orange trawl floats (11)						
	Fiberglass struts						
	SS Stars						
Ark Base	Pad eye 1						
	7/16" Wichard shackle 1						
	Pad eye 2						
	7/16" Wichard shackle 2						
	Pad eye 3						
	7/16" Wichard shackle 3						
	Pad eye 4						
	7/16" Wichard shackle 4						
	Pad eye 5						
	7/16" Wichard shackle 5						
	Zinc hull anode 1						
	Zinc hull anode 2						
	Zinc hull anode 3						
Mooring bridle	Dyneema bridle length 1						
	1/2" SS screw pin shackle 1						
	Dyneema bridle length 2						
	1/2" SS screw pin shackle 2						
	Dyneema bridle length 3						
	1/2" SS screw pin shackle 3						
	Dyneema bridle length 4						
	1/2" SS screw pin shackle 4						
	Dyneema bridle length 5						
	1/2" SS screw pin shackle 5						
	MasterLink (2-shackle)						
	MasterLink (3-shackle)						
	MasterLink - base						
	Zinc collar anode						
Down line	3/4" swivel shackle						
	1" Megabraid down line						
	SS thimble (top)						
	Galv thimble (bottom)						
Anchor bridle	3/4" galv shackle						
	Pear shaped link						
	1/2" galv shackle 1						
	3/8" galv shackle 1						
	1/2" galv chain 1						
	1/2" galv shackle 2						
	3/8" galv shackle 2						
	1/2" galv chain 2						
	1/2" galv shackle 3						
	3/8" galv shackle 3						
	1/2" galv chain 3						
Anchor	Skrew Anchor 1						
	3/4" galv shackle 1						
	3/8" galv shackle 1						
	Skrew Anchor 2						
	3/4" galv shackle 2						
	3/8" galv shackle 2						
	Skrew Anchor 3						
	3/4" galv shackle 3						
	3/8" galv shackle 3						

Figure S18: Ark maintenance. (Left) Ark maintenance checklist for assessing long term integrity of components and (Right) images of zinc hull anodes attached to stainless steel struts Ark base and zinc collar anodes attached to the stainless steel Masterlink in the mooring system. Anodes should be removed and replaced as necessary to protect the stainless-steel components from degradation.
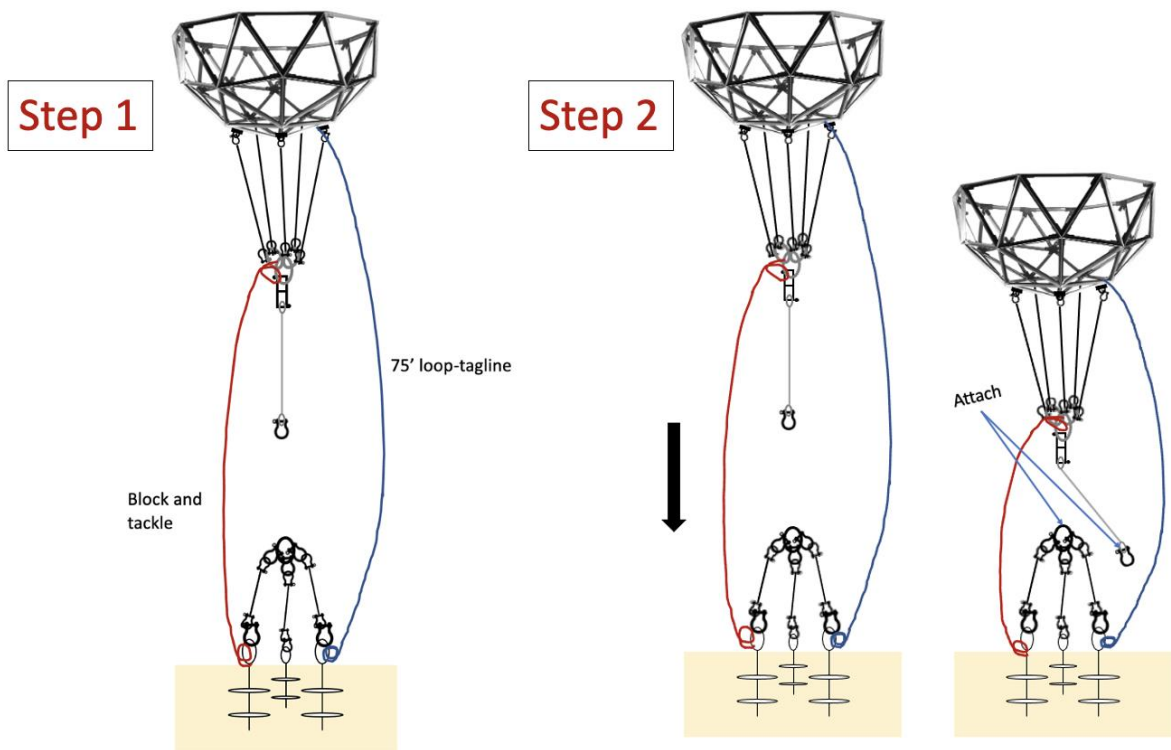
Figure S19: Attachment of the Arks to their mooring system. The positively buoyant Ark structures is pulled to depth using a block and tackle in order to attach the downline to the mooring system. In Step 1, the block and tackle is unspooled in order to attach one side (the end with the becket and cam) to the anchor point, and the other end to the base of the Ark mooring bridle. A safety "loop-tagline" that is attached to the Ark base and a single anchor point may be used for security in case of block and tackle failure. In Step 2, the block and tackle is engaged to pull the structure to depth. The structure is 300 lbs positively buoyant and the block and tackle has a 6:1 purchase; thus, the force required to pull the Ark to depth is approximately 50 lbs. At the end of Step 2, the shackle at the base of the downline should be fastened to the galvanized pear-shaped link at the top of the anchor bridle, then the tension can be transferred to the mooring system and the strain gauge removed. **Note**: Divers should maintain continuous observation of the sand anchors to make sure they are not failing under the various loading scenarios of the installation.


Figure S20: Three sand anchors are installed in a triangular arrangement to provide redundancy in holding power. To install the anchors, the lower disk of the sand anchor is first buried in the sand, and then a long turning bar placed through the anchor eye is used to twist the anchor into the substrate until only the eye remains above the sand.

Figure S21: Shell Arks may be attached to a pallet and lifted via a forklift to load them onto vessels or transport them as needed.
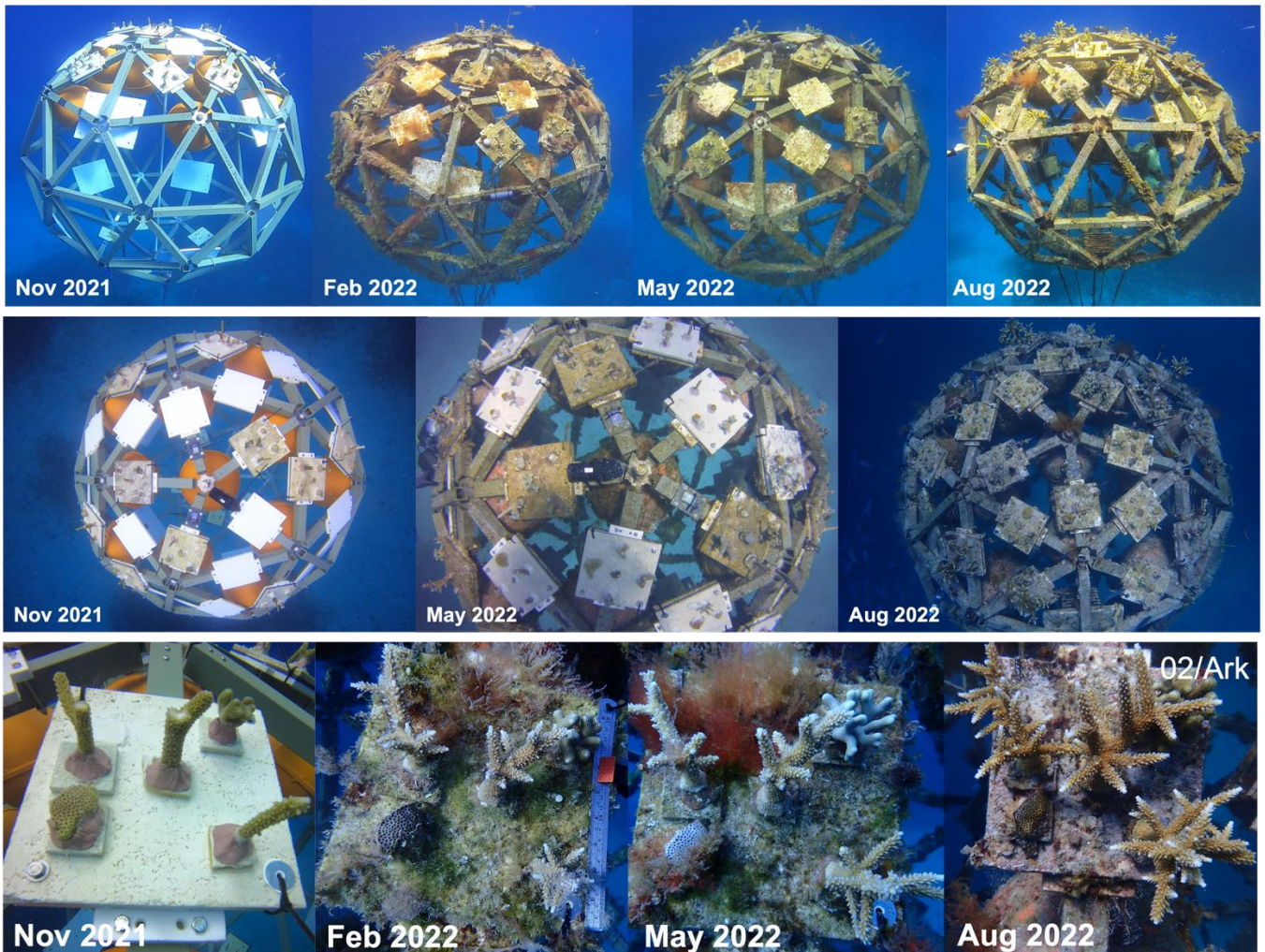
Figure S22: Time series of Shell Arks. (Top and Middle) Successional time series of biofouling on Shell Arks from over 9 months. (Bottom) Time series of one coral plate (with 5 coral nubbins attached) on a Shell Ark over 9 months.
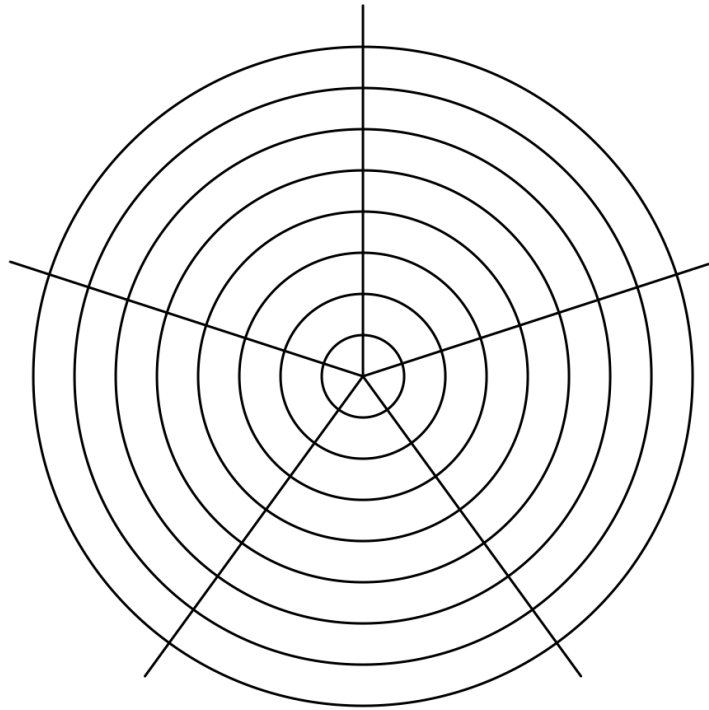
4   Two Platform Ark Manufacture & Assembly

Coral Arks are 1V frequency polyhedral structures (also called "icosahedra") constructed from "struts" and "hubs," with struts used to assemble the polyhedral frame and hubs used to secure these struts in place at each vertex. Arks can be built using various polyhedral geometries and frequencies and can be built as a dome (half-polyhedron) or a full polyhedron. Higher frequency polyhedrons provide more mounting locations and enhanced strength but have a higher material cost.

Arks are assembled by inserting the struts into the holes in the connectors and angling the strut downwards until they "lock" in place in the connector. This process is repeated until the half-dome or full polyhedron is constructed. Assembled polyhedrons can then be transported to the deployment site for anchoring.
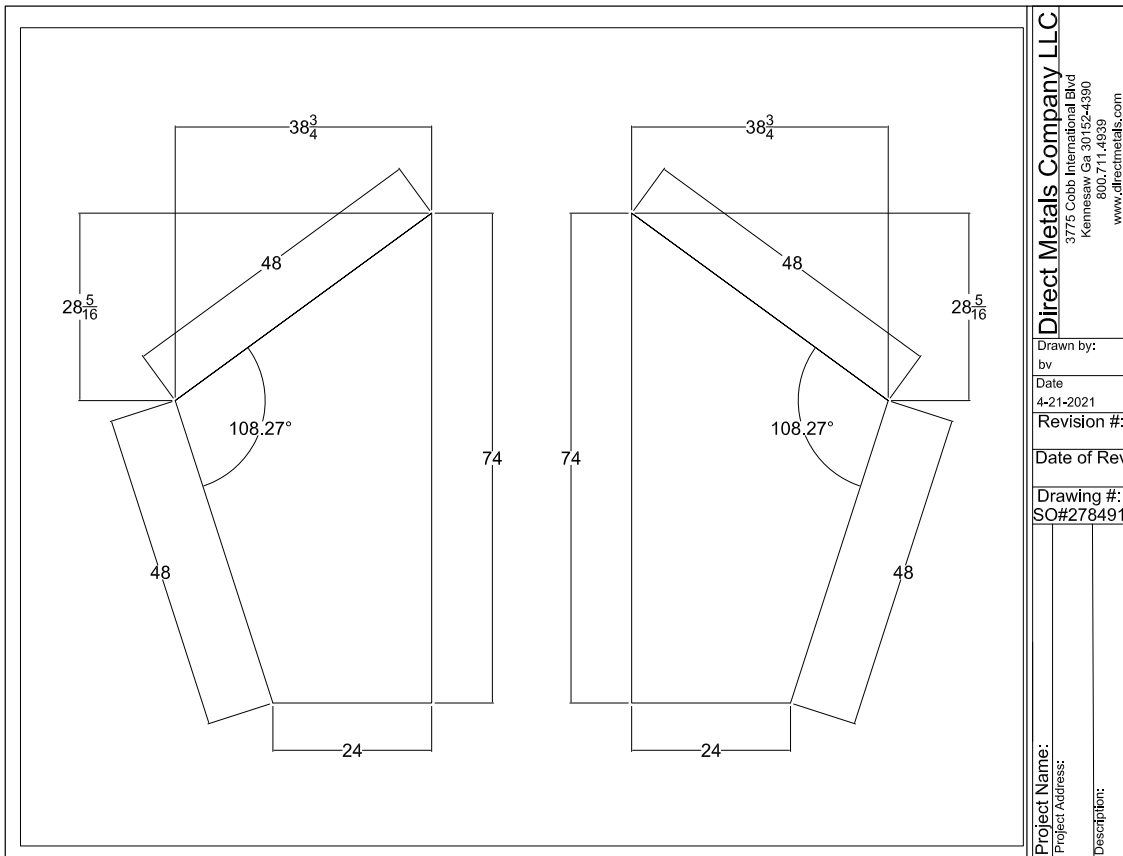
Table S6: Manufacture and assembly of components for Two-Platform Arks frame.

Ark	Component	Task #	Basic description	Detailed description	Tools required	Time estimate per unit (min)	Total number needed per Ark	Total time to complete task (min)	Refer to drawing #
Two Platform	Struts	1	Cut struts	Cut 1" pipe to 4 ft lengths	Ratcheting PVC cutter or miter saw	1	30	30	
Two Platform	Struts	2	Drill four holes in each strut	Drill a 1/4" hole through both walls of the PVC 1.5" from the end of the strut. Drill another 1/4" hole 2 inches away from the first hole, towards the center of the strut. Repeat for the other side of the strut, ensuring all holes are along the same plane.	Drill bit (1/4")	3	30	90	
Two Platform	Hubs	1	Cut hubs	Cut 6" pipe to 4" lengths.	Band saw	2	12	24	
Two Platform	Hubs	2	Drill five equidistant holes in each hub	Mark the center line of each hub at 2". Mark the location of five equidistant points on the hub that intersect the center line. Using a 1.5" hole saw, drill five holes in each hub symmetrically around the midline.	Drill press, 1.5" hole saw and arbor	15	12	180	Figure SI 22
Two Platform	Hubs	3	Cut hub end caps	Cut 6" PVC endcaps to remove the bottom 2-3 inches (shortening to ~4"). Drill a 3/8" hole through the center of each endcap.	Band saw, drill bit (3/8")	5	2	10	
Two Platform	Platform	1	Cut molded fiberglass grating	Use waterjet to cut molded fiberglass grating platform into mirrored half pentagon shapes.	Waterjet	60	4	240	Figure SI 23
Two Platform	Platform	2	Cut fiberglass I-beam	Cut 5 ft length of structural fiberglass I-beam into 5, 1 ft long segments.	Miter saw, saw blades	1	5	5	
Two Platform	Platform	3	Drill four holes in each fiberglass I-beam	Drill a 1/4" hole 2 inches from the end of each fiberglass I-beam length. Drill another 1/4" hole 2.25 inches away from the first hole towards the center of the I-beam. Repeat for the other end of the I-beam (4 holes total per length).	Drill bit (1/4")	3	5	15	

Figure S23: Template for marking and drilling equidistant holes in 6" PVC to form hubs.

Figure S24: Technical drawing for manufacture of Ark platforms from molded fiberglass grating.

Figure S25: Assembly of Two-Platform Ark framework. Struts are inserted into hubs and locked into place via bolts and locknuts, and then a stainless-steel wire rope is passed through the finished structure to increase the strength. Two platforms are then added, bisecting the Ark horizontally.

Table S7: Manufacture and assembly of components for Two-Platform Ark mooring system.

Ark	Component	Task #	Basic description	Detailed description	Tools required	Time estimate per unit (min)	Total number needed per Ark	Total time to complete task (min)	Refer to drawing #
Two Platform	Mooring system	1	Make double-spliced Spectra lengths for buoys and Ark base	Splice a 1/2" stainless steel sailmaker thimble into one end of a length of 1/2" Spectra rope. Splice another 1/2" stainless steel sailmaker thimble into the other end. Total length should be ~5 ft.	Outsourced	Outsourced	Outsourced	Outsourced	
Two Platform	Mooring system	2	Make double-spliced Nylon length for Ark downline	Splice a 1" stainless steel sailmaker thimble into one end of a length of 1" nylon rope. Splice a 1" heavy duty galvanized thimble into the other end. Total length will depend on anchoring depth.	Outsourced	Outsourced	Outsourced	Outsourced	
Two Platform	Mooring system	3	Swage thimbles into both ends of two cable systems	Hydraulically swage a 3/8" stainless steel thimble into one end of a 3/8" stainless steel cable. Add one 6" PVC end cap onto this cable through the center hole on the end cap. Swage another thimble onto the other end of the cable (cable has swaged eyes at both ends). Repeat for a second cable.	Outsourced	Outsourced	Outsourced	Outsourced	
Two Platform	Mooring system	4	Add turnbuckle and attach both ends of cabling system	Use Jaw-Jaw turnbuckle system to connect the inner ends of the two cabling systems. Total length should be approximately the distance from Ark top to bottom.	Outsourced	Outsourced	Outsourced	Outsourced	

Figure S26: Two-Platform Arks. (Left) Two-Platform Ark prior to beach deployment. (Middle left) Two-Platform Ark shortly after attaching to the mooring system. Lift bags at the top of the Arks are used to provide temporary buoyancy prior to the addition of mooring buoys. (Middle right) Two-Platform Ark after the addition of limestone ARMS. (Right) Two-Platform Ark system after 1 year of deployment.

5   Methods for sample/data collection & processing

Sample and Data Collection

Physical parameters

1. ***Dissolved Oxygen***
   1.1. Calibrate DO sensors following manufacturer recommendation. Verify probe readings in the same water prior to use to account for slight differences in temperature/DO measurements.
   1.2. Deploy reef DO sensors on the reef with the optode placed within 5 cm of the benthos and deploy Ark DO sensors on the Ark mounting framework. DO sensors may also be placed in the Ark interior, or replicate sensors may be added.
   1.3. DO sensors should be deployed throughout the water sampling window (ideally, several days) to (1) match molecular and microbial metrics to oxygen saturation values and (2) to determine diel fluctuations associated with each site.
   1.4. For long term deployments, sensors should be checked periodically for fouling and sensor drift.

2. ***Energy dynamics*** – HOBO light & temperature pendants are a reliable and cost-effective method to capture long term fluctuations in temperature and light intensity.
   2.1. Mount HOBO pendants to the top of the Ark and to an adjacent spot on the reef, facing vertically towards the surface.
   2.2. Sensors may require periodic monitoring to clean fouling from the light sensor.

3. ***Water characters*** – Multiprobes provide reliable and simultaneous measurements of pH, salinity, dissolved oxygen, temperature, and redox state (among other potential sensor additions).
   3.1. Calibrate sensors following manufacturer recommendations.
   3.2. Deploy on Arks and reef sequentially or simultaneously during water sampling period.

4. ***Flow dynamics*** – Acoustic dopplers such as Acoustic doppler current profilers (ADCP) and Acoustic doppler velocimeters (ADV) collect current magnitude and directional data throughout the water column or at a single point, respectively, and can describe turbulent flows surrounding and within the Arks framework.
   4.1. Deploy ADCP on the seafloor to collect current measurements throughout water sampling period or for long term current assessment.
   4.2. Deploy ADV in the Ark interior, facing the center of the structure, to characterize turbulent flows in the interior of the structures, which have implications on water chemistry transformations and recruitment of mobile organisms.

5. ***Ark Physics*** – HOBO 'G' pendants are a reliable and cost-effective method to capture long term data on Ark physics, including tilt and acceleration, and can be used as a proxy for long-term flow patterns.
   5.1. Deploy HOBO G pendants on the Ark exterior, facing up. Sequential uses of these loggers should maintain the same attachment orientation.

6. ***In-water weight*** – Floating structures can be weighed using a tension/compression load cell, or strain gauge, to determine if the in-water weight of the community is increasing. This may serve as a rough proxy for community calcification, and thus coral growth, in restoration and conservation projects. Submersible load cells may be deployed long term or periodically to capture buoyant weight.

   6.1. Attach the submersible load cell to a block and tackle pulley system which can be used to temporarily transfer tension on the mooring line to the strain gauge system.

   6.2. Attach the base of the block and tackle to a secure location on the Ark mooring system, such as an intermediate shackle point or to the seafloor anchor. Attach the top of the load cell to a secure location on the Ark mounting framework.

   6.3. Without removing or altering mooring components on the Ark, pull line through the block and tackle pulley system such that tension is transferred from the Ark mooring system to the pulley system, cleating the line with each pull.

   6.4. Ensure mooring line is completely slacked to allow strain gauge to collect in-water weight measurements.

   6.5. Slowly transfer tension from block and tackle pulley system to Ark mooring line, checking to ensure shackles and other mooring components are properly seated and secure.

   6.6. For long term data collection, load cell can be integrated into the mooring system as an "in-line" component. Dataloggers can be periodically switched out to collect data from long term sensors.

Macro Ecology

1. ***Fish abundance & biomass*** – For either of the below-described methods, surveys should be performed at the desired frequency on (1) the Ark, (2) the surrounding reef benthos, and (3) for a parcel of empty water column approximately equivalent to the volume of the Ark, as a control for pelagic and transient water column fish communities. Fish biomass and abundance should be normalized to this volume.

   1.1. Stationary point counts – see Bohnsack & Bannerot, 1986 and Hylkema et al., 2020 for procedure. Briefly:

       1.1.1. Two divers identify their target site for data collection and remain 10m+ from site. One diver (the recorder) collects video footage while the other (the counter) counts and records fish data.

       1.1.2. The counter records the species, abundance, and size (to the nearest 5 cm) of fish inside the designated volume of water for 10 min.

       1.1.3. The divers swim closer to the target site and record species, abundance, and size of smaller, cryptobenthic fish within the sampling volume.

       1.1.4. Divers repeat for the next site.

   1.2. Video-based fish biomass estimates – see Letessier et al., 2015 and Neuswanger et al., 2016 for procedures. Briefly:

       1.2.1. Assemble a stereo video system using two GoPros mounted at an 18-degree angle inwards, and properly calibrate using a calibration frame [5].

       1.2.2. Position stereo video system underwater with the target site in full view. Divers should exit the water and allow Go Pros to record video for at least 30 min to capture natural fish communities associated with each site.

       1.2.3. Recommended GoPro settings are to film in Wide View, 60 frames/s, in 2.5K or 1,080 resolution. Automatic stabilization is also recommended.

2. *Benthic cover* – Benthic communities dominated by non-calcifying organisms, such as turf and fleshy macroalgae, can drive microbial and biogeochemical processes in opposition of calcifying organisms such as crustose coralline algae and scleractinian corals. We recommend quantifying percent cover of benthic organisms on Arks and seafloor control plots monthly during early successional stages, and later quarterly, as a metric for ecosystem health. See Roelfsema, Phinn & Joyce, 2006 and Wilson, Graham & Polunin, 2007 for procedures. Briefly:

   2.1. Divers capture top-down photos of coral plates, ARMS plates, Ark mounting framework, or equivalent surface area on reef benthos using camera equipped with flash.

   2.2. Alternatively, pre-trained divers can generate percent cover estimates from underwater surveys using a dive slate and a quadrat.

3. *Coral growth* – Coral growth and calcification are commonly used metrics to quantify reef success and determine changes in a reef structural complexity over time. We recommend quantifying coral growth on Arks via a combination of the following methods at the desired frequency. Briefly:

   3.1. **Total linear extension –** see Johnson et al., 2011 and Lirman et al., 2014

      3.1.1. Divers manually measure coral fragment dimensions using a ruler and record measurements on a dive slate.

      3.1.2. We recommend measuring (a) maximum vertical height (measured from the base of the coral fragment), (b) maximum horizontal extension (measured between the two furthest points of the coral fragment, and (c) 90 degrees to maximum horizontal extension (measured along the axis rotated 90 degrees from maximum horizontal extension).

   3.2. **3D Photogrammetry –** see protocols detailed in Lange & Perry, 2020 and Million et al., 2021

      3.2.1. Diver places a ruler scale adjacent to the target object (individual corals or coral plates).

      3.2.2. Diver collects a set of overlapping images of target object using an "umbrella"-shaped flight path. This process commonly requires 70–200 photos, depending on the size of the object—smaller and less complex objects require fewer photos.

      3.2.3. Diver records the number of coral plate or other identifier on a slate, photographing it before or after each image set for later identification of photo sets.

   3.3. **In-water weight** – This is a modification of the technique described in Jokiel, Maragos & Franzisket, 1978. Measurements using the load cell (described in detail above) can complement other finer-resolution coral growth metrics to generate a metric of community level growth/calcification.

      3.3.1. Follow procedure described in main protocol or above (Section 5)

4. *Coral health* – We recommend complementing diver-based assessments of coral health and survival with physiological proxies for coral health, such as Pulse Amplitude Modulated (PAM) Fluorometry to determine maximum photosynthetic quantum yield (Fv/Fm) of the endosymbiotic zooxanthellae.

   4.1. **Diver-based coral health assessment**

      4.1.1. Health assessments can be conducted in conjunction with total linear extension measurements described above.

      4.1.2. Diver visually assesses status (alive or dead) and general condition (bleached, damaged, healthy, diseased) of each coral fragment. Percent descriptors should be added for finer resolution health data.

      4.1.3. Health of corals can also be assessed post-dive using photos taken of corals or coral plates at multiple angles.

4.2. **PAM Fluorometry –** Fv/Fm ratio generated from this measurement can be used as a proxy for photosystem health and photosynthetic capacity of the endosymbiotic dinoflagellates within coral tissues. See Beer et al., 1998 and Ralph et al., 1999 for detailed procedures. Briefly:

    4.2.1. Diver transports underwater DIVING-PAM to Ark or seafloor site.

    4.2.2. Following manufacturer recommendations, diver collects 3–5 readings at different locations across coral surface, then averages these readings to generate an average maximum photosynthetic quantum yield (Fv/Fm) value.

4.3. *Invertebrate diversity –* DNA-based surveys of the COI gene can generate high-resolution assessments of cryptic diversity [15–17], which can be difficult to perform using traditional diver-based visual surveys.

    4.3.1. Divers collect water sample from desired sampling location (i.e., ARMS unit interior, Arks, or reef) using 2 L Hatay-Niskin bottle (described in detail below)

    4.3.2. Filter at least 1 L of sample seawater through a 0.22 μm PES Sterivex filter and dry the filter using a syringe.

    4.3.3. Freeze filter at -20 °C until DNA extraction and sequencing.

Microbiology and Biogeochemistry

1. *Water sample collection* – Collect 2 L of seawater from each sampling location at desired frequency to complete the below analyses following procedure outlined in Haas et al., 2014. Briefly:

    1.1. Collect water sample in 2 L polycarbonate Hatay-Niskin bottle from Ark or reef sites by passing the open sampling cylinder back and forth in the target sampling location to flush with sample seawater, and then cap the ends.

    1.2. For reef samples, we recommend collecting water from within 0.5 m from the benthos. Depending on project-specific questions, Arks samples may be collected from the Ark interior, exterior, upstream, or downstream of the structures. Duplicate or triplicate samples are recommended.

    1.3. Collect samples moving from downstream of the structures to upstream to avoid contamination associated with sampling downstream of boat or divers

    1.4. During transport, store water samples in a cool, shaded area (at 4 °C if possible). Process sample water within 4 h of collection.

2. *Inorganic nutrients* – For sample collection and analysis of inorganic nutrients (PO_4, NO_x, and NH_4) in seawater, follow procedure outlined in Haas et al., 2014. Briefly:

    2.1. Flush ~100 mL of sample water from Hatay-Niskin bottle through attached tubing and discard.

    2.2. Attach 0.22 μm Sterivex filter and flush with another 100 mL, discarding flow through.

    2.3. Rinse a clean, 20 mL HDPE plastic vial with sample water three times, then fill the bottle to the shoulder.

    2.4. Freeze vial immediately at -20 °C. Keep frozen until analysis.

3. *Bulk dissolved organic carbon (DOC)* – For sample collection and analysis of bulk DOC in seawater, follow procedure outlined in Haas et al., 2014. Briefly:

    3.1. Ensure all glassware and tubing has been washed in 10% HCl to prevent contamination.

    3.2. Filter sample seawater through a same 0.22 μm Sterivex filter as in previous section into a clean, pre-combusted, 40 mL amber borosilicate glass vial. Rinse vial three times with sample water, then fill the bottle to the shoulder.

3.3. Add 3 drops of full strength, molecular grade HCl, then cap with a PTFE-lined silicone septa (with the PTFE septa facing into the vial).

3.4. Store at 4 °C until analysis.

3.5. After 1 L of seawater has passed through the 0.22 μm Sterivex filter, remove filter from the line, dry by pushing air through with a syringe, and freeze at -20 °C for eDNA extraction.

4. *Viral and microbial abundances* – To enumerate virus-like particles and microbial cells in seawater, follow procedure outlined in Haas et al., 2014. Briefly:

   4.1. Add 1 mL of unfiltered sample water to an Eppendorf tube. Add 66 μL of 32% paraformaldehyde and allow to fix in the dark for 15 min.

5. *Microbial biomass* – To determine total microbial biomass and mean cell volume in seawater, follow procedure outlined in Haas et al., 2014. Briefly:

   5.1. Add 1 mL of unfiltered sample water to an Eppendorf tube. Add 20 μL of 25% glutaraldehyde and allow to fix in the dark for 15 min.

6. *Viral and microbial metagenomics –* Thurber et al., 2009 provided a procedure to extract viral DNA from seawater using PEG-precipitation and CsCl density centrifugation. The following protocol is modified from Thurber et al., 2009 to isolate total DNA from viral and microbial communities in seawater.

   6.1. Add 500 mL unfiltered sample water to a 500 mL HDPE bottle. Add 50 g of polyethylene glycol (PEG) and 15 g of NaCl, cap the bottle, and shake vigorously.

   6.2. Allow sample to rest at 4 °C for at least 2 h, mixing intermittently by inversion.

   6.3. Using a peristaltic pump system, pass 500 mL sample through a 0.22 μm PES Sterivex filter. Maintain low flow rate to avoid damaging the sample through excess hydrostatic pressure.

   6.4. Store Sterivex filter at -20 °C until DNA extraction and sequencing.

7. *Flow cytometry* – For sample collection and analysis of microbial community autotroph: heterotroph ratios, follow procedure outlined in Haas et al., 2014. Briefly:

   7.1. Add 1 mL unfiltered sample seawater to a 2 mL cryovial.

   7.2. Add 5 μL of 25% glutaraldehyde and invert to mix. Allow samples to fix in the dark at room temperature for 15–30 min.

   7.3. Flash freeze cryovials in liquid nitrogen and maintain frozen at -80 °C until analysis via flow cytometry as in McDole et al., 2012.

8. *Metabolomics* – For sample processing and analysis of untargeted metabolomics, follow procedure outlined in Dittmar et al., 2008 and Petras et al., 2017. Briefly:

   8.1. Collect remaining filtrate from the 0.22 μm Sterivex (between 0.8 and 1 L) into a HCL-rinsed polycarbonate bottle for untargeted metabolomics. Note: volume should be kept the same for all samples.

   8.2. Acidify the filtrate samples with concentrated HCl until the pH of the sample reaches 2.0 (typically 0.12% acid for seawater). Check pH with pH strips to confirm.

   8.3. Activate PPL resin as follows without letting them run dry:

      8.3.1. Three times the column volume with 100% LC-MS grade MeOH

8.3.2. Three times the column volume with acidified H_2O (1 mL of 37% HCl into 1 L of LC-MS grade H_2O; pH 2.0).

8.3.3. Three times the column volume 100% LC-MS grade MeOH again.

8.3.4. Three times the column volume of acidified H_2O again.

8.4. Place pipette tip of tubing into the sample bottle and turn on the vacuum pump.

8.4.1. Adjust the vacuum pump to a flow rate between 8 and 16 mL/min

8.5. After all the filtrate sample is loaded, rinse it with two column volumes of pH 2 H_2O to remove salts from the resin.

8.6. Dry the resin with nitrogen gas until the color of the cartridge changes to a light yellow.

8.6.1. Skip this step if you are in the field and do not have access to nitrogen. You may dry them later.

8.7. Freeze the cartridges, ideally at -80 °C but alright in -20 °C for a short period.

Sample Processing & Analysis

1. **Microscopy**

   1.1. *Viral and microbial abundances –* see Haas et al., 2014

   1.1.1. Place a 0.02 µm pore size Whatman Anodisc filter onto the glass filter stand of the vacuum-filtration rig. Cover with a glass filter tower and use a metal tower clamp to secure.

   1.1.2. Add 3 mL of molecular grade, DNA-free water to the filter tower. Add 1 mL of paraformaldehyde-fixed sample. Pipet up and down to evenly distribute sample across filter.

   1.1.3. Turn on vacuum to pull sample water through filter until dry.

   1.1.4. Place dried filter, face-up, on a 100 µL drop of 10x SYBR Gold solution in a Petri dish and allow to stain for 20 min in the dark.

   1.1.5. Rinse filter in a 100 µL drop of molecular grade water, dab excess water from the bottom of the filter with a kim wipe, and mount on a microscope slide using a slide mount solution (a 0.02 µm-filtered solution of 10% ascorbic acid, 1x PBS, and 100% glycerol). Add cover slip.

   1.1.6. Enumerate viruses (small white dots) and microbes (larger white circles) on an epifluorescent microscope (excitation/emission: 325–375/537 nm). Determine abundances manually or using image processing software such as ImageJ. A minimum of 200 cells should be counted per sample.

   1.1.7. Calculate virus-to-microbe ratio based on resulting viral and microbial abundances.

   1.1.8. Store prepared slide in a slide box at -20 °C.

   1.2. *Microbial biomass –* see McDole et al., 2012 and Haas et al., 2014

   1.2.1. Place a 0.2 µm pore size Whatman Anodisc filter onto the glass filter stand of the vacuum-filtration rig. Cover with a glass filter tower and use a metal tower clamp to secure.

   1.2.2. Add 3 mL of molecular grade, DNA-free water to the filter tower, then add 1 mL of glutaraldehyde-fixed sample. Pipet up and down to evenly distribute sample across filter.

   1.2.3. Turn on vacuum to pull sample water through filter until dry.

   1.2.4. Place dried filter, face-up, on a 100 µL drop of 25 ng/mL DAPI solution in a Petri dish and allow to stain for 20 min in the dark.

   1.2.5. Rinse filter in a 100 µL drop of molecular grade water, dab excess water from the bottom of the filter with a kim wipe, and mount on a microscope slide using a slide mount solution (a 0.02 µm-filtered solution of 10% ascorbic acid, 1x PBS, and 100% glycerol). Add cover slip.

1.2.6. Capture 10+ photos of microbial cells (or at least 200 cells total) on an epifluorescent microscope (excitation/emission: 358/461 nm).

1.2.7. Use image processing software such as ImagePro or ImageJ to determine abundances and dimensions (length and width) of each cell.

1.2.8. Cell volumes (μm^3) is calculated from length and width measurements by assuming each cell has the shape of a cylinder with hemispherical endcaps. See McDole et al., 2012 and Haas et al., 2014 for calculations and bacterial size-dependent relationships, which can be used to generate estimates of Total Biomass (g/10 m^3).

2. Water chemistry

2.1. *Bulk Dissolved Organic Carbon (DOC)*

2.1.1. Analyze bulk DOC via high-temperature catalytic oxidation as described by Carlson et al., 2010.

2.2. *Inorganic Nutrients*

2.2.1. Analyze nutrient concentrations using flow injection analysis as described by Guildford & Hecky, 2000.

2.3. *Untargeted Metabolomics*

2.3.1. The sample is eluted from the resin in 2 mL of LC-MS grade MeOH

2.3.1.1. Pipette the methanol into the LC vial using 1 mL pipette.

2.3.1.2. Force the resin through using a 50 mL plastic syringe

2.3.1.3. Dry the sample down in a Centrivap (typically overnight) at room temperature.

2.3.2. Once the sample is dry, store it at -80 °C or -20 °C or resuspend the dried extract for LC-MS analysis.

2.3.3. For LC-MS analysis, resuspend the sample in 100 µL of 80% LC-MS grade MeOH + 0.1% FA by pipetting the solvent up and down over the DOM pellet.

2.3.4. Transfer the resuspended sample to a micro glass insert inside of a 1.5 mL HPLC vial.

2.3.5. The sample is now ready for LC-MS/MS analysis.

2.3.5.1. After the sample has been analyzed, store it at -80 °C.

3. Image-based measurements

3.1. *Benthic cover* – see Roelfsema, Phinn & Joyce, 2006 for full procedure. Briefly:

3.1.1. Import photos into ImageJ or similar software. Overlay each photo with a grid of dots (ideally, 100 dots per image).

3.1.2. Visually identify the substrate under each dot to the highest taxonomic resolution possible. Examples include: (1) turf algae, (2) benthic cyanobacterial mat, (3) macroalgae (*Dictyota spp),* (4) coral (*Pseudodiploria strigosa),* (5) crustose coralline algae, (6) sponge, and (7) sand.

3.1.3. Sum identities to generate a benthic percent cover for each image.

3.2. *3D Photogrammetry* – see Lange & Perry, 2020 and Million et al., 2021 for full procedure. Briefly:

3.2.1. Upload photo sets for a target object (coral plate or individual coral colonies) to Agisoft Metashape software. Exclude blurry or poor-quality photos from analysis.

3.2.2. Use Metashape software to align photos using settings described in Lange & Perry, 2020

3.2.3. Perform error reduction on photo set.

3.2.4. Use Metashape to generate dense point-cloud reconstructions of the target object.

3.3. *Fish biomass* – see Neuswanger et al., 2016 for full procedure. Briefly:

3.3.1. Upload fish monitoring videos into VidSync software and synchronize footage time between videos from each camera

3.3.2. Use VidSync software to perform calibration and correct for distortion from still images of calibration frame *in situ*

3.3.3. VidSync will use 3-D positioning and triangulation to calculate fish biomass and abundance from fish monitoring videos.

6 Results from Hydrodynamic Modeling and Arks Prototype Testing

A series of modeling and experimental tests were conducted in order to select a geometry with the desired strength and physical characteristics to serve as a midwater platform for propagating reef biodiversity.

Scale models of 1V frequency solid and hollow Arks structures (frequency describes the number of triangles that comprise the structure, with higher frequencies containing larger numbers of triangles) were subjected to wind tunnel tests to investigate their hydrodynamic characteristics and test their structural stability under hydrodynamic loading [25]. The motion of fluid across an object creates vibrations that can compromise structural integrity over the long term. It is therefore advantageous to build a structure that does not "resonate" on its own. Solid and hollow models were subjected to a pinging test to determine natural frequencies of the structures. Both models were also tested in a wind tunnel at velocities that correspond to environmentally relevant water current speeds to determine the drag coefficient of each structure as it interacts with a fluid medium. Hollow Arks models exhibited lower natural resonance and produced less drag, and thus were selected for further testing.
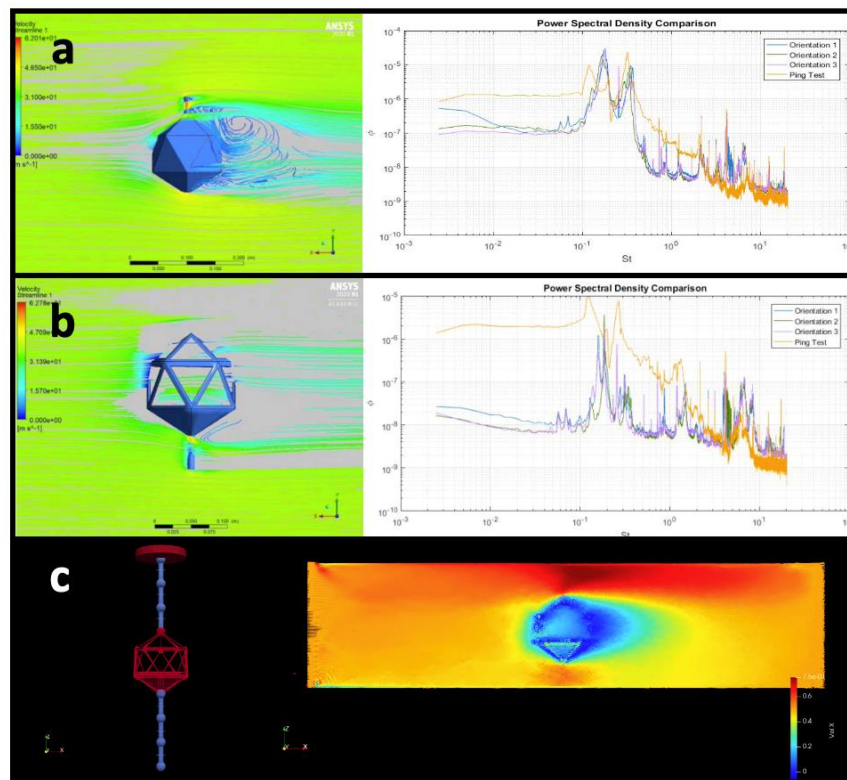

Figure S27: Wind tunnel tests were conducted to assess the hydrodynamic characteristics of Ark models. (a) solid and (b) hollow scale models of Arks. Accompanying plots represent power spectral density analyses and dominant Strouhal numbers, indicating frequencies induced by flow. The hollow Ark model was then simulated using flow regimes from Curacao to predict the magnitude of reduction in internal flow speed as water passes through the structure (c).

Hollow models of Arks structures were then modeled in natural flow scenarios using detailed computational models of the currents and bathymetry surrounding the Caribbean island of Curacao, a site at which two Two-Platform Arks were later deployed. Small-scale flow was simulated around a basic

model of a hollow, 1V Arks structure at 10 cm resolution using Smooth Particle Hydrodynamics (SPH) for current speeds up to 5 m/s. These models predict a 50% reduction in flow speed in the interior of the Arks structures relative to the surrounding water.

Next, multiple-element hydrodynamic models were developed for both Two-Platform and Shell (1V and 2V frequency polyhedra) structures to design Coral Arks systems that can withstand hydrodynamic forces expected in both typical flow conditions and extreme, hurricane-level scenarios. These models incorporated hydrodynamic forces on the Arks structure driven by currents (ambient and storm-associated), by waves (ambient and storm-associated), and forces on the mooring/anchoring system (cable stress, drag, and required strength of cables and anchor). The basic approach was to project the elements on the side of the structure facing the current into a plane projection, and to do the same for the opposite side of the structure. Based on the SPH results, it was assumed that the water current inside the structure would be reduced by half (therefore, the current acting on the planar projection on the opposite side of the structure would be half the strength of that acting on the side of the structure facing the current).

Figure S27b shows the resulting initial calculated forces on the Shell Ark that would be expected from ambient currents ranging up to 6 knots (~3 m/s; hydrodynamic model element 1). Also shown is the modelled tilt of the structure relative to the seafloor under these flow conditions. **Figure S28** shows the resulting initial calculated forces on the 2V Coral Ark that would be expected from ambient waves based on wave dispersion calculations in 10 m water depth, with the top an Ark at 5 m depth, wavelength of 11.1 m and amplitude of 0.35 m (hydrodynamic model element 2). Current speeds and wave conditions during both ambient (non-storm) and hurricane conditions were obtained from buoy data in the vicinity of Isla Vieques (Caribbean Regional Association for Coastal Ocean Observing [CARICOOS], www.caricoos.org), a site at which two Shell Arks were later deployed. Note that under ambient (non-storm) conditions, current speeds typically top out at approximately 2 knots (1 m/s).
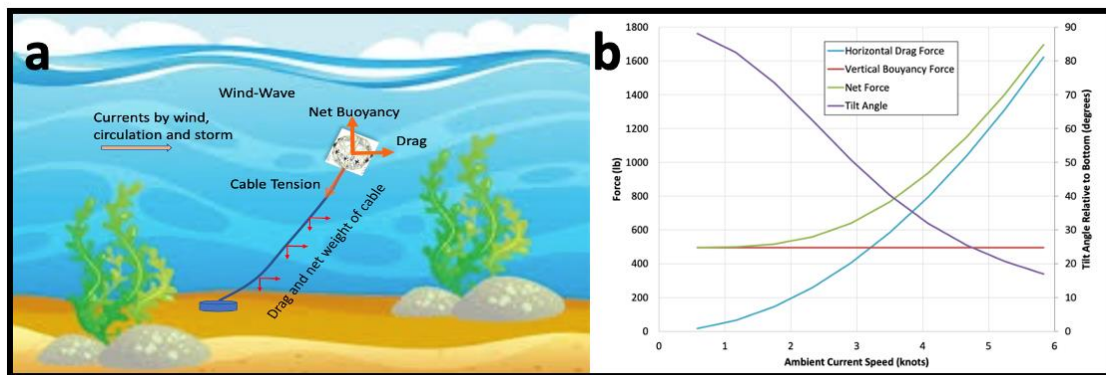

Figure S28: Hydrodynamics modeling. (Left) Generalized schematic of hydrodynamics modelling approach used. Models integrate hydrodynamic forces due to (1) currents, (2) waves, and (3) the combined effect of tension and drag forces on the mooring/anchoring system. (Right) Estimated horizontal drag force (blue), net hydrodynamic force (green), and fixed buoyant force (red) in pounds (lb) on a Shell Coral Ark based on ambient current speeds up to 6 knots (~3 m/s) and assumptions described above. Also shown is the estimated tilt angle of the structure (purple), which increases as currents increase in speed.
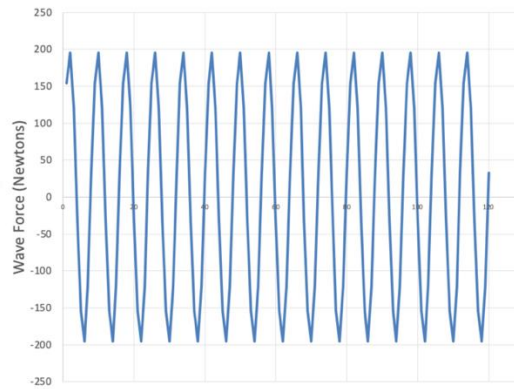
Figure S29: Estimated hydrodynamic force (in Newtons; 200 Newtons ~45 lbs) on a Shell Coral Ark at 5 m depth in 10 m of water based on ambient typical wave conditions and assumptions described above.

Prototypes of the Two-Platform (1V, 1.25 m radius) and Shell (2V, 1.5 m radius) Arks structures were then constructed in San Diego for in-water testing. Testing was focused on validating and refining several criteria contained in the models: (1) the drag coefficients on the Arks systems, (2) the reduction in current strength that occurs within Coral Arks structures of different geometries as water passes through the structures, and (3) overall hydrodynamic model validation (i.e., does the model accurately predict the measured force on the structure during testing).

We used a fixed-testing approach (a mooring test) to determine the internal reduction in flow and a mobile-testing approach (a towing test) to simulate stronger currents that the Coral Ark may experience during storm events. These tests used an acoustic doppler current profiler (ADCP) to measure currents in the vicinity of the testing, an acoustic doppler velocimeter (ADV) to measure currents within the Arks system, and a submersible load cell to refine drag coefficients originally obtained in wind tunnel testing. Drag coefficients for each Arks structure were calculated by towing the Arks structures behind a vessel with the load cell spliced in-line with the towing line and a tilt sensor to record changes in the Ark's orientation relative to the vertical axis. These coefficients were then integrated into the tension/drag component of the hydrodynamic models.
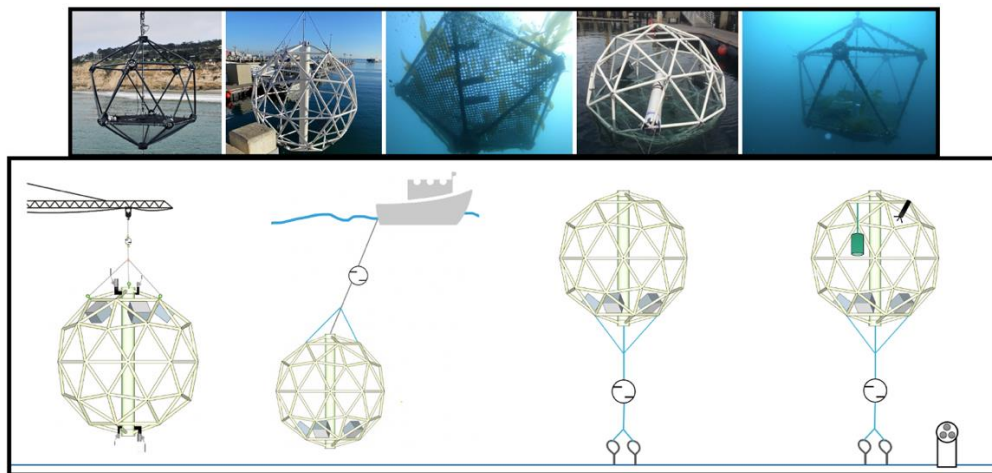
Figure S30: 1V and 2V prototype Arks structures were subjected to crane tests, towing tests, and mooring tests in San Diego to validate and refine values contained in hydrodynamic models.

Overall, data collected during testing of both Arks prototypes demonstrate that the hydrodynamic models developed can be used to accurately simulate and predict the drag, the tension, and the tilt angles resulting from hydrodynamic forces on the structures under varying water current speeds. Based on the calculated forces from these models, mooring systems for the Arks later deployed in Vieques were designed with all individual components capable of withstanding 3,500 lbs (1,600 kg) of breakout force.
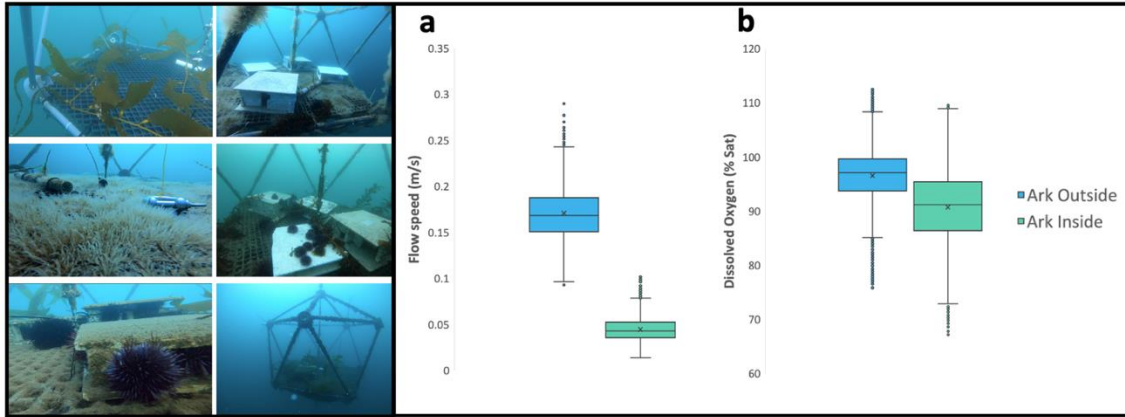
Figure S31: A Two Platform Ark was deployed for 6 months off the coast of San Diego. During this time, measurements were collected for (a) flow speeds and (b) dissolved oxygen concentrations both inside and outside the structures.

Analysis of flow speeds on the inside and outside of Arks using acoustic dopplers demonstrated that the flow passing through the Arks becomes turbulent, resulting in a significant reduction (40–70%) in current speed within the Arks interior relative to the surrounding water. Dissolved oxygen concentrations on Arks were found to be lower within the Arks interior relative to the surrounding water, possibly linked to reduced flow inside the structures. We predicted that the local differences in flow magnitude and direction across Arks would result in local differences in other water characters as well, such as dissolved oxygen and pH. To test this, we measured physical parameters (flow speed, dissolved oxygen, pH, and temperature) at several locations inside and outside Arks structures to develop "maps" of physical conditions associated with Arks structures. These results were used to identify optimal locations to translocate corals and seeded ARMS to the Arks. For example, high flow and dissolved oxygen concentrations at the top of Arks provides an enhanced environment for coral growth, while the turbulent internal environment provides conditions more similar to those experienced by cryptic communities inside the reef matrix. Shell Arks in Vieques were therefore designed with coral plates attached to the top of the structures and ARMS attached in the interior.

Projects using Coral Arks as coral mitigation tools are currently underway in the Caribbean. One of these projects, funded as a demonstration through the Environmental Security Technology Certification Program (ESTCP) within the Department of Defense (DoD), is using Coral Arks to support the ongoing munitions cleanup effort at the Vieques Naval Training Range (VNTR) by housing and maintaining corals translocated from seafloor munitions. Coral Arks offer a new technology for coral mitigation that is expected to result in higher success rates, additional ecosystem benefits, and lower overall costs associated with coral mitigation, compared to traditional approaches. The testing described above informed and supported the development of two Coral Arks structures that were deployed in Vieques, Puerto Rico in November 2021 with logistical and in-kind support from the Naval Facilities Engineering Command (NAVFAC) Vieques Restoration Program team.

7 Strain Gauge Manufacture, Assembly, & Use

Table S8: Manufacture and assembly of components for submersible strain gauge system to measure in-water weight of Coral Arks.

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Strain Gauge	1	Install eyebolts into load cell	Screw a M16 x 2, 27 mm thread length eyebolt into either side of a STA-8-1T tension/compression load cell, using Loctite 262 threadlocker to seal.	Threadlocker, torque wrench	1	1	1	
Strain Gauge	2	Cut and machine datalogger housing	Cut 1-1/2 clear PVC pipe and machine one end to integrate the datalogger housing cap (see drawing). To the other end, attach a 1-1/2 PVC cap using PVC primer and glue.	Miter saw, lathe	15	1	15	Figure SI 31
Strain Gauge	3	Cut and machine datalogger housing cap	Cut 2" PVC rod to drawing.	Miter saw, lathe	*Outsourced*	*Outsourced*	*Outsourced*	Figure SI 32
Strain Gauge	4	Splice male connector to load cell wires	Use wire strippers to expose wires in the load cell cable and on the male SubConn connector lead. Splice these two cables together by soldering the wires (black to black, red to red, green to yellow, white to white) and seal with heat shrink.	Soldering iron, wire strippers, solder, heat gun	10	1	10	
Strain Gauge	5	Waterproof splice	Using a rubber mold, fill mold with a polyurthane potting compound to fully encapsulate the spliced wires. Let dry before removing carefully.	Polyurthane resin and hardener	60	1	60	
Strain Gauge	6	Install female connector into datalogger housing cap	Using PTFE tape, install female SubConn connector into the threaded hole at the top of the datalogger housing cap until snug.	PTFE tape, crescent wrench	5	1	5	Figure SI 33
Strain Gauge	7	Attach datalogger housing to load cell.	Attach datalogger to a cut piece of fiberglass sheeting using a vibration-damping routing clamp, secured around the clear PVC pipe on the housing. Attach this assembly to the load cell via a clamping U-bolt placed around the waterproof strain relief located at the middle edge of the load cell.	Table saw, wrench, screwdriver	60	1	60	Figure SI 33
Strain Gauge	8	Install Datalogger	Install Bridge101A 30mV Datalogger into the housing by wiring the leads from the female SubConn connector to the datalogger.	Jewelers screwdriver	2	1	2	Figure SI 33
Strain Gauge	9	Waterproof datalogger housing	Install a greased O-ring into the O-ring groove on the datalogger housing cap. Install two screws through both the clear PVC wall and the datalogger housing cap.	O-ring grease, hex key	2	1	2	Figure SI 33
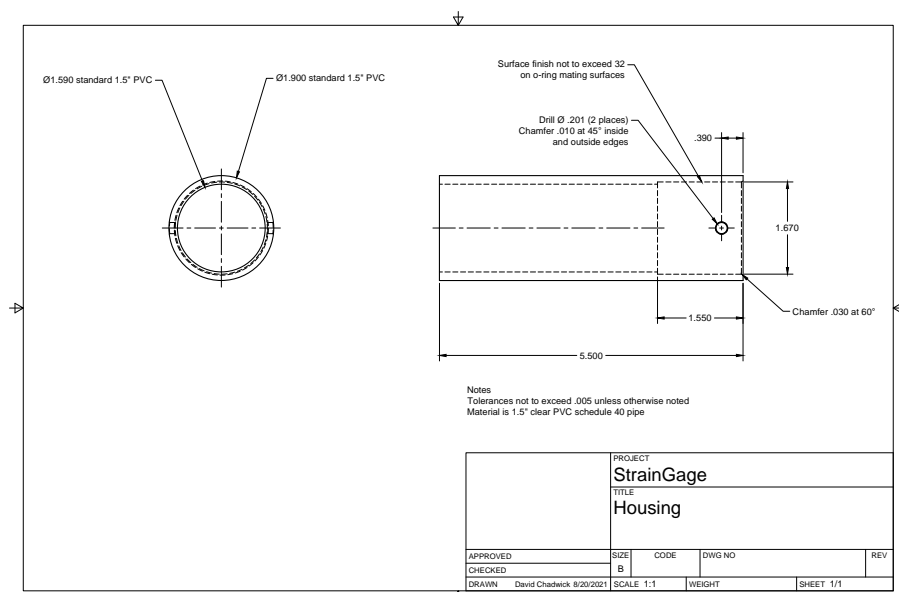
Figure S32: Technical drawing for the Bridge101A 30mV datalogger submersible housing.
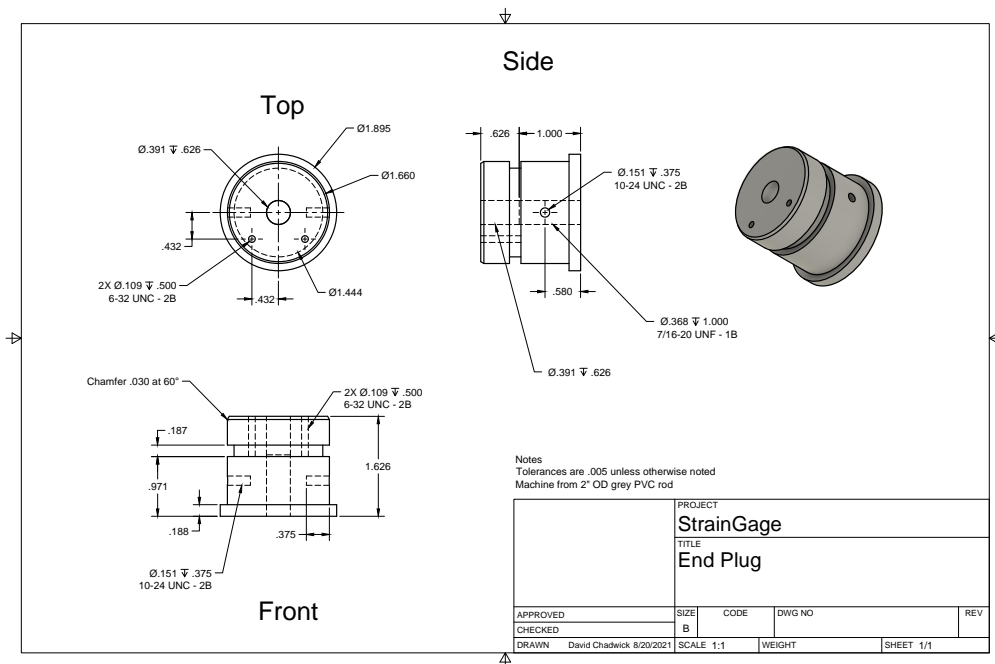
Figure S33: Technical drawing for the Bridge101A datalogger submersible housing end cap.
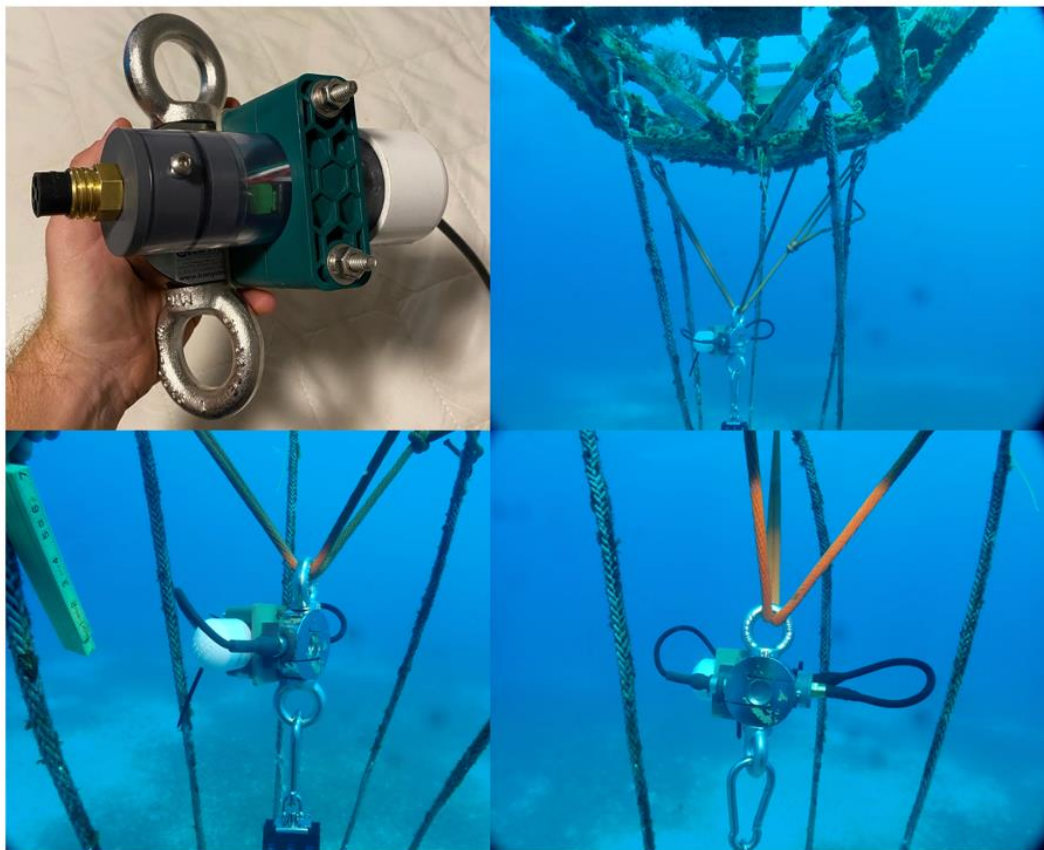
Figure S34: Strain gauge. (Top left) Fully assembled strain gauge and submersible datalogger housing. (Top right, bottom left and right) Use of strain gauge to measure in-water weight of Coral Arks. A block and tackle is used to transfer tension from the mooring line to the strain gauge system.

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