Triton–C
Detailed Design Report: Surface Float

DE-FOA-0001418: Demonstration of an Advanced Multi-Mode Point Absorber for Wave Energy Conversion
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Principle Investigator: Tim Mundon. Ph.D.
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Milestone 6
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Following drawings provided (see Index in Reference for more detail):
17115.01-100-002_Triton-C General Arrangement
17115.01-230-001_Painting and Markings
17115.02-100-01--_Triton-C Assembly Drawings
17115.01-000-002_Triton-C Mooring Arrangement
17115.01-500-001_Triton-C Cooling System

Document Version Control

Version	Version Date	Summary of Changes	Author
R0-0 (Draft)	3/19/19	Initial Draft	KDS
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R0-2	10/23/19	Cooling system and drawing updates	KDS
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R1	11/5/19	Final edits	KDS

Review

Name	Role	Approval
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Kate Stinson	Engineering Project Manager	

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Summary

The Triton-C Hull is a structural body designed for maximum motion in response to waves in order to generate maximum power extraction in the drivetrains. The Power Take Off equipment and all related subsystems are housed within the hull. The hull is moored to the seafloor.

Surface Float (Hull)

General Layout

The surface float includes external and internal features for power generation and survival and includes the following subsystems: mooring, hull, externals (deck, paint, surfaces, draft lines, logos, mast, safety system, and hatch) and internals (paint, surfaces, structure, grating, light, housing, foundations, HVAC, fire protection, and bilge).

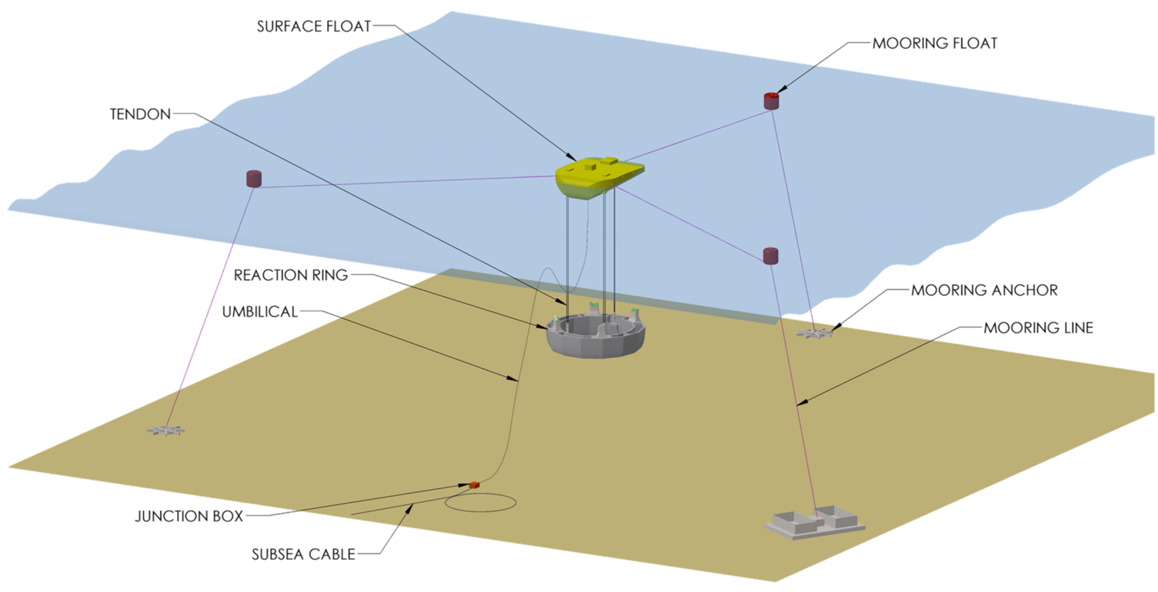

Figure 1. General Layout of Triton- C

Figure 2 shows the relationship of the surface float to other systems within the Triton-C, both at the surface and subsea. The hull is a structural body connected to all other systems shown again in the diagram in Figure 2.

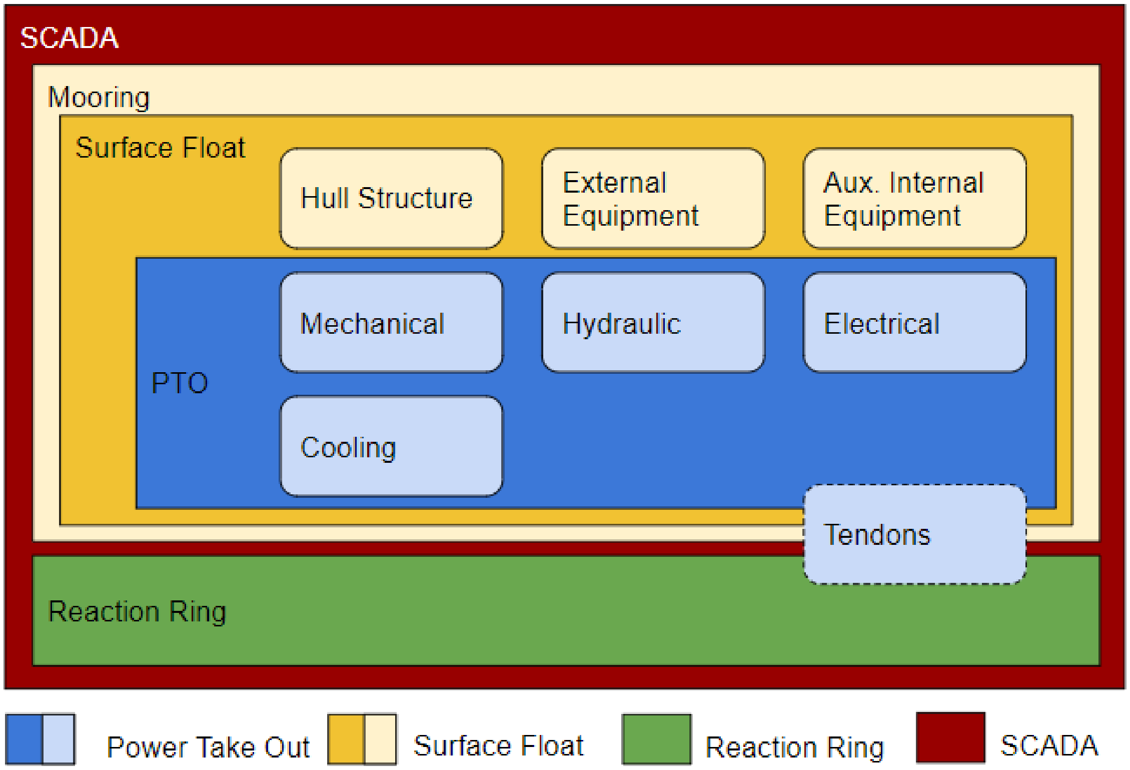

Figure 2. Triton-C system diagram

Mooring

The Triton-C has a three-point mooring arrangement designed to provide soft horizontal station-keeping while exerting minimal vertical forces on the WEC. The general architecture consists of an upper line (hawser) connecting the Triton-C hull to a submerged mooring float, and a lower line (riser) connecting the mooring float to the anchor. The configuration in Figure 3 is shown for illustrative purposes only, but is mostly indicative of the arrangement.

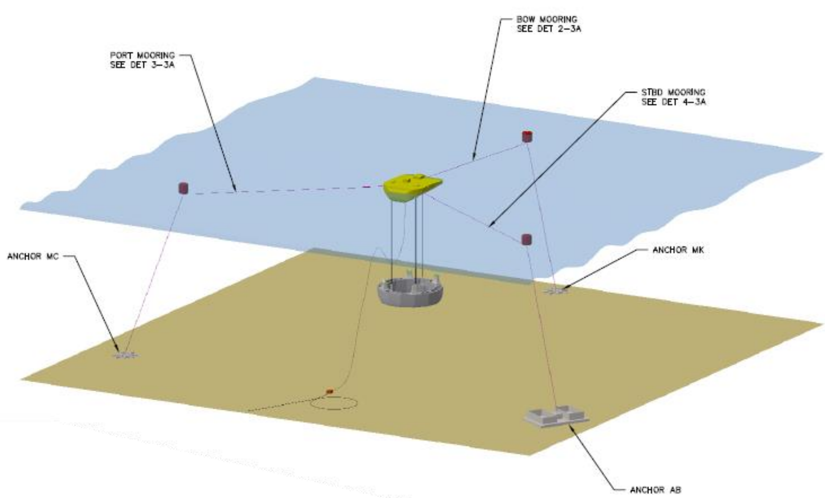

Figure 3. Triton-C mooring arrangement

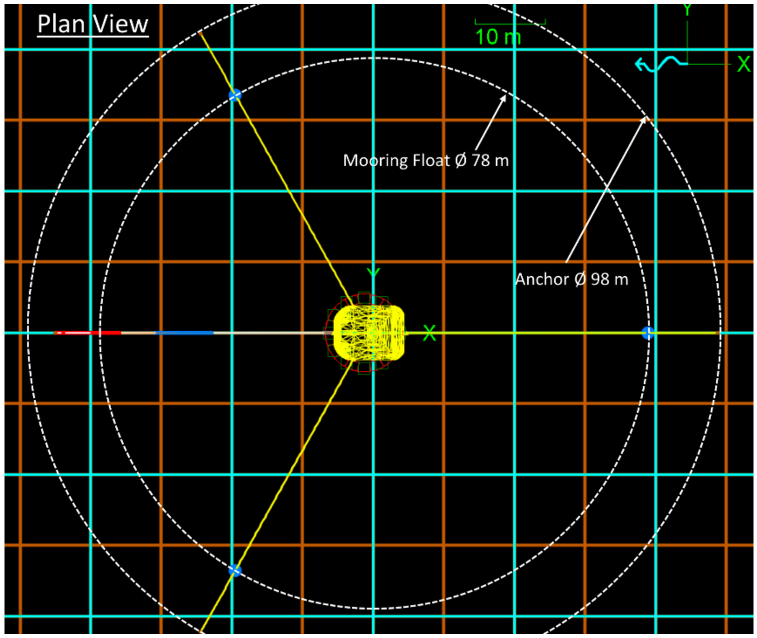

Figure 4. Mooring system plain view

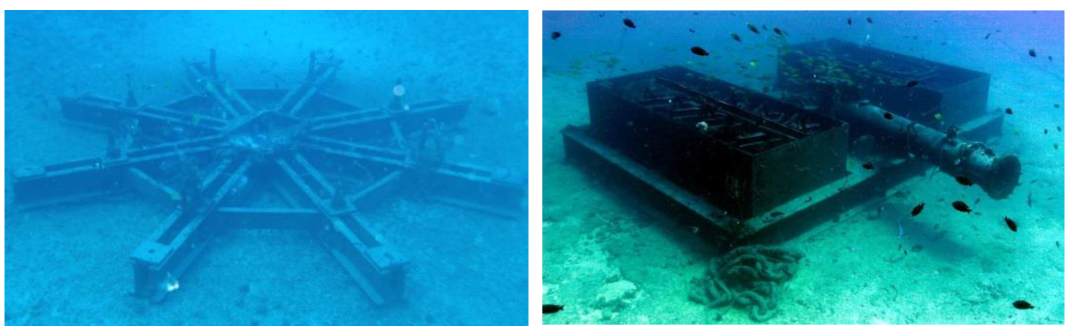

Figure 5. Images of anchors at WETS, 30m berth. (Left) MC & MK. (Right) AB

The WETS 30m berth site has three pre-installed anchors from an earlier deployment by Ocean Power Technologies. The anchors are positioned on a 160' radius circle centered about the WEC. Locations of these anchors are shown in Figure 4. There is a slight variation in depth for each anchor, ranging from 30.8-32.7 m, summarized in Table 1. Triton C will be installed such that the bow mooring line attaches to Anchor MK, the port mooring line attaches to Anchor MC, and the starboard mooring line attaches to Anchor AB. This means the bow points 60° to the east of north. Due to the directionality of the wave resource, shown in Table 1, we expect the largest loads on anchors MC and MK.

Table 1. WETS anchor coordinates, 30 m berth. X and Y coordinates relative to Triton-C centroid

Anchor ID	**Triton-C connection**	**X [m]**	**Y [m]**	**Water Depth [m]**
MK	Bow	48.77	0	32.3
MC	Port	-24.38	42.23	32.7
AB	Starboard	-24.38	-42.23	30.8

Anchors MC and MK are rock-bolted anchor structures with a spoke and wheel construction and are secured to the seafloor with eight 1” diameter rock bolts (Figure 5 left). In 2002, individual bolts were tested in shear and in tension [2]. In shear, the weakest bolt began to yield at 28,250 lbs. In tension, the frame began to yield at 64,296 lbs when pulling one of the bolts.[1]
While there are 8 bolts on each anchor, visual inspection in 2012 showed that some of the bolts can move laterally and therefore are assumed to be ineffective. For anchor MC, 2 of the 8 bolts were determined to be loose. For anchor MK, 3 of the 8 bolts were determined to be loose.
Anchor AB is a large 200T gravity anchor (Figure 5 right) and has a design capacity of 890 kN (200 KIPS) vertical load. Its shear capacity is not documented but would depend on the friction between the anchor and the seafloor, however due to the mooring arrangement, the shear loading of the AB anchor is not significant.

Detailed dimensions of the three anchors may be found in Appendix A – Anchor Schematics.

The MC and MK anchors see all the mooring load for this installation, although their construction substantially limits their capacity in shear. As a result of this, a taut arrangement with subsea mooring buoys was selected, shown in Figure 6. In this arrangement, the lower line provides a more vertical force on the anchors, thus minimizing shear loads.

A nylon rope was selected to provide a low modulus and high elongation, thereby maximizing Triton-C motions and power capture. Whitehill wirelay rope (3NQ) was selected due to its superior fatigue life over braided ropes [10]. Roulette thimbles will be used at the ends each nylon lines to allow a favorable D:d ratio and minimize fatigue at the mooring eyes and connections. To avoid chafing and facilitate connections, chain pigtails will be connected to the ends of the nylon risers and hawsers where they attach to the mooring floats, anchors and hull.

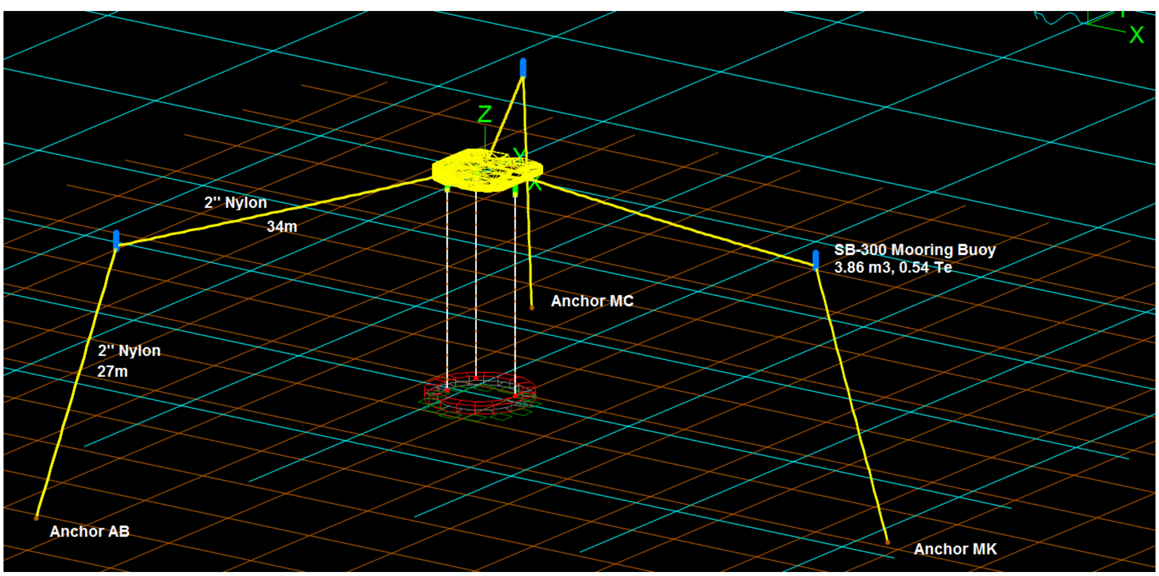

Figure 6. Mooring system isometric view

[1] Additionally, in 2012, the entire anchors (MC & MK) were proof tested to 220 kN (50 KIPS) vertical load [4].

The line support buoys (mooring buoys) were used in a previous deployment and our intention is to re-use these as they are currently owned by UH and available for this deployment. They will be located at approximately 3-5m below the surface. The properties for the mooring buoys (Ocean Guard SB-300) are summarized in Figure 6.

OCEAN GUARD SUPPORT BUOYS

BUOY MODEL	BUOYANCY NET		BUOY WEIGHT		DIAMETER OVERALL		HEIGHT OVERALL		WORKING LOAD	
	LBS	KG	LBS	KG	FT	M	FT	M	LBS	TONS
SB-25	551	250	158	72	2.6	0.8	2.6	0.8	22,000	10
SB-50	1,102	500	285	129	3.2	1.0	3.2	1.0	22,000	10
SB-75	1,653	750	390	177	3.5	1.1	3.5	1.1	22,000	10
SB-100	2,205	1,000	475	215	3.8	1.2	3.8	1.2	40,000	18
SB-125	2,756	1,250	537	244	4.1	1.2	4.1	1.2	40,000	18
SB-150	3,307	1,500	584	265	4.3	1.3	4.3	1.3	40,000	18
SB-175	3,858	1,750	687	312	4.6	1.4	4.6	1.4	40,000	18
SB-200	4,409	2,000	819	371	4.8	1.5	4.8	1.5	40,000	18
SB-250	5,511	2,500	931	422	5.2	1.6	5.2	1.6	40,000	18
SB-300	6,614	3,000	1,200	544	5.5	1.7	5.5	1.7	45,000	20
SB-350	7,716	3,500	1,300	590	5.8	1.8	5.8	1.8	45,000	20
SB-400	8,818	4,000	1,612	731	6.0	1.8	6.0	1.8	45,000	20
SB-450	9,921	4,500	1,712	777	6.2	1.9	6.2	1.9	45,000	20
SB-500	11,023	5,000	1,945	882	6.4	2.0	6.4	2.0	45,000	20
SB-600	13,228	6,000	2,302	1,044	6.8	2.1	6.8	2.1	45,000	20
SB-700	15,432	7,000	2,500	1,134	7.2	2.2	7.2	2.2	45,000	20

* ACTUAL VALUES FOR ABOVE SIZES MAY VARY +/- 15% DUE TO VARIATIONS IN MATERIALS, AND TOLERANCES.

SB-300 MOORING BUOY

Figure 7. Mooring buoy [1]

A summary of each mooring leg is presented below:

<u>Bow Mooring Leg:</u>

- Anchor MK
- 3 m chain (approx. 1.5”)
- 22m riser (2.5” Whitehill nylon with roulette thimbles)
- 1 m chain (approx. 1.5”)
- SB300 subsea buoy
- 1 m chain (approx. 1.5”)
- 38 m hawser (2.5” Whitehill nylon with roulette thimbles)
- 1 m chain (approx. 1.5”)
- Load pin shackle

<u>Port Mooring Leg:</u>

- Anchor MC
- 3.4 m chain (approx. 1.5”)
- 22 m riser (2.5” Whitehill nylon with roulette thimbles)
- 1 m chain (approx. 1.5”)
- SB300 subsea buoy
- 1 m chain (approx. 1.5”)
- 38 m hawser (2.5” Whitehill nylon with roulette thimbles)
- 1 m chain (approx. 1.5”)
- Load pin shackle

<u>Starboard Mooring Leg:</u>

- Anchor AB
- 1 m chain (approx. 1.5”)
- 16.5 m riser (2.5” Whitehill nylon with roulette thimbles)
- 1 m chain (approx. 1.5”)
- SB300 subsea buoy
- 1 m chain (approx. 1.5”)
- 38 m hawser (2.5” Whitehill nylon with roulette thimbles)
- 1 m chain (approx. 1.5”)
- Load pin shackle

Bow Load pin shackles (LCM systems) will be installed at each of the hull mooring eyes and will be used to measure mooring loads. Cables will be connected to the Triton-C hull with wet mateable connectors.

Hull

The hull structure is made up of both internal and external components which are part of the surface float of the Triton-C device. The hull is the major structural system that houses the drivetrains and auxiliary systems, as well as providing the hydrodynamic shape for maximum power capture. Figure 8 show the structural frames that make up the hull as rendered within the structural drawing.

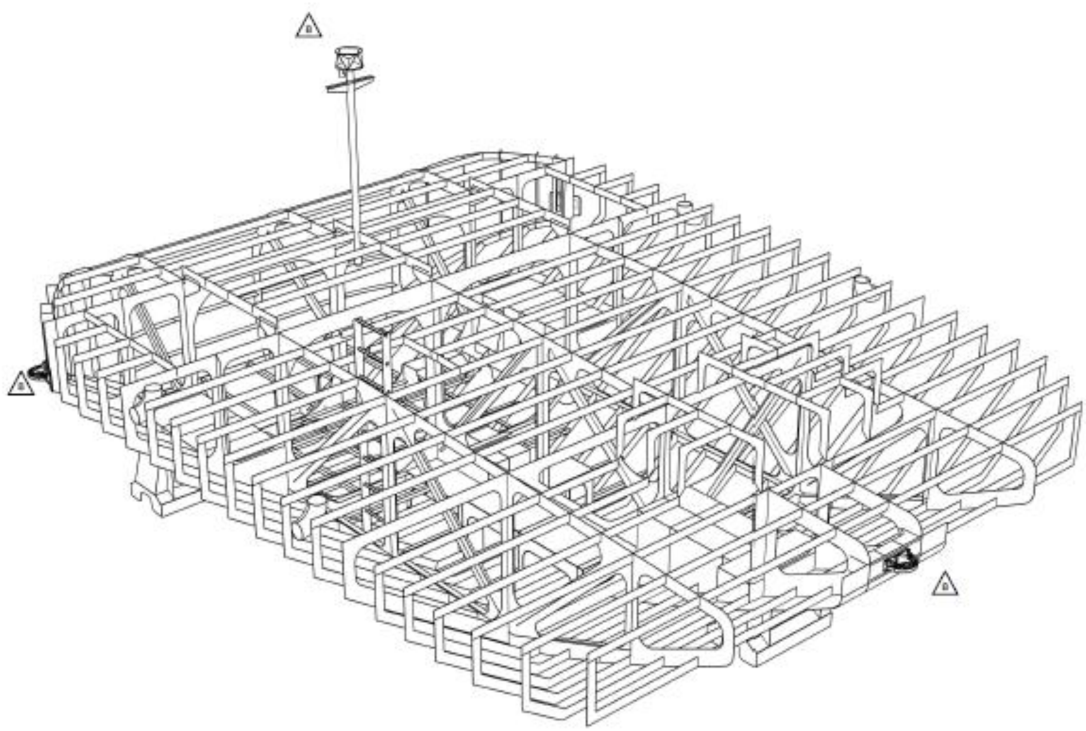

Figure 8. Structural framing within the hull of the surface float

The hull of the Triton-C is manufactured out of steel, and the deck layout is shown in Figure 9. The hull is air-tight and completely sealed from the environment, with the exception of valves that will allow air from inside the hull to exit in the case of an overpressure event (such as would be triggered in the case of activation of the fire extinguishing system). Personnel access inside the hull will be through a raised access hatch on the deck. A system of raised safety rails on the deck will allow personnel to attach to safety lines, while the deck will be covered with a non-skid surface where practical (as indicated in Figure 9). All raised edges will be rounded for safety. The hull will be NEPA, ESA, NHPA, MBTA, RHA, compliant abiding by containment, ingress, and protection standards and risk management.

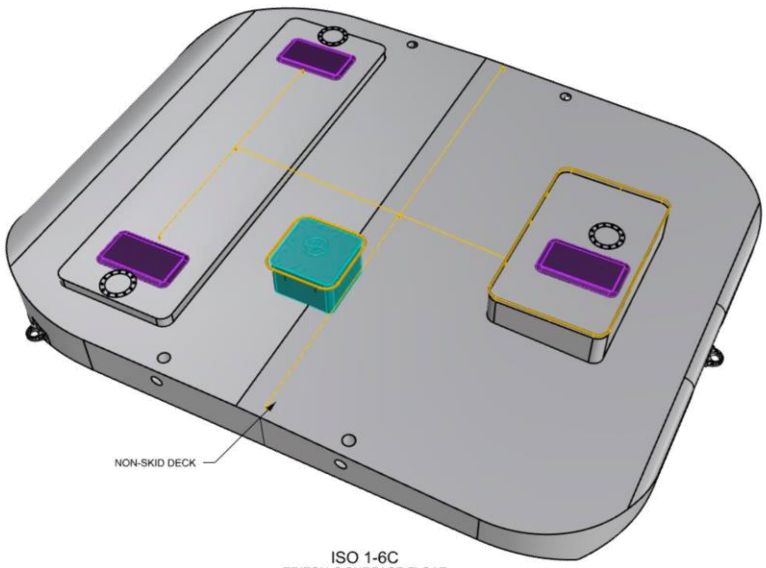

Figure 9. Hull assembly shows the major features including recessed service vessel mooring points, mooring padeyes, and major drivetrain blisters, and access hatch.

The hull will be finished with International Paint *Interthane* 990V in yellow above waterline and International Paint *Interspeed* 642 anti-fouling in black below the waterline. Other markings will be similar to that shown in Figure 10 & Figure 11, although final logo and branding is still to be determined. Navigation identification will be provided by a light, AIS - class-B transponder and radar reflector located atop a mast central to the deck. The marking and lighting plan will be reviewed by the United States Coast Guard.

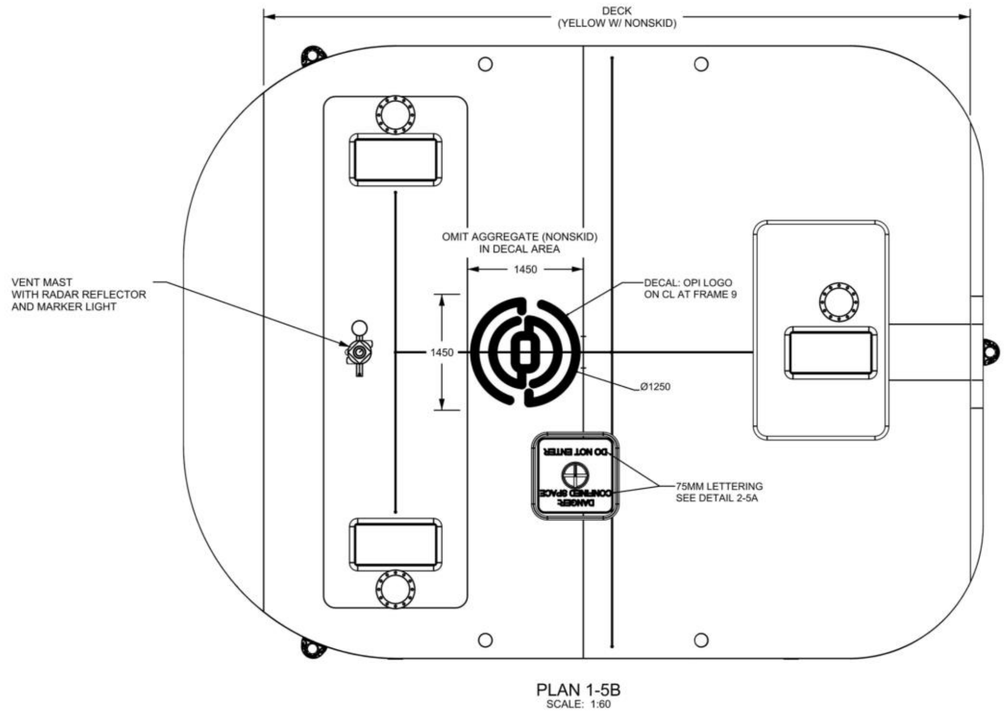

Figure 10: Plan view of Marking, lighting and paint diagram

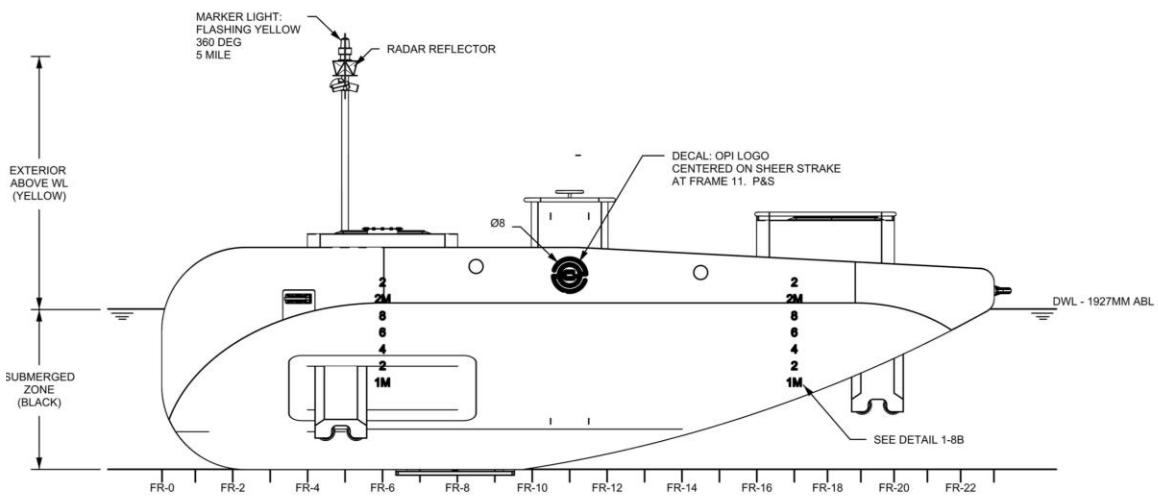

Figure 11. Side view of preliminary marking, lighting and paint diagram

The three drivetrains and related auxiliary equipment reside within the hull. The hull structure is constructed from Grade 50 steel and uses a novel 'slotted box partition' style construction for interlinking frames and stiffeners. Attached to this frame and body are steel foundations to mount the drivetrains, hydraulic skids, electrical cabinets, and various sub systems for cooling and hydraulic piping. Other areas where the hull is reinforced are where the mooring padeyes and tie up elbows are located. The interior space of the Triton-C hull can be accessed through a single point of entry (hatch) located on the deck. There are Also two access hatches for ventilation and drivetrain access.

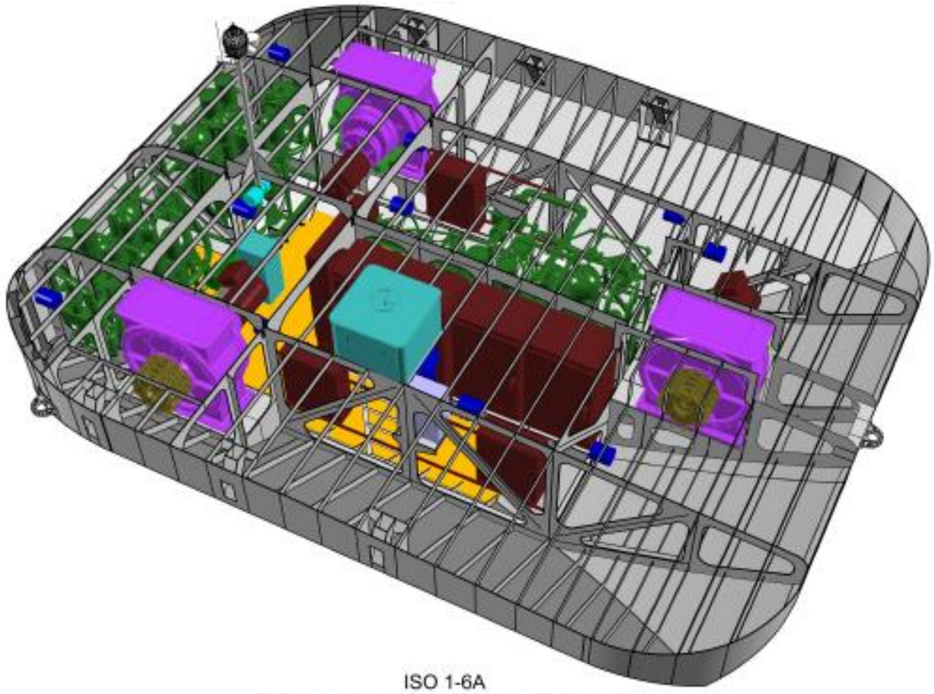

Figure 12. Hull assembly showing drivetrain components: drivetrain gearbox shown in purple

Other equipment within the hull support the functionality of the drivetrain: cooling system reservoir, the bilge system, fire suppression and protection, lighting, 360 cameras, composite deck grating, cable trays for instrumentation, as well as environmental-conditioning desiccant. This is further detailed in the General Assembly and related drawings as found in the Appendix.

Cooling system

The cooling system for Triton-C drivetrain will consist primarily of a closed freshwater cooling loop connected to an open seawater loop. A 15% glycol and 85% deionized water mixture will be the main freshwater loop in the system which is circulated through the hydraulics, drivetrain brakes, and electrical systems. A passive keel cooler is used on the freshwater cooling system to manage cooling loads during normal operations. The cooling pump will flow at around 50 GPM. During extreme wave operations, the drivetrain systems will produce larger heat loads and in which case the seawater cooling system will add additional cooling capacity via heat exchanger. This seawater cooling system will be active during events such as grid loss and extreme storm operations. These cooling loops are described in the flow diagram that is Figure 13.

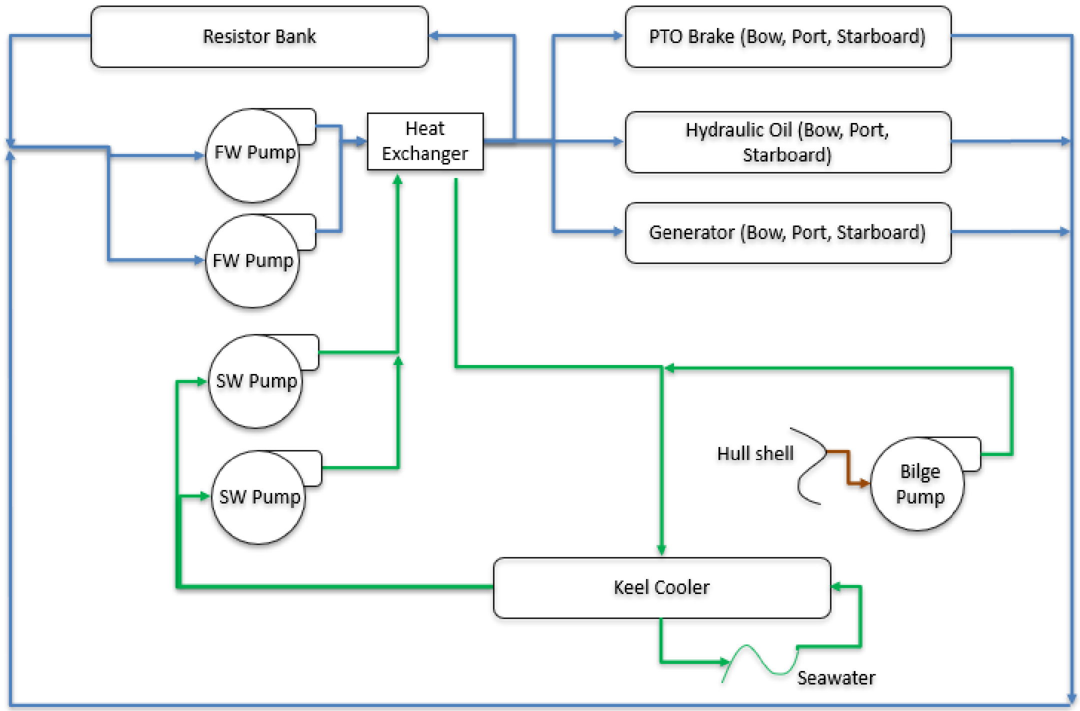

Figure 13. Cooling system flow diagram includes heat sinks and sources as the coolant flows through sub systems (freshwater blue, saltwater green)

The high-level flow diagram omits the detail design including the freshwater reservoir as well as various other mechanical components such as valves, piping, and the keel cooler. Each sub system and component will be further described below.

Cooling loads

The cooling system supplies freshwater coolant to four heat sources within each drivetrain inside the surface float: the resistor bank, the generator, the hydraulic oil heat exchanger, and the dynamic brake. Three of these systems reside within the drivetrain while the resistor bank resides within the auxiliary electrical system.

The largest load on the cooling system is the resistor (load) bank. This component will dissipate electrical power as needed through heat. This single component's heat load sizes the majority of the cooling capacity needed for the Triton-C. Figure 14 shows a general layout of the resistor bank. This sub system's loads are high when operation is in extreme waves and there is a grid fault condition.

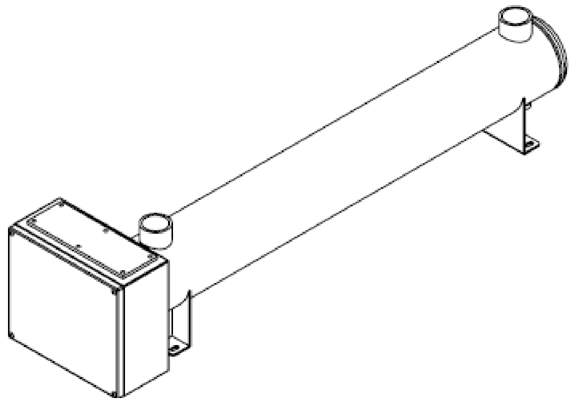

Figure 14. Resistor bank ISO view [2]

Another source of heat in the PTO system is the generator. This cooling sub system runs under all operational conditions. The coolant flows through cooling ports designed into the motor/generator. The generator requirements for fluid properties are the most restrictive within the entire cooling system and therefore drive the fluid properties chosen: 85% de-ionized freshwater and 15% glycol. Figure 15 show where the cooling ports are located on the generator housing. Each drivetrain generator has parallel flow loops (bow, port and starboard). Generator cooling loads are highest during extreme waves.

Figure 15. Generator cooling ports [3]

The third cooling subsystem is the hydraulic oil heat exchanger. This component resides within the hydraulic drivetrain skid mounted to the frame of the hull. This cooling loop is connected to an oil loop within low pressure side which supplies oil to the drivetrain manifold. Heat loads on this subsystem are dynamic, but highest during extreme waves where a high spring force is needed to limit displacement of the tendon.

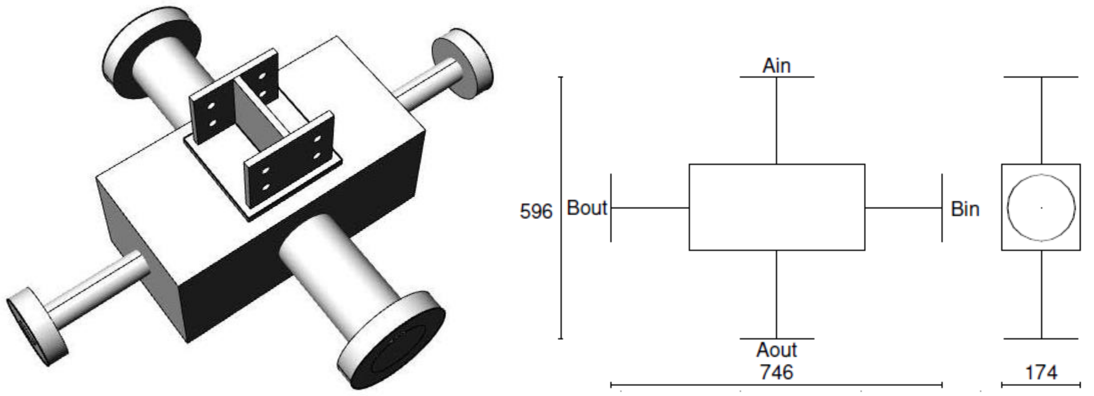

Figure 16. Hydraulic oil heat exchanger model and dimensions [4].

The last major subsystem being cooled by the cooling system is the dynamic brake. The dynamic brake is located on opposite side of the gearbox from the generator. Heat loads on the brake are highest in the case of a generator failure event.

Figure 17. Eaton Airflex dynamic brake: cooling ports located on each sandwiched plate at the top [5].

The following table summarizes the heat loads by system on a high level.

Table 2. Maximum of heat load by sources within the PTO

Component	**Normal Operation [kW]**	**Extreme Waves [kW]**	**Fault Case Grid Loss/Gen Fail [kW]**
Resistor bank	10	30	30
Generator (per generator)	4	4	4
Dynamic brake (per PTO)	4*	30*	30*
Hydraulic oil (per heat exchanger)	8*	8*	8*
Hotel Max Load	51	100	84

*Values provided are indicative based on predicted maximums and not necessarily seen concurrently by all subsystems.

Freshwater

The remaining parts of the cooling system are the heat exchangers and mechanical equipment that help coolant flow throughout the cooling system: keel cooler, pumps and respective motors, as well as the coolant reservoir. The reservoir is designed to supply additional coolant to the system in case of a leak or loss of fluid. The freshwater loop is a closed system.

Figure 18. Freshwater, bilge, and saltwater pump and motor assembly [6]

The freshwater and saltwater loop runs off a 1 hp pump driven by a motor and variable frequency drive. The freshwater loop has a main pump and a backup to minimize the likely hood and effect of a cooling system failure.

The freshwater loop is primarily cooled through a keel cooler. This cooler is sized for normal operations as well as extreme waves where the heat exchanger can be applied. It has a heat capacity of 21kW for a system flow rate of 45 gallon per minute. Figure 19 show the general design of the 50-inch (length) keel cooler specified for the system. More detail can be found in the cooling system drawing in Appendix.

Figure 19. Keel cooler [7]

Seawater

The seawater loop contains the same pump and motor design as the freshwater loop system, however, it runs on an independent pump utilized only during extreme wave conditions. The seawater loop is connected to the bilge pump via a one-way valve, which is only to be used in a case of extreme water ingress. The seawater loop also has extra conditioning on the coolant seawater as it is an open system. Seawater flows into the cooling loop and runs through a strainer before entering the heat exchanger and then being pumped back out of the coolant piping. The seawater system transfers heat from the freshwater system via a heat exchanger extreme waves and fault cases.

Heat exchanger

This heat exchanger between the freshwater and seawater cooling systems was design for maximum heat loads on the cooling system. The main driver of this load is the resistor bank followed by brakes and generator cooling. All of these major heat loads occur during extreme sea events. The chosen design of this heat exchanger is a plate design such as the Sperre design shown in Figure 20.

Figure 20. Freshwater-seawater heat exchanger

References

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Appendix A – Anchor Schematics