Assembly Engineering Report

ER Rocket Inc.
Embry-Riddle Aeronautical University
Daytona Beach, FL
Dr. Scott Martin

April 18th , 2025

I. Assembly

A. Tools for Assembly

For the assembly of necessary structural components in Low Earth Orbit (LEO), there are a variety of tools and systems that must be used. To handle large payloads, there are two versions of robotic arms that will assist in assembly. These include the Canadarm2 and the Japanese Experiment Module Remote Manipulator System (JEMRMS). Canadarm2 has been in operation onboard the ISS for the past 20+ years and has proven its reliability with the Space Shuttle program moving thousands of payloads. While the Canadarm2 will be handling the larger payloads, the JEMRMS will be responsible for assisting astronauts in unpacking systems such as the nuclear reactor, and other small assemblies. To manipulate and secure payloads to robotic arms, an assembly known as a Grapple Fixture must be welded or attached to the individual components that the end manipulators attached to both robotic arms will fix onto. These fixtures will be explained in depth in Section D.

With the absence of oxygen in space, welding can cause some trouble. To combat this, there are multiple types of welding techniques such as friction stir welding, laser welding, and even conventional gas metal and plasma arc welding. These welding techniques can be used to attach structures together in an efficient way. In areas where conventional tools and bolts are hard to reach, or components are too large, welding allows these parts to be assembled in a structurally sound manner. If any bolts are used, the most common tool used by astronauts is the Pistol Grip Tool [1]. This tool features a grip designed to be used with bulky space suits during Extravehicular Activities. This drill type of tool features a torque range of less than 1 ft-lb to 38 ft-lb at a speed of 5 to 60 rpm. This Pistol Grip Tool can be seen in Figure 1.

Fig. 1 Pistol Grip Tool Used by Astronauts During Extravehicular Activities

To protect the welds securing the grapple fixtures to the payloads from solar radiation and drastic temperature changes, sealant will be applied to their surfaces. Information on this sealant can be found in the Tank System Report.

II. Fixture Design and Placement

The CAD model for the payload bay and fixtures was developed based on available images posted online [3] and information from the SpaceX Starship User Guide. [4] The latest version of Starship features approximately 120 internal stringers and multiple ring stiffeners, forming a barrel-like skeletal structure within the payload bay, as shown in Figure 2 and 3. The material used in starship main body is stainless stain 304, hence the fixture would also be made with SS304. According to the Starship User Guide, SpaceX is responsible for providing appropriate fixtures to secure different payloads from multiple customers. However, since the operation remains in a conceptual stage and limited information is publicly available, likely due to business confidentiality, custom fixtures were designed to support and restrict the movement of specific payloads.

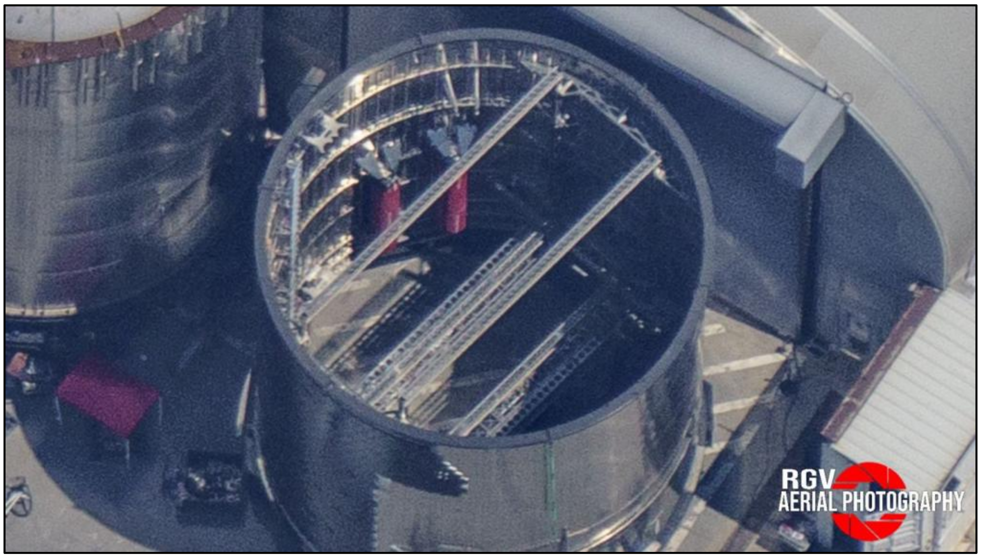


Fig. 2 Five Hoop Stiffeners can be Seen within the Payload Bay Barrel

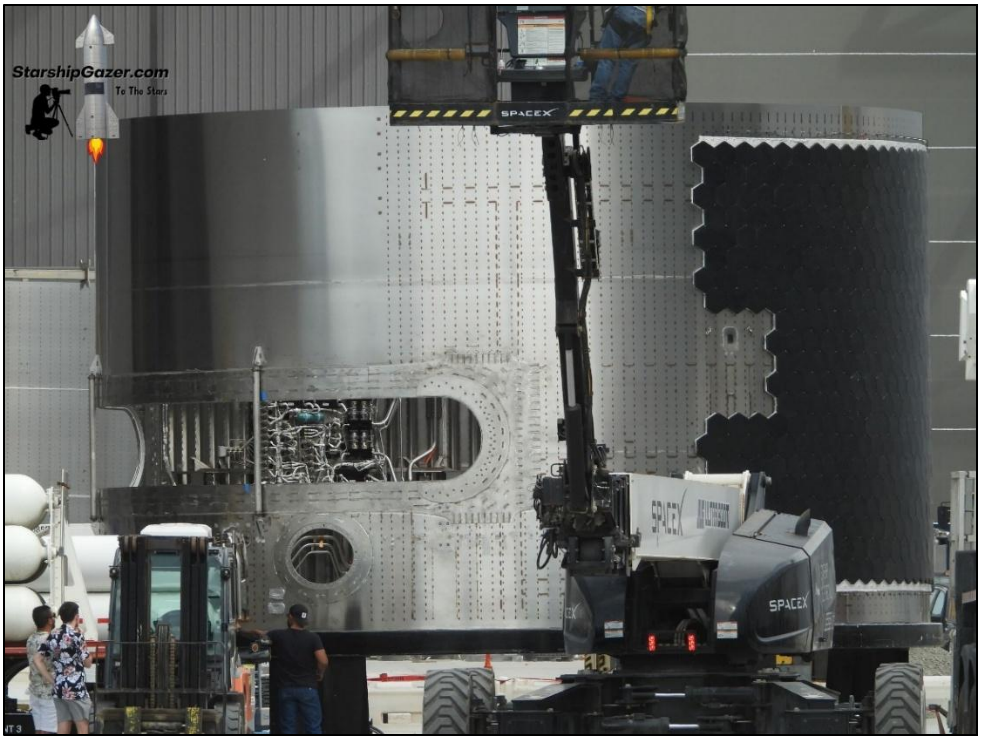


Fig. 3 The Internal Stringer of the Starship Payload Bay

The Starship's wall thickness is 4mm, [5] which is relatively thin despite the presence of a solid skeletal frame. To prevent unnecessary stress on the walls, the fixture design prioritizes securing the payload primarily downward, with the assumption of the bottom floor of the payload bay will provide sufficient support for payloads, utilizing the floor as the main support structure. This approach ensures structural integrity while accommodating the payload efficiently without compromising the spacecraft's framework. The payload bay door is designed to open in a clam-shell configuration, see Figure 4 below for reference. Due to this design, the fixture layout also prioritizes easy access for unloading and reusability. The fixtures are tailored to support various payloads while maintaining adaptability for different mission requirements.

Fig. 4 The Starship Payload Launch Sequence from the Starship User Guide

The current fixture design approach provides a comprehensive solution for securing payloads within the Starship payload by maintaining operational flexibility. Further refinements and additions were incorporated as more details became available, including additional structural analysis to optimize fixture strength and reliability, integration testing with simulated payload conditions, and verification of compatibility with various payload shapes and sizes.

A. Payload Bay CAD

The payload bay CAD model was created based on available information, consisting of a wall thickness of 4 mm, 120 vertical stringers and five ring reinforcements. The payload bay is split in half to ensure the door operates as advertised in the Starship User Guide. The ring reinforcement includes a mounting recess, serving as the mounting channel for the fixture. Figure 5 (left) provides an isometric view of the half payload bay, while Figure 5 (right) offers a close-up view of the mounting recess in the ring reinforcement.

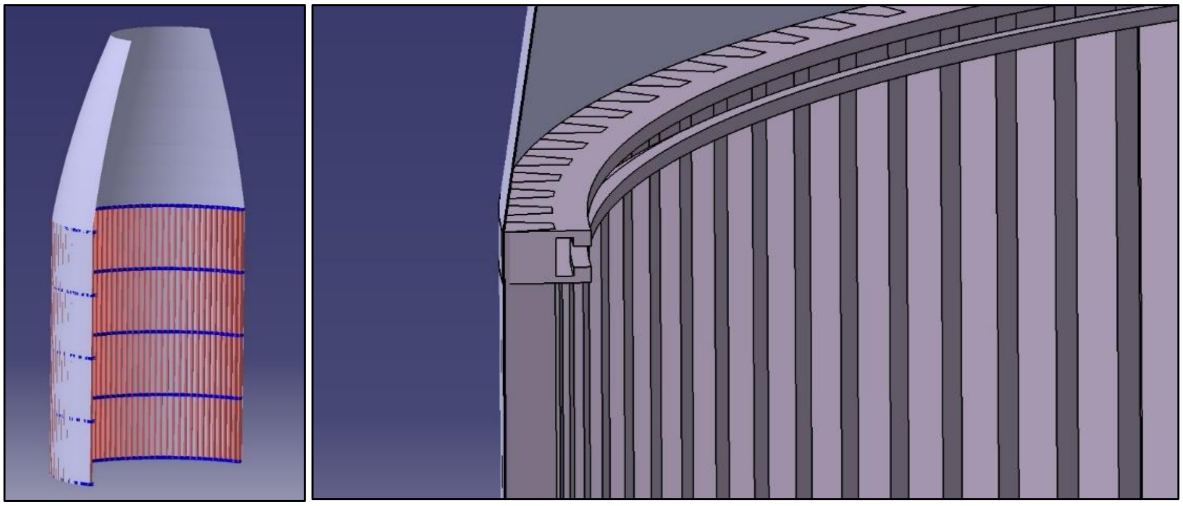


Fig. 5 (Left) Isometric View of the Half Payload Bay and (Right) the Close-up View of the Mounting Recess of the Ring Reinforcement

B. Zvezda Payload Fixture

The Zvezda Life Support Module is secured within Starship's payload bay using custom-designed fixtures. These fixtures ensure stability during launch, transit, and docking by connecting with Starship's internal skeletal structure, including vertical stringers and ring stiffeners. The fixtures are designed to fit Zvezda's cylindrical shape while evenly spreading the load across Starship's payload bay structure.

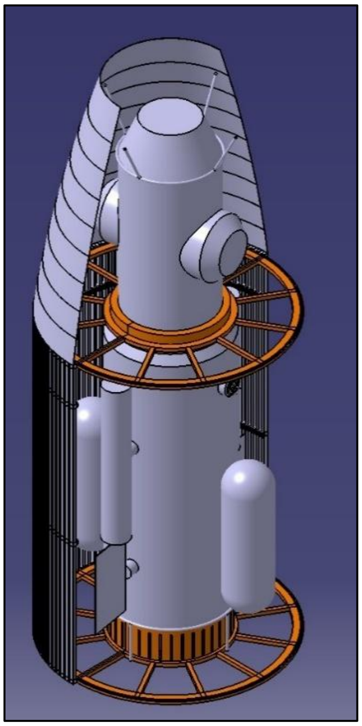


Fig. 6 Isometric View of the Fixtures, Zvezda, and Starship

The fixtures are carefully positioned to maximize compatibility with Starship's internal framework:

1. Mounting Recesses: Both fixtures utilize pre-designed recesses within Starship's ring reinforcements for precise alignment.
2. Ease of Access: The clam-shell payload bay door design enables easier installation and removal of Zvezda during orbital operations.
3. Adaptability: The fixtures are designed to accommodate varying mission requirements without compromising structural integrity. The fixtures avoid putting pressure on modules attached to the exterior of Zvezda. This increases the structural stability of the entire launch by designing the fixtures to hold Zvezda around its central body.

C. Bottom Fixture

This is the primary support for the Zvezda module by bearing its weight and preventing lateral movement during launch and flight operations

Design Features:

1. Ring Structure: The bottom fixture consists of a circular ring with radial supports that align with Zvezda's base geometry. The fixture was designed with gaps where Zvezda's interstage truss would be to avoid damaging the structure,
2. Mounting Lugs: These lugs fit securely into the recesses of Starship's bottom ring reinforcement, ensuring a firm attachment.
3. Material: Stainless Steel 304 (SS304) is used due to its high yield strength (7.43×108Pa) and resistance to environmental factors such as temperature fluctuations and radiation.

Load Distribution:

The fixture transfers static loads directly to Starship’s payload bay floor, minimizing stress on its walls.

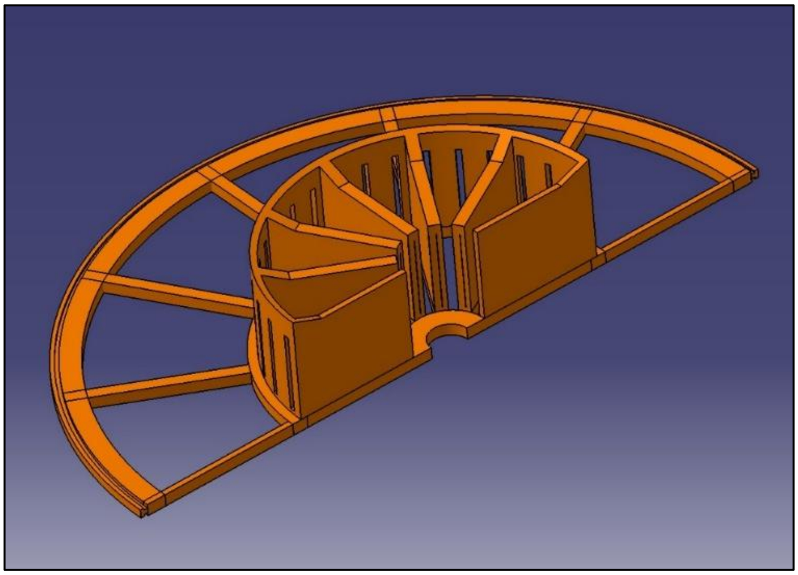


Fig. 7 Bottom Fixture Supporting Zvezda Module

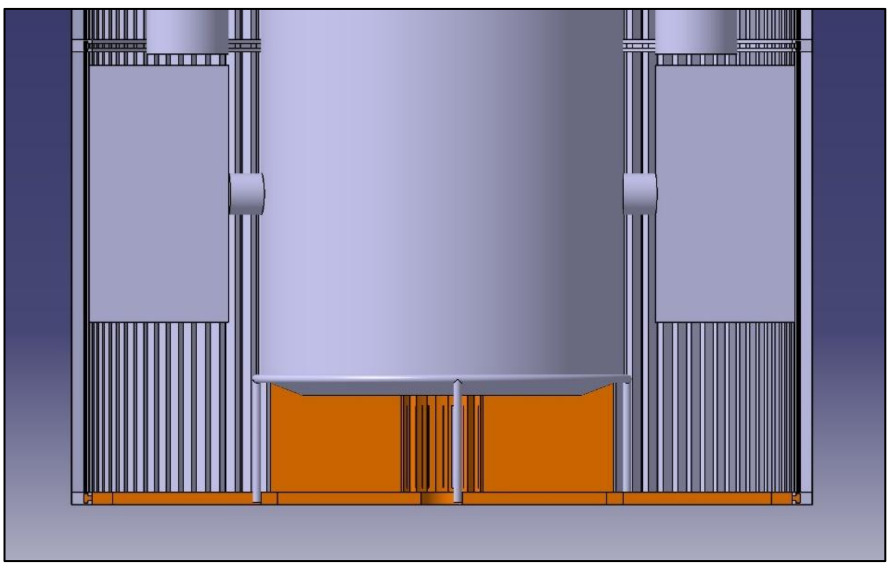


Fig. 8 Bottom Fixture Shown with Zvezda and Starship

D. Top Fixture

The top fixture stabilizes Zvezda’s upper section against dynamic forces such as vibrations and lateral accelerations during ascent.

Design Features:

1. Semi-Circular Ring: Contoured to match Zvezda’s upper curvature, with integrated vertical supports for additional rigidity.
2. Radial Slots: These slots interface with Starship’s upper ring stiffeners to restrict rotational movement.
3. Material: SS304 ensures consistent mechanical properties across all fixtures.

Load Management:
The top fixture counters upward motion while stabilizing Zvezda against lateral forces.

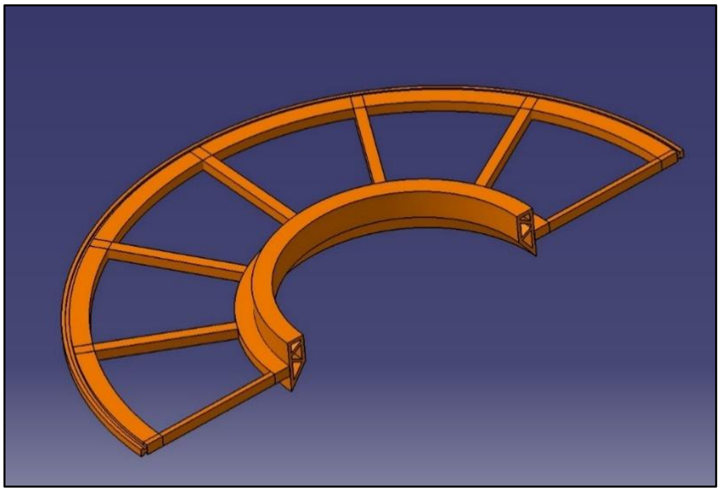


Fig. 9 Top Fixture Supporting Zvezda Module

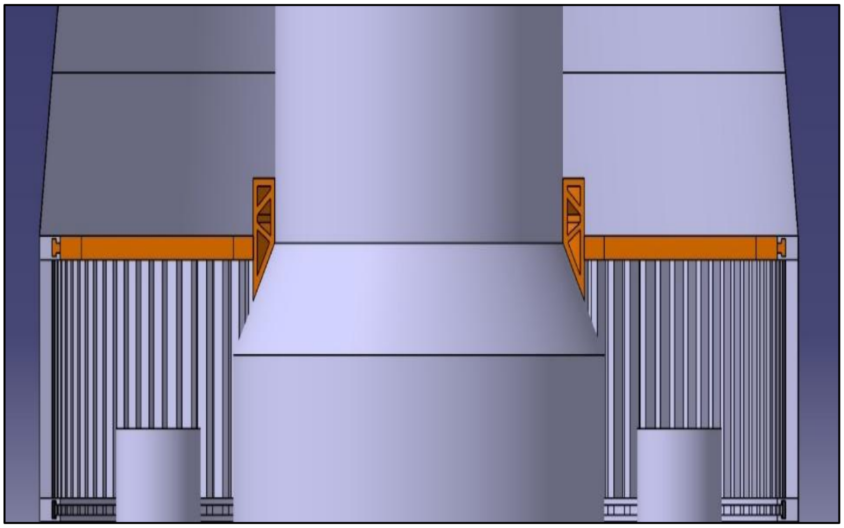


Fig. 10 Top Fixture Shown with Zvezda and Starship

E. Fuel Tank Payload Fixture

The fuel tank payload fixtures consist of a mid-fixture, mid-to-bottom ring connector rods, and a bottom ring fixture. All ring fixtures have a mounting lug that fits into the mounting recess of the payload bay ring reinforcement, ensuring a firm connection. Figure 11 shows the original tank holding fixture assembly next to the revised version of the fixture.

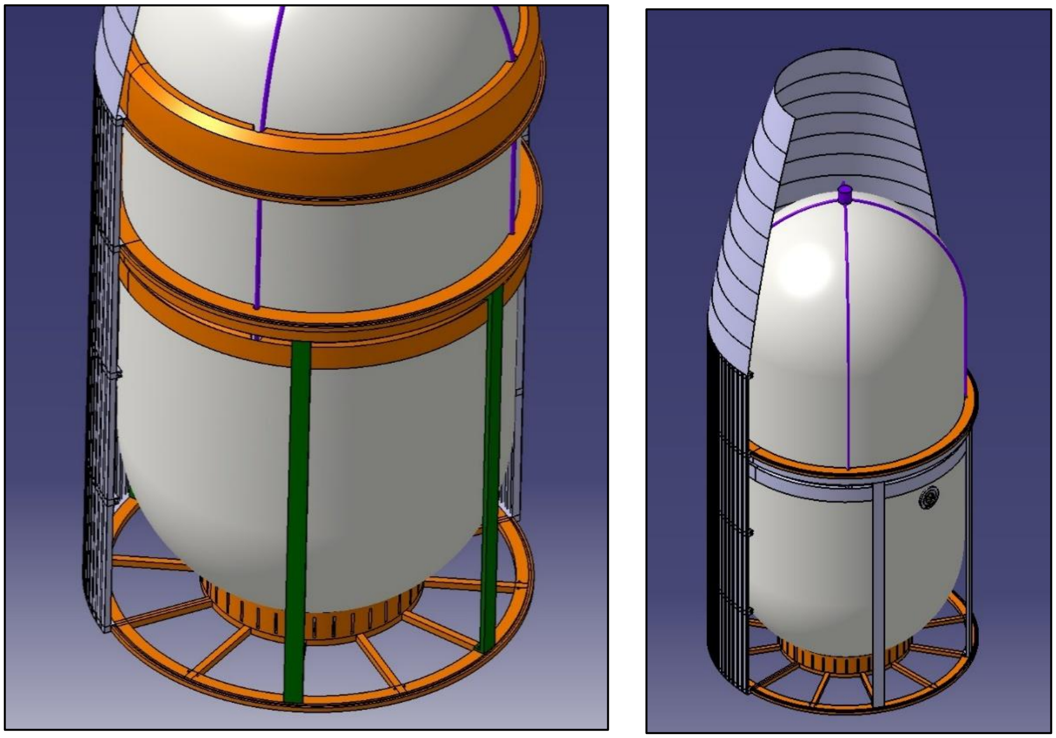


Fig. 11 Hydrogen Tank with Cuff Truss Attached. The Original Fixture Designs (Left) and the Revised Version of Fixtures Design (Right)

Originally, the fuel tank holding fixture had a top ring fixture, as shown in Figure 12, positioned at the intersection of the spherical and cylindrical sections of the fuel tank. This fixture was contoured to match the tank's curved surface, and its slightly bent structure acted as a resistance to counteract any upward movement of the tank. The enlarged surface area reduced pressure on the tank, minimizing the risk of external structural damage. After performing stress and vibrational tests, however, it was found that the top ring fixture was not necessary to contain the fuel tank. Additionally, the top ring fixture put the weight of the fuel tank launch over Starship's capacity. Upon redesigning the holding fixture, the unnecessary top fixture was removed.

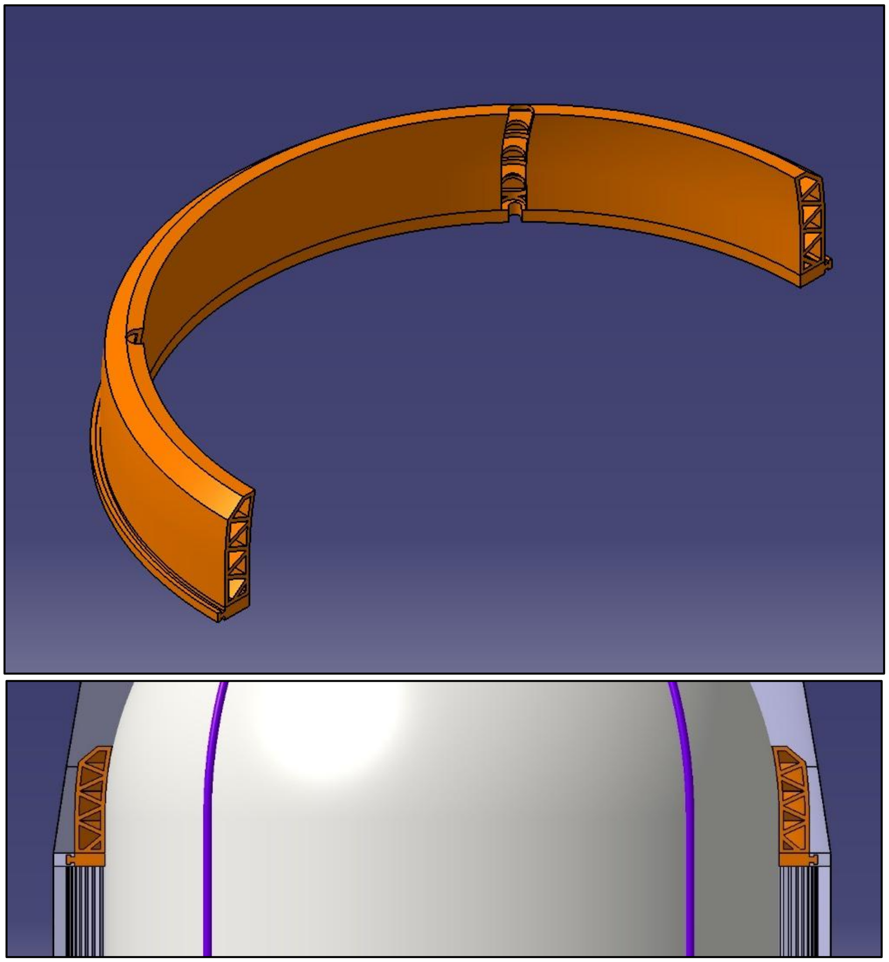


Fig. 12 The Isometric view of Top Ring Fixtures of Fuel Tank (Top) and Top Ring Fixture in Payload Bay (Bottom)

The mid-ring fixture, as shown in Figure 13, secures the middle section of the tank while incorporating a caved-out space to accommodate the cuff truss. Since the cuff truss is welded to the tank as a single, non-detachable unit, the mid-ring slots provide additional restrictions on tank movement during launch. The external side of the mid-ring fixture includes a cavity for the mid-bottom connecting rod, strengthening the structural integrity of the fixture assembly.

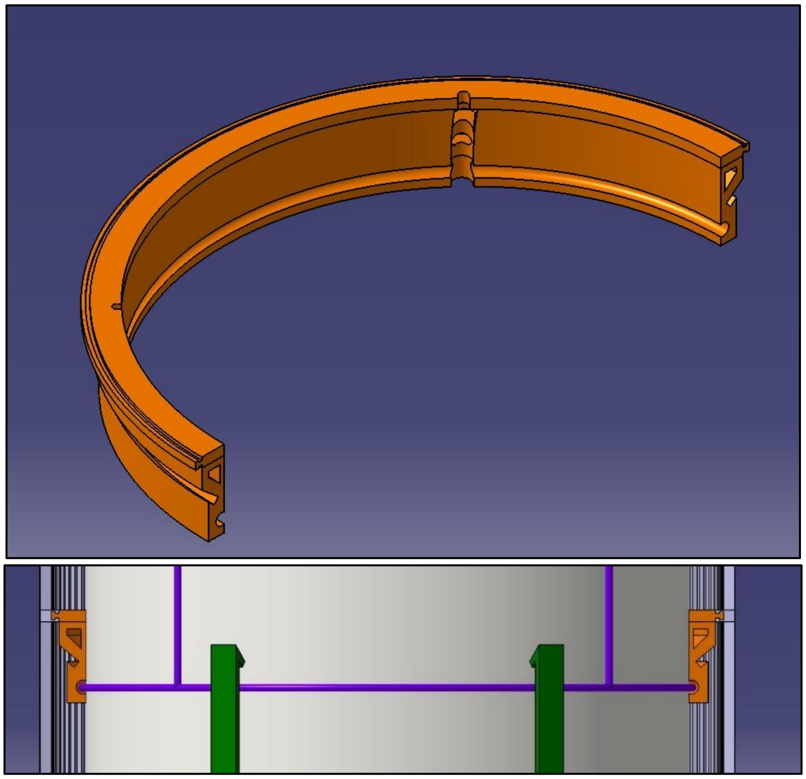


Fig. 13 Fuel Tank Mid Ring Fixture (Top) and Mid Ring Fixture in Payload Bay (Bottom)

The mid-bottom connecting rod links the mid-ring fixture to the bottom ring fixture, as seen below in Figure 14. It is bolted to the bottom ring fixture, with two rods placed in each half of the payload bay at 30-degree intervals from the center of the mid-ring fixture. This configuration enhances load distribution and fixture stability.

Fig. 14 Connecting Rods (Green) Attached to Top and Bottom Ring Fixtures

The bottom ring fixture, shown in Figure 15, serves as the primary support at the payload bay floor. The center component of the fixture is carved out to accommodate the spherical bottom of the tank, allowing it to rest securely while preventing lateral movement. This design ensures that the fuel tank remains firmly in place throughout the mission. It was also designed to take up minimal space, so that more room would be available in the payload bay for items attached to the fuel tanks, such as the cryocooler assemblies.

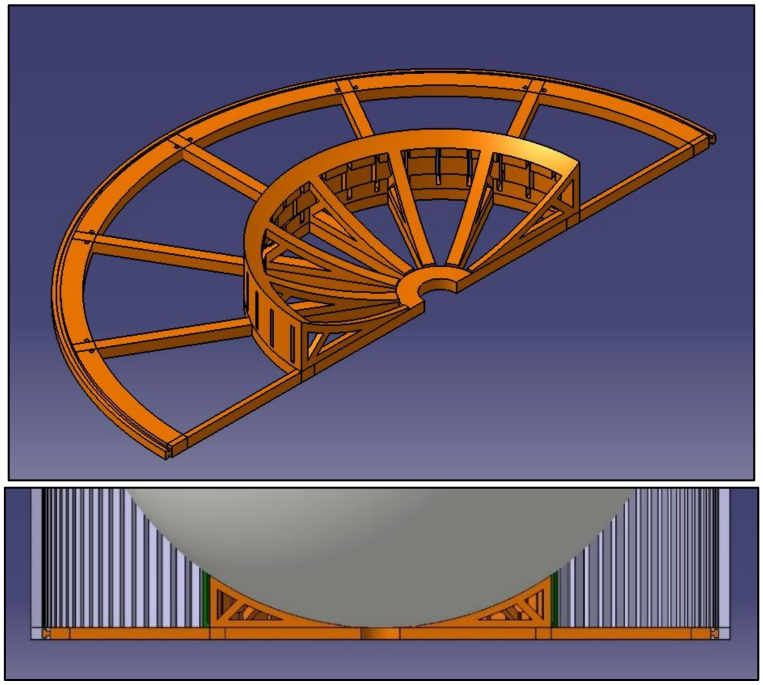


Fig. 15 Bottom Ring Fixture (Top) and Bottom Ring Fixture in Payload Bay

I. Electric Power Payload Fixture

The electric power payload fixtures consist of both a top ring fixture and bottom ring fixture. Both ring fixtures have a mounting extrusion that locks into the groove of the payload bay ring reinforcement, ensuring a firm connection. Figure 16 shows both fixtures which hold the electric power assembly within the payload bay frame.

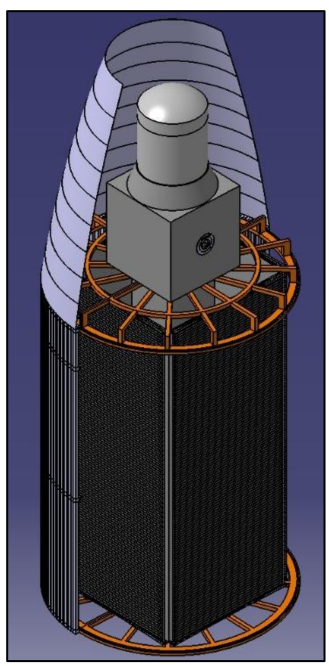


Fig. 16 Electric power assembly with Fixtures (Orange) in Starship Payload

The top ring fixture, as shown in Figure 17, is positioned between the top of the radiator and the bottom of the Brayton Loop System, with the boom slightly extended to allow space for the fixture. The arms of the fixture which hold the bracket to the central boom are extended above the radiator both to accommodate its height and resist any upwards movement of the assembly.

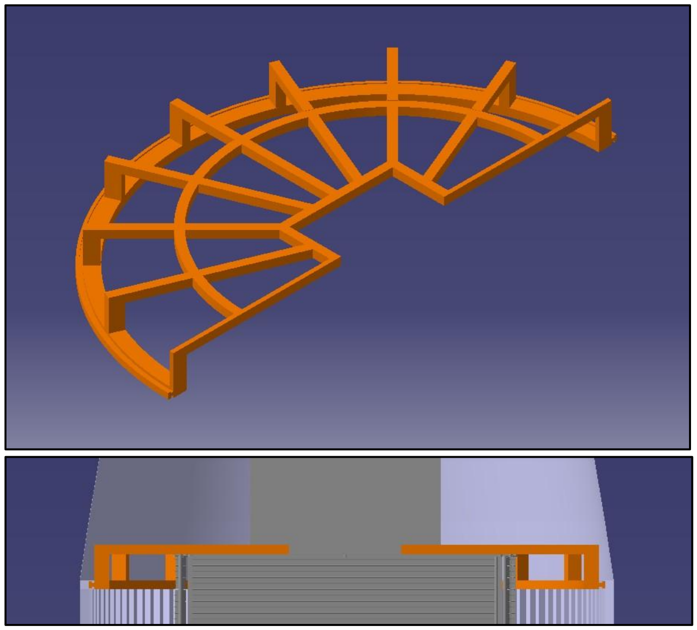
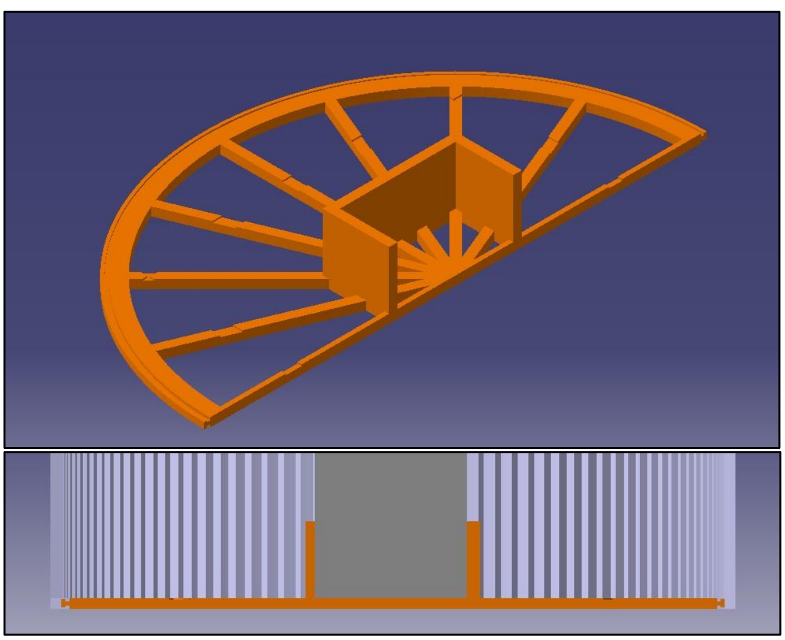


Fig. 17 Isometric View of Top Electric Power Assembly Ring Fixture (Top) and Front View of Top Ring Fixture with Electric Assembly in Payload Bay (Bottom)

The bottom ring fixture, shown in Figure 18, serves as the primary support at the payload bay floor. The center rectangular bracket is designed to clear the space between the radiator and the boom when the Starship Bay is unlatched and is fitted securely to the central boom, preventing lateral movement. Additionally, the notches in the supporting arms of the fixture allow clearance for the folded radiator panels. The fixture is designed to distribute the majority of the load to the boom so as not to cause damage to the radiator panels.



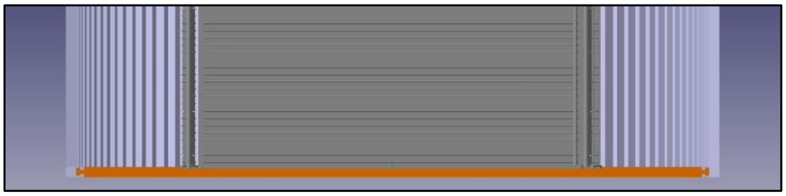


Fig. 18 Isometric View of Bottom Electric Power Assembly Ring Fixture (Top), Front View of Boom Fitted into the Central Rectangular Bracket of the Ring Fixture (Middle), and Front View of Bottom Ring Fixture with Radiator (Bottom)

J. RS-25 and VASIMR Payload Fixture

For the RS-25 and VASIMR engine payloads, two different fixture rings were created, as seen in Figure 19. The VASIMR engine is secured in the upper section of the payload bay using two U-shaped fixtures, as shown in Figure 20. The opening of the U-shaped fixture is designed to fit precisely around the VASIMR engine housing. The bottom side of the fixture features two extension tabs that restrict rotational movement of the VASIMR engine assembly, as seen in Figure 21. This fixture was placed in the top of the payload bay to provide sufficient distance from the RS-25s, a requirement stated and detailed in the Certification Report.

To house the RS-25 engines, six circular plates were integrated onto the bottom floor, as illustrated in Figure 22. These plates have a recessed depth that allows the nozzle end of the RS-25 engines to sit securely within them, as demonstrated in Figure 23. The raised edges of the circular plates serve to restrict lateral movement, ensuring that the engines remain stable and properly aligned during launch and flight operations. An additional spider-shaped fixture is designed to fit within the central space of the RS-25 engine array. This fixture features extended arms that interconnect the six engines, providing structural support and additional stabilization. It serves as a designated gripping point for the Canadarm2 robotic arm, allowing for secure handling and unloading of the RS-25 engines while minimizing the risk of damage during transfer operations. An additional post was added to the base's center to attached to the bottom of the holding arm's plate. This serves to restrict vertical movement of the RS-25s during the launch process. The holding arm is attached around the neck of all 6 RS-25s, so installing the post to connect the holding arm plate to the fixture base plate will hold the engines in place in all directions.

This launch also contains 2 RCSs, seen housed between the chemical and electrical engine assemblies. These RCSs are housed by a clamping mechanism designed to be operated by hand rather than opened by the Starship fairing. The fixtures feature a bolting rod across the face of the RCS to prevent slippage during launch. The top pressure plate of the clamp is designed to hold the RCS from moving during launch which has a bolt that may be manually tightened and loosened. The fixtures were designed to avoid the nozzles to prevent any damage that could be incurred during flight and only apply force to the main body structure.

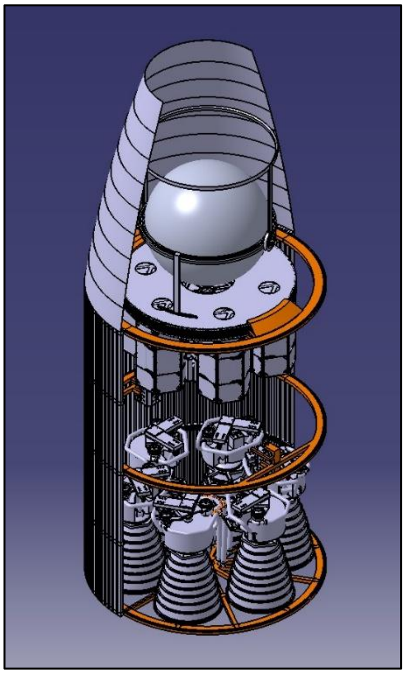


Fig. 19 Fixtures for VASIMR on Top, Fixtures for the RCS in the Middle, and the Fixtures for RS-25 at the Bottom

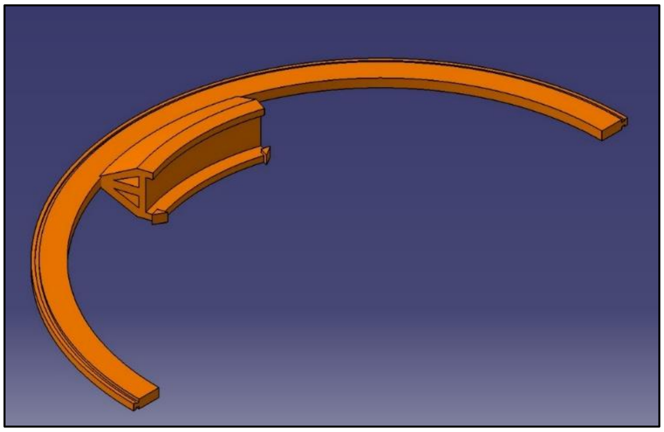


Fig. 20 Isometric view of the VASIMR U-shape Fixture

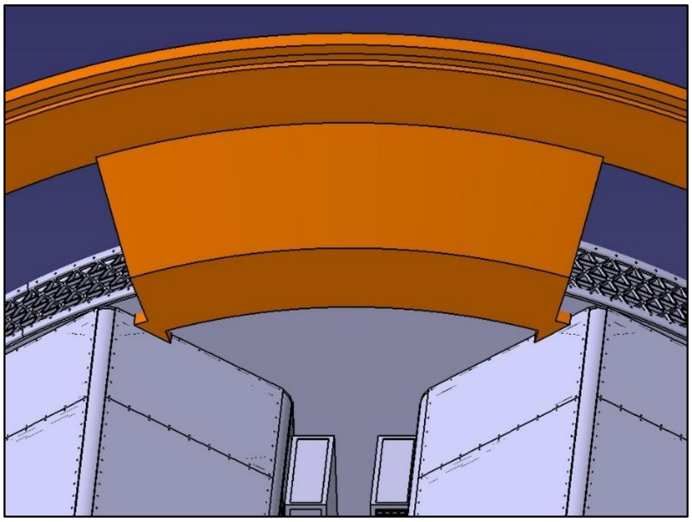


Fig. 21 Bottom View of the U-shape Fixture with VASIMR in Position. The Extended Tabs Restrict the VASIMR to Form a Rotational Movement

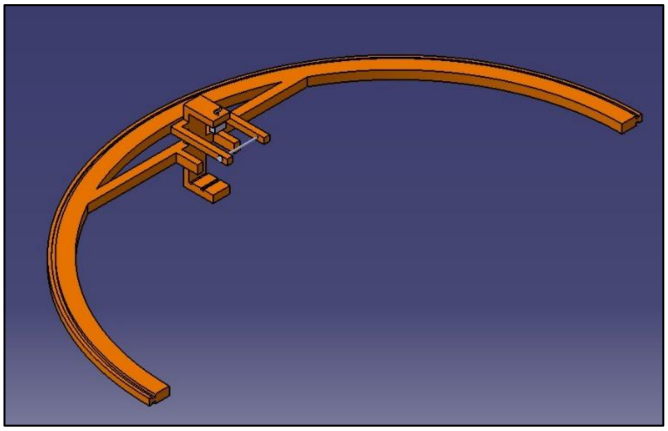


Fig. 22 Isometric View of Clamping Fixture for RCSs

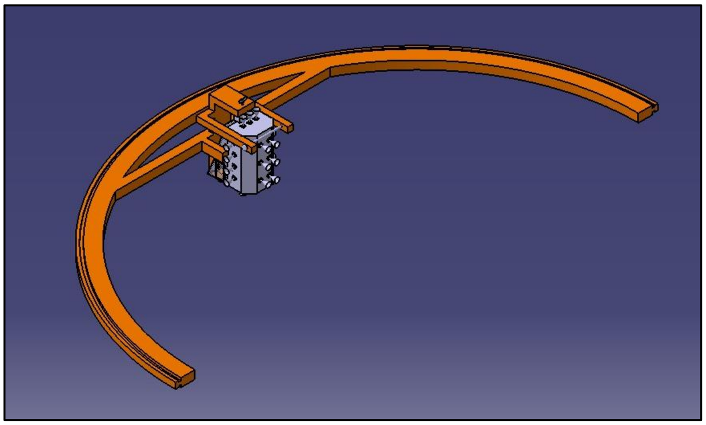


Fig. 23 RCSs Clamped into Fixture with Pressure Plate

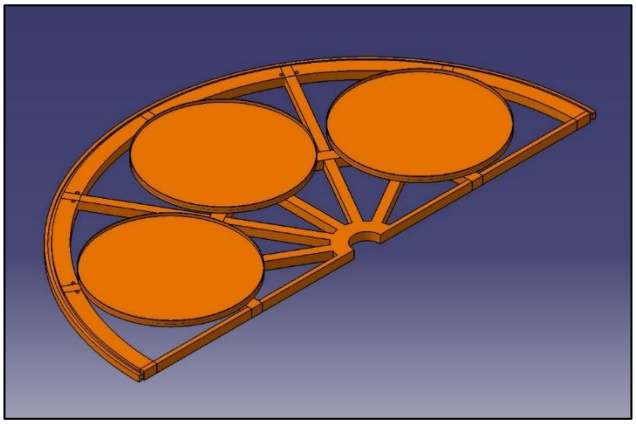


Fig. 24 Isometric View of Circular Fixture for RS-25 Engines

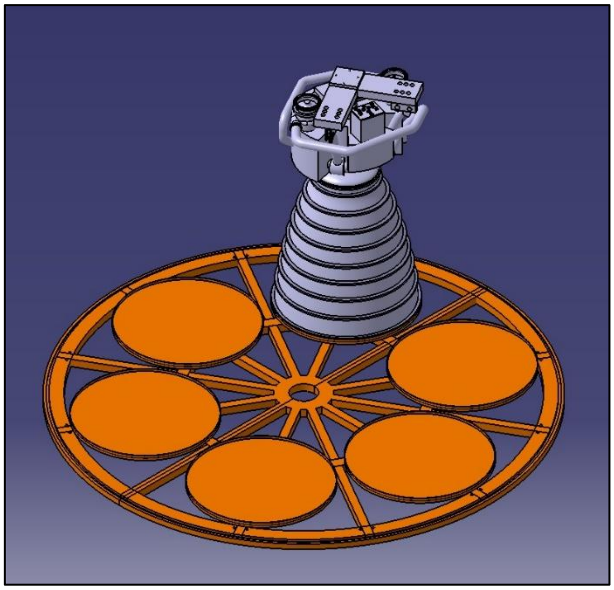


Fig. 25 RS-25 Positioned on the Circular Fixture Base Plate

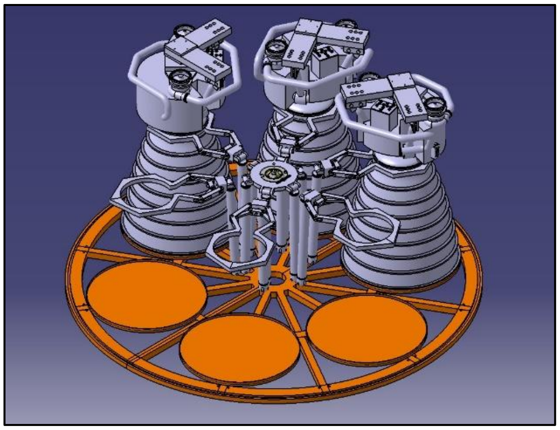


Fig. 26 Three RS-25 Positioned on the Circular Fixture Base Plate with Holding Arm

EMBRY-RIDDLE
Aeronautical University

K. ISS Boom and Boom Holding Fixture

Initially, the rocket was planned to build off the ISS. The docking ports on the ISS would be used for Starship and for the assembly of the rocket. This plan was rejected, however, because of the Canadarm2's range. The Canadarm2 has a range of 15 meters and is able to move itself along the body of the ISS. With how long the rocket is, though, the arm would not be able to reach the majority of the body to assemble it. The rocket also could not be built parallel and adjacent to the ISS because solar panels and other extrusions would interfere with the assembly.

A new plan was then initiated to create a boom that would mount perpendicular to one end of the ISS. Models and pictures of the ISS were analyzed to find its clearest side. It was discovered that one lateral face of the ISS was void of any extrusions, so this face was chosen for the boom's location. The boom would employ IDAs on each of its ends, one end securing to the end of the ISS and the other would be connected to the rocket assembly. The IDA on the outer end of the boom would mount to the electrical assembly's side. The proceeding rocket modules would then be assembled from the bases of the electrical assembly, parallel to the ISS. The boom was also designed to be 14 meters long to move the rocket assembly far enough away from the ISS that there would be no collisions, even with small degrees of motion. The 14-meter length is also within the range of the Canadarm2 (with a range of 15 meters), so the arm can traverse the length of the ISS while assembling the rocket. This way, the arm is able to perform the entire assembly of the rocket without having to move itself onto the rocket because the entire assembly is within range.

Upon review of the plan, it was concluded that one boom at the front end of the rocket assembly may not restrict movement enough in the case of an assembly error. These errors may arise from Canadarm2 colliding with the rocket from misalignments or programming errors. In the event of these errors, with only one boom at the front end, the rocket's bottom end may have enough freedom to sway enough to collide with the ISS. While this is extremely unlikely, precautions were taken to minimize these chances to zero. A second boom, identical to the first, was introduced to the launch plan. This second boom would mount alongside the ISS and attach to the Zvezda life habitat's mid-section. This would provide a second point of contact between the ISS, booms, and rocket assembly. With two points of contact, the risk of the rocket and ISS was reduced to negligible concerns.

The boom with IDAs attached to either end can be seen in Figure 27.

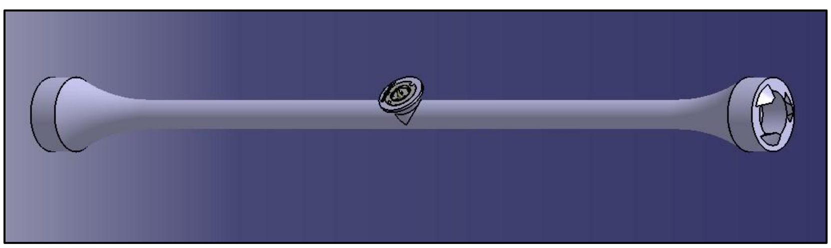


Fig. 27 The Boom with IDAs on Both Ends and the Grapple Fixture on the Center

To bring these booms up to the ISS, holding fixtures were designed to hold both at once. While bringing both booms up at the same time limited their size, it reduced the number of launches by 1, saving $75 million, and the booms were able to be designed thin and light enough to fit two in one launch while being sufficiently strong. These holding fixtures are pictures in Figure 28.

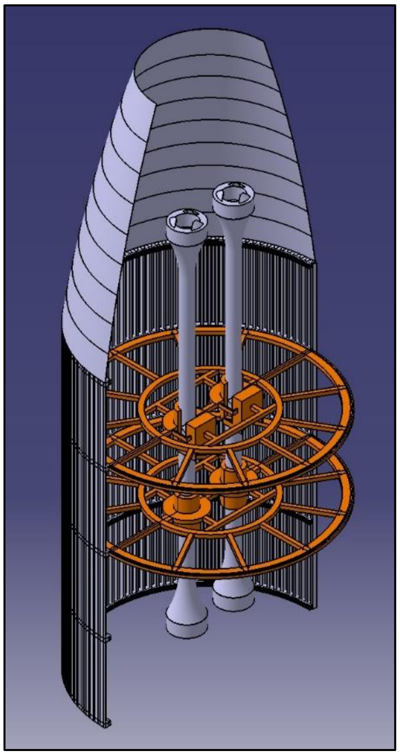


Fig. 28 The Booms and the Fixtures in the Payload Bay.

The boom payload fixtures followed design concepts seen in previous fixtures, with the semi-circular structural configuration. The outer ring is the prime attachment interface with the spacecraft reinforcement ring, while radial struts connect the outer ring to the central fixture and provide the necessary axial support along with maintaining structural integrity. As seen in Figure 29, the lower fixture assembly for the ISS Boom consists of two semi-cylindrical blocks that provide a snug fit, essentially clamping together the ISS booms and minimizing movement during launch. At the center of the fixture assembly, as shown in Figure 30, there are two fixture types in the fixture design: one is a semi-cylindrical support block same as utilized in the lower assembly, while the other is a box-shaped fixture specifically designed for housing the grapple fixture.

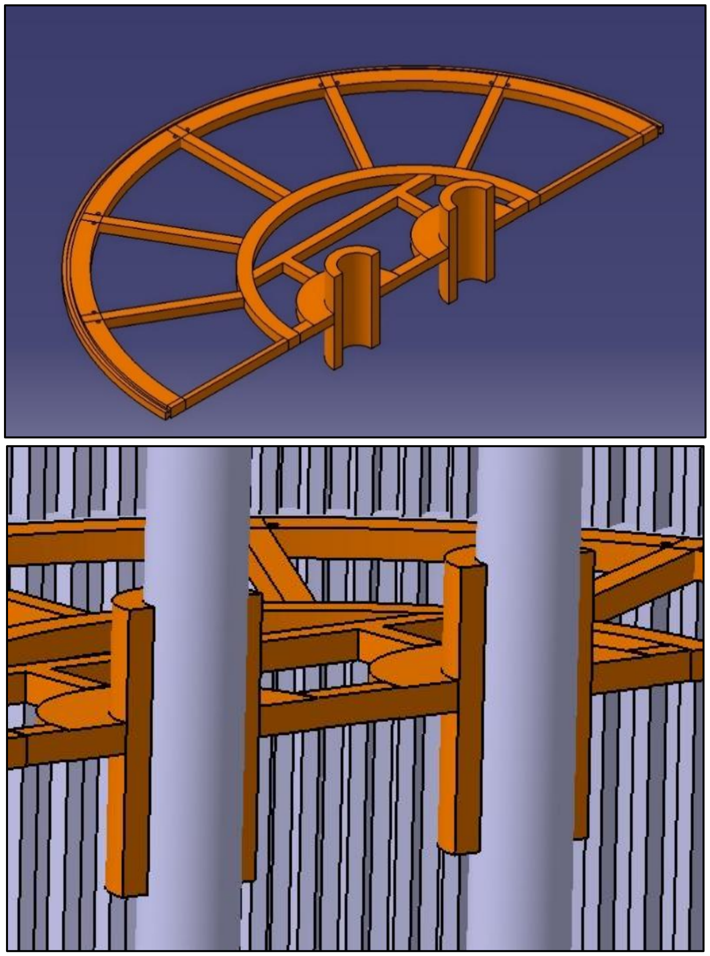


Fig. 29 The Isometric View of ISS Boom Fixtures Semi Cylindrical Block Version (Top) and the Fixture with the ISS Booms in Position (Bottom).

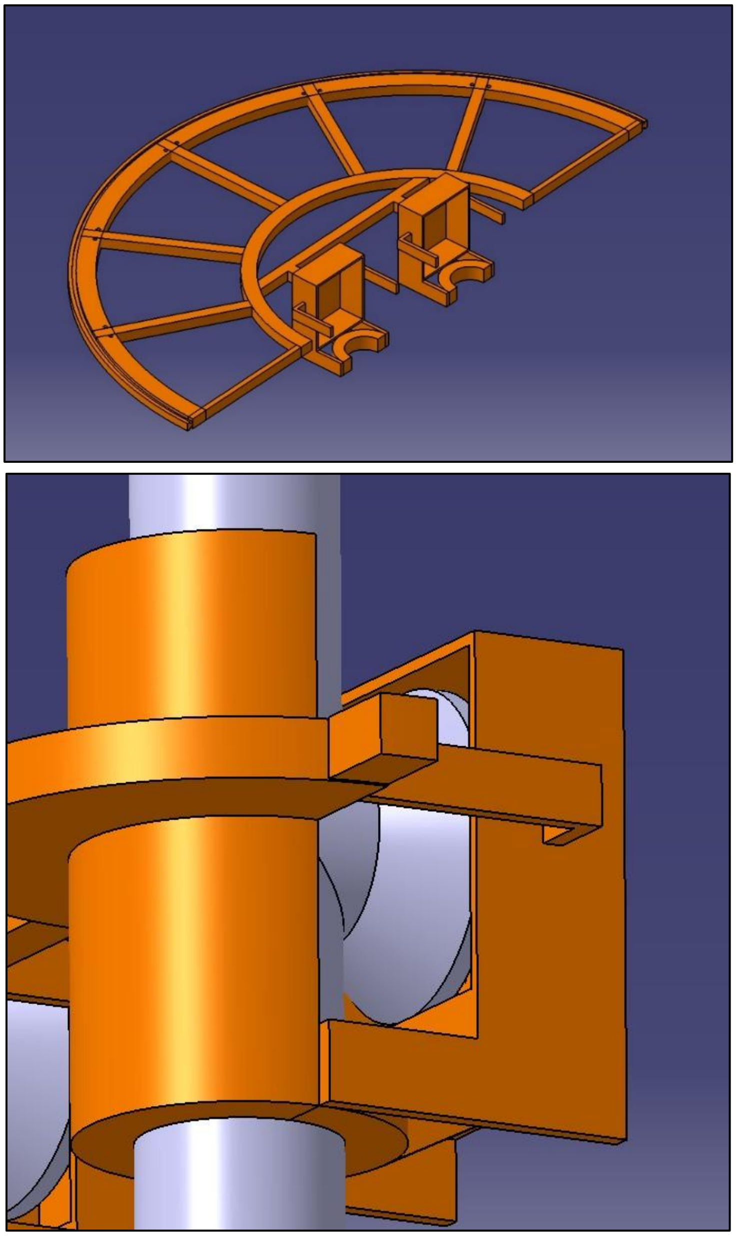


Fig. 30 The Isometric View of ISS Boom Fixtures Box-Shaped Version (Top) and the Side View of the Fixture with the ISS Booms in Position (Bottom).

F. Grapple Fixture

To manipulate parts in Low Earth Orbit (LEO), the International Space Station (ISS) has two manipulators known as the Canadarm2 and the Japanese Experiment Module Remote Manipulator System (JEMRMS). To use these arms in correspondence with the payloads being delivered, an assembly known as a Flight-Releasable Grapple Fixture (FRGF) must be used and attached to payloads. To ensure that the FRGF is a viable option to orient payloads, the following table can be found presenting the maximum allotted forces the Mounting plate can experience.

Table 1: FRGF Maximum Forces.

Torsion Moment	Bending Moment	Shear Load	Axial Load
3100 Nm	3100 Nm	2000 N	1000 N

The FRGF consists of a mounting plate with 3 alignment arms labeled as “Cam Arms” extending from the Location Cams [2]. This mounting plate also consists of an alignment rod (Grapple Shaft) which the end effector of both the Canadarm2 and JEMRMS will use to not only attach to the payload but also align the mounting plate centrally into the manipulator. This FRGF will be welded onto all the payloads to give the robot arms a spot to hold onto them, so the astronauts may unpackage, orient, and assemble the rocket modules together.

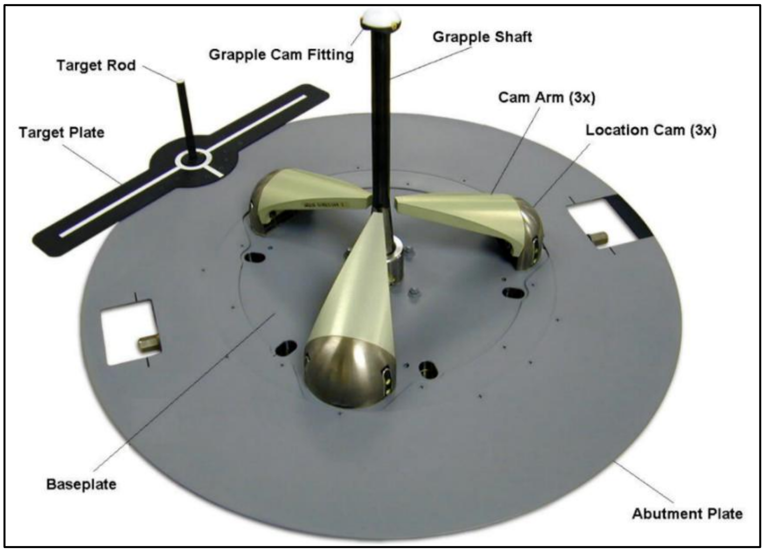


Fig. 31 Flight Releasable Grapple Fixture

As mentioned previously, both Candarm2 and JEMRMS have an end effector to capture payloads equipped with the FRGF. These end effectors use a combination of mechanical, electrical, and vision-based systems to capture and secure payloads delivered to the International Space Station (ISS). Using three cables aligned in a circular pattern, these create a “snare”. While the payload is approaching the arm or vice versa, the snare system is released to align the grapple fixture with the target plate and allows the fixture to mate with the end effector. Upon mating, the snare then closes onto the Grapple shaft and pulls the payload into a locking position. This system allows the robotic arms to align and orient the payloads in an effective manner.

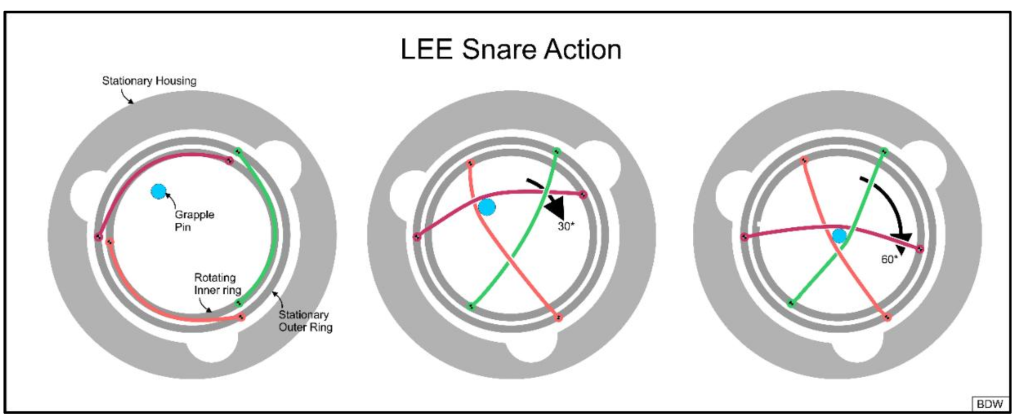


Fig. 32 LEE Snare Diagram

III. Detailed Assembly Procedure

As described in the Launch Vehicle Report, the various rocket modules will be launched in the order described in Table 4. Once Starship arrives and docks at the ISS, each payload will be removed from Starship and assembled together. As mentioned previously, the robot arms will attach to the grapple fixtures mounted on each assembly to maneuver them around. Note that a 180-degree rotation will occur between launches 11 and 12.

Table 2: Summary of Launch Sequence and Key Items.

Launch No.	Content
1	Booms
2	Electrical Power Assembly
3	Life Habitat Assembly
4	Top Central Oxygen Tank
5	Top Oxygen Tank #1
6-7	Top Hydrogen Tanks #1 and #2
8	Bottom Central Oxygen Tank
9-11	Bottom Hydrogen Tanks #1, #2, and #3
12	Top Oxygen Tank #2
13-14	Top Hydrogen Tanks #3 and #4
15-17	Bottom Hydrogen Tanks #4, #5, and #6
18	Rocket Engines and RCSs
19	Astronaut Crew

The steps to assemble the rocket, including unloading, assembling, and the methods to do so, are outlined below.

Booms

1. Launch #1 arrives at ISS and docks using standard practices with Starship's IDAs.
2. The Starship fairing opens, with half the holding fixtures attached to it, freeing the payload for movement.
3. Canadarm2 attaches to the first boom at the grapple fixture mounted to the side of the boom.
4. Canadarm2 removes the boom from Starship and attaches it to the end of the ISS by way of an IDA mounted to the end of the boom.
5. Canadarm2 returns to Starship and removes the second boom from the payload bay.
6. Canadarm2 installs the second boom at the IDA near the ISS's midpoint.
7. Starship fairing closes and follows standard undocking procedure, then returns to Earth.

Electrical Assembly

1. Launch #2 arrives at ISS and docks using standard practices with Starship's IDAs.
2. The Starship fairing opens, with half the holding fixtures attached to it, freeing the payload for movement.
3. Canadarm2 attaches to electrical assembly at the grapple fixture mounted to the side of the boom.
4. Canadarm2 removes electrical assembly from Starship and attaches it to the boom at the end of the ISS by way of an IDA mounted to the side of the electrical assembly.
5. JEMRMS is used to remove the outer lid of the TRUPACT-II by way of a grapple fixture mounted on its top face. JEMRMS continues to hold the outer lid.
6. Canadarm2 moves astronauts to the TRUPACT-II system, where the astronauts remove the inner lid by hand.

7. Canadarm2 attaches to the grapple fixture mounted on the top of the reactor and removes the reactor from the TRUPACT-II.
8. Astronauts replace the inner lid on TRUPACT-II.
9. JEMRMS replaces the outer lid on TRUPACT-II.
10. Astronauts detach the TRUPACT-II from the boom and seal the TRUPACT-II outer lid to its body.
11. JEMRMS attaches to the grapple fixture on top of the TRUPACT-II and moves it back to the Starship payload bay.
12. Canadarm2 places the reactor on top of the boom while astronauts attach it using the same mechanism that held the TRUPACT-II.
13. Astronauts connect all power cabling necessary to draw power from the reactor and ensure physical connections are secure.
14. Starship fairing closes and follows standard undocking procedure, then returns to Earth.

Life Habitat Assembly

1. Launch #3 arrives at ISS and docks using standard practices with Starship's IDAs.
2. The Starship fairing opens, with half the holding fixtures attached to it, freeing the payload for movement.
3. Canadarm2 attaches to life habitat assembly at the grapple fixture mounted to the side of the it.
4. Canadarm2 removes life habitat from Starship and positions it adjacent to the electrical assembly such that the top of the life habitat's interstage truss is in contact with the bottom of the electrical assembly's radiator and boom.
5. Astronauts weld the tops of the truss points to the bottom of the radiator and boom, establishing the connection between the life habitat and electrical assemblies.
6. The IDA on the end of the boom at the center of the ISS is connected to the IDA on the side of Zvezda, creating a second point of contact between the rocket and ISS.
7. Astronauts connect all necessary cables between the two modules, providing power to the life habitat and its connected modules. Power cables are also connected to the RCS modules on the side of Zvezda and piping to and from the helium tanks is checked for proper standing.
8. Starship fairing closes and follows standard undocking procedure, then returns to Earth.

Top Central Oxygen Tank

1. Launch #4 arrives at ISS and docks using standard practices with Starship's IDAs.
2. The Starship fairing opens, with half the holding fixtures attached to it, freeing the payload for movement.
3. Canadarm2 attaches to the oxygen tank at the grapple fixture mounted to the side of it.
4. Canadarm2 removes oxygen tank from Starship and positions it adjacent to the life habitat assembly such that the bottom points of the life habitat's bottom interstage truss are in contact with the top of the oxygen tank.
5. Astronauts weld the points of the interstage truss to the top of the oxygen tank.
6. Astronauts connect all necessary cables between the life habitat and the oxygen tank. The piping from Zvezda to the oxygen tank is connected by the astronauts with all seals checked prior to operating.
7. Starship fairing closes and follows standard undocking procedure, then returns to Earth.

Top Oxygen Tank #1

1. Launch #5 arrives at ISS and docks using standard practices with Starship's IDAs.
2. The Starship fairing opens, with half the holding fixtures attached to it, freeing the payload for movement.
3. Canadarm2 attaches to the oxygen tank at the grapple fixture mounted to the side of it.
4. Canadarm2 removes the oxygen tank from Starship and positions it adjacent to the side of the center oxygen tank such that their central rings are lined up and the proper distance away from each other. This

tank is placed on the side of the central oxygen tank such that it is between the ISS and rocket and from Canadarm2's point of view, it is the middle of the 3 it can place on the central tank's side.

5. Astronauts retrieve connecting rods from Starship payload bay and return them to the oxygen tanks.
6. Astronauts weld a connecting rod to the two central rings on the oxygen tanks.
7. Astronauts connect all necessary cables and pipes between the life habitat and the oxygen tank.
8. Starship fairing closes and follows standard undocking procedure, then returns to Earth.

Top Hydrogen Tanks #1 and #2

1. Launch #6 arrives at ISS and docks using standard practices with Starship's IDAs.
2. The Starship fairing opens, with half the holding fixtures attached to it, freeing the payload for movement.
3. Canadarm2 attaches to the hydrogen tank at the grapple fixture mounted to the side of it.
4. Canadarm2 removes the hydrogen tank from Starship and positions it adjacent to the side of the center oxygen tank such that their central rings are lined up and the proper distance away from each other. This tank is placed on the side of the central oxygen tank such that it is between the ISS and rocket and from Canadarm2's point of view, it is the lowest of the 3 it can place on the central tank's side.
5. Astronauts retrieve connecting rods from Starship payload bay and return them to tanks.
6. Astronauts weld the connecting rods to the two central rings on the center oxygen tank and hydrogen tank.
7. Astronauts connect all necessary cables and pipes between the life habitat and the hydrogen tank.
8. Starship fairing closes and follows standard undocking procedure, then returns to Earth.
9. The procedure is repeated identically for Launch #7. The new hydrogen tank is placed on the side of the central oxygen tank such that it is between the ISS and rocket and from the Canadarm2's point of view, it is the highest of the 3 it can place on the central tank's side.

Bottom Central Oxygen Tank

1. Launch #8 arrives at ISS and docks using standard practices with Starship's IDAs.
2. The Starship fairing opens, with half the holding fixtures attached to it, freeing the payload for movement.
3. Canadarm2 attaches to the oxygen tank at the grapple fixture mounted to the side of it.
4. Canadarm2 removes the oxygen tank from Starship and positions it beneath the top central oxygen tank such that the top central oxygen tank's bottom trunk structure is in contact with the top of the bottom oxygen tank.
5. Astronauts weld the bottom of the trunk to the top of the bottom oxygen tank, connecting the two.
6. Astronauts connect all necessary cables between the life habitat and the bottom central oxygen tank.
7. Starship fairing closes and follows standard undocking procedure, then returns to Earth.

Bottom Hydrogen Tanks #1, #2, and #3

1. Launch #9 arrives at ISS and docks using standard practices with Starship's IDAs.
2. The Starship fairing opens, with half the holding fixtures attached to it, freeing the payload for movement.
3. Canadarm2 attaches to the hydrogen tank at the grapple fixture mounted to the side of it.
4. Canadarm2 removes the hydrogen tank from Starship and positions it adjacent to the side of the center oxygen tank such that their central rings are lined up and the proper distance away from each other. This tank is placed on the side of the central oxygen tank such that it is between the ISS and rocket and from Canadarm2's point of view, it is the lowest of the 3 it can place on the central tank's side.
5. Astronauts retrieve connecting rods from Starship payload bay and return them to tanks.
6. Astronauts weld the connecting rods to the two central rings on the center oxygen tank and hydrogen tank.
7. Astronauts connect all necessary cables and pipes between the life habitat and the hydrogen tank.
8. Starship fairing closes and follows standard undocking procedure, then returns to Earth.

9. The procedure is repeated identically for Launch #10 and #11. The new hydrogen tank is placed on the side of the central oxygen tank such that it is between the ISS and rocket and from the Canadarm2's point of view, it is the highest of the 3 it can place on the central tank's side.

Rotation

1. Both boom IDAs are detached from the rocket assembly, leaving the rocket free floating in space.
2. The RCSs on the sides of Zvezda are activated to slowly rotate the rocket assembly. Special care is given to the moment produced, with consideration for the uneven distribution of weight from tanks only being attached to one side of the rocket. Small impulses are generated to conserve helium and rotate the rocket 180 degrees over the course of 5 days.
3. Upon completion of 180-degree rotation, Canadarm2 attaches to the grapple fixture mounted on the side of the life habitat assembly.
4. In conjunction with the RCSs, Canadarm2 guides the rocket back to the booms where the IDAs redock to the rocket.
5. Once the rocket is rejoined with the ISS via the booms and IDAs, astronauts perform inspections on docking joints and full body of rocket to check for any damage, misalignments, or disconnection of wires or pipes.

Top Oxygen Tank #2

1. Launch #12 arrives at ISS and docks using standard practices with Starship's IDAs.
2. The Starship fairing opens, with half the holding fixtures attached to it, freeing the payload for movement.
3. Canadarm2 attaches to the oxygen tank at the grapple fixture mounted to the side of it.
4. Canadarm2 removes the oxygen tank from Starship and positions it adjacent to the side of the center oxygen tank such that their central rings are lined up and the proper distance away from each other. This tank is placed on the side of the central oxygen tank such that it is between the ISS and rocket and from Canadarm2's point of view, it is the middle of the 3 it can place on the central tank's side.
5. Astronauts retrieve connecting rods from Starship payload bay and return them to the oxygen tanks.
6. Astronauts weld a connecting rod to the two central rings on the oxygen tanks.
7. Astronauts connect all necessary cables and pipes between the life habitat and the oxygen tank.
8. Starship fairing closes and follows standard undocking procedure, then returns to Earth.

Top Hydrogen Tanks #3 and #4

1. Launch #13 arrives at ISS and docks using standard practices with Starship's IDAs.
2. The Starship fairing opens, with half the holding fixtures attached to it, freeing the payload for movement.
3. Canadarm2 attaches to the hydrogen tank at the grapple fixture mounted to the side of it.
4. Canadarm2 removes the hydrogen tank from Starship and positions it adjacent to the side of the center oxygen tank such that their central rings are lined up and the proper distance away from each other. This tank is placed on the side of the central oxygen tank such that it is between the ISS and rocket and from Canadarm2's point of view, it is the lowest of the 3 it can place on the central tank's side.
5. Astronauts retrieve connecting rods from Starship payload bay and return them to tanks.
6. Astronauts weld the connecting rods to the two central rings on the center oxygen tank and hydrogen tank.
7. Astronauts connect all necessary cables and pipes between the life habitat and the hydrogen tank.
8. Starship fairing closes and follows standard undocking procedure, then returns to Earth.
10. The procedure is repeated identically for Launch #14. The new hydrogen tank is placed on the side of the central oxygen tank such that it is between the ISS and rocket and from the Canadarm2's point of view, it is the highest of the 3 it can place on the central tank's side.

Bottom Hydrogen Tanks #4, #5, and #6

1. Launch #15 arrives at ISS and docks using standard practices with Starship's IDAs.
2. The Starship fairing opens, with half the holding fixtures attached to it, freeing the payload for movement.
3. Canadarm2 attaches to the hydrogen tank at the grapple fixture mounted to the side of it.
4. Canadarm2 removes the hydrogen tank from Starship and positions it adjacent to the side of the center oxygen tank such that their central rings are lined up and the proper distance away from each other. This tank is placed on the side of the central oxygen tank such that it is between the ISS and rocket and from Canadarm2's point of view, it is the lowest of the 3 it can place on the central tank's side.
5. Astronauts retrieve connecting rods from Starship payload bay and return them to tanks.
6. Astronauts weld the connecting rods to the two central rings on the center oxygen tank and hydrogen tank.
7. Astronauts connect all necessary cables and pipes between the life habitat and the hydrogen tank.
8. Starship fairing closes and follows standard undocking procedure, then returns to Earth.
9. The procedure is repeated identically for Launch #16 and #17. The new hydrogen tank is placed on the side of the central oxygen tank such that it is between the ISS and rocket and from the Canadarm2's point of view, it is the highest of the 3 it can place on the central tank's side.

Rocket Engines

1. Launch #18 arrives at ISS and docks using standard practices with Starship's IDAs.
2. The Starship fairing opens, with half the holding fixtures attached to it, freeing the payload for movement.
3. Canadarm2 moves astronauts into the payload bay where the astronauts release the 2 RCSs from the holding fixtures. The astronauts manually hold the RCSs while the Canadarm2 moves them to the rocket assembly. The astronauts then weld the 2 RCSs to opposite bottom hydrogen tanks.
4. Astronauts connect all necessary wires and pipes to the RCSs and double-check their connections.
5. Canadarm2 returns to Starship payload bay.
6. Canadarm2 attaches to the VASIMR engine assembly at the grapple fixture mounted to the side of it.
7. Canadarm2 removes the VASIMR engine assembly from Starship and positions it beneath the bottom central oxygen tank such that the interstage truss on top of the Argon tank is adjacent to the bottom of the oxygen tank.
8. Astronauts weld the tops of the truss points to the bottom of the oxygen tank.
9. Astronauts connect all necessary cables between the other modules and the VASIMR engine assembly.
10. Canadarm2 returns to Starship and attaches to the RS-25 engine assembly at the grapple fixture mounted to the top of the holding arm. Astronauts undo attachment between grapple fixture bottom plate and central post to RS-25 plate.
11. Astronauts connect power cords from Canadarm2 grappling face to holding arm power supply.
12. Canadarm2 removes the RS-25 engine assembly from Starship and rotates the assembly such that the tops of the RS-25 engines are facing the bottom of the hydrogen tanks.
13. The holding arm extends its joints such that the central diameters of the RS-25 engines match the central diameters of the hydrogen tanks.
14. Canadarm2 positions the RS-25 engine assembly beneath the hydrogen tanks such that the tops of the RS-25 engines are in line and in contact with the engine mounting structures present on the bottom of the hydrogen tank rings.
15. Astronauts retrieve bolts from Starship payload bay and return to engine assembly
16. Astronauts use Pistol Grip Tools to attach the RS-25 engines to their respective mounts using bolts.
17. Astronauts connect all necessary cables between the life habitat and the RS-25 engines.
18. Starship fairing closes and follows standard undocking procedure, then returns to Earth.

IV. References

[1] Naden, N., and Prater, T. J., "A review of welding in space and Related Technologies," *NASA*

[2] International External Robotic Interoperability Standards (IERIS).

[3] Jax, "It's electrifying: Starship's upgraded Payload Deployment System," Ringwatchers Available: https://ringwatchers.com/article/s33-pez.

[4] Starship users guide Available: https://www.spacex.com/media/starship_users_guide_v1.pdf.

[5] Berger , E., "Inside elon musk's plan to build one starship a week-and Settle Mars," Ars Technica Available: https://arstechnica.com/science/2020/03/inside-elon-musks-plan-to-build-one-starship-a-week-and-settle-mars/.