Ares I Linear Mate Umbilical Plate and Collet

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Abstract

This paper will present umbilical carrier plate design and testing performed at KSC for the ARES 1 Upper Stage. The focus will be on the innovative linear mate ground carrier plate and electric solenoid actuated collet mechanisms. The linear mate ground umbilical plate is a unique, two-piece, design where an outer plate is first aligned and locked to the vehicle, and then an inner plate translates to engage the commodity connectors. The collet uses a spring-loaded over-center mechanism and redundant electric solenoids to release a traditional collet locking device. A high level discussion of the umbilical arm will also be presented as a corollary to the umbilical plate designs.

Introduction

Umbilicals discussed in this paper were designed to support the Constellation Program Ares I launch vehicle shown in Figure 1. The Constellation program was initiated in 2006 to build a human rated launch vehicle to replace the aging Space Shuttles. The Kennedy Space Center (KSC) Launch Pad was redesigned for the Ares I rocket to use the clean pad concept. The launch tower is now located on the Mobile Launcher (ML) platform, as shown in Figure 1. The launch tower was designed to house the T-0 umbilical arms, T-0 sway damper and stabilizer, and the crew access arm, along with all the ancillary support equipment.

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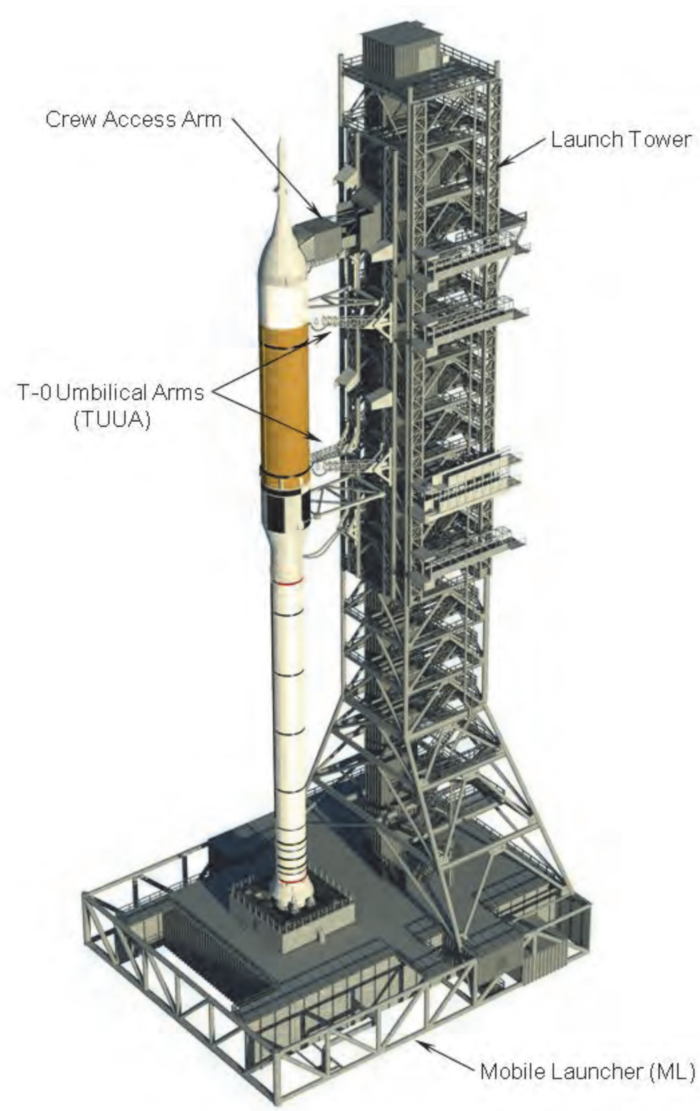


Figure 1. Ares I Vehicle on Mobile Launcher

The umbilical arms utilize a tilt up counterweighted configuration and rotate up as the vehicle rises from the ML. The tilt-up umbilical arm (TUUA) design is shown in Figure 2. This is relevant because the motion of the arm for connecting and disconnecting from the vehicle is a major driver in the design of the ground umbilical carrier GUCP (umbilical plate) and the linear mate mechanism. The GUCPs are located at the end of the TUUA umbilical arms. A typical GUCP (Ares I Instrument Unit) is shown in Figure 3. The GUCP houses the QDs for transferring fluids, ECS (environmental control system), and electrical power/data between the ground and the vehicle. In this innovative design, the two primary functions of the GUCP are separated. The first function of attaching to the vehicle is done by the Outer Plate (OP) and the second function of transferring commodities between the ground and vehicle is done by the linear mate Inner Plate (IP). The other innovative mechanism introduced in this design is the fail safe T-0 solenoid actuated collet which structurally connects the GUCP to the vehicle during ground operations. These umbilicals have the potential to improve the performance and reduce the cost of the next NASA rocket to launch from Cape Canaveral.

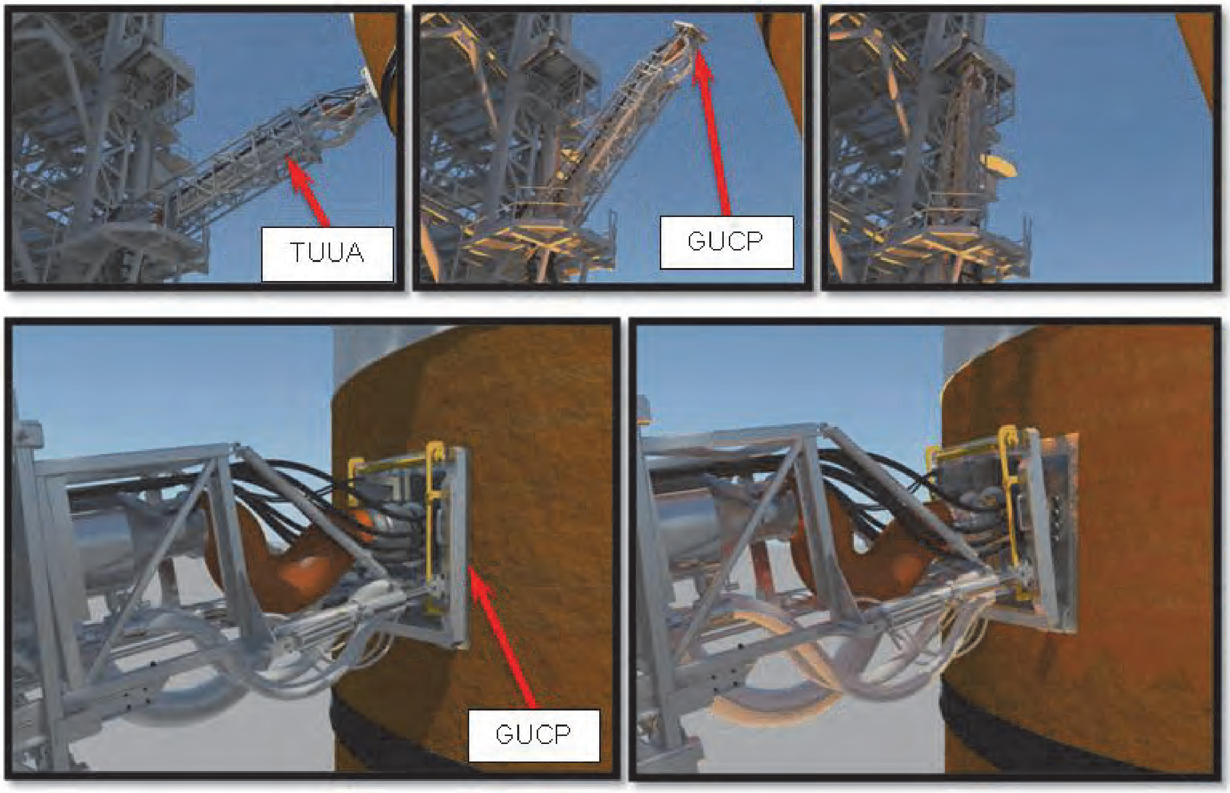


Figure 2. TUUA Model Disconnecting and Tilting Up

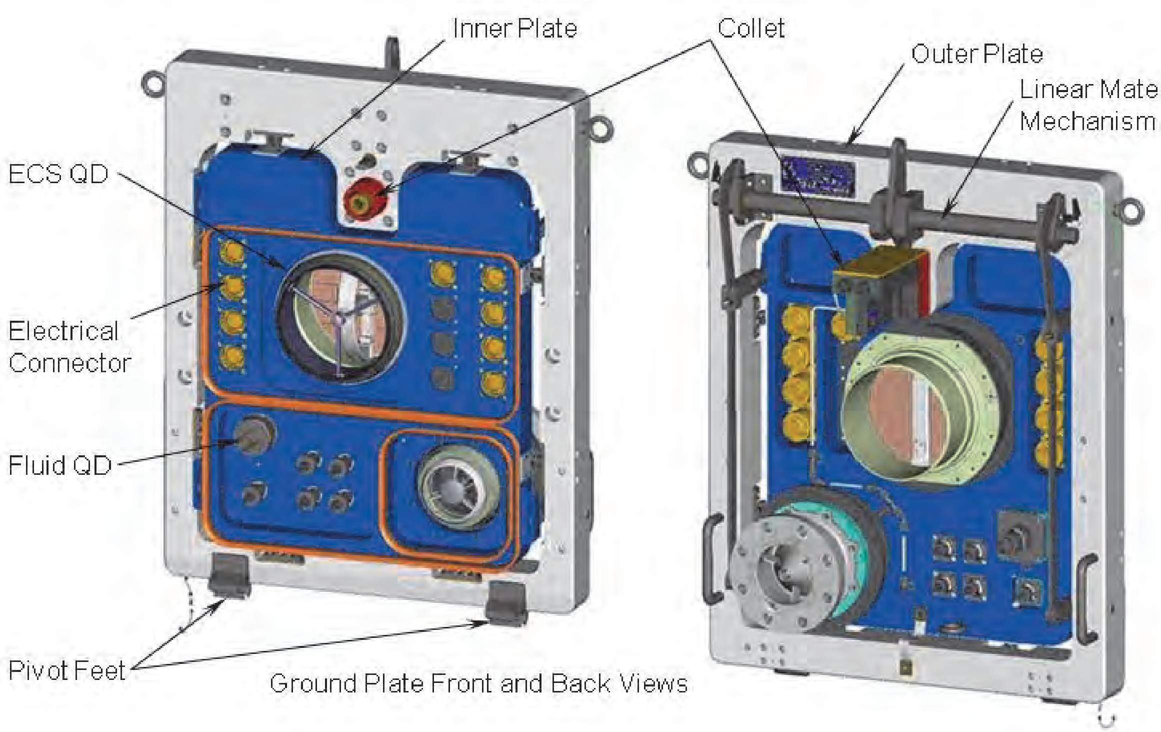


Figure 3. Ares I GUCP (Instrument Unit)

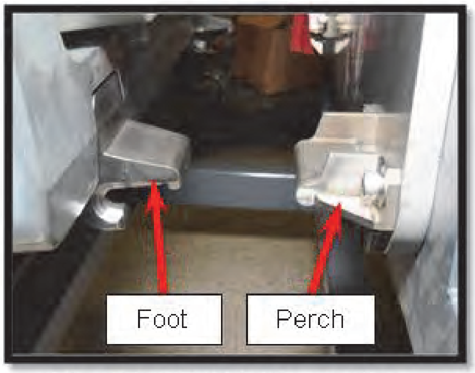
GUCP Function and Mechanisms

The umbilical has two primary functions. One is to transfer fluid commodities and electrical power/data between the rocket and ground. The second is to provide a safe T-0 disconnect to remove the commodities connections at the time of launch.

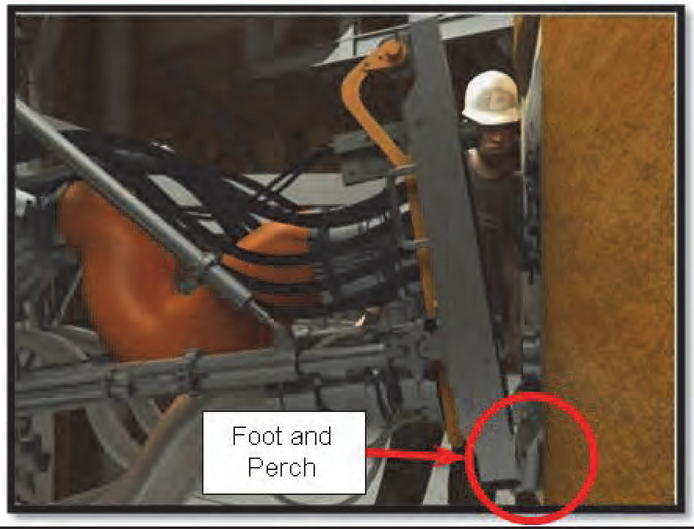
<u>Connecting the Umbilical</u>
In this design the outer plate (OP) provides the connect/disconnect function from the vehicle and the structural interface designed for ease of connection and safe disconnection at T-0.

Connection of the GUCP to the vehicle is done in the VAB (vehicle assembly building). To make the connection operation ergonomically friendly, it is preferred to have the GUCP in a tilted back (foot-forward) orientation shown in Figure 4. The GUCP starts in a 10° tilt back position and is extended by actuators on the TUUA toward the vehicle with the pivot feet at the bottom being the leading portion. In this process the technician guides the GUCP forward and visually verifies that the pivot feet are aligned to the vehicle perch (foot bracket). After the pivot feet are engaged, they form a hinge, which allows the GUCP to pivot up to the vertical (0°) position as it is being pushed forward. At this point the collet located at the top of the OP is engaged to lock the GUCP to the vehicle's flight umbilical plate. The linear mate mechanism makes this process much easier by allowing the QDs to be retracted and not in contact with the vehicle while the GUCP is being connected. After the outer plate is connected to the vehicle, the linear mate mechanism is used to extend the inner plate (IP) and plug-in all of the ground connections in one motion. The components of the linear mate mechanism are shown in Figure 5.

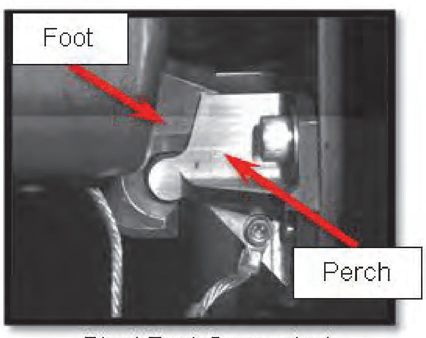
Step 1 – Extend GUCP to Engage Pivot Feet



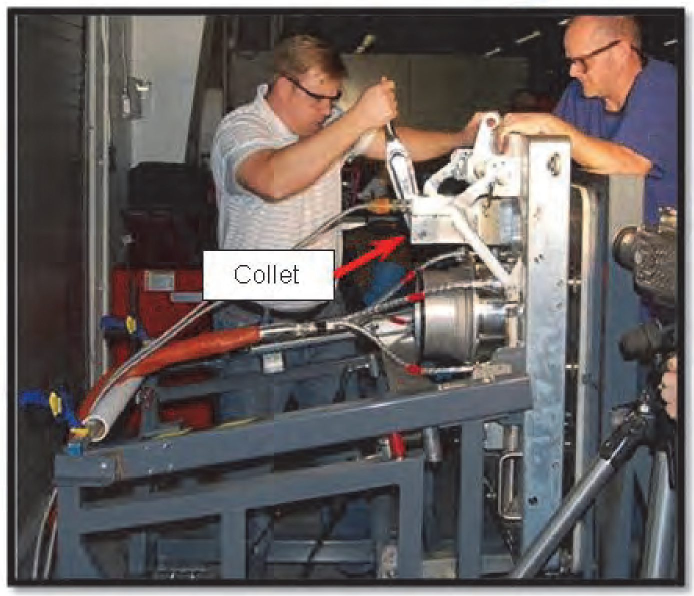
Pivot Feet Prior to Connection



Step 2 – Rotate Plate to Vertical and Engage Collet
Outer Plate is now aligned and locked to vehicle (Picture from testing)



Pivot Feet Connected
(Picture from high speed testing video)



Step 3 – Linear Mate Mechanism Translates Inner Plate to Engage Commodity Connectors

Inner plate translates to engage commodity connectors as actuation nut is manually rotated. Mechanism is locked with two ball lock pins and remains locked through launch.

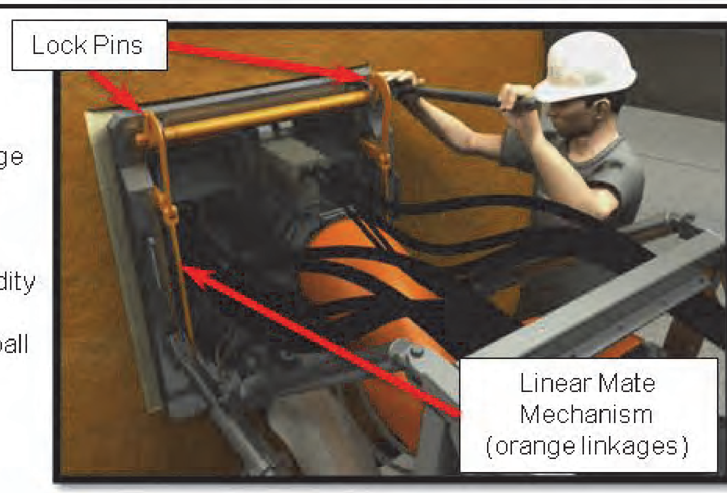


Figure 4. Umbilical Connection Sequence

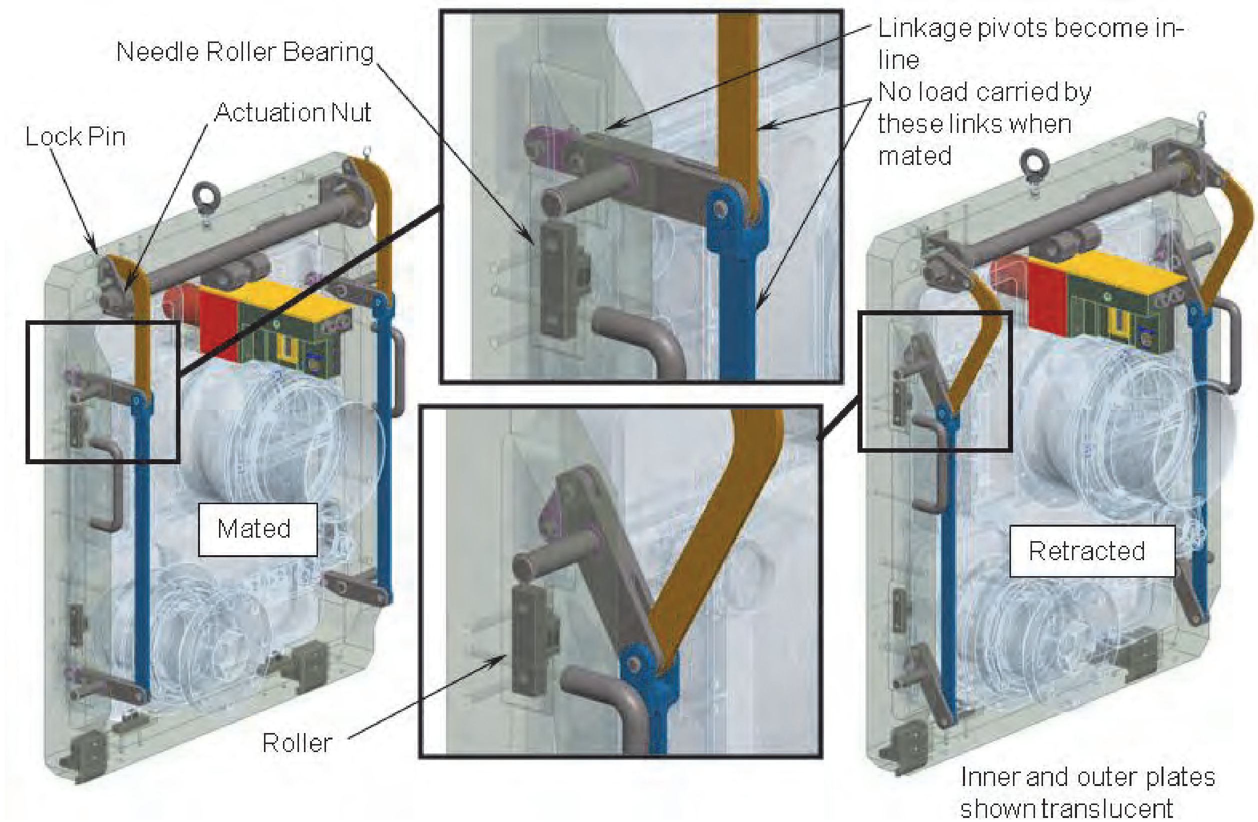


Figure 5. Linear Mate Mechanism Details

The linear mate mechanism consists of a series of parallel linkages that move the inner plate approximately 38 mm (1.5 inches). The inner plate is supported on eight needle roller bearings shimmed for a precise alignment and smooth in/out translation. The linkages are moved by turning the actuation nut with a standard 1-1/8 inch wrench as shown in Figure 6. In the mated position the load bearing linkages are in a straight (singularity) position which transfers all of the reaction loads into shear on the pins and has zero forces in the latching (gold) and horizontal (blue) linkages in Figure 5.

The 6061-T6 Aluminum 6061 plate carries up to 44,500 N (10,000 pounds) of separation load when all lines are pressurized. The deflection and stresses in the plate and mechanism were analyzed with FEA (finite element analysis) to ensure they were within acceptable safety margins. Deflections of the inner plate were limited to 1/8 inch and all the components have a minimum stress safety factor of 2:1 for yield.

Complexity added by the linear mate mechanism is more than overcome by the problems that it solves. The two-step mate operation provides high confidence for technicians by aligning the umbilical prior to mating the critical connections. Linear engagement allows mating of fluid and electrical connectors in the same operation. Previous angular mate umbilicals made electrical connections in a separate operation after the initial mate.

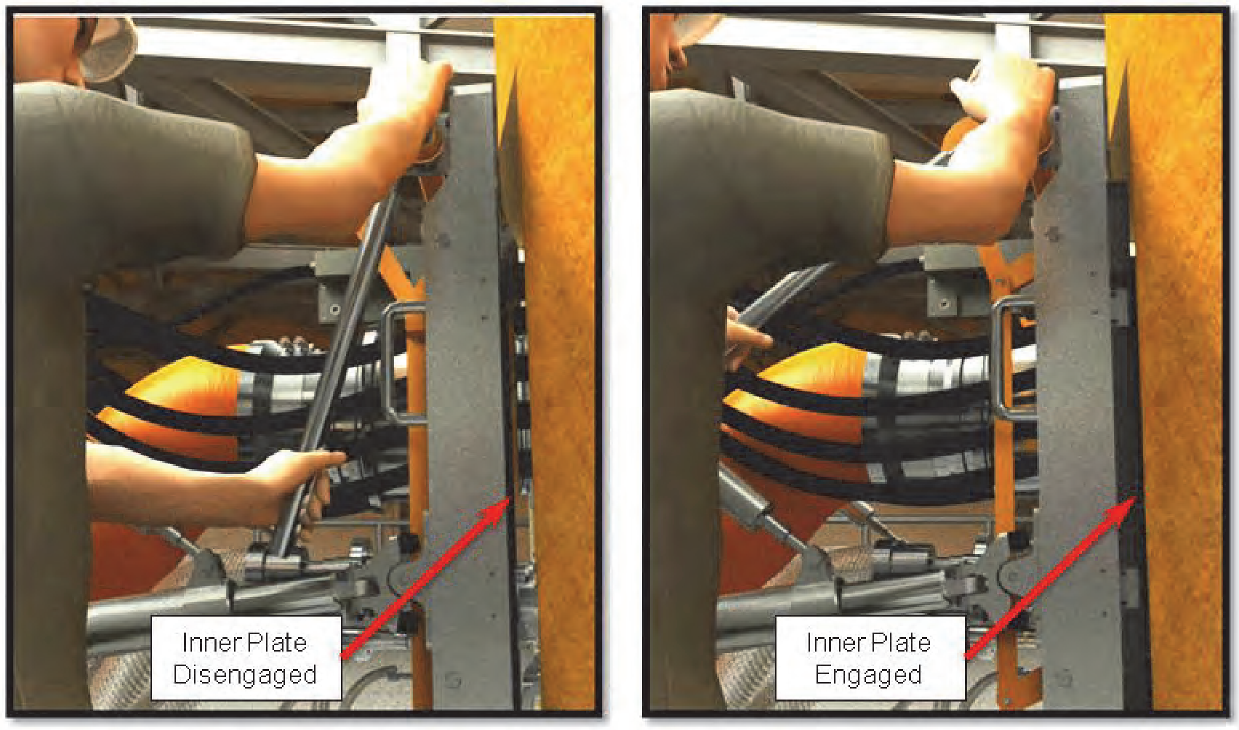


Figure 6. Linear Mate Mechanism Engagement – *Inner plate translates to engage commodity connectors as actuation nut is manually rotated. Mechanism is locked with two ball lock pins and remains locked through launch.*

Disconnecting the umbilical

The TUUA arm is passively (counter weight) biased to tilt up and pull away as the GUCP releases. At T-0 the command is given to release the collet. First the GUCP pivots away from the rocket approximately 10° about the hinge line of the pivot feet. Once the GUCP has pivoted, the toe of the pivot foot is no longer engaged with the vehicle receptacle. At this point the TUUA pulls the GUCP away from the vehicle and begins to tilt-up to the retracted position. The rise of the TUUA/GUCP is tuned to match the speed of the vehicle. It takes approximately 4 seconds to disconnect and stow the GUCP.

Ideally there is no net force applied to the vehicle during disconnect (some small forces may be present due to vehicle drift and other misalignments). The linear mate mechanism is in the forward (plugged-in) locked position during disconnect, resulting in an angular separation of the QDs. Compliance in the QDs allows for an angular disconnect. This was verified through extensive testing with the prototype GUCP to make sure no QD damage occurred during angular disconnect.

Fail safes are built into the design. In case of a collet release failure, a frangible pin is sheared by the vehicle motion which releases the GUCP. Force for the secondary release is transferred to the GUCP from the TUUA by a wire rope. A high momentary load is transferred to the vehicle during the secondary release.

After release, the GUCP is retracted into a safe house where it is protected from the rocket exhaust blast forces and contamination. Figure 2 shows the retract sequence. A cover plate is extended over the QDs, which are facing up after retraction, to environmentally seal and protect them from the rocket exhaust. After launch the ML is returned to the VAB where the GUCP is inspected and refurbished for the next launch.

Solenoid Actuated Collet

A locking device with a highly reliable release method was required for the GUCP. Designs such as collets, ball lock devices, pneumatic actuation, and non-explosive actuators (NEA) were evaluated. Ball locks, used on many heritage designs, are load limited when compared to collets. Pneumatic actuation is simple, but requires an expensive redundant pneumatic control system. NEA, also called a burn wire device, uses an electrical signal to melt a wire that retains the locking device. Replacement operation time and unit cost were very high for the NEA. The collet locking device was chosen due to success on Space Shuttle and X-33 designs. A solenoid actuated collet release mechanism was developed for the Constellation program for use in T-0 separation of the flight and ground umbilical plates, as well as T-0 release of drop weights in the Vehicle Stabilization and Damping System. It uses a simple, yet effective method for locking and releasing the collet, thus making it very easy to use and extremely reliable. Early testing of the mechanism has proven both of these to be true.

The collet is loosely based on a heritage Space Shuttle and X-33 program designs. Similar to collets used as tool holders in machining equipment, this collet consists of a round bar with a tapered surface that is split into multiple ‘fingers’ to allow radial displacement. These particular collets are made from a beryllium-copper alloy to take advantage of its non-sparking property when struck, thus preventing the ignition of residual hydrogen at the umbilical interface. The inner diameter of the collet is smaller than the outside diameter of a coaxial pin. When the pin is driven forward, through the small diameter of the collet, it expands the collet fingers, as shown in Figure 7. When the collet is inserted into a matching receptacle, and the pin is driven into the fingers, it locks the two pieces together.

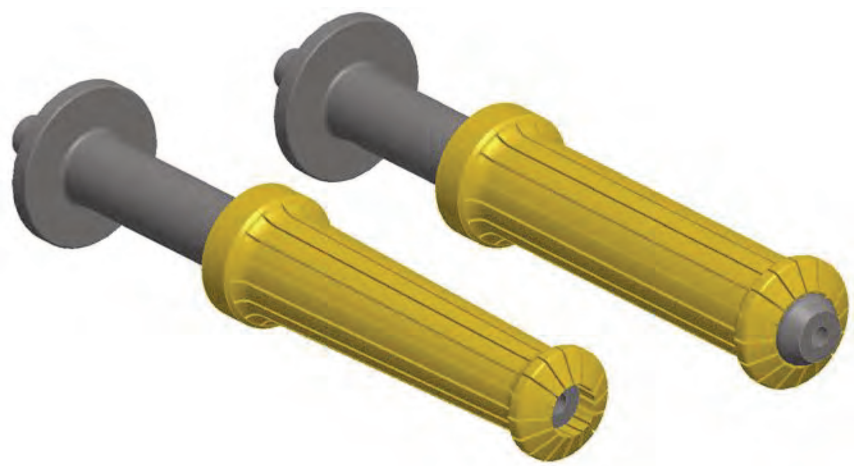


Figure 7. Collet Expanded and Collapsed (nominal) – *Machined part with flexible fingers expands to engage flight receptacle when pin is inserted.*

The innovation for this particular collet, shown in Figure 8, is the use of an over-center mechanism to drive the pin forward, lock it into place, and then release the pin. A cam is rotated to drive the over-center linkage from an unlocked to a locked position, storing energy in a spring connected to the coaxial pin during the motion. The spring rate was chosen based on data collected from the X-33 program collet testing, which showed the pin needs approximately 1112 N (250 pounds-force) to pull the pin. A 175 $^{N}/_{mm}$ (1000 $^{lbf}/_{in}$) spring was chosen to provide 3336 N (750 lbf) to pull the pin, which is three times the expected load. Once the linkage is pushed pass center, the energy in the spring attempts to force the linkage to continue in the same direction, but the motion is restrained by a fixed hard stop. Figure 9 show the linkage in the locked and unlocked positions. Since the spring is still exerting force on the linkage, it effectively locks it into place. This locks the coaxial pin inside the collet and prevents the collet fingers from collapsing. In this particular mechanism, the over center mechanism is only past center by about 1.27 mm (.050 inch) and needs about 100 pounds-force to push the linkage past center.

An electric solenoid is perfect for this application since they can exert a lot of force but only over a small distance. In this case, a pair of commercial-off-the-shelf (COTS) solenoids were wired into independent circuits for redundancy. Each solenoid sits adjacent to one of the linkages in the mechanism. When 60 VDC is applied to the solenoids, each one applies over twice the expected force to drive the linkage past center. The stored energy in the spring then pulls the coaxial pin out of the collet fingers. An elastomer bumper is installed to absorb some of the impact from the pin.

A prototype of this collet mechanism was fabricated by the in-house machine shop at KSC and has undergone some preliminary testing. When both solenoids are energized simultaneously, the collet mechanism is released from the receptacle in about 8 ms. If only one solenoid is energized, to simulate a failure of a solenoid, the collet releases in about 12 ms. During the Ground Umbilical Carrier Plate testing mentioned later in this document, the collet underwent over 150 mate/de-mate cycles without any degradation in performance. With only a few launches per year for the Constellation program, this simulated over 20 years of use. Only some minor wear due to abrasion was noted at the pin and collet interface.

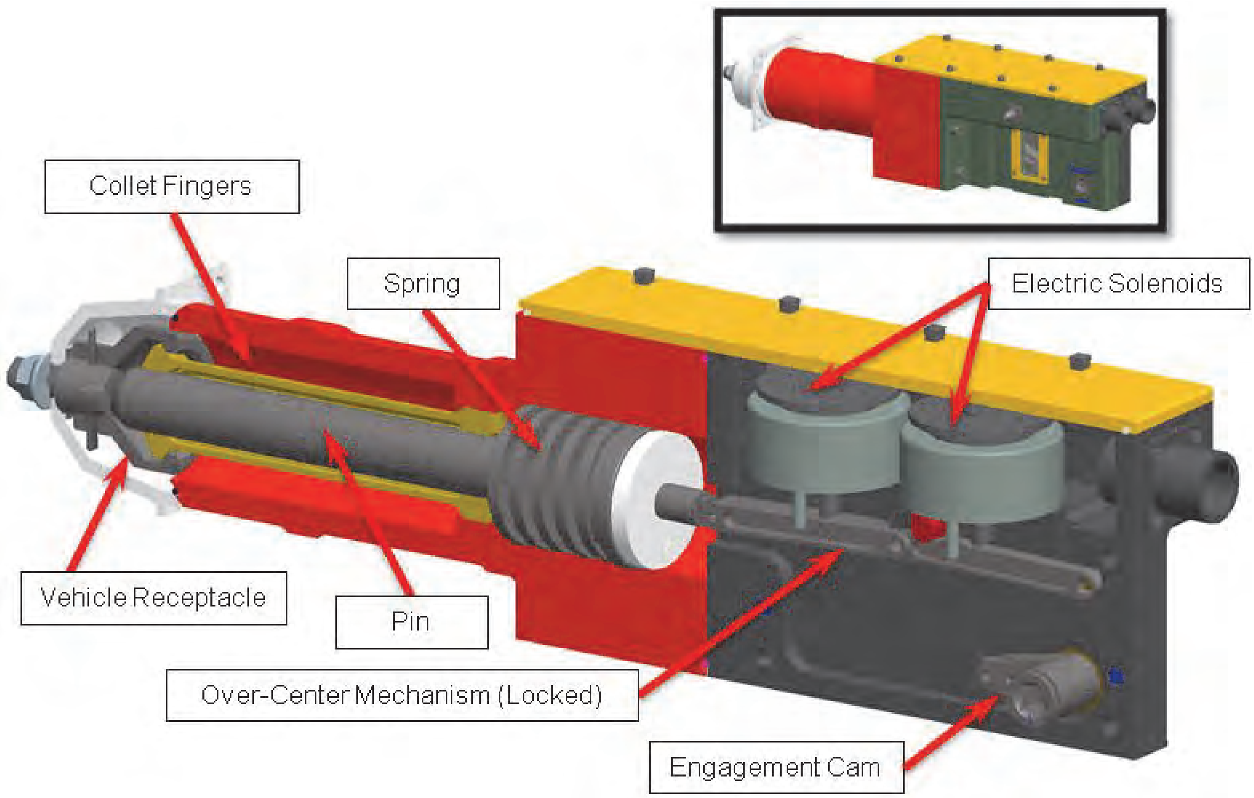


Figure 8. Solenoid Actuated Collet – *Locked to vehicle receptacle*

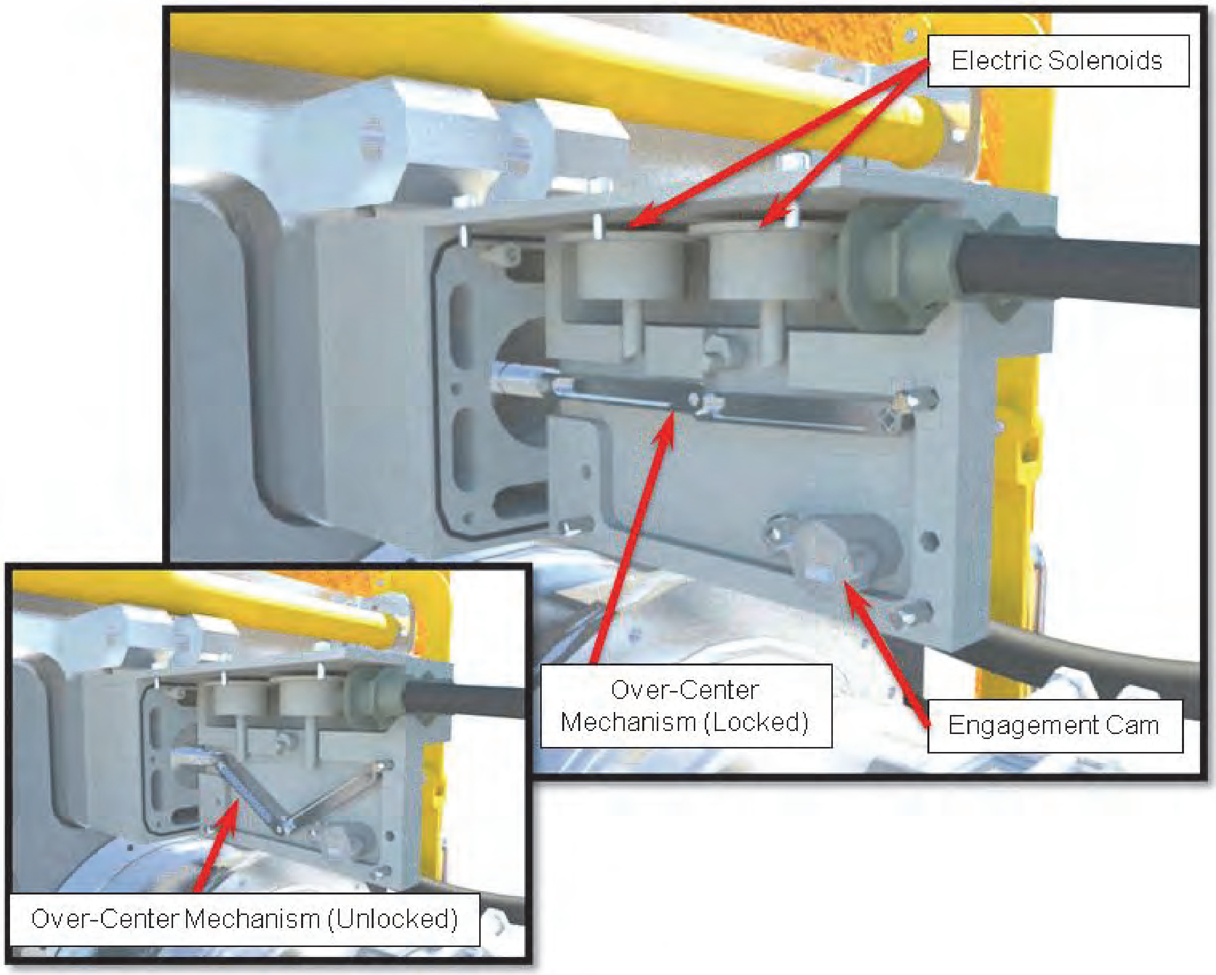


Figure 9. Solenoid Actuated Collet - *Locked and Unlocked Positions*

Even though it is Ground Support Equipment (GSE), the collet uses NASA-STD-5017, "NASA Technical Standard: Design and Development Requirements for Mechanisms" for design of flight mechanisms as guidance. All rotating joints feature redundant rotating surfaces and sliding joints are coated in friction-reducing material. The stored energy in the spring is more than twice what is expected to release the pin and each solenoid exerts twice the expected force on the over-center mechanism. These design details result in an extremely reliable mechanism for releasing loads of up to 44,500 N (10,000 lb). The solenoid actuated collet has other applications, such as a replacement for high cost pyrotechnic release devices.

Testing and Lessons Learned

Development of the linear mate GUCP was conducted through a series of design and test prototypes which incrementally demonstrated the efficacy of this design. Lessons learned from previous programs were used throughout the design to improve the operation and safety of the umbilicals.

One of the first items tested was the counterweighted tilt up arm design. A full scale prototype TUUA was built and tested with our Launch Simulator as shown in Figure 10. This testing proved the original design concept, helped validate the dynamic models, and pointed out some needed design improvements such as shock absorber sizing, and GUCP attachment strut design improvements.

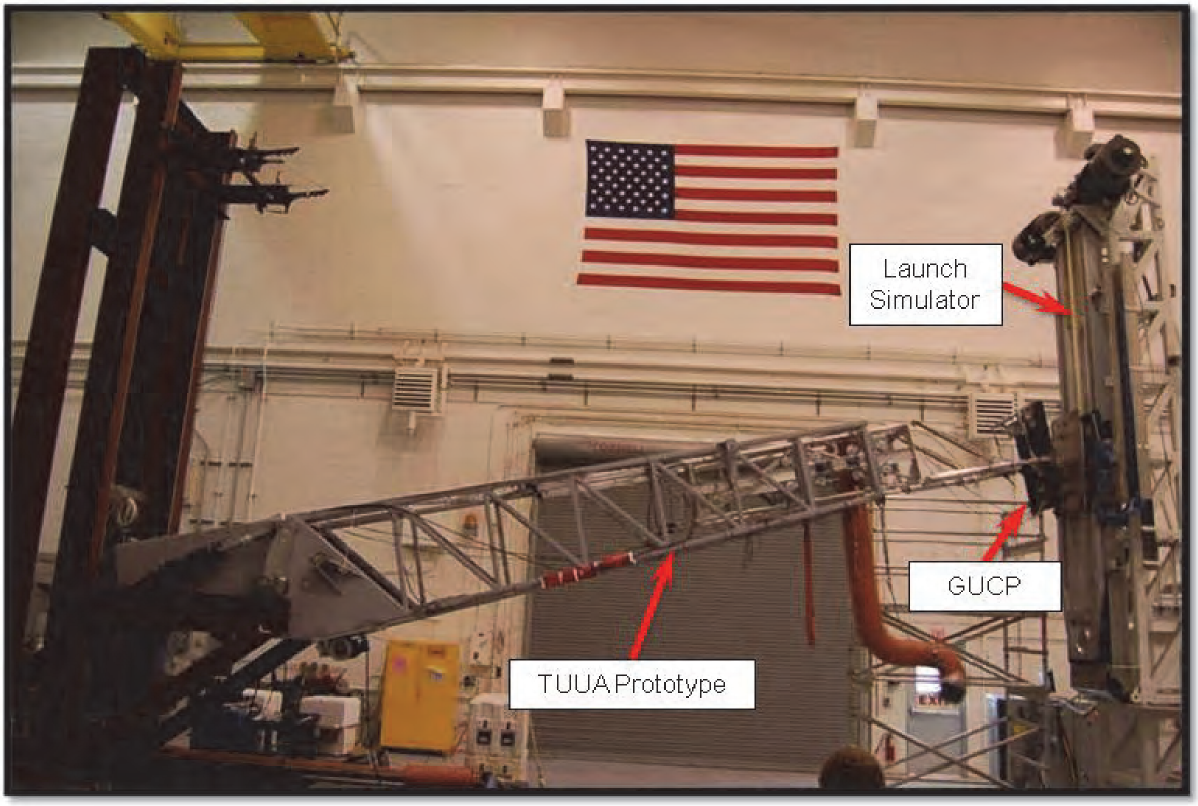


Figure 10. Prototype TUUA Testing

This sequence of connecting and disconnecting the umbilical incorporated many of the lessons learned from previous programs. Experience from the Shuttle program Tail Service Masts (TSM) umbilical drove the pivot foot design and alignment method, allowing the new design to eliminate the laborious adjustment of the GUCP pivot foot. Umbilical mating actuators were also built into the TUUA to make positioning of the heavy (nearly 400 lb) GUCP much easier.

Other critical components were tested, such as the electrical and fluid QD angular mate and demate functions. Some of this testing is shown in Figure 11. It was discovered that angular mating, which was the traditional method in previous umbilicals, was going to be a problem. Previous systems required fluid connectors to mate through a low angle as the plates were joined. Physical restrictions required a much higher mate angle for the ARES I umbilicals. Electrical connectors were damaged and the critical cryogenic fill QD did not align properly.

Figure 11. QD Mate/Demate Testing

The linear mate mechanism was the solution to the problems discovered during angular mate testing. Angular demate was still possible because of the extraction motion from the receptacles did not require a precise alignment. Angular compliance in the QD design allowed for the 3°-5° rotation during disconnects.

Once the design of the linear mate GUCP was completed, a fully functional prototype was built and put through extensive functional testing. A special test fixture was built, shown in Figure 12, to simulate mating and demating dynamics, measure loads, and verify all the functions of the GUCP.

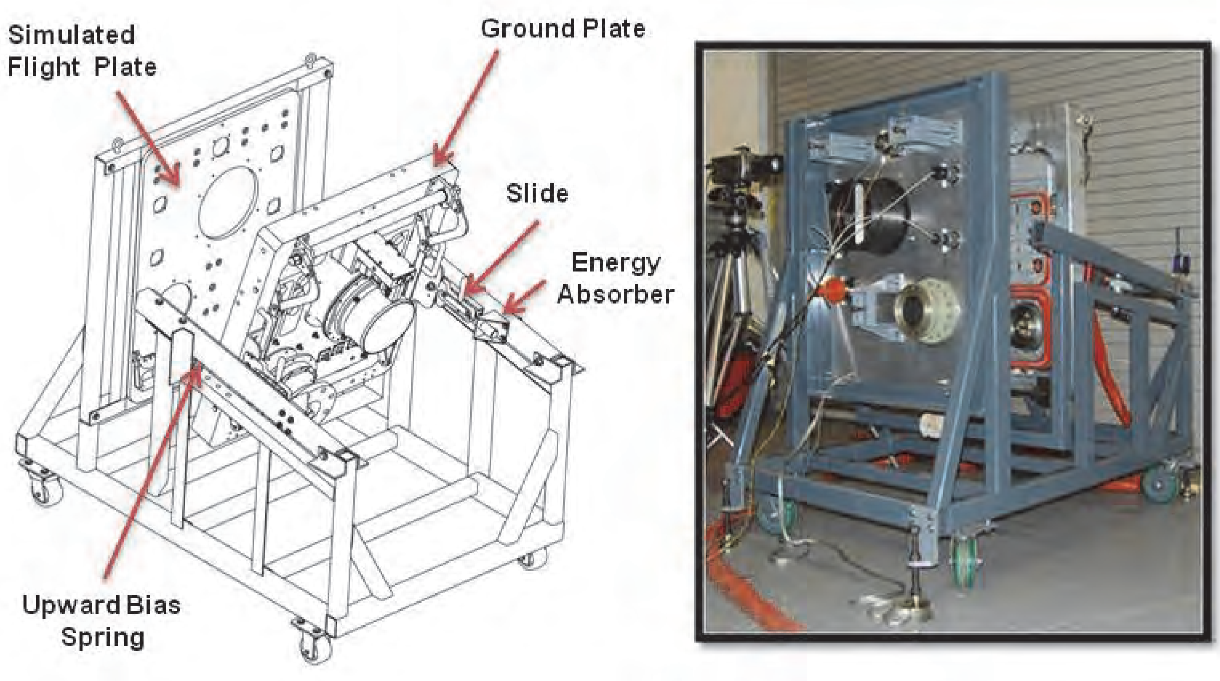


Figure 12. Umbilical Plate Test Fixture

Experience with the Saturn and Shuttle swings arms, and the Shuttle ET (external tank) vent drop down umbilical was incorporated during the design of the TUUA. The design of the TUUA and linear mate GUPC eliminated many of the drawbacks of these previous systems, such as the complexity of the drop down design, and the much more fail safe tilt up motion of the arm vs. APOLO swing arms which could endanger the vehicle during a retraction failure. Another lesson learned and corrected in this design was the operation where the Space shuttle umbilicals plates were connected first, then the electrical connectors were installed. The separate operation avoided the angular mate problems, but created extra work, delays and higher cost.

Conclusion

Over the 4 year period since the start of the Constellation program KSC has developed a new generation of improved state of the art umbilicals. These new umbilicals draw on 40 years of experience and incorporate many improvements such as the TUUA, linear mate GUCP, and solenoid actuated collets. These umbilicals have the potential to improve the performance and reduce the cost of the next NASA rocket to launch from Cape Canaveral.

Complexity added by the linear mate mechanism is more than overcome by the problems that it solves. The low risk two-step mate operation provides high confidence for technicians. This umbilical combines the precision alignment of a linear umbilical with the simple demate function of a traditional angular umbilical. Linear engagement allows mating of fluid and electrical connectors in the same operation.

The solenoid actuated collet is a new method to reliable release a high load. The use of redundant solenoids is an all new method for T-0 umbilical systems. The combination of the release and engagement function into a single over-center mechanism is the key to the simple operation. The solenoid actuated collet has the potential to replace many high cost pyrotechnic release devices.

The development effort is not over. In the next phase a fully flight certified version of the umbilical is being built and scheduled to be completed in early 2012. This umbilical will be fully functionally tested at KSC using a vehicle motion simulator with cryogenic fluid transfer, and will be put through a full range of launch, abort, and simulated environmental conditions. The collet will also be used during this test providing more valuable data and life cycle testing. The goal is to use it for the future SLS (Space Launch System) rocket to be launched from KSC.