

SPACE SHUTTLE SEPARATION MECHANISMS

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ABSTRACT

The development of Space Shuttle separation devices is reviewed to illustrate the mechanisms involved in separating the Orbiter from the Boeing 747 carrier aircraft and from the externally mounted propellant tank. Other aspects of the separation device development to be discussed include design evolution, operational experience during the Orbiter approach and landing tests, and the work to be accomplished before an operational system becomes a reality.

INTRODUCTION

The separation of the Space Shuttle Orbiter from the Boeing 747 carrier aircraft and from the external tank (ET) will be reviewed in this presentation; however, several other crucial separation events occur during a typical Shuttle mission. These include the separation of the Shuttle vehicle from the launch platform at lift-off and separation of the two solid rocket boosters attached to the ET approximately 2 minutes into the flight (fig. 1). Actual structural separation of the Orbiter from the ET is preceded by the separation and retraction of the fuel and oxidizer lines and of the electrical connections between the Orbiter and the ET.

The Orbiter and the Boeing 747 carrier aircraft are shown before release in figure 2. The first separation occurred in 1977 during a series of test flights. The purpose of these test flights was to verify Orbiter handling capabilities and to verify the adequacy of all systems used in the approach and landing procedures. For both the earlier test flights and the actual orbital flights, the separation hardware provides structural attachment of the Orbiter until the time of release and then mechanical release within the system design constraints.

The purpose of this paper is to summarize the development of the structural separation system of the Orbiter for (1) launching the Orbiter from the 747 aircraft during flight tests and (2) releasing the Orbiter from the ET during orbital flight operations.

Two particular developmental problems are discussed for the Orbiter/747 aircraft separation system: (1) the development of the separation device, a pyrotechnic-actuated bolt, and (2) the requirement for lateral as well as fore and aft motion capability at separation. For the orbital flight separation system, a significant developmental problem is that of obtaining a sufficiently

smooth surface on the Orbiter after release. The purpose of this requirement is to control the aerothermal heating on the spacecraft to prevent excessive structural temperatures during entry.

DESIGN REQUIREMENTS

The separation system design requirements may be divided into two general categories: structural and mechanical. The separation hardware is the primary structural load path between the Orbiter and the 747 and between the Orbiter and the ET; hence, the hardware must satisfy the spacecraft overall structural design requirements. For the separation event, the system acts as a mechanical device and must satisfy the design requirements to assure a safe separation. The importance of this system is evident. A structural failure before separation, a failure to separate, or an improper separation could be catastrophic.

The structural design requirement for the Orbiter/747 separation is to provide structural support of Orbiter/747 interfaces for flight environments. The mechanical design requirements for the Orbiter/747 separation are the following.

1. To accommodate unrestrained horizontal motion at release
2. To accommodate the load measurement system
3. To accommodate ground adjustment of the Orbiter incidence angle
4. To provide redundancy in the release device and initiation
5. To separate without fragmenting

The structural design requirement for the Orbiter/ET separation is to provide structural support at Orbiter/ET interfaces for prelaunch, launch, and boost environments. The mechanical design requirements for the Orbiter/ET tank are the following.

1. To provide release of the Orbiter from the external tank for normal and abort separation
2. To preclude degradation of Orbiter functional systems after operation
3. To satisfy aerothermal smoothness criteria after separation
4. To provide redundancy in the release device and initiation
5. To separate without fragmenting

The requirements for the Orbiter/747 and Orbiter/ET design systems are similar; however, the Orbiter/747 system requires the capability to accommodate horizontal relative motion at release in addition to the obvious requirement

for unrestrained vertical motion. The purpose of this requirement is to allow the Orbiter to move relative to the 747 at release without inducing additional forces or impulses that would complicate the separation dynamics. The horizontal motion capability would allow the Orbiter to move forward and aft because of differences in drag between the two vehicles.

The requirement to measure interface attachments loads had a twofold purpose: to confirm the flight conditions for release and to monitor the structural loads during the various phases of mated flight. Representative design flight loads for the two separation systems are summarized as follows.

1. Orbiter/747

a. Forward attachment (combined loads)

Tension = 154.8 kN (34 800 lbf)

Radial = 90.3 kN (20 300 lbf)

b. Aft attachment (combined loads)

Tension = 425.7 kN (95 700 lbf)

Forward = 206.0 kN (46 300 lbf)

Side = 147.0 kN (33 000 lbf)

2. Orbiter/ET

a. Forward attachment

Tension = 529.3 kN (119 100 lbf)

Radial = 404.8 kN (91 000 lbf)

b. Aft attachment

Bolt tension = 1579.1 kN (355 000 lbf)

The incidence angle between the Orbiter and the 747 was preset based on aerodynamic and separation dynamic analyses. However, the ability to change this angle based on updated analyses and flight test data was required for separation as well as for ferrying the Orbiter. For the approach and landing test (ALT) system, the design was also influenced by the goal of minimizing the development of different release devices for this specialized application.

As previously mentioned, a very stringent requirement for aerothermal smoothness at the outer moldline has resulted in a difficult developmental problem for the release device at the Orbiter/ET forward attachment. Redundancy in the release system and separation without fragmentation are required for both systems.

CONFIGURATION DESCRIPTION

Orbiter/747 Separation

Figure 2 shows the Orbiter spacecraft attached to the 747 aircraft before release and figure 3 shows the combination just after separation. The one forward and the two aft structural attachments are represented in figure 4. At each attachment, a load cell measures the vertical and horizontal interface loads. To avoid the development of several different separation mechanisms for this very specialized test program, a single pyrotechnic bolt design (fig. 5) was selected for the three attachments. One separation bolt is used at the forward attachment and three bolts are used at each of the two aft attachments to carry the interface loads before separation. At each aft attachment, three electrical connectors carry pyrotechnic and communications wires and are designed to part immediately after structural release.

It should be noted that the separation bolt (fig. 5) fractures in tension at the separation plane - an ideal situation for the Orbiter/747 system. However, this device does not satisfy the stringent outer moldline smoothness criteria for entry from orbital flight, so a similar device, which fractures in shear internally, is being developed for that application.

Orbiter/ET Separation

Figure 6, illustrating the major components for separation of the Orbiter from the ET shows details of the forward and aft structural attachments. At the forward attachment, release is accomplished by the shear-type separation bolt previously mentioned. Figure 7 shows in detail the shear section of the bolt before and after separation. After the piston shears the bolt shank, it pushes the lower section of the shank free of the spherical bearing, and the bottom of the piston stops flush with the outer surface of the bearing.

At the two aft attachments, a frangible nut is used as the release device. Once the Orbiter is safely separated from the ET, doors close over the cavities left at the point of structural, feedline, and electrical umbilical attachments.

SEPARATION SYSTEM DEVELOPMENTAL PROBLEMS

Of the problems encountered during the development of the separation system, the following examples illustrate a variety of mechanical design problems and their solutions.

ALT Separation Bolt

The pyrotechnic-actuated separation bolt used for the ALT flights failed to separate during a functional test of a production bolt, just before the

start of qualification testing. This failure occurred after several successful development tests of nearly the same configuration. The functional failure occurred using one production cartridge in the lower chamber at a temperature of 219 K (-65° F). Several additional tests incorporating various changes were attempted before a successful separation was achieved with a modified bolt. The failure could not be definitely attributed to any specific inadequacy in design, construction, or material during these additional structural and functional tests. However, a series of cartridge tests indicated that output pressure was dependent on cartridge propellant loading pressures. In effect, the bolt was redesigned, resized, and underwent a new series of development tests. The principal modification consisted of reducing the fracture area to increase the ease of fracture, thereby reducing the structural margin. The pyrotechnic cartridge loading pressures were also modified to obtain more uniform chamber pressures. This particular hardware failure, which is discussed in more detail in reference 1, was never fully duplicated during the failure investigation. However, a combination of design changes and the additional developmental work resulted in the bolt successfully passing qualification tests and interface certification tests before the Orbiter/747 mated flight tests. This particular hardware problem illustrates a design compromise by decreasing the hardware structural margin to increase overall functional reliability.

ALT Aft Attachment Redesign

The original design concept for the Orbiter/747 aft attachments used linear-shaped charge explosive devices to sever the attachment structure at the separation plane (fig. 8(a)) to satisfy the design requirement for possible lateral motion at release.

Two additional concepts are illustrated in figures 8(b) and 8(c). These concepts involve the use of frangible nuts like that used at the Orbiter/ET aft structural attachments (fig. 6). Although these concepts did incorporate a pyrotechnic device already under development, neither concept provided the degree of horizontal motion at release as that in the final design. Both concepts were undesirable in that bolt withdrawal was required for a clean separation and a momentary hangup could occur. However, because of the massive structure involved at the aft attachment to satisfy the Orbiter/747 load requirements and because of the additional pyrotechnic device that would have to be developed for this concept, it was decided that a separation concept using the existing separation bolt design was desirable and would be cost-effective. The baseline design that resulted (fig. 4) incorporates three separation bolts at each aft attachment. These bolts react the tensile loads at the interface, and a shear surface approximately 1.3 cm (0.5 in.) deep reacts the forward and side loads. It was judged that this shear surface would not significantly affect the vehicle dynamics at release. Interface certification tests and flight tests have confirmed this to be the case. This design was a logical approach to satisfy the design requirements as well as to minimize the development of pyrotechnic devices.

Orbiter Outer Moldline Criteria

For the Orbiter/ET forward structural attachment, a stringent design requirement exists to maintain a smooth outer surface after separation to minimize the aerodynamic heating on the lower surface of the Orbiter during entry. The aerothermal requirement is a maximum step of ± 0.043 cm (± 0.017 in.) and a gap no greater than 0.089 cm (0.035 in.). Many developmental approaches have been considered, including various combinations of release devices, close-out mechanisms, and doors.

Early design concepts for the Orbiter/ET structural attachments used electrical/mechanical release devices (fig. 9). These devices were soon discarded in favor of pyrotechnic-actuated release devices because of the positive structural attachment before release and the highly reliable pyrotechnic function at release. A preliminary design goal during the early phases of the Space Shuttle Program was to use completely reusable separation devices (primarily because of the Orbiter's quick-turnaround requirement) rather than pyrotechnic devices that had to be replaced after each flight. Figure 10 shows the initial pyrotechnic devices chosen for the forward attachment. Because of the smoothness requirement for the outer moldline, the reusable devices were soon replaced by the pyrotechnic separation bolt design.

The tension-type separation bolt was originally intended for this application; however, because the fracture plane was not within the aerothermal requirement and because of increased loads at this attachment, the shear-type separation bolt (fig. 7) was adopted. The shear bolt has the advantage of an internal fracture surface and a slight disadvantage in that the sheared bolt shank must be ejected from the monoball fitting for separation to be complete. It should be noted that the shear bolt has one pressure chamber with two pyrotechnic cartridges to satisfy the Space Shuttle redundancy requirements. This developmental problem illustrates a very difficult detail design challenge because of a combination of specific design requirements.

FLIGHT PERFORMANCE RESULTS

Before the first flight of the Orbiter/747 combination, the structural adequacy and functional operation of the separation system were demonstrated by analysis and by extensive ground tests. To date, the ALT separation system has been used for five Orbiter free flight tests and it has also served as an emergency system for Orbiter jettison on mated flight tests, both manned and unmanned. The ALT system operated successfully during the first free flight test on August 12, 1977, and has performed well during all other flight tests. In all tests, the pyrotechnics have functioned and the bolts have broken cleanly. The Orbiter and 747 crews have reported only a moderate "thump" as the bolts have separated. In all cases, onboard and chase plane photography have verified a normal release and separation.

After each flight test, the separation interfaces were thoroughly inspected during buildup of hardware for the next flight. Only minor problems associated with the pyrotechnic and umbilical electrical connectors were encountered. Because pyrotechnic connectors have a tendency to gall at the initiator interface (presumably because of pyrotechnic shock), they have had to be replaced periodically. These connectors were lockwired to the initiator bodies during the later flights to preclude any possibility of the connectors becoming disengaged.

The load measurement system functioned well during flight tests. Before the free flight tests, the system provided data to verify loads and aerodynamic predictions. During the free flight tests, the system provided backup data to verify the Orbiter/747 separation conditions for Orbiter launch.

CONCLUDING REMARKS

The approach and landing test phase of the Space Shuttle Orbiter flight test program has been successfully concluded. The developmental problems have been solved in a variety of ways without compromising the operational capabilities of the vehicle. A significant amount of testing and analysis remains to be accomplished before the actual orbital flight separation system is operational. However, developmental testing has already confirmed the adequacy of the basic design approach for these separation devices. For orbital flight separation, other types of pyrotechnic devices could be used and may be adopted in the future. Changes may occur to increase the Orbiter operational capabilities, to reduce operational costs by using refurbishable components, or to minimize the pyrotechnic mechanical shock by devices that operate at lower energy levels.

REFERENCE

1. Ritchie, Robert S.: Space Shuttle Orbiter Separation Bolts. Paper presented at the 12th Aerospace Mechanisms Symposium, April 27-28, 1978.

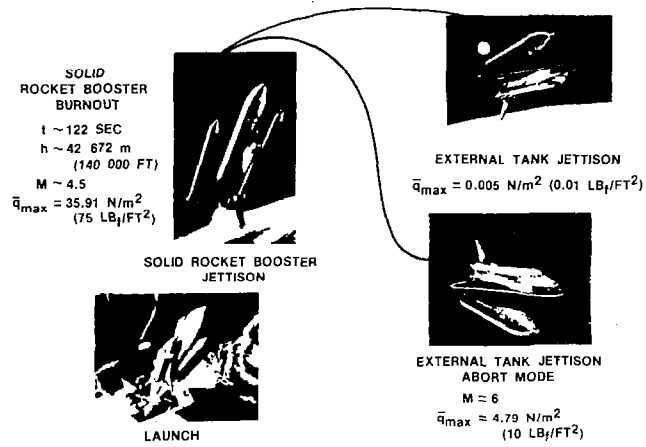


Figure 1. - Orbital flight separation mission profile.



Figure 2 - Orbiter/747 configuration before release

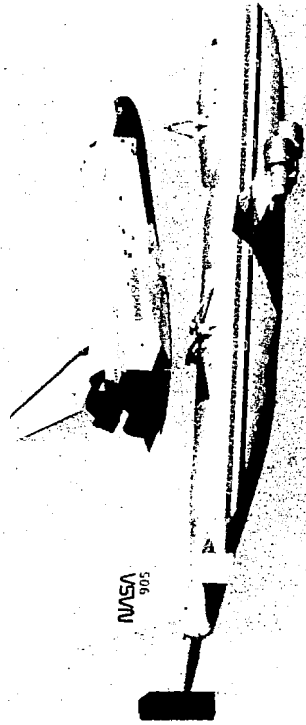


Figure 3a - View of the Orbiter/747 after release

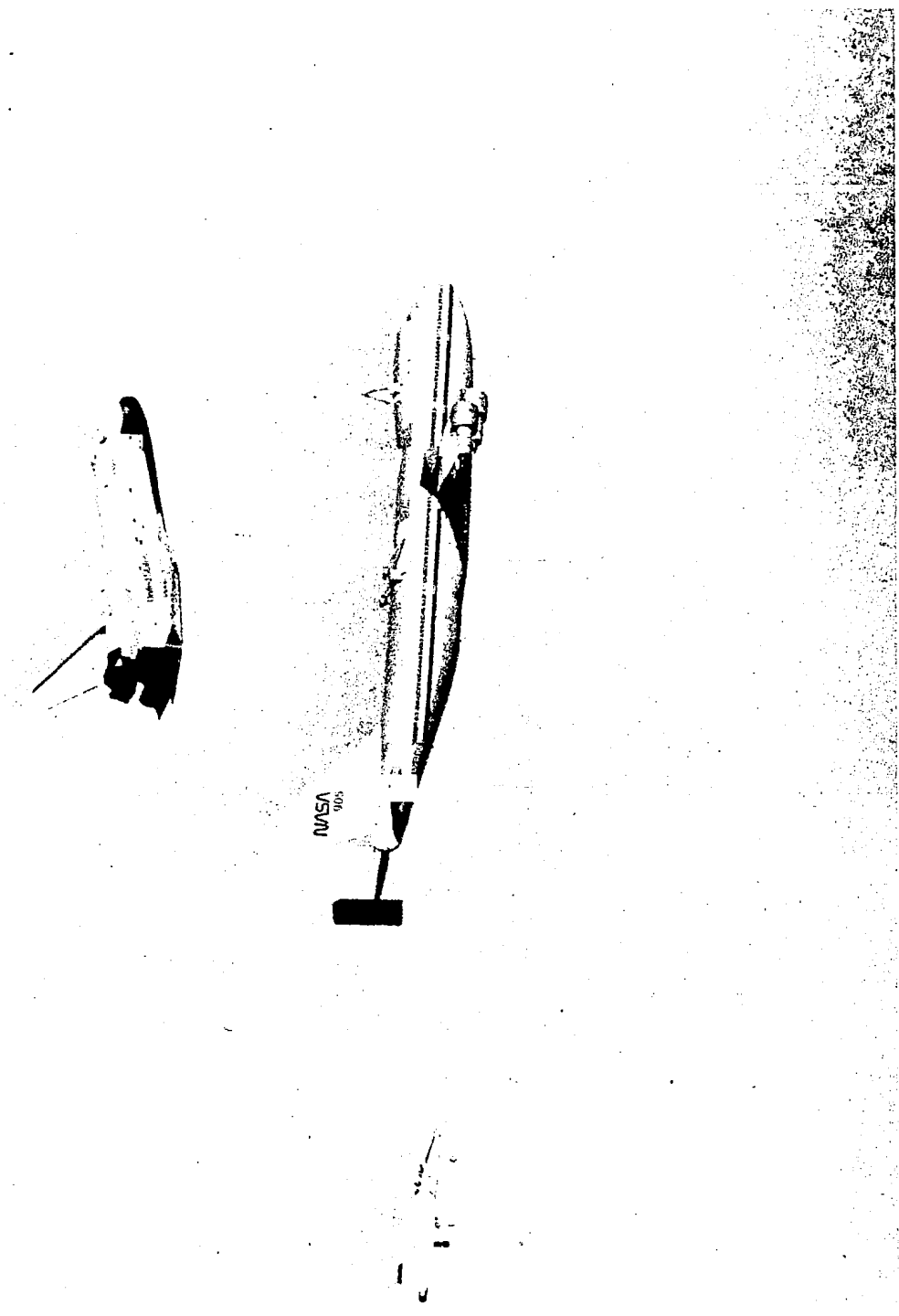


Figure 3b - View of the Orbiter/747 after release

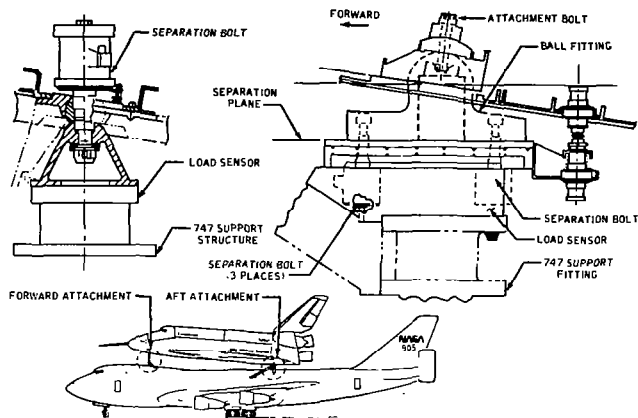


Figure 4 - Orbiter/747 separation system

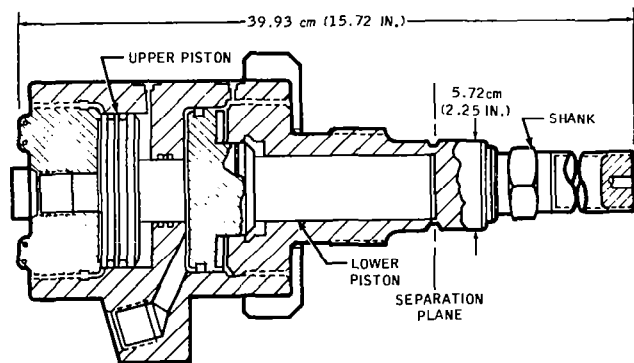


Figure 5 - Orbiter/747 separation bolts

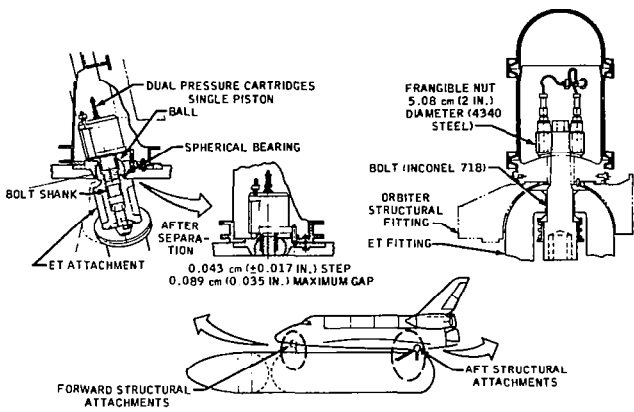


Figure 6.- Orbiter/ET separation system.

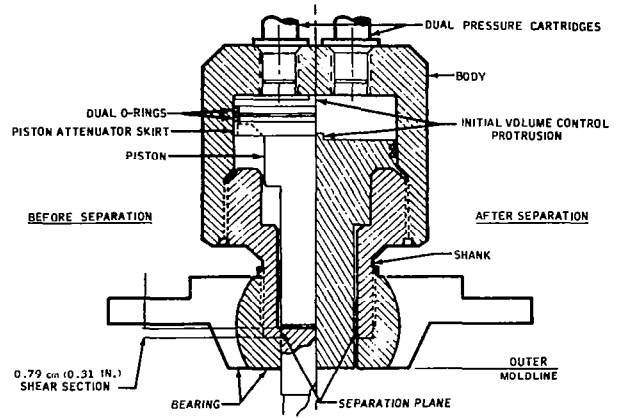
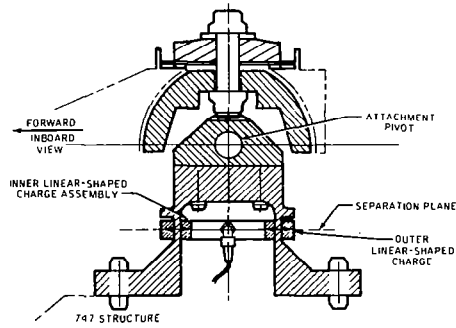
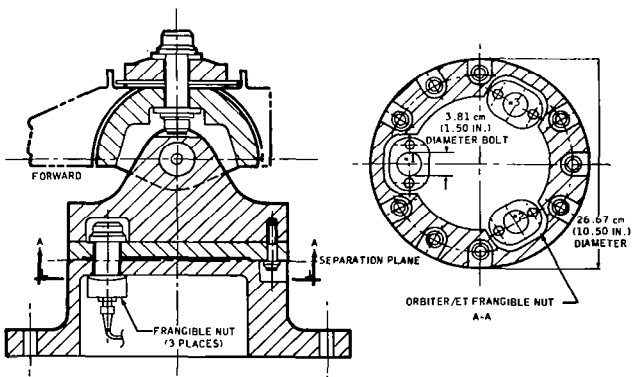


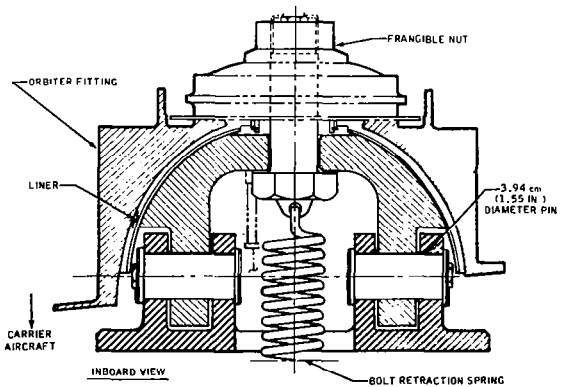
Figure 7.- Shear flange separation bolt.



(a) Linear-shaped charge separation device.



(b) Multiple frangible nut configuration.



(c) Single frangible nut configuration

Figure 8.- ALT aft attachment.

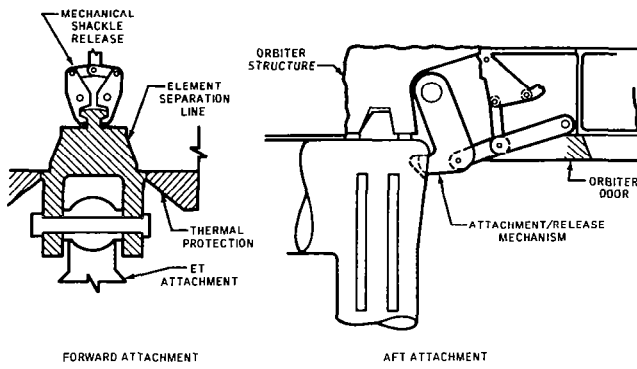


Figure 9.- Orbiter/ET structural attachments (ET request for proposal configuration).

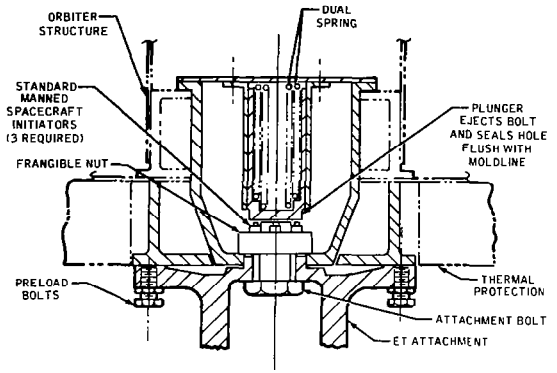


Figure 10.- Orbiter/ET forward attachment (frangible nut configuration).