THE DEVELOPMENT OF STAGING MECHANISMS
FOR THE JAPANESE SATELLITE LAUNCHER MU-3SII

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ABSTRACT

This paper describes the staging mechanisms of the Japanese satellite launch vehicle Mu-3SII involving a unique separation and jettison mechanism for the nose-fairing. The design requirements, the design features and the development problems are presented in this paper together with their solutions.

INTRODUCTION

The Institute of Space and Astronautical Science has developed a solid propellant launch vehicle, the Mu vehicle, for scientific satellites, and has successfully launched 9 scientific satellites and 4 test satellites. A next-generation version, the Mu-3SII, 27.8 m in total length, 1.65 m in maximum diameter and 61 metric tons in total weight, is now in the final stage of development. The development of the staging mechanisms has almost been completed. In this paper, the staging mechanisms of the vehicle are described, stressing the unique separation and jettison system of the nose-fairing and strap-on boosters.

SEPARATION AND JETTISON SYSTEM FOR THE NOSE-FAIRING

The nose-fairing of the Mu-3SII launch vehicle protects the payload, the 3rd stage rocket motor and the optional kick-motor (or 4th stage motor, if it is required for a specific mission), and maintains the desirable aerodynamic configuration during the ascent phase through the atmosphere. The fairing, a hemisphere-cone-cylinder-cone (hammer-head) configuration as shown in Fig. 1, is 6.85 m long and 1.65 m in diameter. The main part of the fairing structure is made of Fiber Reinforced Plastic (FRP) honeycomb sandwich with Graphite Fiber Reinforced Plastic (GFRP) facing covered with a layer for heat protection. The total weight of the fairing involving the separation and jettisoning system is 480 kg.

Requirements

1) The fairing must be capable of jettison without collision, contamination or debris in either a 2nd-stage 5 G acceleration phase with 60 Pa. dynamic pressure or a coasting phase after the burn-out of the 2nd motor.

2) The disturbance caused by the separation and jettison must be less than the counteracting capacity of the actuator of the 2nd stage attitude control system.

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3) The fairing structure and the clamp/release mechanism must withstand a loading corresponding to a 4 deg attack-angle with a 0.15 MPa dynamic pressure and a Mach number of 2.6.

4) A payload envelope of 1.4 m diameter must be assured during the ascent phase and separation/jettison phase.

5) The system must function with high reliability.

Selection of the Mechanisms

During the selection of the clamp/release and jettison mechanism for the fairing, the following guidelines were formulated in order to attain high reliability, rigidity and strength for the total fairing system.

1) The halves of the fairing should be clamped to each other continuously or at many points along the split lines.

2) The clamp mechanisms between the halves and between the fairing and the 2nd stage should be released by ignition of a minimum number of pyro initiators.

3) The jettison system should be of the clamshell type.

According to the above-mentioned guidelines, the separation and jettison mechanisms described below were selected. A latch mechanism using balls was also considered. However it was not adopted because of its complexity.

Technical Description

1) The Clamp/Release Mechanism Between the Halves of the Fairing

This mechanism is shown in Fig. 2. The halves of the fairing are provided with many protrusions with wedge-shaped cross sections along the split lines. Figure 2(a) shows the mechanism in the clamped state, where each pair of protrusions are clamped by a clamp-block. The clamp-blocks are linerally linked along the split line, and the bottom end of the train of linked clamp-blocks is retained by the marman bands at the bottom of the fairing. Figure 3 shows the detail of the bottom end of the train. The clamp mechanism can be released by freeing the train of linked clamp-blocks and pulling up the train to the release position. Figure 2(b) shows the released mechanism.

2) The Marman Clamp Between the Fairing and the top ring of the 2nd Stage

The end of the marman clamp bands are fastened to each other by bolts and separation-nuts at the end-blocks. As can be seen in Fig. 5, the marman clamp also retains the train of clamp-blocks by holding the end-ball of the train in the socket between the two end-blocks of the marman band. The marman clamp can be released by the action of the separation-nuts. Each fastening of the marman band is carried out by two separation-nuts, and the action of any one of them can release both the marman clamp and the restriction of the chain of clamp-blocks, providing the system with redundancy.

3) Double-Action Pyro Actuator

The double-action actuator at the top of the nose fairing is shown in Fig. 4. The actuator consists of: two squibs, a gas-generator, piston-A with arms for pulling up the trains of the linked clamp-blocks, piston-B, and two cylinders as shown in the figure. The system has two squibs for the ignition of the gas-generator in order to provide the system with redundancy. The action of piston-A pulls up the freed trains of the linked clamp-blocks to the release position. The port to cylinder-B, which was closed before the action of piston-A, is opened by this action. Piston-B is restrained by the shear-pins until the pressure in cylinder-B increases to 5 MPa. so that piston-B pushes away the other half of the fairing, providing the halves of the fairing with sufficient velocity after the cutting of the shear-pins.

4) Separation-Nut

The above-mentioned separation-nut consists of a nut split into 3 pieces, a nut housing, a piston and a cartridge. Before the release action, the 3 pieces of the split nut are retained in the housing and compose a normal nut. When the cartridge is ignited, the nut-housing is pushed away by the gas-pressure and the pieces of the split nut scatter, releasing the fastening.

The Release and Jettison Sequence

The sequence of events during fairing separation is as follows:

1) Simultaneous ignition of all the squibs of the separation-nuts and the gas-generator by means of an electric current.

2) Within 10 msec, the release action of the separation-nuts followed by release of the marman clamp and the train end-balls of the linked clamp-blocks.

3) Within 30 msec, action of piston-A of the actuator, which pulls up the trains of the linked clamp-blocks to the release position through the levers. After this action, the two halves of the fairing are fastened to each other only by the shear-pin at the top of the fairing. The gas-inlet port to the cyliner-B is opened by this action.

4) Approximately 300 msec - 400 msec after the ignition of the squi , action of piston-B of the actuator, which pushes one of the halves of the fairing away from the other, providing them with necessary separation velocity. This action starts when the pressure inside the cylinder increases sufficiently to enable the shear-pins to be cut.

Development Problems

1) Actuator

During the beginning phase of the development, spring actuators were used to pull up the trains of the linked clamp-blocks and to push away the halves of the fairing with sufficient separation velocity. However, it was found

that a relatively large force was occasionally necessary in order to pull up
the train of linked clamp-blocks. This occurred because of the spring force
of the actuator, which always acts so that the halves separate from each
other, and because of the variation of the friction coefficient between the
protrusions along the split lines and the clamp-blocks. It proved difficult
for the light weight spring actuator to provide the halves with sufficient
initial velocity. Therefore, a powerful double-action actuator with a
gas-generator was adopted, in spite of the increase of the number of squibs.

2) Initial Separation Velocity of the Halves

As can be seen in Fig. 5, the centers of gravity of the halves move up
slightly before the halves fall outward and downward during the jettisoning
process. Therefore, the halves must be provided with sufficient velocity to
climb this "hill" of potential energy in the acceleration phase of 5 G. It
was found from ground tests that the force produced by the pyro actuator does
not provide the halves with tanslational velocity efficiently because of the
elastic deformation of the halves caused by the actuator force. This problem
was overcome by an increase in the operational pressure of the actuator and an
increase in the stroke length of piston-B.

3) Deformation of the Fairing

The main structure of the unseparated fairing deforms under external
ascent loads. The trains of the linked clamp-blocks must follow this
deformation. As a result, the trains are sometimes subjected to a relatively
large load. The load on the trains is especially high in the bottom area,
where the deformation of the main structure is large, because of the high
bending load and because of the tapered configuration in this area. This
problem has been overcome by reinforcing the main structure and by introducing
buffer devices with preloaded springs as shown in Fig. 3, which permit some
deformation.

Tests

1) Functional test

During the process of developing the fairing, separation and jettison
tests were performed 8 times. The last 4 tests were qualification tests
utilizing the final configuration.

All the separation and jettison tests were carried out under ground
conditions. The performance under flight conditions during both the
acceleration phase and the coasting phase -- was estimated by means of
analytical simulation based on the measured data of the ground tests. The
effects of air, especially the negative pressure inside the fairing caused by
the separation action, was conspicuous, although the test adapter was provided
with relatively large holes. The effect of elastic deformation on the initial
separation velocity of the halves was also significant. All these effects
were taken into account, based on the measured pressure inside the fairing and
the measured vibration. The results of the numerical simulation indicated
normal functional performance in both the acceleration phase and the coasting
phase.

2) Load Test

The fairing was subjected to a load equivalent to an attack angle of 4 deg with dynamic pressure of 0.15 MPa. The maximum bending moment at the bottom end of the fairing was 0.32 MN-m. The main structure was fractured by 98 percent of the above-mentioned load in the third test, after twice withstanding the 100 percent load.

THE SEPARATION AND JETTISON MECHANISM OF THE STRAP-On BOOSTER

The first-stage rocket motor of the Mu-3SII vehicle is accompanied by two strap-on boosters which must be jettisoned after burn-out. The boosters are 9.1 m long and 0.735 m in nominal diameter. A strap-on booster weights 5.1 metric tons before ignition and 1.1 tons after burn-out.

Requirements

1) The joint between the strap-on booster and the core motor must withstand the longitudinal load caused by the 0.35 MN thrust of each strap-on booster and the lateral inertial force due to the lateral bending vibration of the vehicle.

2) The sub-boosters must be separated from the core motor and must be jettisoned without collision, excessive shock or disturbance on the core motor. The acceleration just before the separation is nominally 3.8G. The nominal dynamic pressure at that time is 95 KPa. with a Mach number of 3.2 and a roll rate of less than 0.3 rps.

In the selection of the separation and jettison mechanism, the following guidelines were adhered to:

1) The separation mechanism should be designed and adjusted to provide the strap-on boosters with both the initial attitude and the initial translational and angular velocity for a collison-free jettison action.

2) Separation and jettison should be perfumed with a minimum number of pyro initiators.

Following the above guidelines, the separation and jettison mechanism shown in Fig. 6 was selected. A feature of this mechanism is that the front and rear braces push the strap-on boosters away from the core-motor when the boosters travel rearward, and therefore the initial attitude and velocity of boosters can be easily adjusted by selection of the length of the braces and their attach points.

The trajectories of the strap-on boosters after the separation were numerically calculated taking account of the aerodynamic force and the effect of the plume of the core-motor exhaust jet. This analysis was used to determine the attach points and lengths of the braces. No assist-rocket-motors for separation were adopted because of the possibility of damaging the core motor casing and because of the increase in the required number of pyro initiators.

Technical Description

Figure 6 shows the separation and jettison mechanism for the strap-on boosters. Figure 6(a) shows the mechanism before the separation. The thrusts of the strap-on boosters are carried to the core motor mainly by the thrust-tubes. The bottom part of each booster is supported by the thrust-tubes, rear braces and a rear attach-fitting. The top part of each booster is supported by the front attach-fitting, which restricts the relative movement of the booster in the radial and circumferential directions, and the stabilizers, which restrict the rotation of the booster around the front attach-fitting. The front brace can be shortene telescopically and is preloaded by a compression-spring installed inside. Therefore, the relative movement in the axial direction is not restricted at this station.

Separation and jettison is initiated by action of the separation-nuts installed in the thrust-tubes, disconnecting the tubes. Subsequently, the strap-on boosters are pushed rearward by the aerodynamic drag and the inertial force due to the acceleration caused by the thrust of core motor. As a result, the front portion of the booster moves axially rearward and the front braces are shortened. After a certain amount of rearward travel of the top part of the booster, the front attach-fitting is freed and subsequently the front braces push the booster away from the core-motor when the braces have been shortened to the limit. The rear portion of the booster is pushed away from the core motor by the rear braces from the beginning of the jettison action. After a certain amount of rotation of the braces, the compressive loads on the braces decrease, and finally the braces are pulled away from the core-motor as shown in Fig. 6(b). The rear braces are fixed to both the core-motor and the booster in the state shown in Fig. 6(a), and can carry both tensile and compressive loads. However, the core-motor-side ends of the rear braces are freed by a certain amount of rotation of rear-braces. Therefore, the braces, stabilizers and most of the thrust-tubes are jettisoned, together with the boosters, as shown in Fig. 6(b).

A Development Problem

As has been mentioned, the front-braces are shortened in the initial phase of separation. After a certain amount of shortening, they impact the stroke-ends and they begin to function as rigid rods. As a result of these impacts, the braces and the adjacent structure are subjected to a shock load. It is difficult to use powerful buffers to reduce the shock, not only because the space for installation is limited, but also because too powerful buffers may prevent the braces from being shortened to the expected length when conditions, such as thrust and dynamic pressure, vary, and may in the worst case result in a failure of the release of the front attach-fitting. Therefore, a certain level of shock is unavoidable in the separation action.

The estimation of the shock level during the early phase of design was somewhat difficult because the shock level depends on the effective flexibility of the structures, which is sometimes governed not only by the longitudinal stiffness of the braces but also by the local dynamic deformations of the joint structures, core-motor and boosters. The shock load was estimated by a law of similarity based on the results of sub-scale

(1/2-scale) ground tests as well as the numerical simulation in the final step
of development based on the measured stiffness data of prototype structural
components.

Tests

As a first step in the development tests, the 1 2-scale ground tests were
carried out seven times. Three of them were in the zero-spin condition and
the others were with a spin of 0.5 rps. The functional performance was
confirmed and the loads during separation were measured.

In order to confirm the functional performance, loads at separation and
the motion of the strap-on boosters subsequent to the separation in nearly
actual conditions, a separation test was carried out under flight conditions
with an approximately 1/2-scale vehicle. It was observed by means of an
on-board TV camera, ground telescope cameras and telemetry data, that the
separation action and the subsequent motion of the boosters were normal.

Full-scale structural components were subjected to a load of 100 to 150
percent of the design load and it was confirmed that they withstood the
loads. No separation tests using the full-scale mechanism have been performed.

INTER-STAGE SEPARATION SYSTEMS

The Mu-3SII-1, the first vehicle of the Mu-3SII series, has four
interstage joints as listed in Table 1, because an optional kick-motor has
been installed for an interplanetary mission. However a detailed description
of the joint between the kick motor and the payloads is omitted in this paper
because it is an ordinary marman clamp joint.

The Interstage Separation System Between the 1st and 2nd Stages

The interstage structure between the 1st and 2nd stages joins the Y-rings
of the motor casings of each stage. The nozzle of the 2nd stage rocket motor,
thrust vector control equipment, side-jet equipment and hemispherical
end-plates of the motor casings are installed inside the interstage joint.
Therefore, an open-petal joint was adopted as shown in Fig. 7, because of the
large diameter of the nozzle of the 2nd stage installed in the joint, and to
reduce the inert mass of the joint to be left on the 2nd stage after the
separation. A truss structure was selected for the joint, which has the
advantage of ease of access to the equipment installed around the nozzle. As
can be seen in Fig. 7(a), in the clamped state the top nodes of the triangular
trusses are fastened to the upper-stage structure directly by bolts and
separation-nuts. Two separation-nuts are used for each fastening point, and
action of any one of them releases the fastening, providing redundancy. This
system is used because the load on the joint was estimated to be relatively
large. Figure 7(b) shows the joint in released state. The relative velocity
of 0.8 m/s is provided by 12 separation springs installed at the fastening
points. The petals of truss are opened by the torsion spring installed at the
hinges.

Functional separation tests were carried out under ground conditions by using a full-scale proto-model, and normal functioning was confirmed. The load tests were also carried out wqith a maximum combined load of 1.3 GN-m bending, 0.99 GN compression and 0.27 GN shear. The equivalent bending stiffness of the joint was measured in the static load test as shown in Table 1.

The Inter-Stage Separation System Between the 2nd and 3rd Stages

An open-petal joint was also selecteo for the 2nd and 3rd inter-stage joint for the same reasons as mentioned above. However, as can be seen in Fig. 8, a marman clamp is used instead of the direct fastening by separation-nuts, for the following reasons.

1) The 3rd stage motor casing is nearly spherical. Therefore, it is not provided with a Y-ring. Furthermore, the thickness of the titanium casing is very small (2.5 mm). As a result, a concentrated load on the 3rd motor casing is not permissible.

2) The inert mass of the 3rd stage should be decreased as much as possible.

3) The load on the joint is not as great as it is on the above-mentioned joint.

As can be seen in Fig. 8 (b), only the V-ring of the marman clamp is left in the 3rd stage as the inert mass of the joint. The relative separation velocity of 0.9m/s is provided by separation springs. The petals are opened by the torsion springs at the hinge and the centrifugal force due to the spin of 2rps.

Separation tests were carried out on a spin table under a 2rps spin. Normal function was confirmed. It has been estimated from the observed motion of the upper stage that the disturbance due to the separation action causes only 0.4 deg. nutation of the 3rd stage of the actual vehicle in the worst case. It has also been confirmed that the joint withstands up to a maximum combined load of 0.53GN-m bending, 0.24GN compression and 0.23GN shear.

The Inter-Stage Separation Systems Between the 3rd Motor and the Kick-Motor

As shown in Fig. 9 and Table 1, an ordinary marman-clamp joint with a lightweight, lattice, cylindrical structure made of carbon fiber reinforced plastic was selected for the inter-stage separation system between the 3rd motor and kick-motor. This system was selected in order to decrease the inert mass of the upper stages. This joint is not an open-petal-type. However, it was confirmed that a collision-free separation can be performed based on the measured data of the dynamic unbalance of the 3rd motor after static firing tests, and the estimated unbalance of the 3rd motor after static firing tests, and the estimated inevitable unbalance of the upper stage as well as the measured motion at the separation ground test.

CONCLUDING REMARKS

Staging systems for the Mu-3SII satellite launcher, including the unique separation and jettison systems for the strap-on boosters and nose-fairing, have been developed. Normal performance of the sytems is expected based on functional tests, load tests and numerical simultions utilizing test data, and will be confirmed in the first launch of the vehicle in January 1985.

ACKNOWLEDGMENTS

Table 1   INTER-STAGE JOINTS FOR Mu-3SII-1

Location	1st and 2nd	2nd and 3rd	3rd and KM[a]	KM and PL[b]
Length	2.0 m	1.36 m	0.86 m	0.17 m
Maximum Diameter	1.65 m	1.42 m	0.82 m	0.50 m
Type	Open-Petal Direct Fastening by Separation Nuts	Open-Petal, Merman Clamp	Marman Clamp	Marman Clamp
Structure	Truss	Truss and Panel	Lattice made of CFRP	Cylindrical Shell
Equivalent Bending Stiffness	$3 \times 10^8 \text{Nm}^2$	$8 \times 10^7 \text{Nm}^2$	$6 \times 10^6 \text{Nm}^2$	$1 \times 10^6 \text{Nm}^2$
Relative Separation Velocity	0.8 m/s	0.9 m/s	2.1 m/s	2.2 m/s

(a) KM = Kick Motor,
(b) PL = Payload
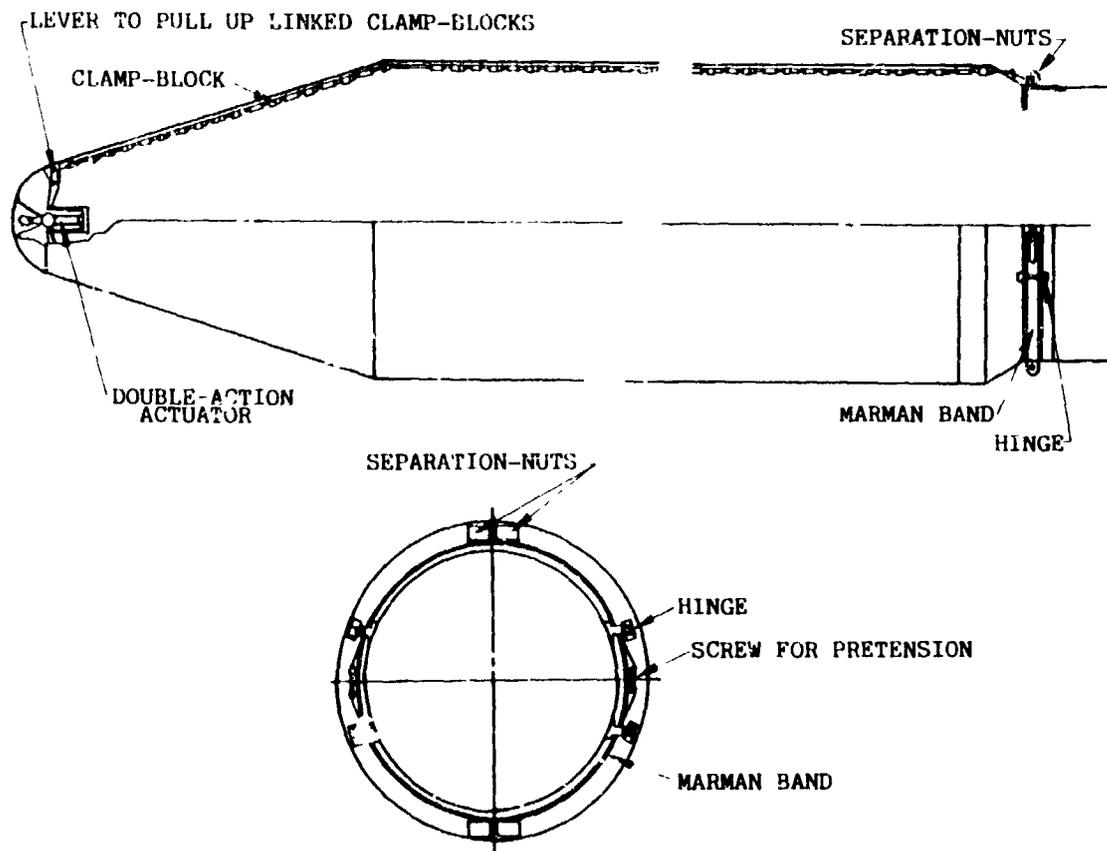
Figure 1. Nose-Fairing Separation and Jettison System

(a) CLAMPED STATE

(b) RELEASED STATE
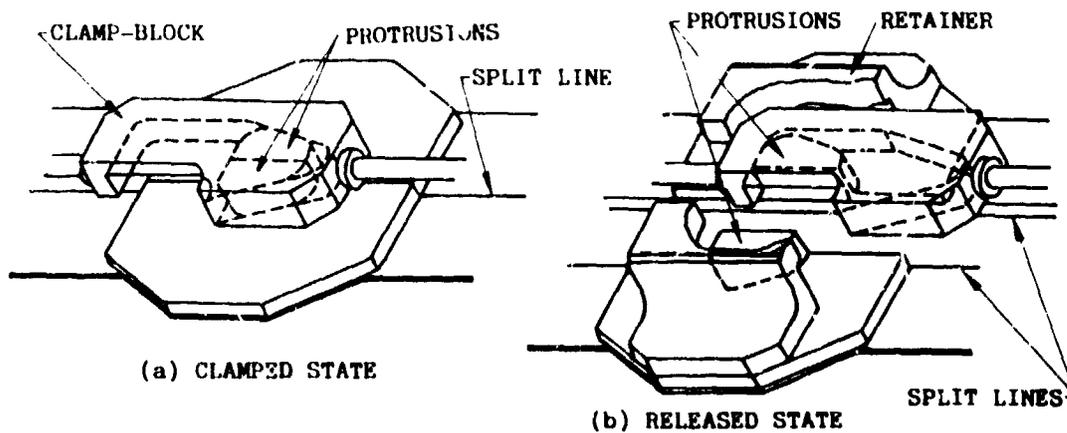
Figure 2. Clamp Mechanism Along Split Line
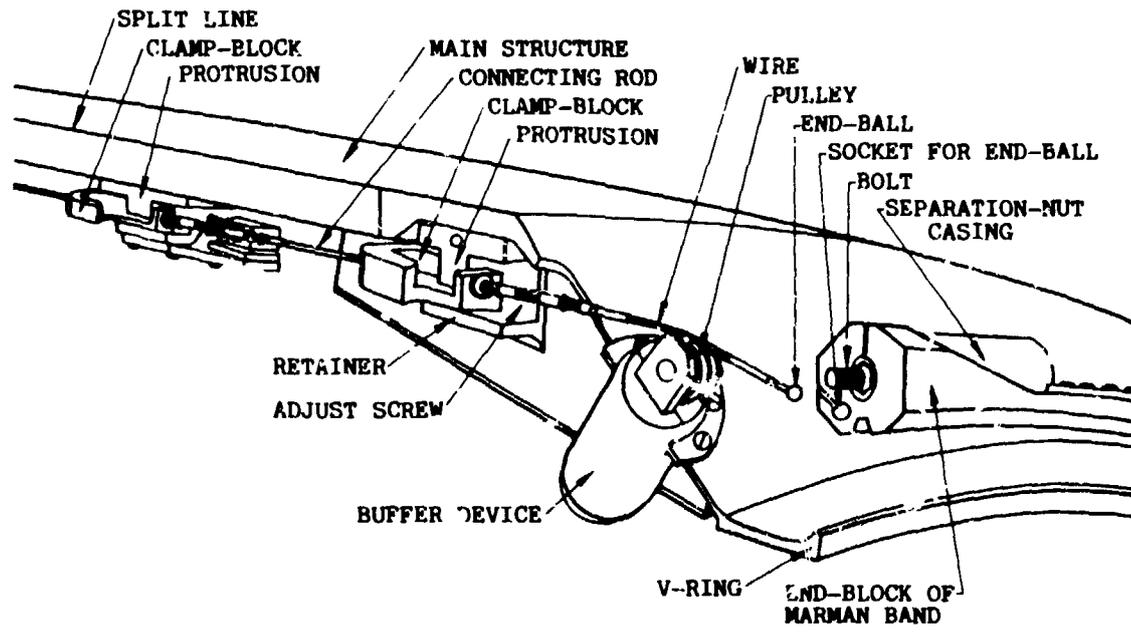
Figure 3. Detail of Bottom End of Split Fairing
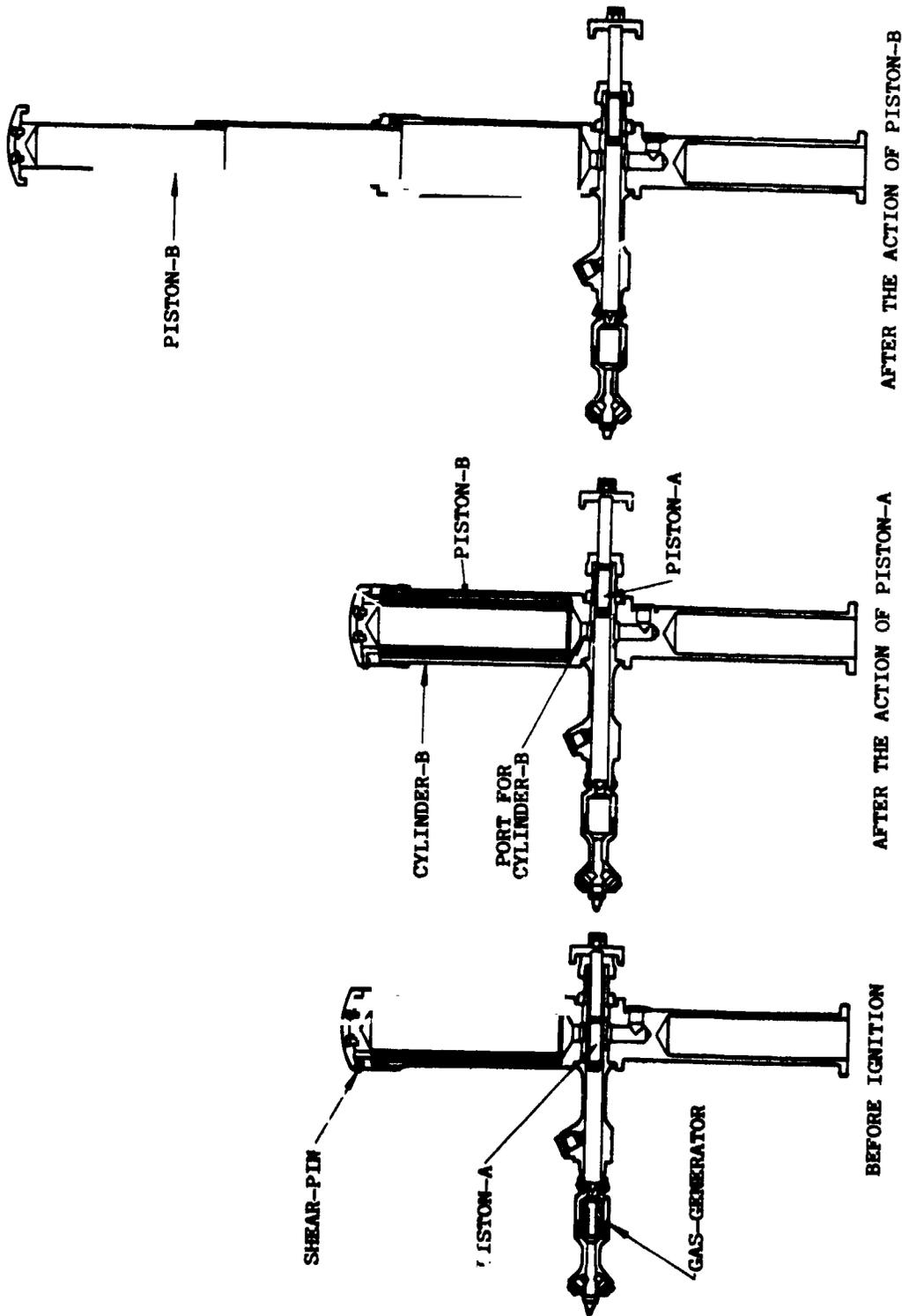
Figure 4. Double-Action Pyro Actuator

C - 4
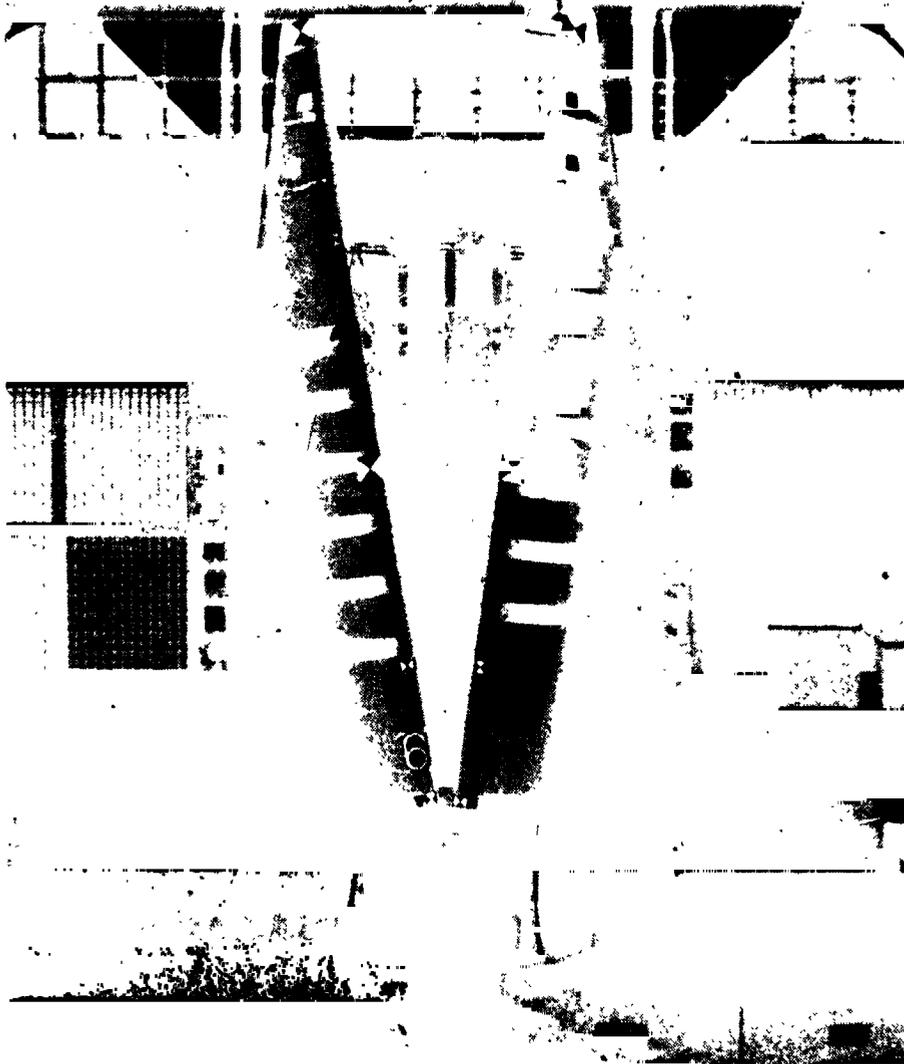
Figure 5. Nose-Fairing Separation and Jettison Test

FRONT
BRACE

STABILIZER

FRONT
ATTACH-FITTING

REAR
BRACE

THRUST-TUBE

REAR
ATTACH-FITTING

STRAP-ON BOOSTER

FRONT BRACE

STABILIZER

SEPARATION-NUTS

THRUST-TUBE

REAR ATTACH-FITTING

REAR BRACE
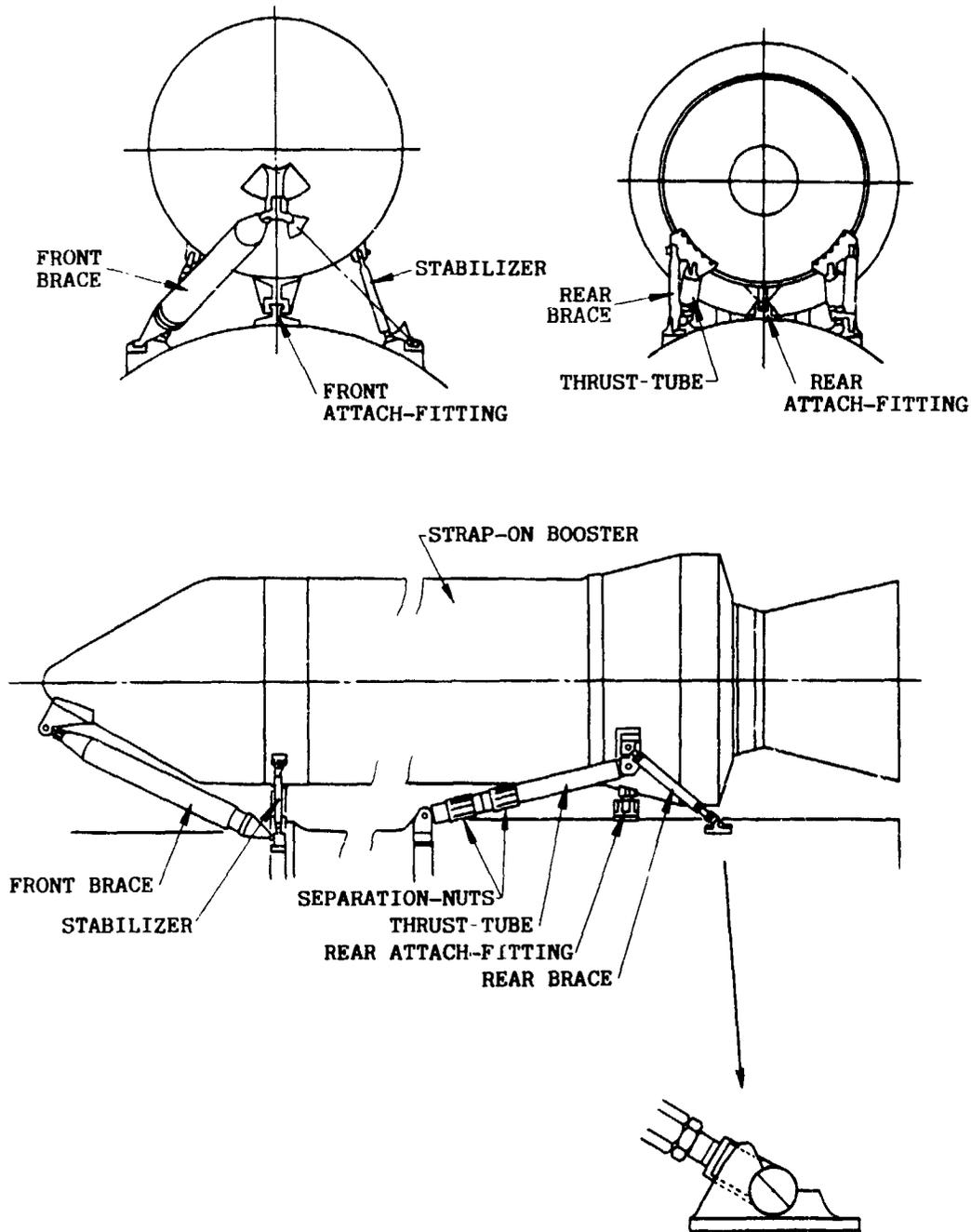
Figure 6 (a) Strap-on Booster Separation and Jettison System
(Before Separation)

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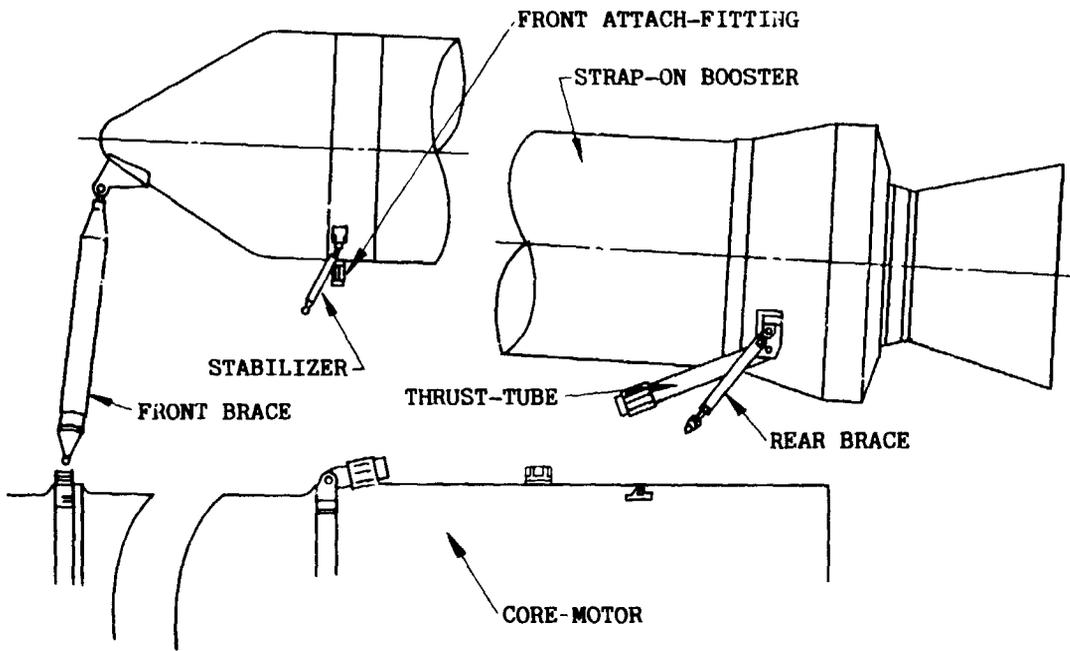
Figure 6 (b). Strap-on Booster Separation System
(After Separation)

-NOZZLE OF 2ND MOTOR

1ST STAGE-

SEPARATION SPRING-
, HINGE

-2ND STAGE
-TRUSS
SEPARATION-NUTS
`TORSION SPRING

(a) Before Separation

,SEPARATION SPRING

,TRUSS

1ST STAGE-
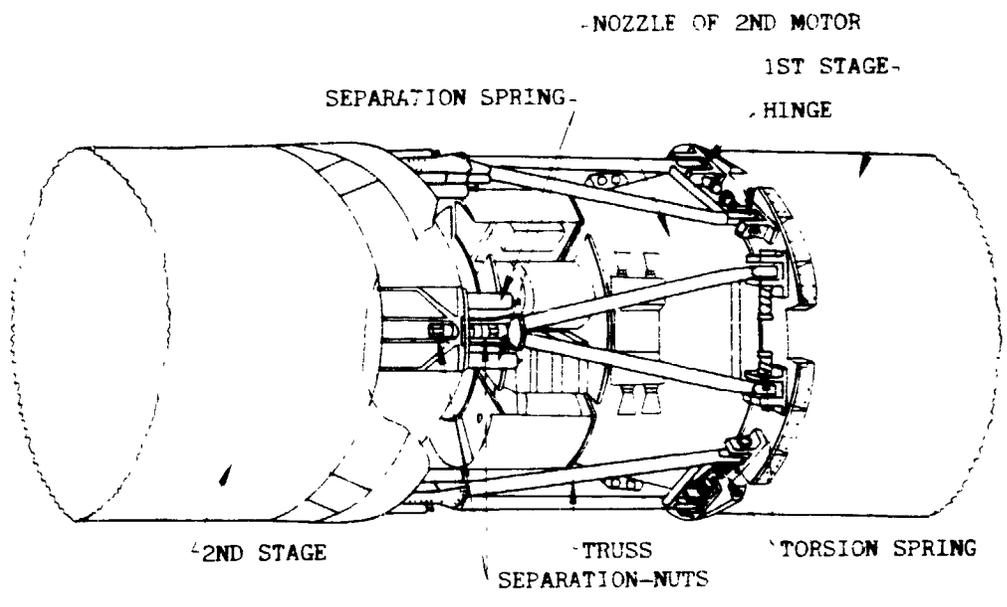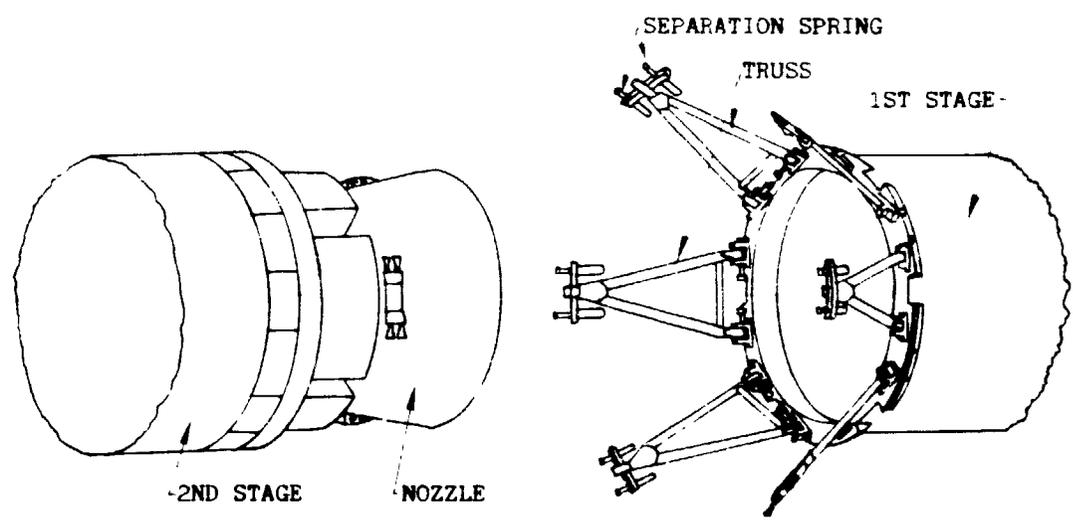
-2ND STAGE
-NOZZLE

(b) After Separation

Figure 7. Inter-Stage Joint Between 1st and 2nd Stages

Figure 8.
Inter-Stage Joint
Between 2nd and 3rd stages

NOZZLE OF 3RD MOTOR
SEPARATION-NUTS
TRUSS
HINGE
2ND STAGE

3RD STAGE
MARMAN BAND

(a) Before Separation

MARMAN BAND
2ND STAGE

3RD STAGE
TRUSS
MARMAN BAND

(b) After Separation
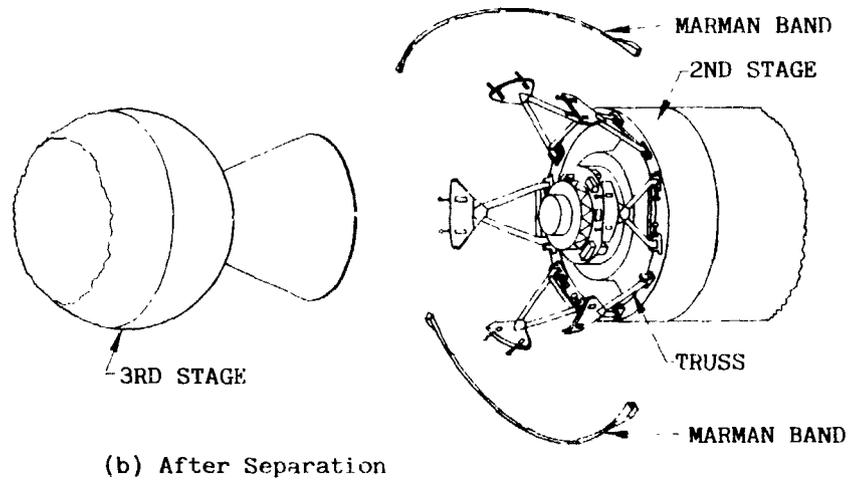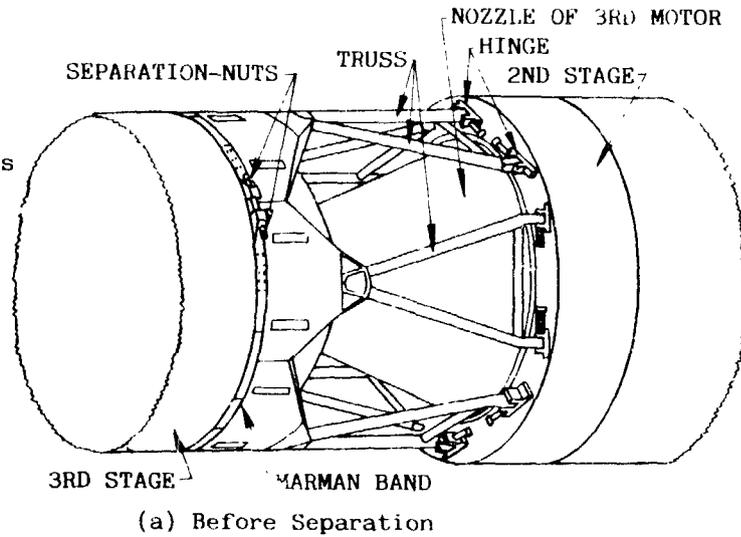
Figure 9.
Inter-Stage Joint Between
Kick Motor and 3rd Stages

SEPARATION-NUTS
SPRING

MARMAN BAND
KICK-MOTOR
3RD STAGE