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SEPARATION AND STAGING MECHANISMS FOR
THE INDIAN SLV-3 LAUNCH VEHICLE

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ABSTRACT

This paper describes a unique separation and jettison system for the ascent fairing and a staging system for the apogee motor of the first Indian satellite launch vehicle. Design features, development problems, and mission constraints are discussed in addition to the solutions adopted. A qualification summary is included for each system, and flight results obtained from SLV-3 launches are described.

I. SEPARATION AND JETTISON SYSTEM FOR THE ASCENT FAIRING

INTRODUCTION

The Indian satellite launch vehicle (SLV-3) is a four-stage, solid-propellant space vehicle capable of putting a 50 to 60 kg payload in low-Earth orbit. The ascent fairing, protecting the payload and its apogee motor, must be separated and jettisoned from the vehicle at an altitude of 90 to 100 km during the coasting phase of stage 2. The fairing, a hemisphere-cone-cylinder configuration, is 2.45-m (96-in) long and 0.8 m (31.5 in) in diameter. The material is a phenol-glass honeycomb sandwich of 14.5-mm (0.57-in) thickness.

The separation and lateral jettison system for the fairing is a cold-gas-actuated, hydropneumatic system. The principal components are: four latch modules, two nitrogen gas bottles, high pressure lines, check valves, and tube fittings. A groove joint with spring thrusters was selected for the circumferential separation interface.

MISSION SPECIFICATIONS

For the SLV-3, the following specifications were placed on the fairing release and jettison system:

- The system must ensure collision-free separation from the vehicle during stage 2 motor coast phase at an altitude of 90 to 100 km
- A minimum jettison velocity of 1.5 mps (4.92 ft/sec) will be provided
- Allowable disturbance to upper stage must be ≤ 0.5 deg/sec

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- No contamination or debris is permitted
- System pyros will initiate on an electrical command of 2 Amps with 10-ms duration through snapoff from vehicle
- System weight should be ≤ 18 kg and the fairing interface joint must react vehicle loads
- Because the vehicle assembly must be mounted horizontally in the launcher, the fairing must have load capability in the horizontal position
- A reliability of 0.985 at a confidence level of 85 percent must be demonstrated
- Orientation of the fairing separation plane will be 90° to the vehicle pitch axis and 45° to the launch tower

A combination of four latch mechanisms to clamp the fairing along the longitudinal split line and a circumferential groove joint for the vehicle interface were selected (Figure 1). Separation mechanisms currently available are of a wide variety. A choice was made after extensive evaluation of the merits and demerits of candidate systems. Because a single point actuation and multipoint release system has the highest reliability¹ the choice was narrowed to a single point actuation of the four latch mechanisms.

The actuation system consists of high pressure nitrogen gas bottles opened by a pyro valve. On initiation, the gas pressure is conveyed to the latch mechanisms through high pressure lines. This gas pressure provides the necessary force at the latching mechanisms to cause release, thereby freeing the fairing halves along the longitudinal splitline.

The joint at the vehicle circumferential interface is shown in Figure 2. This consists of a groove joint--the female groove provided on the fairing end rings, and the corresponding male configuration on the vehicle. This passive separation interface does not require additional release mechanisms. Springs are provided both in the latching mechanisms and groove joint for jettison. At release, the springs impart a lateral velocity of 1.9 mps to each of the fairing halves.

Redundancy has been incorporated in the actuator design by providing two nitrogen gas bottles and by isolating them in the pneumatic circuit by in-line, nonreturn (check) valves. The pressure feed lines are filled with hydraulic oil, MIL-H-5606D, from the check valve onwards for improved event timing.

TECHNICAL DESCRIPTION

The release and jettison system has the following principal subsystems:

- Latch system with springs
- Gas bottle with pyro valve
- Groove joint with springs

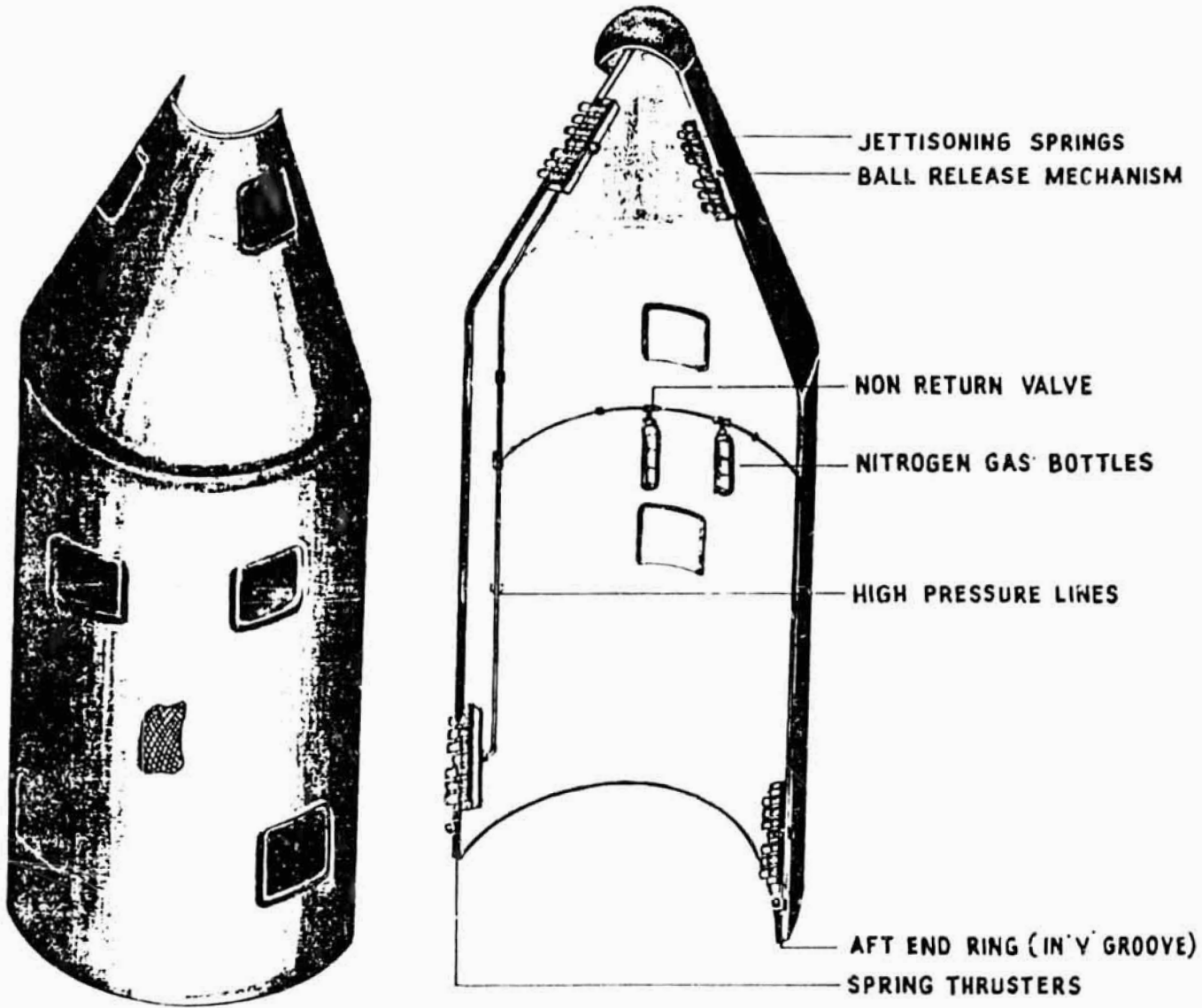


Figure 1. Heat Shield Separation and Jettisoning System Configuration

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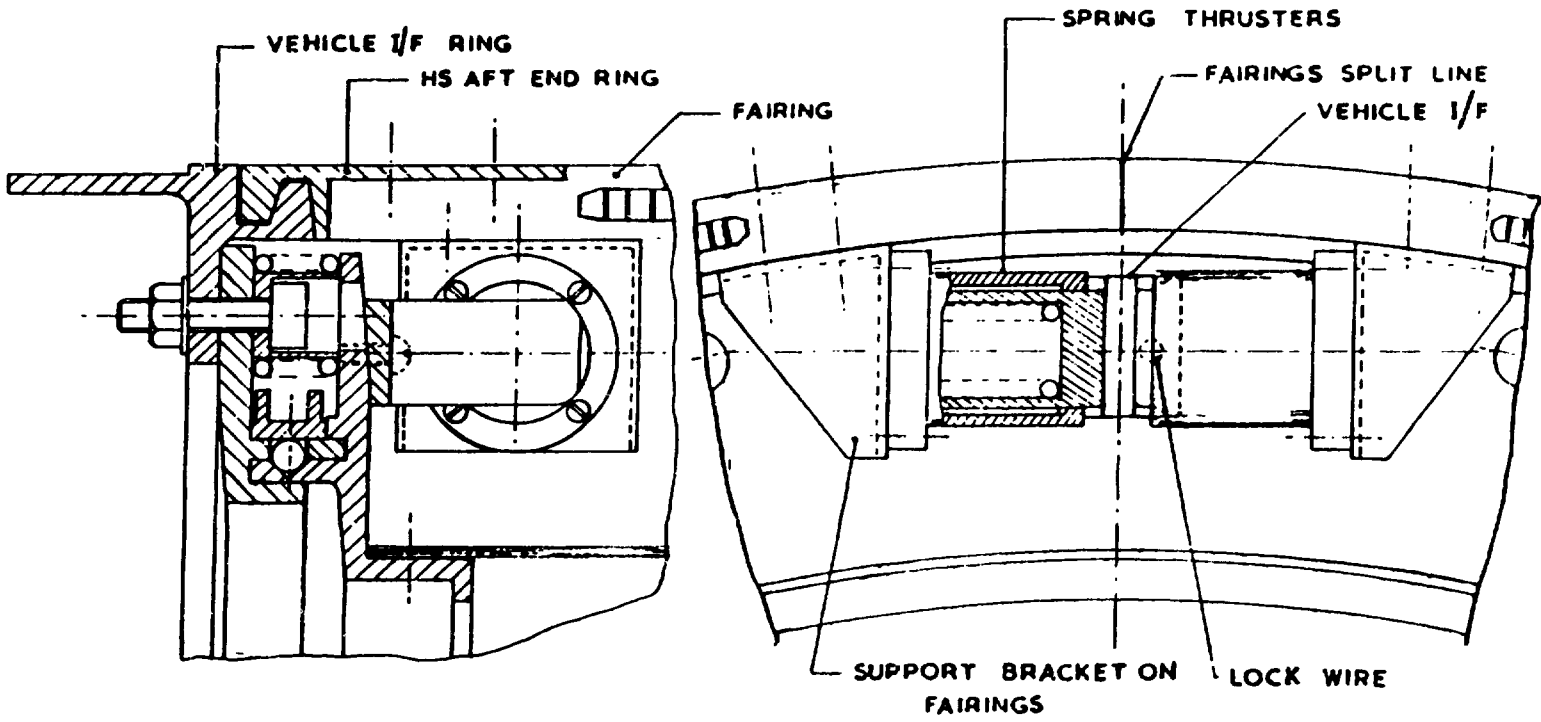


Figure 2. Groove Joint Assembly

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Latch System with Springs

The latch system, shown in Figure 3, consists of a ball release mechanism (BRM), and six spring thrusters. Open coiled helical compression springs of 22-mm OD and spring rate of 76.5 N/cm (43.6 lb/in) are used. The springs are arranged symmetrically, three on each side, and a telescopic mechanism is used for loading/unloading. Aluminum alloy angle sections closed at both ends are used as the principal top and bottom latch housings for mounting the units. The housings are provided with floating plate nuts to allow for fastening from outside the fairing, and to accommodate any hole misalignment. The latch, a preloaded assembly, is installed as a module to join the two fairing halves.

The BRM consists of a stud, a hexagonal housing, a spring, and an M-10 bolt for fastening. A piston moving inside the stud is locked by three balls extending through three radial, equally spaced holes drilled in the stud. These steel balls, which project from the stud outside diameter in the locked condition, are seated inside the hexagonal housing. Three 90° conical seats are provided, 120° apart, on the inside bore of the housing. In the locked condition, the housing and the stud of the BRM act as an integral unit and can be bolted to the aluminum alloy housing. On release, initiated by the forward motion of the piston, the balls recede radially inward and their external projections disappear, thereby releasing the bolted hexagonal housing. The balls are contained in the stud on the piston recess and the ball retainer spring prevents their escape. The jettison spring thrusters are bolted to the bottom latch housings and on release impart the required jettison velocity to the fairing halves. The individual thruster spring compressions can be adjusted with close tolerance to maintain the mating plane at the top latch housing. The springs are closely matched with +3 percent tolerance on stiffness. By suitably matching the springs during assembly, the effect of differential force is reduced.

Gas Bottle with Pyro Valve

The gas bottle consists of a cylindrical shell that is 75 cu cm in volume and 40 mm in diameter, with one end spherical and the other end open. The material is aluminum alloy, AA-6351. A releaser that also serves as a filling adapter is screwed into the open end of the bottle. This releaser incorporates a diaphragm that is punctured by a pyro valve. Nitrogen gas at 15 MPa is filled through the releaser filling port.

Groove Joint with Springs

The circumferential groove joint is shown in Figure 2. The female groove is provided in the aft end ring of the fairing and the male groove at the vehicle interface ring. Both rings are made of AISI 4340 alloy steel forged and machined. The joint is dry lubricated with molybdenum disulphide for easy

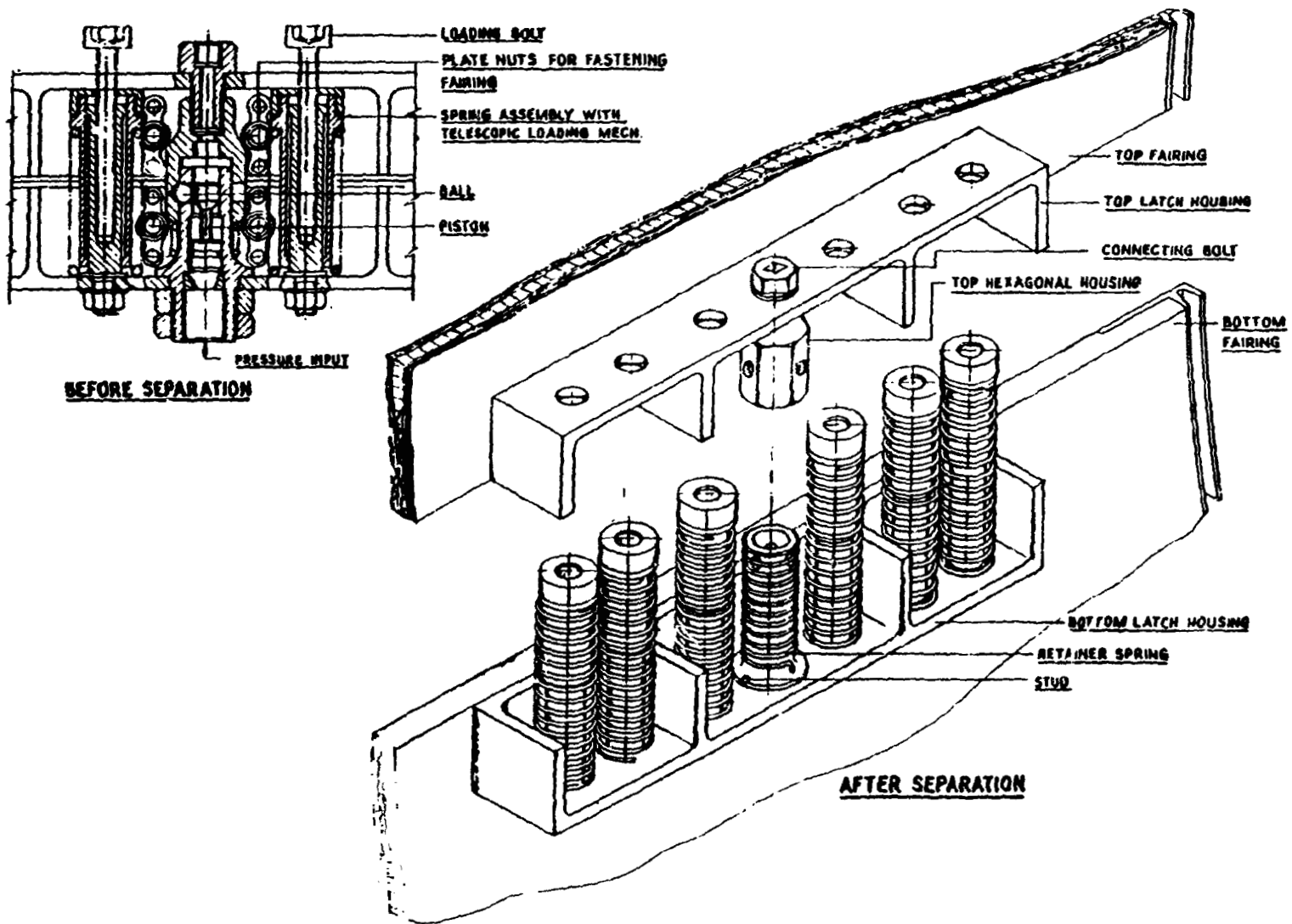


Figure 3. Latch System

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assembly and jettison. Four spring thrusters are located at the split plane. These thrusters impart lateral thrust to the fairing halves with respect to the vehicle. After the fairing is assembled to the vehicle, the thrusters are preloaded by removal of a lock wire.

SYSTEM PERFORMANCE

Separation and Jettison System

This system performed as expected, developing a jettison velocity of 1.65 mps (5.4 ft/sec) within an action time of 19 ms. The total system weight was 15.7 Kg. The shock caused by jettison was recorded to be less than 5 g. The latch module had release pressures ranging from 2.8 to 4.0 MPa. The total force exerted by the six thruster springs are 1750 N with a net compression of 38 mm on release. The balls of the BRM are arrested by the retainer springs, thus ensuring no free-flying debris. Figure 4 shows an action photograph of the fairing jettison. Figure 5 shows the latch assembly before and after release.

Pyro Valve

The pyro valve is piston actuated to puncture the aluminum alloy diaphragm of the gas bottle. The functional delay of the valve was within 10 ms. The actuating pressure cartridge had a single initiator and dual bridge wires with the following electrical characteristics:

- No fire current--500 mA; 5-min duration
- All fire current--1 A 50-ms duration
- Recommended firing current--2 A; 10-ms duration

The valve, which was tested to establish a reliability of 0.975 at 85 percent confidence level, is a totally contained system.

Groove Joint with Springs

The groove joint was 800 mm (31.5 in) nominal diameter and was structurally tested to the following loads:

- Bending moment--15,000 N-m
- Axial load--23,000 N
- Shear force-- 6,500 N

The total spring force for each fairing half, acting on this joint, was 270 N. The springs were located 60 mm (2.36 in) from the fairing split plane.

Nonreturn Valve and Compression Tube Fittings

A standard nonreturn valve for 6.35-mm diameter tubing was used in the pneumatic circuit. The valve had a rated pressure of 21 MPa and a crack-

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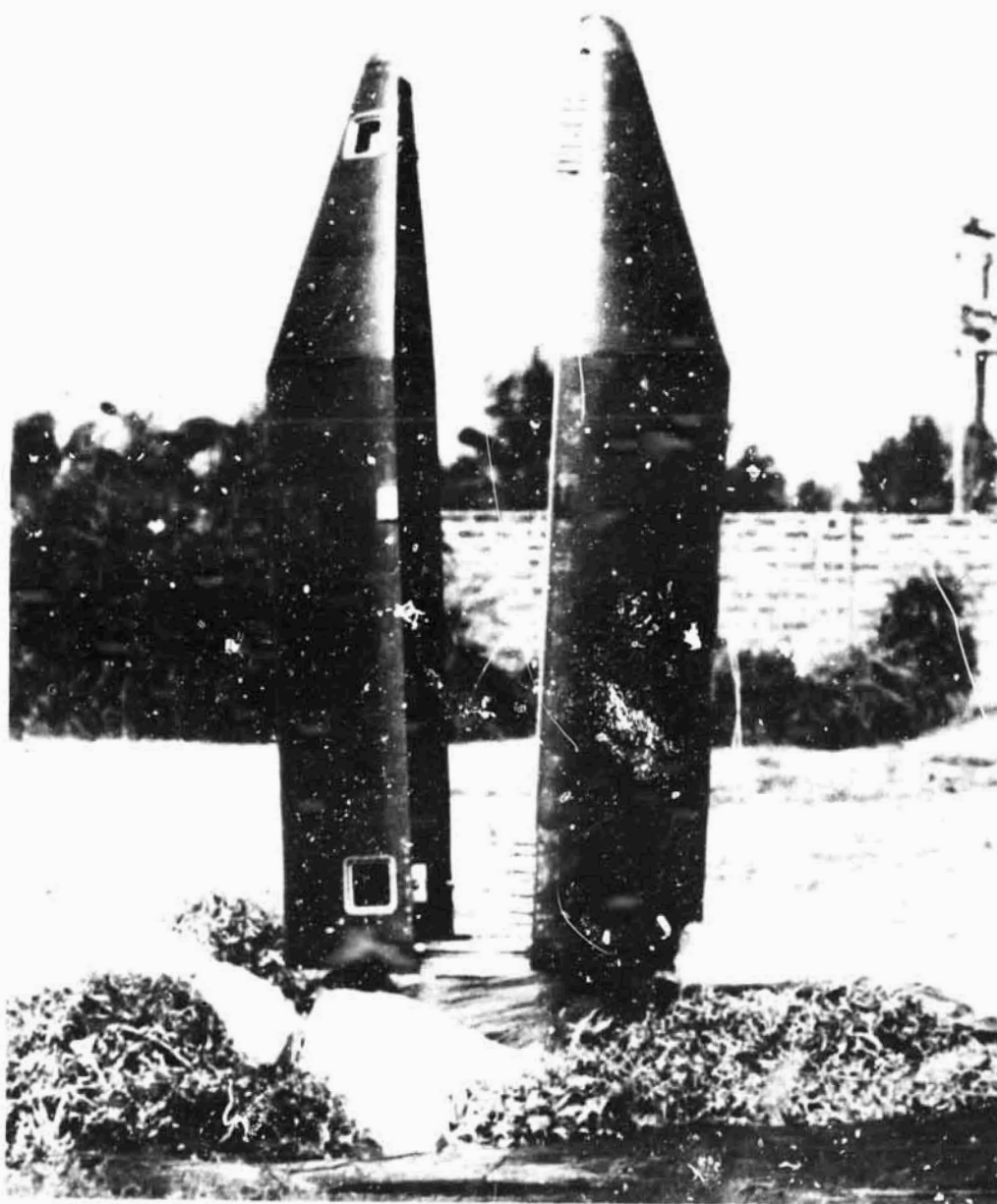


Figure 4. Heat Shield Fairing Jettisoning--In action (1 g condition)

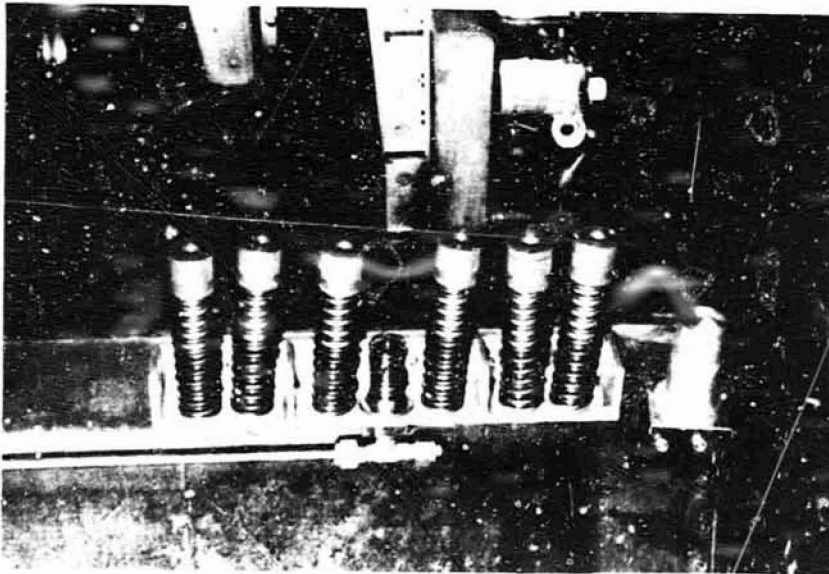
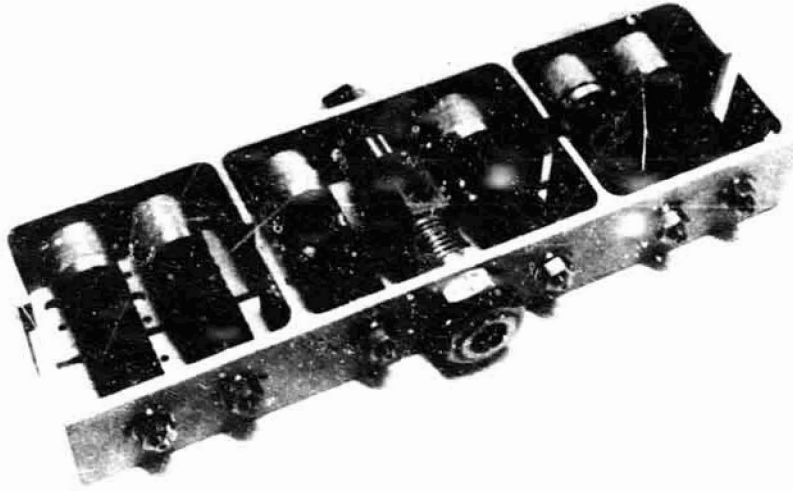


Figure 5. Latch Assembly

ing pressure of 7×10^{-5} Pa. Single ferrule compression tube fittings of elbows, tees, and straight connectors were used at the joints of the tubing.

DEVELOPMENT PROBLEMS

Development problems encountered in this system were:

- Achieving precision fabrication of the BRM
- System functional test failures during the initial phase
- Matching of resultant force and center of gravity of FRP fairings

Elaborating on the first problem, the BRM fabrication required high precision, especially in locating the ball-seating holes which carried angular tolerances of ± 5 arc-mins on the 120° spacing. A drilling fixture precise within ± 30 arc-secs was necessary to achieve this. In addition, the inside piston, a moving part, is of case-hardened steel, with a hardness of 55 to 60 Rockwell "C" scale. The piston required concentricity to within 20 microns. Attempts at achieving this precision by grinding on the outside diameter resulted in a high rejection rate. Finally, critical dimensions on the BRM housing required grinding the external flat surfaces. The dimension across the flats was toleranced to 30 microns. This was necessary because the flats served as a reference to control the depth of the ball seating.

The first few functional tests failed because of asynchronous release of the fore and aft latch pairs. Investigation revealed time delays on the order of 20 to 40 ms, which caused the forward pair to release first and the aft pair to fail to release. This time delay was a result of the spring load of the forward pair being transmitted to the aft pair. Because of the load increase on the aft pair, the pressure was insufficient to produce release. Initially, gas bottle pressure was only 7 MPa (70 bars). Two solutions were implemented:

- Reduction of relative release delays of the two pairs of latches by adjusting the locations of the pressure input point
- Increase of actuation pressure to 15 MPa which further reduced the relative delay.

Another problem encountered was the large uncertainty in the location of the center of gravity (c.g.), inherent with FRP fairings. Because of the nature of the groove joint, the resultant force vector is required to pass through the fairing c.g. within a tolerance of ± 15 mm. Location of the resultant force vector above the c.g. would not result in separation, so ballasts were added to adjust the c.g. within the design limits.

RELIABILITY MODELLING

A fairing reliability requirement of 0.985 with 85 percent confidence level was specified by the mission. Apportioning this reliability between

the structure and separation-jettison systems, structural performance should be demonstrated to a reliability of 0.995 and jettison to a reliability of 0.985. The overall confidence level was apportioned according to the following model law:

$$(1 - C) = (1 - C_s) (1 - C_g)$$

where

C = Overall system confidence level

C_s = Structural confidence level (including thermal)

C_g = Separation and jettison system confidence level

Accordingly, the system confidence level of 0.5 was arrived at after fixing the structural level at 0.7. This required that 34 jettison system tests be performed successfully. To satisfy this requirement, the system has undergone 40 successful jettison tests.

QUALIFICATION TESTS

System qualification tests are divided into three categories: functional, structural, and environmental. Table 1 shows the test summary. Table 2 shows the test levels used for environmental simulation. The fairing, after undergoing vibration and shock tests, was functionally tested for jettison. The performance proved normal. A typical one-g trajectory plotted from high speed movie data is shown in Figure 6.

FLIGHT TEST QUALIFICATION

The system was qualified in four flight tests of SLV-3. The system performed successfully in all flight tests. The performance was monitored by means of telemetry from microswitches at each latch, event monitor, and snap-off plugs. The vehicle disturbance rates were within specifications, and the system performed normally.

II. BALL LOCK MECHANISM AS A STAGING SYSTEM FOR APOGEE MOTORS

INTRODUCTION

The apogee motor of the SLV-3 and a satellite weighing 400 kg (881.8 lb) were to be separated from the spent third stage at an altitude of 400 km (248.6 mi). This procedure required that the interstage connecting the apogee motor be axially separated without any collision.

Because of mission constraints on the SLV-3 vehicle, it was required that the separation system impart minimal separation disturbances and a differential velocity of 1 mps while releasing no contamination or debris.

Table 1
Qualification Test Summary

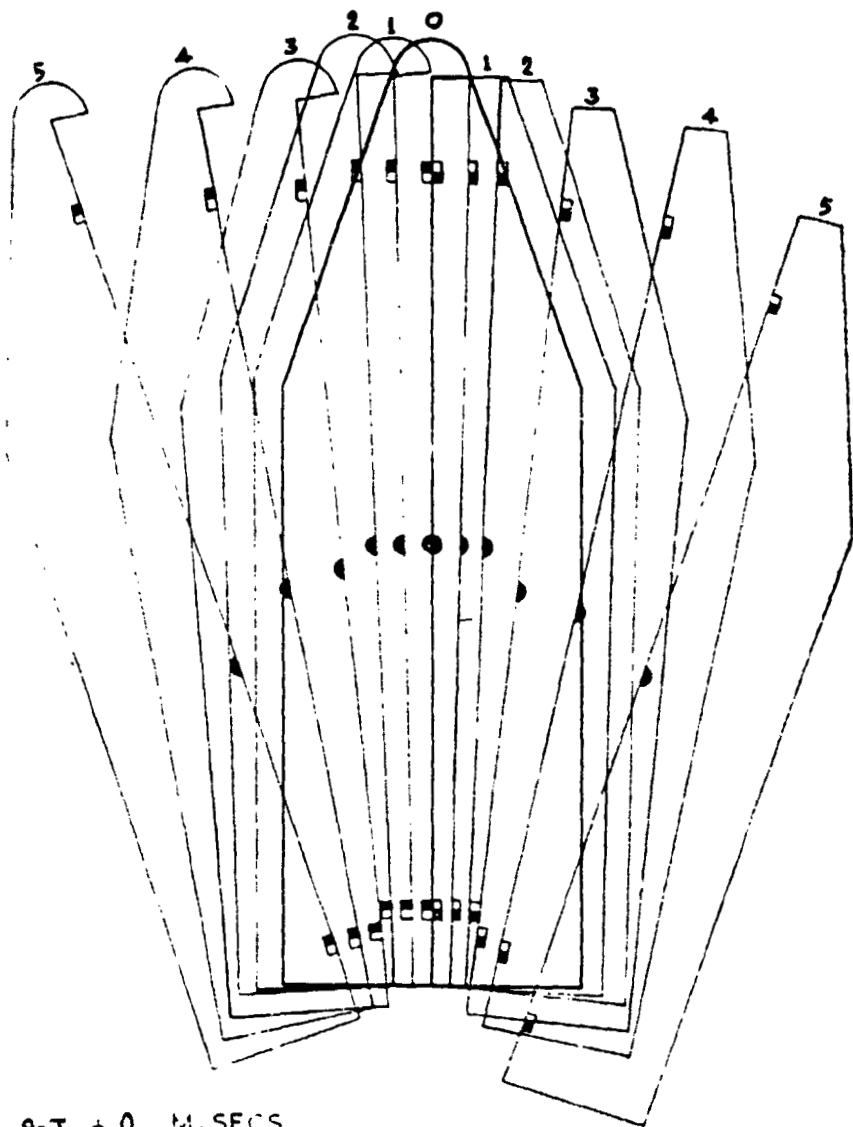
| No. | Type of Test | No. of tests | Result | Remarks |
|-----|---|--------------|----------------------------------|---|
| 1 | Functional at ● 1 g condition | 40 | Successful. Velocity 1.65 mps | Jettisoning velocity measured & verified with prediction |
| | ● 0 g condition | 3 | do | Falling platform facility is used* |
| 2 | Structural test | 3 | Normal | Verified joint rota- tion of groove joint 1.5×10^{-9} rad/Nm** |
| 3 | Environmental tests ● Vibration ● Shock | 3 | System functioned normal | |
| | | 3 | | |
| 4 | Flight tests | 4 | do | Disturbance rates 0.34 deg/sec |

*A facility having a platform fall freely guided by columns, thus simulating
'0' g

**Improves good category beyond 30 percent of test loads

Table 2
Vibration and Shock Test Levels

| Type | Axis | Freq. range | Level | Sweep rate |
|--------------------------------------|----------|---|--|------------|
| Sine | ZZ | 10 to 50 50 to 100 Hz | 1.2 mm DA 6 'g' | 20 oct/min |
| | XX & YY | 10 to 80 Hz 80 to 1000 Hz | 0.2 mm DA 2.7 g | 20 oct/min |
| Type | Duration | Band width Hz | PSD g^2/Hz | G rms |
| Random XX ZZ | 2 min | 20 to 35 350 to 1350 1350 to 2000 | 0.0024 to 0.04 uniformly | 6.9 g |
| Axis XX & YY | 2 min | do | 0.003 to 0.04 uniformly | 7 g |
| Shock pulse- half sine wave | ZZ axis | 100 Hz | Shock test level 40 g $\pm 10\%$ | 3 shocks |



0-T + 0 M. SECS
 1-T + 100 "
 2-T + 200 "
 3-T + 300 "
 4-T + 400 "
 5-T + 500 "

● POSITION OF CG
 ■ POSITION OF LATCHES

Figure 6. Trajectory of Separated Fairings

A ball lock mechanism was selected as a staging device for this application. The choice was based on its proven reliability on 560-mm (1.84-ft) diameter sounding rocket flights and various trade studies for achieving highest system reliability.

MISSION SPECIFICATIONS

The SLV-3 required the following third stage separation system specifications:

- The system should ensure clean, collision-free separation from the vehicle during the stage 3 motor coast phase
- The system should function at an altitude of 390 to 400 km (242 to 286 mi)
- A minimum of 1 mps (3.3 ft/sec) relative axial velocity is to be provided
- Tipoff rates imparted to the upper stage during separation should be <0.5 deg/sec
- No contamination or debris is permitted
- The system pyros must initiate on electrical command through snapoff from the vehicle (recommended firing current is 2 A for 10 ms)
- The system should meet a reliability of 0.995 at an 85 percent confidence level
- As a structural joint it should be capable of withstanding flight loads and environmental conditions
- The system must be located between the aft end ring of the apogee motor and the forward end ring of the interstage structure
- Size
 - Inner diameter--648 mm (25.5 in)
 - Outer diameter--767 mm (30.2 in)
 - Length--48 mm (1.9 in)
- Allowable weight--7 kg (15.4 lb)
- Electrical interface
 - The mechanism must accommodate six snapoff connectors oriented symmetrically about the vehicle pitch axis

TECHNICAL DESCRIPTION

The ball lock system is shown in Figures 7 and 8. The system consists of upper and lower stage adapter rings held together by steel balls which in turn are held by a retainer ring. The retainer ring is provided with escape holes for the balls. In the locked condition, the holes in the retainer ring are given an angular offset. During release, the retainer ring is rotated by two pyro thrusters (one for redundancy), nullifying the offset. The pyro thrusters are initiated by pressure cartridges on electrical command from the central sequencer of the vehicle. Retainer ring rotation is limited by a stopper.

Helical compression springs positioned between the flanges impart the required differential velocity. The lower stage (outer) ring is provided with

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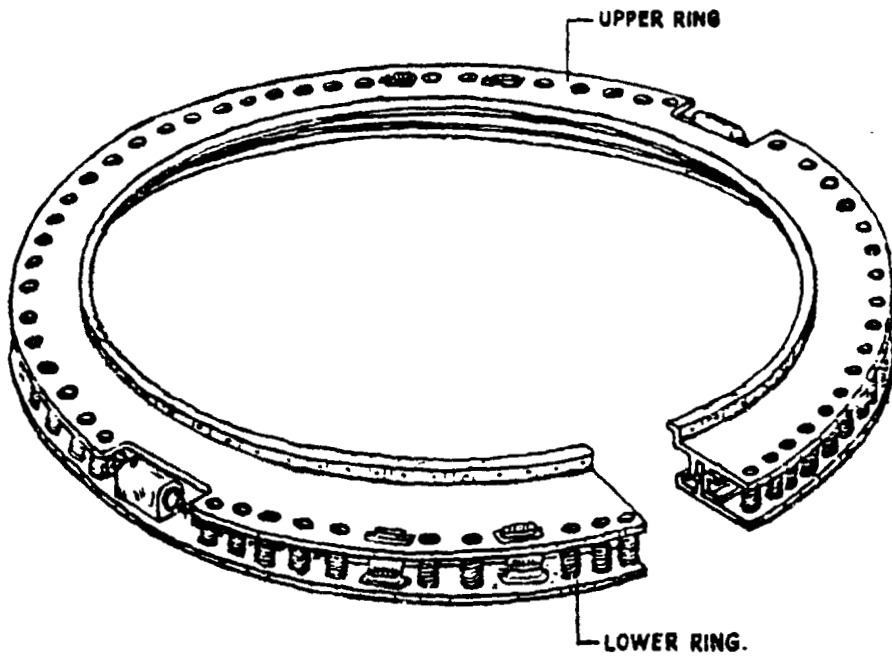


Figure 7. Ball Lock Mechanism Before Separation

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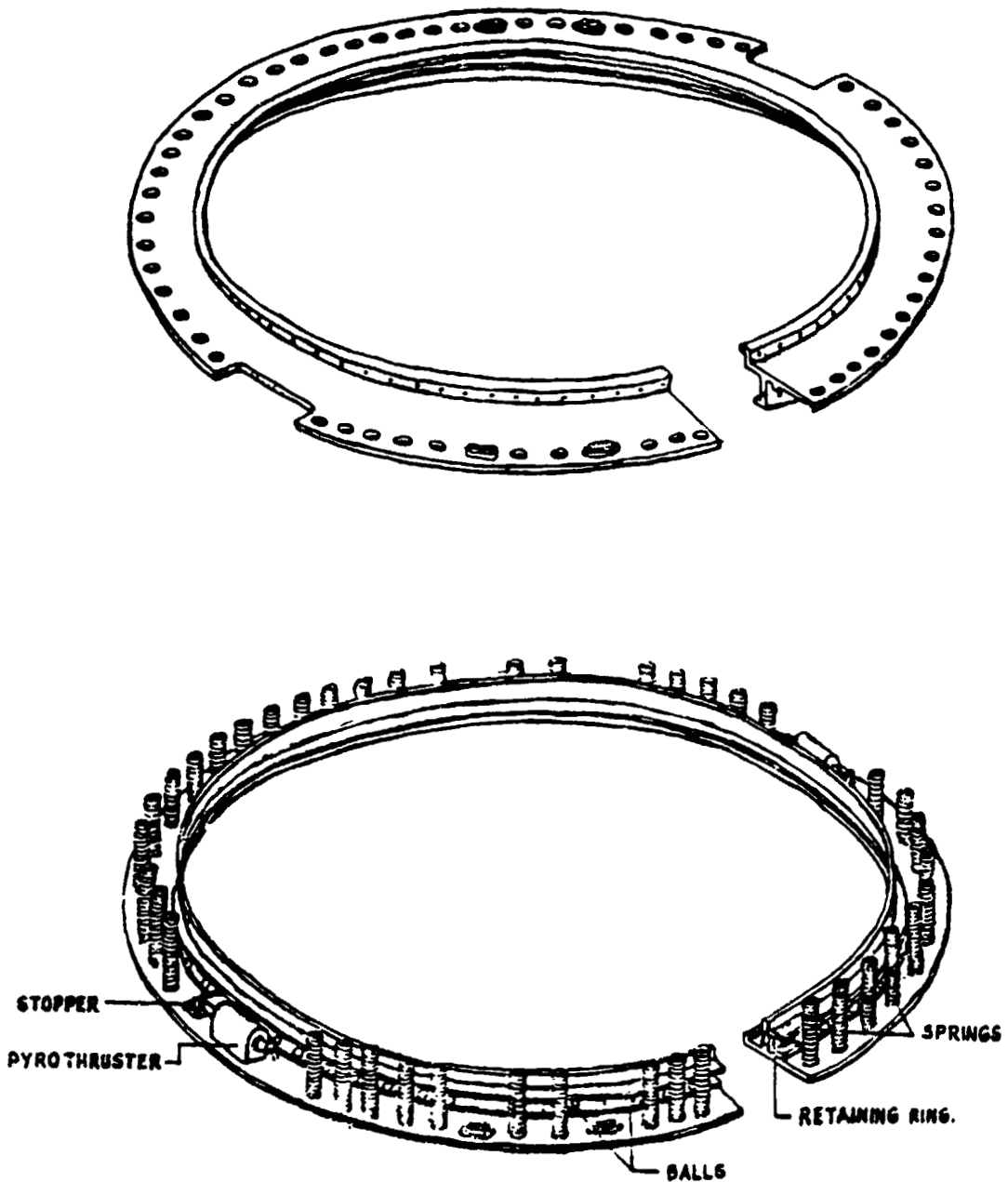


Figure 8. Ball Lock Mechanism After Separation

through holes for the balls in the locked condition and the upper stage adaptor ring is provided with conical ball seats. The radial component of the spring force pushes the balls outward and releases the inner ring, thus ensuring a clean separation.

The adaptor flanges have provisions for fastening the upper and lower flanges. In the locked position, the retainer ring is held positively by shear screws to prevent accidental rotation caused by shock, vibration, and other vehicle loads. The pyro thruster is a piston-cylinder type. The piston provides the necessary ring rotation force through pressure developed by the cartridges inside the cylinder (Figure 9).

DESIGN CONCEPTS

The system was designed for 1.4 times the maximum anticipated flight bending moment. The sections were designed for bending, axial, and shear loads. A margin of safety of 1.5 to 2 was built into this design. The number of balls was selected based on the load on each ball and the corresponding contact stress induced on the conical ball seats. The load on each ball was evaluated from:

$$M_u = \sum F_n r_n^2$$

$$= \sum F_n r^2 \sin^2 \theta_n$$

where

F_n = Force on the n^{th} ball contact

θ_n = Circumferential angle made by the n^{th} ball

The contact stresses were evaluated based on the coefficient of friction between the aluminum alloy and steel. The joint stiffness was predicted by determining contact deflection. Table 3 shows the calculated deflection and joint rotation.

The functional design was determined by finding the net radial outward component caused by spring force on the ball acting on the retainer ring (Figure 10). The net torque required to rotate the ring is the sum of all the radial component forces multiplied by the friction coefficient between the steel ball and the retainer ring. Because these components are made of hardened steel (the ring hardness is 30 to 35 Rockwell "C" scale), the indentation was very low (0.01 mm) and the friction coefficient was assumed to be in the 0.08 to 0.10 range. The shear screw in the pyro thruster provides functional safety for any accidental release.

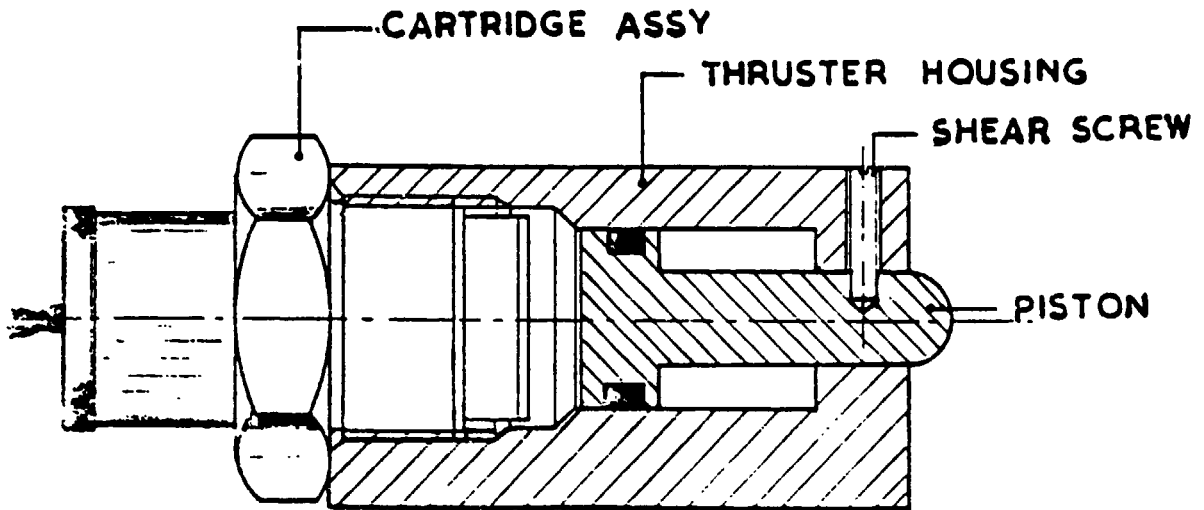


Figure 9. Pyro Thruster

Table 3
Contact Surface Deflections

| θ in degrees | Radial distance in mm (inch). | Deflection in mm (inch). | Rotation in radians |
|---------------------|-------------------------------|--------------------------|---------------------|
| 90 | 327.00 (12.87) | 0.05559(0.00219) | 0.0001700 |
| 84 | 323.43 (12.73) | 0.05519(0.00217) | 0.0001706 |
| 78 | 312.86 (12.32) | 0.05399(0.00213) | 0.0001726 |
| 72 | 295.77 (11.64) | 0.05203(0.00205) | 0.0001759 |
| 66 | 272.90 (10.74) | 0.04933(0.00194) | 0.0001808 |
| 60 | 245.25 (9.66) | 0.04599(0.00181) | 0.0001875 |
| 54 | 214.02 (8.43) | 0.04204(0.00166) | 0.0001963 |
| 48 | 180.59 (7.11) | 0.03758(0.00148) | 0.0002080 |
| 42 | 146.41 (5.76) | 0.03272(0.11129) | 0.0002235 |
| 36 | 112.97 (4.45) | 0.02757(0.00109) | 0.0002440 |
| 30 | 81.75 (3.22) | 0.02227(0.00088) | 0.0002724 |
| 24 | 54.10 (2.13) | 0.01695(0.00067) | 0.0003133 |
| 18 | 31.22 (1.23) | 0.01180(0.00046) | 0.0003780 |
| 12 | 14.14 (0.56) | 0.00699(0.00028) | 0.0004943 |
| 6 | 3.57 (0.14) | 0.00280(0.00011) | 0.0007843 |

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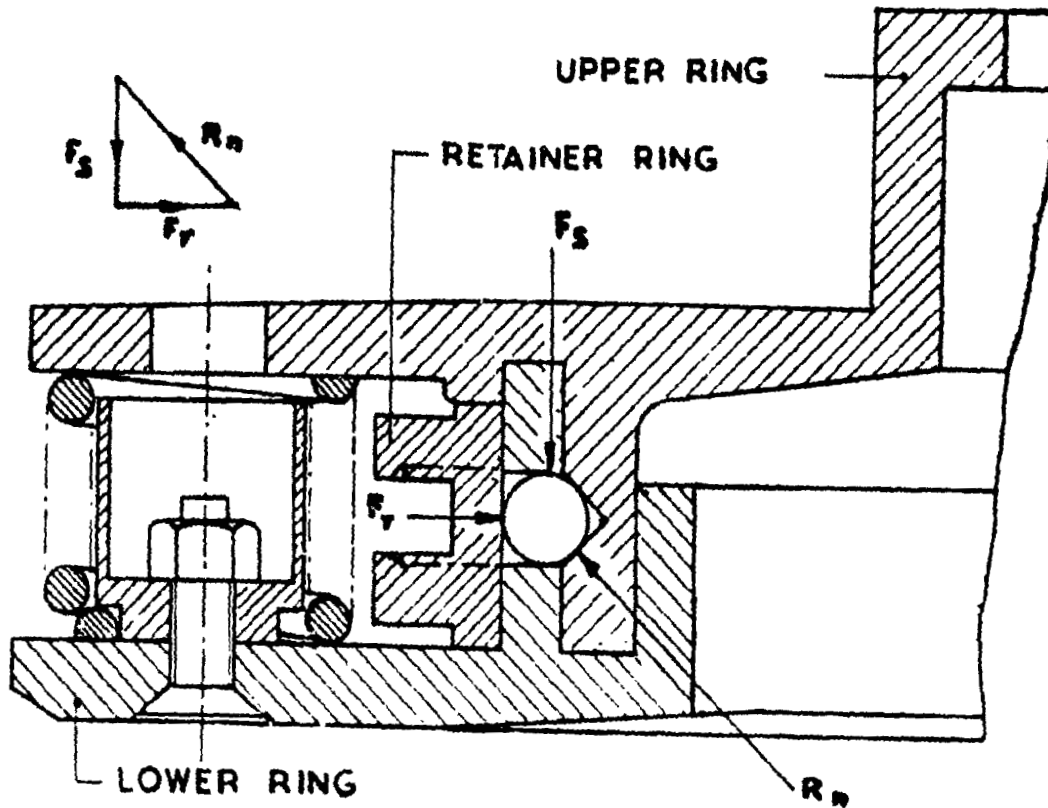


Figure 10. Equilibrium of Forces

The springs for jettison were fully guided during expansion and were screened for a tolerance of +3 percent on stiffness. The dimensional screening ensured identical springs for controlling the net compression. Based on energy and momentum balance, the differential velocity requirement was calculated from the spring energy

$$M_s V_s + M_e V_e = 0$$

$$\frac{1}{2} M_s V_s^2 + \frac{1}{2} M_e V_e^2 = \frac{1}{2} K \delta^2$$

M_s, V_s = Mass and velocity of the upper stage

M_e, V_e = Mass and velocity of the lower stage

K = Total spring constant

δ = Net compression

SYSTEM PERFORMANCE

The ball lock system functioned successfully in separation and jettison of the connecting stages. A differential velocity of 1.2 mps (3.9 ft/sec) was imparted within a time of 15 ms. The measured shock was 3 g and the disturbance rate was 0.14 deg/sec in the roll direction. The system was tested to demonstrate a reliability of 0.995 at an 85 percent confidence level. The system was fully contained and the balls, springs, and retainer ring all remained with the lower stage as designed. No flying loose parts were observed.

The principal diameter of the ball lock system at the separation plane was 696 mm (27.4 in). The system assembly was structurally tested for its joint characteristics. The test loads were:

- Bending moment--11,768 N-m (8,675 ft lb)
- Axial load--56,879 N (12,786 lb)
- Shear force--6,031 N (1,355 lb)

The deflection was 0.07 mm (0.0029 in) and the joint (flexibility constant) was 4.4×10^{-8} rad/N-m (5.02×10^{-9} rad/in-lb). The performance of the joint was within acceptance limits.

The pyro thruster, a piston-cylinder type, had a pressure cartridge of dual-type squibs with electrical characteristics the same as that of the pyro valve of the gas bottle previously mentioned. The cartridge was individually proven for its reliability requirements. Figure 11 shows the assembly of the ball lock system and the pyro thruster.

DEVELOPMENT PROBLEMS

Development problems included: controlling the spring characteristics, dealing with contact stress during dynamic loading, and fabrication of the ball seating, especially controlling the depth.

Matching and symmetrical distribution of springs necessitated selection from a large supply and resulted in higher cost of the system. The contact stress was higher than predicted, and when the same assembly was vibrated and structurally tested, the stiffness of the joint was found to have changed. This problem was solved by providing a hard-chromium coating with a thickness of 20 to 30 microns. The joint stiffness was increased to 4.44×10^{-8} rad/N-m (moderate category). In order to achieve this, a precision fixture was needed. The fixture provided a reference surface and drilling was used to achieve the controlled depth.

QUALIFICATION TESTS

The tests were divided into functional, structural, and environmental tests. The environmental conditions simulated were vibration, shock, and thermal soak.

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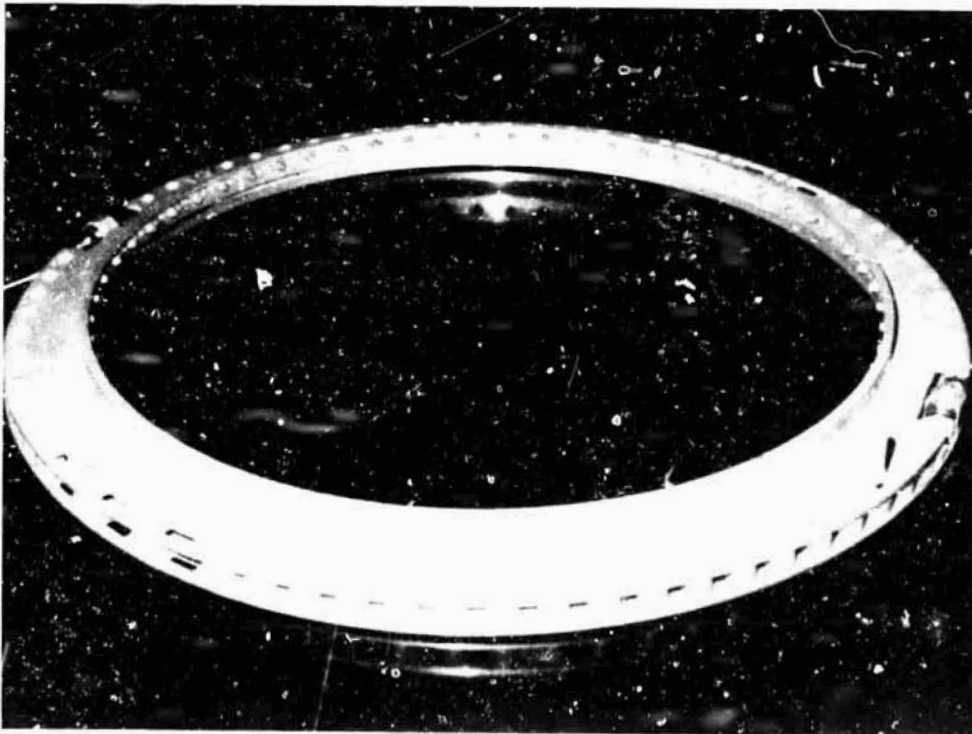


Figure 11. Ball Lock Staging System and Pyro Thruster

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Functional tests were performed both in grounded and free-fall conditions to evaluate the disturbance levels. The functional tests in zero gravity were performed with a simulated mass-inertia model to verify differential velocity and disturbance characteristics. Limitations in the disturbance measurement were caused by the atmosphere and its damping effect on the measured rates. The results showed that the pitch and yaw rates were insignificant, whereas the roll rate had a value of 0.14 deg/sec. In the structural test, the system performed normally, as predicted. The joint stiffness was, according to specification, of moderate class. The vibration and shock tests were stipulated to qualify the system in the functional mode after these environmental loadings. The thermal-soak test was carried out at 70°C with a one-half hour soak to qualify for the expected temperature inside the heat shield during flight. The system function was tested and found normal. A qualification test summary is shown in Table 4.

CONCLUDING REMARKS

The staging and the heat shield systems meet all the mission requirements. These systems have successfully performed their function in all four SLV-3 flight tests. Both systems have excellent performance characteristics of low shock, low-disturbance rates, and complete freedom from contamination. No free-flying debris occurs in these systems. In this respect, these systems fare one order higher compared to a merman band system and so are attractive for launch vehicle applications of a similar class.

Table 4
Qualification Test Summary

| Sl.No. | Type | No. of test | Performance | Remarks |
|--------|-------------------------------|-------------|--------------|--|
| 1 | Functional - 1 g condition | 15 | Normal | Clean separation. |
| | - 0 g condition | 3 | do | Measured disturbance rate in roll 0.14 degree/sec (No significant pitch and yaw rates) |
| 2 | Structural | 2 | As predicted | Joint falls in moderate category |
| 3 | Vibration* | 1 | do | Functioned normal after vibration. |
| 4 | Shock* | 1 | do | do |
| 5 | Thermal soak at 70°C | 1 | Normal | Functioned normal after soak |
| 6 | Flight test | 4 | do | Disturbance rate less than 0.1 degree/sec |

*Levels are as per Table 2

REFERENCE

Gluckman, I. B., "Aerospace Vehicle Separation Mechanisms-Selection, Design and Use Considerations," Lockheed Missiles & Space Company, Inc., Fifth Aerospace Mechanisms Symposium, Sunnyvale, California, 1970.