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PYROTECHNIC SHAPED CHARGE SEPARATION SYSTEMS FOR AEROSPACE VEHICLES

by Floyd Z. Smith

Lewis Research Center

Cleveland, Ohio

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ABSTRACT

A detailed design and test development program was conducted to establish an acceptable separation system design for vehicle staging and shroud separation on the Atlas-Centaur two-stage vehicle. The flexible linear-shaped charge separation systems resulting from this program were demonstrated to be functionally reliable through an extensive design evaluation and qualification test program. These test programs contributed significantly towards updating and improving the state of the art of shaped charge design application, particularly at cryogenic temperatures in an air environment.

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SUMMARY

A detailed design and test development program was conducted to establish an acceptable separation system design for vehicle staging and shroud separation on the Atlas-Centaur two-stage vehicle. The flexible linear-shaped charge separation systems resulting from this program were demonstrated to be functionally reliable through an extensive design evaluation and qualification test program. These test programs contributed significantly towards updating and improving the state of the art of shaped charge design application, particularly at cryogenic temperatures in an air environment.

The successful application of the flexible linear-shaped charge to the Centaur space vehicle has established this severance medium to be a highly refined and reliable design for utilization in aerospace-vehicle-separation systems.

INTRODUCTION

To obtain maximum payload capability, aerospace launch vehicles must minimize all possible vehicle deadweight. This objective is usually accomplished by a multistage vehicle design incorporating lightweight separation systems. One separation system under intensive development in recent years incorporated the flexible linear-shaped charge (FLSC) severance concept. This report describes the FLSC separation systems employed on the Centaur vehicle. Primary emphasis is directed toward system descriptions with secondary emphasis given to test substantiation of these systems.

The first part of this report describes the three separate severance systems used in the Atlas-Centaur vehicle (to accomplish nose fairing and insulation-panel separation and staging for the Atlas-Centaur vehicle). A detailed description of the system components is also presented. The flexible linear-shaped charge system used consists of a V-shaped lead tube containing a high-explosive core. When the explosive is detonated by an electrical charge, a high-temperature explosive jet cuts through the structural members, as shown in figure 1. One of the most impressive features of the flexible linear-shaped charge is the way it can be bent and routed (with reasonable precautions to prevent breaking the thin line of powder) in intricate patterns on a metal panel. Because the energy is so well focused by the shaped charge configuration, it is possible to produce clean cuts.

The second part of this report briefly describes the component and assembly testing performed during the design and development of the system. Numerous evaluation tests were conducted to appraise accurately the reliability of the system under adverse effects of the combined action of temperature, altitude, humidity, vibration, and air. Other tests were conducted to evaluate the effect of ice and frost forming in the space between the shaped charge and the material to be cut, the effect of core contamination, and also the effect of gaps in the core. Additional tests were conducted to determine the ability of the explosion to propagate along a linear-shaped charge with consecutively reducing bend radii. Still other tests were conducted to evaluate the effects of cryopumping, contamination, and gaps in the detonator devices.

Design proof tests conducted on subassemblies included insulation-panel and nose-fairing separation tests at sea level, nose-fairing jettison tests at altitude, and Atlas-Centaur staging at sea level and altitude. Qualification tests were conducted to demonstrate the ability of FLSC separation systems to initiate, propagate, and cut under the most adverse combinations of flight temperature, humidity, vibration, and altitude. The tests were conducted at the NASA Lewis Research Center and at the General Dynamics/Convair Fort Worth and San Diego divisions.

TYPICAL FLSC SEPARATION SYSTEM

Before the separation systems used in the Centaur vehicle are described, a typical flexible linear-shaped charge (FLSC) separation system is considered which incorporates all the components essential to the proper functioning of such a system.

The basic component of the FLSC separation system is the shaped charge, which consists of a V-shaped, flexible lead tube containing a high explosive core (RDX, cyclotrimethylenetrinitramine) as shown in figure 1(a). This tube is placed in an inverted V-position over the structural member to be cut. The tube can be placed either in contact with the member or at a standoff distance from the member to allow tolerances for installation purposes. The maximum standoff distance is determined by the size of the explosive core and the strength of the material to be cut. The lead sheath is so designed that the explosive cutting jet is pointed directly toward the material to be cut, although fragmenting of the entire lead sheath does occur. The base metal is cut by a high-temperature explosive jet, formed during inversion of the V-shaped core. Through the combined action of high temperature and pressure, the base metal in contact with the jet erodes at the cutting plane. This process is illustrated in figure 1(b).

Since pyrotechnic propagation is continuously self-sustained throughout the length of the flexible linear-shaped charge, it is desirable to have some device to transfer the pyrotechnic energy from one joint to another over material that should not be cut. This transfer is accomplished by a mild detonating fuse (MDF). The MDF consists of a small-diameter, flexible metal tube containing a detonating core composition (PETN, pentaerythrite tetranitrate). The MDF tube is designed to be nonfragmenting but flexible enough to permit routing it over a structure without risking damage to this structure during activation of the system. Since it is possible to initiate detonation of the MDF at either end, two lengths of the flexible linear-shaped charge can be connected to form any desired intermittent pattern.

To ensure positively that the pyrotechnic energy will be transferred at a FLSC-MDF joint, two nonelectric detonators are used as a coupler in a detonation transfer joint. The end of the FLSC is bonded into the open end of one nonelectric detonator, and the MDF is bonded into the open end of another nonelectric detonator. The two nonelectric detonators are then connected with a coupling ring. Figure 2 shows a detailed drawing of the detonation transfer joint.

The nonelectric detonator (NED) (fig. 3) consists of a metal shell containing an explosive charge (PETN) at its closed end and a cylindrical cavity at its open end. The NED can be activated from either end, and, thus, can be installed at the input or output ends of MDF and FLSC leads.

To initiate detonation of the entire system, an electric detonator is required. This detonator transforms electrical energy into pyrotechnic energy by electrically heating a bridge wire that is in contact with a heat-sensitive explosive charge. A detailed drawing of the electric detonator is presented in figure 4. Electrical input into this detonator is less than 5 amperes. However, to avoid premature firing from stray electrical fields, the electric detonator is designed to require an input current greater than 1 ampere.

The electric detonator, nonelectric detonator, and mild detonating fuse are used in the dual detonator assembly, as shown in figure 5. This assembly receives the initial propagation impulse (usually from the vehicle auto pilot) and transforms it into pyrotechnic energy to initiate detonation of the flexible linear-shaped charge.

All these components are then assembled into a typical separation system, as shown in figure 6. A quick reference summary describing each of the components and their function in the separation system is provided in table I.

CENTAUR FLSC SEPARATION SYSTEMS

The following sections present a general description of the Centaur separation system, a detailed description of each of the systems, and a discussion of the similarities and differences of each system.

GENERAL

Three individual FLSC separation systems are used on the Atlas-Centaur vehicle (fig. 7). These systems are (1) the insulation-panel severance system, (2) the nose-fairing severance system, and (3) the Atlas-Centaur staging severance system. Each system functions entirely independent of the other. During the Atlas sustainer phase of flight, the insulation panels and the nose fairing are simultaneously severed from the Centaur tank. Immediately following severance, the four insulation panels are jettisoned from the vehicle. Final separation and jettison of the nose fairing are not initiated until approximately 60 seconds later to provide additional thermal protection for the payload. After the Atlas sustainer engine is cut off, the Atlas-Centaur stages are separated by the staging separation system. This sequence of events is depicted in figure 8.

Although the three FLSC systems are similar in design, the size of the shaped charge is different in each system. The nose-fairing separation system uses 7.0 grains per foot (14.8 mg/cm) of RDX, the insulation-panel separation system uses 10 grains per foot (21.2 mg/cm), and the staging separation system uses 15 grains per foot (31.8 mg/cm). Weights and dimensions of these flexible linear-shaped charges are presented in table II.

The thermal environments of the three systems differ considerably. The Atlas-Centaur staging system must sustain a thermal environment between 251° and -220° F (395° and 133° K); the insulation-panel system, between 250° and -278° F (394° and 101° K); and the nose-fairing system, which is exposed to the most severe environment of the three, between 240° and -320° F (389° and 78° K). These extreme thermal conditions affected the detailed design of the separation systems considerably. Helium purges surrounding the nose-fairing system are required to prevent cryopumping problems. Cryopumping consists of the continuous condensation of nitrogen (N_2) and oxygen (O_2) from the air at cryogenic temperature. The resulting buildup of layers of solid N_2 and O_2 in the standoff area interferes with the flexible linear-shaped charge in cutting through the structure.

Insulation-Panel Separation System

The insulation panels cover the Centaur liquid-hydrogen tank (10-ft or 3.05-m diam) from the nose fairing to the interstage adapter (16 ft or 4.88 m long), as shown in figure 9. The panels provide thermal protection and airborne purge confinement as well as structural continuity for resisting thermal and aerodynamic loads. The panels consist of inner and outer fiber-glass skins bonded to polyurethane foam-filled fiber-glass honeycomb cells and are fabricated into four panel quadrants. Each panel quadrant contains an integral tunnel running the full length of the panel to cover tank-mounted equipment. To preclude the possibility of panel flutter during flight, the panels are installed on the tank under a pretension load.

The four panel quadrants are bolted together along four panel seams and bolted to the vehicle at an aft tank-mounted seal plate. They are also attached to the interstage adapter by eight panel hinges. Details of these connections are shown in figure 9.

The four panel seams and aft seal-plate attachment are severed by the insulation-panel FLSC separation system. One angle of each of the four longitudinal seams and the entire aft seal plate are severed. The location of the flexible linear-shaped charge and the members to be cut are also shown in figure 9. Each of the longitudinal seams and the aft seal plate are severed to allow each of the four panels to be jettisoned from the vehicle independent of each other. The panel hinges provide controlled guides to direct the panels away from the vehicle at separation.

The forward ends of the panels are attached to the nose fairing by a fiber-glass-mesh forward seal, as shown in figure 10. This seal is severed by the nose-fairing separation system, which is activated simultaneously with the insulation-panel separation system.

The pyrotechnic hardware of the insulation-panel FLSC separation system consists of four longitudinal-seam FLSC assemblies mounted entirely on two of the four panels and two circumferential FLSC assemblies mounted on the aft seal plate. This system utilizes 96 feet (29.3 m) of FLSC and is schematically illustrated in figure 11.

Dual detonator assemblies are located external to the panels to assure that their temperature environment does not drop below -65° F (219° K). Initiation of the system originates at the dual detonators, each of which contains two electric detonators that feed four nonelectric detonators. The function of only one electric detonator in only one dual detonator is required to activate the complete FLSC system. The other electric detonator is provided for backup assurance.

Following its initiation at the dual detonators, pyrotechnic propagation proceeds along eight MDF leads into nonelectric joints to the four longitudinal FLSC assemblies and aft circumferential FLSC assemblies. In the event of malfunction of one of the detonators, additional initiation redundancy is provided by two MDF leads connecting the longitudinal FLSC's at the forward end of the two panels.

The pyrotechnics utilized throughout the insulation-panel separation system consist of 10 grains per foot (21.2 mg/cm) of RDX in all FLSC and 2 grains per foot (4.24 mg/cm) PETN in all MDF. The FLSC grain size, standoff height (gap between the FLSC and the base metal), thickness of base metal cut by the FLSC, base metal material, minimum temperatures, and other pertinent details of this design are presented in table III.

Qualification test temperatures and flight temperatures for each component are presented in figure 11. The thermal environment of insulation-panel FLSC assemblies does not drop below -278° F (101° K) under the most adverse ground-hold conditions.

Nose-Fairing Separation System

The nose fairing protects the payload from aerodynamic drag forces and heating during the boost phase and provides a prescribed environment for the spacecraft throughout flight. Its construction is similar to that of the insulation panels, consisting of a fiber-glass composite structure fabricated into two nose-fairing halves. The fairing halves are pinned together at their split line by explosive actuated pin pullers and are secured to the vehicle structure through a circumferential aluminum tension band. Details of this connection are shown in figure 12. The tension band or "tie" is utilized to transfer nose-fairing bending moments into the tank structure during the vehicle boost phase. Each fairing half is hinged to provide positive guidance of the fairing during jettison.

The nose-fairing FLSC separation system cuts both the forward seal and the aluminum tension tie. Locations of the flexible linear-shaped charge and the members to be cut are shown in figure 12.

The pyrotechnic components of this separation system consist of two semicircular assemblies attached to the two nose-fairing halves. This system utilizes 32 feet (9.8 m) of FLSC and is schematically illustrated in figure 13.

Two dual detonator assemblies, the same as the panel dual detonators except that they contain two rather than four MDF leads, initiate propagation. The dual detonators are secured to the outside surface of the nose-fairing sections and are protected from aerodynamic heating by fiber-glass fairings.

Following its initiation at the dual detonators, pyrotechnic propagation proceeds along four MDF leads into nonelectric detonation transfer joints to the FLSC assemblies.

The pyrotechnics utilized in the nose-fairing separation system consist of 7 grains per foot (14.84 mg/cm) of RDX in the FLSC and 2 grains per foot (4.24 mg/cm) of PETN in all MDF. The FLSC grain size, standoff height, thickness of base metal cut by the FLSC, base metal material, minimum temperature, and other pertinent details of this design are presented in table III.

Qualification test temperatures and flight temperatures for each component are given in figure 13. The minimum temperature environment experienced by the dual detonator assemblies is -65° F (219° K). However, routing the FLSC from the nonelectric detonation transfer joints, mounted externally to the nose fairing, to the surface of the circumferential tension tie involves a temperature gradient from -100° to -320° F (200° to 78° K). The primary reason for this severe temperature drop is the result of the metal-to-metal conduction path from the liquid-hydrogen tank to the tension tie. Because of this low-temperature environment, the nose-fairing FLSC separation system is the most critical in terms of design.

To permit complete structural assembly of the vehicle (including purge leak tests and preflight tanking tests) prior to the assembly of flight pyrotechnics, the tension tie and forward seal are permanently installed prior to assembly of the FLSC. The nose-fairing FLSC, by virture of this design, must function in an air environment at temperatures conducive to cryopumping oxygen and nitrogen into the FLSC jet formation groove. To preclude the possibility of cryopumping into this groove, helium purge ports are provided in the fiber-glass FLSC retainer fore and aft of the FLSC groove, as shown in figure 12. These ports provide a constant supply of pressurized helium to the groove. The pressurized helium assures positive outward-acting pressure that prevents external air from cryopumping into the groove.

Atlas-Centaur Staging Separation System

Following the Atlas sustainer engine cutoff, the Atlas-Centaur staging separation system severs the interstage adapter from the Centaur upper stage. This separation is similar to the nose-fairing separation system insofar as pyrotechnic components are concerned. A schematic drawing of this system is shown in figure 14.

Interstage-adapter skin thicknesses, established by structural requirements during the boost phase, require that this system sever a greater thickness of aluminum than the other systems. For this reason, an FLSC size of 15 grains per foot (31.8 mg/cm) of RDX is used. A detailed drawing of the structural member cut by this system is shown in figure 15. The standoff height, thickness of base metal cut by the FLSC, base material, minimum temperature, and other pertinent details of this design are presented in table III.

Qualification test temperatures and flight temperatures for the pyrotechnic components are given in figure 14. The temperature environment of this system is always greater than -220° F (133° K).

DESIGN EVALUATION TESTS

Because existing FLSC development testing was recognized as being inadequate, an extensive design test and development program was initiated for Centaur to ensure proper operation of the FLSC systems prior to flight.

The requirement for the FLSC system to function under extreme thermal conditions (-423° to 250° F or 21° to 394° K) introduced many new design problems. Cryopumping problems at temperatures below the liquefaction temperature of nitrogen and oxygen created severe design obstacles that demanded state-of-the-art design improvements to ensure flight reliability. To achieve this goal, a comprehensive list of design requirements was established by the Lewis Research Center and General Dynamics/Convair during the initial stages of the FLSC system design. These design requirements are presented in the appendix.

The evaluation of the adverse effects of the combined action of temperature, altitude, humidity, vibration, and air on the FLSC separation systems design proposed for Centaur was accomplished through a continuous design evaluation test program conducted by General Dynamics/Convair concurrently with the designing of these systems. The following section of this report summarizes those tests that most significantly affected design of the final system.

FLSC Bruceton Standoff Tests

Prior to the selection of a flight configuration, representative numbers of each size grain loading of FLSC were subjected to a series of Bruceton-type tests (ref. 1) at room temperature to determine cutting probability at various standoff distances. During this series of tests, all test parameters, including environment, base metal thickness, and grain loading, were held constant with only the standoff (distance between FLSC and base metal) varied to determine the limits of cutting probability. Based on the results of a representative number of specimen tests, the cutting probability of each size grain loading was determined for various standoff dimensions. Figure 16 graphically illustrates the results of Bruceton tests performed on 10-grain-per-foot (21.2-mg/cm) FLSC. The figure reveals that a 0.072-inch (0.183-cm) thickness of aluminum at room temperature can be cut to a reliability level of 99.999 percent, provided that the standoff dimension does not exceed 0.045 inch (0.114 cm). The curve in figure 16 is determined from formulas given in reference 1.

FLSC Standoff Ice Tests

A series of tests was conducted on flight hardware at cryogenic temperatures (-320° F or 78° K) in an air environment to evaluate the cutting capability of 7-grain-per-foot (14.84-mg/cm) FLSC with various ice-filled standoff distances above the flight base metal (0.030 inch or 0.076 cm of aluminum). Results of approximately 50 tests revealed that at liquid-nitrogen temperatures and with ice in the standoff area, the cutting ability of FLSC is maintained up to a standoff distance of 0.040 inch (0.102 cm). Standoff distances in excess of 0.040 inch (0.102 cm), however, were proved marginal and resulted in random failures to cut the base metal. Similar tests with frost in the standoff area resulted in good cutting at standoff distances up to 0.150 inch (0.381 cm). During all tests, the FLSC groove was covered with flight-type nonporous tape (polyethylene terephthalate - polytetrafluoroethylene) to ensure a contamination-free groove and a normal formation of the explosive jet.

FLSC Core Contamination Tests

Lengths of FLSC were initiated at -410° F (28° K) after core exposure to various contaminants, including methyl ethyl ketone, trichloroethylene, high-flash naphtha, toluene, petroleum ether, and methanol (fig. 17). All FLSC propagated completely, which indicated that the contaminants tested did not seriously affect propagation reliability.

FLSC Gap Tests

Lengths of 7-grain-per-foot (14.84-mg/cm) FLSC were slit in two, butted together, and propagated at -410° F (28° K) to determine the magnitude of gap in the FLSC lead sheath and powder train that can be tolerated without critically affecting propagation reliability. Results revealed that the FLSC was extremely sensitive to gaps at -410° F (28° K). Gaps of 0.010 inch (0.025 cm) repeatedly resulted in propagation failures which established, without question, that cracks in the FLSC lead sheath or powder train present potential FLSC propagation failure modes. Figure 18 schematically illustrates a typical gap test setup.

FLSC Elongation Tests

Various sizes of FLSC were loaded in tension from room temperature to -410° F

(28^{O} K) to determine the variation in FLSC elongation properties over this temperature range. Results revealed only a slight loss in modulus of elasticity of the FLSC lead sheath at cryogenic temperatures, which indicated that the FLSC lead sheath was remarkably flexible and, therefore, not readily susceptible to cracking at cryogenic temperatures. Table IV provides percent elongation data for 7-grain-per-foot (14.84-mg/cm) FLSC from -100^{O} to -400^{O} F (200^{O} to 33^{O} K). Change-of-length comparison tests were also conducted to obtain an indication of the differential contraction rates between all dissimilar materials utilized in the Centaur separation systems. Figure 19 illustrates the change of length of 321 stainless steel, 6061-T6 aluminum, and antimony lead with respect to epoxy fiber glass from 150^{O} to -452^{O} F (339^{O} to 4.4^{O} K).

FLSC Bend Propagation Tests

A series of tests was conducted at -420^{O} F (22^{O} K) to evaluate the propagation reliability of FLSC at consecutively reducing bend radii. Segments of 7- and 15-grain-per-foot (14.84- and 31.8-mg/cm) FLSC were bent about the FLSC axis of symmetry or an axis 90^{O} to the axis of symmetry and were initiated at -420^{O} F (22^{O} K) to determine the minimum bend radii at which propagation can be assured. The test configuration and results are presented in table V. Results indicated continuous propagation at cryogenic temperatures in all FLSC bend radii greater than 0.13 inch (0.33 cm), provided that controlled forming techniques are utilized during fabrication. All propagation failures occurred in the 7-grain-per-foot (14.84-mg/cm) FLSC, which indicated that the small RDX core in the 7-grain-per-foot (14.84-mg/cm) FLSC is more critically affected by small bend radii than the larger grain sizes.

FLSC Velocity Tests

A series of tests was conducted to determine the variations in propagation velocity in bent and straight sections of 7-grain-per-foot (14.84-mg/cm) FLSC at temperatures ranging from room temperature to -410^{O} F (28^{O} K). The propagation velocity in each piece of FLSC was not greatly affected by variations in bend radii or temperature, which indicated that FLSC propagation velocities remain relatively unchanged regardless of the temperature environment or the type of bends incorporated. FLSC propagation velocities ranged from 23 900 to 25 900 feet per second (7300 to 7900 m/sec). Further limited investigations, however, indicated that propagation velocities tend to decrease as the cross-sectional area of the grain is reduced, which indicated that the propagation velocity of smaller grains may exhibit greater sensitivity to temperature and/or bend radii.

Table VI provides velocity data for straight and curved sections of 7-grain-per-foot (14.84-mg/cm) FLSC at room and cryogenic temperatures.

FLSC Groove Contamination Tests

A series of tests to evaluate the effect of contamination in the jet-formation groove area of the FLSC was conducted to determine critical contamination levels. All tests conducted at room temperature and -410° F (28° K) with water, ice, and liquid and solid nitrogen in the groove area resulted in base metal cutting failures. Test results emphasized the importance of the design to guarantee a contamination-free groove area both at room and cryogenic temperatures. As the result of these tests and other supporting tests, a nonporous tape was incorporated to isolate the FLSC groove, and helium purge ports were designed into the nose-fairing FLSC retainers. Pressurized helium flowing through the ports eliminated the possibility of cryopumping into the FLSC groove area.

Detonator Gap Tests

A series of tests to evaluate the effect of increasing gaps between nonelectric detonators on propagation reliability was conducted at cryogenic temperatures. Results indicated excellent propagation reliability when end-to-end detonator gaps are 0.05 inch (0.127 cm) or less and when no contamination exists in the gaps between detonators, that is, the detonation transfer assembly is completely sealed and free of contamination.

Detonator Gap Contamination Tests

A series of tests to evaluate the effect of contamination (cryopumping) on the propagation reliability across detonator gaps was conducted to determine temperature environment and other contamination limitations on detonator joint designs (table VII). Results indicated that ice or liquid or solid nitrogen in the gap between detonators degrades the propagation reliability across detonator gaps. Thus, all detonator transfer assemblies must be completely sealed and located in temperature environments above the liquefaction temperature of oxygen and nitrogen.

FLSC Core Wicking Tests

The purpose of this series of tests was to determine the possibility of water wicking into the FLSC core through an exposed end. One end of each open-ended FLSC specimen was immersed in approximately 2 inches (5.08 cm) of distilled water for the soak period, as shown in table VIII. A 12-inch (30.48-cm) specimen and a 48-inch (121.9-cm) specimen were removed at the end of each interval. The 48-inch (121.9-cm) specimen was fired from its dry end at -400° F (33° K) and the 12-inch (30.48-cm) specimen was sectioned and examined visually. The distance from the immersed end at which propagation stopped is presented in table VIII for each soak period.

The witness plates beneath the FLSC showed evidence that the shaped charge jet had less energy immediately prior to stopping. Also, the cut penetration into the witness plate became less and the jet waivered. On the basis of these tests, it was concluded that water wicking can impair the cutting action of FLSC and that the exposed ends of all FLSC should be completely sealed with potting compound.

DESIGN PROOF TESTS

Maximum preflight confidence in the final FLSC separation systems was obtained through an extensive design proof test program conducted at General Dynamics/Convair, Point Loma, and the NASA Lewis Research Center. The intent of this test program was to demonstrate system reliability by performing full-scale and reduced-scale systems tests utilizing flight-type hardware and simulating flight conditions as accurately as test techniques permitted. Major tests conducted included

(1) Insulation-panel cryogenic separation tests at sea level
(2) Nose-fairing cryogenic separation tests at sea level
(3) Insulation and nose-fairing jettison tests at sea level
(4) Nose-fairing jettison tests at altitude
(5) Atlas-Centaur staging tests at sea level and at altitude
(6) FLSC qualification tests
(7) Separation system production lot acceptance tests

Each of the most significant test programs is described briefly to illustrate the magnitude of test effort undertaken to establish the FLSC separation systems as flight qualified.

Insulation-Panel Cryogenic Separation Tests at Sea Level

Two successive, successful full-scale insulation-panel separation tests from a fully cryotanked Centaur vehicle at sea level were conducted to demonstrate the ability of the insulation-panel FLSC separation system to separate the insulation panels under realistic flight thermal conditions, as well as to demonstrate the ability of the insulation panels to rotate free of the tank following FLSC separation. To achieve the objectives of this test, a flight-type Centaur tank, with flight-type insulation panels mounted under flight pretension loads, was cryotanked with liquid hydrogen and liquid nitrogen (substituted for liquid oxygen) to simulate launch conditions (fig. 20). Although this test was conducted at sea level rather than at altitude and did not include the effect of aerodynamic drag forces and heating conditions, the test accurately simulated flight cryogenic temperatures that exist between the tank and panels and in all components of the FLSC separation system.

Subsequent to a cryogenic soak period duplicating the period of time from tanking to panel jettison in flight, the panels were cut free of the Centaur tank by the FLSC separation system and permitted to rotate 5° into restraining catchers. Because of the complexity of the structural stand required to contain the cryogenically loaded Centaur tank, a complete jettison of the panels was considered impractical and was, therefore, not attempted. During each of the two tests, the liquid hydrogen and liquid nitrogen were detanked two times subsequent to a soak period comparable with a typical launch pad ground hold to simulate the effect of launch aborts on a full-scale system. At activation, under a system output current of 5 amperes, all FLSC separation systems functioned satisfactorily.

Nose-Fairing Cryogenic Separation Tests at Sea Level

Two successive, successful full-scale nose-fairing separation tests from a fully cryotanked Centaur vehicle at sea level were conducted to demonstrate the ability of the nose-fairing FLSC separation system to separate flight-type nose fairings under simulated launch conditions (fig. 21). These tests were conducted in a manner similar to that of the insulation-panel cryogenic unlatch tests with the exception that nose fairings rather than panels were separated and rotated from the Centaur vehicle. Accurate simulation of cryogenic conditions between nose fairing, tension tie, forward seal, and FLSC separation system (figs. 12 and 13) was achieved to evaluate the effect of cryopumping on all jettisonable hardware.

Subsequent to a cryogenic soak period, the fairings were cut free of the Centaur tank by the nose-fairing FLSC separation system and permitted to rotate 20° into restraining shock-absorber catchers.

This series of tests verified the separation capability of the nose-fairing FLSC separation system and established the FLSC temperatures that could be expected because of launch thermal conditions.

Insulation-Panel and Nose-Fairing Jettison Tests at Sea Level

Two successive, successful full-scale insulation-panel and nose-fairing jettison tests were conducted separately (figs. 22 and 23) from a jettison tower under simulated flight accelerations. During these tests, the panels and fairings were separately propelled up a jettison tower at sea level and ambient temperature to flight acceleration levels, at which time they were separated by the activation of their FLSC separation systems and jettisoned into horizontally positioned jettison nets.

Both series of tests successfully demonstrated the ability of the FLSC separation systems to sustain, safely, predicted flight accelerations and shock loadings prior to initiation.

Although these tests verified the reliability of the mechanics of separation, it became apparent during this program that nose-fairing separation tests at flight altitude (vacuum) conditions would be necessary to evaluate the true effect of nose-fairing deflections (during jettison) on the Centaur vehicle and spacecraft structures.

Nose-Fairing Jettison Tests at Altitude

A series of full-scale nose-fairing separation tests was conducted in the Lewis Space Power Chamber (fig. 24) simulating flight altitude conditions to evaluate accurately the effect of the increased nose-fairing jettison velocities and dynamic-response level attained at altitude (300 000 ft or 91 440 m) on the separation dynamics of the nose fairing and to verify the reliability of the flight FLSC separation system in a vacuum. As suspected, the nose-fairing jettison velocities were greatly increased in a vacuum, which significantly affected the dynamic response of the jettisoned fairings. Although the nose-fairing FLSC separation system proved to be functionally reliable during these vacuum tests, local structural redesign of various pyrotechnic attachments was necessary to eliminate the possibility of structural failure of the attachments due to the instantaneous shock-loading created during FLSC initiation at flight altitude conditions. Failure of any pyrotechnic attachment on the nose-fairing structure was considered prohibitive because the resulting debris could create potential hazards to the spacecraft or could create an inteference with fairing jettison.

Atlas-Centaur Staging Tests at Altitude

In addition to Point Loma tests, two Atlas-Centaur staging separations were simulated in the Lewis Space Power Chamber. Full-scale sections of the Atlas and Centaur vehicles were used (fig. 25). These tests established the ability of the Atlas-Centaur staging system to function at flight altitude conditions. Sea-level tests at Point Loma had demonstrated the ability of this system to function at cryogenic temperatures.

FLSC Qualification Tests

A design proof test program was established to demonstrate the ability of the three FLSC separation systems to initiate, propagate, and cut reliably under the most adverse combinations of flight temperature, humidity, vibration, and altitude. To provide an adequate test bed to evaluate these conditions, a test fixture (fig. 26) was designed with the capability of simultaneously testing at least one component each of all flight pyrotechnic hardware existing in the three FLSC separation systems. The fixture permitted the assembly of all test hardware in accordance with flight installation procedures and provided for realistic flight electrical activation of the systems. The fixture consisted of two separate tanks to permit cooling with liquid helium (-420° F or 22° K) at the nose-fairing FLSC attachments and with liquid nitrogen (-320° F or 78° K) at the insulation-panel and Atlas-Centaur attachments to assure a conservative thermal environment for each FLSC separation system during qualification testing.

All hardware tested was randomly selected from the production lots supporting flight vehicles. All electric and nonelectric detonators were randomly selected from flight production lots, whereas all MDF and FLSC hardware were fabricated from flight production lots but shortened in length to be compatible with the size limitations of the test fixture. Table IX presents a comparison of the numbers of flight-type hardware utilized per flight and per test.

To ensure complete qualification of the FLSC separation systems, 38 tests were conducted to the requirement that all tests be successively successful in accomplishing complete propagation of all pyrotechnic hardware and severance of all base metal. All predicted flight environments were simulated by the FLSC qualification test environments tabulated in table X.

The assembly of each test specimen included flight-type base metal hardware installed beneath all FLSC. After each test assembly was subjected to its prescribed test environment, the FLSC separation systems were activated per flight electrical sequence and, subsequent to testing, were inspected for completeness of propagation and satisfactory severance of base metal hardware.

A comparison of tables IX and X reveals that a total of 228 electric detonators, 1216 nonelectric detonators, 304 lengths of MDF, and 304 lengths of FLSC were activated in support of this qualification program. This quantity is sufficient to simulate approximately 19 successful Centaur launches. All components performed satisfactorily in every test.

Following the completion of this qualification test program, two cryogenic multiabort tests were conducted on additional test specimens to demonstrate the cryogenic abort capability of the FLSC system. During these tests, the FLSC components were cycled between room temperature and their minimum flight temperature. Nine launch aborts were simulated without evidence of system degradation.

Production Lot Acceptance Tests

Following the successful completion of the FLSC qualification program, a production lot acceptance test program was initiated to provide verification of the flight acceptability and storage life capability of the production lots supporting each Atlas-Centaur flight. To accomplish this program, each flight set of FLSC hardware and two corresponding sets of test hardware were manufactured simultaneously from the same production lots and by the same technicians. Both flight and test hardware were stored side by side until approximately 6 months prior to the launch date supported by this hardware, at which time the test hardware was subjected to the environmental conditions of Test Series 2 (table X) prior to ignition. Successful completion of this test established a flight acceptable status for the FLSC hardware supporting that particular flight and served to verify the storage-life capability for that FLSC assembly.

FLIGHT HISTORY

Centaur, the nation's first space vehicle to utilize the FLSC severance technique to perform all major systems separation, achieved its initial flight success from Cape Kennedy, Florida on November 27, 1963. By late 1967, eleven flights using the separation system described previously had been successfully completed. The initial Surveyor flight (AC-10), programmed to soft-land a Surveyor spacecraft on the Moon, was a success on the basis of Centaur performance as well as of Surveyor spacecraft achievement of mission objectives. In all flights, the FLSC separation systems performed precisely as planned, successfully severing and jettisoning the insulation panels and nose fairing, and successfully accomplishing Atlas-Centaur staging in flight. The reliable function of this design must be attributed to the extensive design evaluation test and qualification test programs conducted during and subsequent to the design phase of the FLSC separation system. Both test programs contributed significantly towards updating and improving the state of the art of FLSC design application, particularly at cryogenic temperatures in an air environment.

CONCLUDING REMARKS

The successful application of FLSC on the Centaur space vehicle has established this severance medium as a highly refined and reliable design for utilization in aerospace-vehicle-separation systems. As proved during the development and mission phases of the Centaur program, this concept can be designed reliably provided that the following design requirements are enforced:

1. Operational temperatures of FLSC in an air environment should be limited between 250° and -270° F (394° and 106° K) wherever possible.
2. Utilization of FLSC in thermal ranges below -270° F (106° K) in an air environment requires a design that will eliminate the possiblity of cryopumping oxygen or nitrogen into the FLSC standoff groove. The groove must be free of contaminants to ensure proper formation of the cutting jet during FLSC propagation.
3. Reliable utilization of FLSC as a cutting medium can be assured if the FLSC is mounted in precision-machined retainers accurately mated to the base metal to assure desired standoff dimensions.
4. All detonation transfer connections should be end to end with positive gap control.
5. Initiation redundancy should be provided throughout the FLSC separation system to assure successful function in the event of local component failures.
6. An extensive design evaluation test program at flight environmental conditions should be conducted to establish the safe working limitations of each FLSC grain size and of all detonators to be employed.
7. Full-scale systems tests should be conducted to verify the reliability of the system under simulated flight conditions.
8. A complete flight qualification test program should be conducted to verify the reliability of the final design at extreme flight environmental conditions.
9. All pyrotechnic hardware, including FLSC, MDF, and electric and nonelectric detonators to be utilized for flight, should be established as controlled components through all phases of production, and storage and all production lots coded to permit shelf-life control.
10. A production lot acceptance test program should be initiated to provide verification of the flight acceptability and storage-life capability of the production lots supporting each flight.

11. Installation of all FLSC separation systems should be controlled by detailed assembly procedures specifying step-by-step assembly details, including detailed techniques for inspecting the assembled hardware for correct FLSC standoff dimensions.

If these design requirements are rigidly enforced, an FLSC separation system can be designed to ensure functional reliability for any space vehicle requirement.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 11, 1968,
491-05-00-02-22.

APPENDIX - DESIGN REQUIREMENTS FOR FLEXIBLE LINEAR-SHAPED CHARGE SEPARATION SYSTEM

The following list of design requirements was established by the NASA Lewis Reseach Center and General Dynamics/Convair during the initial stages of the FLSC system design to ensure reliable performance in the extreme thermal environment of the Centaur vehicle:

(1) All jettison system FLSC, MDF, and NED pyrotechnic hardware shall be capable of functioning over a temperature range of -423° to 250° F (21° to 394° K).

(2) All electric detonators shall be capable of functioning over a temperature range of -65° to 250° F (219° to 394° K).

(3) All pyrotechnic hardware shall be protected from aerodynamic heating with maximum allowable temperatures not to exceed 250° F (394° K).

(4) All electric detonators for the nose-fairing FLSC shall be mounted on the nose fairing.

(5) All electric detonators for the insulation-panel FLSC shall be mounted on the insulation panels.

(6) All electric detonators for the staging system FLSC shall be mounted on the interstage adapter.

(7) The design shall provide for dual initiation of all lengths of FLSC in each system for initiation redundancy.

(8) All electric and nonelectric detonators shall be mounted end to end for propagation reliability.

(9) All detonator joints shall be screwed together with positive gap control between detonators.

(10) All detonators shall be completely enclosed and sealed.

(11) All nonelectric detonators (end primers) and FLSC shall be firmly bonded.

(12) All joints shall be completely sealed to prevent liquid entering as a result of cryopumping or inclement weather.

(13) All flight components shall have ample rigidity to preclude damage resulting from bending or vibration and to permit assembly as precision hardware to control FLSC standoff dimensions.

(14) All separation systems shall possess a 1-watt - 1-ampere no-fire capability (ref. 3).

(15) Solvents detrimental to explosives shall not be used.

(16) Cold helium gas shall not impinge on system components.

(17) Activation of the system shall not result in metal shrapnel, cracking, or splitting of metal components.

(18) Provisions shall be made to keep all contamination, including ice and liquid due to cryopumping, out of the FLSC groove.

(19) The design shall permit all components to be easily X-rayed at some point prior to installation.

(20) The system shall be designed with as much simplicity as is consistent with reliability and must be capable of being installed and inspected by people of normal dexterity to the requirements of an installation and inspection procedure.

(21) Attachments utilizing tapped holes in aluminum shall not be used.

(22) The internal configuration of all pyrotechnic joints shall be standardized throughout the system, although mounting provisions may vary.

(23) PETN end primers and MDF shall be used throughout.

(24) RDX shall be used in all FLSC.

(25) The design shall use a minimum number of field joints.

(26) The separation system shall be designed to allow inspection of FLSC standoff dimensions after installation.

(27) The design shall incorporate the same end primers throughout the system.

(28) Installation of pyrotechnics shall be accomplished after structural assembly of the vehicle, including helium-purge leak checks and preflight cryogenic tanking tests to minimize the number of cryogenic aborts applied to the FLSC separation systems.

(29) The maximum permissible length of fiber-glass shrapnel shall be 18 inches (45.7 cm) with a weight not to exceed 1/4 pound (0.113 kg).

(30) Joints shall be designed to permit X-raying after installation.

(31) Environmental component tests shall be conducted on all proposed joint configurations prior to releasing production drawings.

(32) Field-installed seals shall be bonded to the major structure.

(33) The FLSC systems, including all supporting pyrotechnics, shall be capable of withstanding a minimum of three cryogenic flight aborts without evidence of system degradation.

(34) The entire FLSC separation systems shall be qualified to a flight qualification test program.

(35) Production lot controls shall be established to control the production and shelf life of all pyrotechnics.

REFERENCES

1. Culling, H. P.: Statistical Methods Appropriate for Evaluation of Fuze Explosive-Train Safety and Reliability. NAVORD Rep. No. 2101, Naval Ordnance Lab., 1953, App. A.

2. Anon.: Technical Information on DuPont Military Specialties. Bulletin No. ES61-1A, E. I. DuPont de Nemours, Co., Inc.

3. Anon.: General Range Safety Plan. AFM TCP-80-2A, United State Air Force.

TABLE I. - FLSC SEPARATION SYSTEM CONCEPT

Hardware components		Separation function	Hardware function	Component	System
Primary pyrotechnic	Supporting				
Electric detonator (ED)	--------------	Initiation	Transform electrical energy into pyrotechnic energy		
--------------------	Dual detonator assembly (DDA)	Initiation	Contain ED's and NED's to controlled tolerance gap		
Nonelectric detonator (NED)	--------------	Transfer detonation	Transfer pyrotechnic energy to MDF and FLSC assemblies		
Mild detonating fuse (MDF)	--------------	Transfer detonation	Transfer pyrotechnic energy from point of electrical initiation to FLSC severance assembly		
--------------------	Detonation transfer joint (DTJ)	Transfer detonation	Contain NED's to controller minimum gap		
Flexible linear-shaped charge (FLSC)	--------------	Severance	Provide cutting edge through base metal by inversion of V-shaped explosive core		

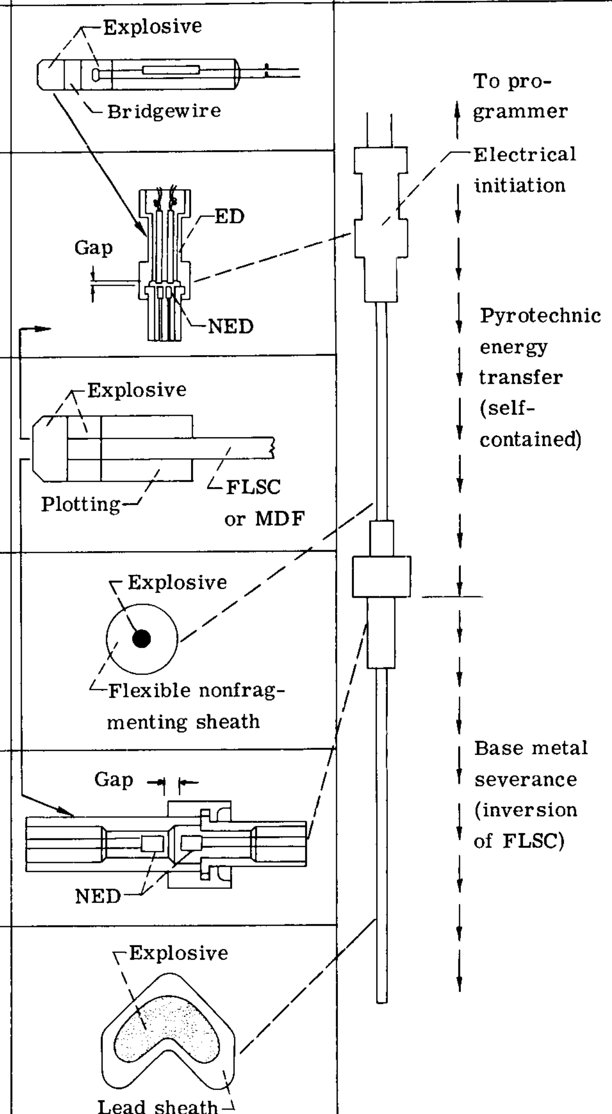
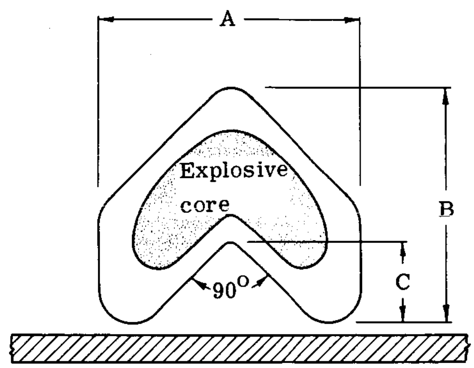


TABLE II. - APPROXIMATE DIMENSIONS AND WEIGHTS OF

VARIOUS SIZES OF FLSC USED ON CENTAUR

[Ref. 2.]



Location on Centaur	RDX explosive weight		Dimensions					
	grains/ft	mg/cm	Height, B		Width, A		Grove depth, C	
			in.	cm	in.	cm	in.	cm
Nose fairing	7.0	14.8	0.067	0.170	0.100	0.254	0.020	0.051
Insulation panel	10.0	21.2	.080	.203	.099	.251	.012	.030
Stage	15.0	31.8	.095	.241	.135	.343	.021	.053

TABLE III. - SUMMARY OF FLSC DESIGN DETAILS

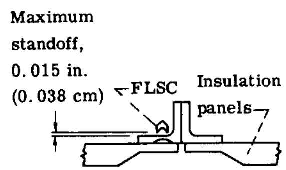
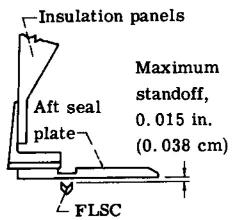
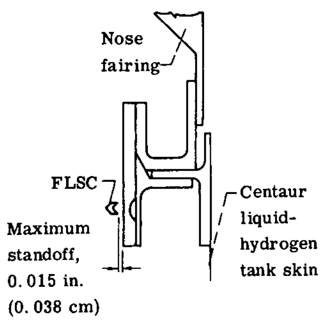
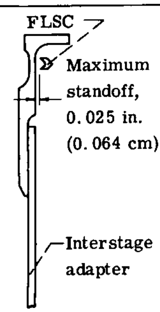
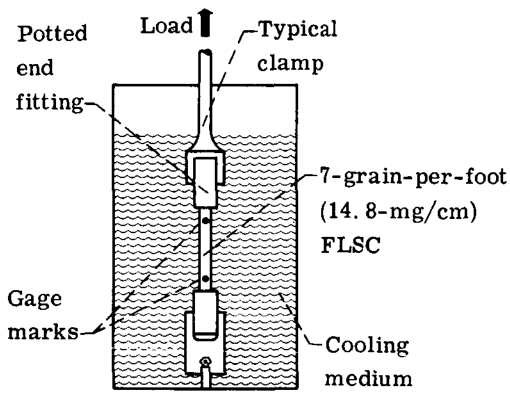
Separation system	Typical FLSC installation in system	FLSC grain size		Maximum standoff height		Base metal			Minimum temperature				FLSC retainer
						Aluminum designation	Thickness		Flight		Qualification test		
		grains/ft	mg/cm	in.	cm		in.	cm	°F	°K	°F	°K	
Insulation panel (longitudinal)		10	21.2	0.015	0.038	2024-T4	0.070	0.178	-240	122	-320	78	Fiber glass
Insulation panel (circumferential)		10	21.2	0.015	0.038	6061-T6	0.070	0.178	-278	101	-320	78	Fiber glass
Nose fairing		7	14.8	0.015	0.038	6061-T6	0.030	0.076	-320	78	-368	51	Fiber glass and helium purge port
Staging		15	31.8	0.025	0.064	2024-T42	0.090	0.229	-220	133	-320	78	Fiber glass

TABLE IV. - PERCENT ELONGATION AND TENSILE STRENGTH OF 7-GRAIN-PER-FOOT (14.8-mg/cm) FLSC



(a) Specimens loaded to failure

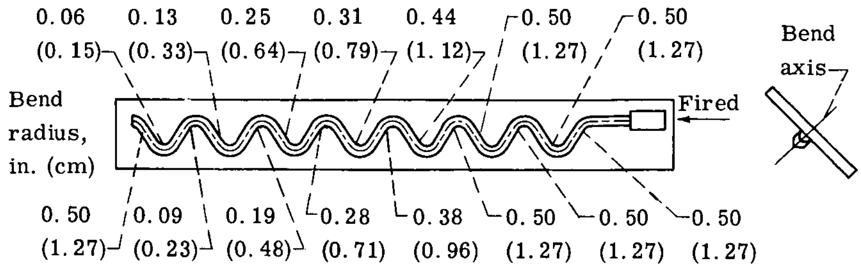
Temperature		Failure load				Elongation, percent	
°F	°K	Average		Lowest		Average	Lowest
		lb	N	lb	N		
-400	33	60.0	267	55.0	245	13.5	8.0
-320	78	41.9	186	39.0	173	18.4	9.0
-200	144	38.2	170	32.5	145	14.7	14.0
-100	200	26.7	119	25.0	111	8.8	8.0

(b) Specimens loaded by thermal contraction (no failure)

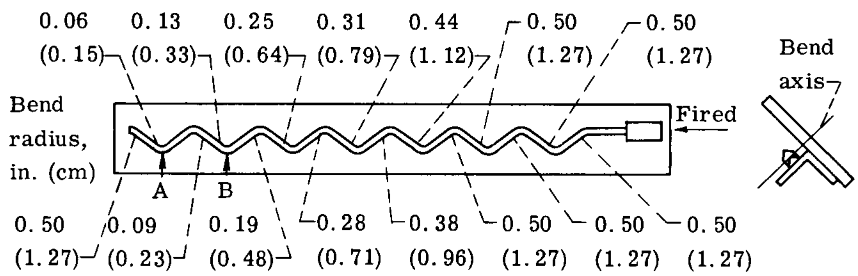
Temperature		Load		Elongation, percent
°F	°K	lb	N	
-400	33	27.5	122	5.0
-320	78	24.5	109	3.0

TABLE V. - FLSC BEND TESTS

[Four specimens per test; temperature, -420° F (22° K).]



Series 1



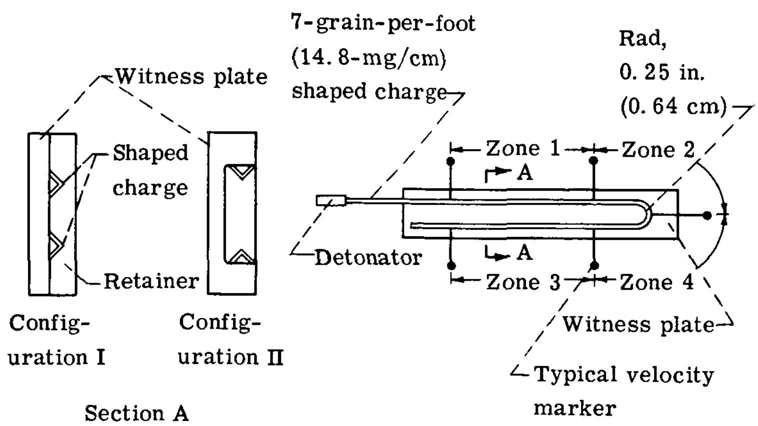
Series 2

Series	Type of shaped charge		Results
	grains/ft	mg/cm	
1	15	31.8	Specimens propagated completely
	7	14.8	Specimens propagated completely
2	15	31.8	Specimens propagated completely
	7	14.8	Two specimens propagated completely; one specimen failed at point A; one specimen failed at point B

TABLE VI. - RESULTS OF VELOCITY TESTS OF

IN-PLANE BEND PANEL

[Twelve specimens per test.]



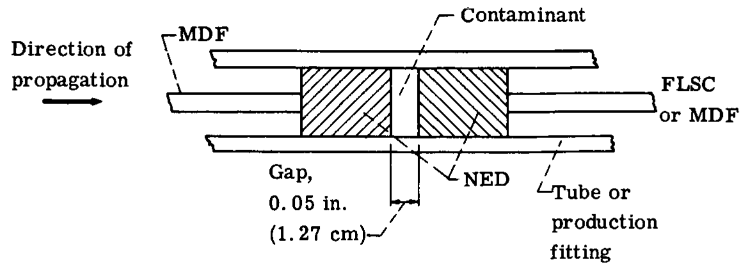
(a) Configuration I

Temperature		Zone			
°F	°K	1	2	3	4
		Average velocity, m/sec			
-400	33	7630	7590	7498	7312
Room	Room	7989	7670	7490	7397

(b) Configuration II

Temperature		Zone			
°F	°K	1	2	3	4
		Average velocity, m/sec			
-400	33	7705	7622	7552	7233
Room	Room	7877	7978	7780	7400

TABLE VII. - NONELECTRIC DETONATOR (NED) PROPAGATION TESTS

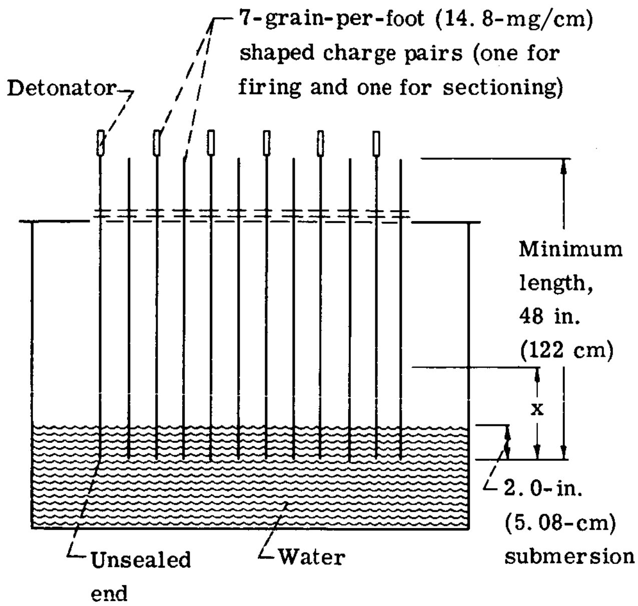


Material in gap between nonelectric detonators	Temperature		Number of tests	Number of failures	MDF	FLSC		
	^{o}F	^{o}K			Grain load			
					2 grains/ft (4.24 mg/cm)	7 grains/ft (14.8 mg/cm)	10 grains/ft (21.2 mg/cm)	15 grains/ft (31.8 mg/cm)
Water (no containment)	Room	Room	5	0	X	--	--	--
Ice (no containment)	-100	200	5	0	X	--	--	--
Ice (in tube)	-100	200	5	0	X	--	--	--
Liquid nitrogen (in tube)	-320	78	5	0	X	--	--	--
Solid nitrogen (in tube)	-420	22	8	6	X	--	--	--
Liquid nitrogen (with production fittings)	-320	78	9	2	X	3	3	3
Ice (with production fittings)	-400	33	9	0	X	3	3	3
Solid nitrogen (with production fittings)	-400	33	12	0	X	4	4	4
Liquid nitrogen (with production fittings)	-320	78	[a]4	3	X	4	--	--
Liquid nitrogen (with production fittings)	-320	78	[a]4	1	X	4	--	--

[a]Nonelectric detonators with manufacturing cracks used in these tests.

TABLE VIII. - FLSC CORE WICKING TEST RESULTS

[All specimens fired at -400° F (33° K) in gaseous helium atmosphere.]



Time in water, days	Distance from end that shaped charge stopped propagating, x	
	in.	cm
1	5.33	13.52
2	4.30	10.91
5	7.40	18.80
6	7.66	19.45
7	6.08	15.43
8	6.95	17.65
9	6.55	16.62
12	7.79	19.80
13	8.62	21.88
14	7.68	19.50

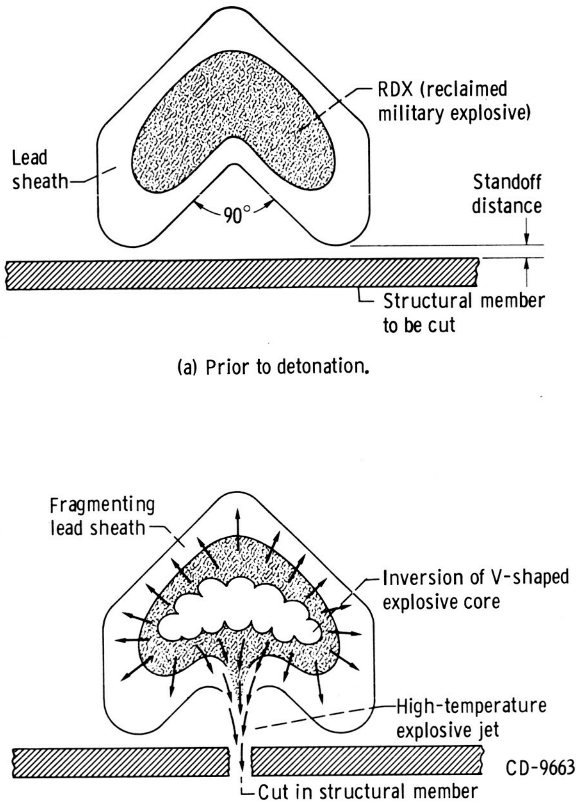
TABLE IX. - COMPARISON OF FLIGHT AND TEST PYROTECHNIC HARDWARE

Pyrotechnic hardware	Separation system pyrotechnic hardware								Configuration comparison
	Nose fairing		Insulation panels		Atlas-Centaur staging		All systems		
	Hardware units used per -						Total hardware used		
	Flight	Test	Flight	Test	Flight	Test	Flight	Test	
Electric detonator (ED)	4	2	4	2	4	2	12	6	Identical
Nonelectric detonator (NED)	16	8	32	16	16	8	64	32	Identical
Mild detonating fuse (MDF)	4	2	10	4	4	2	18	8	Reduced length on test unit
Flexible linear-shaped charge (FLSC)	2	2	6	4	2	2	10	8	Reduced length on test unit

TABLE X. - FLSC QUALIFICATION TEST ENVIRONMENTS

Series	Number of tests	Thermal cycles	Nose fairing FLSC, °F	Nose fairing FLSC, °K	All other FLSC, °F	All other FLSC, °K	Dual detonator, °F	Dual detonator, °K	Atmosphere	Humidity, percent	Rain, in./hr	Rain, cm/hr	Vibration	Altitude, ft	Altitude, m
			Temperature of separation system components												
I	5	1st	-395±15	36±8.3	-305±15	86±8.3	-65±20	219±11.1	Air	95±5	--	------	Axial	--------------	--------------
		2nd	-395±15	36±8.3	-305±15	86±8.3	-65±20	219±11.1	Air	95±5	--	------	---------	--------------	--------------
II	5	1st to 3rd	-395±15	36±8.3	-305±15	86±8.3	-65±20	219±11.1	Air	95±5	--	------	---------	--------------	--------------
		4th	-395±15	36±8.3	-305±15	86±8.3	-65±20	219±11.1	Gaseous nitrogen	95±5	--	------	Axial	60 000 to 90 000	18 300 to 27 450
III	5	1st	80±10	300±5.6	80±10	300±5.6	80±10	300±5.6	Air	Uncontrolled	[a]4	[a]10.16	---------	--------------	--------------
		2nd	-395±15	36±8.3	-305±15	86±8.3	-65±15	219±8.3	Gaseous nitrogen	95±5	--	------	Tangential	60 000 to 90 000	18 300 to 27 450
IV	5	1st to 3rd	80±10	300±5.6	80±10	300±5.6	80±10	300±5.6	Air	Uncontrolled	[a]4	[a]10.16	---------	--------------	--------------
		4th	250±10	394±5.6	250±10	394±5.6	160±10	344±5.6	Air	Uncontrolled	--	------	Tangential	60 000 to 90 000	18 300 to 27 450
V	6	1st	-395±15 Plus aerodynamic heating	36±8.3	-305±15 Plus aerodynamic heating	86±8.3	-65±20 Plus aerodynamic heating	219±11.1	Gaseous nitrogen	95±5	--	------	Radial	60 000 to 90 000	18 300 to 27 450
VI	6	1st	-65±20 Plus aerodynamic heating	219±11.1	-65±20 Plus aerodynamic heating	219±11.1	-65±20 Plus aerodynamic heating	219±11.1	Air	95±5	--	------	Radial	60 000 to 90 000	18 300 to 27 450
VII	6	1st	100±10 Plus aerodynamic heating	311±5.6	100±10 Plus aerodynamic heating	311±5.6	100±10 Plus aerodynamic heating	311±5.6	Air	95±5	--	------	Radial	60 000 to 90 000	18 300 to 27 450

[a]Duration of rain, 2 hr.



(a) Prior to detonation.

(b) During detonation.

Figure 1. - Flexible linear-shaped charge (FLSC) cross section.

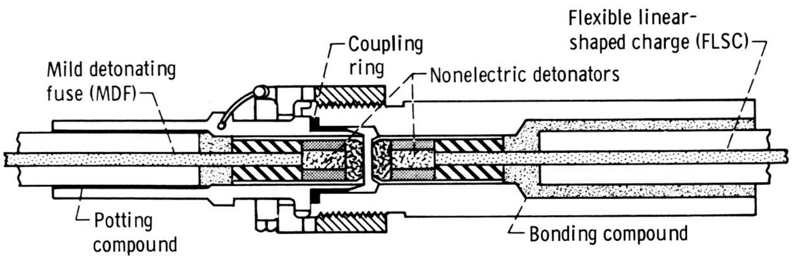


Figure 2. - Detonation transfer joint.

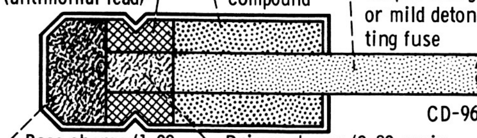


Figure 3. - Nonelectric detonator.

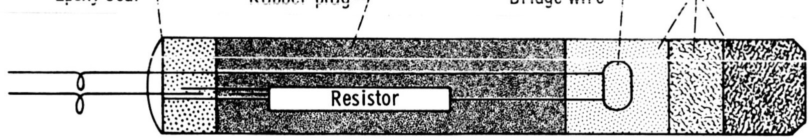


Figure 4. - Electric detonator.

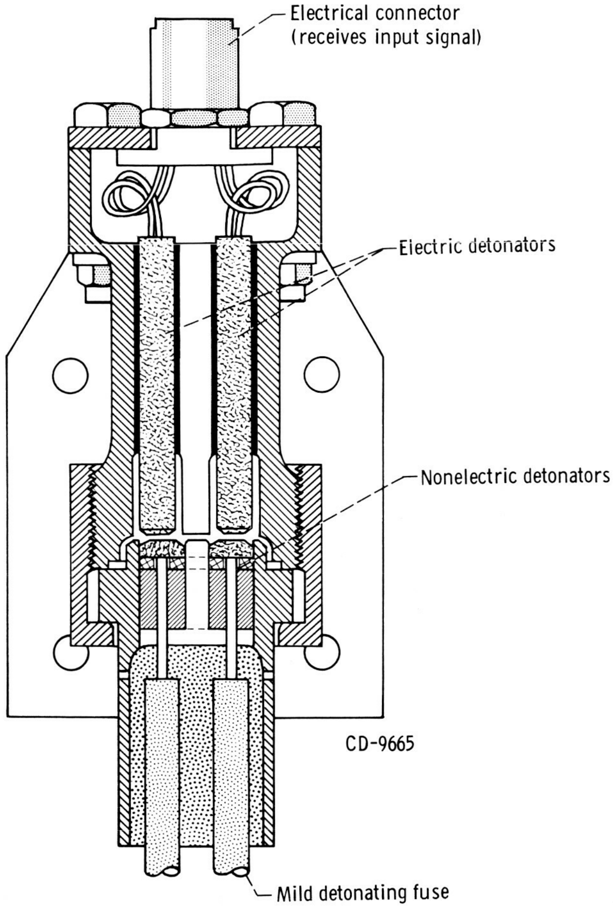


Figure 5. - Dual detonator assembly.

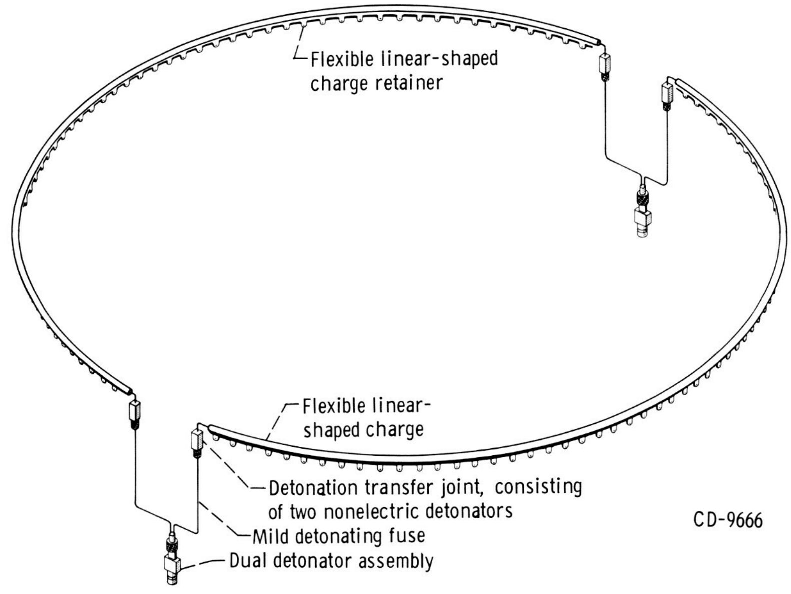
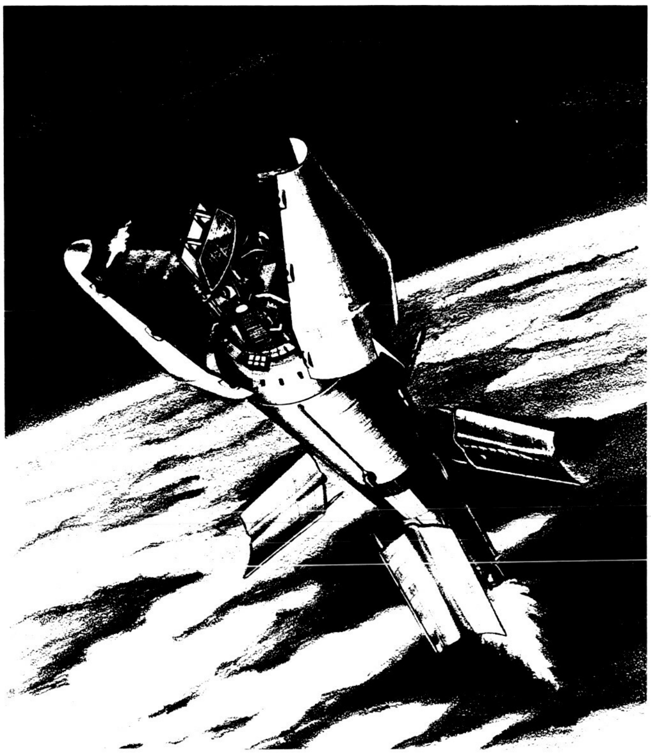
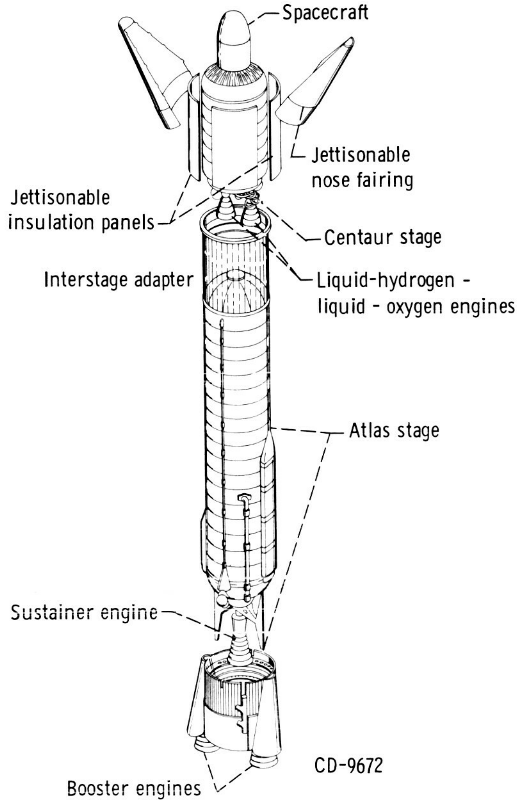


Figure 6. - Typical flexible linear-shaped charge separation system assembly.



(a) Jettisoning of insulation panels and nose fairings.



(b) Schematic diagram of jettisonable structures.

Figure 7. - Atlas-Centaur vehicle.

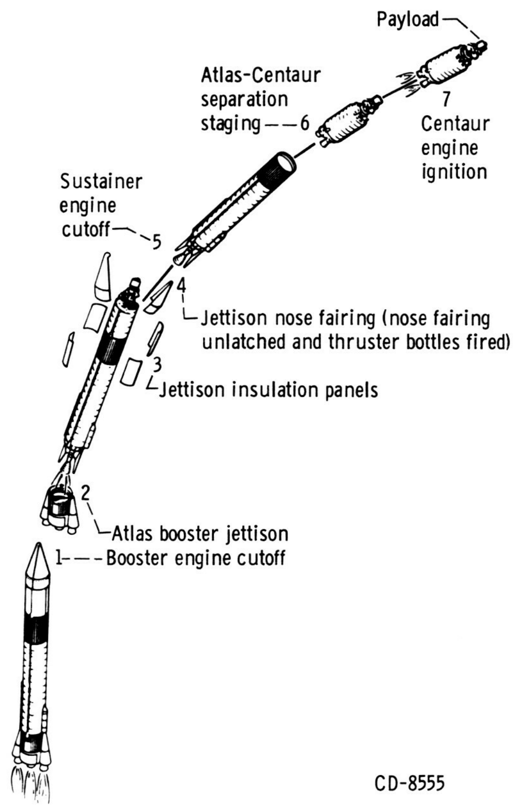


Figure 8. - Typical Atlas-Centaur events profile.

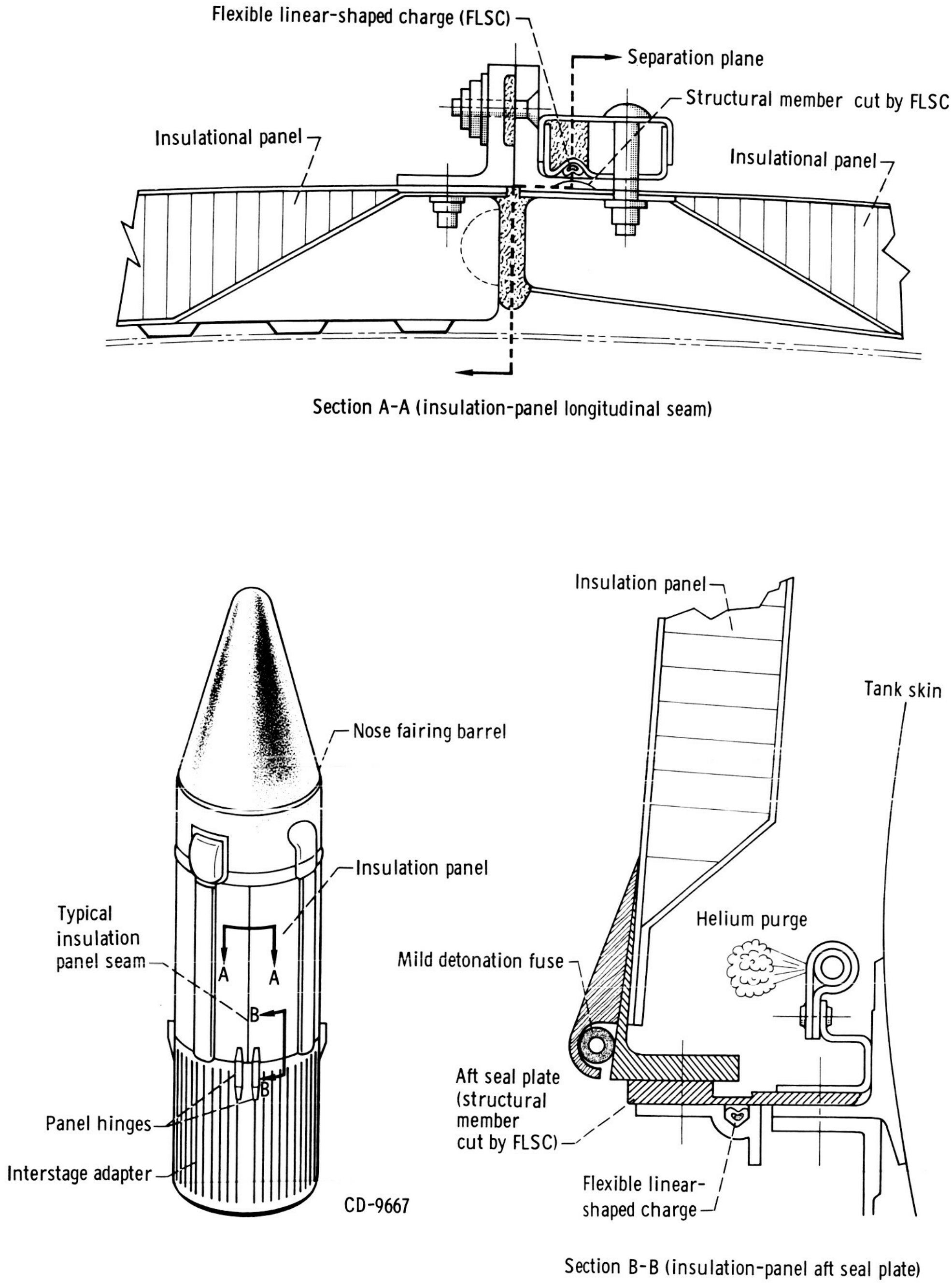


Figure 9. - Insulation-panel attachment details.

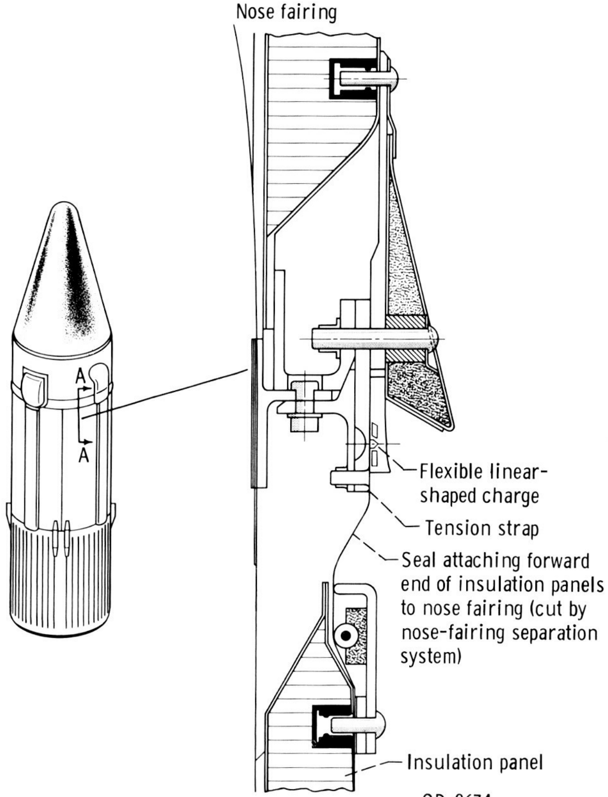


Figure 10. - Insulation-panel forward attachment detail.

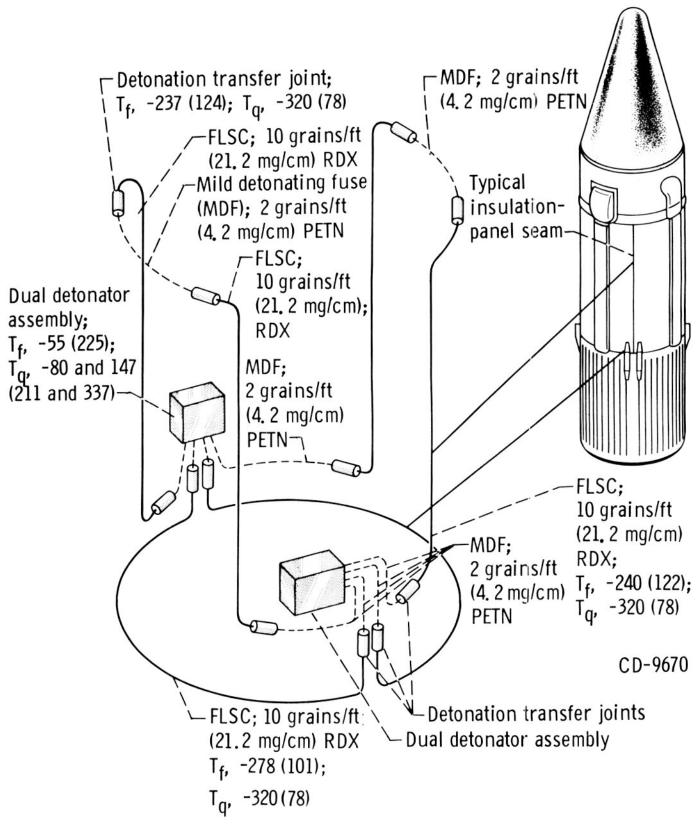


Figure 11. - Insulation-panel separation system. (Flight temperatures T_f and qualification test temperatures T_q are given in °F (°K).)

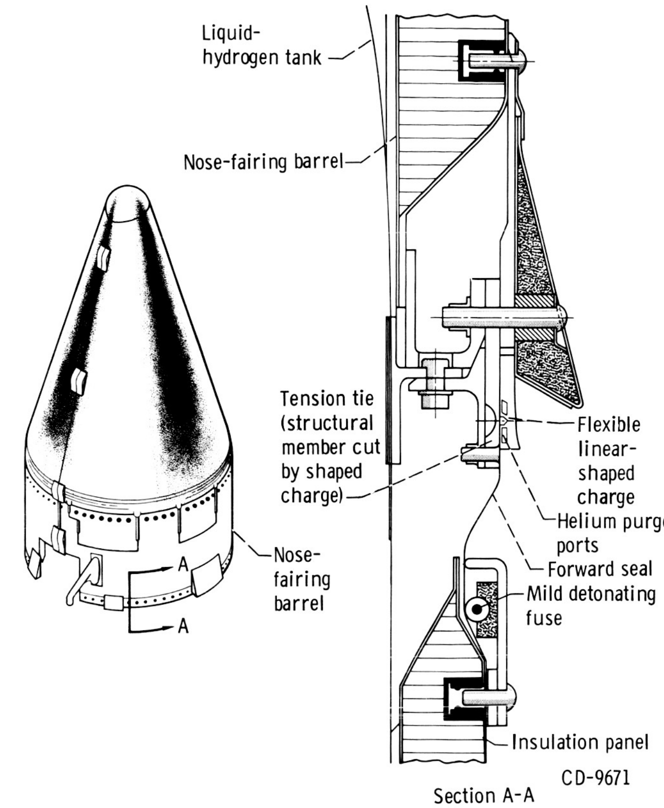


Figure 12. - Nose-fairing barrel attachment details.

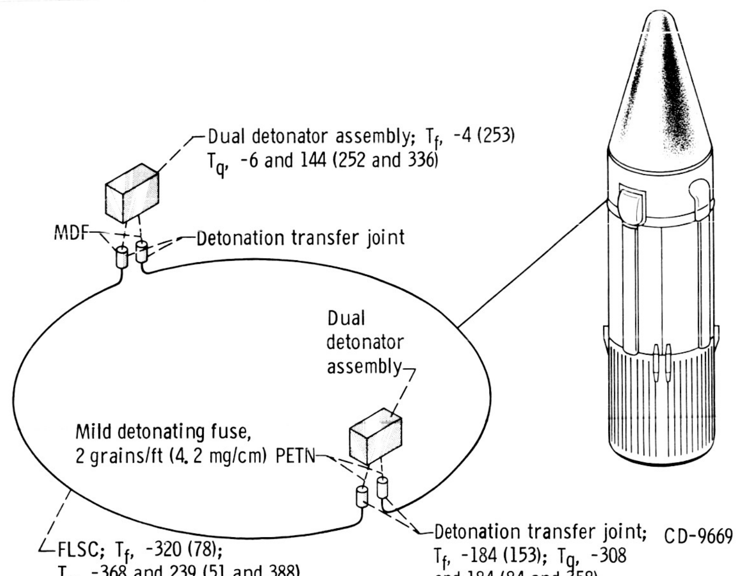


Figure 13. - Nose-fairing separation system. (Flight temperature T_f and qualification test temperatures T_q are given in °F (°K).)

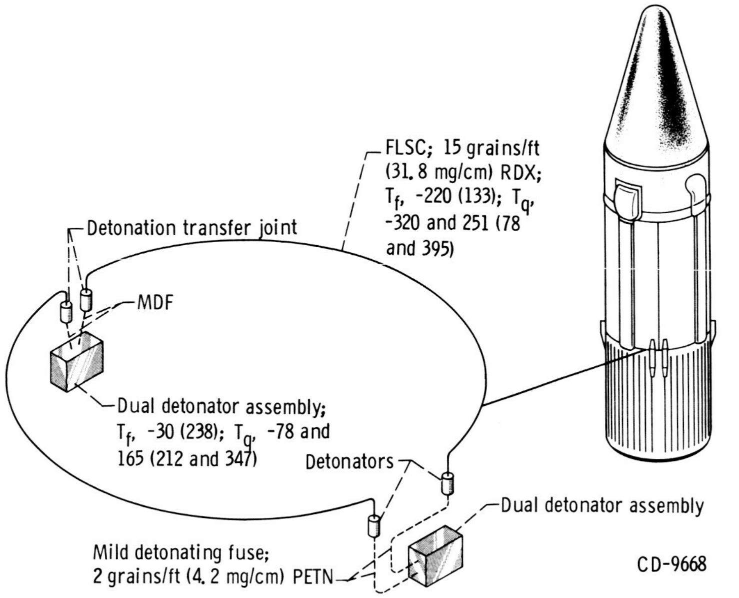


Figure 14. - Atlas-Centaur staging separation system. (Flight temperatures T_f and qualification temperatures T_q are given in °F (°K).)

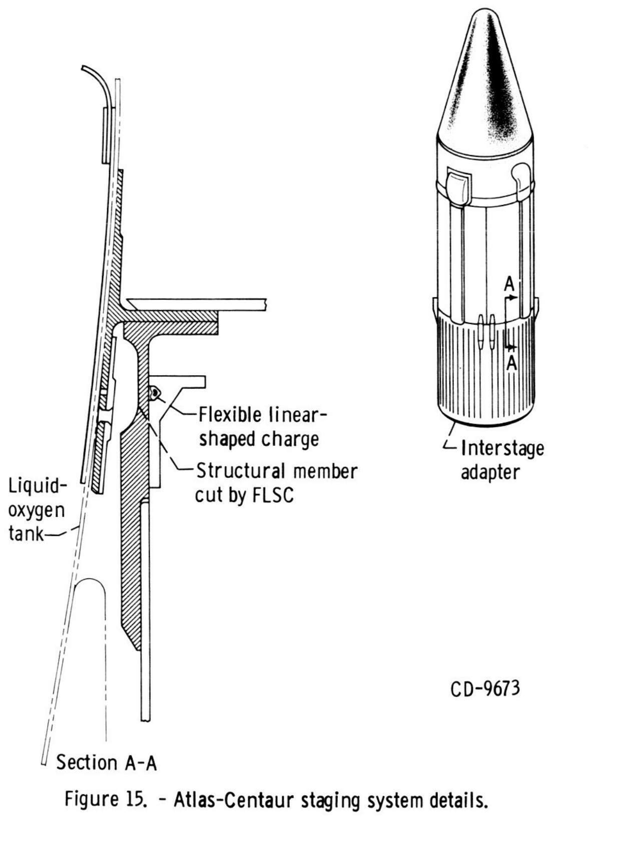


Figure 15. - Atlas-Centaur staging system details.

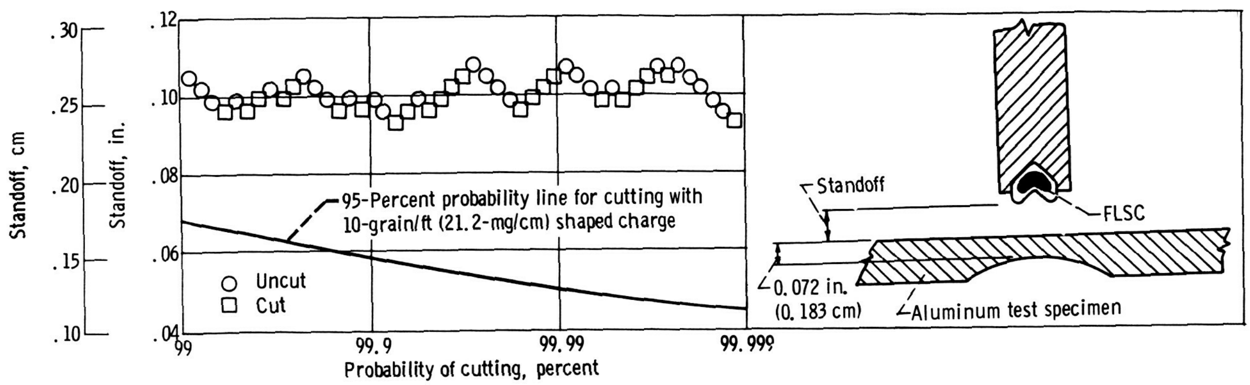


Figure 16. - Results of 10-grain-per-foot (21.2-mg/cm) FLSC Bruceton tests at room temperature.

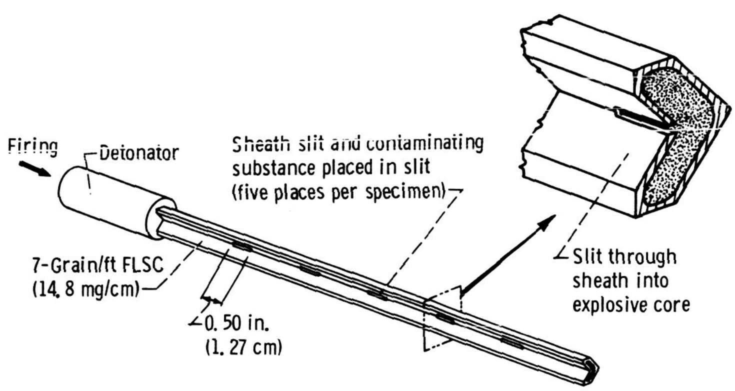


Figure 17. - FLSC core contamination tests. Contaminating substances, methyl ethyle ketone, trichloroethylene, high-flas naphtha, toluene, petroleum ether, and methanol; quantity, three; test temperature, -410° F (28° K); results, all propagated.

FLSC specimen	Gap		Temperature		Number propagated	Number failed
	in.	cm	°F	°K		
Ends butted	0.00	0.00	Room	Room	4	0
	.00	.00	-400	33	1	3
With gap	0.010	0.025	Room	Room	2	2
	.010	.025	-400	33	0	4

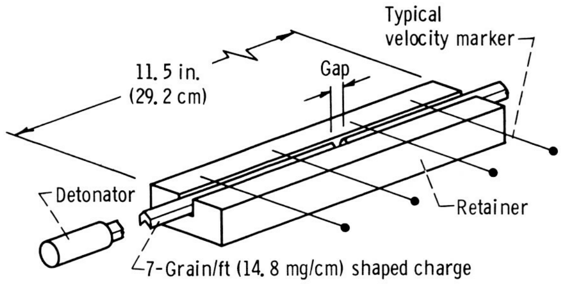


Figure 18. - FLSC gap tests.

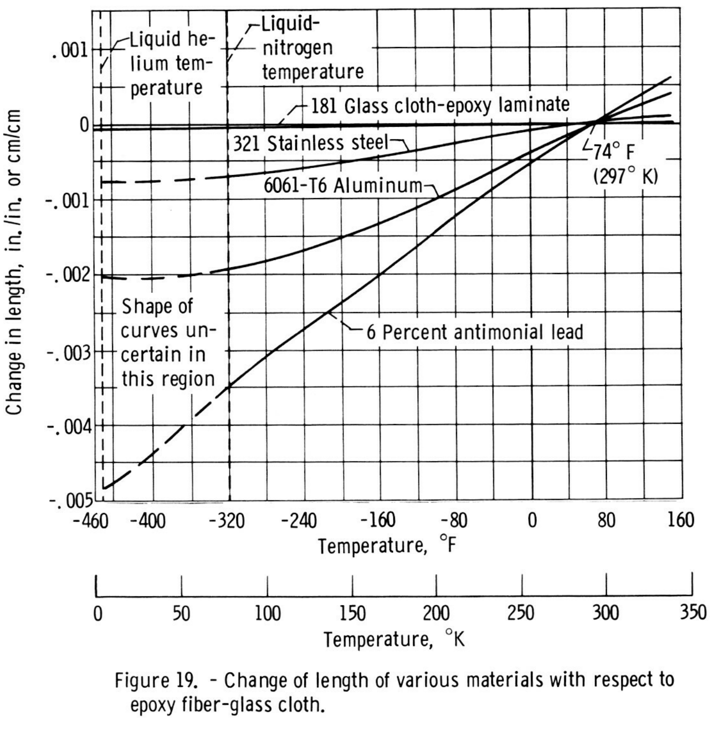


Figure 19. - Change of length of various materials with respect to epoxy fiber-glass cloth.

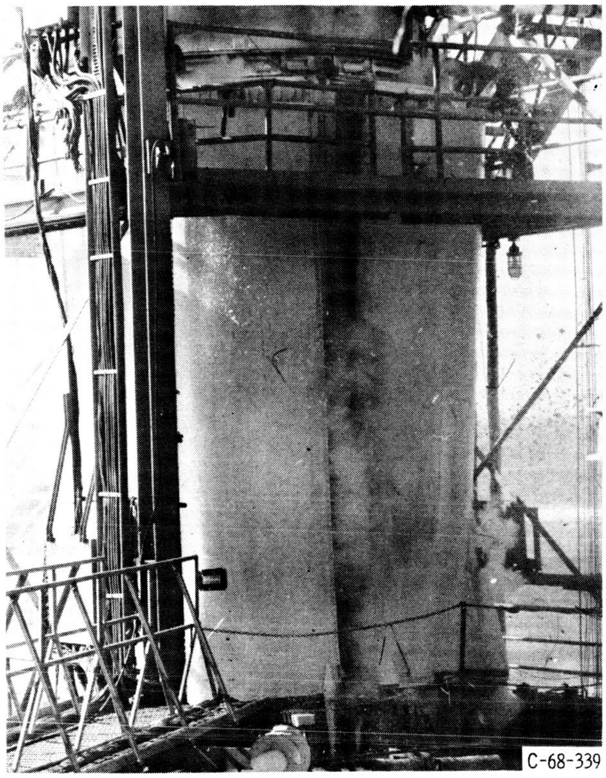


Figure 20. - Insulation-panel cryo-unlatch test.

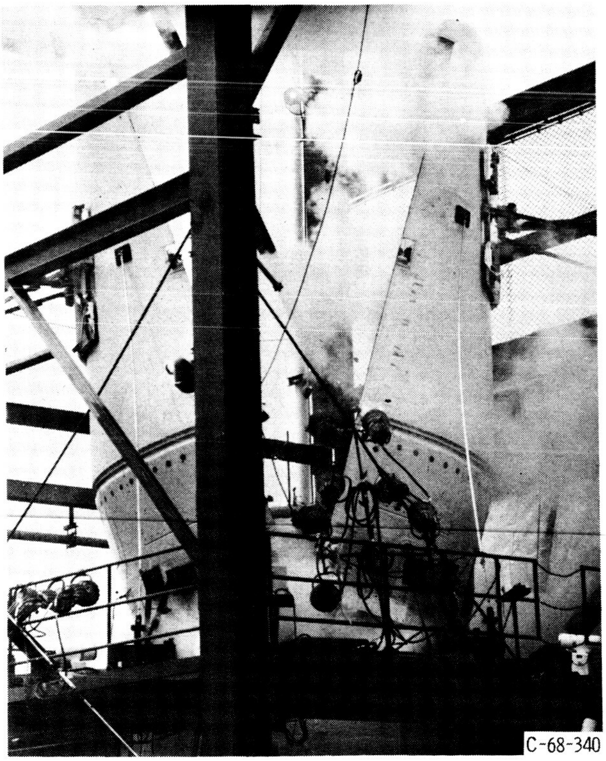


Figure 21. - Nose-fairing cryo-unlatch test.

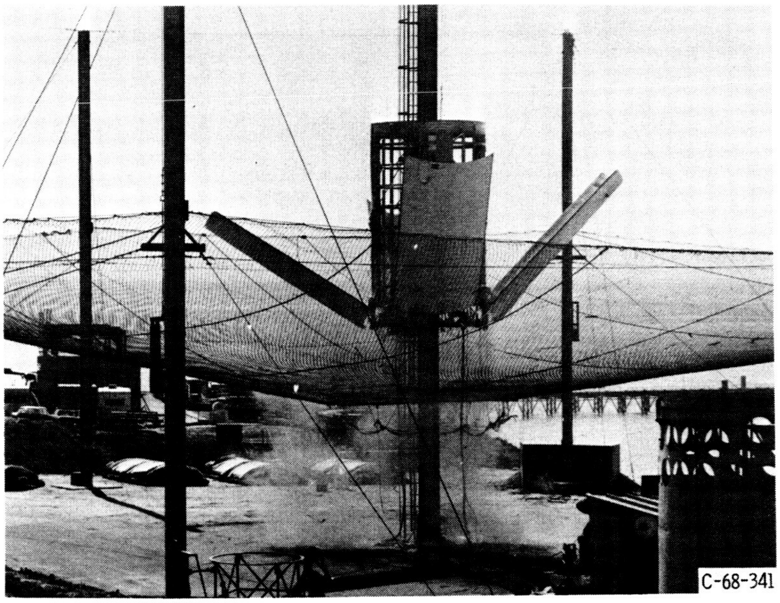


Figure 22. - Insulation-panel jettison test at sea level.

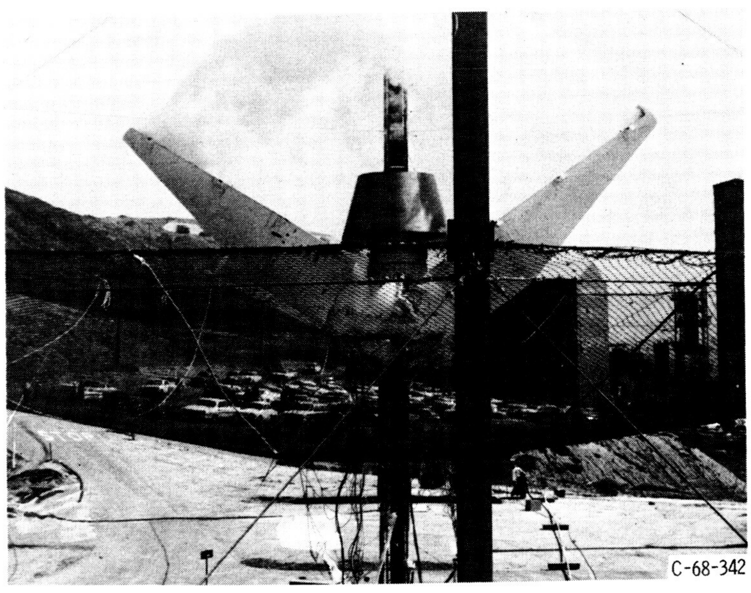


Figure 23. - Nose-fairing jettison test at sea level.

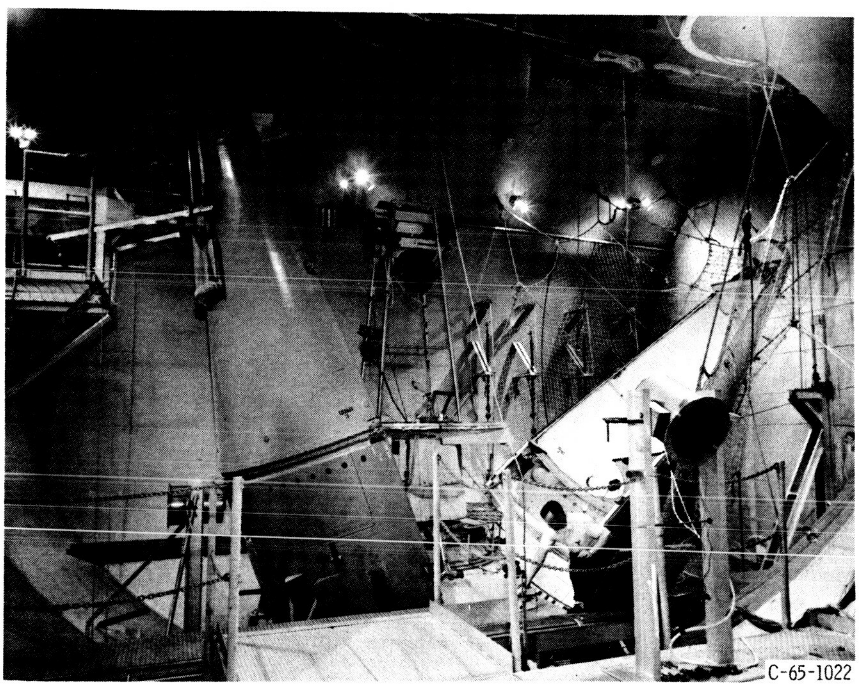


Figure 24. - Nose-fairing jettison test at altitude.

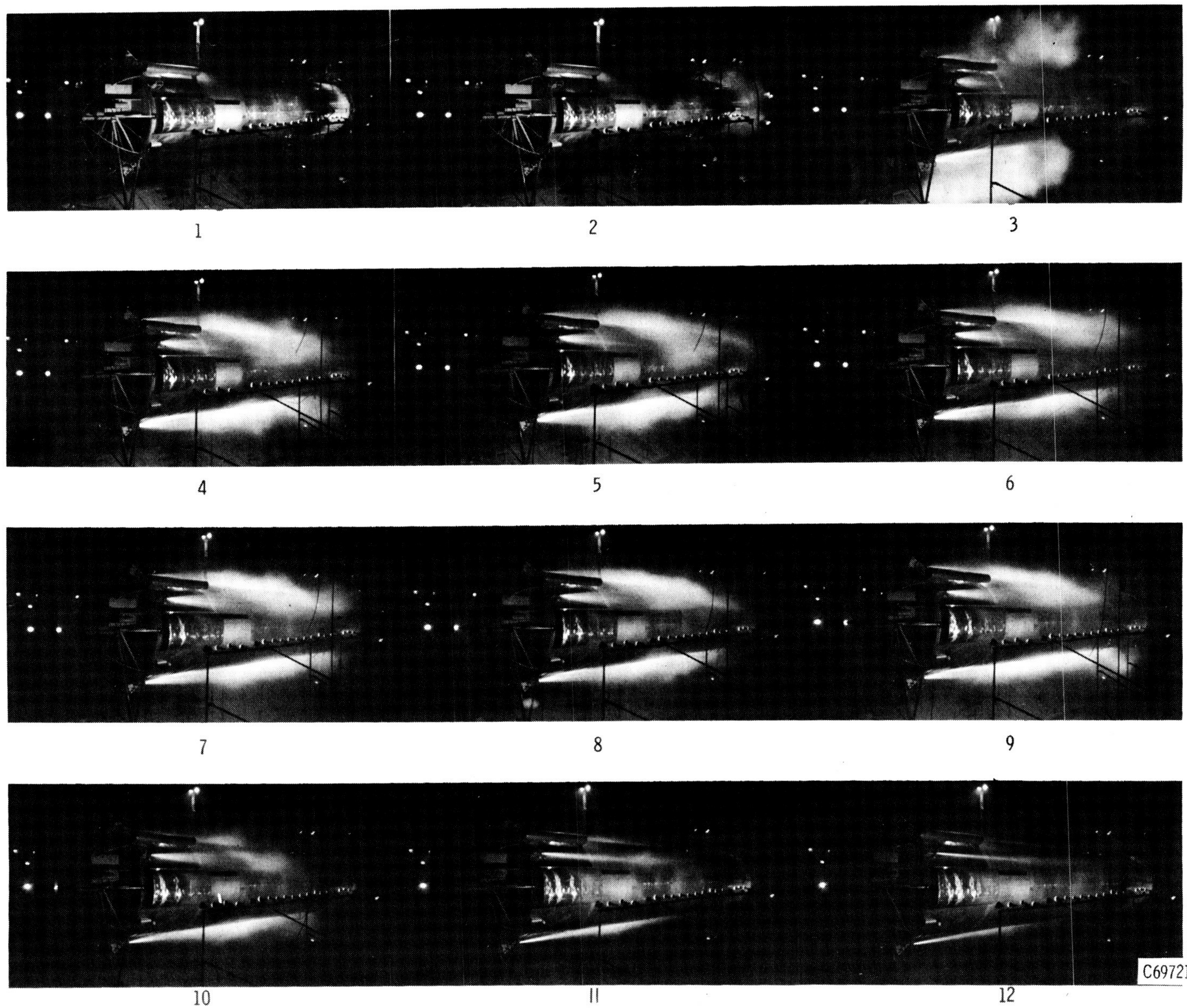


Figure 25. - Atlas-Centaur staging sequences.

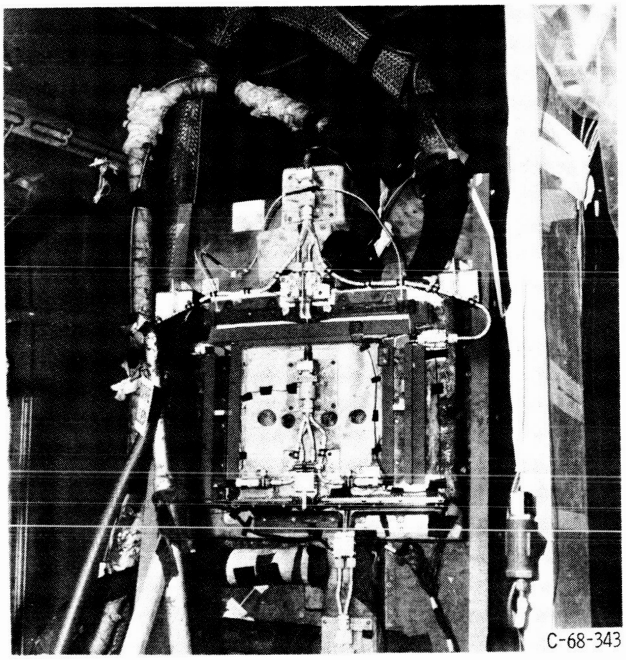


Figure 26. - FLSC qualification test fixture.