NASA
SPACE VEHICLE
DESIGN CRITERIA
(STRUCTURES)

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FLIGHT SEPARATION MECHANISMS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

GUIDE TO THE USE OF THIS MONOGRAPH

The purpose of this monograph is to provide a uniform basis for design of flightworthy structure. It summarizes for use in space vehicle development the significant experience and knowledge accumulated in research, development, and operational programs to date. It can be used to improve consistency in design, efficiency of the design effort, and confidence in the structure. All monographs in this series employ the same basic format – three major sections preceded by a brief INTRODUCTION, Section 1, and complemented by a set of REFERENCES.

The STATE OF THE ART, Section 2, reviews and assesses current design practices and identifies important aspects of the present state of technology. Selected references are cited to supply supporting information. This section serves as a survey of the subject that provides background material and prepares a proper technological base for the DESIGN CRITERIA and RECOMMENDED PRACTICES.

The DESIGN CRITERIA, Section 3, state *what* rules, guides, or limitations must be imposed to ensure flightworthiness. The criteria can serve as a checklist for guiding a design or assessing its adequacy.

The RECOMMENDED PRACTICES, Section 4, state *how* to satisfy the criteria. Whenever possible, the best procedure is described; when this cannot be done, appropriate references are suggested. These practices, in conjunction with the criteria, provide guidance to the formulation of requirements for vehicle design and evaluation.

FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. A list of all published monographs in this series can be found at the end of this document.

These monographs are to be regarded as *guides* to the formulation of design requirements and specifications by NASA Centers and project offices.

This monograph was prepared under the cognizance of the Langley Research Center. The Task Manager was J. R. Hall. The author was D. H. Mitchell of TRW Systems Group/TRW Inc. A number of other individuals assisted in developing the material and reviewing the drafts. The technical adviser was R. M. Boykin, Jr., of NASA Langley Research Center. In particular, the significant contributions made by C. P. Berry and K. L. Christensen of McDonnell Douglas Corporation; J. R. Edson of The Boeing Company; W. J. Fitzgerald of The Aerospace Corporation; A. B. Leaman of Lockheed Missiles & Space Company; S. Merkowitz and C. D. Pengelley of General Dynamics Corporation; G. W. Pape of North American Rockwell Corporation; and H. C. Scott of LTV Aerospace Corporation are hereby acknowledged.

NASA plans to update this monograph when need is established. Comments and recommended changes in the technical content are invited and should be forwarded to the attention of the Design Criteria Office, Langley Research Center, Hampton, Virginia 23365.

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FLIGHT SEPARATION MECHANISMS

1. INTRODUCTION

Parts of a space vehicle must be separated during flight to jettison stages and components that are no longer needed, to uncover equipment, or to deploy payloads. For a mission to be successful, the separations must occur at the correct times of flight and with minimum changes in the attitude and rotational rates (i.e., tip-off errors) of the continuing body. There must be no recontact between the separating bodies, no detrimental shock loads induced in the structure, and no excessive or harmful debris. A separation mechanism that does not meet these requirements can produce attitude errors and tumble rates of the continuing body that are too large for its attitude-control system to accommodate, can damage its structure and critical equipment, and can cause failure or degradation of the mission.

Failure of separation mechanisms has adversely affected mission performance in several instances; for example:

- A Vanguard satellite failed to achieve orbit because the second stage of the launch vehicle was damaged at separation.
- On several early satellite launches, booster stages failed to separate.
- On a military mission, the final booster stage overtook and bumped the spacecraft after separation, damaging critical equipment in the spacecraft.
- On a recent military mission, an extendible boom was damaged at separation and failed to extend.
- During an Apollo launch, the pyrotechnic shock of a separation was of sufficient magnitude to close propellant-isolation valves in the reaction-control system of the spacecraft. The crew was unable to maneuver the spacecraft until the valves could be opened.

This monograph presents criteria and recommends practices for the design and testing of mechanisms for separating space-vehicle stages, payloads, and pods. The advantages and disadvantages of various separation techniques are presented and the characteristics of typical devices that have been used to effect separation are discussed. The mechanical and structural elements that maintain load-path continuity and accomplish separation are emphasized, rather than the auxiliary devices used to time, energize, interconnect, and monitor separation events. Separation dynamics, the effects of environments and operating conditions, and methods of analyzing and testing separation mechanisms are also discussed. The separation of fairings and payload aerodynamic shrouds is a complex subject and will be considered in another monograph in this series.

In designing separation mechanisms, the following factors must be considered: (1) adequate clearance between the separating bodies; (2) shock transmission to the payload or structure of the continuing body; (3) damage to or contamination of the continuing body by debris resulting from the operation of the separation mechanism; and (4) the ability of the mechanism to withstand the natural and induced environments encountered during service.

The designer can choose from among a considerable number of separation components that have been designed, tested, and flown on space vehicles. This approach is usually taken to avoid the cost of new designs and tests associated with development of components. Separation-dynamics analyses of varying degrees of complexity are conducted to assess the performance of the mechanism. Functional tests of the separation mechanism are conducted to demonstrate satisfactory performance and, in some cases, tests are performed to show that the mechanism can operate satisfactorily after or during exposure to the anticipated service environments.

This document is complemented by other monographs in this series: staging and separation loads, design-development testing, qualification testing, and acceptance testing. Other monographs on related subjects are planned, including structural response to mechanical shock, mechanical shock induced by explosives, and shroud separation.

2. STATE OF THE ART

2.1 Design

Separation mechanisms have been used since the space effort began. Until the mid-1960s, many different design concepts were used (refs. 1 to 5). However, in recent years there has been a trend toward using a few, well-established concepts, and the separation-mechanism components have become more refined. Since the established designs are usually adequate, there has been little interest in developing new concepts.

New confined-explosive release techniques have been developed (refs. 6 and 7), but these are just beginning to come into use. If successful, the new techniques will provide greatly simplified separation mechanisms.

Most of the information on separation mechanisms is contained in internal company documents which receive little if any general distribution; there is not much material on the subject in the available literature.

2.1.1 Release Devices

Two basic approaches have been used to design a structure that will carry loads until the time of separation and then break cleanly into two or more sections. The first is to design a continuous structure to carry the loads and then to add a device that cuts the structure cleanly on command. The second is to design two separate structures that are attached at a prescribed mating surface until separation is initiated. The first approach has led to the use of explosive release devices that cut along a line, while the second has generally led to the use of clamps, diaphragms, and/or point-release devices such as explosive bolts and nuts. Each approach has been used successfully many times, and the choice of an approach for a particular space vehicle usually depends on the requirements of the mission, on the experience of the designer, and on whether existing hardware can be used.

Two critical design considerations for a release device are the possible shock loading and the damage from debris to adjacent structure. In table I in the Appendix, various types of release devices are described and compared in terms of these considerations. Other special considerations for each device are also listed.

The use of ordnance with most release devices introduces design constraints based on safety considerations during the handling and operation of the devices. Because some electroexplosive devices (EEDs) may be accidentally ignited by radio-frequency (RF) energy or electrostatic discharge, they must be designed to withstand a specified current or power level without ignition. The common range-safety standard is the power necessary for one ampere of current in the EED or one watt of applied power (whichever is greater) for a period of five minutes. This standard was established arbitrarily and was not based on a detailed analysis of typical environments. It has caused a great deal of controversy in recent years and should be reevaluated to establish a more realistic range-safety standard for RF sensitivity.

There is no explicit range-safety standard on electrostatic discharge, even though a difference of potential caused by the buildup of static electricity in the body of a technician could ignite an EED when touched. Such incidents have at times resulted in casualties which have led to the adoption of special handling and installation procedures, such as grounding to prevent charge buildup. In addition, some effort has been made to redesign EEDs to protect them from electrostatic discharge; for example, EEDs are protected by metal caps or shorting plugs during installation. Present industry standards call for EEDs to withstand 20 to 25 kilovolts from a 500-microfarad capacitor with 0- to 5000-ohm series resistance.

Space-environment effects on ordnance represent a new problem introduced by the longer-term missions involving entry spacecraft or planetary vehicles. For cartridge-type ordnance, the effects of storage and of space environment are similar. Temperature versus time is more important than the external pressure since the cartridges are internally sealed. The effects of space environment on detonating cords and shape charges have not been completely defined; for instance, little information has been obtained on the effects of radiation on this type of ordnance. Outgassing or subliming of the explosive is possible, but it appears that temperature is still more important than external pressure. The current trend is to use explosives that can survive higher temperature and vacuum, such as HNS, when these effects are critical, rather than the common RDX-type materials. Long-term environment-exposure tests are then conducted to verify acceptable performance of the ordnance.

V-clamp bands are excellent release devices for small-diameter vehicles because they are simple, they provide a field joint, and they produce a relatively clean, low-shock separation. They are usually designed in segments, with several V-clamps attached to each band and severable load-carrying devices, such as explosive bolts, connecting the segments. V-clamp joints can be designed to withstand the same magnitude of structural loads as other release devices, but may become heavier than the other devices when they are used with large-diameter vehicles. In addition, as the band diameter increases it becomes more difficult to distribute the band-clamping force evenly around the clamp circumference during installation. For these reasons, V-clamp bands are generally not used on vehicles larger than 60 inches in diameter. Shock and contamination from the V-clamp devices are minimal, but a considerable amount of energy is stored because of preload on the bands at installation. It is often necessary to restrain the bands after separation to keep them from striking the continuing body. This is usually accomplished by the use of springs or cables on the expended stage.

Diaphragms have been used successfully to separate the stages of several relatively small-diameter, solid-propellant boosters (e.g., ref. 8). The devices consist of a one-piece circular coupling with a central disc and integral petals extending outward from the central disc. A "T"-flange at the outer extremities of the petals is threaded and serves to connect the two stages because it is screwed into internal threads at the nozzle-exit plane and internal threads on the lower-stage adapter. When the upper-stage motor is ignited in flight, the pressure of the exhaust gases deflects the central disc away from the motor's nozzle and causes the petals to bend (and sometimes fracture) at the point where they join the central disc. This rotates the T-flange inward and disengages the threads holding the stages together.

Diaphragms are usually designed to operate at exhaust-gas pressures of 30 to 50 psi (200 to 340 kN/m^2). Diaphragms are often used for atmospheric separations so that fins on the continuing body (or other attitude-control devices) can be used to correct the errors introduced by the separation. If the vehicle is spun (for stability), the separation joint may be keyed to prevent the stages from unscrewing and causing a premature separation.

Point-release devices usually contain redundant ordnance with demonstrated overall reliability for ordnance ignition ranging from 0.999 to 0.9999. Without redundancy, this reliability falls to the 0.98 to 0.999 range. The mechanical parts of the device are usually not redundant and, although the mechanical parts are highly reliable, they are assigned a lower reliability value (0.995 is typical) than the redundant ordnance because sufficient test data have not been accumulated to substantiate higher numerical reliability values. Thus, to obtain higher reliability for the separation mechanism, the mechanical parts are made redundant, as well. An example of mechanical redundancy is a V-clamp band that allows separation when only one point-release device operates.

The most promising new concept in release devices is the confined linear explosive technique. With this concept, the detonation of the explosive causes a tube of metal (ref. 6) or elastomer (ref. 7) to expand and break the load-carrying structure without releasing contaminants or fragments. This offers all the advantages of quick, clean release, with none of the contamination associated with many line-cutting release devices. It is hoped that the shock levels of these new devices will be lower than the levels of existing devices.

2.1.2 Separation-Impulse Devices

Many techniques have been used to provide the impulse to give a specified relative momentum, and hence separation velocity, between separating bodies. However, stage ignition, auxiliary rockets, thrust reversal, and springs have been the most frequently used techniques in vehicles made thus far. These and other common separation-impulse devices are described in the Appendix in table II. Some of the release mechanisms listed in table I (Appendix), such as the linear-shaped charge and the mild detonating fuze, can also provide the necessary separation velocity, although not efficiently. A separate device is therefore usually used to provide the impulse necessary for separation. One novel, inexpensive approach is to seal an interstage compartment at a pressure of one atmosphere on the earth's surface and then allow the trapped gas to expand in the vacuum of space during separation. Because the current separation-impulse device designs can meet a variety of requirements, there is little need for a significant breakthrough in the state of the art unless drastically new separation requirements occur.

Stage ignition, or "fire-in-the-hole" staging, where the engine of the continuing stage is ignited at the time of stage separation, eliminates the need for devices to provide the separation impulse, but may require vent openings in the expended stage. This technique has been used successfully many times, but it requires detailed analysis and tests of gasdynamic effects on tip-off (ref. 9), of possible nozzle-choking conditions, of debris hazards, as well as evaluation of structure and equipment in the cavity that may require tie-down mechanisms. Additionally, the heat pulse reflected from the trailing stage may make it necessary to protect the continuing stage by adding thermal insulation to the rear of the continuing stage. If the stages have large overlap, such as an antenna or engine nozzle protruding into the trailing stage, there may also be severe clearance problems with this type of separation.

Auxiliary rockets that exert either positive thrust on the continuing stage or retrothrust on the expended stage have been successfully used to provide the separation impulse for a variety of boosters. The rockets can usually be integrated in the vehicle with minimum interference with other vehicle systems. If the rockets are on the continuing stage, their thrust vectors are usually oriented to prevent unintended spin-up or tumbling of the stage. If the rockets are on the jettisoned stage, their thrust vectors are sometimes oriented to cause tumbling and lateral movement of the stage so that it is removed from the vicinity of the continuing stage. Contamination of the continuing stage can be reduced by mounting the rockets as far from the separation plane as possible and by canting their thrust vectors outward. Even with this design approach, there may be such unacceptable contamination as to require that other separation-impulse devices be used.

Thrust reversal has been used successfully to separate the stages of vehicles having solid-propellant motors. Thrust reversal is a simple concept in which a portion of the exhaust gases are directed forward through ports to overcome primary nozzle thrust. The reverse-thrust ports are located in the side of the rocket, usually toward the front, with their thrust axes inclined forward. The port closures are blown open at a predetermined time of flight or vehicle velocity. The ports are designed to cancel primary nozzle thrust or to provide a small net amount of reverse thrust to achieve a relative separation velocity between the separating stages. It is necessary that the thrust reversal occur in the proper sequence with stage separation, and with ignition of the motor of the continuing stage. The sudden opening of the ports and the ensuing reverse thrust create a sizable shock transient and disperse a considerable amount of contamination in the form of debris and products of combustion. These effects must be studied in detail to ensure that the continuing stage is not damaged.

In terms of cost and reliability, springs are ideal separation-impulse devices when there are stringent tip-off requirements such as payload separation. Helical compression springs are the most common type of springs used for separation. A single spring is adequate for separation when the bodies are spinning, but three or more are used for nonspinning separations or when the allowable tip-off errors are small. As many as 30 springs have been used to reduce the out-of-tolerance effects of a given spring on tip-off rates and to lower the spring-stroke length necessary to induce the desired velocity change.

Commercial springs, usually of steel, can be used if the axial stroke and the forces in each of the three directions are measured carefully during compression of each spring and those springs with similar characteristics are paired and positioned to compensate for differences in the strokes and forces. As described in reference 10, this matching of springs has provided four-spring separation mechanisms that produced tip-off rates of 0.5 deg/sec and lower. The springs were constrained from lateral motion by spring cups on each body and were attached to the jettisoned body to keep them from flying free after separation. Spring cartridges have also been used with good results. When spring cartridges are used, it is only necessary to measure and compensate for differences in the axial force of the springs. When a large amount of energy is necessary to provide the required relative motion between bodies, a separation-impulse system using springs may be heavier than other systems.

The design of separation-impulse devices is affected by residual thrust in the expended stage. On stages with solid-propellant motors, an unexplained phenomenon sometimes occurs: the solid propellant continues to burn after separation and causes a small amount of positive thrust in the expended stage (ref. 11). This "chuffing" or "chugging" can cause the expended stage to overtake and bump the continuing stage. A similar problem has occurred on stages with liquid-propellant motors when there is a reignition, or "burp," after the nominal shutdown of the motor. These problems have been overcome by igniting the motor of the continuing stage soon after separation, by programming a long coast time between nominal burnout and separation to allow the residual thrust to die out, or by moving the expended stage from the vicinity of the continuing stage after separation by using one of the auxiliary devices discussed in Section 2.1.3. The burp problem on liquid-propellant engines has also been relieved by changing the fuel/oxidizer mixture ratio.

2.1.3 Auxiliary Devices

Some of the auxiliary devices used in conjunction with separation mechanisms are described in table III in the Appendix. These special devices assist the separation maneuver by guiding or changing the spin rate of the continuing stage or tumbling the expended stage; or the devices may sever electric or hydraulic connections between the two stages, or create an electric signal for use with other mechanisms. One auxiliary device consists of a single separation spring that provides the torque to spin up and the compression force to separate the continuing stage simultaneously. This has been used several times on small piggyback satellites and has proven to be a very inexpensive method of effecting both separation and spin-up. Because the auxiliary devices listed in table III (Appendix) are not essential parts of the separation mechanism itself, they will not be discussed in detail.

2.2 Analysis

A vital part of separation-mechanism development is the dynamic analysis of both the separation mechanism and the bodies to be separated. This may range in complexity from the analysis of simple, rigid-body, one-degree-of-freedom models to intricate, nonlinear computer simulations in which each body has six rigid-body degrees of freedom, may be spinning, and elastic effects are considered. Customarily, the analysis is used to predict the nominal performance of the mechanism and to estimate tip-off errors due to standard tolerances on the various design parameters. It has also become common to perform a failure-modes-and-effects analysis in which failure modes are assumed and their effects on the performance of the separation mechanism evaluated, at least in a qualitative sense.

In general, two levels of analysis have been used successfully. In cases where no complex forces act on the bodies, simple planar models have been used to analyze nonspinning separations and simple transverse-moment models have been used to analyze spinning separations. The separation mechanism is designed to operate successfully when each parameter that affects tip-off or hang-up, such as tolerance effects, assumes its most adverse value (e.g., a combination of smallest moment of inertia, smallest axial spring rate, and largest lateral spring rate). Often, several iterations of the analysis are necessary to determine the worst combination of parametric values (equivalent, in statistical terms, to large sigma values – possibly 9 or 10) and to confirm satisfactory separation of the bodies under this condition. Although the simple analysis does not account for the effects of coupling and of complex forces and moments, this shortcoming is conservatively compensated for by the requirement for satisfactory separation under the worst combination of parametric values. This type of analysis has proven successful for most simple separations and has led to the design of separation mechanisms with high intrinsic reliability.

When complex forces or moments act on the bodies, the mission is man rated, separation-mechanism weight is critical, or mission requirements are stringent, then complex, nonlinear computer simulations of separation are performed. In this type of analysis, the forces and moments acting on each body are accounted for in detail, each body is allowed rigid-body motion in six degrees of freedom, gyroscopic coupling is included for spinning cases, and elastic effects may be considered. In addition, statistical studies are performed to assess the effect on separation motion when the value of each parameter is allowed to vary throughout its tolerance band. The expense of conducting these studies is often reduced by using Monte Carlo techniques instead of by computing the separation motion for every possible combination of parametric values.

Another technique for complex separation analyses is to determine the partial derivative of each error source. The partial derivatives, together with the range of values of each parameter, can be used to determine the possible tip-off error attributable to the variation in the value of each parameter. The tip-off errors from all parameters are then combined to give the total possible error. The favored technique for combining the errors is to add directly all the errors attributable to correlated parameters and to add the errors attributable to uncorrelated parameters by the root-sum-square method. This technique gives a close approximation of the results that could be obtained with a more rigorous mathematical approach and avoids a large number of computer runs.

The partial-derivative error analysis also identifies the principal sources of tip-off error and the parameters which should be closely controlled, and those which can be allowed to vary without producing excessive errors. This information is especially useful for cost/weight tradeoff studies. The partial-derivative approach offers the best practical way to analyze the separation mechanism and to evaluate possible errors.

Depending on the time in the flight when separation is programmed to occur, a rigorous separation analysis considers the effects of the aerodynamic environment, wind shears or gusts, fuel sloshing, engine-nozzle flow separation, sequencing of events, control-system interactions, mass and inertia properties of the separating bodies, gyroscopic coupling, and details of the separation mechanism itself. Solution of the equations of motion that simulate separation usually requires integration by a digital, analog, or hybrid computer. References 10 and 12 present rigorous separation analyses of nonspinning and spinning exoatmospheric spacecraft separations, respectively, while reference 13 presents a typical analysis of separation in the atmosphere. Representative simulations of a man-rated mission are described in references 14 and 15; references 16 and 17 present Monte Carlo studies.

Separation-dynamics studies of separations that occur in the earth's atmosphere have generally been more complex than studies of those which occur in space. As an example, if ignition of the engine of the continuing stage occurs when the separating bodies are within a few vehicle diameters of each other, gas recirculation flow can cause complex gasdynamic interactions between the bodies. Depending on the dynamic pressure at the time of separation, the body geometry, the engine-exhaust gas flow, and the venting geometry, the gasdynamic interactions can cause tip-off errors and angular rates in the thrusting body that can in turn cause the separating bodies to collide. To prevent collision, the separating bodies are sometimes mechanically guided for the first few feet of axial motion. In addition to the danger of collision, unexpectedly high structural loads and heating may occur in the area of the separation mechanism, and the recirculation and engine-exhaust gas flows can impart unexpected velocity to the separating bodies, thus changing their expected trajectories. Such complex atmospheric separation problems, their analyses, and methods of testing the separation-mechanism design in detail are discussed in references 18 to 22.

Even when there is no immediate ignition of the engine of the continuing stage (as in the separation of an unpowered payload stage from the last booster stage, or when a programmed coast period follows the separation of stages), collision can occur after separation in the atmosphere because of the flow field (aerodynamic wake) behind the continuing body. The characteristics of this wake depend on the altitude, forebody shape, Mach number, and the relative axial and lateral positions of the two bodies.

Separation mechanisms for use in the atmosphere have often included auxiliary devices such as extra drag flaps, tumble motors for nonspinning separations, single-yo tumble systems for spinning separations, or staggered-fire retros to alter the trajectory of the expended stage and get it out of the wake and vicinity of the continuing body. This problem and analytical techniques for evaluating such auxiliary devices are discussed in reference 23.

Separations that occur outside the atmosphere are usually easier to analyze because the nonlinear aerodynamic forces are not significant. A rigorous analysis of these separations, however, must consider the effects of attitude-control-system forces and torques, partial failure of separation-mechanism ordnance, sequencing of events, nozzle-flow separation, fuel sloshing, mass and inertia properties of the two bodies, and details of the separation mechanism itself.

2.3 Tests

Tests are usually conducted to demonstrate that the separation mechanism will operate properly under service conditions. Several varieties of tests are performed, and these are identified and briefly described in table IV in the Appendix. Development tests may be conducted if the separation mechanism is a new design, if it uses new components, or if the environmental conditions or performance requirements are expected to be more severe than those previously encountered. Development tests may range in complexity from environmental-exposure tests of components to sophisticated functional-demonstration tests of full-size separation mechanisms, depending on the degree of confidence in analytical methods and the similarity to or success of previous separation-mechanism designs.

Components of the separation mechanism usually undergo the same type of qualification and acceptance tests as other components of the vehicle. Qualification tests verify that design requirements have been achieved; acceptance tests check for workmanship flaws on flight hardware. Ordnance in particular must be given extensive lot qualification and surveillance testing (ref. 24) to demonstrate satisfactory ignition and mechanical characteristics. Qualification tests are generally performed on ordnance devices separately from the qualification tests of the overall separation mechanism.

Ground testing of full-size hardware for separation of large-body vehicles in atmospheric-flight environments is quite difficult; therefore, wind-tunnel tests of scale models are often performed and the test results are used in conjunction with the results of flight tests of the full-sized vehicle. Part of the separation event is simulated in each phase of the testing (ref. 20) and the data from all phases are correlated to permit a judgment of the adequacy of the separation system's performance. Correlation of the data is difficult in many instances because not all of the parameters scale in the same manner, and ambient conditions cannot be controlled precisely during flight tests. Therefore, the wind-tunnel tests sometimes have to be repeated with more refined input data.

The difficulty of ground testing mechanisms for exoatmospheric separation lies in the proper simulation of vacuum and zero-gravity conditions. Vacuum chambers are generally used, and if they are large enough, separation drop tests can be conducted inside the chamber to simulate both effects. When chambers are not available or when the specimen is too large to be drop-tested in a chamber, zero-gravity conditions are simulated by supporting the test specimen along a noncritical axis (pendulum suspension or horizontal testing on a friction-free surface) or by drop tests in the atmosphere. If these test methods are not feasible, gravity effects on the test data are often corrected by analytical means. When drop tests are performed in the atmosphere, aerodynamic effects are kept small by conducting tests indoors or in shielded areas whenever possible, by keeping velocities low, and by adding streamlining shields.

Problems in supporting the test specimen arise in simulating separation of spinning stages. Because bearings will introduce improper lateral moments, these separations are usually simulated by free-flight tests: either drop tests or free-rise tests. In the free-rise tests, the specimen is accelerated upward before separation occurs and the separated bodies are captured when they stop rising, thereby reducing the possibility of damage to the specimen from the catching mechanism. Other problems arise in testing separation systems for spinning bodies, especially if spinning-falling body data must be recorded. Considerable care is taken in developing the test procedures and the means of recording the test data. Danger from flying parts during the test is avoided by enclosing the test fixture in a protective shield or, if this is not possible, by removing personnel and equipment from the test area.

Spinning-body tests also pose problems of recording test data accurately. Perturbations to spinning-body separations result in coning of the spinning body. The magnitude of coning depends on the spin rate and mass moment of inertia of the spinning body and on the manner in which small impulses or unbalanced forces are applied to it. The cone half angle is usually small, and the test instrumentation must be accurate enough so that the contribution of various error sources to the total error can be identified. If the instrumentation error is sufficient to prevent accurate measurement of the test data, then optical systems, calibrated grids, and high-speed motion-picture cameras are used to magnify and record the test data. A separation test and optical recording system are described in reference 25.

It is difficult to record shock data in tests of some separation mechanisms. Separation mechanisms that include EEDs generate complex shock and, in some cases, significant contamination and fragmentation when separation occurs. (Data from actual flights are contained in ref. 26.) Recording the shock during tests of these mechanisms often presents special problems, such as when the frequency of the data causes saturation of the recording instruments and when shock levels exceed the range of the instrument calibration. Other problems occur in mounting the accelerometers used to record the test data. Incorrect shock-measurement data are also obtained when the natural frequency of the recording instrument is within the frequency range encountered in the test, or when the zero point on the recording scale shifts during the test. The problems associated with measuring separation-mechanism shocks are discussed in detail in references 27 and 28.

3. CRITERIA

Space-vehicle separation mechanisms shall maintain structural continuity under ground and flight loads, physically separate the structural segments on command, and impart necessary relative motion between the separating segments without producing forces, motions, stresses, or debris that impair the stability, structural integrity, or mission of the continuing segment(s). The feasibility of new separation concepts shall be demonstrated by appropriate development tests. The structural and functional adequacy of the separation mechanism under the anticipated environments and service conditions shall be demonstrated by both analysis and test.

3.1 Design

Separation mechanisms shall be designed to withstand limit structural loads without excessive deformation and to withstand ultimate structural loads without failure. Separation mechanisms shall also be designed to separate structural segments only on command, without recontact of the segments, and without causing damage or contamination, and without imparting excessive attitude errors to the continuing segment. Separation mechanisms shall be designed for reliability of performance commensurate with the specified overall system reliability of the vehicle.

At least the following factors shall be accounted for in the design of separation mechanisms:

- Natural and induced environments to which the mechanism will be exposed
- Stiffness and dynamic characteristics of the separating bodies
- Physical and functional interfaces between the separating bodies
- Physical and functional interfaces between the separation mechanism and other vehicle systems
- Mass properties of the separating bodies
- Applicable range-safety standards and requirements.

3.2 Analysis

Analysis and/or test data from similar mechanisms and components shall be used to verify that the following separation-mechanism performance requirements are met under the anticipated operating conditions:

- Adequate structural continuity before separation
- Adequate clearance between the separating segments
- Adequate relative separation velocity

- Allowable tip-off errors resulting from separation

- Functional ability in a partial failure mode.

Mathematical models of the separation mechanism and the separating bodies shall be sufficient to simulate accurately all significant motions of the separating bodies. The analysis shall account for all significant disturbances that affect separation, such as (1) improper sequencing; (2) vibration; (3) drag from service lines; (4) contamination; (5) control-system response; (6) improper firing of ordnance; (7) restrained movement (binding); (8) engine-plume impingement; (9) aerodynamic heating; (10) degradation from long-term orbit life; (11) structural relaxation; and (12) rocket-thrust misalignments.

3.3 Tests

Sufficient tests of separation mechanisms shall be conducted to establish the feasibility of new component or separation-mechanism concepts, to demonstrate satisfactory performance of separation mechanisms or components, and to ensure that flight articles conform to specifications.

3.3.1 Development Tests

The feasibility of new concepts for components or separation mechanisms or techniques shall be established by appropriate development tests. For atmospheric separation, the aerodynamic characteristics of the separating bodies shall be determined by appropriate wind-tunnel development tests.

3.3.2 Qualification Tests

Satisfactory performance of separation mechanisms following exposure to the anticipated service environments shall be demonstrated by appropriate qualification tests. Dimensional compatibility of the separation mechanism with the separating bodies shall be demonstrated by an appropriate fit-check test.

3.3.2.1 Environmental Tests

Environmental qualification tests shall be conducted to demonstrate the ability of the separation mechanism to operate satisfactorily after exposure to at least the following worst-case conditions:

- Static loads

- Random and/or sinusoidal vibration
- Shock
- Acoustic noise
- Temperature
- Vacuum
- Pressure
- Humidity.

These conditions shall be applied in realistic sequence and combinations while the separation mechanism is inoperative unless special considerations require that they be applied during a functional demonstration test.

3.3.2.2 Functional Tests

A functional test shall be conducted on separation mechanisms unless performance data from similar devices used in the same type of application and in similar environments indicate the adequacy of the design. If a full-scale test of the separation mechanism is not conducted, the release device shall be demonstrated to function under simulated operating conditions. The full-scale functional separation test shall demonstrate:

- Satisfactory clearance between the separating structures
- Acceptable relative separation velocity
- Allowable tip-off errors
- Lack of physical damage to the separating bodies, components, and equipment resulting from separation
- Allowable shock levels
- Lack of, or allowable, contamination
- Adequate functioning of the mechanism in a partial-failure mode where redundancy is included.

When the anticipated service environment is different from the ambient conditions of the test area, the effects of service temperatures, pressures, or aerodynamic conditions shall be appropriately accounted for in the various tests. If critical, the separation mechanism shall be preconditioned prior to functional testing to account for vibration, shock, and thermal effects encountered before operation.

3.3.2.3 Ordnance

The no-fire and all-fire characteristics of all ordnance devices used in separation mechanisms shall be demonstrated by test. At least the reliability of ignition of all ordnance devices used in separation mechanisms shall be demonstrated by test.

3.3.3 Acceptance Tests

Compliance of flight-separation mechanisms with established system specifications shall be demonstrated by appropriate acceptance tests.

4. RECOMMENDED PRACTICES

Development of a separation mechanism involves the efforts of many engineering specialists, such as mission planners, trajectory analysts, guidance and control analysts, separation dynamicists, structural analysts, vibration analysts, and ordnance experts. The separation-mechanism designer must carefully integrate information and data from these specialists to design an effective separation mechanism. Close coordination between the various specialists is essential during all phases of design and testing of the separation mechanism.

4.1 Design

The best way to select a separation mechanism is to choose qualified flight-proven hardware such as the Apollo Standard Initiators, wherever practical, even at the expense of a slight weight increase. At the same time, however, the designer must be sure that the environments to which a flight-proven component has been qualified are at least as severe as those expected for the mission planned. The designer should recall that a "flight-proven" component is not necessarily made to operate under all possible flight conditions.

If it is impractical to use proven hardware for the separation mechanism, several different designs should be developed in some detail before the final choice is made. Factors that should be considered in the final selection include reliability, cost, complexity, system weight, jettisonable weight, and compatibility with other parts of the system. Tradeoff studies should be documented so they can be used in future designs.

Separation-mechanism reliability is usually ensured by prudent mechanical-design practices. Although the application of standard reliability statistics to mechanical systems is often inappropriate, redundancy can be used to increase the numerical value. Mechanical redundancy is especially important because the numerical reliability assigned to the mechanical elements of separation mechanisms is usually lower than that of other separation-system elements, such as explosive devices. Mechanical redundancy should be used wherever practical; mechanical reliability can be determined by using data and techniques described in reference 29. If explosive ordnance is used in the separation mechanism, redundant initiation of the explosive is recommended. In addition, the initiators should receive redundant initiation signals. Methods of evaluating the reliability and safety of explosive-ordnance systems are given in reference 30.

The constraints on specific separation-mechanism devices presented in tables I, II, and III in the Appendix should be considered in selecting an appropriate device for a particular vehicle. The general constraints on hardware selection are the amount of space and weight available for the separation mechanism, the required relative separation velocity, the maximum allowable tip-off errors, sensitivity to shock of equipment near the mechanism, and the loads to be carried before separation. Generally, no structure or component should extend across the separation joint unless necessary; guides such as rails, rollers, and sway braces should be avoided wherever possible to avoid friction and binding; the mechanism should be designed to maintain as much clearance between the bodies as possible to provide for unforeseen malfunctions and dimensional growth.

4.1.1 Release Devices

There is no clear-cut advantage to either the linear-shaped charge (LSC) or the mild detonating fuze (MDF); the selection of one or the other depends on the details of the requirements of each separation joint. Both devices should be considered in some detail in a tradeoff study before making the final selection. The new noncontaminating release devices should also be considered (refs. 6 and 7).

If the LSC is used for skin cutting, only one LSC should be used for each severing location; however, the charge should contain more explosive loading than is actually required to sever the structure. Usually, the next larger standard size LSC than that required for marginal severance of the structure should be selected. Because blast, contamination, and fragmentation are quite severe when the LSC is used (and increase as explosive loading increases), care must be exercised to avoid excessive overdesign of the LSC-explosive loading. There is some indication, however, that shock is independent of explosive loading if the charge is sufficient to sever the structure (ref. 27). Blast shielding may be required, and shock mounting of such critical components as electrical relays should be considered. The LSC must be handled carefully (not bent or kinked) because the cross-section shape of the charge is critical to its proper operation. A change in the shape may cause a cutting failure. A supporting holder is necessary to maintain the proper distance between the LSC and the structure to be cut. This distance should be determined by development tests. For increased reliability, the LSC should be ignited by dual initiators.

The MDF makes use of an explosive charge to fracture a notched joint, rather than to cut through unnotched structural skin, as does the LSC. The MDF's orientation with respect to the notched joint and its cross-sectional shape are not as critical as they are with the LSC, so there are fewer problems in handling the MDF before installation. However, fragmentation may be greater than with the LSC, and an estimate of the size and velocity of fragments should be made by suitable analysis or test. If these fragment characteristics are such that damage to the continuing stage appears likely from operation of the release device, then shields should be considered to protect the vehicle from the fragments. For increased reliability, dual systems should be used to ignite the MDF.

All ordnance devices used in separation mechanisms must comply with range-safety requirements. It is recommended that the same care as with any other explosive be taken in handling ordnance devices in the field. The RF environment to which each initiating element will be exposed should be evaluated and the separation mechanism designed and tested to withstand the environment without activation of the initiators. For extremely severe environments, RF filters and/or shielding should be used to protect the initiators.

Ordnance devices exposed to long-term, hard-vacuum conditions before operation should be examined in more detail than devices exposed to more ordinary conditions. Satisfactory performance should be verified by life tests of the devices under thermal-vacuum conditions. The effects of exposure to radiation should also be evaluated.

Every effort should be made to select a proven design for a point-release device from among those shown in table I (Appendix) because of the cost and time required to qualify a new design. The recommended type of point-release device is the nonfragmenting explosive-nut assembly, which operates without producing gas and fragments that may damage other parts of the vehicle.

For maximum reliability, separation mechanisms using mechanical-explosive point-release devices, such as explosive bolts or nuts, should be designed to contain as few components as possible. In addition, the mechanism should operate, although with degraded performance, even if one or more of the release devices fails. If a release-device failure occurs, it is better to have large tip-off errors that can be partially or entirely corrected by the attitude-control system of the continuing body than for the bodies to remain attached.

Ideally, all pieces of the separation mechanism should be restrained or captured after separation. This reduces the amount of space debris that might collide with other satellites or that requires tracking. This cannot always be done, however.

V-clamp bands should be designed so that separation can occur with allowable tip-off errors if only one of the severable connections operates. The bands should be restrained after separation so that they do not fly off or flap loosely and strike the continuing stage.

4.1.2 Separation-Impulse Devices

There is no single preferred separation-impulse device for booster stages where the continuing stage is powered by rocket. Any of three common techniques – fire in the hole, auxiliary rockets, or thrust reversal – is recommended, depending upon the requirements of the mission, the available hardware, and the designer's experience. The problems discussed in Section 2 and presented in table II (Appendix) should be considered, however, before a final selection is made.

Springs are recommended as the simplest, least expensive payload-separation-impulse device. For simple spinning separations, one spring may be adequate; for nonspinning or critical spinning separations, a set of three or more springs, matched by the techniques discussed in reference 10, is recommended. Spring guides should be avoided unless absolutely required to ensure lateral stability of the springs because they increase the likelihood of binding or friction. The total force in the compressed springs should be less than the weight of the payload. This simplifies mating of the stages and prevents separation on the launch stand if the release device is accidentally activated.

4.1.3 Auxiliary Devices

The auxiliary devices used in conjunction with separation mechanisms vary widely in purpose and design (table III, Appendix), depending on the characteristics of a particular vehicle. Accordingly, few generally applicable recommendations can be made for their design.

Auxiliary devices should be designed so they can guide bodies, sever electrical connections, provide "turn-on" signals for the continuing stage, and perform other functions without interfering with the basic function of the separation mechanism, which is that of parting the bodies and providing the necessary relative motion between them. Actually, however, the design of auxiliary devices is more strongly influenced by the vehicle's characteristics than by the need to avoid undesirable effects on the separation maneuver. For example, the design of a yo-tumble system is more strongly influenced by the mass properties of the body to be tumbled (i.e., the expended stage) and the allowable length and weight of the yo-system cable than by the requirement of preventing a collision of the yo weight with the continuing stage.

It is recommended that auxiliary devices for separation mechanisms be designed to impart as little separation impulse or retarding force to the continuing body as possible. It is also recommended that the use of guide rails or rollers be minimized or avoided whenever possible. The risk of binding or hangup of the stages outweighs the advantage of a known separation path.

4.2 Analysis

To aid in the selection and design of the separation mechanism, mathematical simulation of the separation dynamics is essential. Information on critical design problems can usually be obtained only from a mathematical study of the separation event. Clearances, relative separation-velocity requirements, collision avoidance, tip-off errors, allowable perturbations, and automatic controls response due to separation are the types of information desired from these design-support studies. Failure-modes-and-effects studies should also be performed where appropriate.

At least a simple, rigid-body separation analysis should be performed on all separation mechanisms. The analysis can be planar for nonspinning separations, but simple spinning-body effects should be included if separation is to occur during spin.

If complex forces or moments occur, or if the overall system is man rated, then complex computer simulations of the separation event are recommended. Each body should have six rigid-body degrees of freedom, all important forces and moments should be included, the sequencing of events should be simulated, and any significant elastic effects should be included.

The partial-derivative technique is recommended for determining the magnitude of errors resulting from the various disturbances and variations in dimensions and mass properties of the separating bodies and separation mechanism. The errors from all sources should be combined in a statistical manner (those from correlated sources added directly and those from uncorrelated sources added by the root-sum-square process).

When additional analysis is warranted to reduce hardware weight, or is required for man-rated systems, then detailed simulation of the separation event should be performed. Care must be taken to ensure that all critical parameters and their variations are examined during such a study.

4.3 Tests

Development tests should be performed to generate data for detailed separation analyses and to resolve any uncertainties of the separation mechanism's preliminary design. Qualification testing, at both the complete mechanism and the component levels, should be conducted to demonstrate that the performance of the separation mechanism complies with design objectives. Full-scale functional tests should be performed on separation mechanisms of new design, but these tests can be waived if the design is sufficiently similar to one previously used. Satisfactory performance of the release device must, however, be demonstrated on each new design.

A fit check of mating stages of the vehicle should be performed as early in the design as possible. This is especially important if each stage is designed by a different organization. All flight hardware in the area of the interface should be mounted in the planned location and position on each stage and a simple test made to ensure proper fit and adequate clearance when the stages are joined.

Whenever possible, environmental tests should be performed in the same sequence as the environments are imposed on the separation mechanism during its service life.

Functional ground and flight tests of separation mechanisms should be performed to demonstrate adequate system reliability, collision avoidance, satisfactory relative separation velocity, allowable shock and contamination, lack of damage, and proper operation and sequencing. Ground tests are preferable because data acquisition is easier, cost is usually lower, and test conditions can be more accurately controlled than in flight tests. To compensate for the effects of gravity during ground tests of separation mechanisms, the separating bodies should be suspended from long cables attached at the center of gravity of each body (ref. 10). Air bearings can be used to perform the same function. Spinning separations should be simulated by drop tests of the separating bodies into a net (refs. 25 and 31) or by free-rise tests with the bodies captured near the top of their rise.

When functional ground tests are performed under ambient conditions, care should be exercised in extrapolating the test results to actual operating conditions because different conditions can produce different results. There have been numerous instances where test results were extrapolated to make design decisions, but these extrapolations were later proved to be invalid. Whenever possible, test data should be obtained that include the design points so that the results can be interpolated rather than extrapolated.

Test data should be recorded and documented to show that the separation mechanism complies with design requirements, for analysis of possible test failures of the mechanism, or to use in developing mechanism designs. Test data should be of the following types: (1) high-speed motion pictures of the functional separation test and other tests, as applicable; (2) oscillograph and/or magnetic-tape recording of data from the shock and vibration tests; (3) still photographs of test equipment and components; (4) rate-gyro and accelerometer telemetry data from flight or ground tests; and (5) reports describing the test specimen, test equipment, and the results.

High-speed motion pictures provide the best record of possible fragmentation and of clearance between the separating bodies, but rate gyros and accelerometers provide the best data on tip-off errors and relative velocities. Magnetic tape is recommended as the best means of recording test data because a computer can be used to analyze the data and to modify it electronically (i.e., filter it for frequencies of interest) when desired. Special care should be taken in shock tests to make sure that the instrumentation and recording equipment are properly set for the shock levels and frequencies that are anticipated. A preliminary dry-run test of the ordnance alone is recommended wherever possible to check out the instrumentation and recording equipment.

APPENDIX

Tables Cited in the Text

TABLE I. – RELEASE DEVICES

Type of device	Description	Main load path before separation	Shock loading	Fragmentation and contamination	Special considerations
Linear-shaped charge (LSC) (ref. 3)	Column of explosive encased in a continuous metal sheath; explosive energy focused along a line by shape of the sheath cuts structure	Continuous structure	Extremely high	Very significant	Also can provide separation impulse, but inefficient; simple and reliable; shock loading depends on thickness and type of material to be cut (ref. 27); distance between LSC and structure is critical
Mild detonating fuze (MDF) (ref. 3)	Metal-clad detonating cord threaded into a slot on structure; explosion ruptures notched structure	Notched structure	High	Very significant, but can be contained	Omnidirectional; also can provide separation impulse (depends on method of mounting), but inefficient; spreads explosive energy more than LSC, decreases shock loading but increases fragmentation unless internal shields or containment devices are included; can be made more reliable than LSC
V-clamp bands with point-release devices (refs. 3, 10)	Clamp (usually segmented) which fits over mated flanges on two bodies; held in place by tension bands until released	Through clamp at joint	Moderate; depends on band-release mechanism and on amount of preload in bands	None if bands are restrained by springs (point-release device may create problem)	Requires point-release device (usually ordnance); hard to measure or predict preload; very reliable; design problems include segmented joint rigidity, alignment, seating during assembly, angle of "V," and preload to prevent gapping
Diaphragm (ref. 8)	Diaphragm coupler between stages is deflected by engine exhaust of continuing stage or small auxiliary motor; this releases engaging threads on petals	Through diaphragm coupler at joint	Low	Low	Thread shapes and diaphragm slots must be designed to transmit loads but also to deflect and disengage properly; diaphragm must deflect at pressure below that which will damage or degrade engine

TABLE I. – RELEASE DEVICES – Concluded

Type of device	Description	Main load path before separation	Shock loading	Fragmentation and contamination	Special considerations
Fragmenting explosive bolts, nuts (ref. 3)	Notched bolt or nut with internal explosive charge	Through bolt	Moderate	High	Can also be used to release V-clamp band; reliability increased by parallel initiation or double-ended bolts; shear applications require enough axial force to eject parts from hole; may require capture
Nonfragmenting explosive nut assembly	Sealed explosive mechanism frees bolt followed by piston impact which ejects bolt	Through bolt	Low	None	All gas and fragments contained by nut assembly; high reliability with redundant EED; may require capture
Impact-failure bolts (ref. 1)	Type of explosive bolt; consists of sealed necked-down bolt with internal explosive charge which drives a piston; impact causes tension or shear failure in necked-down section	Through bolt	Low	None	Reliability increased by parallel initiation system; can be loaded only in tension or shear; may require capture
Pin pullers or pushers (gas or spring actuated) (ref. 1)	Pin holds bolt stud or connecting link; gas pressure induced by firing squib in sealed unit pushes or pulls pin from its hole in stud or connection	Through bolt and pin	Low	None or small	Reliability increased by parallel initiation system; design problems include alignment and matching of force, displacement and time characteristics of pin units, and lateral loads
Soft joint	Stages free and held together by inertia forces until drag on expended stage or ignition of continuing stage causes separation	Through joint (small overlap)	None	None	Friction and binding must be minimized; may include pin puller to prevent premature separation; restricts maneuvering before separation
Ball-lock pins	Ball-headed bolt held by lock on expended stage; gas-operated pistons release locks for separation	Through ball lock	Low	None	Design problems are alignment, friction, binding, and tip-off; reliability increased with multiple gas generators manifolded to each unit

TABLE II. – SEPARATION-IMPULSE DEVICES

Type of device	Description	Complexity	Weight	Typical separation-velocity range	Special considerations
Stage ignition ("fire in the hole") (refs. 1, 9)	Continuing-stage motors fired upon disconnection of stages; exhaust-gas pressure creates separation force as well as acceleration of continuing stage	Moderate to high (detailed analyses and tests required)	Low	5 to 10 ft/sec (1.5 to 3 m/sec)	Interstage venting areas (blast doors) must be adequate to prevent overload and choking of motors; wind-tunnel tests required to establish design pressure environments; blast doors may not be necessary for higher separation velocities
Auxiliary rockets (ref. 1)	Cold-gas, hot-gas, or solid-propellant rockets, fired to provide axial and/or lateral separation forces, can be located on continuing or jettisoned stage	Simple, except for critical alignment if attached to continuing stage	Moderate	10 to 20 ft/sec (3 to 6 m/sec)	Thrust must be aligned to principal axes if attached to continuing stage; situations where all rockets do not operate must be examined; exhaust gases may affect area surrounding rocket on vehicle
Thrust reversal	Pressure-venting device on front of solid-propellant rocket motor reverses thrust of expended stage on signal; exhaust gases also impart some separation impulse to continuing stage	High (extra parts and detailed analyses and tests required)	Moderate	1 to 2 ft/sec (0.3 to 0.6 m/sec)	Gas-exhaust plumes can heat, move, contaminate, or cause local loads in continuing stage; design must prevent collisions with fall-away articles such as port covers
Springs (refs. 10, 12)	Single or multiple helical or leaf springs force bodies apart upon release	Simple	Moderate	0.2 to 6 ft/sec (0.06 to 1.8 m/sec)	Matching of springs can compensate for spring strokes and forces which could cause tip-off; lateral stability provided by design of spring or by guides; single spring can also be torqued to provide spinup of continuing stage; calibrated spring cartridge assemblies can be used for very critical separation requirements

TABLE II. – SEPARATION-IMPULSE DEVICES – Concluded

Type of device	Description	Complexity	Weight	Typical separation-velocity range	Special considerations
Aerodynamic effects	Lift and/or drag devices remove the expended body from the continuing stage	Simple but requires detailed analyses and tests	Low if no extra surfaces required	0.5 to 1 ft/sec (0.15 to 0.3 m/sec)	Detailed staging analyses must be performed and results verified by wind tunnel tests; separation may be difficult to simulate by test
Gas-operated pistons	Piston is forced against continuing stage by gas pressure generated in cylinder	Moderate to high	Moderate to high	5 to 10 ft/sec (1.5 to 3 m/sec)	Also provides release; reliability increased by parallel initiation systems; design problems include alignment and matching of piston force-time characteristics
Bellows (ref. 1)	Stages separated as bellows expand; may be preloaded in compressed position or activated at time of separation	Moderate	Moderate	5 to 10 ft/sec (1.5 to 3 m/sec)	Also provides release; design problems include alignment, matching of force-time characteristics, and sealing of preloaded bellows

TABLE III. – AUXILIARY DEVICES

Type of device	Function	Description	Design considerations
Rails, rollers	Guide two bodies until all or part of separation is achieved	Rails or track and rollers which allow bodies tc separate axially while lateral motion is controlled	Binding, friction, and structural relaxation loads at separation must be avoided or minimized
Sway braces, linkages	Guide expended stage away from continuing stage	Mechanical linkages that move attached body to the side into the air stream	Binding and friction must be avoided or eliminated; complex separation analysis
Electrical and hydraulic disconnects	Sever electrical and fluid connections between stages	Guillotine-type cutters or male-female connectors that are pulled apart by stages or have own release springs	Release or hangup forces of disconnect devices should be small compared to those of separation impulse device; if not, separation force must be increased; electrical circuits must be de-energized to prevent short circuits when they are cut by guillotine
Separation switches	Indicate successful separation, "turn-on" next stage, and/or initiate next event	Microswitches installed between bodies; separation allows them to be activated	Forces must be very small; usually installed in pairs to increase reliability
Yo-tumble system (ref. 3)	Causes spinning expended stage to tumble and move away from continuing stage after separation	Weight on cable, located off the CG of expended stage, unwraps from spinning body, and causes it to despin, cone, and tumble due to unbalanced forces	Release must be delayed until continuing stage has separated sufficiently; correct weight and cable length
Tumble rockets (ref. 3)	Causes expended stage to tumble away from continuing stage after separation	Small rockets located off the CG of expended stage give the stage a lateral velocity and cause it to tumble	Ignition of tumble rockets must be delayed until the continuing stage has separated sufficiently; can be used on a spinning, expended stage
Spin-up and despin mechanisms	Changes the spin rate of the continuing body; (spin-up for injection or in-orbit stability; despin for active attitude control)	Uses small rocket motors, cold or hot gases, or the separation spring itself to give an angular impulse to the continuing stage; yo-yo system can also be used for despin (ref. 3)	Maneuver can be performed before, during, or after separation; expelled gases should not impinge on solar cells or other critical hardware; resultant torque must be aligned to body's principal axes to prevent coning

TABLE IV. – SEPARATION-MECHANISM TESTING

Type of test	Purpose	Description
Development	To determine feasibility of new devices or techniques	Can be as extensive or simple as necessary, depending on confidence in analysis and previous designs
Qualification-environmental	To verify resistance to design environments under worst-case service conditions	Series of tests to expose mechanism to ultimate design loads and worst conditions expected in service; tests are usually run consecutively and, depending on the mission, consist of static loading, vibration, shock, thermal, vacuum, or humidity preconditioning to operation
Qualification-functional	To verify design adequacy of entire mechanism	Suspension or zero-g simulation with mass and inertia models of separating bodies; flight hardware for separation mechanism; actual ordnance; wind-tunnel tests if separation is to occur in atmosphere; fit check performed early in test program to verify satisfactory interface
Qualification-ordnance	To establish satisfactory performance characteristics and reliability of ordnance device(s)	Firings under actual conditions to determine no-fire and all-fire characteristics (details in ref. 24)
Acceptance-environmental	To verify satisfactory manufacturing workmanship of each flight mechanism	Short series of vibration and thermal tests, usually low test levels
Acceptance-ordnance	To verify that a particular lot of flight items is built to specification	Firings of selected samples from lot to determine no-fire and all-fire characteristics (details in ref. 24)

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SP-8034	(Guidance and Control)	Spacecraft Mass Expulsion Torques, December 1969
SP-8035	(Structures)	Wind Loads During Ascent, June 1970
SP-8036	(Guidance and Control)	Effects of Structural Flexibility on Launch Vehicle Control Systems, February 1970
SP-8037	(Environment)	Assessment and Control of Spacecraft Magnetic Fields, September 1970
SP-8038	(Environment)	Meteoroid Environment Model – 1970 (Interplanetary and Planetary), October 1970
SP-8040	(Structures)	Fracture Control of Metallic Pressure Vessels, May 1970
SP-8042	(Structures)	Meteoroid Damage Assessment, May 1970
SP-8043	(Structures)	Design-Development Testing, May 1970
SP-8044	(Structures)	Qualification Testing, May 1970
SP-8045	(Structures)	Acceptance Testing, April 1970
SP-8046	(Structures)	Landing Impact Attenuation for Non-Surface-Planing Landers, April 1970
SP-8047	(Guidance and Control)	Spacecraft Sun Sensors, June 1970
SP-8050	(Structures)	Structural Vibration Prediction, June 1970

SP-8053	(Structures)	Nuclear and Space Radiation Effects on Materials, June 1970
SP-8054	(Structures)	Space Radiation Protection, June 1970
SP-8055	(Structures)	Prevention of Coupled Structure-Propulsion Instability (Pogo), October 1970
SP-8056	(Structures)	Flight Separation Mechanisms, October 1970
SP-8057	(Structures)	Structural Design Criteria Applicable to a Space Shuttle, January 1971
SP-8060	(Structures)	Compartment Venting, November 1970
SP-8061	(Structures)	Interaction with Umbilicals and Launch Stand, August 1970

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