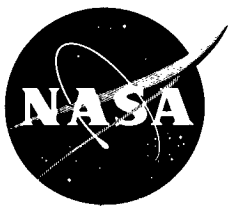
NASA
SPACE VEHICLE
DESIGN CRITERIA
(GUIDANCE AND CONTROL)

NASA SP-8034

SPACECRAFT MASS EXPULSION TORQUES



DECEMBER 1969

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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. This document, "Spacecraft Mass Expulsion Torques," is one such monograph. All monographs in this series issued prior to this one are listed on the last page of this document.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that the criteria sections of these documents, revised as experience may indicate to be desirable, may eventually become uniformly applicable to the design of NASA space vehicles.

This monograph was prepared under the cognizance of the Electronics Research Center by S. Schalkowsky and M. Harris of Exotech, Inc. An advisory committee, consisting of the following engineers and scientists, assisted in the effort·

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Additional contributions were made by other engineers and scientists of NASA and the aerospace industry.

Comments concerning the technical content of these monographs will be welcomed by the National Aeronautics and Space Administration, Office of Advanced Research and Technology (Code RVA), Washington, D.C. 20546.

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SPACECRAFT MASS EXPULSION TORQUES

1. INTRODUCTION

All torques that tend to disturb the attitude of a spacecraft must be considered in the design of spacecraft attitude-control systems. One of these torques, the torque that may result when mass is expelled from a spacecraft, is the subject of this monograph.

Mass can be ejected from the spacecraft in the solid, liquid, or gaseous state. Determination of the mass expulsion torque requires knowledge of the characteristics of the mass flow and the moment associated with the reaction force. Mass expulsion disturbance torques can occur in several different ways and are grouped in this monograph in three categories:

- Disturbance torques attributable to anomalous behavior or operation of equipment intended to produce a force or torque on the vehicle
- Disturbance torques caused by equipment intended only to expel mass
- Disturbance torques caused by unintended mass expulsion; e.g., outgassing or sublimation

Experience has shown that disturbance torques associated with mass expulsion can result in degradation of control-system performance; anomalous spin and attitude behavior; premature depletion of expendable fuel; and, in some cases, mission failure. The designer must be aware of the sources of mass expulsion disturbance torques and of procedures for minimizing their effects on the control system. Control over these effects may require special features in hardware design, hardware assembly procedures, and operating procedures.

Three design considerations associated with disturbance torques caused by mass expulsion are (1) identification of the source and assessment of the magnitude of the torque, (2) determination of an acceptable magnitude, and (3) control over spacecraft characteristics during design and development to assure that the mass expulsion torque will not exceed the acceptable magnitude. This monograph treats only items (1) and (3) because determination of acceptable magnitudes for mass expulsion torques is primarily a systems decision requiring knowledge of attitude-control system design, mission requirements, and the magnitude of

other disturbance torques; e.g., solar pressure, gravitational effects, magnetic interactions, or man and equipment motion.

The scope of this document is limited to mass expulsion effects during space flight; effects occurring during launch and de-orbit are excluded. Allied disturbances resulting from excitation of flexible structures by mass expulsion systems are covered in another monograph.

2. STATE OF THE ART

Knowledge regarding disturbance torques resulting from the expulsion of mass from spacecraft has developed largely where flight data indicated anomalous or unpredicted behavior of the spacecraft spin or attitude. Detailed investigation frequently revealed that these phenomena can be explained by a mass expulsion disturbance torque. As a result of these experiences, investigation of the effects of both obvious and potential sources of mass expulsion has been initiated, analytical methods and test facilities to study and measure the magnitude of these effects have been developed, and design techniques to insure their minimization have evolved.

2.1 Review of Design and Flight Experience

For the purposes of this monograph, the many sources of mass expulsion disturbance torques have been classified into those intended to expel mass and those where mass expulsion is unwanted or unintentional. Where the mass is expelled intentionally, a further division was made according to the purpose of the mass expulsion.

Category 1a: *Sources intended to produce a force or torque that is necessary for the proper operation of spacecraft*.—This category includes disturbance torques resulting from anomalous design or operational conditions of position- and attitude-control equipment. Most of the mass expulsion disturbances that have been identified from flight experience fall into this category. Examples include

(1) Leakage of fuel or pressurizing agent
(2) Thrust vector misalinement
(3) Reaction forces resulting from plume impingement on the vehicle
(4) Anomalous firing time

Category 1b: *Sources intended to expel mass but that place on the spacecraft forces or torques which must be controlled or minimized.*—Generally problems have arisen only when these disturbances, which occur infrequently, perhaps only once during the flight, were overlooked or their magnitude underestimated. Examples include

(1) Dumping of residual propellants
(2) Venting of compartments, subsystems, and spacecraft
(3) Subliming mechanisms
(4) Payload separation and ejection
(5) Equipment jettison

Category 2: *Unintentional sources where neither the force nor the expulsion of mass are premeditated in spacecraft design.*—This category includes outgassing, sublimation, and leakage from spacecraft equipment. Because operational and reliability considerations impose strict requirements on spacecraft material selection, no documented instances of disturbance torques from mass expulsion effects in this category have been found.

2.1.1 Disturbances from Category 1a Sources: Anomalous Thrustor Behavior

Leakage

The spin-stabilized Pioneer 6 spacecraft had the capability of precessing its spin axis by using gas jets mounted on an eractable boom. After the spacecraft achieved its initial orientation, a nearly exponential decay in the gas pressure, coupled with a similar decrease in spin rate, indicated a leak in the nitrogen supply system (figs. 1 and 2). The pressure in the bottle did not continue to decay exponentially, showing that the source of the leak was not located at the high-pressure bottle. It was assumed that the leak was in the pressure regulator valve and that the gas was flowing out through the relief valve. The slight reduction in spin rate supported the thesis that the leaking nitrogen gas was not ported through the nozzle, because the flow would have produced an increase in the spin rate (ref. 1); the nozzle was canted to produce a torque about the spin axis to compensate for the reduction in angular momentum as the gas moved from the bottle to the nozzle at the end of the boom. Fortunately, the leakage rate was small. After 6 months in orbit, the pneumatic system still contained a pressure of 150 psi (ref. 2). On subsequent flights, the pressure vessel cradle design was modified to provide better vibration isolation and the problem did not recur.

On the interplanetary spacecraft Mariner 4, pneumatic valve leakage prevented the radiation-torque control system from achieving the desired stability (ref. 3). The control system included vanes to adjust the torque caused by solar radiation force so that any low-magnitude

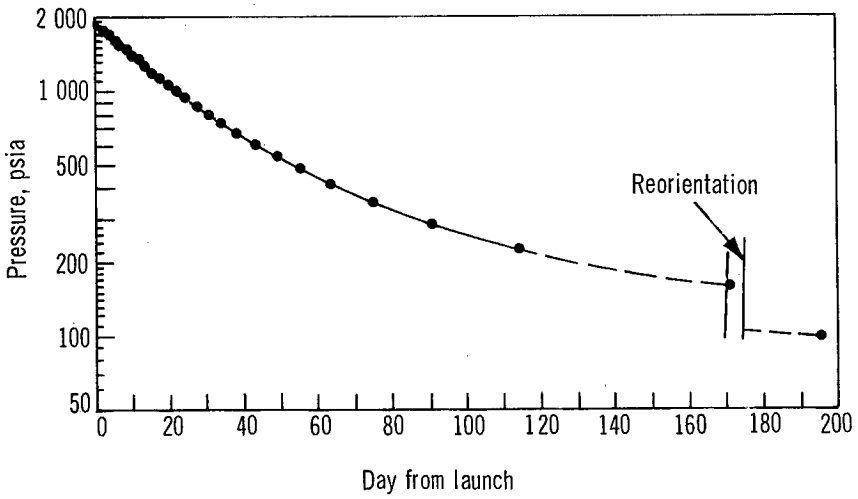


Figure 1.–Variation of Pioneer 6 nitrogen bottle pressure after initial orientation.

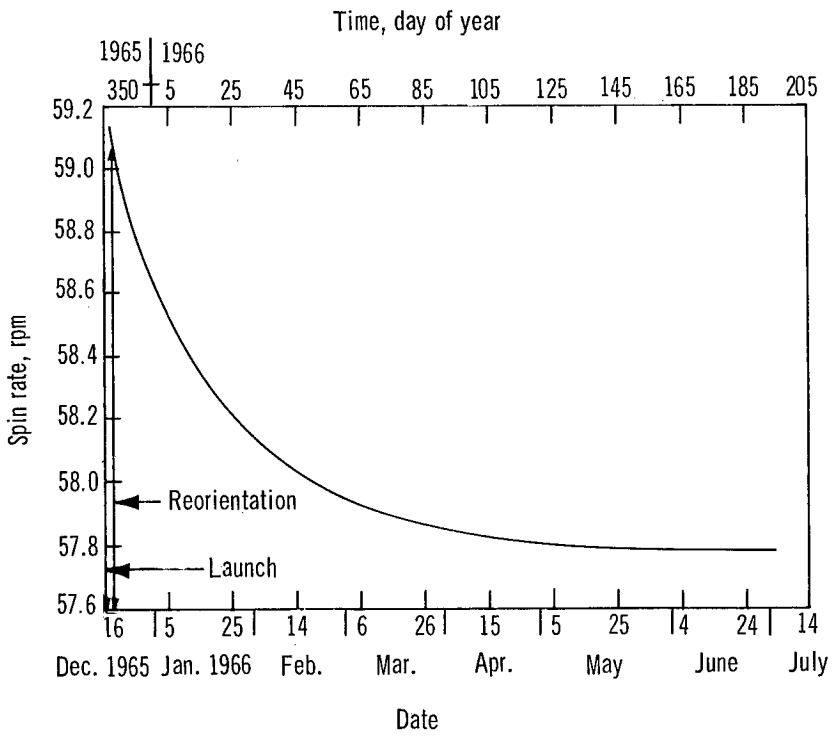


Figure 2.–Variation of Pioneer 6 spin rate with time.

constant torque acting on the spacecraft would be canceled. The solar vanes were activated after the pneumatic control system had achieved limit cycle operation in the cruise mode. It was anticipated that the solar vanes would hold the spacecraft attitude within the deadband of the pneumatic control system. The system succeeded in reducing the initial unbalance torque, but steady state operation was not achieved. Subsequent analysis and test indicated that the leakage rate of the pneumatic valve varied with each actuation and that the magnitude of the torque variation exceeded the maximum restoring torque of the vane system. The maximum torque disturbance was on the pitch axis as indicated by the limit cycles on figure 3 (ref. 4). The limit cycle shown occurred in the 82nd day of flight. The yaw disturbance is approximately 2.5 dyne-cm, while the pitch torque is about 10 dyne-cm. Roll torques were not estimated because the roll channel data were more noisy and the telemetry resolution more coarse. The pitch, yaw, and roll torques varied in a random manner from one limit cycle to the next. The variation was greatest in the pitch axis, where a change of about 15 dyne-cm occurred (ref. 4). These disturbances on the Mariner 4 spacecraft contributed significantly to a 300-km trajectory error at Mars (ref. 5).

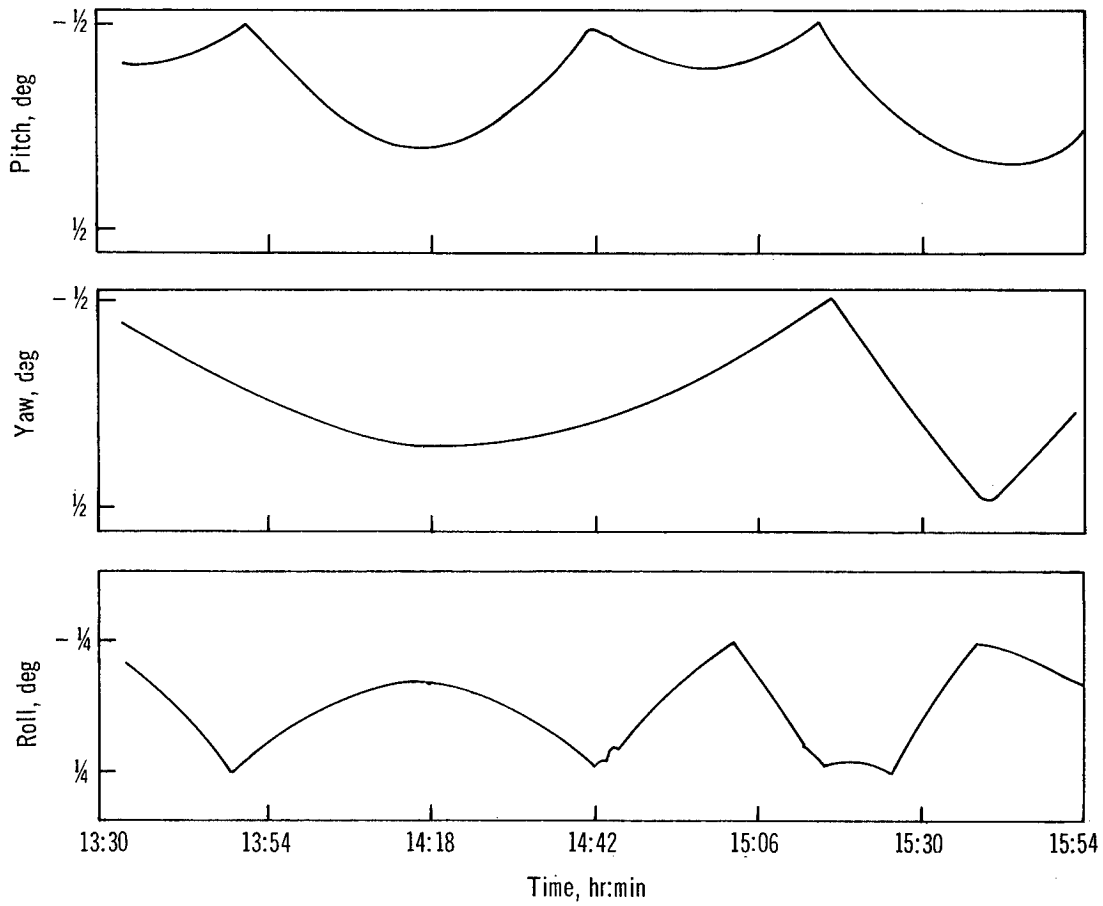


Figure 3.–Mariner 4 limit cycles.

Mariner 5 also experienced disturbance torques attributed to valve leakage. These torques, however, were well within the allowed leak tolerance and had a negligible effect on the Mariner 5 trajectory (ref. 5).

The ATS 3 spacecraft had, as an experiment, two resistojet thrustors with nominal thrusts of 10 and 100 μlb. The experiment was to change the spacecraft's spin rate in predictable amounts and thus accurately deduce the resistojet thrust levels. When the flow valves were opened initially, thrust levels in excess of 1 mlb were observed and an unpredicted mass expulsion torque on the spacecraft resulted. The anomaly was attributed to leaks of the regulator valves that controlled the flow of ammonia from the supply reservoir to a plenum chamber. To eliminate this mass expulsion problem on the ATS 4 spacecraft's operational resistojet system, new regulator and flow valve designs were used and normally open explosive valves were placed in the lines as a backup to the flow valves.

A loss of pressure in the reaction jet control system was observed on both ATS 1 and Intelsat 2. Both spacecraft were spin stabilized, operated in synchronous equatorial orbits, and employed hydrogen peroxide reaction jets for station keeping and attitude control. The hydrogen peroxide was pressurized with nitrogen gas. In each case a rapid loss of pressure was observed following the end of the eclipse period. Figure 4 (ref. 6) shows the ATS 1 pressure history. Originally it was thought that ice crystals or sludge in the valves prevented complete closure resulting in exhaustion of the H_2O_2 propellant. Data obtained from a nutation experiment with ATS 1 revealed that a change of mass commensurate with the loss of propellant had not occurred. It was concluded that the loss of pressure was caused by nitrogen leakage. Because the slowness of the leak precluded rupture or failure of a component, the pressure relief valve was identified as the most likely cause of the leak.

Thrust Vector Misalinement

On the OGO 4 spacecraft, one of the experiments required a circular antenna mounted at the end of a boom. The antenna was erected by pressurizing an inflatable Mylar ring with a blow-down pneumatic system. The ring had a small venting orifice to allow the pressurizing gas to exhaust, the stiffness of the ring being sufficient to maintain the proper shape after initial erection. The exhaust vent was to be oriented so that the net force created by the escaping gas would pass through the center of mass of the spacecraft. However, this vent was misalined and the resulting torque caused the spacecraft to yaw 90° before the attitude-control system could regain control.

Thrust vector misalinement was also responsible for disturbances on one of the Vela spacecraft. The Vela spacecraft utilize a dual-spin, zero-momentum type of attitude-control system. The main spacecraft structure spins at approximately 1 rpm during normal operation, and the angular momentum is canceled by a counterrotating reaction wheel. During injection into orbit, the spacecraft is stabilized at a higher spin rate. Despin to the cruise rate occurs shortly after injection. During the despin, thrust vector misalinement caused a

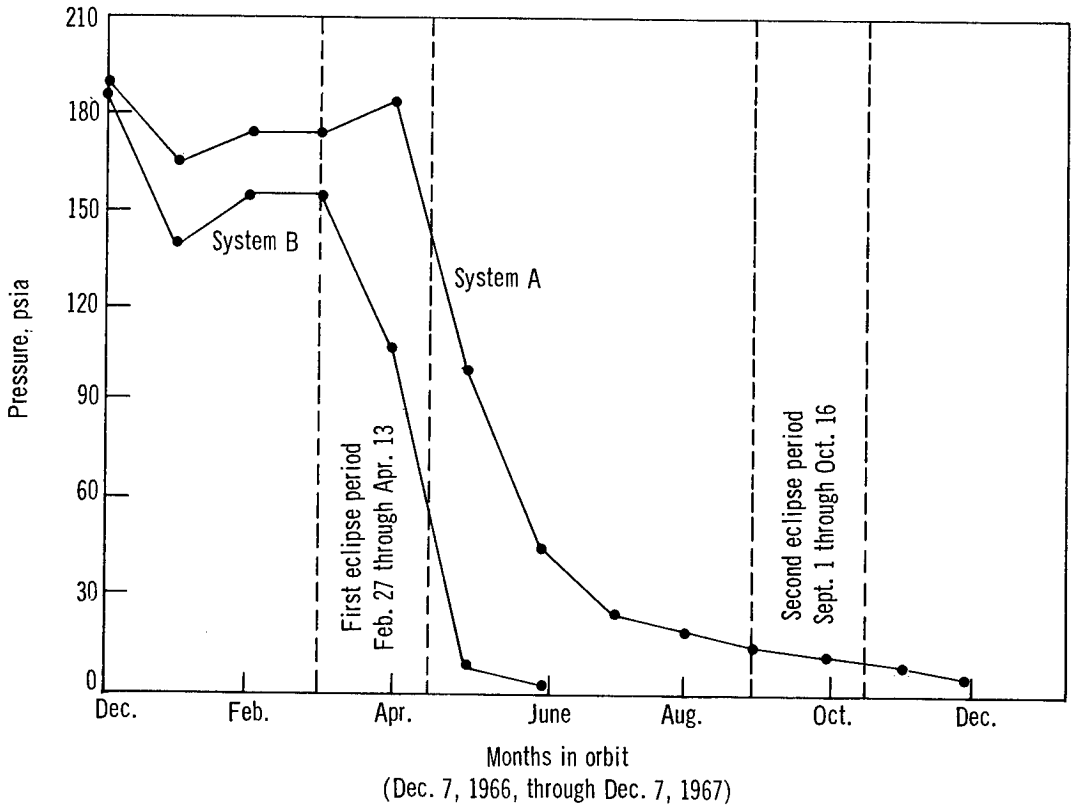


Figure 4.–H_2O_2 systems pressure on ATS 1.

wobbling motion to develop that intensified because the spacecraft was dynamically unstable over part of the range of spin rates encountered. Three-axis active control had to be initiated to insure that the wobbling motion would not cause the spacecraft's sensors to lose their attitude references.

Plume Impingement

On the Vela, a combination of thrust vector misalinement and jet plume impingement on the spacecraft generated a disturbance torque that reduced the normal mode spin rate by about 1.5 percent. Apparently the misalinement of the thrust vector was not entirely caused by mechanical tolerances but also by divergence of the vector from the nozzle centerline. Conclusive evidence was not available, but the indications were that the discrepancy between the expected and the actual thrust vector exceeded 1°.

Another example of attitude disturbance caused by jet plume impingement occurred on an Agena flight. A pneumatic attitude-control system is used during engine operation to counteract roll moments. Pitch and yaw are accommodated by thrust vector control of the

engine. During engine operation, turbine exhaust was expelled nominally parallel to the main engine jet. The impingement of this exhaust on the main engine skirt produced a roll moment that was larger than any of the other environmental moments to be overcome by the attitude-control system. In this case, exhausting the turbine into the main engine eliminated the impingement problem.

On Burner 2, the position of the jet nozzles was such that the exhaust plume from the hydrogen peroxide control thrustors impinged on the after section of the spacecraft. This impingement caused a 10- to 12-percent reduction in the control force available from these jets and a corresponding reduction in the expendable fuel margin. Because the fuel margin was considerably greater than 10 percent, the impingement did not create any serious problems.

On Nimbus 1, a study of plume shapes and impingement forces was undertaken after the attitude-control jet was moved from the base of the control package to the top of the antenna support section (refs. 7 and 8). The study was motivated by the suspicion that jet plume impingement on the solar paddles would adversely affect capture and attitude control. Both analytical and experimental methods were employed in the investigation. While there was some lack of agreement between the results of the two methods, it was concluded that the impingement torques were not negligible. To eliminate the impingement effects, the jet nozzles were canted upward so that the plume centerline would be 20° above the upper edge of the solar paddles when the paddles were vertical. This caused a decrease in the control force and, along with other considerations, made necessary an increase in the gas storage requirements.

Timing Errors

Anomalous firing time can result in failure to obtain the predicted torque impulse and phase from a thrustor even when other sources of disturbing torques are either eliminated or included in the design calculations. Monopropellant systems using anhydrous hydrazine have exhibited a small but not always negligible thrust continuing for many seconds after apparent shutdown. This thrust occurs because a trace of fuel remains in, and continues to flow over, the catalytic bed.

Because control valves have finite opening and closing times, variations in the thrust-versus-time characteristics occur. The Mariner 4 spacecraft experienced thrust impulses that were twice as large as planned because of valve characteristics and impulse tail-off as gas trapped between the valve and the orifice escaped. On Mariner 4, the difference between the actual and the expected torque when a control valve was fired was as large as 5 dyne-cm. On Mariner 5, this change varied randomly and was as large as 3 dyne-cm. Another difficulty that has been experienced is the extraneous firing of control valves when double pulses are generated by noise in the electronics. Because thrust buildup is a function of the length of time the valve is open, extraneous pulses can greatly increase the torque applied to the spacecraft.

2.1.2 Disturbances From Category 1b Sources: Dumping, Venting, Ejection

Venting and Propellant Dumping

When propulsion engines are shut down and residual fuel jettisoned, considerable thrust and torque may be experienced by the spacecraft. On Pegasus 1, an unanticipated buildup in spin rate occurred and was attributed to the venting of residual LH_2 and LO_2 left on board after S-4 engine cutoff. The geometry of the vents was such that the gas, after escaping the valves, expanded against the meteoroid detector panels causing a torque around the roll axis (ref. 9). There was insufficient time prior to the launchings of Pegasus 2 and 3 to correct the design. Modification of the venting system reduced the spin rate from 10°/sec on Pegasus 1 to 6.5°/sec on Pegasus 2 and 3; this confirmed the thesis that impingement of the vented residuals caused the spin.

Sublimation

An example of a torque disturbance that has been attributed to sublimation occurred on satellite 1963-38B launched in October 1963 (ref. 10). This was a gravity-gradient-stabilized satellite with libration damping provided by a combination of magnetic hysteresis damping rods and a mass connected to the end of a long boom by an ultraweak spring. The spring was encapsulated in biphenyl to prevent damage during handling and launching. Biphenyl was also used to maintain the spring-mass elements secure during deployment of the boom. After the boom was extended, the biphenyl sublimed, first releasing the end-mass and then allowing the spring to extend one coil at a time. The spring container opened only on one side, creating a lateral vent through which the subliming biphenyl exhausted (fig. 5). There was a reaction force normal to the boom axis and the resulting torque caused the satellite to tumble. Figure 6 shows the attitude history of this satellite.

To avoid tumbling on satellite 1963-49B, a cylindrical shroud was placed around the biphenyl container (ref. 10). This shroud was designed to deflect the subliming biphenyl so that it exhausted approximately parallel to the boom axis. Figure 7 (ref. 10) illustrates the attitude history of satellite 1963-49B. Prior to biphenyl lock release, no large-angle oscillations in attitude were observed. After the biphenyl lock was released, the satellite oscillated and then tumbled from the 17th to the 25th day at which time the biphenyl had completely sublimed. This oscillation and tumbling motion are believed to be caused by the subliming biphenyl because when the biphenyl was present, a net thrust in the direction of the satellite's motion of about 2×10^{-6} pounds was generated. This thrust increased the nominal orbit period of 107.1 min at a rate of about 0.084 sec per orbit. When the subliming biphenyl was exhausted, both the torque and the resultant rate of increase in orbital period disappeared.

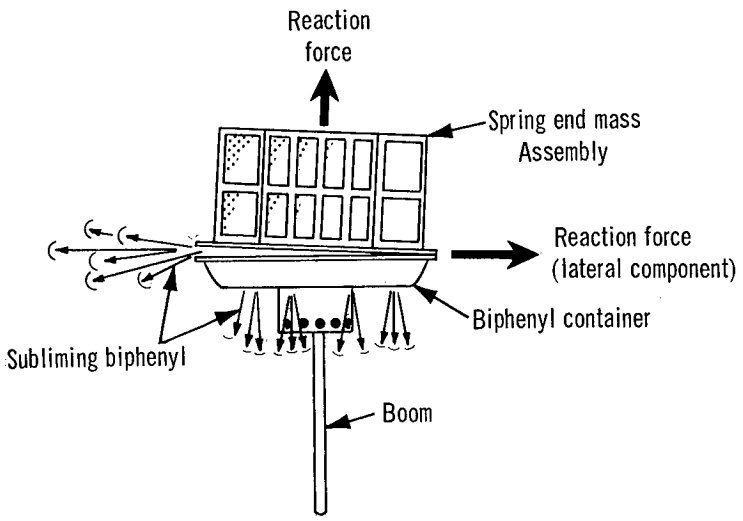


Figure 5.–Reaction force of subliming biphenyl.

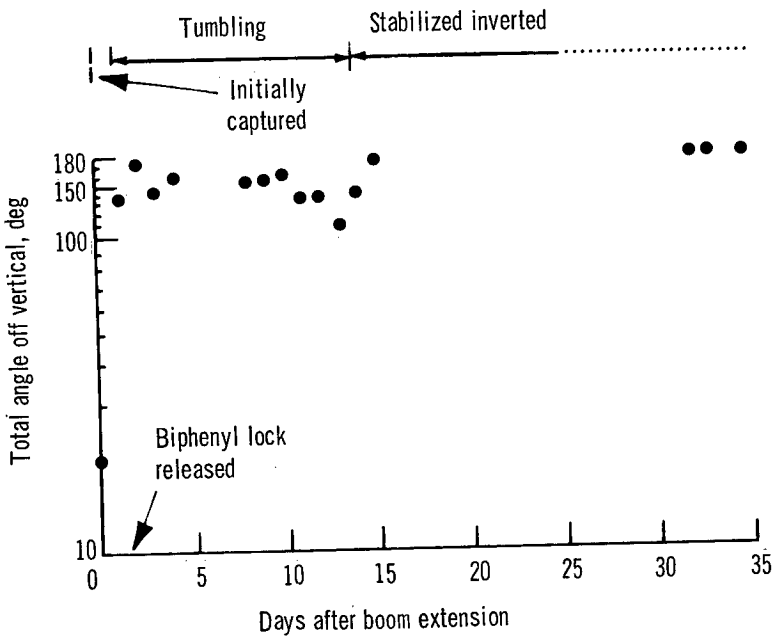


Figure 6.–Attitude history of satellite 1963-38B.

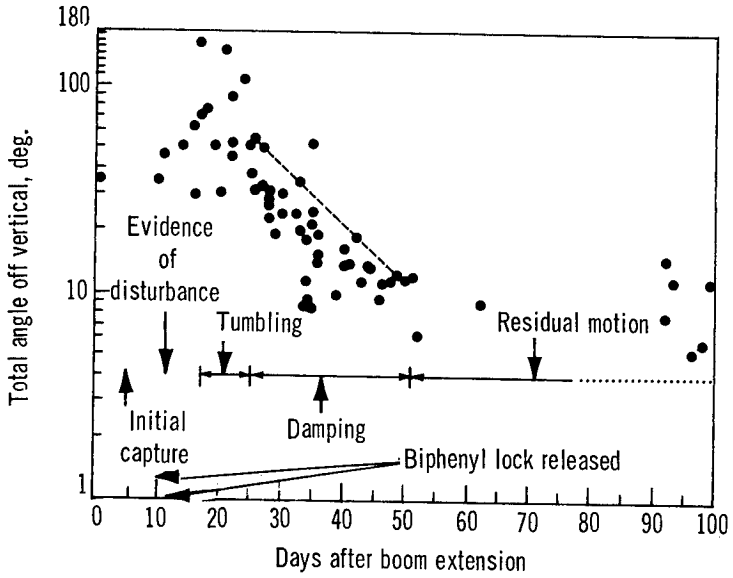


Figure 7.–Attitude history of satellite 1963-49B.

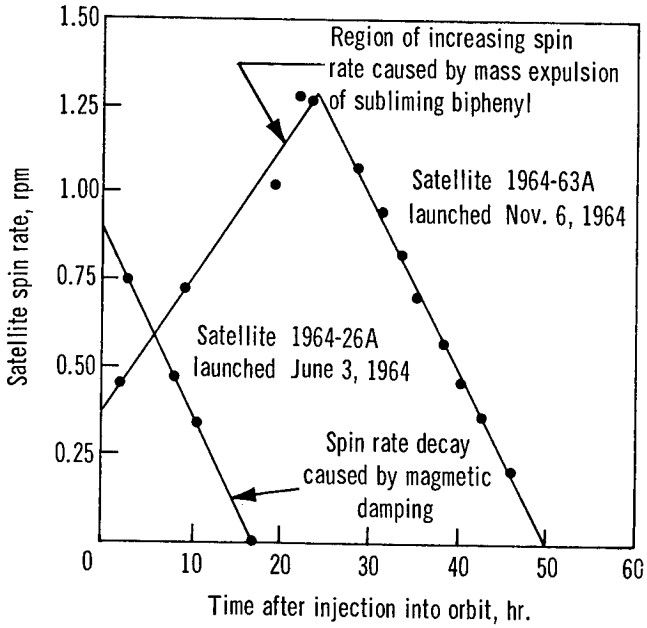


Figure 8.–Spin rate history of satellites 1964-26A and 1964-63A.

The despin histories of satellites 1964-26A and 1964-63A, shown in figure 8, give further examples of the effects of sublimation. These satellites employ a subliming biphenyl clamp that provides a delay of approximately 10 min in the separation of the satellite from the fourth stage rocket. In the normal operational sequence, a yo-yo device (described in ref. 11) despins the satellite fourth stage combination to approximately 1 rpm. The heat of the rocket casing causes the biphenyl to sublime rapidly and separation ensues, and magnetic hysteresis rods finally reduce the satellite spin rate to zero.

On satellite 1964-26A, the biphenyl vapor was ducted and exhausted from the satellite under controlled conditions. Satellite 1964-63A did not employ ducting, and biphenyl vapor condensed on the comparatively cold surfaces of the solar paddles. Because the paddles were all canted at an angle of 45° with respect to the spin plane, the subsequent resublimation of the biphenyl from the solar paddles produced a net torque along the spin axis that exceeded the despin torque supplied by the hysteresis rods. As a consequence, the spin rate increased until the sublimation of the biphenyl from the solar paddles was completed. This required about 24 hr, after which the hysteresis rods despun the satellite in the normal manner.

2.2 Analysis

Analytical models for mass expulsion disturbances permitting accurate determination of the resulting forces and torques are not available. The methods of treating gas and fluid dynamics in the analysis of jet propulsion have been applied to certain problems associated with venting and impingement (ref. 12). The real problem in assessing mass expulsion disturbance is identification. Once a source has been identified, gross approximations are usually sufficient to estimate the maximum disturbance.

Some of the techniques employed in evaluating the magnitude of the disturbance from various sources are described in the following paragraphs.

Leakage

A nominal value for gas leakage based on specifications or test data is often used in determining propellant requirements. A conservative estimate of the maximum disturbance torque is obtained by calculating the impulse that could be added if all the leakage took place through one of the nozzles (ref. 13). A more precise method of calculating leakage thrust is the one developed by B. Dobrotin, E. A. Laumann, and D. Prelewicz (ref. 4). This method has been substantiated by laboratory test data.

Thrust Vector Misalinement

A standard procedure is to assume a fixed misalinement of from one to several degrees and evaluate the torque or angular impulse. Additionally, the location and variation in the center of gravity of the spacecraft is estimated or determined from mass properties data.

Plume Impingement

The analysis is complex and the properties of the surface, angle of attack, and characteristics of the flow must be known or assumed. The approximate plume shape is determined either analytically or by test. Approximation by determining the amount of momentum flux intercepted and redirected usually yields sufficient accuracy for preliminary design considerations. An arbitrary fixed angular cone of 35° to 50° half angle is often assumed as the extreme boundary of the plume.

Venting

Evaluation of the torque resulting from equipment venting requires knowledge of the direction and rate of mass flow. When analytical evaluation of these quantities is impossible or too complex, appropriate experimental measurements are used. An upper bound for the generated torque can be obtained by assuming that the direction of the velocity of the expelled mass coincides with the centerline of the exit port.

Anomalous Firing Time

The usual procedure is to consider the effects of statistical variations on the nominal design value either through tests or educated guesses.

2.3 Test Methods

Direct measurement of mass expulsion disturbance is rarely feasible because the facilities for the simulation of the space environment and because equipment for the measurement of the torque levels are generally unavailable. Instead, test techniques are usually limited to measurements on components, testing to obtain input data for torque calculations, and simulations from which estimates of the torque can be obtained. These indirect measurements also involve difficulties:

(1) Significant disturbance torques may arise from forces in the 1 to 10 dyne range and the sensitive equipment for the detection and measurement of these forces may not be readily available.
(2) The Earth gravity environment may invalidate or distort test data.

(3) Vacuum facilities may have insufficient pumping capacity to maintain the proper test environment during the time that mass expulsion phenomena occur, as for example, during the full-scale firing of a thrustor
(4) The volume of the test chamber required to eliminate interactions with the chamber walls may exceed that of the available facilities
(5) Hazards associated with actual exhaust products may require the substitution of a test gas with the attendant problems of scaling or adjusting the test data

The force output characteristics of small thrustors can be measured in a vacuum chamber, but larger thrustors are normally tested at atmospheric pressure and the results extrapolated to vacuum conditions. On Mariner 2, the system was tested by actually firing the rocket motor in a simulated space environment (ref. 14), but such a test would be extremely difficult on a larger spacecraft.

Impingement forces have been determined with fair success by measuring the force on small test plates suspended at appropriate angles and positions in rocket or jet plumes. The data provided by a series of such tests can be used to compute the impingement force on an extended surface (ref. 7).

Disturbance torques generated by a subliming solid have been investigated by suspending a sample of the solid on a torsional pendulum in a vacuum chamber and allowing the sublimed particles to vent through a suitable orifice.

Leakage testing of cold gas systems and components is commonly performed in the qualification of the system, and test techniques for the measurement of leak rates in the 10^{-2} to 10^{-10} atm-cc/sec are well known (ref. 15). These techniques range from immersing the system in water and counting bubbles for large leakage rates to the use of tracer gases, usually helium, and a mass spectrometer when very low leakage rates must be measured. In determining the mass expulsion torques arising from leakage, it is also necessary to know leak locations as well as rates. It is often assumed that all the leakage occurs through one of the control nozzles because, in most cases, this represents a worst-case situation.

While disturbance torques from jettisoned objects, such as covers, ports, shrouds, and nosecones, are generally obtained analytically, data obtained during ground testing of the ejection mechanism can be used to check the calculations. If the event is photographed using a high-speed camera and the trajectory of the jettisoned object determined, the separation impulse can be computed.

The main source of test data for mass expulsion torques is recorded flight telemetry. This source of data has been particularly significant in evaluating torques caused by propellant dumping and venting, thrustor misalinement, and control jet leakage and misalinement.

2.4 Summary

Flight experience has shown that mass expulsion torques cause significant disturbances in the attitude control of a spacecraft. The difficulty of modeling the physical or geometrical parameters of most mass expulsion processes limits the usefulness of analytical calculations. Test results are limited because simulation of the critical parameters of the space environment is beyond the present state of the art. The current approach to estimating mass expulsion disturbance torques consists of a combination of the following techniques:

(1) Identification of likely sources of mass expulsion based on flight experience
(2) Assessment of the torque magnitude from data obtained on similar sources flown in previous missions and augmented by analysis and tests
(3) Elimination during spacecraft design of avoidable sources of mass expulsion and minimization of the disturbance torques caused by functional mass expulsion devices

3. CRITERIA

Disturbance torques arising from mass expulsion should be considered in the design of spacecraft attitude-control systems. A determination should be made as to whether the mass expulsion torques acting in combination with all other disturbance torques degrade the performance of the attitude-control system. If mass expulsion is an important factor in the system design, it is essential that steps should be taken throughout the spacecraft development to insure proper design so as to limit or control the magnitude of the disturbance torques.

3.1 Survey Space Vehicle Design for Sources of Mass Expulsion Torques

The spacecraft should be examined to identify all systems and equipment that can expel mass either during normal operating conditions or during and after recovery from unusual conditions imposed by thermal, mechanical, or radiative stress. This assessment should include all potential sources of mass expulsion. Particular attention should be given to the following:

(1) Leakage from control valves, check valves, pressure regulators, storage containers, fill valves, interconnecting piping and fittings, pressure relief valves, and plenum chambers

(2) Variation in thrust vector resulting from mechanical or thermal shifts in the position or angular orientation of the thrustor, changes in nozzle geometry, variation in thrust magnitude when paired thrustors are employed, and shifts in the location of the spacecraft's center of mass
(3) Impingement of exhaust plumes from nozzles, jets, and vernier and main engines onto adjacent spacecraft surfaces and extended structures, e.g., solar panels, antennas, booms, piggyback payloads
(4) Venting of gases trapped within the spacecraft, venting of gas or vapor generated by batteries and fuel cells, venting of vapor from cryogens and relief valves in pressurized systems, and discharge of waste matter
(5) Dumping or jettisoning of residual fuel from propulsion engines, including gaseous and fluid discharge and evaporation or sublimation of fuel on chamber walls, ducts, and piping
(6) Gaseous products from subliming mechanisms, such as clamps, spring and boom release devices, and deployment timers
(7) Recoil forces from separation and ejection of multiple payloads
(8) Impulsive reaction from release and jettison of nosecone, covers, clamps, shields, and other expendable parts
(9) Outgassing, sublimation, and leakage from components, experiments, sealed containers, lubrication reservoirs, and high-vapor-pressure materials and coatings

3.2 Determine Potential Magnitude of Disturbance Torques

A conservative estimate of mass expulsion disturbance torques should be based upon the results of analyses and tests of contributing sources and related shifts in the spacecraft's mass center. Because these torques are difficult to determine accurately, a worst-case combination of torque and mass-center shift should be assumed for the estimate to determine if attitude control may be degraded to an unacceptable extent.

3.3 Minimize and Control Disturbance Torques

When mass expulsions are important sources of disturbance torques, such sources should be identified and eliminated or minimized early in the spacecraft design. The extent of such efforts should be commensurate with the potential hazard that these torques pose to mission performance.

Where mass expulsions are an intentional or inherent characteristic of spacecraft operation, their contribution to torque can be minimized but, generally, cannot be eliminated. The torques associated with these sources should be minimized by considering the interactions with other spacecraft systems. The disturbance torques caused by the residual mass expulsion should then be conservatively evaluated and their effects accounted for in the design of the control system.

Potential sources of unintentional mass expulsion should be eliminated or, when elimination is not possible, design and mission modifications that would reduce the risk of performance degradation should be considered. During mission design, a delay in the initiation of attitude control should be considered to allow for the time decay of mass transfer from sources of this category.

The effects of minimizing mass expulsion torques should be evaluated for possible conflicts with other functional requirements of spacecraft design. The requirement that contaminants be expelled at relatively high velocity to reduce the risk of contaminating sensitive surfaces increases the possibility that a disturbance torque will be generated. Such requirements should be examined to insure compatibility with attitude stabilization requirements and capability.

4. RECOMMENDED PRACTICES

4.1 Identify Sources of Mass Expulsion

All components that normally expel mass or might do so under environmental stresses should be identified as early as possible in the design phase of the spacecraft development program.

The classification of sources given in section 2 and the discussion of flight experience indicate the scope and level of detail appropriate in the assessment of mass expulsion sources. The level of difficulty and required detail of examination to identify sources increases from category 1a, with such obvious sources as attitude-control thrustors, to category 2, which includes materials that may sublime or outgas under various combinations of environmental conditions. Subliming or outgassing sources are generally excluded from listings of materials and components intended for use in spacecraft because they may also cause contamination of scientific payload instruments, optical equipment, and windows. Close coordination and communication with propulsion, mechanical, and materials design groups are recommended to provide for early and continued awareness of spacecraft components and materials that will expel mass.

4.2 Assess Disturbance Torques

4.2.1 Effects From Thrustor Systems

The major causes of disturbance torques from thrust-generating systems are (1) misalinement of the thrust vector (for engines without thrust vector control) from the planned vector relationship to the mass center and (2) impingement of the exhaust plume on the spacecraft structure. Swirling of the exiting mass and differential magnitude errors may also cause unwanted torques. Differential magnitude errors occur when the thrust along an axis is not actually canceled by a supposedly equal magnitude in the opposite direction on that axis, e.g., $|+T_x| \neq |-T_x|$, even when the thrust is properly alined. For reaction-control systems, disturbance torques are caused by misalinement and impingement and also by leakages and anomalies in timing and total impulse transferred.

Misalinement Effects

Thrust misalinement problems tend to increase as nozzle size decreases. Generally, larger nozzles can have thrust misalinement as small as 0.1° or 0.2°, whereas small nozzles often have as much as 1° or 2°. A nozzle can be mechanically alined to about 15 arcmin, but this alinement will be degraded by subsequent handling and environmental stresses. On a new design, thermal distortion coupled with mechanical discontinuities have often caused misalinement of 1° or 2°; this misalinement can be reduced to about 0.2° to 0.3° by refinement of the design. Mechanical discontinuities caused by the addition of a ceramic nozzle extension or a throat insert, and manufacturing irregularities of all sorts can, in combination with thermal irregularities, produce significant thrust misalinements.

The disturbance torque caused by thrust misalinement can be determined by measuring or estimating the thrust magnitude and direction and the moment arm between the spacecraft's mass center and the line of action of the thrust. Generally, only the magnitude of the thrust is known accurately. The thrust direction and the moment arm can be estimated by considering the following factors:

(1) The maximum displacement between the geometric axis of the thrustor and a specified mass center location
(2) The deviation between the specified and actual mass center
(3) The deviation between the geometric axis of the thrustor and the actual line of thrust (this is determined by testing the thrustor and usually cannot be assessed as precisely as the foregoing factors)

A reasonable estimate of the maximum torque can be obtained using these factors in combination with the maximum thrust magnitude.

The torque impulse is estimated by taking 1 or 3 percent (1 percent for refined or well-established standard thrustors; 3 percent in cases of new or unproven designs) of the total force impulse, i.e., linear momentum change obtained during firing, and multiplying it by the distance between the spacecraft's mass center and the thrustor's line of action. The average magnitude of the disturbance torque is obtained by dividing the torque impulse by the thrustor actuation time. Because only the magnitude of the disturbance torque is obtained, a worst-case direction should be assumed. When sizing the actuators for spacecraft attitude control, this implies that the torque should be assumed to be directed along one of the control axes. When determining expendable propellant requirements, this assumption is conservatively interpreted as a torque displaced at a 45° angle from a control axis.

Impingement Effects

Exhaust plume impingement on nearby surfaces produces viscous and pressure forces that degrade the thrust magnitude and alter the thrust line of action. The plume extends over a considerable volume. For many configurations, particularly those with complex or variable geometries, the disturbance torque caused by the impingement is difficult to determine analytically. An analytical or experimental determination of the plume characteristics will enable the designer to determine which (if any) surfaces of the spacecraft are within the plume boundaries.

An often-used technique for determining plume characteristics is the method of characteristics solution that regards the flow, assumed to be steady, as emanating from a source placed at the intersection of the walls of the nozzle. The flow field is represented by surfaces, assumed to be moving through the medium, whose characteristic equations are numerically integrated to yield the desired results (refs. 16 and 17). Another technique is the analytical approximation described by Hill and Draper (ref. 18). Although not as accurate, close to the nozzle, as the method of characteristics solution, this method yields increasingly better results as the downstream distance from the nozzle increases. The Hill and Draper plume characteristics approximation should be sufficiently accurate for spacecraft design involving cold gas nozzles. At distances far from the nozzle, the mass flow is essentially radial, as shown in figure 9 (from ref. 18); the mass

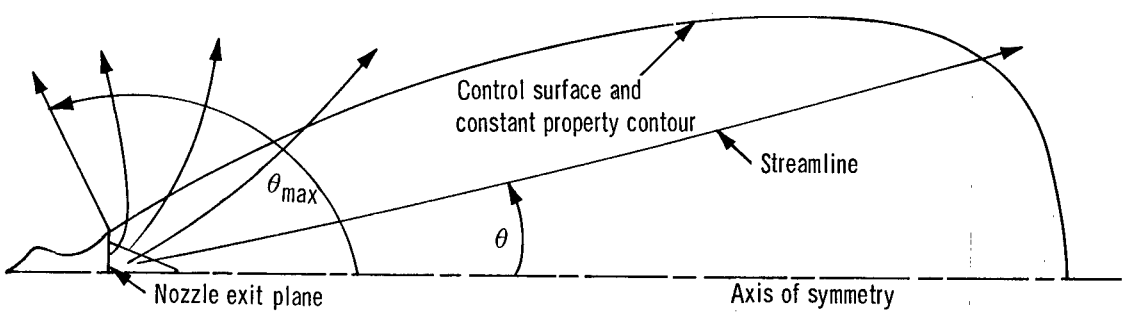


Figure 9.—Schematic flow pattern of a cold gas nozzle exhausting in a vacuum.

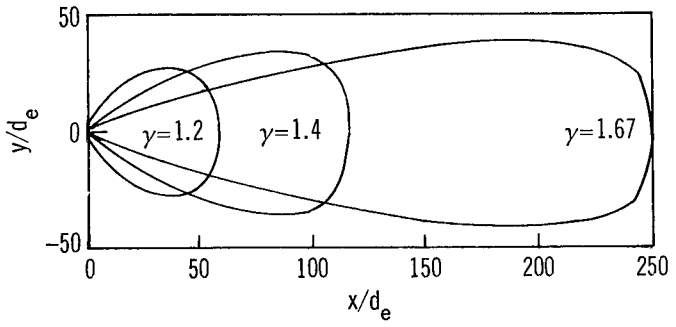


Figure 10.—Contours of constant density ratio $\rho/\rho_c=10^{-6}$ for $A_2/A_t=25$.

density varies along each streamline as $1/r^2$ where r is the radial distance. The mass flow is described by defining the mass flux per unit solid angle $d\dot{m}/d\Omega$ as a function of the displacement angle θ from the axis of symmetry. The rapid decrease in $d\dot{m}/d\Omega$ as θ increases can be approximated by the normalized function

$$\frac{(d\dot{m}/d\Omega)_\theta}{(d\dot{m}/d\Omega)_{\theta=0}} = \exp\left[-\lambda^2(1-\cos\theta)^2\right] \tag{1}$$

where λ is the plume shape parameter. This function is normalized by using the value of $(d\dot{m}/d\Omega)_{\theta=0}$ at an x/d_e (distance along plume to nozzle exit diameter) ratio of 250 as illustrated in figure 10 (from ref. 18).

The value of λ changes from one constant property contour (control surface as shown in fig. 9 on which the mass properties are constant) to the next because of variations in the fluid speed along the streamlines. At distances far from the nozzle, λ approaches the asymptotic value λ_∞:

$$\lambda_\infty=\left[\pi^{1/2}\left(1-\frac{C_f}{C_{f\,\max}}\right)\right]^{-1} \tag{2}$$

where C_f is the vacuum thrust coefficient defined as

$$C_f=\left\{\frac{2\gamma^2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left[1-\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{1/2}+\left(\frac{P_2}{P_1}\right)\frac{A_2}{A_t}$$

and

$$C_{f\,\max}=\left[\frac{2\gamma^2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\right]^{1/2}$$

where

γ = specific heat ratio
P_1 = chamber pressure
P_2 = nozzle pressure
A_2 = nozzle area
A_t = nozzle throat area

The maximum vacuum thrust coefficient $C_{f_{max}}$ is obtained when the area ratio of the nozzle is infinite.

Constant property contours obtained by using equation (1) are illustrated in figure 10 for three values of γ.

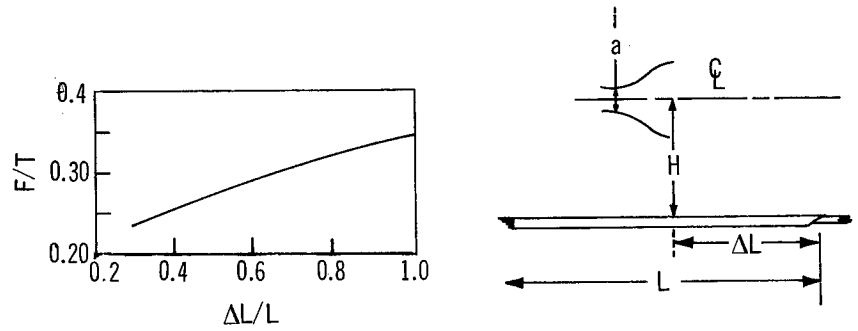
In general, the half angle between the centerline and constant property contour is a complicated function of parameters including specific heat ratio, expansion ratio, temperature, mach number, and nozzle geometry. Theoretically, it varies from about 15° to 90° and defines boundaries for any given fraction of the total momentum flux. The frequently made assumption that 90 percent of the momentum flux is contained within 35°-50° of the centerline of the plume is not recommended in view of the dependence of the half angle on the aforementioned parameters. The assistance of propulsion specialists is recommended to obtain an assessment of the momentum flux associated with the plume. Their results should be used to calculate the expected impingement forces and associated torques.

The uncertainties involved in analytical methods for determining disturbance torques caused by impingement limit their usefulness. If the results of analysis show that plume impingement is probable, tests should be made of the configuration whenever possible to obtain a more reliable assessment of the magnitude of the torque. When low angles of incidence are possible and the intercepting surface is parallel to the centerline of the flow, the normal force on the surface may be a considerable fraction of the nozzle thrust. Experimental data obtained for a cold gas flowing from a nozzle onto a flat plate is illustrated in figure 11.

A useful technique in the assessment of plume impingement disturbance torques is to measure impingement forces on a small plate placed in various positions in the test plume. The use of this technique to evaluate the effects of the roll nozzle plume impingement on the solar paddles of the Nimbus satellite is described in reference 8.

Leakage

Leakage from reaction jet control system can be minimized or eliminated by controlling the cleanliness of the system during fabrication and assembly (ref. 19) and by close control of the mechanical integrity of the system. In a limit-cycle reaction jet system, valves have been known to stick slightly open because of foreign particles lodged in the valve or other



Test conditions

Exit mach number	: 3.0	Chamber pressure	: 230 psia
Thrust, T	: 3.26 $lb_{f\ max}$	H/d	: 8
Force, F	: Force impinging on flat plate, lb_f	Angle of plate relative to nozzle, ℄	: 0
Gas	: Air at 530° R		

Figure 11.–Variation of normal force with plate position.

malfunction. Provisions should be considered for overriding the automatic system so that a jet can be operated on command to dislodge contamination causing malfunction. For low leakage rates, the method developed by B. Dobrotin et al. (ref. 4) is recommended for calculating leakage thrust.

Anomalies in Timing Characteristics

When performance requirements depend on thrustor operating-time characteristics, these characteristics must always be confirmed by testing.

An abnormally large minimum impulse often occurs as the gas trapped between a valve and a nozzle escapes. Similarly, when a pressure regulator is used in a cold gas system, leakage at the regulator may cause a rise in pressure at a valve and result in a large initial impulse when the valve is actuated following a long period of inactivity. This condition also occurs when the system switches from high- to low-pressure operation. Valve operation will continue to produce a high thrust level until the high-pressure gas trapped between the regulator and the valve is exhausted.

Monopropellant systems using anhydrous hydrazine tail off in thrust after the end of the firing pulse. Thrust tail-off parameters are the catalyst bed temperature, the length of the catalyst bed, and the duty cycle to which the catalyst is exposed. For an 8-lb thrustor, the measured tail-off of monopropellant hydrazine was about 25 percent of the total thrust

during a 15-sec tail-off period (ref. 20). Experimental results indicate that when the catalyst bed is fully wetted, when the evaporation is exponential, and when the thrust level has decreased to 10 percent of the peak thrust, the thrust tail-off can still be as great as 30 percent of the total impulse. Redesign should enable this thrust tail-off to be decreased to about 15 percent of the total impulse.

4.2.2 Effects of Subliming Mechanisms

Whenever subliming materials are used, the disturbance torque created by their mass expulsion must be considered. Consideration must also be given to the possibility that the subliming material will condense onto a comparatively cold spacecraft surface and generate a disturbance torque when it resublimes.

The torque caused by subliming material can be reduced by controlling the path of the sublimed material. One method of eliminating the condensation of subliming material is to employ a tube or nozzle that will direct the gas away from all spacecraft surfaces. When this method is used, the thrust axis of the exit tube or nozzle should pass through the mass center of the spacecraft so that the disturbance torque is minimized.

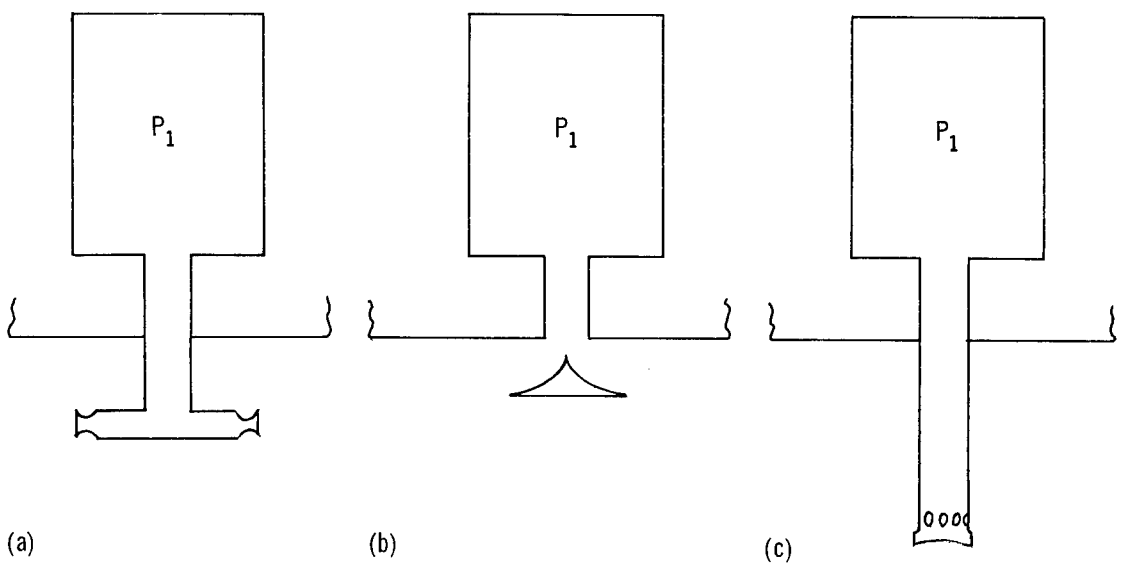


Figure 12.–Typical exit configurations of equipment for compartment venting. P_1 = chamber pressure. (a) Simple "tee" exit nozzle. (b) Standoff deflection plate. (c) Extended pipe with nonpropulsive orifices.

When subliming materials condense onto the spacecraft's surfaces, the materials will probably resublime with a period of a few hours to several days. The resubliming rate depends mainly on the temperature of the surface on which the material condensed (ref. 20). When activation of the attitude-control system cannot be delayed until after resublimation is complete, the system must be capable of providing torques that are large compared to those produced by any subliming or resubliming material.

Control of the direction of the efflux of subliming material is the obvious and direct method of minimizing the disturbance torques that may result. Precautions should be taken to insure that any shrouds used to direct the efflux of subliming material are effective for all vehicle configurations. Various nonpropulsive venting concepts are depicted in figure 12.

4.2.3 Effects of Payload Ejection and Equipment Jettison

Payload Ejection

Disturbance torque impulses caused by payload ejection and the payload tipoff rates must be considered by the control-system designer. If the launch vehicle carries multiple payloads or performs other functions in orbit, then the effects of payload ejection on the launch vehicle will also be important. Disturbance torques on the payload or launch vehicle occur when the separation force does not pass through the respective mass centers.

Tipoff of a spring-loaded payload generally results in a nonzero tumble rate that should be considered by the control-system designer. At separation or tipoff, a retaining band is released, enabling the spring-loaded payload to be ejected. The springs do not expand at identical rates and the unequal momentum impulses that are generated often cause the payload to tumble. The rate of tumble can be computed by considering the differences in the rates of expansion of the individual springs.

Effect of impingement of a plume on a separated payload or launch vehicle must be considered when either body is provided with control thrustors. On the Burner 2 spacecraft, the payloads were spun up immediately after ejection and additional propellant was included for the attitude-control thrustors to enable the spacecraft to counter the torques caused by impingement of the payload's exhaust plume. Degradation of performance caused by these torques can be eliminated or minimized by deferring activation on the respective bodies of the propulsion or reaction-control systems until considerable separation has been achieved.

Equipment Jettison

Equipment jettison usually produces a small transient disturbance torque that has a negligible effect on the long-term performance of the control system. However, when such torques may cause unacceptable disturbance in early stages of the mission, the resulting impulse must be considered in terms of propellant requirements. When the distance between the jettisoned equipment and the spacecraft's mass center is large, the line of action of the separation force should pass as close to mass center as possible.

Propellant Jettison

Because of the difficulty of predicting flow behavior and impingement forces caused by dumped liquids, testing is usually required to establish approximate patterns and magnitudes. Furthermore, because space environmental conditions are difficult to simulate during tests, the values obtained from the test must be used conservatively.

When a spacecraft's attitude must be maintained during propellant jettison and venting operations, magnitude and duration of the disturbance torque must be estimated to define torque-producing requirements for attitude-control actuators and gas or propellant needed for the mission. Conversely, when acquisition of the final attitude can be accomplished from a random position and a mass expulsion attitude-control system is used, activation of the control system should be delayed until the propellant dumping or venting operation is completed.

Equipment and Compartment Venting

Equipment, such as fuel cells, batteries, and cryogens, produce liquids or gases that must be vented. To insure that this venting does not produce excessive disturbance torques, exit configurations such as illustrated in figure 12 are used to nullify net thrust. These nullifying nozzles reduce the residual thrust to about 10 percent of the thrust from an unbaffled nozzle. Because of the possibility of impingement, all nearby spacecraft surfaces should be simulated during tests of the nullifying nozzle. The possibility of the vented material contaminating the spacecraft's sensors or condensing on a spacecraft surface and resubliming also must be investigated.

Estimation of Torque Caused by Venting

To determine the torque created by the expulsion of gas from a spacecraft, both the direction and rate of gas flow must be known. Both quantities are difficult to determine analytically and, therefore, experimental measurements are often needed. The mass expulsion force can be estimated by using the equation

$$\mathbf{F}=\frac{dm}{dt}\mathbf{v}_e \tag{3}$$

where

$\frac{dm}{dt}$ = mass time rate of change of the system, kg/sec

$\mathbf{v}_e$ = velocity vector of expelled mass relative to the vehicle, m/sec

If the gas temperature is known,

$$|\mathbf{v}_e| = \sqrt{3kT/M} \tag{4}$$

where

k = Boltzmann's constant, J/°K
T = absolute temperature, °K
M = mass of a single molecule, kg

Assuming that the force generated by the gas expulsion has a moment arm **r** with respect to the mass center of the spacecraft and that the direction of $\mathbf{v}_e$ coincides with the centerline of the exit port, an upper bound can be placed on the generated torque. Consider as an example satellite 1963-38B. The gravity-stabilized satellite tumbled for 14 days because of the sideward thrust generated by subliming biphenyl. The rate of sublimation is a function of the temperature of the solid and the exposed surface area. Thus, the sublimation rate at a given temperature is in terms of kg/sec/m^2. The torque **L** generated by the subliming biphenyl is defined by

$$\mathbf{L} = \mathbf{r} \times \mathbf{F} = \mathbf{r} \times \frac{dm}{dt}\ \mathbf{v}_e \tag{5}$$

$$L = |r| \frac{dm}{dt}\ \frac{3kT}{M}^{1/2} \tag{6}$$

Substituting APL-supplied data for satellite 1963-38B into equation (5) to obtain the magnitude of this torque gives

$$L = (30\text{ m})(5.28 \times 10^{-7}\text{ kg/sec}) \left[\frac{3(1.381 \times 10^{-23}\text{ J/°K})(300\text{°K})}{1.82 \times 10^{-25}\text{ kg}}\right]^{1/2}$$

$$L = 4.15 \times 10^{-3} \quad \text{N-m (41 500 dyne-cm)}$$

This torque far exceeds the gravitational torque and indicates that the satellite will tumble as the result of the mass expulsion. Experience with the satellite as described in an earlier section tends to confirm the validity of the analysis.

4.2.4 Effects of Outgassing from Materials

The elimination of all materials that outgas from a spacecraft is difficult. When a satellite is placed into orbit and for some time thereafter, organic and other materials will exude gas molecules. If the vector sum of the velocity vectors of these gas molecules as they emanate from the satellite does not pass through the satellite's mass center, torques will result that can produce undesirable attitude disturbances. These outgassing torques are usually negligible compared to the torque levels generated by a satellite's attitude-control system. However, passively stabilized satellites rely on very weak restoring torques and the outgassing torques can produce a significant disturbance.

Recommended practices to avoid outgassing are

(1) Avoid porous materials that could entrap and then slowly release a significant volume of gas.
(2) Provide one or more holes in the spacecraft's body through which the released gas can escape freely and nonpropulsively.
(3) For satellites whose attitude-control system generates torques of the order of the outgassing disturbance torques, do not activate the attitude-control system until a few days after the satellite has been placed in orbit or until outgassing torques decrease to a negligible level.

4.3 Testing

As discussed in section 2.3, direct test evaluation of mass expulsion torques is seldom feasible. However, when mass expulsion effects may adversely affect control-system performance, tests of individual components and subsystems, augmented by analysis, will be required.

Leakage

Reaction-control systems are usually tested to determine leakage rates. Thrustors should be checked for leakage. Leakage tests can be performed underwater by observing the bubbles to locate the sources and by measuring the volume of escaped gas to determine the relative leakage rates. These tests can also be performed by filling the reaction-control system with helium or introducing a small percentage of helium with the gas normally used in the system, and determining the rate of gas escape and the leakage points by using such equipment as mass spectrometer helium-leak detectors. Valves can be tested for leakage by placing them in a plastic hose and placing the open end of the hose under water.

Alinement

Thrustor alinement is tested by determining the spacecraft's mass center and verifying the thrustor location and orientation. The mass center is determined by measuring the mass properties of the spacecraft; the thrustor location and orientation are determined by metrology. Test determination of the actual thrust axis of the thrustor is beyond the state of the art.

Impingement

Tests to determine the impingement forces resulting from exhaust plumes are particularly important when the angle of attack, i.e., angle between the centerline of the plume and the impinged surface, is very small. Measurements of the impingement forces on simulated sections of the spacecraft surface embedded in the exhaust plume from a nozzle are feasible. When the impinging plume is a hot gas, contains a mixture of constituents, or is a mixture of vapor and liquid, testing becomes difficult, scaling is frequently not feasible, and extrapolations from tests made with a substitute gas will usually be required for approximating the effects.

Sublimation

When the exhaust products from subliming materials are ducted and expelled from orifices or nozzles, simulation tests to determine the associated disturbance torques are advisable. One such test is to mount a simulated expulsion system at one end of a counterbalanced bar suspended on a torsion wire and to measure the forces generated by the subliming material. The test should be performed in a vacuum; the temperature of the subliming material and surroundings must be maintained at the expected operating temperature in a space environment.

Operating Characteristics

Reaction-control thrustors should be tested under conditions that closely simulate the actual flight environment to verify the thrust-versus-time characteristics. Piping configurations should be identical to the flight model so that the effects of trapped gas can be measured. The effects of variations in gas pressure and temperature should be checked. If the thrust measurement equipment is not sufficiently sensitive to insure detection of residual thrust after shutoff, an upper bound on the residual thrust should be analytically established using the results of leakage tests.

Equipment Jettison

When the reaction from jettisoned equipment can cause significant disturbance torques, the impulse applied to the payload is estimated from the trajectory of the payload. High-speed photography can be used to provide trajectory data when the separation mechanism is tested.

Propellant Jettison

Adequate tests to determine the disturbance torques caused by propellant dumping or venting operations have not been developed. Flight-test data augmented by an analysis to convert available data to data relevant for the specific case can provide the required disturbance torque magnitudes. Flight plans should include a safety margin to enable the completion of the propellant jettison.

Venting

Tests will generally be required to determine the characteristics of the vented material (except for air or predetermined pressurizing agents) and the reaction force at the exit port.

Outgassing

Outgassing information is obtained from vacuum weight-loss studies generally conducted as part of the material evaluation program during spacecraft development. Calculation of the time delay required to insure that the disturbance torques caused by outgassing are negligible can be based on an analytical determination of flow rates through outgassing orifices.

APPENDIX

NOMENCLATURE

A_2	Nozzle area
A_t	Nozzle throat area
C_f	Vacuum thrust coefficient
$C_{f_{max}}$	Maximum vacuum thrust coefficient
$d\dot{m}$	Differential mass flux
$d\Omega$	Differential solid angle
$\mathbf{F}$	Force vector
k	Boltzmann's constant
L	Torque magnitude (scalar)
$\mathbf{L}$	Torque vector
M	Molecular mass
P_1	Chamber pressure
P_2	Nozzle pressure
r	Radial distance (scalar)
$\mathbf{r}$	Moment arm vector
T	Absolute temperature
T_x	Component of thrust along the x-axis
$\mathbf{v}_e$	Exhaust velocity vector
γ	Specific heat ratio
θ	Angle measuring the displacement of the streamline from the symmetry axis
λ	Plume shape parameter

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SP-8002 (Structures)	Flight-Loads Measurements During Launch and Exit, December 1964
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SP-8016 (Guidance and Control)	Effects of Structural Flexibility on Spacecraft Control Systems, April 1969
SP-8017 (Environment)	Magnetic Fields–Earth and Extraterrestrial, March 1969

SP-8018 (Guidance and Control)	Spacecraft Magnetic Torques, March 1969
SP-8019 (Structures)	Buckling of Thin-Walled Truncated Cones, September 1968
SP-8020 (Environment)	Mars Surface Models (1969), May 1969
SP-8021 (Environment)	Models of Earth's Atmosphere (120 to 1000 km), May 1969
SP-8023 (Environment)	Lunar Surface Models, May 1969
SP-8024 (Guidance and Control)	Spacecraft Gravitational Torques, May 1969
SP-8025 (Chemical Propulsion)	Solid Rocket Motor Metal Cases, April 1970
SP-8027 (Guidance and Control)	Spacecraft Radiation Torques, October 1969
SP-8028 (Guidance and Control)	Entry Vehicle Control, November 1969
SP-8029 (Structures)	Aerodynamic and Rocket-Exhaust Heating During Launch and Ascent, May 1969
SP-8031 (Structures)	Slosh Suppression, May 1969
SP-8032 (Structures)	Buckling of Thin-Walled Doubly Curved Shells, August 1969
SP-8033 (Guidance and Control)	Spacecraft Earth Horizon Sensors, December 1969
SP-8035 (Structures)	Wind Loads During Ascent, June 1970

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