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Launched APL spacecraft require special equipment to initiate despin and unfolding of the solar blades; to separate the spacecraft from the launch vehicle injection stage; and to yaw the injection rocket after separation to prevent collision with the spacecraft. This article describes a unique simplified separation system which not only incorporates all these capabilities, but also offers some additional features, including lighter component weight, elimination of batteries, immunity to background disturbances, and operation which is completely independent of the launch vehicle.

a Simplified Passive Spacecraft Separation System

The Applied Physics Laboratory, long a proponent of an independent separation system for its spacecraft and launch vehicles, has developed an effective passive separation system which may eliminate many ground-handling problems attendant to launch preparation while at the same time maintaining reliability.

Preparing the separation system for flight and maintaining flight readiness at the launch site can involve a number of problems. On some occasions, separation batteries have to be replaced in the field after being verified for flight. And, similarly, the sublimation timers require repair and replacement at rather awkward times. Because of the

virtually inaccessible position of the sublimation timers, it is extremely difficult and hazardous to replace them after the spacecraft adapter has been installed on the launch vehicle for spin-balancing the injection stage.

It was reasoned that, if the sublimation timers could be replaced by an equally reliable passive timer that could be tested at will without destruction and would not impose severe ground-handling and environmental restrictions, the field operations would be improved. It was also reasoned that separation simplification and improved inherent reliability could be achieved if the new passive timer could also be configured to provide initiation of the various separation functions without using batteries. The passive timer could be used to actuate simple gun-type triggers for the pyrotechnic bolt cutters, the cable cutter, and the control rocket, all of which are necessary for operation of the system.

Eliminating the need for batteries could be accomplished by using percussion-initiated ordnance squibs, such as those in use throughout the world in aircraft crew ejection systems.

However, in the configuration analysis that followed, it became apparent that it would actually be practical to design a passive separation system which, in addition to the above virtues, would not use *any* pyrotechnic devices.

This concept evolved into the simplified passive separation system described in this article.

APL Satellite Configuration

A typical configuration of an APL spacecraft is an octagonal body of approximately two cubic feet with four long solar blades attached which are literally folded around the injection stage of the launch vehicle during launch. The solar blades are held securely to blade standoffs on the rocket case by tightly wound despin weight cables. The configuration is such that by merely releasing the despin weights, the attached cables cause the spinning stage to despin and allow the spring-loaded solar blades to deploy. This is the familiar "yo-yo" despin system used in numerous spacecraft orbited by the United States. There are two more functions which have to be accomplished with this configuration to complete the post-injection-into-orbit sequence. First, the spacecraft must be separated from the launch vehicle, and finally, the thrust axis of the launch vehicle must be diverted so that the inevitable outgassing from the spent injection rocket, which persists for about 1600 seconds will not cause the rocket to bump the spacecraft,

after separation. This last maneuver is usually accomplished (in non-spinning spacecraft) by means of a low-impulse control rocket whose thrust axis is aligned perpendicular to the main thrust axis of the injection rocket and forward of its center of gravity.

General Description

The simplified separation system is truly passive. That is to say, once assembled and tested in the laboratory, it is thereafter ready for flight, since its readiness can be confirmed at any accessible time by visual inspection. And, once launched, it has the capability of providing automatically the necessary separation functions in the proper sequence with no functional interface with either the spacecraft or the launch vehicle.

Earlier systems relied on a sublimation timer to close the circuits of the various pyrotechnic devices in the proper sequence (Fig. 1). The sublimation timers were attached to special aluminum
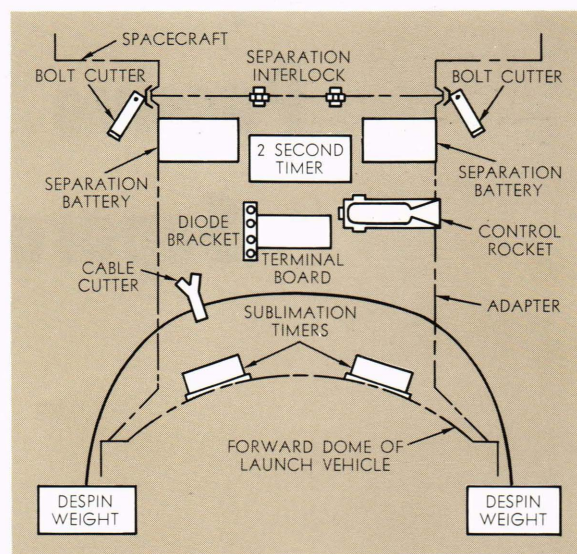

Fig. 1—General arrangement of current separation system.

pads which were previously bonded to the injection rocket head cap before the spacecraft arrived at the launch site. The configuration and locations of these pads on the rocket were determined from prior static firing tests of similar rockets to establish the temperature versus time characteristics of the rocket head cap outer surface. In flight, the heat from the injection rocket was transferred to the base of the sublimation timer, and caused

greatly accelerated sublimation of a solid material in the timer (usually biphenyl) to the ambient vacuum. This action allowed a spring-loaded electrical contact wiper in the timer to make and break the various separation sequence circuits.

Additionally, the passive separation system offers the following characteristics: (a) Less weight—components are 60% lighter than their functional equivalents in earlier systems. (b) No batteries, no wiring or electrical components, nor are any pyrotechnic devices used. (c) Immunity to RF, static, or other electrical background disturbances. (d) No ground environmental temperature limitations. System can survive any temperatures normally expected to be encountered in ground handling and transportation such as the typical ground environment design limits of −60°F to +160°F. (e) Indefinite shelf life, even in the launch-ready configuration. (f) System operation and design features are completely independent of the launch vehicle configuration; there is no functional or physical interface with the vehicle. (g) System can be completely tested any convenient number of times or places (including on the launch vehicle) without hazard to itself or adjacent personnel or equipment. (h) Flexibility—any of the subsystems, the passive delay actuator, the trigger assembly, the cable release assembly, and the control rocket, can be integrated separately or collectively into existing spacecraft separation systems or other mechanical systems, as desired. (i) Accuracy—timing sequences are typically repeatable within ±2% as compared to ±20% for the present sublimation timer system. Although high accuracy is not a stringent requirement in the present application, it is clear that possible future applications involving longer times (many hours) and more mechanical functions would require much greater accuracy than is currently available.

Figure 2 illustrates the various components which compose the simplified passive separation system. The principal subsystem is the passive delay actuator (PDA) trigger assembly, which is actually a pneumatic timer capable of performing work at discrete times after being launched into the vacuum of outer space. The sole input to the PDA is the exposure to the vacuum almost immediately after the launch vehicle lifts off the launch pad, while the output of the integral trigger unit is the 23-lb snap action of each of the two triggers at specified times after liftoff. The first trigger causes the simultaneous release of the two despin weight release cables, while the second trigger causes release of two similar cables which secure special bolt clamps on the main spacecraft

separation clamp. A compression spring provides the force required to separate the spacecraft.

With this arrangement, both the despin weight assemblies and the spacecraft separation clamp can accommodate the new system without redesign. The despin weights are used as is, while their release cable is modified to permit release by unlatching, instead of by explosive cable cutter.
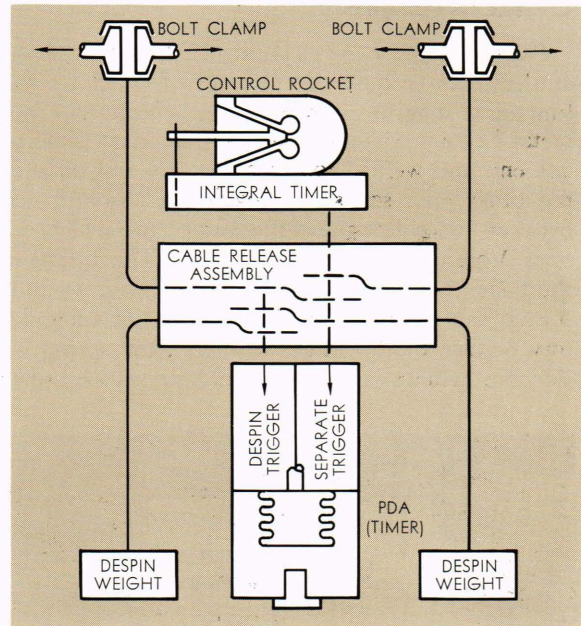

Fig. 2—Block diagram of passive separation system.

Finally, the action of the second trigger also fires the control rocket through an integral 2-second mechanical delay timer. The timer prevents the control rocket from firing before the spacecraft has adequately cleared the adapter during the separation process. The control rocket is a unique development in that it contains no pyrotechnic elements. The impulse is derived from the explosive evaporation of an appropriate fluid when suddenly exposed to the vacuum of outer space.

All of the passive separation system components can be located on the outside of the spacecraft adapter for maximum accessibility and ease of visual inspection. All of the functioning components of the system are securely locked by the trigger shafts upon assembly and remain in this condition until the triggers are armed and fired during the launch cycle. The trigger shafts, in turn, are not physically connected to the passive delay actuator until the latter unit is automatically armed shortly after launching. If it is desired to

accomplish final assembly prior to shipping to the launch site, it will be required that a non-flight safety pin be installed in the PDA to prevent inadvertent operation during air shipment. If it is desired to accomplish final assembly at the launch site and subsequently demonstrate flight readiness, this can be readily accomplished any desired number of times by means of a small test kit.

Detail Description

PASSIVE DELAY ACTUATOR (PDA)—Operation of the PDA is quite simple, as indicated by the functional diagram shown in Fig. 3. Volume 1 is a metal bellows welded to the output shaft plate at one end and welded to the outer case end plate at the other end, so as to provide an absolute seal between the bellows and the outer case, which defines Volume 2 in the illustration. The inside of the bellows is vented to ambient however. Volume 3 is included as a safety device, and is not a mandatory feature of the PDA. Similarly, the spring inside the bellows is not a mandatory feature, since
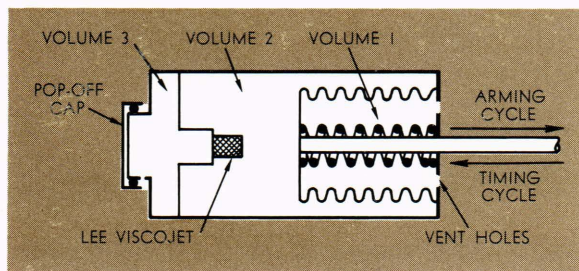

Fig. 3—Functional diagram of passive delay actuator.

the thickness of the bellows material can be made sufficient to provide the required spring force. However, without going to considerable expense the spring rate of a standard bellows cannot be controlled to much better than ±20% of theoretical, whereas the spring rate of an inexpensive compression spring can be controlled to very close tolerances.

When the PDA is on the ground, all three internal volumes are at one atmosphere pressure. However, when launch vehicle liftoff occurs, the ambient pressure rapidly approaches zero, as does the pressure in Volume 1, which is vented to ambient. But prior to this time, two things occur. First, when the ambient pressure drops to about 13 psia, the differential pressure across the pop-off cap is sufficient to provide the force necessary to deploy the cap. The main purpose of the cap is to act as a dust cover during all ground-handling

operations with the PDA. It could very easily be removed manually at last access to the spacecraft as nonflight hardware. However, as a redundant safety feature, the cap is designed to pop-off in flight without noticeably affecting the timing performance of the PDA. Should there be a leak in the cap sufficiently large to bleed off the air in Volume 3 without developing the force necessary to deploy the cap, then the configuration (the size of Volume 3) is such that the timing accuracy of the PDA is virtually unaffected by the leak in the cap. In other words, the size of Volume 3 is selected so that if the leak is small, adequate differential pressure to deploy the cap is reached before Volume 3 bleeds down. If the leak is larger, then the size of the hole is greater than the effective bleed hole in the primary PDA metering device.

The second thing that happens after liftoff is that at about 7 psia ambient pressure (about 20,000 feet altitude) the differential pressure across the bellows shaft plate is sufficient to produce a force in excess of the combined spring forces of the bellows and spring, at which time the bellows shaft moves to the right against a stop. The PDA is now armed, and will always seek to return to its prelaunch position, no matter what happens, including a catastrophic leak anywhere. The maximum force available for arming is about 30 lb whereas the maximum spring return force is about 10 lb.

When the pop-off cap is deployed, the pressure in Volume 3 goes immediately to the zero ambient and the pressure drop across the metering device is equal to the pressure in Volume 2, which is essentially one atmosphere. It is not exactly one atmosphere, since the pressure drops slightly when the bellows shaft plate moves to the right. The metering device is designed to bleed the air from Volume 2 at a precise rate under these conditions. When the pressure in Volume 2 drops below that which will produce a force balancing the total spring (and friction) forces on the bellows shaft and shaft plate, the shaft begins to move very slowly and very smoothly to the left. The system volumes, areas, spring rates and bleed rates have been carefully selected so as to hold the shaft on the stop until about 4 minutes after the launch vehicle has ceased thrusting and the spacecraft is in orbit. This means that the only moving part in the PDA (the shaft plate and its inegral output shaft) is locked up tightly against its stop with an average force of about 6 lb during almost the entire launch flight when the physical environment is at its extreme levels. Then, in the calm of orbital environment, it times out with precision.

It is clear that this precision requires an accurate

metering system, and one which is insensitive to normal handling contamination, normal humidity changes, and normal assembly and testing procedures. Early tests with sintered stainless steel, compressed metal screens and porous ceramic, while demonstrating the basic feasibility of the PDA, also demonstrated the inherent difficulty of the porous material approach to precise air metering. It was soon found that a misplaced finger print, a cloudy day, or other similar situations, including just plain testing would suddenly cause timing changes of 20% or more. This was not surprising, since the bleed hole sizes were measured in microns. The use of a Lee Viscojet* proved to be the solution to the metering problem. In this device, fluid (in this case, air) motion through the viscojet is the result of the differential pressure across the viscojet. As the fluid passes from one spin chamber to the next in the viscojet, the flow is slowed down so that the actual flow through the viscojet exhaust hole is as though the hole were many, many times smaller than it actually is.

Figure 4 shows a typical arrangement of a visco disc as well as detailed drawings of a portion of a viscojet (The viscojet is made up of several visco discs.) The cross-sectional view shows how the flow repeatedly passes through the same disc. The flow path begins on one side at the center of the disc. The exit slot from each deceleration chamber is in a direction which is opposite to the direction of spin. This action forces the liquid to come to rest before it makes its exit from the deceleration chamber. On the smaller sizes, each visco disc is fabricated from three photo-etched plates. On the larger sizes, each disc is of single-piece construction. Each visco disc is covered both top and bottom with a flat-lapped disc. The visco discs and their covers are rigidly and permanently clamped in the cartridge.

The PDA viscojet has approximately 400 spin chambers and a minimum passage diameter of 0.005 inch. It is protected upstream and downstream by filters having more than 100 holes of about 0.004 inch diameter, so the filter open area is hundreds of times greater than the effective hole size in the viscojet, which is about 0.0005 inch. The total size of the viscojet used in the PDA is less than $\frac{1}{2}$ inch long and has a diameter of 9/16 inch. It meters about 6 cubic inches of air at an average differential pressure of about 5 psi in 24 minutes.
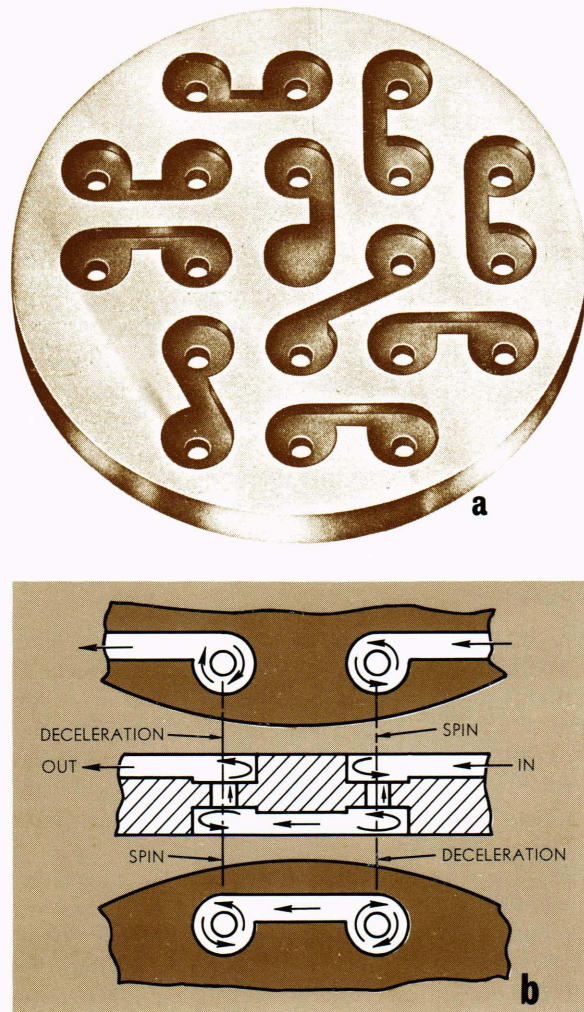

Fig. 4—Lee viscojet: (a) typical arrangement, (b) principles of operation.

Other viscojet configurations being designed for future applications will be capable of metering 1 cubic inch of air in 50 hours, and still have a minimum passage diameter of 0.005 inch.

Whenever the PDA is returned to one atmosphere ambient pressure, such as after a test or after a demonstration, it returns automatically to the prelaunch condition. It can be tested any desirable number of times without degradation. The bellows is of a type which is designed for 100,000 cycles without failure. Ordinarily, laboratory tests are conducted merely by subjecting the PDA (and its integral trigger assembly) to a vacuum and recording of the (trigger) events. However, there are occasions when this is not practical—for example, when the PDA is undergoing a functional test in a vacuum environment, while at the same time being subjected to prototype vibration levels.

In this case a small vacuum pump is used in conjunction with a pressure-tight shake fixture for testing purposes.

TRIGGER ASSEMBLY—The PDA output shaft extends during the arming cycle and slowly retracts again during its timing cycle with a potential force of considerable magnitude. Initially, it was considered that this force would be adequate to perform the necessary work cycles of the separation system, such as pulling lanyards in sequence, etc. However, it was decided later that there would be two important advantages in separating the force output cycles from the timing cycle of the PDA. First, by its very nature, the timing accuracy of the PDA depends to an extent on having a known and reasonably steady load on its output shaft during the timing cycle. A heavy load such as might be caused by a tight lanyard installation could cause the timer to run more slowly than if there were a light, steady load.

Secondly, and perhaps more importantly, it was decided to separate the work output from the timing cycle—not only to increase the magnitude of the work output, but to permit snap action, which is sometimes desirable for lanyard-pulling functions. The trigger assembly (Fig. 5) is functionally disconnected from the PDA on the ground. However during the in-flight arming cycle the PDA output shaft is automatically connected to the trigger assembly by means of a device very similar to a hose quick-disconnect fitting. Thereafter, the triggering shaft moves with the PDA shaft during the timing cycle, and releases two (precocked) triggers at precise, precalibrated, and adjustable time intervals. The two output shafts of the trigger assembly are, in fact, the two lanyards which release respectively the despin and
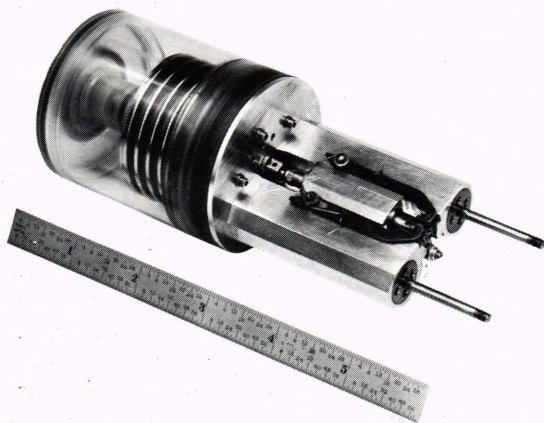
separate cables by means of the cable release assembly described in the next section.

CABLE RELEASE ASSEMBLY—The spring-loaded despin weight release units are locked securely until the desired action time by tying them together with a common cable. In earlier separation systems this cable was cut at the proper time by (redundant) explosive bolt cutters. In the simplified system, however, separate cables from each despin weight release unit are locked together at the cable release assembly, which is located directly above the trigger assembly (Fig. 6). The snap action of the despin trigger shaft causes the immediate simultaneous release of both despin cables; similarly, the other trigger snap action causes the simultaneous release of the bolt clamp release cables.
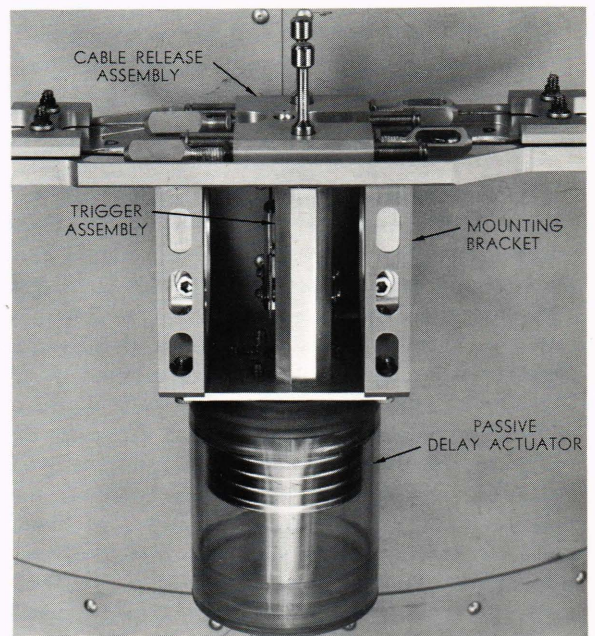

Fig. 6—PDA flight installation showing cable release assembly.

The spring force on each cable is about 15 lb, whereas the force on the trigger shaft required to release a pair of cables is 1 or 2 lb. As stated previously, the force available from each trigger to do this work is about 23 lb so there is adequate safety margin.

SEPARATION CLAMP RELEASE BOLTS—The spacecraft is attached to the flight adapter by means of a split Marman clamp which is normally held in place by bolting the two halves together, thus clamping two identical flanges on the spacecraft and adapter, respectively. In the current separation system these bolts are severed at the proper

Fig. 5—PDA/trigger assembly.

time by explosive bolt cutters which release the Marman clamp and allow a compression spring between the spacecraft and the adapter to separate the two. Since one objective of the simplified separation system was to eliminate all ordnance items, it was necessary to design a structurally equivalent bolt which would not only be capable of mechanical release, but would also fit the space currently occupied by the explosive bolt cutters. After many design approaches were examined, it was decided that the one shown in Fig. 7 would best suit these conditions. This arrangement is
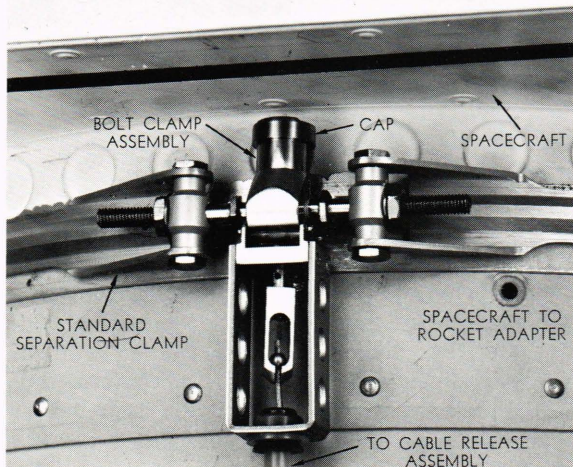

Fig. 7—Bolt clamp flight configuration.

actually a miniature-hinged split Marman clamp. When the two hinged halves are folded together they grip matching flanged ends of the two bolt halves. The hinged clamp halves are then locked together by a spring-loaded cap. The cone angle of the bolt flanges and the mating surfaces of the clamp halves were carefully selected so that when the bolt halves were loaded in tension the hinged clamp halves would always be able to overcome the contact friction and open. It was necessary to limit the surface cone angle so that the opening force on the hinged clamps would not be so great as to jam the spring-loaded release cap. The prototype bolt clamp assembly is shown in the flight configuration in Fig. 7.

Cables from each of the spring-loaded release cap assemblies are terminated at the cable release fixture. Thereafter, when the "separate" trigger snaps, the cables are released, the bolt clamp caps deploy, and the clamps release. The action is virtually instantaneous and simultaneous on both bolts. By using a spring to release the clamp cap

the system activation force is completely disassociated from the tension on the bolt halves.

This configuration allows any desired number of tests to be conducted without degradation of the unit. The prototype bolt clamp has been operated dozens of times in the flight configuration at 20% higher than maximum permissible flight tension loads without degradation of performance.

CONTROL ROCKET—Several methods were considered for providing the necessary control rocket impulse without resorting to the use of pyrotechnics. Most of the methods that were considered were abandoned because of the arbitrary decision that the "rocket" could not be permitted to discharge solid matter, such as slugs, springs, or pressurized cans. It was easy to show that a solid object launched transverse to the injection stage just after separation would not collide with the spacecraft in a normal separation sequence. However, in the case of an abnormal (tumbling) separation sequence, there was a finite probability of the slug colliding with the spacecraft.

The competition narrowed itself down to two acceptable approaches, both of which have been tested extensively in the laboratory. One approach was to release a quantity of cold gas, such as air. The other approach was to evaporate a quantity of suitable liquid into the vacuum of outer space. But, before evaluating these systems it was decided to perform a complete re-evaluation of the dynamic analysis of the spacecraft/adapter separation sequence, since it was known that some of the significant inputs to the last analysis, conducted several years previously, had changed considerably. The result of this analysis was to show that the required control rocket impulse was much less than that provided by the currently used 1.5 lb-sec rocket. This was largely due to the fact that the previous analysis used a 30 rpm spin rate, while the measured spin rates of several recent APL spacecraft at injection was less than 2 rpm, whereas the previous analysis used 30 rpm as an input. The new analysis did indicate that the required impulse to yaw the injection stage after spacecraft separation was less—by a factor of 4, so the design objective for the new control rocket was conservatively established at 0.5 lb-sec.

The reason for the above "engineering footwork" was the erroneous deduction that an explosiveless control rocket, which could produce 1.5 lb-sec of impulse, would not be practical in terms of weight and volume. It has since been determined that the evaporating liquid rocket described below not only can be designed to meet these requirements, but possesses the following additional advantages:

1. Hazard is virtually neglible. It contains no pyrotechnics, and does not burn.

2. It does not require electrical energy to operate, which eliminates the need for the added weight and complexity of batteries, wires, connectors, etc.

3. It is immune to pre-firing from RF or static electricity sources.

4. It is small. Fluid storage volume is only about 1 cubic inch per lb-sec, whereas a cold gas system requires about 100 times this volume, assuming reasonable storage pressure.

5. It can be fired many times in its flight configuration without hazard to itself or adjacent equipment. It can even be fired safely in the laboratory in a thermal vacuum chamber or on a satellite or launch vehicle on the launch pad.

6. Its exhaust products are non-erosive, non-corrosive and non-contaminating.

7. It delivers about an order of magnitude less impulse per pound of rocket than does its solid-propellant counterpart, but is probably considerably better when the necessary solid rocket peripheral equipment is included (batteries, wires, connectors, squibs, etc.).

8. It is inexpensive. Using mass production techniques it could be manufactured for less than its solid propellant counterpart.

9. It should have a high inherent reliability. Its readiness for firing can be verified by visual inspection.

10. Its delivered impulse can be changed at any accessible time before launching (such as on the launch vehicle on the launch pad) merely by changing the amount of "fuel."

11. It can be designed for re-firing in orbit, if required, but its main virtues are associated with one-shot applications.

12. Properly designed, it should be capable of indefinite shelf life without degradation and should be capable of satisfactory operation over a very broad temperature range, such as ±100°F. However, future tests will be required to establish the degree of performance variation with temperature.

There are only three basic features of the evaporating liquid rocket: a transparent pressure vessel, a quantity of high vapor pressure "fuel," and a releasable nozzle closure/seal.

The liquid selection is based on the best compromise of high vapor pressure, low heat of vaporization, low freezing point, ease of handling, compatibility with the pressure vessel, minimum toxicity, and, to a lesser extent, low molecular weight. Nearly any liquid will produce some impulse, when used in this manner, but the ones which best meet these requirements are the freons, several of which have been tested with satisfactory results. Typical of these is Freon-115 which has a 70°F vapor pressure of 117 psia and a freezing temperature of −159°F. Another is Freon-114, which has a 70°F vapor pressure of 28 psia and a freezing temperature of −137°F.

A notable feature of the rocket is that it is transparent. This is to allow visual confirmation at any accessible time that no leak has occurred since the time the rocket was loaded with fuel, whether this was 2 hours or 2 months previous. A typical rocket is shown in Fig. 8 where the material used is LEXAN. The rocket is "fired" by simply removing the nozzle closure seal, and this is accomplished in the case in question by the "separate" trigger motion. However, a nominal 2-second delay is required between the time the spacecraft separates and the time the control rocket fires, so it was necessary to provide an integral mechanical timer in the rocket closure for this purpose (not shown). Timer action is initiated by a lanyard attached to the "separate" trigger.
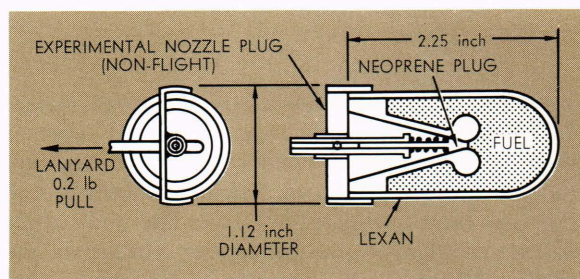

Fig. 8—General configuration of evaporating liquid rocket.

The freon rocket develops its rated impulse when fired, as intended, in outer space. However, it can also be fired at any other desired time into one atmosphere ambient pressure for special systems tests, etc., but at a much reduced impulse. It is designed to be capable of many firings (tests) without degradation of performance.

The accurate determination of impulse delivered by the several rocket configurations tested was made possible by a special test rig. The rig consists of a spinning arm to which the rocket is attached,

a means of firing the rocket remotely after pumping the vacuum chamber down, and a method for remotely measuring rpm of the arm. Firing the rocket was accomplished by securing the nozzle closure with string until ready for firing, and then cutting the string by a remotely actuated Nichrome hot-wire. Recording the rotational speed was accomplished by attaching a disc to the spinning arm which has a hole pattern of 10 holes at one spin radius and one hole at a different spin radius. By placing a light above the holes and two solar cells below the holes, and connecting the cells and power source to a pen recorder, the rpm could be simultaneously recorded in 1/10-revolution and 1-revolution intervals.

About 20 tests were conducted using this equipment and various rocket configurations. Performance in the range of 1 lb-sec per cubic inch was demonstrated.

Fueling the freon rocket is a reasonably easy task. For example, Freon-114 comes from the manufacturer in a pressure vessel that has a valve on top. At room temperature the pressure in this container is 28 psia, or about 13 psig. When the container and its contents are cooled to $+39°F$, the pressure drops to 14.7 psia, which is, of course, 0 psig. The valve can be opened, and the Freon-114 can be poured like any other clear, odorless liquid into the precooled rocket case. If precooling the pressure vessel and/or rocket case is not practical, the pressure vessel can be opened at $70°F$ and a quantity of the Freon-114 poured while boiling into a beaker. When the boiling stops, the liquid has automatically reached $+39°F$, and can be poured into the rocket case. However, this procedure will cause moisture from the atmosphere to be absorbed into the freon. If the rocket is also at $70°F$, the boiling will resume until the case is automatically chilled.

In either of the above loading procedures, the nozzle closure is inserted and sealed when the proper quantity of fuel has been loaded. Thereafter, as the unit is allowed to reach ambient temperature ($70°F$) the rocket internal pressure rises to 28 psia, and is ready for firing. Should a leak develop in the rocket for any reason it would be immediately apparent by the boiling fuel or, subsequently, low fuel level.

Extended Applications of Passive Separation System Components

There are various combinations of the foregoing components which can be used either in passive separation systems or in many other types of flight applications. The PDA can be used as a simple timer in an existing separation system, or it could be used as a timer to initiate antenna erection, boom deployment, high voltage equipment turn-on, cover removal, etc. Similarly, the bolt clamps could be used effectively in a variety of mechanical operations where the use of explosives is undesirable. And, there are many operations which require small one-shot remote rockets, but which may not tolerate the heat, contamination, or power requirements of conventional types.

This article describes a series of components that have been developed for a specific application. However, all of them are scalable, although the degree of scalability has not been established for each unit; nor has this been within the scope of this development program. Of particular interest in this regard, however, is one parallel study to determine the extent to which the timing cycle of a device similar to the PDA could be feasibly extended. Some isolated evaluation tests were conducted, and a number of configurations were established. These indicate that a potential increase in timing cycle of about three orders of magnitude is feasible, and that it would not be unreasonable to attempt to build a reliable lightweight timer based upon these principles but which would have a timing cycle of one year or more with a reasonable accuracy.

Acknowledgments

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