ATMOSPHERIC RE-ENTRY DEMONSTRATOR (ARD): ITS PARACHUTE RECOVERY ASSEMBLY

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A recovery system is developed and tested during the European Space Agency (ESA) Atmospheric Re-Entry Demonstrator (ARD) program. This program demonstrates the ability of a geographically dispersed, international consortium to utilize off-the-shelf components and performance based specifications to develop a recoverable spacecraft during a program with a tight schedule and at relatively low cost. Utilizing latest parachute packaging and deployment technology and design specific interface components the integration of "low tech", off-the-shelf nylon parachutes into a minimal volume vehicle is demonstrated.

Nomenclature

W_V = vehicle suspended weight, lb.
C_{D0} = drag coefficient
S_0 = nominal cloth area, ft.^{2}
Z_0 = deployment altitude
V_0 = deployment velocity, ft/sec TAS or KEAS
Ve_0 = nominal rate of descent, ft/sec
W_{PRA} = parachute recovery assembly weight, lb.
g_0,F_0 = parachute opening load: g's, lb.

Introduction

The Atmospheric Re-entry Demonstrator (ARD) is part of the technological activities of the European Space Agency in the framework of the Manned Space Transportation Program. It consists of a 2.8-ton Apollo-shaped experimental capsule scheduled to be launched on an Ariane 5 flight in 1997 and recovered at sea off the Hawaiian coast.

Program Background and Objectives

This civil cooperative program is managed by Aerospatiale acting as the prime. Its main objectives are twofold. First, it aims to demonstrate the ability of European space industry to design low cost re-entry spacecraft and to master most of the critical phases related to the basic mission, i.e.: orbital flight, re-entry and recovery at sea. Second, this program is to demonstrate the ability to design, build and test a system without using the traditional rigid procurement specification system. This program is governed by performance specifications and encourages the use of off-the-shelf components where applicable.

Responsibility for the Descent and Recovery Sub-System (DRS)[1] for the ARD system is placed with Alenia-Spazio S.p.A. The DRS functions are:

a) to slow down the descent speed and stabilize the capsule in order to ensure a smooth splash down
b) to provide vehicle flotation at sea until recovery onto the ship deck
c) to ensure the visual and electronic localization of the vehicle.

The DRS is composed of the Parachute Recovery Assembly (PRA) and the Flotation Assembly. This paper describes the details of the PRA and its development flight tests.

This low cost program led to a non-conventional approach. The PRA technical specifications were flexible enough to cope with the mandatory performance requirements and allow use of existing parachutes previously developed and tested in adequate speed and dynamic pressure ranges without requiring a new, custom designed system. A contract was awarded to Irvin Aerospace to provide this assembly, based on parachutes used for the Atlas E Thrust Section Recovery System program[2].

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System Description

Requirements of the Operational System

Table 1 lists the PRA system specifications for this system.

TABLE 1 - Parachute Envelope Specification

W_V	2,700 kg (5,864 lb.)
Z_0	7.3 - 17.3 km (23,996 - 56,670 ft. MSL)
V_0	139.3 - 228 m/s (457 - 748 ft/s)
Ve_0	10 m/sec (32.8 ft./sec.) max.
W_{PRA}	250 kg (551 lb.) max.
g_0,F_0	3 g's

System Operation

The deployment begins, governed by an atmospheric pressure threshold, by the pilot chute mortar deploying a 1.07 m (3.5 ft.) nominal diameter flat ribbon parachute at the end of the aerobraking (refer to Table I for deployment envelope).

After a two second delay, the three capsule apex cover hold down pyro-bolts are fired and the cover is separated from the vehicle by the pilot parachute. During this motion the drogue chute pack is extracted from the canister and deployed.

The drogue, a 5.8 m (19.0 ft.) nominal diameter conical ribbon parachute, decelerates the vehicle to main parachute hand-over dynamic pressure and ensures the vehicle stability during the 78 second descent, down to an altitude approximately 5000 m (16,500 ft.). Through a timer signal, the 2-leg drogue/vehicle harness is cut by dual webbing cutters (one cutter per leg). The released drogue extracts the main parachute cluster assembly. During the extraction, the main risers unlace the floatation bag covers and deploy the location beacon antenna.

The cluster of three 22.9 m (75.0 ft.) nominal diameter slotted polyconical main parachutes provides a terminal vertical water entry velocity in the 6 to 7 m/s (19 - 23 ft/sec) range. One of the two vehicle harnesses is cut with a webbing cutter just above sea level to give the vehicle a favorable hang angle to minimize the splash down impact loads.

PRA System Components

The PRA consists of a pyrotechnic mortar-deployed pilot parachute, a drogue parachute, a three main parachute cluster, and articulated attachment fittings with integral pyrotechnic cutters. The system is designed to minimize the number of interfaces with the vehicle. The PRA is located in the rear part of the vehicle, inside a cylindrical canister (Figure 1), surrounded by the flotation bags, high pressure gas bottles and plumbing, and protected against the space environment and heat fluxes by an insulated apex cover. The pilot parachute mortar is mounted directly to the apex cover.

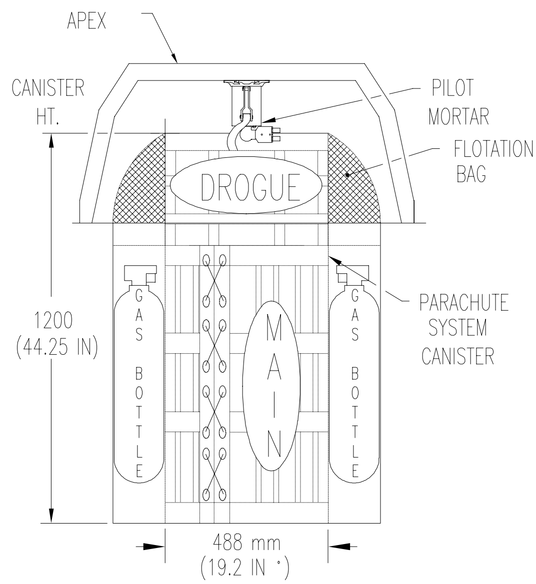

Fig. 1 Descent Recovery System installation.

Pilot Parachute Mortar Subsystem

Pilot Parachute Mortar The pilot parachute mortar is illustrated in Figure 2.

The mortar is integrated in the capsule apex cover (see Figure 1) and Thermal Protection System to ensure a spacecraft rear thermal shield continuity. An early design concern questioned the apex cover venting capacity. If the venting is not sufficient to ensure a minimal pressure differential between the inside of the parachute compartment and the atmosphere there is concern about the pilot parachute's ability to separate the apex cover. To avoid costly analysis, test and redesign, the integral mortar mount is designed to provide approximately 6.6 cm^2 (1.0 in^2) of vent area after the mortar firing.

The mortar is designed with an integral pilot parachute attachment and drogue deployment bag extraction lanyard attachment. This results in one interface control point between the PRA and the vehicle instead of three. This type of integration and reduction of interfaces reduces the scale of the inter-company initiated redesign and allows this type of program to maintain schedule.

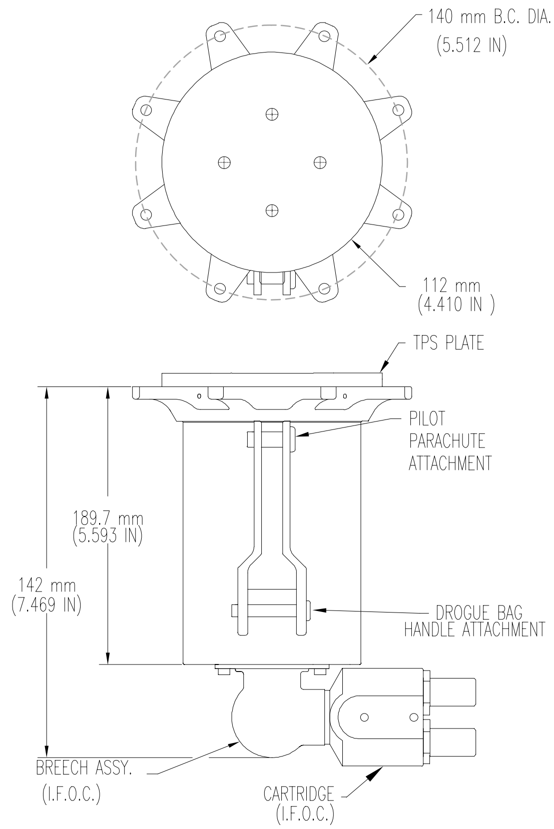

Fig. 2 Pilot parachute mortar.

The mortar is a high/low pressure system. The breech is pressurized to approximately 131 MPa (19,000 p.s.i.) by firing a dual-initiator pyrotechnic cartridge. The hot gas is metered through an eroding orifice to provide a near-constant tube pressure during the pack acceleration. This results in a relatively flat reaction load curve (Figure 3) which provides the maximum pack muzzle velocity for a given energy input.

Pilot Parachute The pilot parachute is based on an existing all-nylon, eight gore, 0.85 m (2.8 ft) flat ribbon parachute with a maximum deployment dynamic pressure capability of 34.7 kPa (725 psf). The only modification consists of the addition of one ribbon to increase the diameter to 1.07 m (3.5 ft). This results in a maximum allowable deployment dynamic pressure of 21.3 kPa (445 psf), well in excess of the deployment envelope maximum of 5.8 kPa (121 psf). The parachute was not redesigned to reduce weight (and simultaneously reduce the large margin of safety) because this would have increased program testing and subsequently program cost and schedule impact.

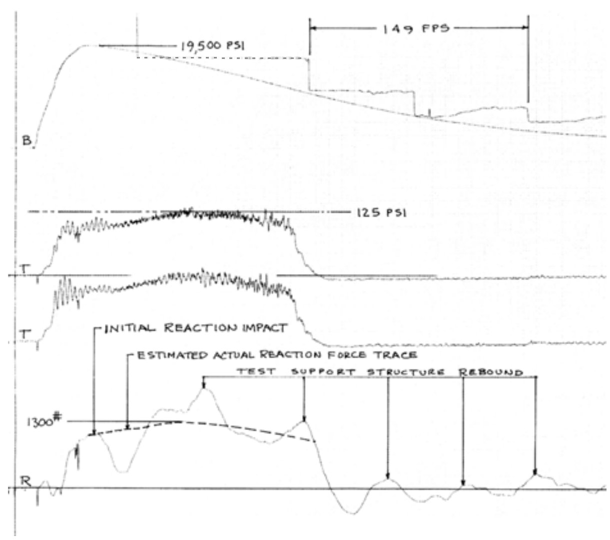

Fig. 3 Mortar breech pressure, tube pressure and reaction load.

P/C Riser The riser is constructed from a single strand of 8.9 kN (2,000 lb.) MIL-Spec Kevlar® cord.

P/C D-Bag The above riser and parachute configuration resulted in a pack density of 0.739 kg/l (0.026 lb./in^3). This is a higher than optimum density for an all nylon canopy but proved manageable and efficient for this program. The deployment bag is a Gore-Tex® and Kevlar® design to reduce weight and volume.

Drogue Parachute Design

Drogue Parachute The drogue is an off-the-shelf design 5.8 m (19.0 ft), 24 gore conical ribbon parachute. A single stage of reefing (50% reefing ratio, 6-second lanyard-actuated pyrotechnic cutters) is incorporated to keep the opening shock load below the 83.4 kN (18,766 lb.) design load.

Drogue Riser The riser consist of four lengths of 1 inch, 10,500 lb. Kevlar® webbing looped to form eight plies. The end of each ply has a single connector link for attachment to the parachute suspension lines

Confluence Fitting A compact confluence fitting (Figure 4) is used to connect the riser to the two drogue vehicle harnesses and to the main pack extraction lanyard.

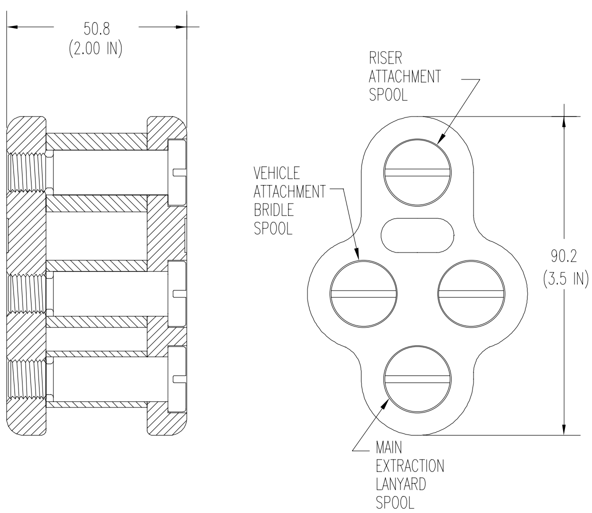

Fig. 4 Drogue confluence fitting.

Vehicle Harness The design of each of the drogue vehicle harnesses incorporates a single continuous mobius strip formed into a four ply loop. The material is 10,500 lb. (46.7 kN) 1 inch Kevlar® webbing.

Drogue Deployment Bag The drogue deployment bag is a low aspect ratio (length to diameter of 1:2.5) cylindrical design. The bag incorporates a vacuum formed Kydex® bottom panel (top when installed in vehicle) with a depression designed to provide clearance for the pilot parachute mortar breech and cartridge. This allows the parachutes (main and drogue) to use more of the available volume without applying any pre-load to the apex cover and provides clearance for pack shift during launch loads.

The drogue pack density is 0.498 kg/l (0.018 lb./in^3). This low density is easy to pack but the deployment bag tends to bulge when the pack restraints are tied tight. The Kydex® plate helped to reduce this bulge to acceptable levels. The entire pack is subjected to an autoclave and vacuum cycle to help "set" the pack into as compact a package as possible.

Main Recovery Parachute Design

Main Canopy The main parachute cluster consists of three off-the-shelf, all nylon, 22.9 m (75.0 ft.), 64 gore polyconical parachutes incorporating an Apollo type slot to control reefed inflation. The parachutes have two stages of reefing (6% and 24% reefing ratio, 6 and 12 seconds) to control opening loads. The slot is located and sized to allow all three parachutes to obtain identical drag areas during the first reefed open stage which then allows very even load sharing on subsequent disreef opening loads.

The canopy gore fabric is tailored with high strength fabric near the crown and lower strength near the skirt.

Vent Bridle To aid the simultaneity of the main parachute opening, each canopy vent was attached to a vent control incremental bridle. The vent control bridle is sewn such that under load it peels apart to provide a constant tension for the length of the bridle's stroke to keep the canopy vent in an upright position and the radials pre-tensioned to allow for symmetrical canopy inflation. The stroke on this bridle is approximately 24.4 m (80 ft.). When the end of the stroke is reached the weak link tie breaks and the bridle separates from the canopy and remains attached to the departing deployment bag.

Upper Riser The riser is constructed from four plies of 6,500 lb. (28.9 kN), 1.75 inch Kevlar webbing with each ply end terminating into a 1.75 inch connector link to which the suspension lines are directly attached. The riser occupied approximately 5% of the main deployment bag volume. Two lanyards

(2,000 lb. Kevlar® cord) are attached to one connector link on each canopy. During the parachute installation into the system these six lanyards are attached to the floatation bag lacing and the location beacon antenna stowage cover. During the main parachute deployment the stroke of these lanyards opens the floatation bag covers and extends the beacon antenna.

Deployment Bag The deployment bags are each 1/3 of a cylinder (Figure 5). When all three bags are packed and tied together they form a single cylindrical pack that fits snugly into the parachute compartment. The high density combined with the high effective aspect ratio (4.5:1), and the small actual cross section of the deployment bags results in the single biggest design hurdle on the program. The canopy was packed using a hydraulic ram and 289 kN (65,000 lb.) of ram force. Each completed parachute pack is individually vacuum packed and autoclaved. When the three packs are laced together the resulting cylindrical pack is vacuumed and autoclaved prior to final pack lacing tightening. This insures a dimensionally stable pack which will facilitate installation into the vehicle at a later date.

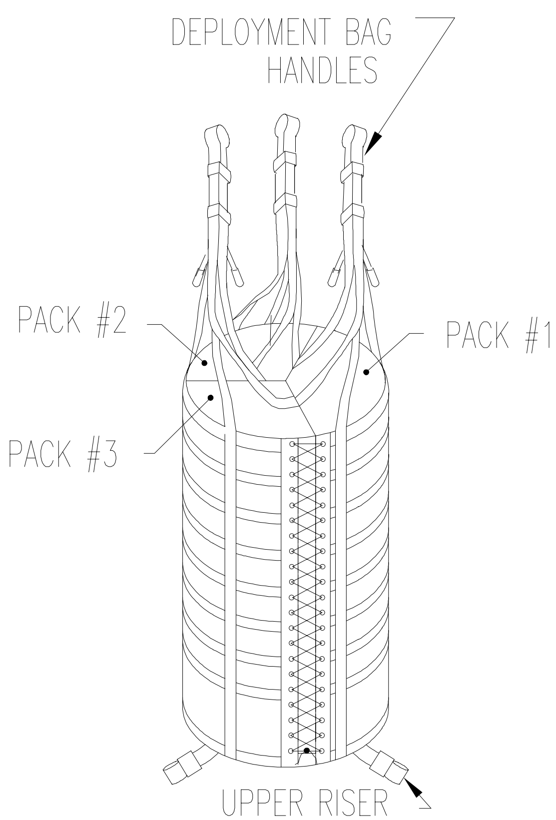

Fig. 5 Main deployment bag cluster.

The size and weight of these parachutes result in a high density pack 0.630 kg/l (0.023 lb/in^3). The use of modern deployment bag construction and materials (Gore-Tex® and Kevlar®) made the installation of these parachutes in this volume technically feasible. This bag construction minimizes the need for extra liners and eliminates such items as split-open bag design (using severed bag lacing techniques) and bulky reinforcements. The Gore-Tex® is an expanded Teflon material and eliminates canopy/bag deployment friction burns even during high velocity deployments. A short cotton liner is used to protect the canopy from the suspension line and riser ties that are attached inside the bag. Each main canopy also has a 1.1 oz. nylon sacrifice panel for protection during the deployment.

The aforementioned canopy protection and deployment bag design allows the drogue parachute to directly deploy the main canopy cluster without the use of an intermediate pilot parachute for main deployment. This is one of the highest velocity deployments of a high density parachute from a small, fixed-aperture deployment bag attempted to date.

Confluence Fitting The three main canopy upper risers attached to a compact confluence fitting (Figure 6) which also attached to the two main parachute vehicle attachment bridles. The design of this confluence fitting accommodates both the 1.75 inch upper riser webbing and the 1 inch attachment bridle webbing without adapters.

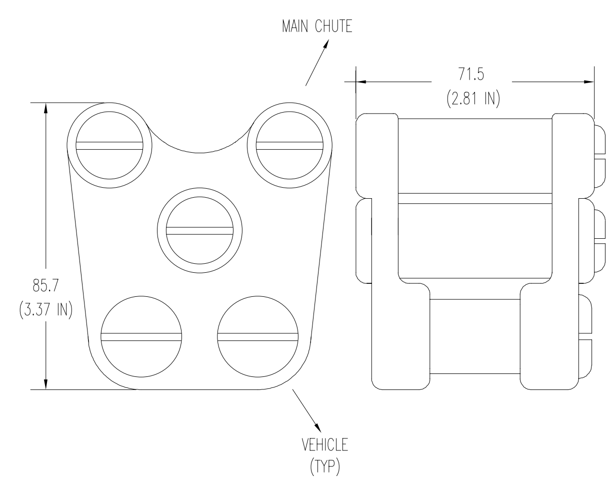

Fig. 6 Main parachute cluster confluence fitting.

Attachment Harness The design of each of the main parachute harness incorporates a single continuous mobius strip formed into a four-ply loop. The material is 12,500 lb. (55.6 kN) 1 inch MIL-spec Kevlar® webbing.

Articulated Attachment Fitting/Cutter Design

From the beginning of the program it was determined that the parachute supplier was also to provide a method of releasing the drogue and main parachutes. The timing and appropriate firing signals for pyrotechnic devices would be supplied by the vehicle. A pyrotechnic-powered cutter is used to perform this function. The cutter uses dual (redundant) initiators in this application. To demonstrate the performance margins, the cutter was fired empty (no webbing between the blade and anvil) using two initiators and with 5 plies of 10,500 lb. Kevlar webbing (25% more than a bridle) using a single initiator. The same type of cutter is used to sever the wiring harness between the vehicle and the apex cover.

The cutter is assembled around the vehicle attachment bridle and onto a stanchion (Figure 7).

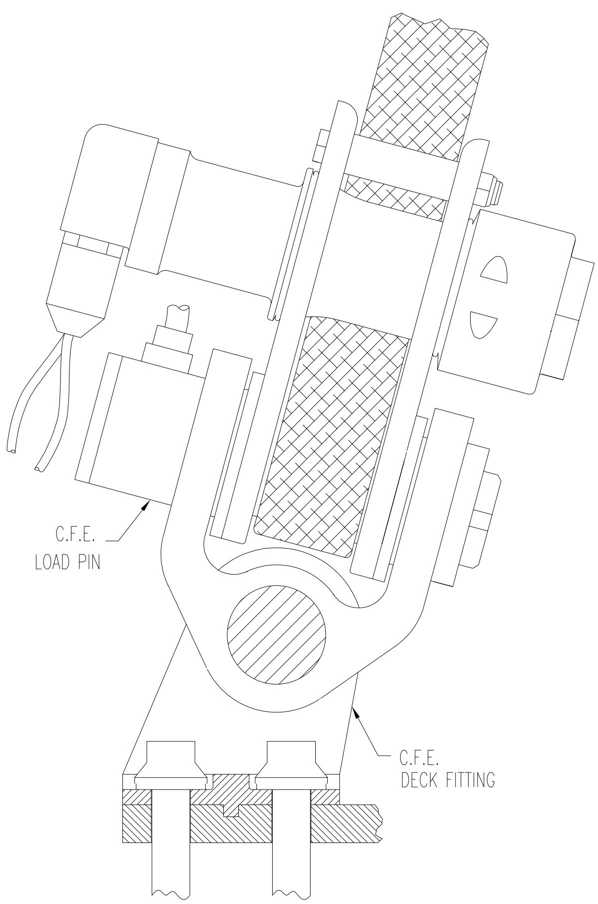

Fig. 7 Harness-to-deck configuration.

The stanchion provides rotation about a single axis to allow the bridles to move from their stowed position into the deployed position. When vehicle stability during parachute deployment was analyzed, a decision was made to provide rotation about a second axis to prevent side loading on the stanchion. This is accomplished by incorporation of a custom U-block. The stanchion and U-block are held together by a customer-furnished load cell that provides parachute load to the on-board data system.

Development Drop Testing

Two successful low altitude flight tests were performed at the NAWC-China Lake, CA during the first quarter of 1995, using a modified, existing cylindrical test vehicle dropped from a C-130. These drop tests were conducted to verify reefing ratios, validate deployment from the high density, high aspect ratio deployment bags and the dynamics of the transition phases.

During the first drop test a range furnished sequencer did not fire the two drogue release cutters simultaneously (due to the method of rigging the on-board timers, not a sequencer failure). This caused the vehicle to yaw prior to the main deployment bag extraction. The resulting extraction across the end of the test vehicle compartment and dynamic flexing of the main bags slightly damaged one main parachute. The opening and descent was nominal despite two 0.6 m (2 ft.), perpendicular tears near the slot and numerous small friction burn holes. The damaged canopy did tend to drift more than normal during the descent due to the unsymmetrical venting. The rate of descent was virtually unaffected (the effect was lost in the standard test data noise). The second test went as planned and produced excellent results with no anomalies.

At the end of the development program a full DRS qualification flight test was performed over the Mediterranean sea, off the western Sicily coast. An ARD full scale test article was lifted up to an altitude of 23 km (75,500 ft.) underneath a 104,500 m^3 (3,690,000 ft^3) helium-filled stratospheric balloon and then dropped. After a 49.5 second free-fall phase, the parachute sequence was initiated under real ARD flight conditions[3&4]. This test, described in Ref. 3 & 4 and was fully successful in demonstrating parachute function, splashdown, floatation and recovery.

Program Operation

One of the secondary purposes of this program is to demonstrate a streamlined procurement and development process for an international space vehicle. One of the perceived difficulties is the vast difference in time zones between the west coast of the United States versus Europe. The time difference allows only one to two hours for direct phone contact within the normal work hours. In practice, one thorough fax could be sent at the end of each day. This allowed the other contractor an eight hour day to answer and pose his/her own questions. This cycle resulted in excellent communication without expensive, high tech solutions such as video conferencing or frequent travel.

REFERENCES

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[2] "Liquid Booster Engine Re-Use, A Recovery System," AIAA Paper 91-0842 .

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