RECOVERY SYSTEM FOR THE EVOLVED EXPENDABLE LAUNCH VEHICLE

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Development and testing of a recovery system for the Low Cost Concept Validation (LCCV) phase of the U.S. Air Force Evolved Expendable Launch Vehicle (EELV) program is discussed. This system demonstrated for the first time the recovery of a liquid fueled rocket engine , a Space Shuttle Main Engine (SSME), from altitude to an ocean touchdown with subsequent refurbishment and engine firing. New technology developed and discussed includes the largest three Ringsail parachute cluster of Apollo heritage, in-flight deployable spray shield, and Propulsion Module (PM) testing approaches to validate the integrated concept.

Nomenclature

C_{Do} = drag coefficient
D_o = nominal diameter, ft.
f_n = PM-helicopter two body natural frequency,Hz.
f_h = helicopter rotor frequency, Hz.
g_o,F_o = parachute opening load: gee's, lb.
k_{TOT} = equivalent spring constant, fabric members
$l_{harness}$ = elongated harness length, ft.
l_o = harness original length, ft.
l_S = parachute line length, ft.
m_h = mass of the helicopter, slugs
m_{pm} = mass of the PM, slugs
S_o = nominal cloth area, ft.^{2}
Ve_o = nominal rate of descent, ft./sec.
V_o = deployment velocity, ft./sec. TAS or KEAS
W_V = propulsion module suspended weight, lb.
W_{PA} = parachute assembly weight, lb.
Z_o = deployment altitude
η_D = drag efficiency, drag area/lb., $C_{Do}\,S_o/\,W_{PA}$

Introduction

The United States Air Force Evolved Expendable Launch Vehicle (EELV) is a program to develop a next generation launch capability for medium and heavy military payloads. Of the four initial contractors competing in the Low Cost Concept Validation phase (LCCV), the Boeing company demonstrated that recovery and reuse of costly propulsion system and avionics components is both technically feasible and commercially viable. Recovery and re-use allows the launch system to make use of the high performance and non-developmental SSME provided by the Rocketdyne Division of Boeing North American.

Irvin Aerospace Inc. provided the parachute recovery system. The LCCV Demonstration Program included the design and test of a fully instrumented boiler plate propulsion module. Testing of this article, which housed an SSME, included crane drops to simulate worst case engine recovery loads, low level helicopter release canal water drops to simulate splash down conditions, and two high altitude helicopter deployments over the Gulf of Mexico. The high altitude helicopter deployment tests were performed to verify the parachute recovery system and spray shield/engine nozzle protection system under splash down environments. The base of operations for these tests was the NASA Stennis Space Center, Mississippi. The launch aircraft was a Mississippi Army National Guard CH-47D Chinook.

The development activity to be fully discussed in this paper include: 1) the main canopy parachute design and improved performance, 2) design and development of a multi-function Riser Termination Fitting (RTF), 3) unique analysis and simulations required to support the program, and 4) a presentation of flight test results.

Program Background and Objectives

Primary system objectives included: (1) validating SSME compatibility with EELV recovery environments, (2) marine environment protection by the spray shield and (3) stable, low descent velocity performance of the main parachute assembly.

Figure 1 illustrates Boeing's partial recovery concept which uses a reusable propulsion module. After the initial boost phase, the PM separates from the booster, reenters the atmosphere, descends to a soft ocean landing after deployment of the drogue/main parachutes and is retrieved with a specially designed recovery vessel for reuse.

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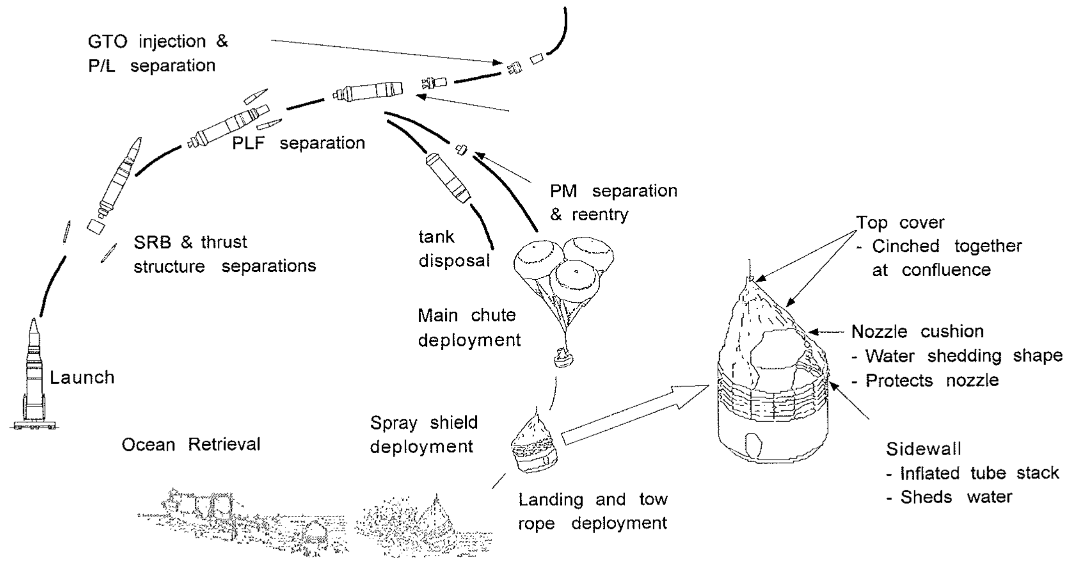

Fig. 1. EELV Propulsion Module Recovery Concept

The ultimate goal of the recovery demonstration was the successful completion of two high altitude helicopter drops with parachute recovery of the PM. Portions of the recovery system, however, were also involved in low altitude crane and helicopter drops to simulate water entry. These tests placed additional requirements on both hardware and system analysis.

System Description

Requirements of the Operational System

The following requirements are the fundamental design specifications for the demonstration. The desired rate of descent was reduced during the early stages of the program from 24 fps to the listed 22 fps.

TABLE 1 - Specification of Design Parameters

W_V	20,000 lb.
Z_0	6,000 ft. MSL
V_0	0-30 KEAS, horizontal flight
Ve_0	22.0 ft./sec.
W_{PA}	1,200 lb.
g_0,F_0	3 gees/60,000 lb.
Type	Ringsail (Cluster of Three)
Reuse Level	Single Use

Components

Main Recovery Parachute

The parachute design selected was an evolved and extended version of the Ringsail parachute featuring technology developed for the F-111 crew escape module in the late 1980's. The EELV canopy featured variable permeability material application and planform modifications to both enhance parachute performance and opening characteristics and to improve stability. The Ringsail canopy was applied in a cluster of three canopies for intrinsic cluster reliability. No canopy re-use was planned due to the salt water contamination.

The final main parachute design is a 136.0 ft. D_o Ringsail parachute with 96 gores. This canopy has seven(7) rings and slots and eight(8) sails. The slots widths are uniform at 3.0 inches high. The canopy used different width after trailing/leading edge tapes and/or hems. The following ring height applied: rings 1-4: 26.0 in. high; rings 5-7 and sails 8-10: 56.0 in. high; sails 11-15: 70.0 in. high. Ring strength and weight varied as: rings 1-4: 90#W/90#F-2.2 oz/yd^2 fabric, rings 5-7 and sails 8-10: 42#W/42#F-1.2 oz/yd^2, sails 11-15: 42#W/42#F-1.1 oz/yd^2) material to tailor the strength and local porosity to provide reliable and consistent opening.

Figure 2 shows the EELV main parachute quarter spherical planform, Ringsail fullness and permeability distribution applied for augmented drag with stability.

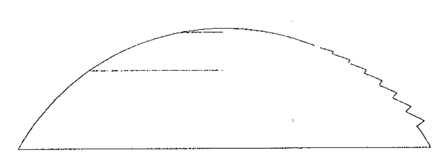

Fig. 2. EELV Ringsail Canopy Planform

The main parachutes incorporate two reefing stages (6.0 and 12.0 seconds). Each stage used three cutters due to the large reefing circle circumference. The design worst case canopy load sharing in the cluster configuration is 40%-40%-20% following Apollo.

The suspension line length ratio (l/D_o) is 1.15, the optimum Ringsail design value per Reference 1.

Spray Shield

The Spray Shield, developed by ILC Dover, is a medium pressure inflatable structure. There are three major subassemblies in the Spray Shield: the inflation plenum, the side wall and the bell cover. All three components are made of polyurethane coated nylon cloth. The Spray Shield configuration is illustrated on Figure 3.

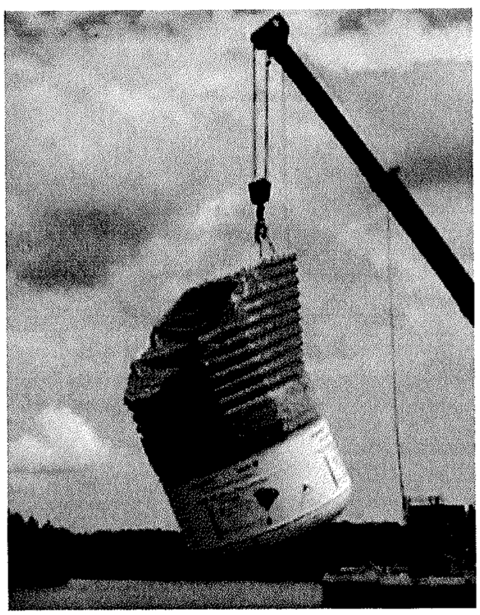

Fig. 3. Spray Shield Configuration

Prior to deployment of the Spray Shield, which takes place during parachute descent, the Spray Shield is packed in an annular ring on the propulsion module aft bulkhead. The cover is opened by electrical cutter during descent followed by delivery of high pressure helium into the plenum. The twelve sided polygon inflated sidewall consists of stacked 12.0 inch diameter tubes. The cylindrical sidewall complete with its bell cover reaches full elevation followed by application of cable tension to the bell cover cinching rings by winch cables routed up the aft harness leg and passing through the RTF. The bell cover is fully cinched against the RTF housing, at which point the winch motor mounted on the aft bulkhead stalls at 700 pounds. The cable clamp internal to the RTF locks the cable from back travel. At this point helium is delivered to the RTF bladder to render the cinched up bell cover weather tight. The clamp force assures the bell cover will keep the falling RTF from striking the SSME nozzle at splashdown after canopy release..

Riser Termination Fitting

The Riser Termination Fitting (RTF) is a unique hardware design developed for this program. The RTF forms a confluence fitting for the three attachment harness legs and the three main parachute upper risers. Additionally, parachute release at splash down was required, a function the RTF fulfilled by upper riser disconnection.

The RTF has three riser attachment spools on the separable cap (upper side of RTF) and three spools on the bottom of the RTF housing (one per attachment harness) as shown in Figure 4. The cap is bolted to the housing.

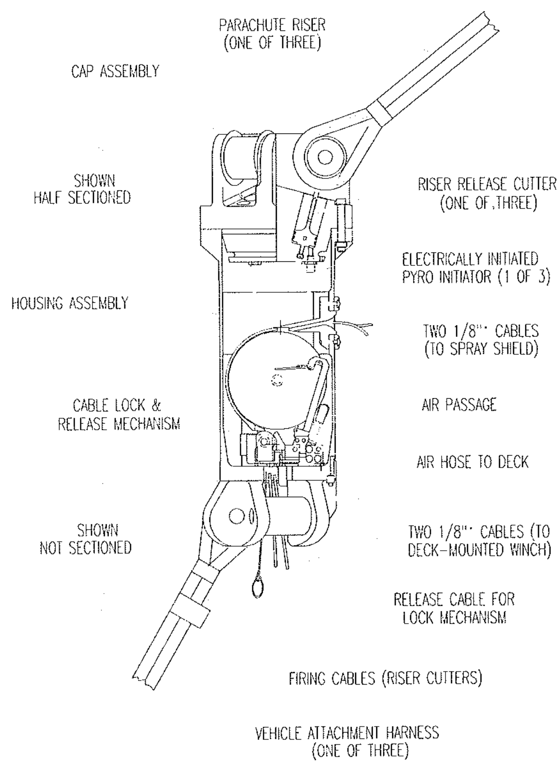

Fig. 4. Riser Termination Fitting

The RTF also provides several functions in the Spray Shield System. It routes for the cinch cable which deploys the bell cover, locks (with external manual override) the winch cable for securing the bell cover to the RTF body, furnishes gas line fittings and ports for the sealing bladder and provides the outer surface around which the cinched-up bell cover seals.

The RTF housing incorporates an internal cable pulley and cable lock mechanism. A winch on the propulsion module deck winches in the cable which then cinches the Spray Shield bell cover tightly against the RTF body. Thus, the RTF functions in conjunction with the Spray Shield to protect the engine from touchdown splash, spray and rain. The RTF housing has an inflatable bladder attached to the cylindrical section which is inflated via a flexible gas line running up one harness leg and attaching to an air fitting and integral air passage in the RTF housing. This bladder inflates to seal the spray shield/RTF housing interface. The cable lock is manually releasable by means of a control cable which exits the bottom of the RTF housing.

Parachute release at touchdown was accomplished by severing each of the three risers at the attachment joint by means of triple pyro-driven blades. The pyro elements were one amp and one watt initiators.

The assembled RTF weighs 33.5 lb.

Vehicle Harness

The canopy loads are transmitted through the RTF and to the vehicle via three vehicle harness legs. These harness members attach to the aft deck of the propulsion module as shown in Figure 5. Each harness leg is designed to withstand the full cluster parachute opening loads. Each bridle is a continuous loop comprising 10 plies (five around the bushing) of 1.75 inch, 20,000 lb. Kevlar webbing.

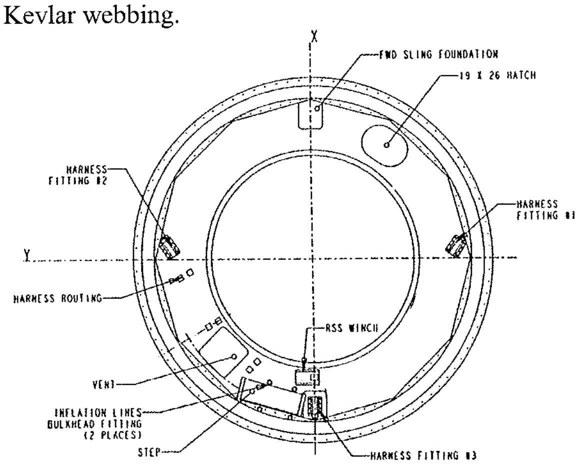

Fig. 5. Bulkhead Configuration

Deck (Harness) Fittings

Each vehicle harness leg connects to a vehicle deck fitting bolted to a reinforced area of the propulsion module deck at the locations shown on Figure 5. The deck fitting is a dual spool design. The design accommodates a drogue riser (or a helicopter sling) which can be severed via a dual pyrotechnic cutter (dual blades) which bolts onto the end of the deck fitting frame. The other spool attaches the main parachute harness. Either spool on a single deck fitting can accommodate the full parachute load.

Vent Control Bridle

Main canopy vent control was designed to minimize load dispersion through the use of a vent control bridle set. 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 a symmetrical canopy inflation. The stroke on this bridle is approximately 140 ft. When the end of the stroke is reached the weak link tie breaks and the bridle separates from the deployment bag and remains attached to the canopy. The bridles had a neoprene rubber recovery float and location aid attached used to recover the canopies after splashdown.

Upper Riser

Each canopy attaches to an upper riser made of eight plies of 10,000 lb., 1.75 in. nylon webbing. Individual riser plies branch to 12 suspension lines via a 15,000 lb. connector link. The riser is designed to handle 40% of the total maximum allowed cluster opening load or 24,000 pounds.

Test Configurations and Operational Issues

Crane/Helicopter Canal Drop Configuration

Initial water entry load testing involved static crane release of the PM and underway drops into the canals at Stennis Space Center.

During the first helicopter captive carry test flight, with the spray shield inflated the helicopter down wash proved to be unacceptably strong and beyond design specs for the spray shield. A set of three extended helicopter lifting slings were designed and built for these canal drop tests. Each sling is a single loop 75 ft. long and constructed from the same 1.75 inch, 20,000 lb. Kevlar webbing used for the vehicle attachment harness.

These slings were attached to the apex fitting on the helicopter hook side and the RTF upper spools on the module side. The inflated and cinched spray shield prevented the RTF from contacting the engine nozzle and the forward motion during the drop allowed the apex fitting to overshoot the vehicle and fall into the water. Figure 6 illustrates the rigging for the canal drops.

Fig. 6. Canal Drop PM Suspension

Gulf Drop Flight Configuration

The launch concept approach approved by the Army National Guard (the helicopter operator) was to hang the packs from the forward hook with the propulsion module carried by three nylon helicopter lifting slings attached to the RTF (see Figure 7) and the apex fitting. The slings are released by opening the cargo hook and the parachutes then deploy as the vehicle falls away. The only thing left with the helicopter was the deployment bags. The propulsion module was suspended from the helicopter with nylon slings sized for frequency compatibility. Figure 8 shows the ferry flight configuration.

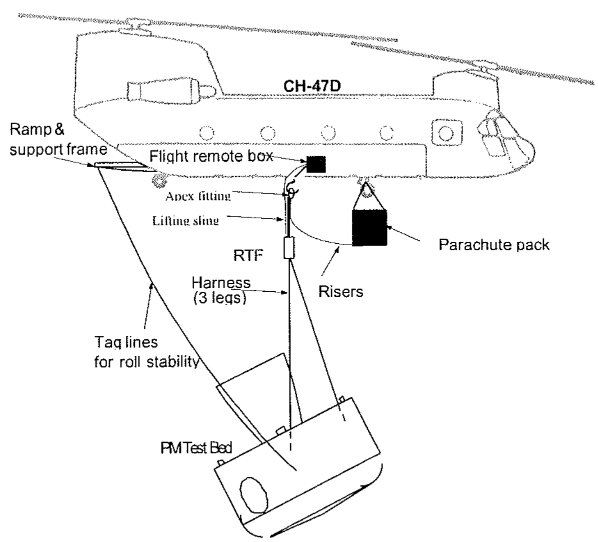

Fig. 7. Gulf Drop Test Configuration

Each suspension sling is a continuous loop constructed from four plies (two around the bushing) of 1.75 inch, 10,000 lb. nylon webbing. These slings each went around one of the RTF upper spools. An upper riser was colocated around each sling. This arrangement allowed slings to carry the load during the ferry flight and when released the upper risers would use the sling as a buffer around the spool. The upper loop of the slings were all placed on a single apex fitting. The apex fitting directly engaged the releasable cargo hook on the helicopter assuring safe captive carry from the pad to release point.

Fig 8. RTF/Helicopter Sling/Riser Rigging

Analysis and Simulation Tasks

Several unique analyses were developed and executed throughout the EELV Demo phase. Figures 7. and 8 show the typical suspension proximity and mass concentrations requiring modeling over the release modes. These included: (1) the analysis of the RTF "snapback" energy during both water entry and test release situations, (2) analysis of the natural frequency of the PM/helicopter two-body system, and (3) detailed simulations of the parachutes and helicopter, RTF, and PM, as a three body problem to support selection of test release conditions plus analysis of damping/energy absorption of the RTF motion during test.

RTF Snapback Energy

Stored energy in PM harness legs was an initial concern. The design issue was that on water entry, the stored energy in the harness legs would sling the RTF toward the fragile engine nozzle. While a valid concern, detailed simulations, including 3-body (Parachute, RTF, and PM) simulations revealed that retention of the parachutes for minimal time (1.0 sec. after water impact) would restrain the RTF and prevent high energy projectile motion.

Further detailed analysis addressed the freefall of the RTF and rotation (following water entry) of the engine nozzle into the RTF. In all cases, the spray shield provided sufficient support to constrain the RTF and prevent contact, provided that the RTF lock held.

Test unique deployments, including crane drops, helicopter drops directly into the water (for water entry loads) and helicopter parachute deployments, presented additional challenges for RTF "snapback" analysis. For all of these analyses, detailed load - elongation characteristics were developed for the Kevlar and nylon webbing types used. These data are presented in Ref. 2. Depending on the test case, the RTF energy was integrated using the the load elongation (LE) curve. The LE curve selected was based on the test case. In general, the unload curve, for either the first cycle, or up to the tenth cycle was used based on the number of load cycles envisioned. For crane drop tests the first cycle was selected, and for helicopters, the work hardened 10^{th} cycle.

The total stored energy was then used to compute damping requirements, or to compute RTF velocity by a work-energy solution. RTF velocities up to 45 fps were predicted as energized by the loaded harness legs.

Helicopter/PM Natural Frequency

The natural frequency of the PM/helicopter combination became an issue for all helicopter carriage flights. The one per revolution rotor frequency of the CH-47D is $f_h = 3.75$ Hz.

Helicopter captive carry criteria specified a frequency isolation between the natural frequency for the two body system (f_n) and the rotor frequency (f_h). The criteria was:

$$f_n \leq 0.7\, f_h \qquad (1)$$

The two body, undamped natural frequency was used from Equation (2) as:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k_{TOT}}{\dfrac{m_h m_{pm}}{m_h + m_{pm}}}} \qquad (2)$$

This criteria provided the test designers with valuable design criteria for the selection of a release configuration. Following the identification of an acceptable frequency isolation configuration (nylon and Kevlar webbing), then a damper configuration which would enable the test, was selected.

Configurations which were finally selected included stiff Kevlar harness legs (3) and 3-6 ft. nylon straps for frequency isolation. Once the nylon straps were included, the helicopter hook attachment (the 7.0 lb. metal apex fitting) defined an object to damp to avoid RTF impact on release.

One important configuration was a long pendant to release the PM in close proximity to the water (wind drift water entry loads), with the helicopter in forward motion. In this case Kevlar member length (70 ft.) provided sufficient frequency isolation. Here the key analysis was a trajectory of the helicopter fitting, following release, to assure a miss of the PM.

Lifting Sling Energy Damping/Attenuation Design

Multiple energy attenuators were supplied to prevent either the apex fitting or the RTF from recoiling into the Space Shuttle Main Engine (SSME) nozzle after helicopter hook release. When the hook is released, the apex fitting recoils towards the propulsion module as the propulsion module separates unless restrained. The energy attenuators to peel apart during separation motion, breaking multiple rows of stitching as the peeling progresses, which absorbs the energy stored in the nylon slings and Kevlar vehicle harness.

RTF and apex fitting energy calculations revealed damping requirements in the 1000 to 3000 ft.-lb. range with typical strokes of 3-4 ft. While these devices are well understood, they are less well quantified, and control had to be precise. As a result, a laboratory test was devised to quantify the performance of a range of damper designs.

The details of these tests are presented in Ref. 2. All dampers were based on MIL-spec nylon webbing with various thread weights and stitch patterns. Finally, a design was selected using five (5) rows of FF nylon tread Type 301 straight stitch into a 1.75 inch, 2,500 lb. nylon base webbing. This configuration delivered 1575 ft.-lbs./ft. of attenuation, with a consistent force characteristic.

Open ended attenuators were selected to provide the required damping and release either the RTF or apex fitting at the end of the power stroke.

PM Deployment Simulation Model

One of the key analyses for program success was the simulation of the PM during helicopter release and parachute deployment Analysis of the PM aero-dynamic characteristics indicated that unless the PM release point was carefully selected, the PM pitch attitude and pitch rate, at parachute line stretch, could induce nozzle contact dynamics during deployment.

To address this concern, a simulation was developed, which addressed the three (3) bodies involved. The bodies modeled included the parachute, the RTF, and the PM. Each body was modeled in 3-DOF.

The parachute pack motion during deployment was constrained to that of the helicopter. Following PM release, acceleration (forward and up) were applied to the helicopter/pack combination. The parachute location at line stretch was thus predicted. The three leg harness was modeled by an equivalent pitch plane harness. The LE characteristics of this Kevlar member are detailed in Ref. 2. In summary, the non-linear LE characteristics of Kevlar, including both the load and unload cycles were modeled to represent damping.

Simulation Results

The simulation results had the predictable high frequency digital characteristics expected from stiff harness leg springs and a low mass (RTF). Satisfactory peak to peak tension computations in the harness legs were achieved by small time steps, to maintain numerical convergence. The result was a tool which could predict PM motion, harness elongation (slack vs. loaded) and RTF position as a function of PM release condition. The release condition could be varied by helicopter forward velocity and PM initial hang angle.

Early results indicated that the RTF for the most part followed the loaded harness leg (light mass, stiff spring) and it was quickly identified that as long as both harness legs were loaded with $l_{harness} > l_0$, , there was no nozzle harness contact.

Figure 9 presents a summary of various release conditions modeled and the resulting dynamics. The figure shows only aft leg unloading as the harness configuration details (forward leg close to c.g.) assures the forward legs to be continually loaded. The release envelope of Figure 10 for helicopter forward velocity and PM hang angle was developed to guide test designers. In the end, a release condition of $V_h \leq 20$ KIAS (≈ 0 KIAS goal) and PM design hang angle = 27° was chosen. Two very successful deployments, with predicted PM dynamics, resulted.

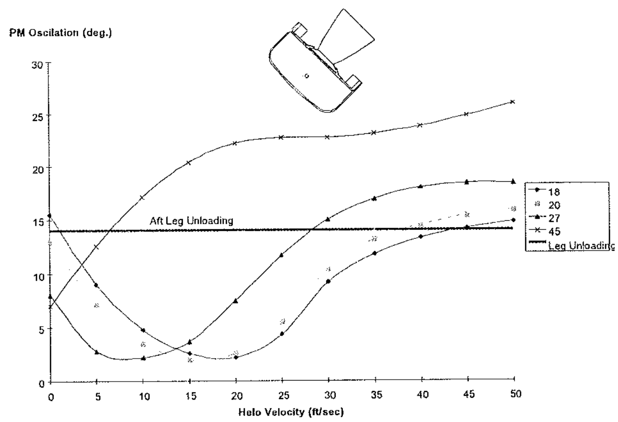

Fig. 9. Initial PM Oscillation vs. Release Condition

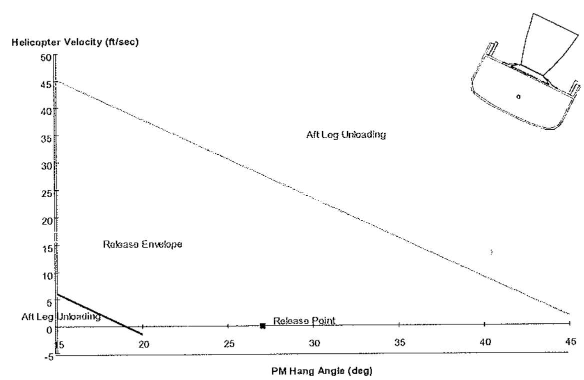

Fig. 10. Release Envelope

Roll Stabilization Issue

Hover hookup and lift off of the PM was planned with the PM rotated to the 27° liftoff position on its mobile ramp transporter. The pack and main vehicle suspension components were secured from the hovering CH-47 downwash. Manual hookup of both the pack set and PM was accomplished by the ground crew using a platform crane for pack positioning and a man-lift.

During the captive carry verification test unacceptable yaw motion of the PM was observed. A 270° yaw counterclockwise occurred, followed by a 420° yaw clockwise rotation. This eventually damped out as the CH-47 reached transfer flight speed of 65-85 KIAS. Random yaw altitude of the PM at the release point was clearly unacceptable because of line twist between the packs and center hook suspension rigging. This also added risk of nozzle contact by the harness during deployment. Based on the analysis, an aligned pack-PM pitch-plane launch was required.

A roll control tag line and welded frame were designed and accepted by the Army National Guard. Mounting the welded frame to floor helicopter floor anchors provided outboard anchor points for the dual tag lines. The tag lines consisted of 5,000 lb.-Kevlar cord terminating with 10 ft. of 4,500 lb. nylon tubular webbing. Electrical disconnect cutters were placed at each PM tag line attach point. Thus, roll control was maintained during the transfer flight, complete with tag line electrical release during the launch countdown and retraction post-launch.

Flight Test Results

A single canopy drop test (conducted at Yuma Proving Grounds) and the two cluster demonstration drops defined the following performance .

The deployment bags and all of the ferry flight components worked as planned. The deployment bags, under constant surveillance, were directionally stable. During the high speed ferry flight the deployment bags did fly at the expected aft trim angle caused by drag. The critical directional stability of both the triple clustered and faired deployment bags and the PM was maintained. Line stretch and first stage reefed opening was achieved with no nozzle contact as shown in Figure 11.

The parachutes opened in a positive fashion and with even inflation. The cluster drag and resulting descent rate were better than predicted. The cluster trim angle was at the optimum design point for drag and stability which contributed to the excellent descent performance. Table 2. summarizes EELV main parachute cluster performance.

The Apollo Earth Landing system produced a clustered drag coefficient of 0.767 on the final missions. The EELV cluster was 0.2 above that level. Drag efficiency of the individual canopy was thus high at η_D=44.0 ft.^{2}/lb.(cluster) or η_D=51.0 ft.^{2}/lb.(single parachute) which are very high values for Ringsail type parachutes.

The RTF functioned as designed. The ferry flight and drop test loads caused no damage. The spray shield cable ran through the RTF cable mechanism as designed and the bladder inflated as required. The upper risers and helicopter lifting slings were all severed after splashdown as planned.

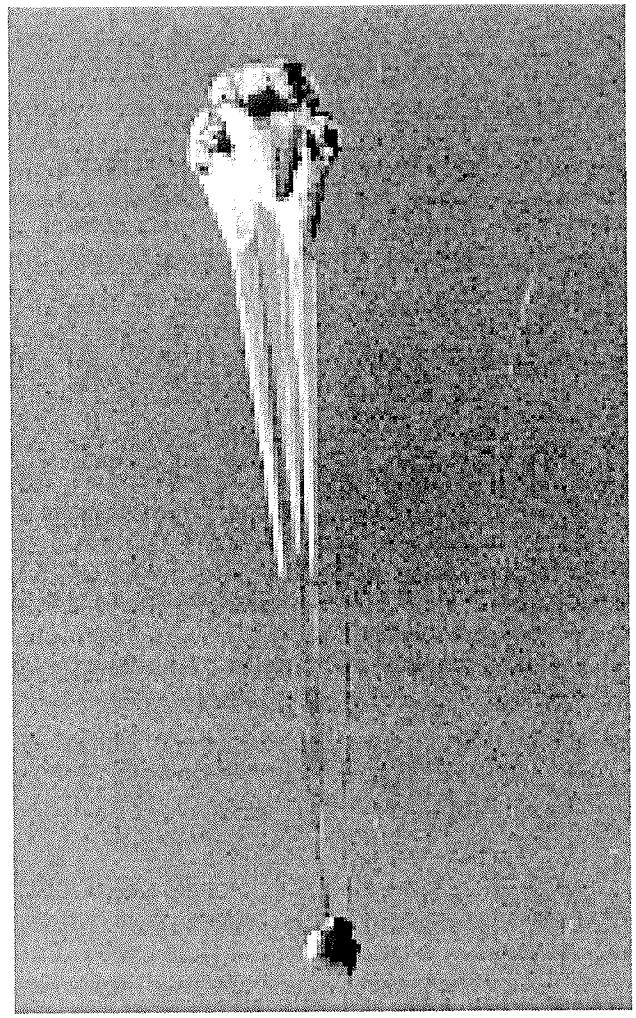

Fig. 11. Stage One Reefed Opening

TABLE 2. - Flight Test Results

-	Single Canopy Test	Gulf PM Drops
S_0	14,527 ft^2	43581 ft^2
W_V	7,000 lb.	20,000 lb.
Z_0	12,000 ft.	4,700 ft.
V_0	227 ft/sec.	Near Hover
Ve_0	19.0 ft/sec.	20.0 ft/sec.
W_{PA}	340 lb.	985 lb.
C_{D0}	1.12*	.965

* Neglects non-standard atmosphere shift, updraft, etc.

Conclusions

The successful series of recovery tests at the NASA Stennis Space Center verified technical feasibility and economic benefits of Boeing's reusable Propulsion Module design concept for future cost efficient launch systems. Full scale prototype hardware of critical propulsion module items were successfully designed, fabricated and tested during an ambitious, rapid prototype program environment which took only 10½ months from go-ahead to completion of full system drop tests in the Gulf of Mexico. New techniques of handling and releasing large helicopter payloads were devised and successfully implemented.

Detailed assessment of the SSME recovery loads and environments showed they were well within Shuttle program experience. The spray shield/RTF combination proved to be a weight efficient, effective, robust design for marine environment protection, thus minimizing flight turnaround operations for the reusable SSME. Parachute system performance was outstanding, proving the feasibility of very low descent rates to minimize module recovery loads as shown in Figure 12. The Ringsail main canopy inflation, stability and drag performance established a new standard for parachute recovery of large space modules.

References

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[2] Taylor, A. and Delurgio, P.,"A Summary of Materials Characteristics as Applied to Detailed Parachute Simulations," 14th ADS Conference Proceedings, AIAA-97-1537, June 1997.

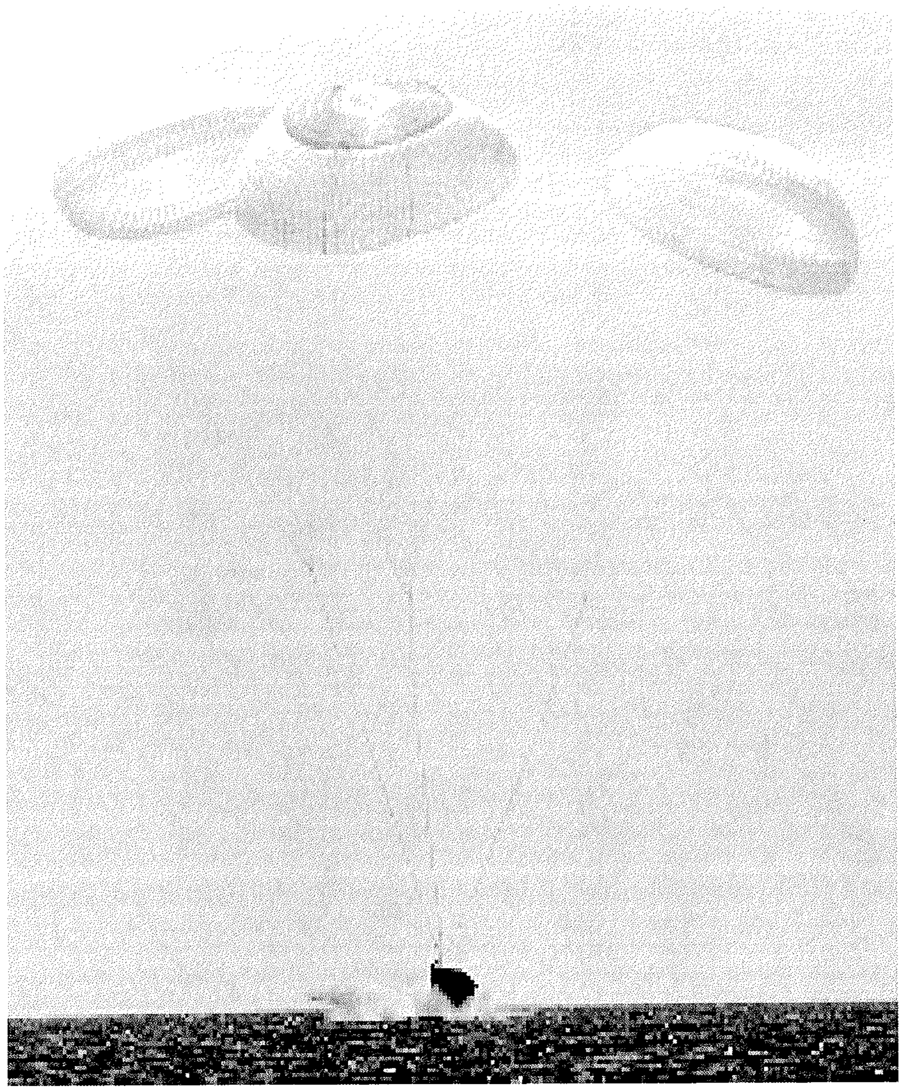

Fig. 12. PM Splashdown in the Gulf of Mexico